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Anthropometric Source Book

Volume I: Anthropometry for Designers

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Yellow Springs, Ohio

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As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and original units are written parenthetically thereafter. The physiological pressure unit used, mm Hg, has not been supplemented with an SI equivalent because of its universal usage in the biomedical field.

16. Abstract

This three-volume publication brings together a large mass of anthropometric data which define the physical size, mass distribution properties, and dynamic capabilities of U.S. and selected foreign adult populations. Aimed specifically to meet the needs of design engineers engaged in the design and execution of clothing, equipment, and workspaces for the NASA Space Shuttle Program, the book is also designed to be of use to human engineers in a wide variety of fields. It is not only a comprehensive source of specific anthropometric information but also a guide to the effective applications of such data. Subjects covered in Volume I include physical changes in the zero-g environment, variability in body size, mass distribution properties of the human body, arm and leg reach, joint motion, strength, sizing and design of clothing and workspaces, and statistical guidelines. Material presented includes such unpublished anthropometric data measured under one-g and zero-g conditions. Also included are 1985 body size projections and actual cutouts of quarter-scale two-dimensional manikins for use by designers.

Volume II contains data resulting from surveys of 61 military and civilian populations of both sexes from the U.S., Europe, and Asia. Some 295 measured variables are defined and illustrated.

Volume III is an annotated bibliography covering a broad spectrum of topics relevant to applied physical anthropology with emphasis on anthropometry and its applications in sizing and design.

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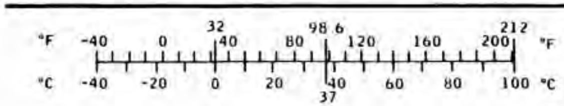
METRIC CONVERSION FACTORS

Approximate conversions to metric measures

Symbol	When you know	Multiply by	To find	Symbol
		LENGTH		
in.	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate conversions from metric measures

Symbol	When you know	Multiply by	To find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in.
cm	centimeters	0.4	inches	in.
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10 000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.036	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

The quality of the interface which connects man with his machines frequently determines the ability and ultimate performance of the man/machine unit. The more dependent man is upon his creations the more critical is the connecting link and nowhere has he been more absolutely dependent upon the man/machine interface than in space flight. For every second of existence in space, for every moment of comfort, for every endeavor, man is completely dependent upon devices of his own making. The interfaces--whether they be space suits or rocket controls and displays--are crucial.

As might have been expected, putting man into space systems has been one of the most expensive and perplexing aspects of spacecraft design. The human body has evolved under, and in response to, the large and ever-present forces of gravity. It is not surprising, then, that when such a body is placed in a weightless environment it frequently finds itself at a distinct disadvantage. Man does, of course, adapt to weightlessness. Some aspects of this adaptation are apparently harmless while others could be incapacitating during and after return to one-g. Thus, in addition to helping the human body in zero-g maintain its mechanical one-g functions, space systems must accommodate changes in the body's size, shape and posture.

The beginning of any man/machine interface is objective knowledge of the full range of man's size, shape, composition and mechanical capacities. Hence, anthropometry is fundamental to successful designs for the future use and exploration of space. The only alternative is the costly process of trial and error.

At this writing we are in the process of designing a space vehicle which will carry large numbers of people, men and women of all nations and races and of a wide range of ages and sizes, into and out of weightlessness. It is inevitable that such a transportation system will be followed by space stations where people will function for long periods in an environment for which their bodies were not designed.

Fortunately, there is a great mass of anthropometric data available on sizeable samples of the world's populations. The first task, then, was collecting, standardizing and presenting sufficient data on the size, shape and mass of samples of the world's populations to give the designer primary information for accommodation of the subjects who will use the shuttle and other vehicles. Contained in this book also is a body of information on strength, reach, range of joint motion and mass distribution properties of the human body which are essential to the design of clothing, equipment and workspaces for use in space vehicles.

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It is not enough, of course, to assemble information. Crucial to the effective use of anthropometric data is an understanding of their origin, limitations and proper application. To this end, chapters on variability of body size, statistical considerations and the application of anthropometry to sizing and design provide additional explanation and instruction to guide the reader in making meaningful use of the data contained in this book.

Central to the concerns of NASA design engineers is the problem of weightlessness. Unfortunately, in spite of 16 years of space flight, hard data on the changes which take place in man's size, shape and function in the zero-g environment are scanty. Interface problems are legion. A suit of clothing will hardly accommodate 10-centimeter changes in girth or 6-centimeter height changes, yet men undergoing such changes have had to operate in closely fitting space suits. A good look at the relaxed posture assumed by man in the weightless environment will suggest why the conventional seat is not only uncomfortable but also requires forceful strapping if a person is to even stay in it. If weightless anthropometric data are scanty and incomplete, they are nevertheless already sufficient to have redirected much of the space medical effort and to explain many of the phenomena described by crewmen which could seriously impede efficient operation unless dealt with. The opening chapter of this volume contains virtually all of what we now know about this subject. It is hoped that the very paucity of data will challenge future investigators to give this field proper attention.

Finally, those of us who are directly involved in space flight operations are grateful for the dedication of the man/machine engineers who make our lot better. We in turn shall make every effort to help them by bringing back the information they need to help us.

William E. Thornton, M.D.
Scientist Astronaut

PREFACE

The Anthropometric Source Book is designed to provide NASA, NASA contractors, the aerospace industry, Government agencies, and a wide variety of industrial users in the civilian sector with a comprehensive, up-to-date tabulation of anthropometric data. Specifically, it is tailored to meet the needs of engineers engaged in the design of equipment, habitability areas, workspace layouts, life-support hardware, and clothing for the NASA Space Shuttle/Spacelab program. The intent is to provide the designer not only with dimensional data but with underlying anthropometric concepts and their application to design.

All available anthropometric data collected in the weightless environment are documented in this three-volume book, which also includes an extensive tabulation of anthropometric data defining the physical size, mass distribution properties, and dynamic capabilities of U.S. and selected foreign populations. The material covers adult males and females of various age groups, socio-educational backgrounds, races, and ethnic backgrounds. Also included are size-range projections for a 1985 population eligible for manned space flight.

Volume I is a nine-chapter treatment covering all basic areas of anthropometry and its applications to the design of clothing, equipment, and workspaces.

Chapter 1, "Anthropometric Changes in Weightlessness," addresses the effects on the human body that occur as a result of weightlessness. Such topics as weight loss, height increases, neutral body posture, strength and body composition, changes in trunk and limb girth, and loss of muscle mass are discussed in detail. In addition to bringing together in a single source the most comprehensive collection of data on anthropometric change in weightlessness that exists in this country, this chapter calls attention to the potential impact of weightlessness on man/machine design and suggests areas of future study essential to the proper design of man's space environment.

Chapter 2, "Variability in Human Body Size," describes and graphically documents the range of human-body variability found among homogeneous groups. Those trends that show significantly marked differences between sexes and among a number of racial/ethnic groups are also presented. This chapter alerts design engineers to the nature and extent of human-body variability and serves as a guide for modifying and designing man/machine systems.

Chapter 3, "Anthropometry," presents tabulated dimensional anthropometric data on 59 variables for 12 selected populations. The variables chosen were judged most relevant to current manned space programs. Appendix A to this chapter is a glossary of anatomical and anthropometric terms. Appendix B covers selected body dimensions of males and females from the potential astronaut population projected to the 1980-1990 time frame. Appendix C contains a 5th-, 50th-, and 95th-percentile drawing-board manikin based on the anticipated 1980-1990 body-size distribution of USAF fliers.

Chapter 4, "The Inertial Properties of the Body and Its Segments," is a user-oriented summary of the current state of knowlege on the mass distribution properties of the adult human body. The data presented lend themselves to mathematical modeling.

Chapter 5, "Arm-Leg Reach and Workspace Layout," is an informative chapter on functional reach measurements relevant to the design and layout of workspaces. Basic reach data are given, along with recommendations for applying corrective factors to adjust for differences in (1) workspace, task, and body position; (2) environmental conditions - primarily gravity forces; and (3) anthropometric characteristics of various populations.

Chapter 6, "Range of Joint Motion," discusses (1) selected reviews of the range-of-joint-motion literature; (2) techniques for measuring range of joint motion; (3) range-of-joint-motion terminology; (4) recommended range-of-joint-motion data for the design engineer; (5) differences in the range of joint motion due to the effects of age, sex, and protective clothing; and (6) the range of joint motion of selected two-joint muscles. Together, chapters 5 and 6 constitute a comprehensive data base and guide to workstation layout.

Chapter 7, "Human Muscular Strength," deals with (1) a general review of human muscular strength, (2) specificity of muscular strength, (3) relationships between static and dynamic muscular strength, (4) strength within the arm reach envelope of the seated subject, and (5) comparative muscular strength of men and women. This chapter should aid design engineers in relating strength data to workspace design.

Chapter 8, "Anthropometry in Sizing and Design," discusses the application of human body-size diversity and quantification to engineering design. Procedures are outlined for using anthropometric data in the development of effective sizing programs.

Chapter 9, "Statistical Considerations in Man/Machine Design," reviews statistical concepts that appear repeatedly in the NASA Anthropometric Source Book and touches on some statistical problems that will typically confront individuals using the data.

Volume I was compiled and edited by the following members of the Anthropology Research Project of Webb Associates, Yellow Springs, Ohio: Edmund Churchill, Lloyd L. Laubach, John T. McConville, and Ilse Tebbetts.

Volume II summarizes the results from anthropometric surveys of 61 military and civilian populations of both sexes from the United States, Europe, and Asia. Some 295 measured variables are defined and illustrated. The variable names are listed in alphabetical order. For each variable, there is a computer order number by which it is identified, a list of surveys in which it was measured, a group of summary statistics, and a series of values for the 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentile of the given population.

Preceding the presentation of the actual data are three indexes designed to assist the reader in the use of the material. The first of these indexes, entitled "Anthropometric Surveys: A Reference List," lists and describes the sources from which all the summary data in this volume were extracted. This enables the user to obtain additional information on any survey population if that is desired. The next index, entitled "Definition of Measurements," includes both written descriptions of all the variables cited and simplified line drawings, where feasible, to illustrate a particular measurement. The third index is provided to further guide the user in identifying and finding measurements relevant to his or her particular needs. It is entitled "Index of Dimensions." The variables are listed by name and are categorized by anatomical region and by anthropometric technique.

Volume II contains a minimum of text-type material and is primarily a handbook of tabulated dimensional anthropometric data. It is probably the most comprehensive source of summarized body-size data currently in existence.

Volume II was compiled and edited by the following members of the Anthropology Research Project of Webb Associates, Yellow Springs, Ohio: Edmund Churchill, Thomas Churchill, Kay Downing, Peggy Erskine, Lloyd L. Laubach, and John T. McConville.

Volume III lists 236 annotated references related to the field of anthropometry. Included are references to every anthropometric survey outlined in volume II, as well as a variety of other works on static and working anthropometry of U.S. and foreign populations, anthropometry of parts of the body related to the design of specific items such as gloves or helmets, joint range and arm reach, mass distribution properties of the body, strength data of various kinds, sizing systems, material on zero gravity, and some general reference works. The references listed were selected by the editors and contributors to volume I. Their objective was to reference those studies, reports, textbooks, and surveys that they deemed most related to their specific subject area and that would be most helpful to the user.

Volume III was compiled and edited by the following members of the Anthropology Research Project of Webb Associates, Yellow Springs, Ohio: Lloyd L. Laubach, John T. McConville, and Ilse Tebbetts.

John T. Jackson
Spacecraft Design Division
Lyndon B. Johnson Space Center

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CHAPTER I
ANTHROPOMETRIC CHANGES IN WEIGHTLESSNESS

by
William Thornton, M.D., Scientist Astronaut
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Man's body has been shaped by the constant force of gravity for the majority of his existence, both as a species and as an individual. His muscles, skeleton, and nervous and cardiovascular systems have all adapted to counter this force. It is not surprising that marked changes occur in such a body when forces of gravity are effectively removed, as in orbital flight. Significant changes in posture, size, shape, fluid quantity, and fluid distribution did occur during space flight (Thornton et al., 1977). Loss of strength, muscle, and body mass and changes in body composition will also occur in the absence of countermeasures (Thornton and Rummel, 1977). Such changes are summarized in table 1.

In addition, man has become dependent upon gravity for many of his actions. Virtually all of his furniture and many of his tools, appliances, and workspace designs are dependent upon gravity's action, both on the devices and on the man.

Placing the human body in such a changed force environment as weightlessness generates a new area of anthropometric study and application and provides a challenge to man/machine designers. The small amount of anthropometric data available from space flight has already been sufficient to indicate the major impact of such data on the design of apparatus for use in space, as well as to redirect many efforts of life scientists. With a new generation of spacecraft, equipment, and space systems now in progress, there is an immediate need to allow for changes due to weightlessness in the initial stages of design. Such changes in the human body must be accommodated if designs are to be efficient.

The primary purpose of this chapter is to document and explain, as fully as possible, the anthropometric data currently available on the human body in weightlessness. Although these data are far from complete and often lacking in rigor, they are virtually all that are available. Where possible, explanations of physiological mechanisms are included in an effort to provide as much understanding as possible of the interaction of the body with this new environment. A few comments on potential applications have been made. Other chapters also address the application of this material and existing one-g data to space-related problems. In many cases, imagination and creativity will be required to combine existing techniques with these data for optimum results.

TABLE 1.- ANTHROPOMETRIC CHANGES IN WEIGHTLESSNESS

Change	Time required for change to occur
May be progressive	
Weight loss	Small initial loss first 1 to 2 days; final course depends on diet, exercise, and other factors.
Trunk and limb girth	Immediate in some areas; slow in others; depends on diet, exercise, and other factors
Loss of muscle mass and strength	Days to weeks; depends on diet, exercise, and other factors
Body composition and density	Days to weeks; depends on diet, exercise, and other factors
Constant and persists throughout flight	
Height increase	2 phases: immediate step; then, hours to days for slower component
Posture	Immediate
Fluid shifts	Hours to 1 or 2 days
Center-of-mass shifts	Days

Some indications of changes caused by weightlessness can be gleaned from anecdotal information supplied by astronauts; stuffy noses, low-back fatigue, blood rushing to the head, the thin "bird legs of space," and suit-donning difficulties all provide hints.

Specific anthropometric measurements made during the American space program prior to Skylab consisted of preflight and postflight weight, a few handgrip measurements, and stereophotogrammetric photographs taken on Apollo 16.[1] Preflight and postflight measurements of leg circumferences and volumes are available from other Apollo studies.[2]

On the Skylab 2 mission (SL-2), strength and fatigue measurements and segmental girth measurements of upper and lower extremities were made before and after flight.[3] Also, in-flight mass measurements (Thornton and Ord, 1977) and one set of in-flight facial photographs were obtained, and preflight and postflight stereophotography and analysis[4] were performed.

On SL-3, the aforementioned measurements were continued and a few body-girth measurements added. Whole-body photographs of the crewmen in anatomical positions were made during flight.[5]

On SL-4, the previously accumulated data were augmented by a set of photographs illustrating free-floating posture. Measurements of segmental limb girths, truncal girths, and heights were obtained throughout the flight (Thornton et al., 1977).

On the Apollo-Soyuz Test Project (ASTP) mission, in-flight height and leg-girth measurements were made.[6,7] Followup one-g studies and analysis are still in progress. Insofar as possible, all of these data are included here and will be described.

In the Russian space program, anthropometric measurements, including postflight strength and limb girths, were made as early as 1968 on Soyuz 4 (Kakurin, 1971). In-flight handgrip forces were measured on the Soyuz 9 and 11 flights; static muscle forces and limb girths were measured on Soyuz 9 and probably on other flights. Preflight and postflight studies of walking were made on Soyuz 9 to 12 (Parin et al., 1974). Additional studies were probably performed. All Russian data available will be presented here.

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[1]P. Rambaut et al.: Nutritional Studies. Ch. 6 of Biomedical Results of Apollo. NASA SP-368, 1975.

[2]W. Hoffler and R. Johnson: Apollo Flight Crew Cardiovascular Evaluations. Ch. 4 of Biomedical Results of Apollo. NASA SP-368, 1975.

[3]W. Thornton and J. Rummel: Measurement of Crew Somatic and Functional Changes in Skylab 1/2. Skylab 1/2 Preliminary Biomedical Report, JSC-08439, 1973, pp. 77-94.

[4]M. Whittle and R. Herron: Stereophotogrammetry. Skylab 1/2 Preliminary Biomedical Report, JSC-08439, 1973.

[5]W. Thornton, W. Hoffler, and J. Rummel: Anthropometric and Functional Changes on Skylab. JSC-08439, 1973, sec. 2-4.

[6]J. W. Brown:. Zero-g Effects on Crewman Height. JSC IN 76-EW-3, 1976.

[7]W. Hoffler et al.: Inflight Lower Limb Volume Measurements. JSC ASTP DTO C, 8, D, 1975.

WEIGHT CHANGES

SUMMARY

Weight loss has been an apparent constant side effect of space flight. It has ranged from 0 to 8 percent of body weight and has borne no fixed relation to mission duration, individual crewman, mission, or vehicle. On Skylab, the causes of such losses were demonstrated. Other than a small initial fluid loss, there is no obligatory weight loss associated with space flight if proper countermeasures are used during flight. On exposure of a person to weightlessness, a shift of fluid from the more dependent portions of the body occurs and 2 percent or less of body weight is lost through diuresis and/or decreased thirst over the first day or two. In a person with a caloric (food) intake which matches his energy expenditures, there will be no further loss. On the person's return to a one-g environment, the fluid lost will be replaced by retention for the first day or two.

It now appears that most of the losses in space flight were caused by inadequate diet. Energy costs on Skylab were surprisingly high - 203 to 212 kJ per kilogram (22 to 23 kcal per pound) of body weight per day - and

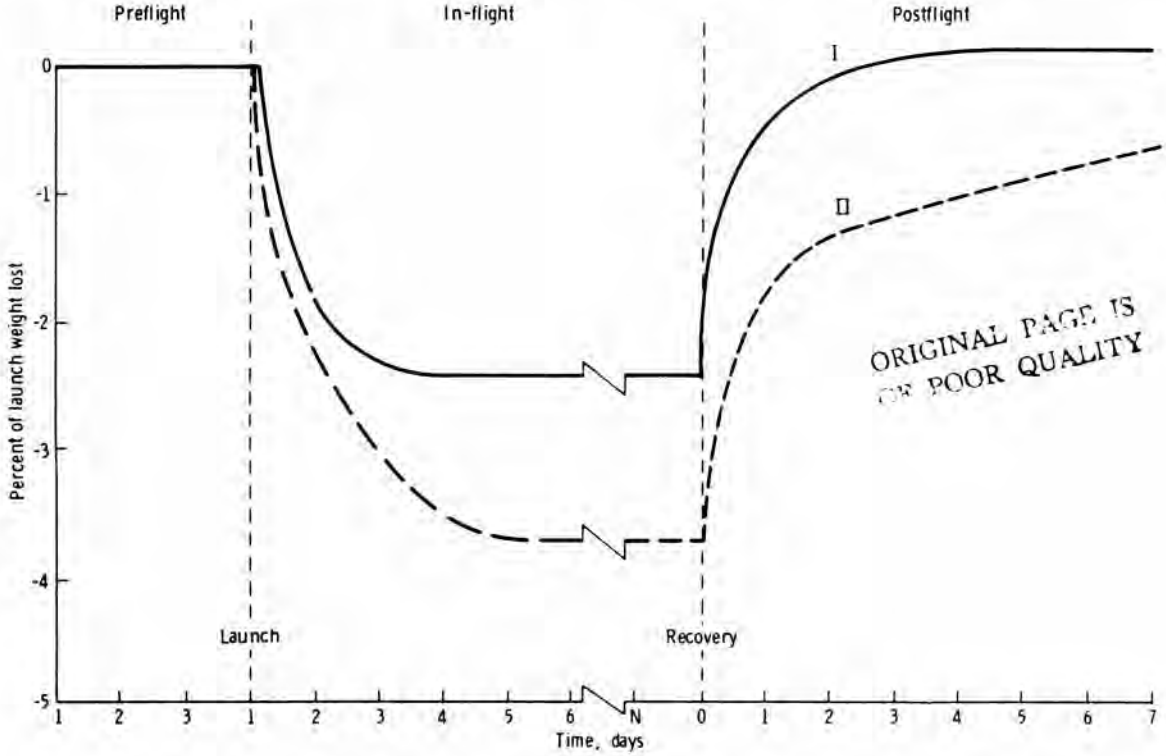

Figure 1.- Typical loss of body weight during weightlessness and gain after recovery.

reflect the pace of crew activity. It also appears that crewmen on most missions will require as much food as they do on Earth; and in some cases, considerably more. On the basis of Skylab data, curve I in figure 1 shows a typical loss that might be expected from normal crewmen in caloric balance. Curve II shows what might be expected from a crewman with a transient decreased intake resulting from a vestibular upset (inner ear disturbance causing vertigo, nausea, or vomiting), an occurrence that will probably affect 30 percent of all astronauts. After the fluid and caloric losses of the first 5 days, crewman II remains in balance until he returns to a one-g environment, at which time the fluid loss is replaced and an increased diet initiates replacement of the tissue loss incurred in the first day or two of flight. Any further caloric excess or deficit would be superimposed on these curves as a loss or gain at approximately 36 mg/kJ (1 lb/3000 kcal) in crewmen with normal body fat. Such losses may be chronic if caused by an inadequate diet, or acute if caused by a transiently increased workload.

Weight Change Data

Virtually every astronaut and cosmonaut has lost weight during space flight. These losses are tabulated in appendix A, tables A-1 and A-2. This potential problem of weight loss is intimately associated with problems discussed in the section on the musculoskeletal system.

On Mercury, Gemini, Apollo, and ASTP missions, astronauts were measured in the nude after voiding with calibrated clinical scales (platform with balance arm) which typically have a resolution of 0.1 kg (0.25 lb). These measurements are given in tabular form in appendix A and plotted against the logarithm of flight duration in figure 2.

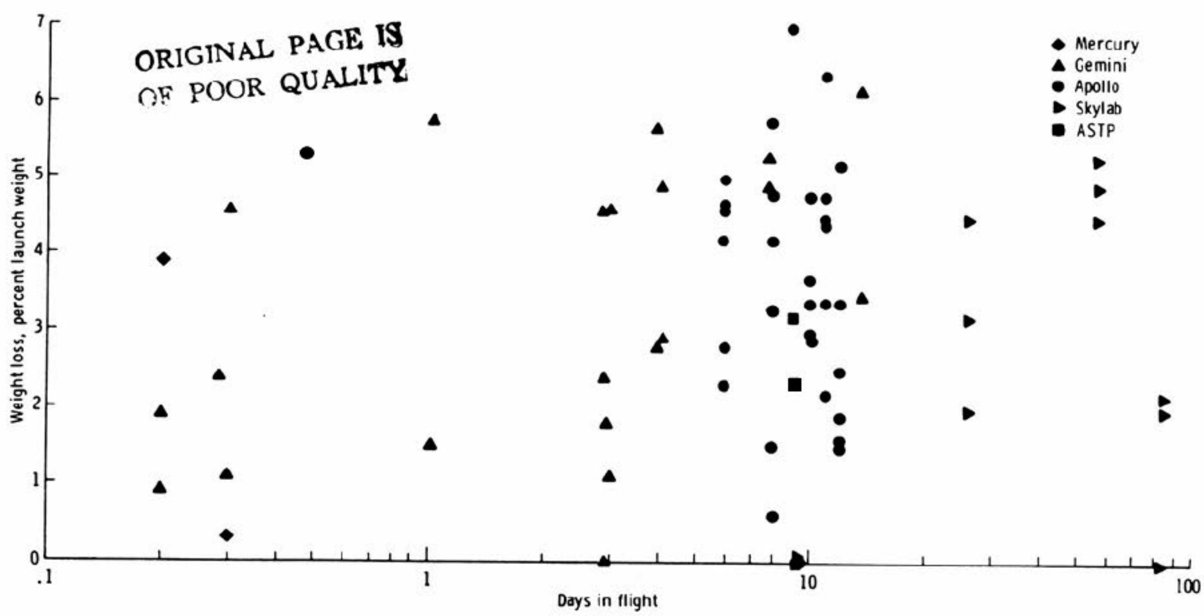

Figure 2.- Weight loss as a function of mission and duration.

On Skylab missions, daily measurements were made before and after flight with calibrated clinical scales each morning; the astronauts were measured in the nude immediately after arising and voiding. Body mass was measured in flight under the same constraints with a nongravimetric mass-measuring device (Thornton and Ord, 1977) which had a repeatability of ±50 g (±0.1 lb) and an absolute error of 0.1 to 0.45 kg (0.25 to 1 lb), with the lower figure more probable.

Data for all Skylab flights are plotted as 3-day sliding averages (i.e., data from each day of measurements are averaged with the preceding and following days' values) against time in figures 3 to 5. Daily weights without averaging are given in appendix A, tables A-3(a) to A-3(c).

Available Russian weight data are given in appendix A, table A-2. The techniques used to determine these data are unknown. It should be noted that many of the Russian weight measurements were made up to 24 hours after recovery.

Results and Comments

On the basis of the data in figure 2 and in table A-1 of appendix A, weight loss would seem to be a consequence of space flight. The amounts of loss were extremely variable even in the same subject. For example, in Stafford, the following variations were observed: 1 day, -5.8 percent on Gemini-Titan 6 (GT-6); 3 days, -1.1 percent on GT-9; 8 days, -1.5 percent on Apollo 10; and 9 days, +0.9 percent on the ASTP mission. Several attempts to show a relationship between weight loss and mission duration (Verigo, 1976) have been unconvincing and break down completely in the face of Skylab results.

Prior to Skylab, the necessary data on food intake, in-flight stresses, and other factors required to understand the losses were simply not available. On Skylab, the in-flight mass measurement plus the knowledge of food intake provided the data for understanding loss mechanisms. Further, the rigidly controlled diet was generally increased on each flight, producing in effect a series of three in-flight experiments. This mass measurement and diet control, plus individual variation and a 56-day one-g chamber simulation (Thornton, 1973) with use of the same restricted diet, provided proof of the primary cause of the losses.

In virtually all of the flights, including most of the Skylab missions, a calorically inadequate basic diet was supplied as a result of the assumption that in-flight requirements were less than those for a one-g environment.[8] Figures 3 to 6 show the opposite to be true. Figure 6 is a plot of normalized weight loss as a function of energy intake. Extrapolation to zero loss shows the surprisingly high energy requirements of 203 to 212 kJ per kilogram (22 to 23 kcal per pound) of body weight per day, or approximately 15 503.1 kJ (3700 kcal) per day for a 77.1-kg (170 lb) man.

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[8]See footnote 1 on p. I-3.

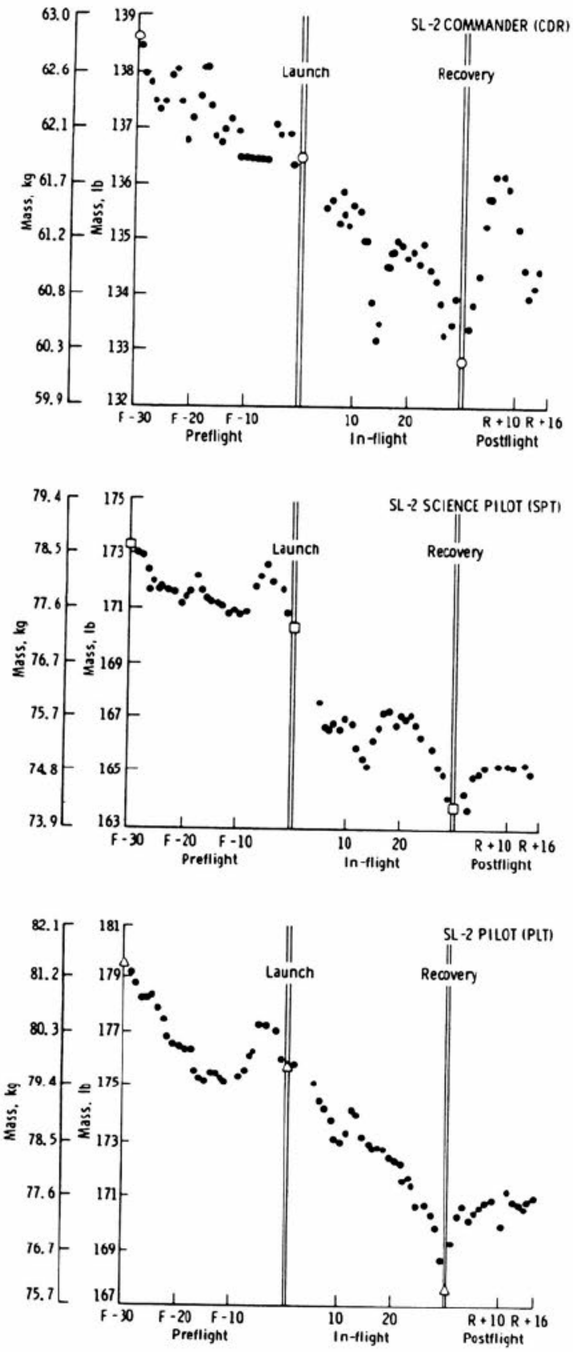

Figure 3.- Changes in body mass of SL-2 crewmen, where F - 10 is 10 days before lift-off, R + 10 is 10 days after recovery, etc.

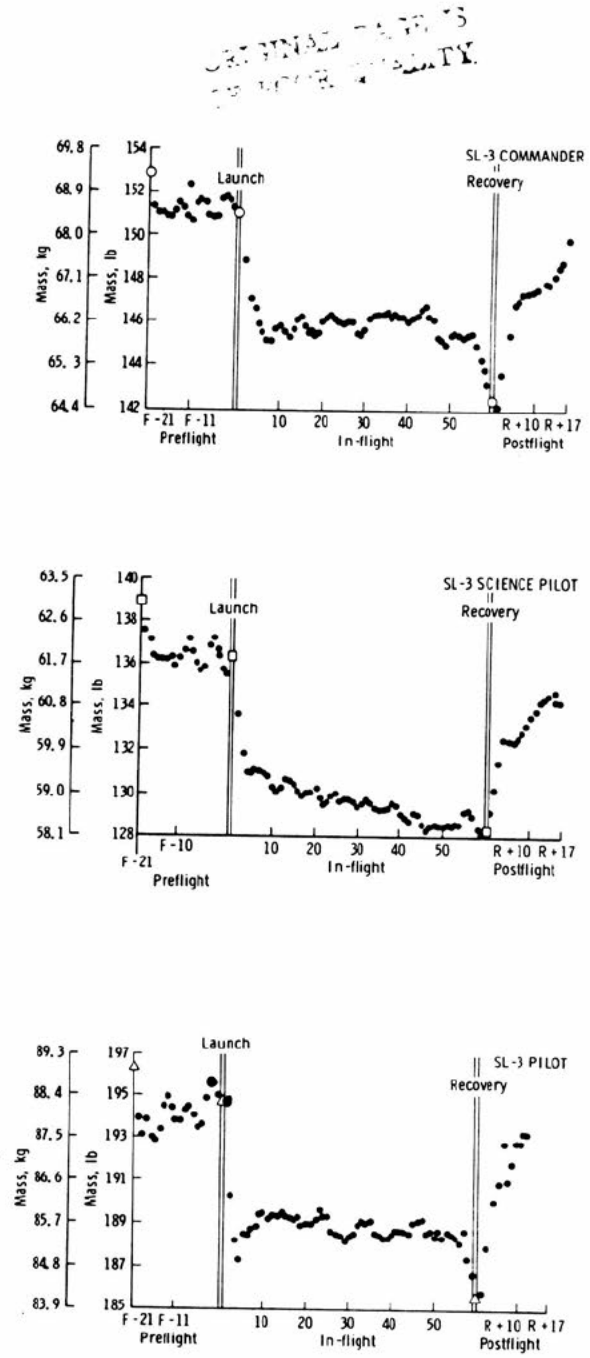

Figure 4.- Changes in body mass of SL-3 crewmen.

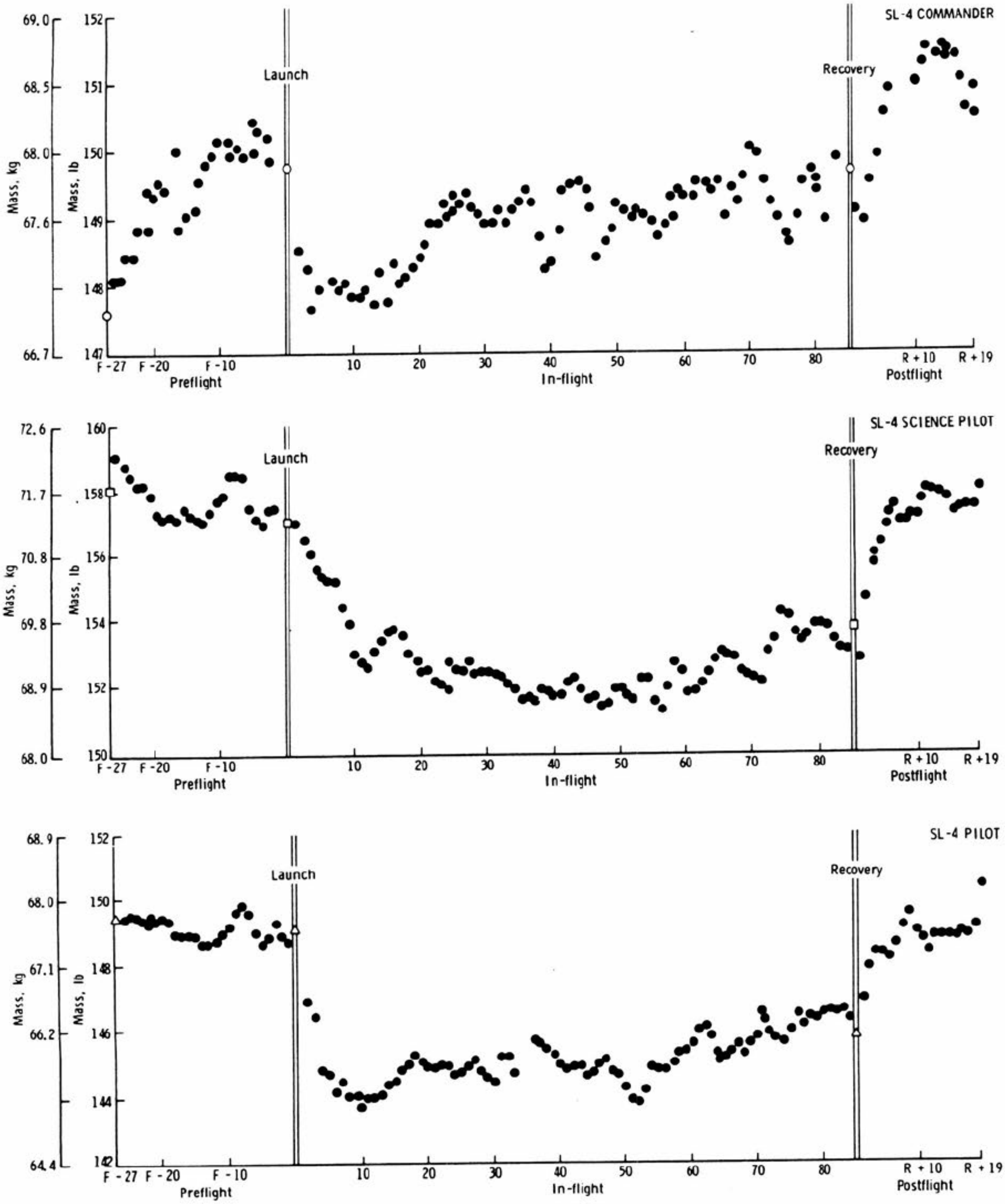

Figure 5.- Changes in body mass of SL-4 crewmen.

These values apply only to the Skylab missions, in which performance requirements were generally scheduled to the minute for hard driving crewmen who often worked well into sleep and other off duty periods. Other flights may have different requirements.

On the basis of the results from Skylab simulation and from Skylab flights, there can be little doubt that the major losses of weight in space have been caused by inadequate caloric intake. Examples of this correlation can be seen in the results for all three crewmen on SL-2 (fig. 3), whose losses started with the controlled diet and continued throughout the mission. A similar pattern was seen preflight in a 56-day Skylab simulation in one subject on an inadequate diet (Thornton, 1973).

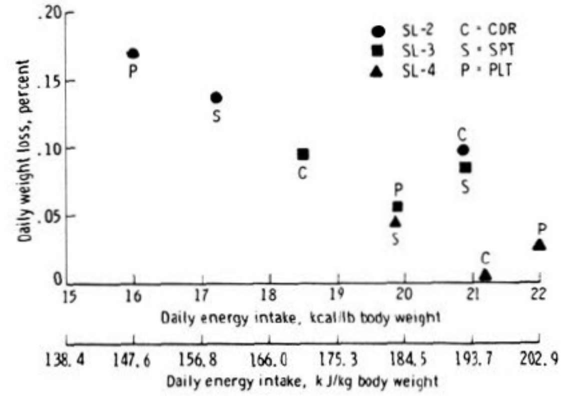

Figure 6.- Average weight loss as a function of average energy intake of Skylab crewmen. The SL-2 CDR, the SL-3 SPT, and the SL-4 PLT had very low body fat and a higher rate of weight loss.

It was observed that temporary weight decreases can be caused by periods of increased activity such as reentry preparations - as in the case of all three SL-2 crewmen (fig. 3) and the SL-3 commander and pilot (fig. 4). Smaller, long-term losses may be superimposed on other changes, as in the case of the science pilot on SL-3 (fig. 4), who had small preflight losses which continued throughout the flight. Another major consideration is poor intake during the first portion of the mission due to vestibular upset. This upset, which may range from nausea and vomiting to poor appetite, played a role in the sharp initial losses observed in SL-3 and SL-4 (figs. 4 and 5).

A second significant source of weight loss is caused by fluid redistribution. On initial exposure of a person to weightlessness, blood and other fluids are shifted from the lower, normally dependent portions of the body to the upper body, with an increase in central blood volume. The body probably attempts a reduction of this volume by diuresis in accord with the hypothesis of Gauer and Henry (1963). The initial loss of approximately 2 percent in the first few days of flight and the same rapid gain for the first few days of recovery are consistent with this theory. Figures 3 and 4 are good examples of such loss and gain.

In summary, the only obligatory weight loss associated with space flight is that associated with fluid redistribution. Major losses to date have been caused by inadequate caloric intake from diets too low in calories or by inadequate food consumption in flight, especially during the first days of flight.

Applications

If diet is adequately controlled, weight losses should cause no difficulty to spacecraft design or operations. There are some center-of-mass shifts involved, but these will be treated elsewhere. Indirectly, this problem will be reflected in the necessity for provision of adequate amounts of food and oxygen.

HEIGHT CHANGES

SUMMARY

Astronauts will "grow" approximately 3 percent in height (typically about 5 cm (2 in.)) during the first day or two of weightlessness and then retain this increase throughout the mission until reexposure to one g, when the process is reversed. It appears that virtually all of this increase is caused by a lengthening of the spinal column; thus, the change is limited to the trunk and neck. Any man/machine interface which is affected by such changes in height and truncal length will be impacted. Potential design problems include pressure suits, clothing, and work stations and control stations with critical eye levels.

These changes which occur in weightlessness are simply the full expression of daily changes on Earth which result from loading and unloading of the spinal column. Figure 7 is a curve typical of height changes which occur in an individual on exposure to weightlessness. The intervertebral disks are viscoelastic structure responsible for the changes, which occur in two phases. When the column load is changed, as - for example - when a person moves from lying to standing or vice versa, there is an immediate change in height, ΔH_1, on the order of 1 percent. Changes in height are inversely related to changes in axial load (e.g., height increases when one changes from the vertical to the horizontal under one-g conditions and vice versa).

If the change in load is maintained, such as during sleep at night, a second, slower exponential change in height, ΔH_2, occurs according to

$$H = H_0 \pm \Delta H_2(1 - e^{-t/T})$$

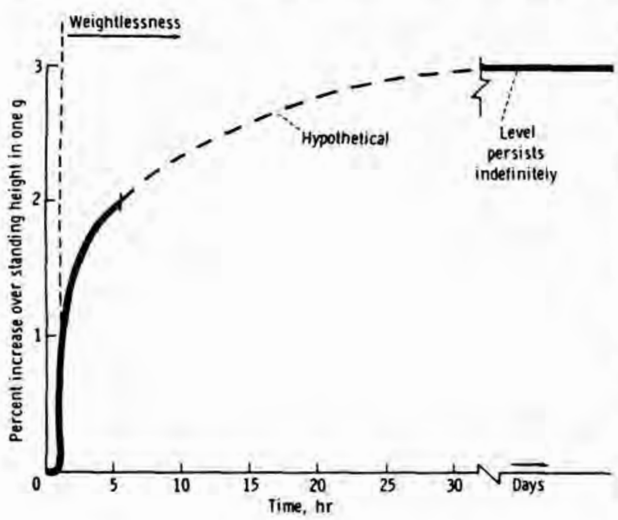

Figure 7.- Typical curve of height changes on exposure to weightlessness.

where

H = height at time t

H_0 = height at time of load change

ΔH_2 = maximum change in height under changed load

t = time since load was changed

T = subject's characteristic response time

On Earth, ΔH_2 typically amounts to some 1+ percent in adults. The magnitude and time response of change is usually reduced with age and is somewhat higher in females. There is considerable individual variation amounting to ±30 to ±40 percent in values of ΔH_1 and ΔH_2. There are also considerable individual differences in response under one-g conditions as compared to maximum change under zero-g conditions. Some crewmen showed virtually the same changes under both conditions, whereas most added another 0.5 to 1.0 percent of height in weightlessness over the maximum changes on Earth.

The following factors should be considered in making one-g height measurements for weightlessness operations: (1) horizontal rather than vertical subject positions are more appropriate; (2) an even closer approximation to height in space can be obtained immediately after the subject has had a night's sleep or been in another horizontal position for a prolonged time; (3) during transition to and from weightlessness, height will change rapidly, especially under added g-loads; and (4) all measurements must be carefully made with the subjects in standard positions (0.16 cm (0.06 in.) is a practical working resolution), with use of a rigid, carefully calibrated jig.

Height Change Data

Height is a fundamental anthropometric parameter of particular importance in space flight. Aside from data developed in annual physical examinations, no records of pre-postflight height can be found prior to SL-3 or in Russian data. A study of in-flight height changes on SL-4 and the ASTP mission was done by Brown.[9] Isolated height measurements were also made in flight on SL-4 as a part of an anthropometric package (Thornton et al., 1977). Followup one-g studies on the SL-4 and ASTP crewmen and other subjects are underway. Pertinent data from these studies are included here.

Most of the preflight height measurements of SL-4 crewmen were obtained by using standard clinical techniques. In flight, the Skylab crewmen anchored themselves with restraint shoes against a wall and were measured from

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[9]See footnote 6 on p. I-3.

vertex to sole of the shoe with a square and calibrated tape. Four series of measurements were made. Conventional clinical methods were used after flight, but more attention was paid to measurement technique and all scales were calibrated and read to closer limits. Similar techniques were used in the ASTP mission except that in-flight vertex height was marked on a bulkhead and this mark was measured from the "floor."

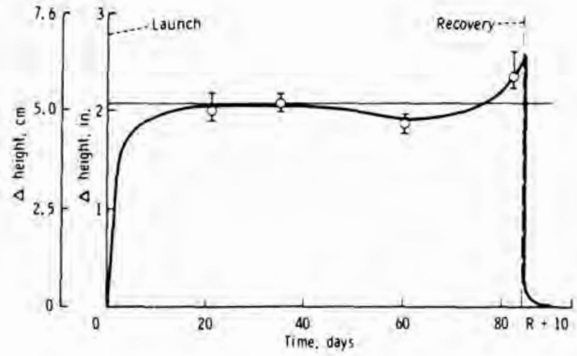

Figure 8.- Graph of mean in-flight SL-4 height measurements.

Initial heights of all astronauts who have flown in space are given in appendix A, table A-1, and preflight, in-flight, and postflight heights of SL-4 astronauts are shown in appendix B, tables B-1 to B-3. Figure 8 is a graph of mean in-flight ΔH measurements of SL-4 crewmen. Skylab 4 crewmen were very similar to each other in height in the one-g environment (±0.25 cm (0.1 in.)). They also showed similar in-flight changes and the data seem consistent, although the author is suspicious of a small systematic error on the last day of in-flight measurement. Postflight measurements were not adequately controlled in terms of time, and the exact course of postflight change is unknown. There was an obvious rapid decrease during the first few hours after recovery in all three crewmen. Two crewmen (CDR and PLT) quickly returned to original height, whereas the SPT followed a more gradual course. Changes in height on going from horizontal to vertical posture were not determined on the day of recovery; but by the second day, such changes were in the expected range (∽2 cm (0.8 in.)) and remained there. Studies of one-g height changes in SL-4 and ASTP crewmen are underway but incomplete at this time.

The ASTP in-flight data[10] had some obvious inconsistencies; but if these points are removed and the maximum increases taken, the data are consistent with Skylab results (see table 2).

Comment and Analysis

Analysis of height changes on Earth provides an understanding of height changes in weightlessness. Although anecdotal information on such changes on Earth is relatively common, there is surprisingly little on the subject in the literature. DePuky (1935) did a study of maximum daily changes in height in a large population and presented a theoretical basis for such changes, but he did not follow their time courses.

[10] See footnote 6 on p. I-3.

TABLE 2.- COMPARISON OF HEIGHT CHANGES IN CREWMEN OF SL-4 AND ASTP

Crewman	Height, cm (in.)			Height change	
	Preflight	[a]MD-9	MD-21	cm (in.)	Percent
		SL-4			
1 (CDR)	173.0 (68.1)	--	177.3 (69.8)	4.3 (1.7)	2.5
2 (SPT)	173.2 (68.2)	--	177.8 (70.0)	4.6 (1.8)	2.6
3 (PLT)	173.2 (68.2)	--	178.8 (70.4)	5.6 (2.2)	3.2
			Mean	4.8 (1.9)	2.8
		ASTP			
1 (ACDR)	181.4 (71.4)	188.0 (74.0)	--	6.6 (2.6)	3.6
2 (docking module pilot (DMP))	179.1 (70.5)	[b]182.9 (72.0)	--	3.8 (1.5)	2.1
3 (command module pilot (CMP))	180.3 (71.0)	186.4 (73.4)	--	6.1 (2.4)	3.4
			Mean	5.5 (2.2)	3.0

[a]MD = mission day.
[b]MD-8.

There are two components of change in height when one goes from one-g to zero-g conditions or otherwise changes the vertical load on the body.[11] The first component is an immediate change (ΔH_1), such as that which occurs when a person stands up after lying. A second, slower change (ΔH_2) also occurs. This change is observed on Earth after a person has experienced prolonged horizontal posture, such as in sleeping. Although both components may be larger in weightlessness than they are on Earth, there is evidence that it is primarily the slow component that increases.

Several explanations for these height changes might be considered. The rapid component (ΔH_1) could be caused by simple deformation of the soles of the feet, the closing of joint spaces, or changes in anatomical geometry such as spinal curvature or intervertebral disk compression. Cursory observation shows insufficient change in spinal curvature to account for this effect. Measurements of tissue deformation or leg joint changes also show these to be negligible. It thus appears that essentially all of these changes occur in the spinal column from contraction and expansion of the intervertebral disks. For example, when changes in height throughout the day are measured with the subject in standing and seated positions, these changes are identical.

This result is entirely consistent with the results of studies of the characteristics of the intervertebral disks by Kazarian (1975) and others. These viscoelastic disks occupy approximately 35 percent of the total length of the spinal column and, under load, show an immediate elastic deformation, followed by a slower creep. The process is reversed on removal of load. Figure 9 illustrates three ΔH curves for a 14- to 16-hour period after a normal 8-hour sleep period. Subject J. T. (represented by the upper curve), immediately after awakening, "lost" 0.7 percent of his previous height on standing. This change, in going from lying to standing or vice versa, typically remains about the same throughout the day in all subjects as it did here. During the day, there was an approximately exponential loss of height (ΔH_2) which reached a total of some 1.8 percent in this younger subject. This shape is typical of the response curve of all normal subjects. The rate and amount of change varies from individual to individual and with age and sex (see table 3). The characteristic or response time of the exponential component also varies, typically becoming shorter with increasing age. Such behavior under load is consistent with the mechanical analog shown in figure 10.

On the basis of a few cursory measurements made by adding weights to a standing subject, S_1 appears to be a linear elastic element described by Force = Constant x Displacement. This spring constant of S_1 provides the rapid changes (ΔH_1) which occur in changing posture. It has considerable individual variation.

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[11]Changes in height are inversely related to changes in axial load (e.g., height increases when one changes from the vertical to the horizontal and vice versa under one g).

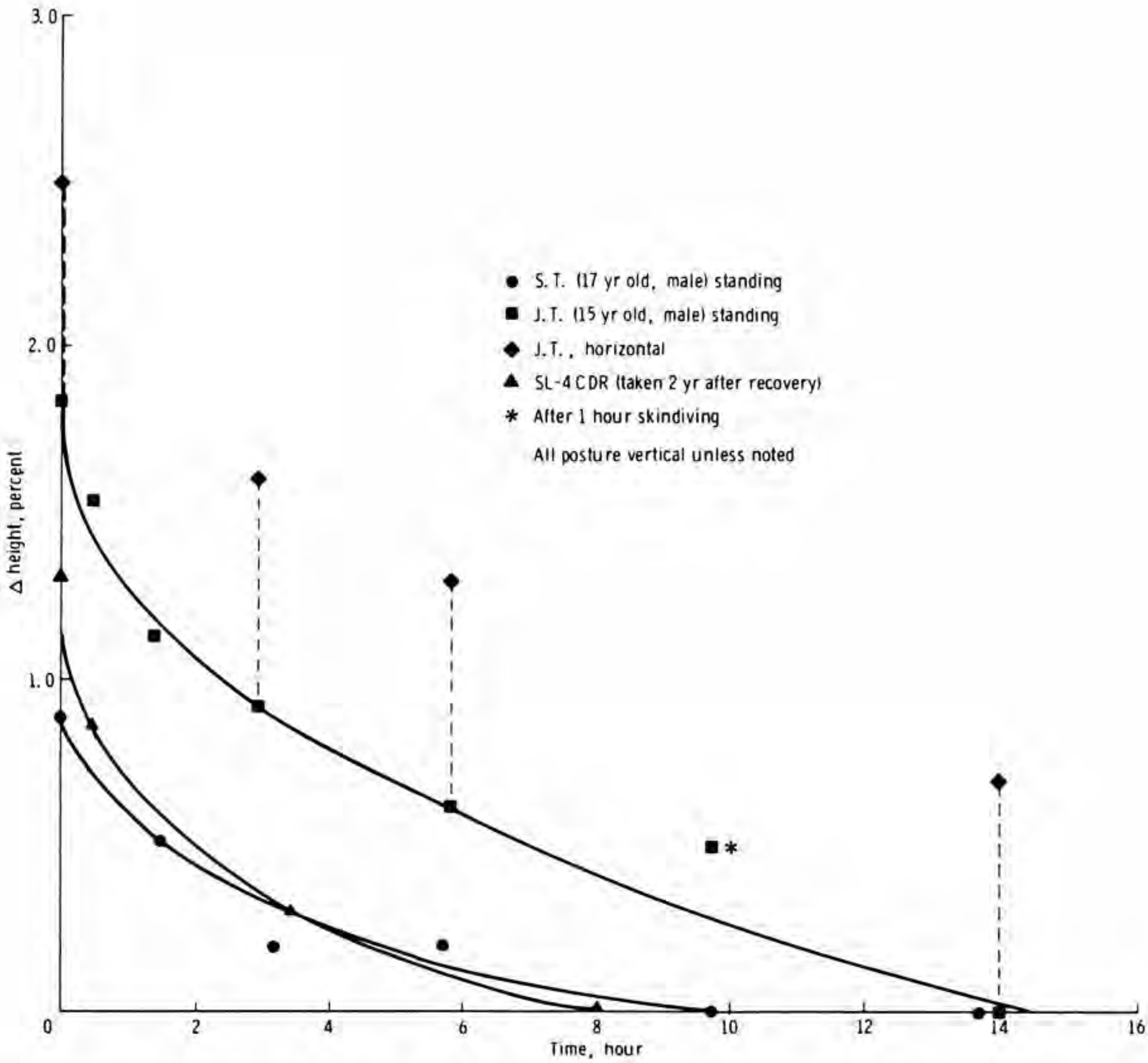


Figure 9.- An illustration of change in height in one g over an 8- to 14-hour period after a normal 8-hour sleep period.

TABLE 3.- CHANGES IN HEIGHT IN ONE g; STANDING AFTER RECLINING, AND STANDING AFTER NORMAL SLEEP PERIOD

Subject	Sex	Age, yr	Measurement day	Normal standing height,	Δ height, horizontal to vertical				Δ height, standing after 8 hr sleep	
				cm (in.)	cm (in.)	Percent	cm (in.)	Percent	cm (in.)	Percent
SL-4 CDR	M	--	[a]R + 1	172.7 (68)	--	--	1.27 (0.5)	0.73	--	--
			R + 5	--	--	--	2.29 (.9)	1.32	--	--
			R + 17	--	--	--	2.03 (.8)	1.18	--	--
SL-4 SPT	M	--	R + 1	172.7 (68)	--	--	2.03 (.8)	1.18	--	--
			R + 5	--	--	--	1.78 (.7)	1.03	--	--
			R + 17	--	--	--	2.03 (.8)	1.18	--	--
SL-4 PLT	M	--	R + 1	172.7 (68)	--	--	1.52 (.6)	.88	--	--
			R + 17	--	--	--	1.52 (.6)	.88	--	--
ASTP CMP	M	--	--	180.3 (71)	1.60 (0.63)	0.89	1.60 (.63)	.89	1.60 (0.63)	0.89
W.T.	M	47	--	185.4 (73)	1.42 (.56)	.77	1.42 (.56)	.77	1.27 (.50)	.68
J.B.	F	30	--	157.5 (62)	1.75 (.69)	1.11	--	--	1.90 (.75)	1.21
J.T.	F	48	--	170.2 (67)	1.60 (.63)	.94	1.60 (.63)	.94	1.60 (.63)	0.94
J.T.	M	15	--	154.9 (61)	1.12 (.44)	.72	1.12 (.44)	.72	3.02 (1.19)	1.95
S.T.	M	17	--	157.5 (62)	1.42 (.56)	.90	1.42 (.56)	.90	1.42 (.56)	.90

[a]R + 1 = 1 day after recovery etc.

As noted in the summary, the second component of change appears to be of the form

$$H = H_0 \pm H_2\left(1 - e^{-t/T}\right)$$

where

H = height at time t

H_0 = height before change in load

H_2 = slow component of height change

t = time since change in load

T = time constant characteristic of individual; may also be expressed in terms of elastic and viscous elements

A typical individual might have the following characteristics.

H_0 = 177.8 cm (70 in.)

T = 30 minutes

If this individual were placed in weightlessness, then 30 minutes later,

$$\begin{aligned} H &= 70 + 0.8\left(1 - e^{-\frac{30}{30}}\right) \\ &= 70 + 0.8\left(1 - e^{-1}\right) \\ &= 70 + 0.5 \\ &= 179.1 \text{ cm } (70.5 \text{ in.}) \end{aligned}$$

and after 3 hours (180 minutes) of weightlessness,

$$\begin{aligned} H &= 70 + 0.8\left(1 - e^{-\frac{180}{30}}\right) \\ &= 70 + 0.8\left(1 - e^{-6}\right) \\ &= 70 + 0.8(0.997) \\ &= 179.8 \text{ cm } (70.8 \text{ in.}) \end{aligned}$$

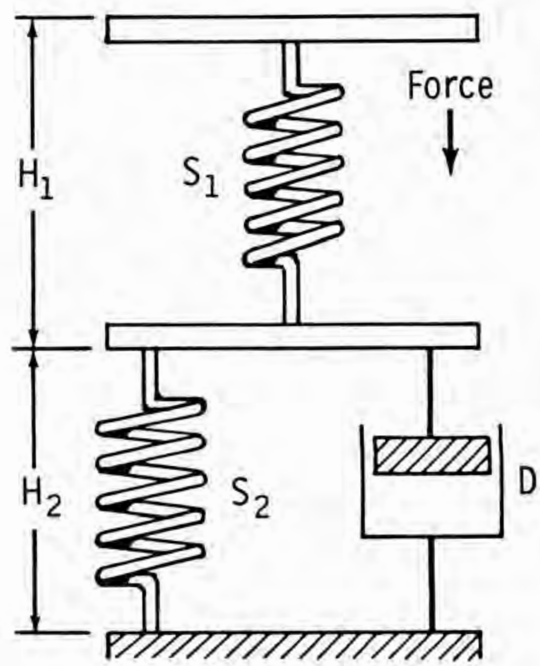


Figure 10.- First-order mechanical analog consistent with changes in axial mechanical loading and unloading. The symbol S_1 represents an elastic component in series with a second elastic component S_2, which is paralleled by a viscous resistance D.

This expression means that if an astronaut's preflight base height is 177.8 cm (70 in.), he will gain approximately 2 cm (0.8 in.) in the second phase of weightlessness "growth." This result is consistent with the behavior of a parallel spring S_2 and a damper D with a response Force = Velocity x Constant, shown in figure 10. A preliminary study of a few male and female subjects shows that females have greater elasticity and that age reduces both elasticity and damping (or viscosity). Such a model is not inconsistent with the anatomy and histology of the disks. One-g height changes in a few subjects, expressed in terms of each of the two components of height change, are given in table 3.

In weightlessness, the changes were greater. The author suspects that the increases were caused by some relaxation of the anterior spinal ligament, which appears to be the limiting element of intervertebral space. Another conceivable explanation of this greater change is the relative increase in tissue fluids that is known to occur in the upper body under a condition of weightlessness. Still other considerations are possible, such as a flattening of normal spinal curvature or a relaxation of ligaments and muscles with an attendant opening of joint spaces of the hips and legs.

At this time, it does not appear possible to predict the total height change in weightlessness from one-g studies. One crewman showed the same amount of change but, in most of the crewmen, weightlessness produced a height increase on the order of an additional 1 percent over that seen on the ground.

Design Applications

The first area of consideration is the problem of closely fitting garments such as space suits, especially in view of some of the difficulties experienced in donning the suits in weightlessness and in view of the planned use of a hard torso suit. If, as appears probable, a change in torso length of 5+ cm (2+ in.) occurs, such a change must be allowed for in this suit.

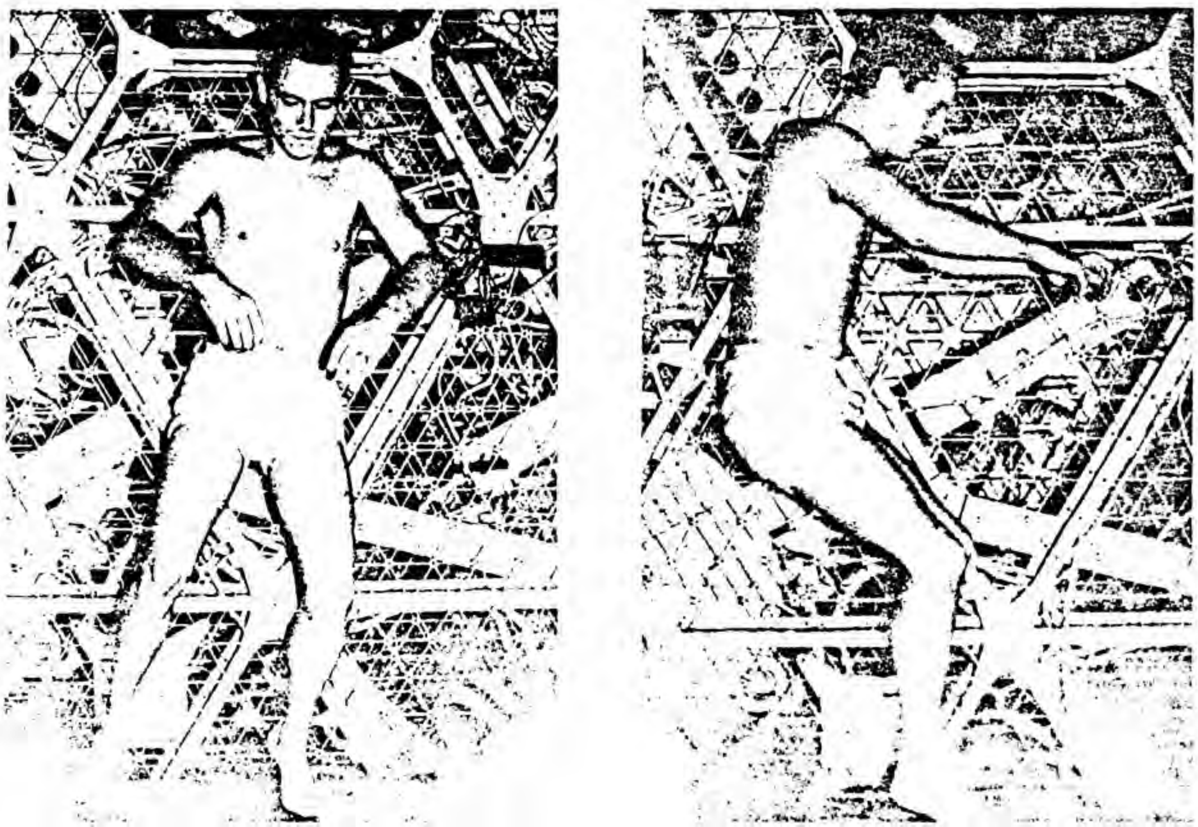
Other areas for consideration are eye heights in critical work station design and in cockpit seating. On Shuttle reentry with a prolonged period of g-load, one can expect a loss of 2.5+ cm (1+ in.) prior to landing. Although this loss would probably not be critical, seat adjustments should be allowed for. The temptation to simply transfer one-g dimensions to zero-g situations must be resisted.

In making one-g height measurements for space operations, several considerations should be observed: (1) horizontal rather than vertical subject positions are more appropriate; (2) an even closer approximation to height in space can be obtained immediately after the subject arises from a night's sleep or other prolonged horizontal position; (3) during transition to and from weightlessness, height will change rapidly; and (4) all measurements must be carefully made with the subjects in standard positions (0.16 cm (0.06 in.) is a practical working resolution).

POSTURE

SUMMARY

In weightlessness, the relaxed, unrestrained human body automatically assumes and indefinitely maintains a single characteristic posture (see fig. 11). To force other postures on the body, either by the subject himself or through external constraint, frequently leads to discomfort, fatigue, and inefficiency. Characteristics of this weightless posture include plantar flexion of the feet and flexion of hips and knees with slight abduction of the legs. The thoraco-lumbar spine is straightened or even slightly flexed anteriorly. Although the cervical spine (neck) is straightened, it is also angled anteriorly, a positioning forcing the head inferiorly and anteriorly and thus lowering the normal angle of vision. Arms and shoulders are elevated, arms are abducted, and there is moderate elbow flexion.



(a) Front view. (b) Side view.

Figure 11.- An SL-4 crewman in a relaxed, unrestrained posture that the human body automatically assumes and indefinitely maintains in weightlessness.

Many one-g positions such as sitting or bending, which depend upon gravity for loading forces, are particularly incompatible with this natural weightlessness posture since active muscle forces or heavy external constraints are required to maintain them and rapidly result in fatigue and pain. On Earth, gravity is also depended upon for stabilization, and some substitute stabilizing mechanism must be provided in flight for many tasks. Foot restraints appear to be the most satisfactory means; but for many tasks, additional body restraints should be available.

All the considerations for design interface with the weightlessness posture cannot be detailed here, but the reader is urged to consult the documentation by Gundersen and Bond[12] and by Jackson et al.[13] and similar detailed considerations as they become available.

Design areas in which this posture must be considered are as follows: work stations and workspace, including equipment; operating and observation stations; any temporary work area in which tasks of even a few minutes in length must be undertaken; rest, sleep, exercise, and eating areas; and virtually every area where man must interface with a vehicle or system in space. Changes in posture must also be integrated with changes in height and shape for proper design.

Postural Changes

The human body in weightlessness naturally assumes and maintains a posture as characteristic of the species and environment as the more upright stance is characteristic of posture on Earth. The weightless posture differs greatly from any normal one-g posture, and the body rebels with fatigue and discomfort against any attempts to force it into one-g postures or appliances consistent with one-g postures. Chief characteristics of the weightless posture, as described in the summary, are shown in figure 11. For comfortable, efficient design, these features must be accommodated. The design engineer must study each situation carefully, thinking in terms of weightlessness rather than one-g. Gundersen and Bond[12] and Jackson et al.[13] have made excellent beginnings in this area.

In the one-g environment, large parts of man's musculoskeletal and neurological systems are dedicated to maintaining a stable position under the forces of gravity. The human body has developed a series of natural positions - standing, squatting, sitting, and lying, among others - dependent upon the amount of support available and upon many other factors, including ethnic history. Most of these resting postures are attained by bringing the various body parts into positions that can be equilibrated against gravity

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[12] Robert T. Gundersen and Robert L. Bond: Zero-g Work Station Design. JSC IN 76-EW-1, 1976.

[13] John Jackson, Robert Bond, and Robert Gundersen: Neutral Body Posture in Zero g. JSC-09551, 1975.

with a minimum expenditure of energy. These positions are dynamic, not static, and depend upon a host of sensor-nerve-muscle loops to constantly apply small corrections. If forces on the body are changed, posture changes accordingly. Development of a large belly, for example, produces lordosis.

Under weightlessness, the body is faced with a totally new situation. Not only are the large antigravity muscles and associated servoloops unopposed by gravity, but the various positions which depend upon gravity for stabilizing forces are now inappropriate. Designs of furniture, machines, and the like which depend upon gravity are usually inappropriate in space (e.g., chairs or a "bicycle" ergometer with a standard seat).

It is not surprising that the body finds a new, entirely different single position of equilibrium, a position usually incompatible with one-g designs. Also, not surprisingly, this new posture caused low-back discomfort in a few crewmen, who found that they could obtain relief by wedging themselves against a structure and pushing to apply force to the back, simulating gravitational forces on Earth. Many astronauts have described some of the design inadequacies and some of the difficulties of working in the weightless environment. Following are typical comments.[14]

> "And so the upshot was that, at the food table and at the ATM panel, you had to hunch down in order to get a decent level . . ."

> ". . . your abdomen and your muscles tensed up and you just got tired of it. What we need to do is remember the postural situation up there and the fact that it is quite natural to be standing up; so you might as well get all of your work surfaces and . . . your eating surfaces up here (indicating chest height)."

> "But one of the things that really bothers you is that you have to remain in a crouch position in order to take these observations. This requires continual muscle tension. I don't mean to be critical. I'm saying it just doesn't work right."

> "When you are adapting things to conform to the human body in zero gravity, you've got to be careful. We found that the body normally wants to assume a more or less erect, slightly arched attitude, and holding yourself in a chair was difficult. The seatbelt helped, although it was hard to adjust."

> "Body posture is one of your big problems."

> ". . . a crouching action is very difficult in zero g; so if you design a foot restraint where there's a posture requiring a crouching action, then you're not helping us at all."

[14]See footnote 13 on p. I-20.

"Your legs tend to come up a little bit so that they're partially bent. I estimate 30° from being in a straight line with your spine, both at the hip joint and at the knee joint. Your shoulders tend to shrug a little bit because you don't have gravity holding them down. Your muscles will tend to pull them up a little bit."

Documentation of this postural configuration was not obtained until SL-4 (Thornton et al., 1977). Photographs were made on the SL-3 flight[15] with the subjects in the erect anatomical position (an example of one-g thinking on the author's part); but on the following mission, preflight, in-flight, and postflight photographs were made with the crewmen in relaxed as well as anatomical posture. Typical photographs from SL-3, with the PLT in forced erect posture, are shown in figures 12 and 13. These photographs added little to existing anthropometric knowledge. The thoraco-lumbar lordotic curve is still present. There is a slight tendency to lean back and incline the head, but this observation was not properly appreciated until the SL-4 photographs with relaxed crewmen were seen. Figure 11 is from this latter series and shows the subject in typical weightless, relaxed posture with eyes closed. Figures 14 and 15 are tracings of such photographs. This posture was seen from the first through the last photographs, showing that such posture was quickly acquired and maintained throughout the mission. Tracings of the segment angles were made from the entire series[16] and are shown in figure 16.

Once documented, this position was easy to recognize in many unposed work situations, such as that shown in figure 17. Further evidence that this postural response is natural to weightlessness was obtained when underwater photographs[16] were made with subjects in the relaxed position (see fig. 18). As can be seen in figure 18(b), the position more closely approximated that assumed in weightlessness when visual cues were removed by blocking vision through the mask.

Mechanisms Leading to Weightlessness Posture

The weightlessness posture adopted in space appears to be inherent and relatively unchanging since it is quickly assumed and showed no significant change in 84 days of weightlessness. This observation was further supported by crew comments. Further, this posture is assumed in water immersion.

Reasons for this posture should provide a fascinating subject of study for anthropometrists, anatomists, neurologists, and physiologists. A full discussion of the subject is beyond the purview of this document, but a few comments are irresistible. Elevation and abduction of the arms might be explained on the basis of increased muscle mass/strength in the abductor-elevator-flexor area, but this argument cannot apply to the legs, where the situation is reversed. Kennedy, at the U.S. Air Force Aerospace Medical

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[15] See footnote 5 on p. I-3.
[16] See footnote 12 on p. I-20.

Figure 12.- The SL-3 PLT in a forced erect posture in weightlessness.

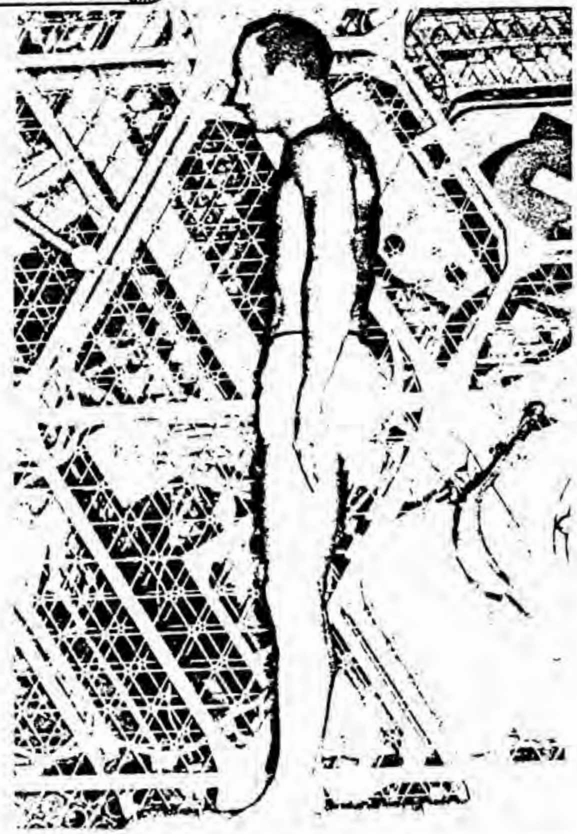

Figure 13.- Side view of the SL-3 PLT in forced erect posture in flight.

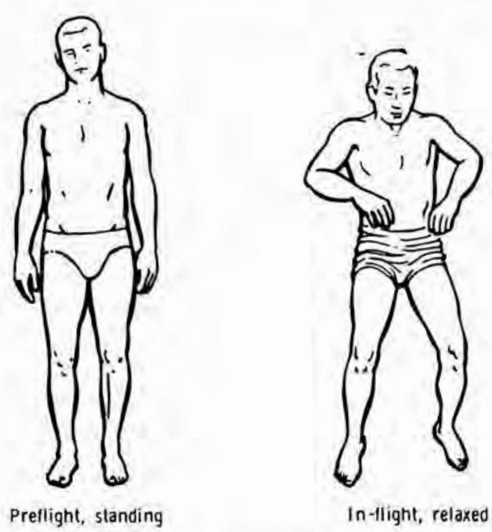

Figure 14.- A front-view comparison of one-g and weightless posture in the SL-4 SPT (tracings from photographs).

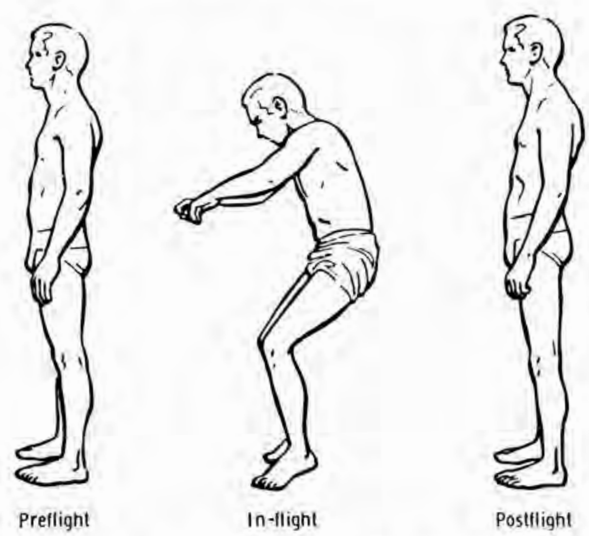

Figure 15.- A side-view comparison of one-g and weightless posture in the SL-4 SPT (tracings from photographs).

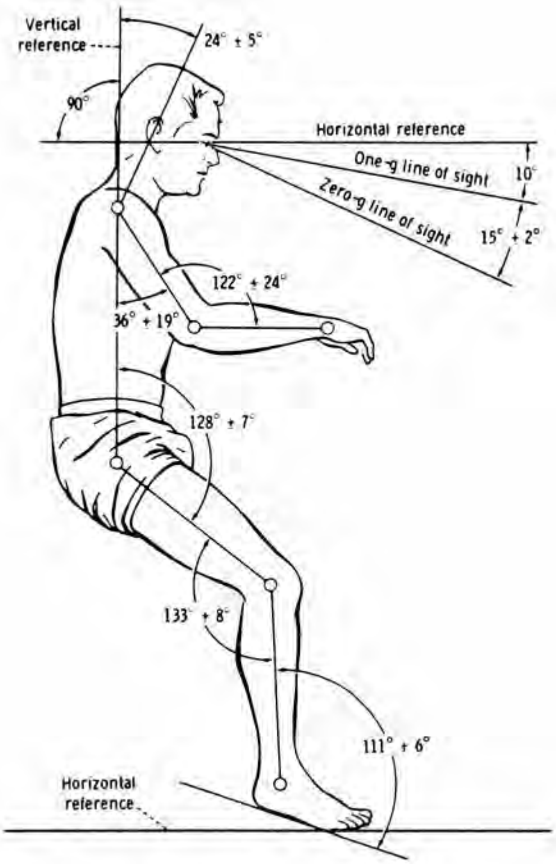

Figure 16.- The segment angles of the weightless neutral body position.

Figure 17.- The body position of the SL-3 PLT while loading film illustrates the relaxed posture in an unposed work situation.

Research Laboratory (AMRL), made a surprisingly good prediction of weightless posture by simply placing links and segments in their midrange (Simons, 1964). Although the link positions in weightlessness must be the result of muscle forces, such forces are not simply the product of available muscle mass/tension. Rather, the tension is controlled by a series of feedback loops which begin with force transducers in muscles and tendons and are modified by a host of other secondary and tertiary inputs. Could the position of limbs then be caused simply by completely unloaded myotatic loops which have their predominant action against gravity? If similar loops are active in the neck region, such a mechanism, plus spinal straightening, might account for cervical angulation. Reasons for straightening of the thoracolumbar spine are not obvious; the pelvis has obviously rotated, but whether this rotation is cause or effect is not yet clear. Much more data will be needed to completely characterize and understand posture and actions under weightlessness conditions.

(a) With unblocked vision.

(b) With blocked vision, resulting in a posture more closely approximating that assumed in null gravity.

Figure 18.- Underwater photographs of subject in a relaxed, neutral buoyancy posture.

Implications and Applications

For efficient man/machine design for space flight, this weightless posture must be taken into account. Space limitations preclude a detailed discussion of design criteria here, but a few general considerations are offered. Insofar as possible, one should start with an absolutely clean slate as regards carryover of one-g design to weightlessness design. Each element of design must be examined only in the light of weightless considerations. Every feature must be examined to see if gravity or one-g orientation influenced the design. If so, the feature must be suspect. The following facts must always be considered.

1. There is no up or down or preferred orientation. Crewmen reset their reference frames at will and without difficulty. There is no reason not to utilize the relative ease of positioning in any reference frame ("up," "down," or "sideways") so long as surrounding spaces are clear.

2. There is no weight to support. Chairs, couches, beds, and other devices to reduce fatigue are useless in this respect. On Skylab, the seat at the Apollo telescope mount console was little used by the first crew and discarded entirely by the second and third crews.

3. Absence of gravity removes body stabilization, which must be provided by alternatives. The primary alternative is a foot restraint, which in many situations appears to be adequate. Both experience and theoretical considerations lead to the conclusion that additional stabilization at the thigh and waist, and perhaps at other points, would be desirable for many tasks.

4. This basically single posture associated with weightlessness must be accommodated if fatigue and discomfort are to be avoided. Having to maintain some positions in weightlessness may produce much more stress than an equivalent position on Earth since muscles might be called on to supply forces which were normally supplied by gravity. Stooping and bending are examples of positions which always caused abdominal fatigue. The natural heights and angles of weightlessness posture must be accommodated. Although more information is needed in many of these areas, available data still provide a point of departure. Some of the areas to be considered are as follows.

a. Since the feet are plantar-flexed at approximately 25 percent, sloping rather than flat shoes or restraint surfaces should be considered.

b. The weightlessness stance is not vertical since hip/knee flexion displaces the torso backward, away from the footprint. Height is now located at a point between sitting and standing; so a work surface must be higher than one designed for normal sitting tasks. The feet are also positioned somewhere between a location directly below the torso (as in standing) and a point well out in front of the torso (as in sitting).

c. Elevation of the shoulder girdle and arm flexion also make elevation of the work surface desirable. Although in weightlessness the head is angled forward and down, a positioning which depresses the line of sight, eye-to-work level may remain practically the same.

d. Under weightlessness, there is no reason to keep work surfaces flat, and they should probably be tilted to accommodate the visual angles.

5. Reference should be made to the publications listed, and to others as they become available, when any weightlessness design is attempted.

The preceding considerations represent only the most rudimentary beginning approach to zero-g design problems. Each case must be approached freshly and with imagination.

SHAPE AND CENTER OF MASS

SUMMARY

The human body has large elastic and fluid components that must change in shape when subjected to change in forces such as occur in going from a one-g environment to weightlessness and vice versa. Other changes in shape may occur through loss or gain of fat and muscle. These changes experienced

on exposure to weightlessness may be classified in three categories according to their time course and origin.

1. Immediate - seconds to minutes, caused by elasticity and plasticity of the body

2. Rapid - minutes to days, caused by fluid shifts

3. Slow - days to months, caused by atrophy of fat and muscle or replacement of muscle by fat

There are immediate changes in height (which also had a slower component, as already described) and in abdominal girth with the subject in anatomical position (standing erect with arms at sides). The latter change may amount to 10 cm (4 in.) or more. In the next day or two, approximately 1 liter of fluid is lost from each leg, much of which goes to the head and supracardiac region where it produces puffiness in the face and mucosal congestion. Both of these changes persist, apparently indefinitely, until the subject returns to a one-g environment.

Slow changes through loss or gain of fat and muscle may be superimposed on the aforementioned changes (i.e., loss of fat will usually further reduce abdominal girth). The time course and magnitude of such changes are entirely dependent upon diet and exercise. An inadequate diet will result in fat and muscle losses, with the ratio depending on individual body-fat percentages. If this diet inadequacy is coupled with inadequate exercise, even more rapid muscle loss occurs. An adequate diet and inadequate exercise will result in an increase of fat and a decrease in muscle. In short, these slow changes are no different from everyday one-g experience.

Without proper exercise, crewmen will lose muscle primarily from their legs. On flights to date, there have been significant losses of body fat and muscle through inadequate diet and lack of proper exercise. Such losses can only hurt crew performance on return to the one-g environment, especially that of the well-conditioned crewman with minimal body fat. Most importantly, with adequate diet and exercise, such tissue changes will be either negligible or nonexistent.

All these changes tend to shift the center of mass cephalad more than can be accounted for by height increases. These changes typically amount to 3 to 4 cm, measured from the soles of the feet.

Although the previously described changes are primarily of interest to the life scientists, accommodations in clothing and other personal gear must be made. Above all, prevention of tissue (fat and muscle) changes must always be considered in system design.

Changes in Shape

Seventy percent of the body is water, with some 30 percent of this being outside the cells. In addition, several body areas mechanically behave as

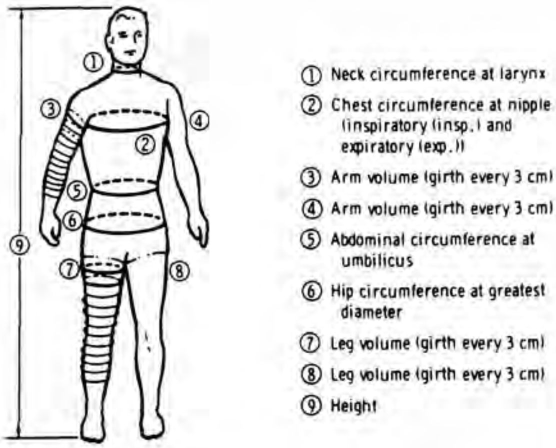

Figure 19.- Anthropometric measurements made on the Skylab crewmen.

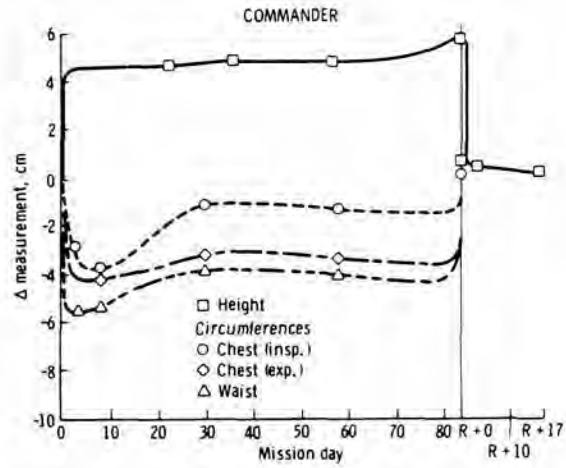

Figure 20.- Truncal girth changes of SL-4 crewmen in an anatomical position in weightlessness with one-g measurements as a baseline.

fluids in elastic compartments, whereas other body components have elastic and plastic properties. It should not be surprising that changes in shape occur as the body is moved from a one-g environment to weightlessness and vice versa. Although these changes probably have more implications for the biomedical researcher than for the man/machine designer, there are several changes that could affect clothing and personal equipment. Such changes in shape also overlap and reflect changes in other anthropometric areas, such as muscle function.

Shape variations can be placed in three categories, based on time course and mechanism.

1. Immediate - seconds to minutes, caused by elasticity and plasticity of the body

2. Rapid - minutes to days, caused by fluid shifts

3. Slow - days to months, caused by atrophy of fat and muscle or replacement of muscle by fat

Immediate Changes

Immediate changes occur in areas of the body containing elastic elements[17] that would be under load in the one-g environment, such as the

[17] Muscle tone is included for present purposes.

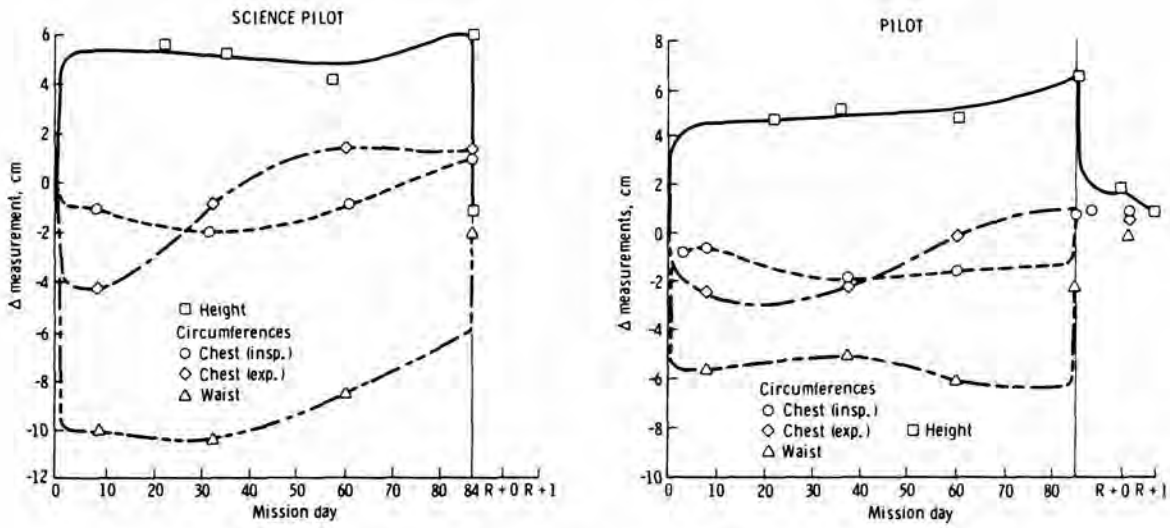

Figure 20.- Concluded.

intervertebral disks (see the section on height) and the abdominal region. In the absence of tissue changes such as fat or muscle loss, these changes will disappear on reexposure of the body to one g. Figure 19 depicts measurements made before and after flight on SL-2, SL-3, and SL-4 and in flight on SL-4. Truncal measurements are tabulated in appendix C, tables C-1(a) to C-1(c). Plots of the immediate changes seen in SL-4 crewmen are shown in figure 20.

Unfortunately, the area of most interest here, the first minutes of weightlessness, must remain a subject of speculation until future flights. The early portions of the curves shown in figure 20 are based on theoretical considerations and one-g measurements. Changes in height have already been discussed. The large waistline reductions may be explained by elimination of equivalent hydrostatic force on the abdominal contents, which may be considered semiliquid here. This liquid column is normally constrained anteriorly and laterally by the abdominal muscles. Under weightlessness, unbalanced forces from these muscles move the contents inward and upward until they are counterbalanced by other elastic forces. In both the United States (Sawin, 1977) and the Russian (Kakurin, 1971) programs, a loss of vital capacity in weightlessness has been documented that probably is in part a reflection of increased visceral pressure against the diaphragm. Another portion of the shift in abdominal volume is accounted for by the general elongation of the trunk through height expansion.

Changes in chest dimensions are smaller and less easy to explain but appear to be consistent. The reduced dimensions could be due to an increase in the costo-vertebral angles secondary to the elongation of the spine, possibly followed by some in-flight adaptation of costo-vertebral ligaments and intercostal and other musculature. There were no significant changes detected in neck and hip girth on SL-4.

Another area in which immediate and probably rapid change is to be expected is the female breast, but there has not yet been an opportunity to make the pertinent studies in this area.

Rapid Changes

The rapid changes that occur over a matter of hours to days are caused by fluid redistribution. Again, the full expression of mechanisms that are active to a lesser degree under one-g conditions is being seen. For example, everyone is familiar with slightly swollen ankles after standing, puffy eyelids after a night's sleep, and similar one-g manifestations of fluid shifts. When the normal adult stands, there is an unbroken column of blood in veins and arteries from heart to foot, with a linearly increasing hydrostatic pressure from the heart downward that reaches 90 mm Hg and more in the foot.[18] The head and neck veins are empty until they reach a level just above the heart. Arterial pressure to head and neck is linearly reduced by the height of its hydrostatic column; that is, portions of the body below the heart have increased fluid pressures, whereas those above the heart have relatively lower pressures. This increased pressure is partially offset by an increased number of elastic elements in the lower body. On exposure of the body to weightlessness, all hydrostatic forces vanish and the venous pressures are essentially equal everywhere, with the tissues below the heart at relatively lower fluid pressures than "normal" and those above the heart at higher fluid pressures. Fluid now tends to move out of the areas below the heart which have increased elasticity and pressures and into those above with less tissue pressure.

Among the first and most consistent "symptoms" of weightlessness were stuffy noses and a feeling of head fullness secondary to increased pressure and fluid shifts. The first evidence of the extent of these fluid shifts was obtained from a set of SL-2 in-flight "mug shots" at the end of the mission showing puffy faces, edematous eyelids, and full head and neck veins. These changes are now well documented (but not measured) and appear to persist as long as one is in weightlessness.

It was not until SL-4 that the magnitudes of the fluid shifts were documented, with in-flight segmental girth measurements of the arms and legs[19] (Thornton et al., 1977). Volumes were calculated from limb girths every 3 cm by assuming that the arms and legs consisted of a series of regular truncated cones. Repeatability was on the order of 100 ml for legs of 70-kg subjects.

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[18]This hydrostatic pressure is added to any existing arterial or venous pressure.

[19]Postflight volume measurements could not show the magnitude of changes, for the volumes change toward normal quite rapidly.

Left-limb volume changes of SL-4 crewmen are graphed in figure 21, and volumes of both legs are tabulated in table 4. Note that volume changes of 1+ liters per leg occurred in all crewmen. It was not possible to follow the right-leg volume changes as closely as those in the left leg because of schedule problems. There were differences between the two, but it was not possible to determine significant differences from available data. However, a total volume of approximately 2 liters was lost from the legs and shifted elsewhere in the body through the elastic forces described. Preflight and postflight measurements were made with the crewman in a supine position to minimize errors from gravitational pooling of blood. This fluid then was tissue fluid, which could have been lost as urine, through inadequate replacement, etc.; however, simultaneous body weight changes could account for only one-half or less of this quantity.

It is also obvious from figure 21 that the arms did not play a significant role. Hips showed a small in-flight loss in circumference (appendix C, tables C-2(a) to C-2(c)), and there was no significant change in the neck. The author suspects that the hip loss was fluid, for, in the one-g environment, there is still appreciable hydrostatic pressure at this level. This previous account leaves only the head and upper torso as possible areas for absorbing the 1 liter or more of fluid. There is no question that the tissues of the head were "wet" (i.e., relatively edematous), but this condition should account for only 100 to 200 ml at most. The remainder must have been distributed within the upper torso but obscured by other changes in this area.

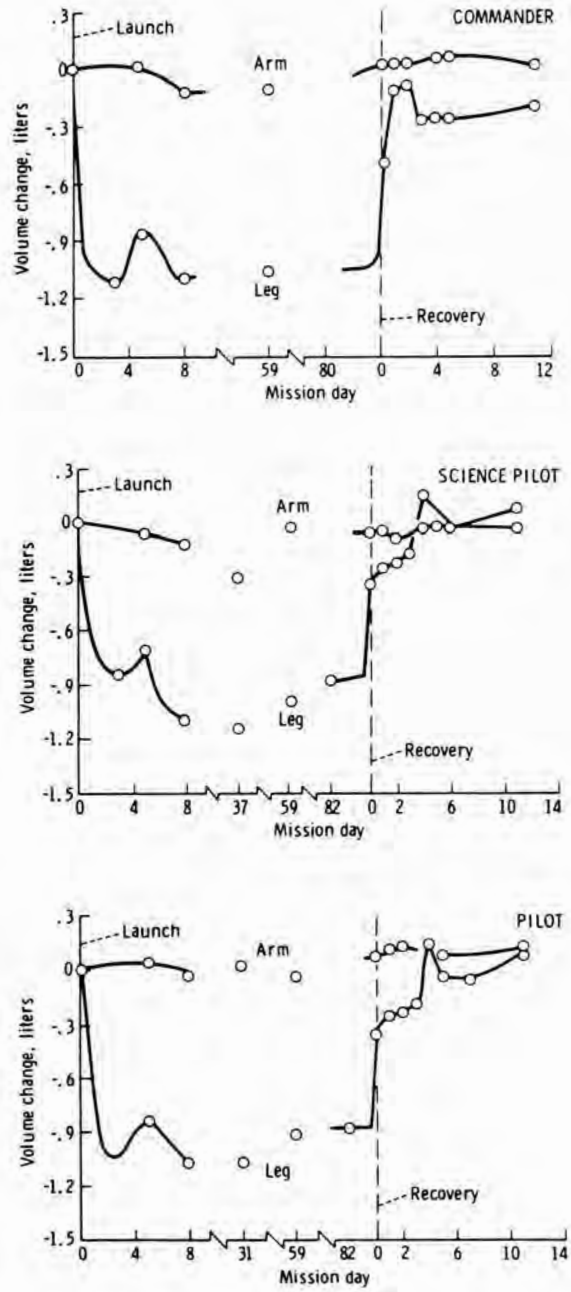

Figure 21.- Changes in left-limb volumes of SL-4 crewmen.

TABLE 4.- LEG-VOLUME MEASUREMENTS OF SL-4 CREWMEN

(a) CDR

Day (a)	Right leg			Left leg		
	Vol., ml	Δ vol., ml	Δ vol., percent	Vol., ml	Δ vol., ml	Δ vol., percent
F - 35	7531.9	56.3	0.75	7445.7	-50.9	-0.68
F - 20	7746.5	270.9	3.62	7573.4	76.8	1.02
F - 9	7455.7	-19.9	-.27	7515.7	19.1	.25
F - 5	7475.6	--	--	7496.6	--	--
MD-3	6671.6	-804.0	-10.75	6370.3	-1126.3	-15.02
MD-5	--	--	--	6625.4	-871.2	-11.62
MD-8	6646.4	-829.2	-11.09	6389.5	-1107.1	-14.77
MD-31	6388.7	-1086.9	-14.54	6294.6	-1202.0	-16.03
MD-57	6295.9	-1179.7	-15.78	6152.2	-1344.4	-17.93
R + 0	6967.1	-508.5	-6.80	6984.9	-511.7	-6.83
R + 1	7220.2	-255.4	-3.42	7354.1	-142.5	-1.90
	6989.1	-486.5	-6.51	6926.5	-570.1	-7.60
R + 2	7225.6	-250.0	-3.34	7412.3	-84.3	-1.12
R + 3	7143.4	-332.3	-4.44	7213.8	-282.8	-3.77
R + 4	7431.8	-43.8	-.58	7228.0	-268.6	-3.58
R + 5	7347.2	-128.4	-1.72	7227.9	-268.7	-3.58
R + 7	7432.8	-42.8	-.57	7261.3	-235.3	-3.14
R + 11	7629.1	153.5	2.05	7405.4	-91.2	-1.22
R + 17	7455.1	-20.5	-.27	7664.6	168.0	2.24
R + 31	7317.7	-157.9	-2.11	7359.8	-136.8	-1.82
R + 68	7747.8	272.2	3.64	7622.3	125.7	1.68

[a]F - 35 is 35 days before flight; MD is mission day on-orbit; and R + 1 is 1 day after recovery.

TABLE 4.- Continued

(b) SPT

Day	Right leg			Left leg		
	Vol., ml	Δ vol., ml	Δ vol., percent	Vol., ml	Δ vol., ml	Δ vol., percent
F - 35	8244.9	300.9	3.8	8237.8	301.9	3.80
F - 30	8120.3	176.3	2.2	7829.1	-106.8	-1.34
F - 19	8374.8	430.8	5.4	7995.1	59.2	.74
F - 9	8192.6	248.6	3.1	8085.5	149.6	1.88
F - 5	7944.0	--	--	7935.9	--	--
MD-3	7106.3	-837.7	-10.5	7100.7	-835.2	-10.5
MD-5	--	--	--	7239.1	-696.8	-8.8
MD-8	7168.6	-775.4	-9.8	6834.5	-1101.4	-13.9
MD-37	--	--	--	6793.6	-1142.3	-14.4
MD-59	--	--	--	7026.0	-909.9	-11.5
MD-81	--	--	--	7039.8	-896.1	-11.3
R + 0	7300.7	-643.3	-8.1	7579.2	-356.7	-4.5
R + 1	7457.9	-486.1	-6.1	7689.4	-246.5	-3.1
R + 2	7747.6	-196.4	-2.5	7710.7	-225.2	-2.8
R + 3	7684.1	-259.9	-3.3	7762.6	-173.3	-2.2
R + 4	8124.3	180.3	2.3	8085.9	150.0	1.9
R + 5	7912.8	-31.2	-.4	7902.5	-33.4	-.4
R + 7	7999.8	55.8	.7	7885.9	-50.0	-.6
R + 11	7976.4	32.4	.4	8015.2	79.3	1.0
R + 17	7985.1	41.1	.5	7966.2	30.3	.4
R + 31	8265.9	321.9	4.0	8522.0	586.1	7.4
R + 68	8375.5	431.5	5.4	8342.4	406.5	5.1

TABLE 4.- Concluded

(c) PLT

Day	Right leg			Left leg		
	Vol., ml	Δ vol., ml	Δ vol., percent	Vol., ml	Δ vol., ml	Δ vol., percent
F - 35	7466.2	138.8	1.9	7717.1	-177.0	-2.2
F - 30	7521.6	194.2	2.7	7768.0	-126.1	-1.6
F - 19	7777.5	450.1	6.1	7948.1	54.0	.7
F - 9	7475.5	148.1	2.0	7881.6	-12.5	-.2
F - 5	7327.4	--	--	7894.1	--	--
MD-3	--	--	--	--	--	--
MD-5	--	--	--	7120.2	-773.9	-9.8
MD-8	6508.7	-818.7	-11.2	6832.7	-1061.4	-13.4
MD-31	6668.1	-659.3	-9.0	6805.9	-1088.2	-13.8
MD-59	6804.7	-522.7	-7.1	6518.3	-1375.8	-17.4
MD-81	--	--	--	6795.4	-1098.7	-13.9
R + 0	7032.2	-295.2	-4.0	7175.4	-718.7	-9.1
R + 1	7084.2	-243.2	-3.3	7431.3	-462.8	-5.9
R + 2	7233.2	-94.2	-1.3	7574.2	-319.9	-4.1
R + 3	7091.5	-235.9	-3.2	7467.8	-426.3	-5.4
R + 4	7250.6	-76.8	-1.0	7594.8	-299.3	-3.8
R + 5	7335.2	7.8	.1	7465.0	-429.1	-5.4
R + 7	7201.6	-125.8	-1.7	7547.3	-346.8	-4.4
R + 11	7523.8	196.4	2.7	7879.9	-14.2	-.2
R + 17	7493.5	166.1	2.3	7777.2	-116.9	-1.5
R + 31	7547.9	220.5	3.0	8043.8	149.7	1.9
R + 68	8097.2	769.8	10.5	7964.8	70.7	.9

If the leg and arm volumes are subdivided, it will be seen that, on a percentage basis, the lower legs lost relatively less fluid than the thighs. This difference may be explained by the greater amount of fluid-containing tissue found in the thighs compared to that found in the relatively bony lower legs. Conversely, the lower arms lost slightly more fluid than the upper arms, a difference which may be explained by the increased elasticity in the lower arms, which have a tissue/bone ratio more nearly approaching unity. The exact time course of these fluid volume shifts remains to be determined, but it is probably exponential and may have some initial oscillations. Fluid redistribution apparently follows a reciprocal course over a time span of 2 or 3 days on return of the body to a one-g environment.

The results of an ASTP in-flight study of leg volumes done by using segmental girth measurements[20] appear to be consistent with the data from Skylab. The detailed data are unpublished, but figure 22 is drawn from the preliminary report.

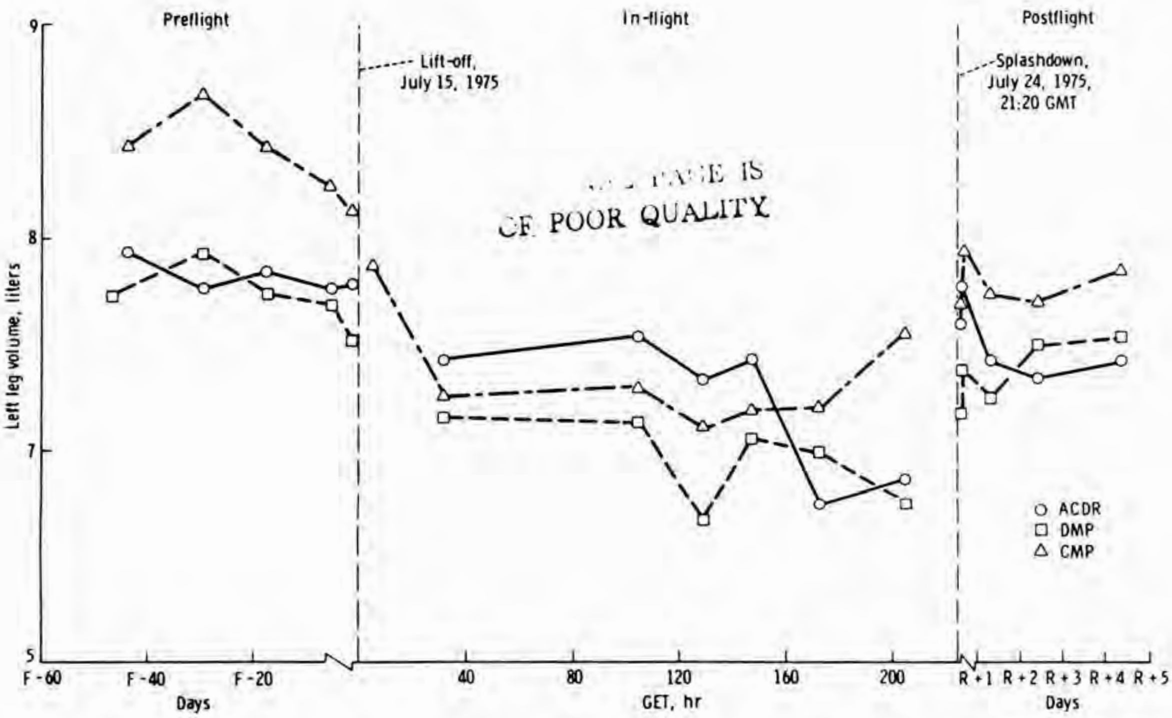

Figure 22.- Left-leg volumes of ASTP crewmen calculated from segmental girth measurements; DMP is docking module pilot, CMP is command module pilot. (Data supplied by Hoffler et al.; see footnote 7, p. I-3.)

[20]See footnote 7 on p. I-3.

It must be recognized that volumes also will be changed by tissue atrophy or hypertrophy. This slower process with a different basis will be discussed next.

One could manipulate the raw leg-girth data in innumerable ways to meet specific needs or curiosity; and for this reason, the raw data on SL-4 limb girths are included in appendix C, tables C-3 to C-5.

Slow Changes

Slow changes over days to weeks, secondary to the disturbance of fat and muscle masses, may be caused by inadequate or excessive diet and exercise. As fluid redistribution appears to be relatively complete in 2 or 3 days after a change from one-g to weightlessness conditions or vice versa, any remaining volume changes are probably tissue changes. If a diet is calorically inadequate, then fat and muscle must be consumed to make up the difference. In subjects with normal body fat, losses will be in both muscle and fat, with most of the initial loss occurring in areas where fat is deposited (abdomen, buttocks, and subcutaneous areas); but if the percentage of body fat is initially low or becomes low, then muscle will be consumed. If exercise to a muscular area is inadequate at a time of inadequate diet, additional local muscle loss will occur. With diet adequate to maintain body mass but insufficient exercise, the muscles will atrophy and fat will be deposited in the usual areas.[21] Available Russian data in this area are given in table 5. These measurements were taken 2 days after flight and should primarily reflect tissue changes. As will be seen, these data are generally consistent with the United States experience. Changes seen in flights of short duration were hardly significant. Both Soyuz and Salyut contained several exercise devices, the scheduled use of which was apparently adequate to maintain upper limbs but not lower. The legs show the major losses of tissue, presumably muscle.

The next available data are from preflight and postflight calf circumference measurements on all Apollo flights and leg volume measurements on two Apollo flights made by Hoffler and Johnson[22] as part of the cardiovascular evaluation. Table C-6 in appendix C, a summary of these data, shows a consistent postflight decrease in calf and total leg volume that persists after the time for fluid redistribution. This decrease represents an appreciable muscle and/or fat loss for relatively short missions.

From the Skylab missions, several sources of data on such changes are available. Postflight leg and arm volumes and in-flight calf circumferences were measured on all Skylab missions, and in-flight leg and arm volumes were measured on SL-4. Herron's preflight and postflight stereophotogrammetry provided an overall survey of body changes (Herron, 1972; Whittle and Herron,

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[21]There is obviously great individual variation in areas of body-fat deposition.

[22]See footnote 2 on p. I-3.

TABLE 5.- POSTFLIGHT CHANGES IN CIRCUMFERENCE FOUND IN U.S.S.R. COSMONAUTS

Spacecraft	Flight duration, days	Circumference change on R + 2					
		Calf, mm	Hips, mm	Shoulder, mm	Upper arm, percent	Thigh, percent	Calf, percent
Soyuz 3 to 8	2 to 5	-2	-7	-5	--	--	--
Soyuz 9	18	-12	-27	-2	-0.3	-3.3	-4.9
Salyut	24	--	--	--	[a]-1.1	[a]-4.4	[a]-5.4

[a]Changes measured post mortem.

1977). Although the data cannot be examined in detail here, when they are considered in view of the following flight conditions, there is a consistent picture that is compatible with current one-g experience and knowledge. All data must be interpreted in view of wide variations in individual and mission diets and exercise.

The SL-2 crewmen clearly had a calorically inadequate diet, and only the CDR exercised at reasonably adequate levels - albeit with the bicycle ergometer which was proven inadequate for maintenance of legs consistent with one-g conditions (see section on strength).

The SL-3 diet was inadequate (see weight section) for the SPT and marginal for the CDR and the PLT. Good arm exercise equipment was available, and this activity was undertaken vigorously; all crewmen used the bicycle at adequate levels on this flight.

The SL-4 diet was adequate to slightly positive for the CDR, inadequate for the SPT until augmented in the middle of the mission, and marginal for the PLT. Arm exercise equipment was available and used; the bicycle ergometer and a makeshift treadmill provided fair protection against leg atrophy.

Table 6 is a summary of values from three areas that should reflect diet and exercise effects on Skylab.[23] Changes in abdominal girth should be a rough gauge of changes in body fat. This supposition appears to be valid

[23]Preflight and postflight arm and leg volumes on SL-2, SL-3, and SL-4 are in appendix C, tables C-3 to C-5 and C-7.

TABLE 6.- CHANGES IN ARM AND LEG VOLUME

AND WAIST GIRTH OF SKYLAB CREWMEN

Measurement	Change, percent				Change, percent/day
	CDR	SPT	PLT	Mean	
		SL-2 (28 days)			
Arm volume[a]	1.4	-1.9	-0.4	-0.3	-0.0107
Leg volume[b]	-5.3	-4.8	-6.7	-5.6	-.2
Waist girth[a]	-.9	-5.7	-5.1	-3.9	-.139
		SL-3 (59 days)			
Arm volume[a]	-11.7	-4.6	1.5	-4.9	-0.083
Leg volume[b]	-7.2	-6.4	-4.6	-6.1	-.1033
Waist girth[a]	-4.1	-3.8	-1.6	-3.2	-.0542
		SL-4 (84 days)			
Arm volume[a]	1.05	-2.49	3.83	0.797	0.0095
Leg volume[b]	-2.2	-2.6	-2.7	-2.5	-.030
Waist girth[a]	1.2	-2.1	-2.4	-1.1	-.013

[a]Measured on R + 1.
[b]Measured on R + 2.

here, both collectively and individually. For example, the SL-4 CDR, who was close to caloric balance, gained in abdominal girth (the only crewman to do so); and normalized flight averages of girth change (percent change per day) also agree with the general increase of food on each mission. Leg changes appear to reflect effects of both food and appropriate exercise, with a ten-fold improvement observed on rate of loss during the last mission as compared to the first. This effect is seen better in figure 23, in which average postflight changes in leg volume for each Skylab crew are plotted.

Note that after fluid redistribution should have been complete, 2 or 3 days after a return to one-g conditions, crewmen of the 28-day mission still had a deficit in leg volume of 5+ percent, which persisted until the end of the measurement period. It is impossible to tell how much of this deficit was due to fat loss and how much was due to muscle loss; but on the basis of strength studies, much of it must have been due to muscle loss. The following 59-day mission, with an increased amount of food intake and exercise scheduled, resulted in essentially the same loss and pattern as that for a mission approximately half as long. The final 84-day mission resulted in less than half the loss, and that was rapidly regained after flight. Somewhat more food and a means of heavy leg exercise were available on this flight wherein a sharp reduction in loss was seen. Losses on all three flights were consistent with strength changes found after flight.

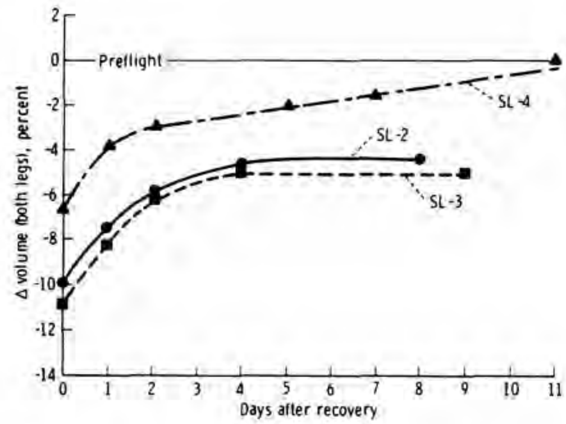

Figure 23.- Average postflight leg-volume changes on Skylab missions.

The results of all of these studies of leg mass are consistent with the following observations. Without protective, heavy exercise, there will be a rapid loss of leg tissue even on relatively short flights, such as Russian Soyuz and American Apollo flights. The rate of loss is greater with inadequate diet, as on the Apollo and SL-2 missions, and is related to the amount and type of exercise. (This subject will be dealt with further in the next section.) A positive view is that such loss of muscle may be prevented by an adequate diet and a proper amount and type of exercise.

Upper Limbs

Arm volumes derived from segmental girth measurements during Skylab missions are tabulated in appendix C, tables C-7(a) to C-7(c). Russian data from the Soyuz 9 to Salyut missions show a relatively greater postflight decrease in leg girth than in arm girth. This result was observed on SL-2 and SL-4 also; but when one looks at average arm volume changes from mission to mission, the volume changes do not correlate with food or exercise or postflight strength changes. Arm volume changes are relatively small and may be lost in the noise of the measurement apparatus, but this possibility is doubtful. Even in the absence of arm exercise devices, the ordinary activities in a spacecraft place moderate demands on upper limbs in contrast to the unused legs.

Center of Mass

With increases of height and shifts of liquid cephalad, the center of mass must change. Such changes were documented on SL-4 (Thornton et al., 1977).

Preflight baseline and postflight center-of-gravity measurements were obtained with a balance board, as shown in figure 24. In flight, a similar balance point was found without the complication of a board by looping a thin cord around the subject, who was "floating" freely, and then pulling the cord at right angles to the body's longitudinal axis to accelerate the crewman. If the cord were off the center of mass, the crewman would "tilt" during the acceleration. It was claimed by the crew that the null point, or center of mass, could be determined within a few millimeters. The use of skin tattoo as a reference is open to question, but it was felt that in practice this tattoo would be as stable as some skeletal landmark. The results shown in figure 25 for the PLT of SL-4 were typical. A slight increase occurred in the later part of the mission, which may represent a slower shift of fluid still further cephalad, a loss of leg tissue that was not obvious, or simply an error. Otherwise, the data seem to be reasonable in direction and magnitude.

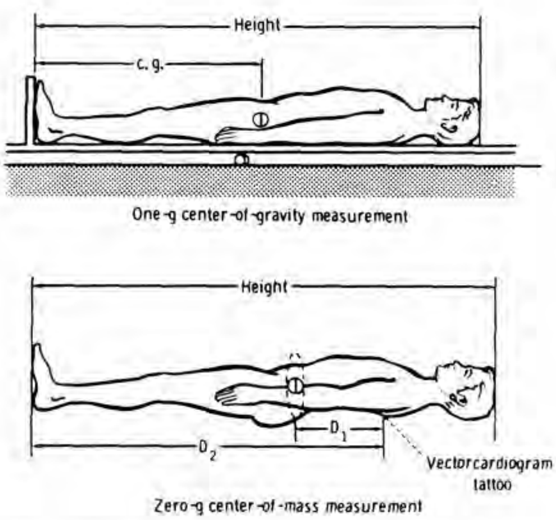

Figure 24.- Measurements used in center-of-gravity and center-of-mass determinations.

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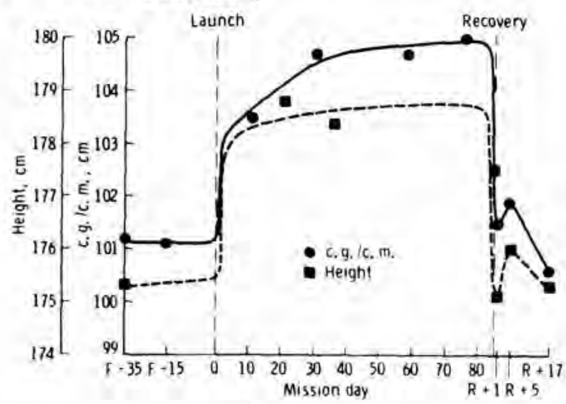

Figure 25.- Preflight (baseline) and postflight center-of-gravity measurements of SL-4 PLT obtained with a balance board. The c.g./c.m. distances were measured from soles of crewman's feet.

Methodology of Anthropometric Measurements for Space Flight

Collection of anthropometric data by conventional direct measurements has many liabilities, especially for space flight. The methodology is tedious, cumbersome, and time-consuming. Exact shapes cannot be determined by girth and similar measurements. Stereophotogrammetry, as applied to the body by Herron et al., appears to be a most attractive alternative, and its utility and accuracy were successfully demonstrated on Skylab. The technique is fully described elsewhere (Herron, 1972; Whittle and Herron, 1977). Briefly, it consists of taking two pairs of photographic plates of the subject, from which - in the laboratory - a rather involved and complex data reduction process yields as many spatial points on the body as desired. From this matrix of points, a computer may generate a variety of data. Some examples are seen in figures 26 and 27. Figure 26 is a single transverse section of the body generated by the computer from points derived from stereophotogrammetry, and figure 27 is a composite of such points. Quantitative areas and volumes may be computed, as may surface areas. A curve of volume as a function of height may be calculated.

Preflight and postflight studies with the use of this technique were done in all Skylab missions. Figure 28 shows a plot of volume as a function of longitudinal axis level for the SL-3 CDR before and after flight. This plot shows the losses in abdominal area that, when taken with weight losses and other data, confirm the loss of adipose tissue. Smaller losses of leg volume may also be seen. Data obtained by using this technique were repeatedly compared to directly measured volumes and girths and other quantities and found to be within their error limits.

The simplicity of obtaining the photographs and the huge amount of data they contain more than offset the time, complexity, and cost of their analysis. This method, with suitable modifications for in-flight usage, is probably the method of choice for dimensional studies of size, volume, and shape

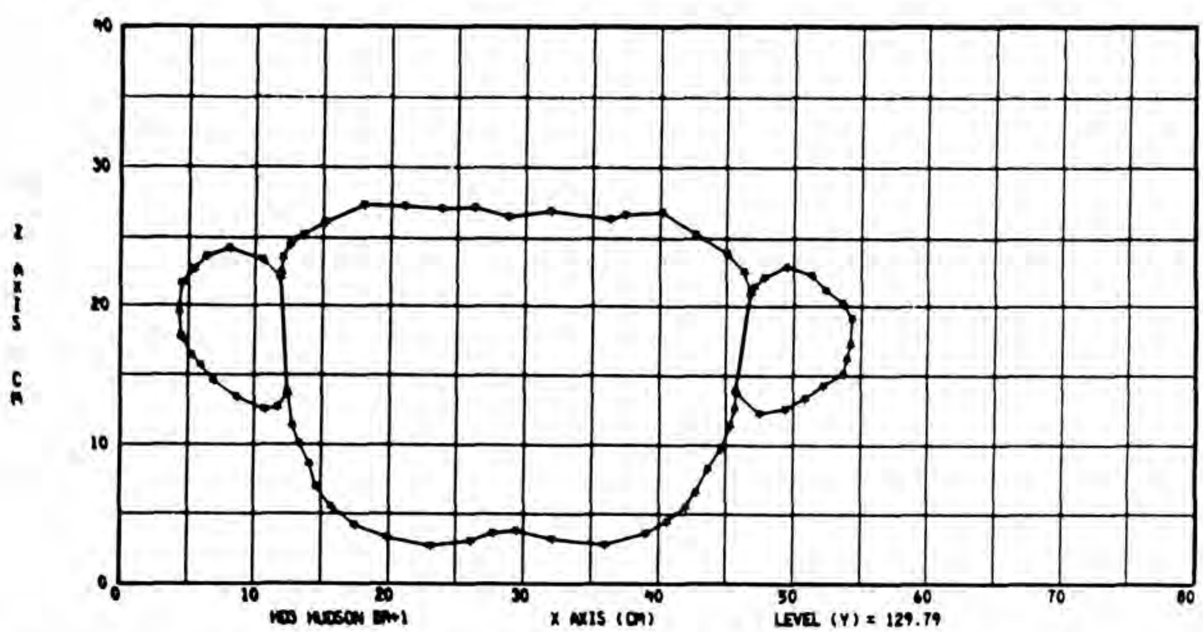

Figure 26.- A single transverse section of the body at shoulder level generated by a computer from points derived from stereophotogrammetry.

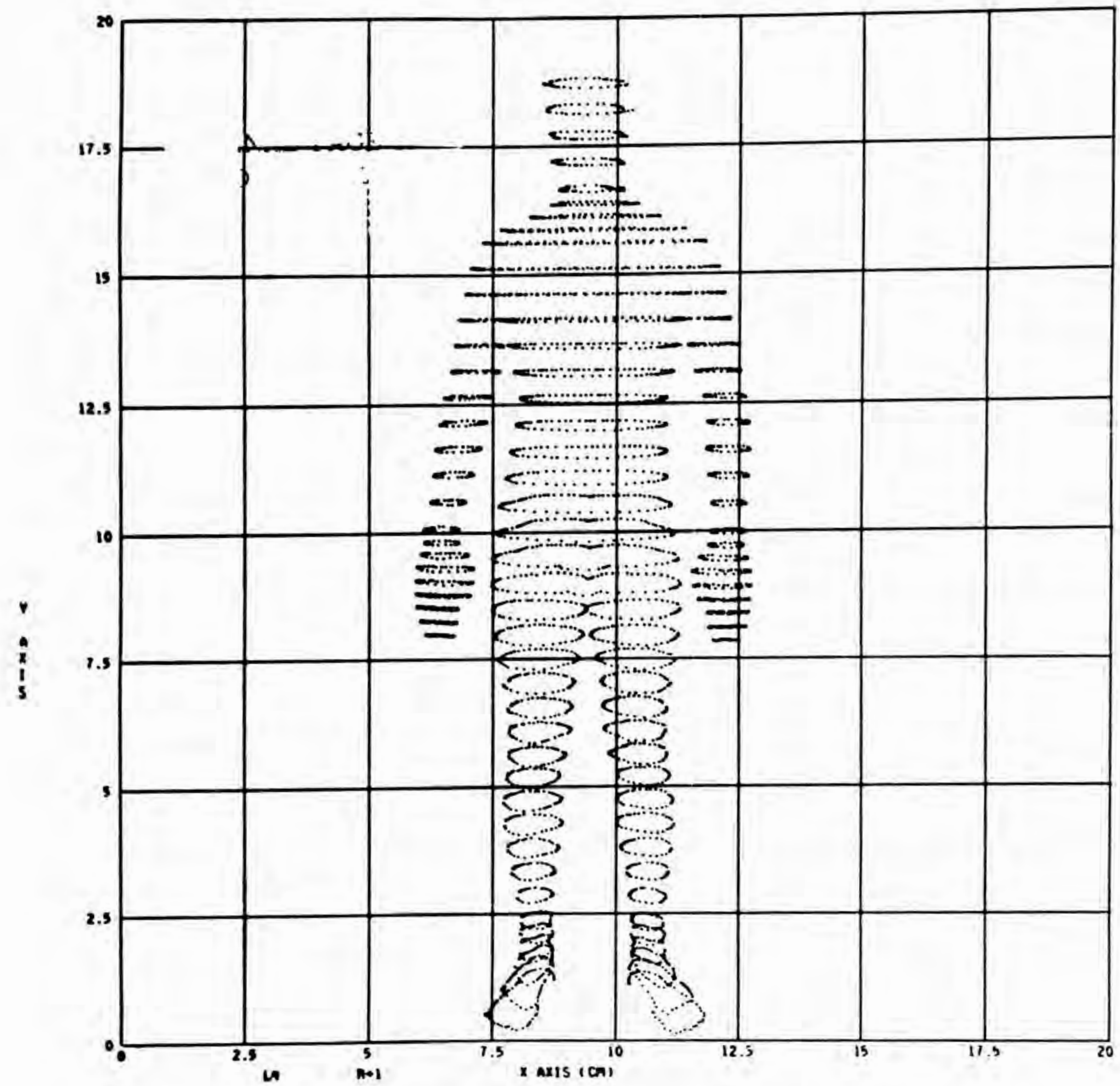

Figure 27.- A composite of transverse body sections made from stereo-photogrammetry.

in the future. The only reservation the author has concerns the attempted usage of this method for obtaining precise volumetric assessments for density (specific gravity) determinations; however, continued refinements may make such precise assessments possible.

Applications

Height is discussed in the second section of this chapter. Although abdominal changes of this magnitude would be serious on Earth for clothing fit, in space the normal posture will tend to increase abdominal girth and clothing will be weightless. However, adjustments should be available in clothing. There will be changes in the female breast area that may also require consideration for comfort and fit.

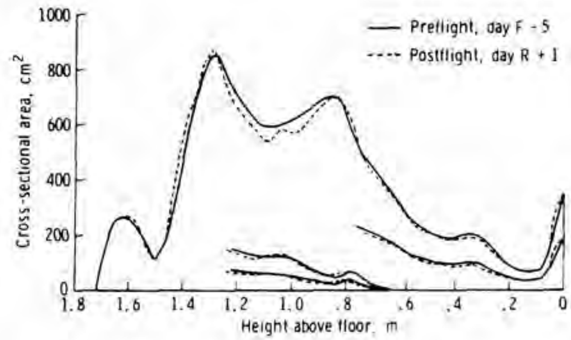

Figure 28.- Volume as a function of longitudinal axis level of SL-3 CDR before and after flight.

Except in unusual, closely fitted garments or equipment, the reduction in leg size should cause no problem. Facial puffiness and stuffy noses will probably remain a part of space flight, and a probably insignificant reduction in field of view may occur. The medical scientist should be primarily concerned in this area.

The magnitude of slow tissue changes should be small. Indeed, slow changes should be largely regarded as a warning that diet and/or exercise is not at the correct level.

Although there will be a significant cephalad shift of center of mass, this effect should cause no concern except with respect to maneuvering units should they have critical balance and control moments.

STRENGTH AND BODY COMPOSITION

SUMMARY

This area is one of the more critical areas for manned space operations of appreciable duration. Large areas of the body, especially back and legs, are composed of antigravity muscles normally subjected to loads of up to several hundred pounds, several thousand times a day.

In weightlessness, these muscles become virtually unused, and disuse atrophy will occur rapidly. There were significant changes in strength and muscle mass following short flights, such as the Apollo and Soyuz flights. Unprotected, the legs can be expected to atrophy to some level consistent with in-flight forces but below that required for supporting or transporting the body under one-g conditions. This loss of strength would cause no problems in weightlessness but would necessitate special reentry considerations and a period of rehabilitation after recovery.

An inadequate diet will increase the deconditioning effects through direct loss of muscle mass, especially in well-conditioned subjects. To prevent such leg muscle losses, an adequate diet and relatively short periods of heavy exercise are required. Any muscle must be exercised at or above its one-g working stress level to prevent loss of function. On the basis of Russian and Skylab experience, a treadmill with axial body loading to body weight levels appears to be the best exercise device. Optimum protocols remain to be demonstrated.

A second undesirable aspect of leg muscle deconditioning is a reduction in gravity tolerance of the cardiovascular system.

Arms will also suffer some atrophy under weightlessness, but this loss will be limited because of the relatively heavier workloads they encounter in weightlessness, where arms must often assume the legs' role in stabilization as well as their usual role of manipulation. Handgrip strength is little affected because of the grasping of loads required in space.

Changes in legs begin immediately on exposure to weightlessness; and as an optimum countermeasure, exercise should begin as early as possible. Although these changes are potentially serious, there is every reason to believe that they can be prevented by proper diet and exercise.

Strength and Composition Changes

From one-g experience, it could be predicted that placing the human body in weightlessness would produce a marked decrease in strength and mass of several major muscle groups, especially major antigravity groups, and would probably affect neuromuscular function. In an active individual, some 40 percent or more of the body is devoted to opposing gravity in standing and walking. Large masses of muscle in legs, hips, and back are normally required to generate forces of hundreds of pounds, thousands of times a day. Unless engaged in manual labor or rigorous training, the hands, arms, and shoulders do much less work, which is reflected in their smaller mass. In weightlessness, the legs become virtually useless and unused except for "perching" and, occasionally, for pushing off in movement. In contrast, the hands and arms remain in use, increasingly in some cases, for grasping and stabilization of the body, as well as for manual manipulations. However, arm and hand forces in weightlessness are usually much smaller than corresponding forces on Earth. Under such circumstances, one would expect a relatively rapid (days to weeks) loss of strength in legs and lower back, followed by atrophy of these areas, with a relative sparing of strength and mass in arms and shoulders. Loss of muscle may be further affected by diet. If the diet is inadequate (see the section on weight changes), especially in crewmembers with low body fat, the caloric deficit will be made up with body fat and muscle (Vanderveen and Allen, 1972). Conversely, if the diet is adequate to maintain body weight, any muscle lost will be replaced with fat deposited in the areas of the body usually subject to such deposition.

Loss of muscle mass and function will cause little difficulty during a flight, for no tasks that require maximum strength of legs and back would be included in on-orbit operations. It is during reentry and after recovery that such reductions in function would be noted. Cardiovascular effects of this loss of leg muscle[24] cannot be covered here but may become critical under gravitational forces in reentry. Should the crew have to make emergency ground exits after, say, an Orbiter landing, such reductions in muscle function could also be serious. If preventive measures are not taken in flight, the crew must expect several days or more of reduced function in the one-g environment after landing; the time factor will depend upon individual characteristics and flight duration. Flights as short as 18 days have caused difficulty in the Russian program (Kakurin, 1971; Parin et al., 1974).

Study and documentation of such changes are far from complete. For one thing, neither Russian nor American programs have been planned to allow deconditioning to follow its normal course, and for good reason. Although the Russians have placed a great deal of emphasis on this aspect of space physiology and operations and have had active programs of investigation and prevention, there was little effort in this area in American programs until Skylab. The following three subsections are a resume of programs and data obtained to date, including Russian data available to the author at this time.

Strength

The state of the art of the study of strength is such that reiteration of a few fundamental considerations is in order. All measurement conditions, including angles, velocities, and types of opposing forces, affect measured muscle forces. Unless otherwise stated, it is assumed that all Russian measurements were of static maximum-effort forces; but nothing else is known about them. American handgrip forces were static, but Skylab measurements were of voluntary maximum-effort isokinetic exertions at a rate of 45^{o}/sec, which produced forces just below maximum-effort static levels.

Equally important to proper interpretation is knowledge of the subject's previous and current training program. Russian Soyuz missions had an unknown exercise regimen that was expanded on Soyuz 9 to include simulated weights, with exercise periods of approximately 2 hours a day. Exercises included "running, walking, jumping, squatting" - but only at simulated weights of 20 kg[25] - and exercise "of the hands, neck, etc., for purposes of coordination" (Kakurin, 1971). The Soyuz 11/Salyut mission had an even more vigorous program - 3 hours a day with loads of up to 50 kg of body weight and a motor-driven treadmill that enabled walking. These exercise factors must be used in interpretation of results. Exercise protocols on Skylab are discussed later.

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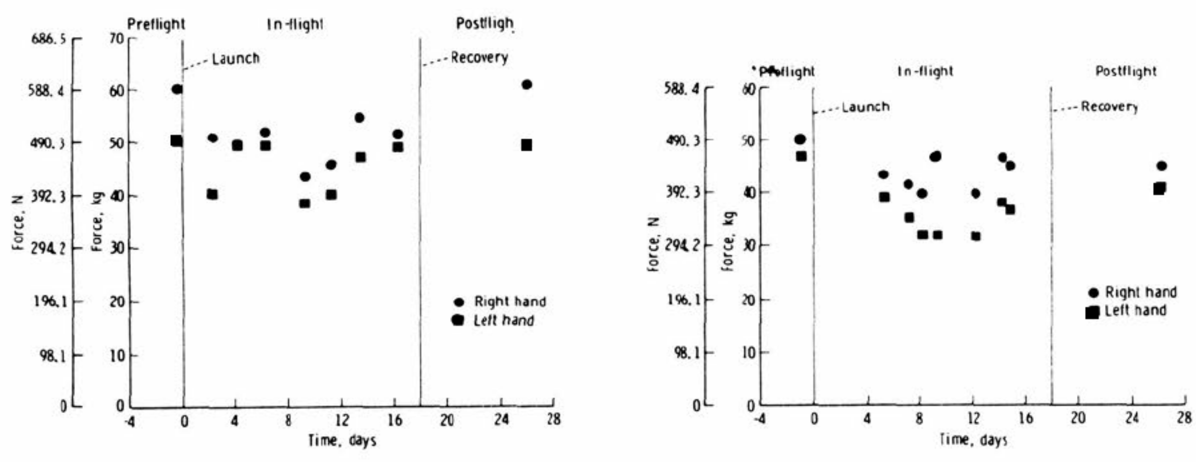
[24]See footnote 5 on p. I-3.
[25]This simulated weight was apparently increased in flight.

The earliest, easiest to make, and probably least important strength measurements are those of the static handgrip forces. Figures 29(a) and 29(b) contain a series of measurements from Soyuz 9. Apparently, Russian investigators felt that neurological inhibition from weightlessness played a part in the reduction of forces seen in flight here, for on the Soyuz 11/Salyut mission, they compared forces with the man restrained as opposed to "free" and found no significant differences (Parin et al., 1974). American Skylab data are summarized in table 7 and show no consistent change except a slight bilateral loss in the PLT on SL-3, who was an unusually powerful man accustomed to heavy one-g work.

These results would be consistent with the view that the hands are probably less affected by space flight than any other muscle group, as a great deal of grasping and other hand functions are performed in flight. All other major muscle groups, and especially the lower limbs, suffer rapid disuse atrophy. This fact was demonstrated in Russian programs and during the Skylab program, which will be described next.

In the Skylab program, a minimum-impact postflight muscle function test was first instituted; later, according to mission demands, exercises and exercise devices were added, and the testing was expanded. The result was a different exercise environment on each flight such that there were three experiments, with the results of each flight affecting the next. The flights will be described chronologically.

Evaluation of the right arm and leg was done before and after flight on all missions with the Cybex Isokinetic Dynamometer. This dynamometer may be rotated in either direction without resistance until an adjustable limit speed is reached. Speed cannot be increased above this limit by forces of



(a) Nikolayev. (b) Sevast'yanov.

Figure 29.- Handgrip forces as a function of time in weightlessness for Soyuz 9 crewmen.

TABLE 7.- GRIP STRENGTH MEASUREMENTS OF SKYLAB CREWMEN

Crewman	Hand	Preflight, N (lb) F - 30	Preflight, N (lb) F - 4	Postflight, N (lb) R + 0	R + 1	R + 2	R + 4	R + 5	R + 11
					SL-2				
CDR	Right	427.0 (96.0)	385.2 (86.6)	397.2 (89.3)	387.0 (87.0)	--	--	--	--
	Left	424.8 (95.5)	383.9 (86.3)	380.8 (85.6)	373.6 (84.0)	--	--	--	--
SPT	Right	556.0 (125.0)	520.4 (117.0)	--	538.2 (121.0)	--	--	--	--
	Left	538.2 (121.0)	462.6 (104.0)	--	478.6 (107.6)	--	--	--	--
PLT	Right	547.1 (123.0)	474.2 (106.6)	458.2 (103.0)	483.1 (108.6)	--	--	--	--
	Left	507.1 (114.0)	444.8 (100.0)	478.6 (107.6)	467.1 (105.0)	--	--	--	--
					SL-3				
CDR	Right	418.1 (94.0)	409.2 (92.0)	416.3 (93.6)	--	--	418.1 (94.0)	--	--
	Left	385.2 (86.6)	403.0 (90.6)	401.7 (90.3)	--	--	387.0 (87.0)	--	--
SPT	Right	453.7 (102.0)	444.8 (100.0)	459.5 (103.3)	458.2 (103.0)	434.1 (97.6)	432.8 (97.3)	--	--
	Left	449.3 (101.0)	475.9 (107.0)	434.1 (97.6)	458.2 (103.0)	468.4 (105.3)	460.8 (103.6)	--	--
PLT	Right	634.3 (142.6)	650.8 (146.3)	582.7 (131.0)	566.3 (127.3)	547.1 (123.0)	551.6 (124.0)	--	--
	Left	598.7 (134.6)	607.6 (136.6)	587.2 (132.0)	576.5 (129.6)	573.8 (129.0)	523.1 (117.6)	--	--
					SL-4				
CDR	Right	390.1 (87.7)	387.0 (87.0)	397.2 (89.3)	387.0 (87.0)	388.3 (87.3)	394.6 (88.7)	390.1 (87.7)	394.6 (88.7)
	Left	375.0 (84.3)	364.7 (82.0)	369.2 (83.0)	351.4 (79.0)	351.4 (79.0)	366.1 (82.3)	347.0 (78.0)	347.0 (78.0)
SPT	Right	502.6 (113.0)	458.2 (103.0)	439.0 (98.7)	452.4 (101.7)	418.1 (94.0)	403.5 (90.7)	434.6 (97.7)	459.5 (103.3)
	Left	499.5 (112.3)	451.5 (101.5)	412.3 (92.7)	410.6 (92.3)	382.5 (86.0)	369.2 (83.0)	395.9 (89.0)	385.7 (86.7)
PLT	Right	441.7 (99.3)	462.6 (104.0)	430.1 (96.7)	431.5 (97.0)	415.0 (93.3)	431.5 (97.0)	438.6 (98.6)	463.9 (104.3)
	Left	401.7 (90.3)	432.8 (97.3)	427.0 (96.0)	427.0 (96.0)	419.5 (94.3)	418.1 (94.0)	397.2 (89.3)	394.1 (88.6)

any magnitude; that is, the constant speed-maximum force of isokinesis is achieved. Input or muscle forces are continuously recorded at a constant angular rate.

The arrangement used on Skylab missions is shown in figure 30. A crewman, after thorough warmup, made 10 maximum-effort full flexions and extensions of the arm at the elbow and of the hip and knee at an angular rate of 45^{o}/sec. A continuous force record was made of each repetition at a rate of 25 mm/sec, and the integral of force - or, under these conditions, work - was recorded on a second channel (see fig. 31).

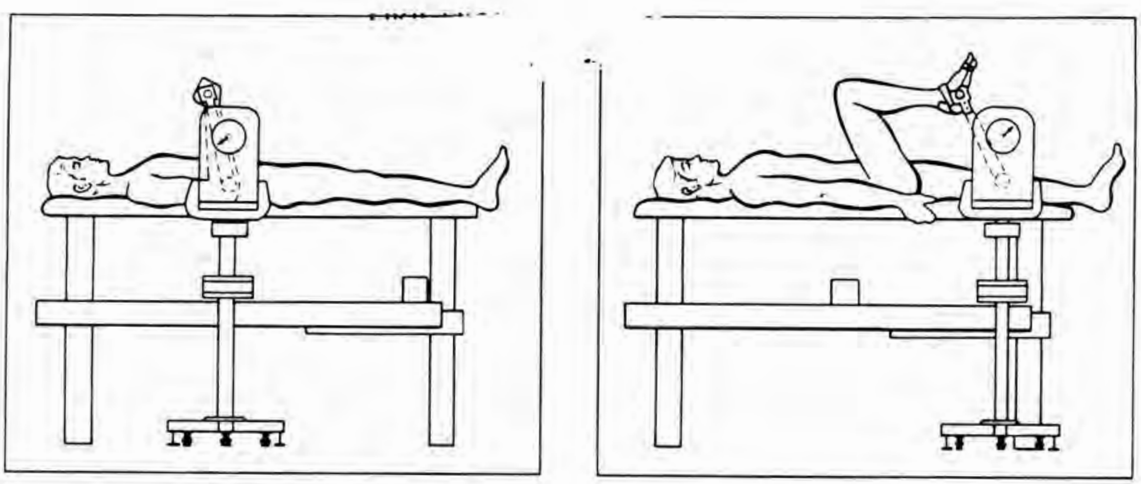


Figure 30.- Arrangement used for Skylab postflight muscle function test.

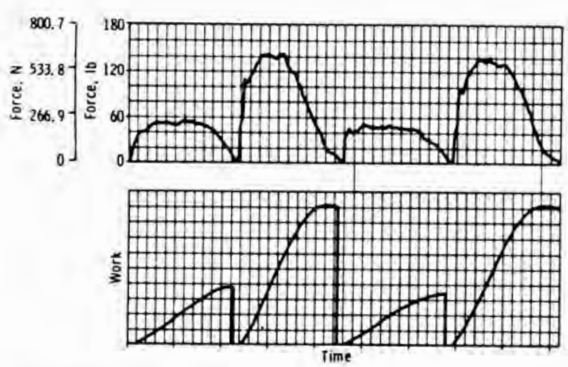


Figure 31.- Recording of right-leg muscle forces of the SL-3 backup PLT.

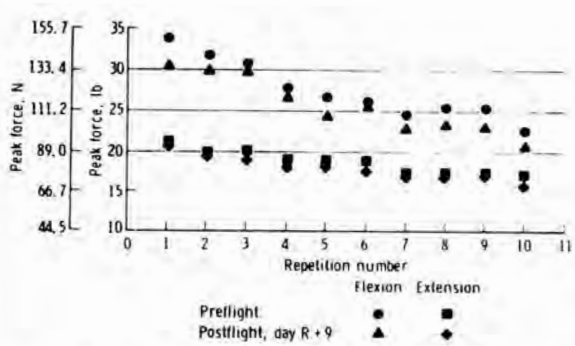


Figure 32.- A plot of peak arm forces of the SL-3 CDR from preflight and postflight curves.

Machine errors are small, 2 to 3 percent or less. At lower angular rates, the test gives a measurement of strength comparable to that achieved in the more commonly used isometric testing but has the advantage of recording this force throughout the whole range of motion, as well as allowing a number of repetitions for statistical purposes. It is sensitive enough to show small changes in performance which may occur in days.

A great deal of information is contained in the recordings made, but only one quantity will be used, the peak force of each repetition. Use of a single point on the tension curve to represent the entire curve may be open to criticism, especially for the leg, in which a number of muscles are involved. However, for the investigators' purposes, the author believes that this method provides a valid measure of strength of the muscles tested.

A plot of such peak points from a preflight and a postflight curve is shown in figure 32. The strength for a given movement is taken as the average of 10 repetitions. As can be seen, a fatigue decrement is present and may vary. It is included in the strength figure by virtue of averaging the 10 repetitions.

On SL-2, only the bicycle ergometer was used for in-flight exercise. The CDR used it in the normal fashion and was the only person on Skylab to use it in the hand-pedal mode. He also was the only person in this crew to exercise at rates comparable to those of later missions.

On this mission, testing was performed 18 days before launch and 5 days after flight. It was recognized that these testing times were too far removed from the time of flight, but it was the best that could be done under schedule constraints.

By the time muscle testing was done on day 5, there had been a significant recovery in function; however, a marked decrement remained. The decrement in leg extensor strength approached 25 percent; the arms had suffered less but also had marked losses (see figs. 33 and 34). The CDR's arm extensors had no loss (fig. 33) since he presumably used these muscles in hand-pedaling the bicycle. This result illustrates a crucial point in muscle conditioning: to maintain the strength of a muscle, it must be stressed to or near the level at which it will have to function. Leg extensor muscles must develop forces of hundreds of pounds, whereas arm extensor forces are measured in tens of pounds. Forces developed in pedaling the bicycle ergometer are typically tens of pounds and are totally incapable of maintaining leg strength. The bicycle ergometer is an excellent machine for aerobic exercise and cardiovascular conditioning, but it simply cannot develop either the type or level of forces required to maintain strength for walking under one-g conditions.

Immediately after SL-2, work was started on devices to provide adequate exercise to arms, trunk, and legs. A mass-produced commercial device, called Mini Gym (designated MK-I), was extensively modified. A centrifugal brake arrangement approximated isokinetic action on this device. Only exercises which primarily benefited arms and trunk were available from this device, as shown in figure 35. Forces transmitted to the legs were higher than those from the ergometer, but they were still limited to an inadequate level since forces could not exceed the maximum strength of the arms, a fraction of leg strength.

A second device, designated MK-II, consisted of a pair of handles between which up to five extension springs could be attached. By using this device with its full complement of accessories, a maximum force of 364.8 N per meter (25 lb per foot) of extension could be developed.

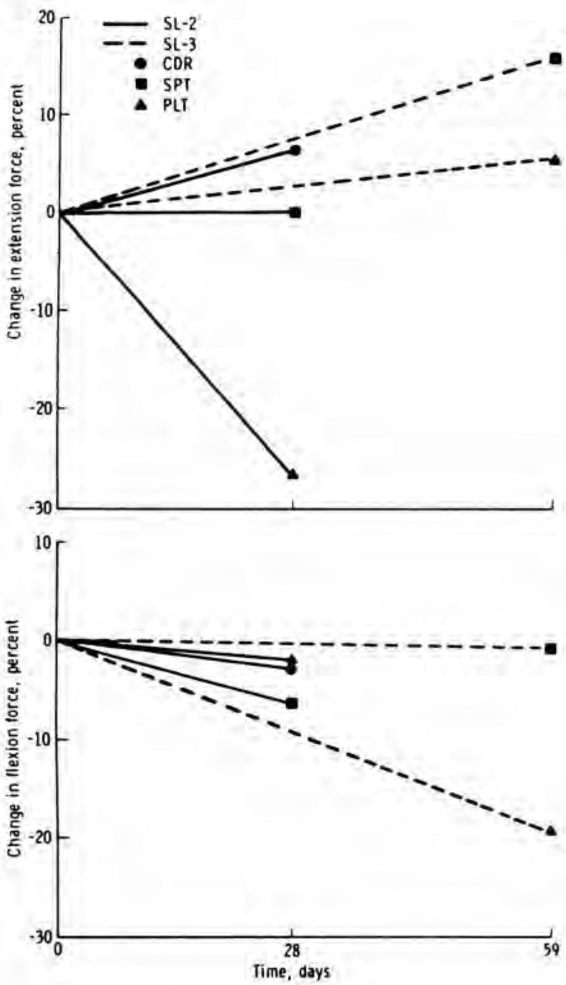


Figure 33.- A plot of the postflight changes in arm forces on SL-2 and SL-3. Positive values represent gain; negative values, loss.

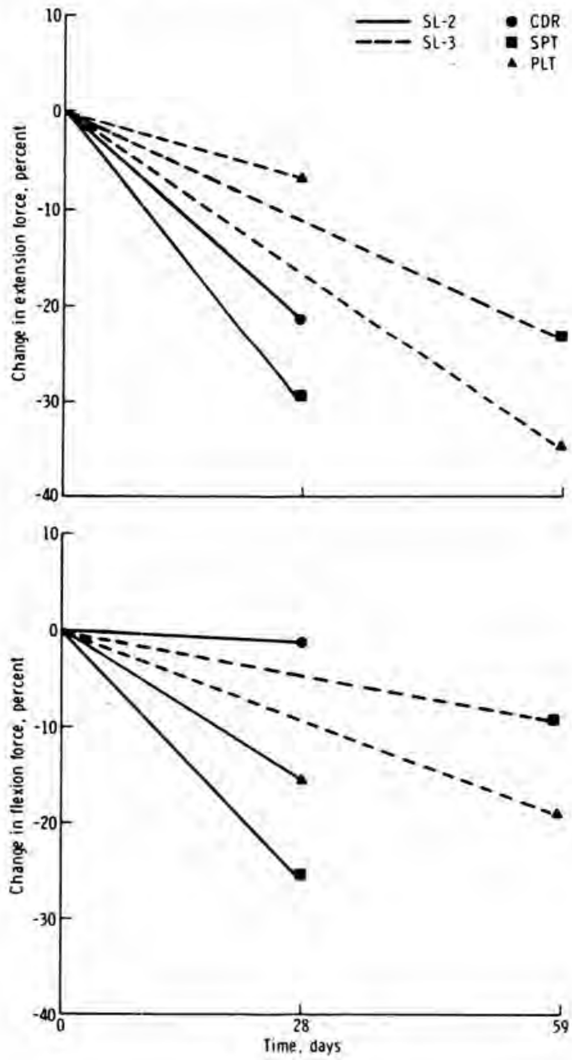


Figure 34.- A plot of the postflight changes in leg forces on SL-2 and SL-3. Positive values represent gain; negative values, loss.

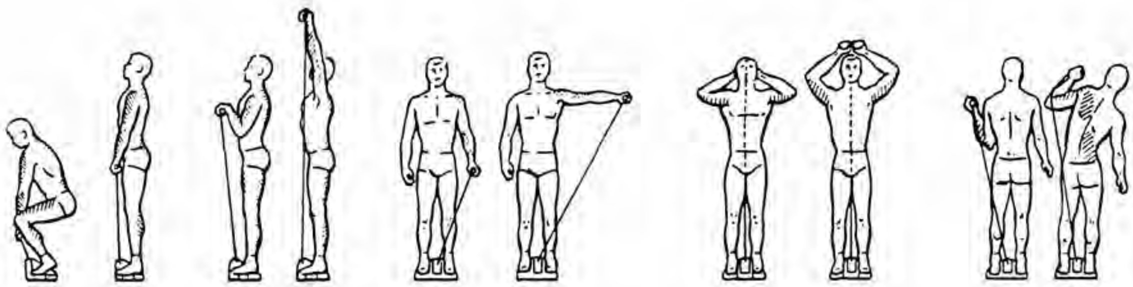


Figure 35.- MK-I exerciser positions.

These two devices were flown on SL-3, and food and time for exercise were increased in flight. The crew performed many repetitions per day of their favorite maneuvers on the MK-I and, to a lesser extent, on the MK-II. Also, the average amount of work done on the bicycle ergometer was more than doubled on SL-3, with all crewmen participating actively.

The results of muscle testing of SL-3 crewmen were markedly different from the results for the SL-2 crew.

Looking at changes in arm forces on SL-3, one sees complete preservation of extensor function, in contrast to SL-2 results (see fig. 33). The SPT showed a marked gain in arm strength. This consequence is the result of putting a good distance runner, which he was, on the equivalent of a weight-lifting program.

Looking now at changes in leg function, in figure 34, one sees a different picture. Results for only two SL-3 crewmen are shown since the CDR suffered a recurrence of a back strain from a lurch resulting from a roll of the recovery ship - possibly another demonstration of the hazard of muscle deconditioning.

Some device which would enable walking and running under forces equivalent to gravity appeared to be the ideal answer to this problem. This need had long been recognized; and immediately after SL-2, work was started on a treadmill for SL-4. As mission preparation progressed, the launch weight of the SL-4 vehicle became crucial; so the final design was simulation of a treadmill in response to weight constraints. The final weight of the device was 1.6 kg (3.5 lb).

The "treadmill," shown in figure 36, consisted of an aluminum-Teflon walking surface attached to the isogrid floor. Four rubber bungees, providing an equivalent weight of approximately 80 kg (175 lb), were attached to a shoulder and waist harness. By angling the bungees, an equivalent to a slippery hill is presented to the subject, who must climb it. High loads were placed on some leg muscles, especially in the calf, and fatigue occurred rapidly; so the device could not be used for significant aerobic work.

On SL-4, the crew used the bicycle ergometer at essentially the same rate as on SL-3, as well as the MK-I and MK-II exercisers. In addition, they typically performed 10 minutes per day of walking, jumping, and jogging on the treadmill. Food intake had again been increased.

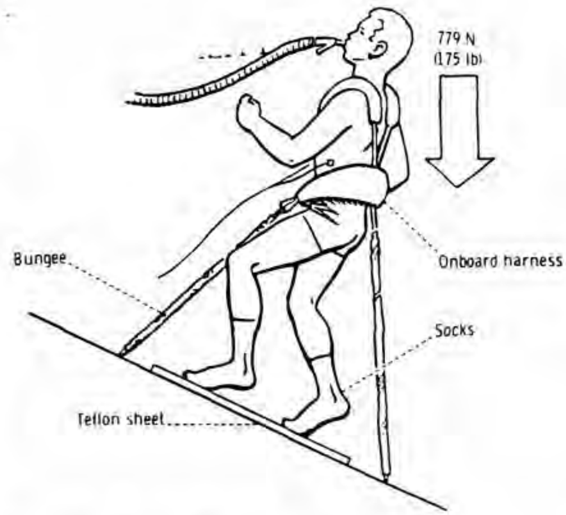


Figure 36.- Skylab treadmill arrangement used to test muscle function.

Even prior to muscle testing, it was obvious that the SL-4 crew was in surprisingly good condition. They stood and walked for long periods without apparent difficulty on the day after recovery, in contrast to the experience of the other crews after the earlier missions. Results of the testing confirmed that a surprisingly small loss in leg strength occurred after almost 3 months in weightlessness. A summary of the exercise and strength testing, shown in averaged values for the three missions, is depicted in figures 37 and 38. One point to be noted is the relatively small loss in arm strength as compared to legs in all missions. This result is reasonable, for in space ordinary work provides relatively greater loads for the arms; the legs receive virtually no effective loading. With the MK-I and MK-II exercisers, SL-4 arm strength increased in flexion and was minimal in extension.

Size is another common measure of muscle condition and has been discussed in the preceding section (see fig. 25).

There was a 4.7- to 9-fold reduction in the rate of loss of leg extensor strength, leg volume, lean body mass, and total body mass from SL-2 to SL-4. One might argue that this reduction simply represents some kind of equilibrium with increasing mission duration, but this conclusion is not consistent with the data in table 8, which show absolute losses.

As shown in figure 39, SL-4 crewmen demonstrated a marked improvement over previous Skylab crews with regard to losses of weight, leg strength, and leg volume. There can be little doubt that use of the added MK-I and MK-II improved the arm performance of the crewmen on SL-2 and SL-3 and equally little doubt that use of the SL-4 treadmill sharply reduced loss of leg strength and mass, since there was negligible increase in leg exercise with other devices on SL-4.

However, it must be recognized that food was another variable present. Virtually all nutritionists recognize that metabolic losses in normal subjects are mixed; i.e., both fat and muscle are lost. Vanderveen and Allen

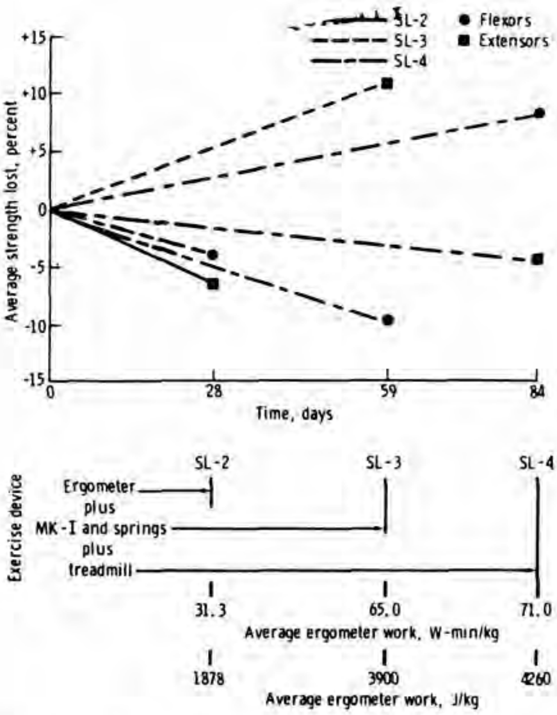


Figure 37.- A plot of the average arm strength changes on Skylab missions.

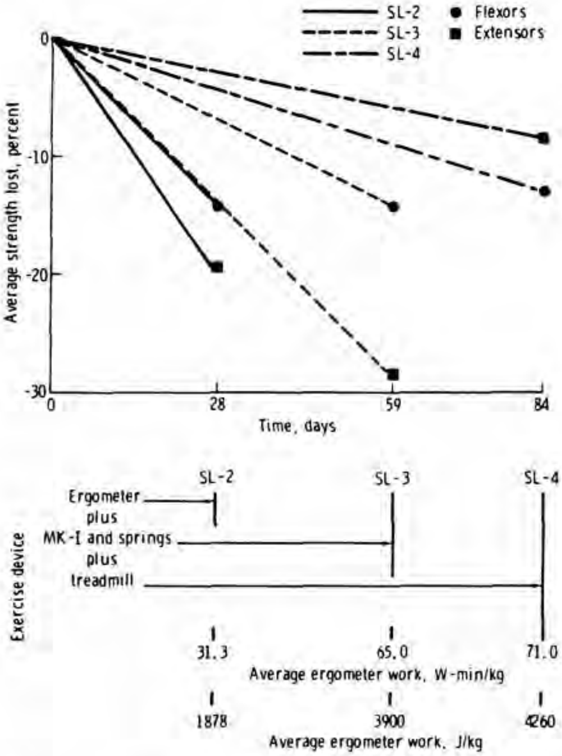


Figure 38.- A plot of the average leg strength changes on Skylab missions.

(1972) deliberately reduced caloric intake during a one-g chamber test simulation of space-flight conditions, using subjects chosen on the basis of being as equivalent as possible to the astronaut population. They found an almost pure muscle loss.

The Russian experience followed similar but much more elaborate lines, which included prolonged bed rest and supine tests on a motor-driven mill flown on Soyuz 11/Salyut, with elaborate force-loading suits to simulate gravity. Hours per day were spent on the treadmill, but at a load of only 50 kg of equivalent weight, in contrast to the 80 kg on Skylab with 70-kg crewmen for 12 to 15 minutes a day.

Some measured parameters from Russian missions are shown in table 9. According to these data, there is a consistent increase in loss of "tone" and strength in the legs, as compared to small arm losses, even on the 3- to 5-day missions. This loss increased sharply on the 18-day Soyuz 9 flight, in spite of prolonged, lightly loaded exercises. Again, such exercise was apparently sufficient for arms, which showed an increase in tone and negligible loss in girth and in wrist strength. It is interesting to note that the right, presumably dominant, wrist lost strength, whereas the left wrist

TABLE 8.- SUMMARY OF SKYLAB CREW AVERAGES OF EXERCISE-RELATED DATA

Skylab mission	Change in leg extension forces (F - 15 to R + 1), percent/day	Change in leg volume (F - 15 to R + 5), percent/day	Change in lean body mass (LBM) (F - 15 to R + 1), percent/day	Change in body weight (F - 1 to R + 0), percent/day	Average daily ergometer exercise, J/kg (W-min/kg) body weight
[a]2	[b]-0.75	-0.160	-0.089	-0.13	1878 (31.3)
[c]3	-.50	-.088	-.019	-.08	3900 (65.0)
[d]4	-.10	-.023	-.011	-.02	4260 (71.0)

[a]Exercise available - bicycle ergometer.

[b]Measured at R + 5 on this flight.

[c]Exercise available - bicycle ergometer, MK-I and MK-II exercisers.

[d]Exercise available - bicycle ergometer, MK-I and MK-II exercisers, treadmill.

TABLE 9.- SOME AVERAGE CHANGES IN MUSCLE PARAMETERS[a]

[From Kakurin (1971) and Parin (1974)]

Flight duration, days	Number of subjects	Change, percent preflight						Δ circumference					
		Tone			Strength			mm			percent		
		Tibialis anterior	Quadriceps	Biceps brachii	Standing	Left wrist	Right wrist	Shin level	Hip level	Shoulder level	Upper arm	Thigh	Calf
					Soyuz 3 to 8								
2 to 5	12	-7.5	-10.4	-5.4	-17	1.7	-1.5	-2	-7	-5	--	--	--
					Soyuz 9								
18	2	-11.2	-13.4	5.5	-29.9	5.7	-6.1	-12	-27	-2	-0.3	-3.3	-4.9
					Soyuz 11/Salyut								
24	3	--	--	--	--	--	--	--	--	--	[b]-1.1	[b]-4.4	[b]-5.4

[a]Measured 2 days after recovery except as noted otherwise.

[b]Measured post mortem.

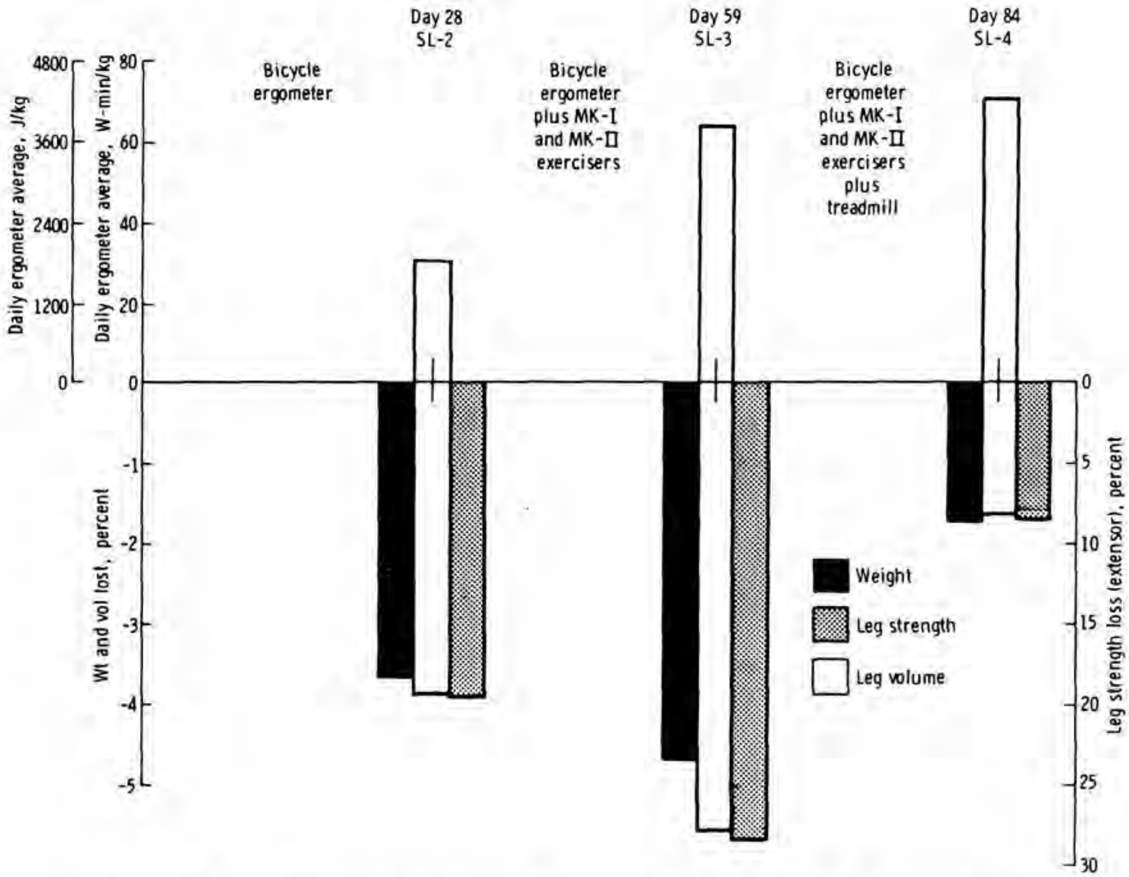


Figure 39.- Exercise-related quantities on Skylab missions.

gained. Although it did not appear statistically significant, one had the impression from Skylab handgrip measurements that the same thing happened there. The author suspects that the nondominant hand was used for grasping and stabilization, whereas the dominant hand was used for manipulation. The in-flight death of the Salyut crew makes functional comparisons impossible.

Another single data point on muscle change was obtained on the ASTP, a 9-day mission (see table 10). It may be a coincidence that crewman 2 lost no leg volume, but he was provided with a shoulder harness which enabled high-force leg exercises to be performed with a rope/capstan device.

Walking

Changes in muscle function were also reflected in postflight gait and posture. There was a general tendency toward hunched posture with slightly lowered head and a "shuffling" gait, with a marked aversion to the upright

TABLE 10.- LEFT-LEG VOLUME CHANGES OF ASTP CREWMEN

Crewman	Preflight volume, liters	Postflight (R+2) volume, liters	Δ volume, liters	Δ volume, percent
1 (ACDR)	7.8	7.40	-0.40	-5.1
2 (DMP)	7.5	7.50	0	0
3 (CMP)	8.1	7.75	-.35	-4.3

posture, especially in the first two Skylab crews. The last crew tolerated upright posture without apparent difficulty just 18 hours after recovery. Unfortunately, the gait and posture were not documented in the American program; but Russian cinephotographic documentation (Parin et al., 1974) showed a marked slowing of all phases of the walking gait (and especially the time with both feet on the ground), an effect which would be consistent with American observations. This result indicates reduced strength in the trunk and legs, possibly complicated by neuromuscular changes.

Body Composition Changes

Other indicators of muscle (and fat) changes are lean body mass determinations. These values were obtained on Skylab missions by means of standard radioisotopic dilution studies.[26] Results are tabulated in table 11. As these studies were made on recovery day (R + 0), before fluid redistribution and replacement were complete, some degree of dehydration was present, which would have the effect of decreasing both lean body mass and lean body mass percentage. Data taken on day R + 2 would have been more representative here, but the R + 0 data are consistent with other muscle data.

The data show a consistent loss of lean body mass but a rate of loss reduced with each mission.Lest someone interpret this result as some kind of adaptation, note that the crew of the shortest mission had the greatest lean body mass loss and the last crew had the least strength loss. Only one individual gained lean body mass (SL-3 SPT). He was the lightest individual; and he used the in-flight arm exercise devices enough to increase his arm strength by 15 percent, in contrast to his one-g regimen of running only.

In spite of this loss of lean body mass, the percentage of lean body mass increased in all crewmen but two, a result indicating the inadequacy of the diet to maintain fat levels even in individuals with body-fat percentages as low as 9 percent.

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[26]Data from studies done by Phil Johnson, Baylor Medical College, and Carolyn Leach, Lyndon B. Johnson Space Center.

TABLE 11.- CHANGES IN LEAN BODY MASS

ON SKYLAB MISSIONS

[By isotopic determination]

(a) By crewman

Crewman	LBM, kg, on -		Δ LBM		LBM, percent,[a] on -		Δ LBM, percent
	F - 1	R + 0	kg	percent	F - 1	R + 0	
SL-2							
CDR	56.6	55.9	-0.7	-1.2	91.9	92.7	0.8
SPT	67.4	65.7	-1.7	-2.5	87.0	[b]88.9	1.9
PLT	71.5	68.5	-3.0	-4.2	88.3	90.1	1.8
SL-3							
CDR	58.2	57.4	-0.8	-1.4	85.0	88.7	3.7
SPT	53.6	54.2	.6	1.1	87.0	92.2	5.2
PLT	73.4	71.1	-2.3	-3.1	84.6	83.1	-1.5
SL-4							
CDR	57.4	56.2	-1.2	-2.1	84.3	82.5	-1.8
SPT	62.3	61.5	-.8	-1.3	87.4	87.8	.4
PLT	63.0	61.8	-1.2	-1.9	91.3	93.9	2.6

(b) By mission

Mission	Duration, days	Mean Δ LBM			
		kg	kg/day	percent	percent/day
SL-2	28	-1.80	6.43×10^{-2}	-1.50	-5.36×10^{-2}
SL-3	59	-.83	1.41×10^{-2}	-2.47	-4.19×10^{-2}
SL-4	84	-1.07	1.27×10^{-2}	-.40	$-.48\times10^{-2}$

[a]LBM divided by body weight times 100.

[b]Measured on R + 1.

The crewmen maintaining body fat are notable. The SL-4 CDR was the only crewman not losing body weight, a result indicating that some lost muscle was replaced with fat. Although the SL-3 PLT lost body weight, he was large and unusually well muscled and obviously lost this muscle at a rate greater than the rate of loss of body weight and thereby maintained his body fat.

Each succeeding mission showed an improvement in rate of loss of lean body mass and rate of change in lean body mass percentage, which can only be attributed to generally improved nutrition and exercise on each succeeding flight.

Applications

This subject of loss of strength and muscle mass is one of the more important aspects of manned space flight, especially for the prolonged missions of the future requiring numerous personnel for manual tasks such as structure assembly and similar operations. The concern is not with operations in space - for there is no reason to think that even unprotected muscle function will ever fall below that routinely required in space flight - but with capabilities on Earth after a return from space flight. Without protection, serious muscle disuse atrophy will begin in the first few days of weightlessness in the major antigravity groups and continue to a functional equilibrium far below that compatible with erect stance and locomotion on Earth. Although this aspect is not discussed, such atrophy will seriously degrade gravity tolerance as well. Thus, unless one is prepared to accept special reentry precautions, followed by an extensive rehabilitation program on return to a one-g environment, adequate in-flight diet and exercise force levels compatible with those required for walking must be provided. This problem of prevention is primarily one for the life scientists; however, the measurements and assessments of muscle condition required are much more familiar to the anthropometrist. A cooperative effort by the anthropometrist, the exercise physiologist, and the industrial physician may be in order.

FUTURE

Unfortunately, the role of anthropometrics, other than when forced to the surface by a specific problem such as suit fit or cockpit layout, has been largely ignored. This neglect cannot be continued unless a long, painful, and inefficient period of trial and error can be afforded in the space program as man expands his time and efforts in space. The pitiably incomplete data informally gathered and presented here should be enough to stimulate better future efforts. Even this small amount of data has been enough to show the potential impact of weightlessness on man/machine design. It was also enough to redirect the efforts and thinking in several life science areas, especially the cardiovascular area.

For this reason, a few NASA investigators are redoubling their efforts in several areas. Most urgent, these investigators believe, is development of improved methods of data collection, especially with regard to time and simplicity, particularly for dynamic data such as strength measurements. A series of developments is underway that, hopefully, will enable rapid, automatic recording and analysis of size, shape, and motion on Earth or in space, of nude or space-suited crewmen. These data will be stored and automatically interfaced with computational facilities so that man may be synthetically interfaced with any desired machine or situation.

The optimum interface may then be tested in space by this improved data gathering and instrumentation, and both models and machines will be improved. Several pioneers have been at work for some time now, showing alternatives to the complications and limitations of tapes, goniometers, static weights, and mockups, including "Combiman" at AMRL, Herron with his application of stereophotogrammetry to the body, and Perrine with isokinetic strength testing, as well as many others. The NASA investigators hope to follow and possibly aid their trailblazing and sincerely hope to be joined by professional anthropometrists more experienced than themselves in investigating this new area of weightlessness, for it is an exciting place to be - and there is both need and opportunity aplenty.

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ADDITIONAL DATA SOURCES

It was originally intended to include all anthropometric data available from space flight in this chapter and the accompanying appendixes, but it soon became obvious that more had been collected than originally allowed for. Although the bibliographic references contain additional data, a good number of known sources were not included. Investigators with appropriate requirements and NASA clearance are directed to the following sources for further information.

1. The Life Sciences Directorate, code DA, NASA Lyndon B. Johnson Space Center, Houston, Texas 77058, which has an archival section in which all zero-g data will eventually be assembled.

2. William Thornton, M.D., code CB, NASA Lyndon B. Johnson Space Center, Houston, Texas 77058, who has most of the raw data, including all anthropometric photographs, complete strength measurement curves, and some related one-g records.

3. Dr. R. E. Herron, Biostereometrics Laboratory, Texas Institute for Rehabilitation and Research, 1333 Moursund Ave., Houston, Texas 77025, who has the original stereophotogrammetric work.

4. Dr. Wycliff Hoffler, code DB53, NASA John F. Kennedy Space Center, Kennedy Space Center, Florida 32899, who has ASTP and other leg-girth data.

5. John Jackson and Jeri Brown, code EW5, NASA Lyndon B. Johnson Space Center, Houston, Texas 77058, who have a variety of data, including zero-g and water-immersion studies.

APPENDIX A

WEIGHT CHANGES OF SPACE-FLIGHT CREWMEN

In table A-1, anthropometric weight changes of U.S. crewmen of the Mercury-Redstone (MR), Mercury-Atlas (MA), Gemini-Titan (GT), Apollo-Saturn (AS), and Apollo-Soyuz Test Project (ASTP) missions are listed. The nude weight of the designated pilot (PLT), command pilot (CP), commander (CDR), command module pilot (CMP), lunar module pilot (LMP), Apollo commander (ACDR), or docking module pilot (DMP) was taken immediately before and after each mission.

In table A-2, weight changes of U.S.S.R. cosmonauts are shown for the Vostok 1 to 6, Voskhod 1 and 2, Soyuz 3 to 9, and Soyuz 11/Salyut missions.

In table A-3, body weights of all Skylab crewmen measured daily during the Skylab 2 (SL-2), Skylab 3 (SL-3), and Skylab 4 (SL-4) missions are presented, together with a range of preflight and postflight measurements. The day of year (DOY), calendar date, and mission day (MD) are listed for convenience. The designator F - 30 represents 30 days before lift-off, R + 0 represents recovery day, R + 16 represents 16 days after recovery, and so forth. The crewman designators are CDR, PLT, and science pilot (SPT). Except for first shipboard weights or as otherwise noted, all ground-based measurements were made of the nude crewmen after the first urination of the day and before breakfast.

In-flight mass measurements were made with use of the body mass measuring device (BMMD). A fifth-order curve fit was used on DOY 151 calibration data for SL-2, a second-order curve fit on DOY 211 calibration data for SL-3, and a fourth-order curve fit on DOY 211 calibration data for SL-4. Where appropriate, corrections have been made for clothing weight and one-g conditions.

TABLE A-1.- WEIGHT CHANGES OF U.S. ASTRONAUTS

Flight	Flight duration, days:hr:min	Crewman	Age, yr	Height, cm(in.)	Weight, kg(lb) Preflight	Weight, kg(lb) Postflight	Weight change kg(lb)	Weight change percent
MR-3	00:00:15	PLT	37	180.3 (71)	--	--	--	--
MR-4	00:00:15	PLT	35	170.2 (67)	--	--	--	--
MA-6	00:04:55	PLT	40	179.1 (70.5)	--	--	--	--
MA-7	00:04:56	PLT	37	179.1 (70.5)	69.8 (154)	67.1 (148.0)	-2.7 (-6.0)	-3.9
MA-8	00:09:13	PLT	39	177.8 (70)	80.2 (176.8)	80.0 (176.3)	-.2 (-.5)	-.3
MA-9	01:10:19	PLT	36	172.7 (68)	66.7 (147)	63.3 (139.5)	-3.5 (-7.75)	-5.3
GT-III	00:04:53	CP	38	170.2 (67)	71.7 (158)	70.3 (155)	-1.4 (-3)	-1.9
		PLT	34	175.3 (69)	74.4 (164)	73.8 (162.8)	-.6 (-1.5)	-.9
GT-IV	04:01:56	CP	36	180.3 (71)	71.0 (156.5)	68.9 (152)	-2.0 (-4.5)	-2.9
		PLT	34	180.3 (71)	78.5 (173)	74.6 (164.5)	-3.8 (-8.5)	-4.9
GT-V	07:22:55	CP	38	172.7 (68)	68.9 (152)	65.5 (144.5)	-3.4 (-7.5)	-4.9
		PLT	35	168.9 (66.5)	69.8 (154)	66.1 (145.8)	-3.7 (-8.2)	-5.3
GT-VI	01:01:51	CP	42	177.8 (70)	80.0 (176.3)	78.8 (173.7)	-1.2 (-2.6)	-1.5
		PLT	35	182.9 (72)	77.6 (171.0)	73.0 (161.0)	-4.5 (-10)	-5.8
GT-VII	13:18:35	CP	37	177.8 (70)	73.7 (162.5)	69.2 (152.5)	-4.5 (-10)	-6.2
		PLT	37	180.3 (71)	76.9 (169.5)	74.2 (163.5)	-2.7 (-6.0)	-3.5
[a]GT-VIII	00:10:41	CP	35	180.3 (71)	73.8 (162.7)	--	--	--
		PLT	33	182.9 (72)	78.5 (173.0)	--	--	--
GT-IX	03:00:21	CP	35	182.9 (72)	78.9 (174.0)	78.0 (172.0)	-.9 (-2.0)	-1.1
		PLT	32	182.9 (72)	78.2 (172.5)	74.6 (164.5)	-3.6 (-8)	-4.6
GT-X	02:22:46	CP	35	175.3 (69)	73.9 (163.0)	72.1 (159)	-1.8 (-4)	-2.4
		PLT	35	180.3 (71)	74.2 (163.5)	70.8 (156)	-3.4 (-7.5)	-4.6
GT-XI	02:23:17	CP	36	168.9 (66.5)	69.3 (152.7)	68.0 (150)	-1.2 (-2.7)	-1.8
		PLT	36	170.2 (67)	68.5 (151.0)	68.5 (151.0)	0 (0)	0
GT-XII	03:22:34	CP	38	180.3 (71)	77.1 (170.0)	72.7 (160.3)	4.4 (-9.7)	-5.7
		PLT	35	177.8 (70)	75.3 (166.0)	73.2 (161.3)	-2.1 (-4.7)	-2.8

[a]Mission aborted.

TABLE A-1.- Continued

Flight	Flight duration, days:hr:min	Crewman	Age, yr	Height, cm(in.)	Weight, kg(lb)		Weight change	
					Preflight	Postflight	kg(lb)	percent
AS-7	10:20:09	CDR	45	177.8 (70)	88.0 (194.0)	86.1 (189.8)	-1.9 (-4.2)	-2.2
		CMP	38	175.3 (69)	71.2 (157)	66.7 (147.0)	-4.5 (-10)	-6.4
		LMP	36	177.8 (70)	70.8 (156)	67.6 (149)	-3.2 (-7)	-4.5
AS-8	06:03:00	CDR	40	177.8 (70)	76.6 (169)	72.8 (160.5)	-3.8 (-8.5)	-5.0
		CMP	40	180.3 (71)	78.0 (172)	74.4 (164)	-3.6 (-8)	-4.7
		LMP	35	172.7 (68)	64.4 (142)	62.6 (138)	-1.8 (-4)	-2.8
AS-9	10:01:00	CDR	39	180.3 (71)	72.1 (159)	69.6 (153.5)	-2.5 (-5.5)	-3.5
		CMP	36	182.9 (72)	80.7 (178)	78.2 (172.5)	-2.5 (-5.5)	-3.1
		LMP	33	182.9 (72)	72.1 (159)	69.4 (153)	-2.7 (-6)	-3.8
AS-10	08:00:03	CDR	38	182.9 (72)	77.5 (171)	76.4 (168.5)	-1.1 (-2.5)	-1.5
		CMP	38	175.3 (69)	74.8 (165)	72.3 (159.5)	-2.5 (-5.5)	-3.4
		LMP	35	182.9 (72)	78.5 (173)	73.9 (163)	-4.5 (-10)	-5.8
AS-11	08:03:18	CDR	38	180.3 (71)	78.0 (172)	74.4 (164)	-3.6 (-8.0)	-4.7
		CMP[b]	38	180.3 (71)	75.3 (166)	72.1 (159)	-3.2 (-7.0)	-4.2
		LMP	39	177.8 (70)	75.7 (167)	75.3 (166)	-.4 (-1.0)	-.6
AS-12	10:04:36	CDR	39	168.9 (66.5)	67.7 (149.3)	65.8 (145)	-1.9 (-4.3)	-2.9
		CMP[b]	40	170.2 (67)	70.4 (155.3)	67.1 (148)	-3.3 (-7.3)	-4.8
		LMP	37	176.5 (69.5)	69.2 (152.5)	63.5 (140)	-5.7 (-12.5)	-8.2
AS-13	05:22:54	CDR	42	180.3 (71)	80.5 (177.5)	74.2 (163.5)	-6.3 (-14.0)	-7.9
		CMP	38	181.6 (71.5)	89.3 (197.0)	84.4 (186.0)	-4.9 (-11.0)	-5.6
		LMP	36	176.5 (69.5)	70.8 (156.0)	67.8 (149.5)	-3.0 (-6.5)	-4.2

[b]Designated crewmen spent period at 1/6 g; all other crewmen remained in weightlessness throughout mission.

TABLE A-1.- Concluded

Flight	Flight duration, days:hr:min	Crewman	Age, yr	Height, cm(in.)	Weight, kg(lb)		Weight change	
					Preflight	Postflight	kg(lb)	percent
AS-14	09:00:01	CDR	47	180.3 (71)	76.2 (168.0)	76.6 (169.0)	0.4 (1.0)	0.6
		CMP[b]	37	177.8 (70)	74.8 (165.0)	69.4 (153.0)	-5.4 (-12.0)	-7.3
		LMP	40	180.3 (71)	79.8 (176.0)	80.3 (177.0)	.4 (1.0)	.6
AS-15	12:07:11	CDR	38	182.9 (72)	80.2 (176.8)	78.9 (174.0)	-1.3 (-2.8)	-1.6
		CMP[b]	39	179.1 (70.5)	73.5 (162.0)	72.1 (159.0)	-1.4 (-3.0)	-1.9
		LMP	41	172.7 (68)	73.2 (161.5)	70.7 (156.0)	-2.5 (-5.5)	-3.4
AS-16	11:01:51	CDR	41	175.3 (69)	78.9 (174.0)	75.5 (166.5)	-3.4 (-7.5)	-4.3
		CMP[b]	36	177.8 (70)	61.4 (135.5)	58.5 (129.0)	-2.9 (-6.5)	-4.8
		LMP	36	181.6 (71.5)	73.0 (161.0)	70.5 (155.5)	-2.5 (-5.5)	-3.4
AS-17	12:13:51	CDR	38	182.9 (72)	80.3 (177.0)	76.1 (167.8)	-4.2 (-9.2)	-5.2
		CMP[b]	39	181.6 (71.5)	75.7 (167.0)	74.6 (164.5)	-1.1 (-2.5)	-1.5
		LMP	37	175.3 (69)	74.8 (165.0)	72.9 (160.8)	-1.9 (-4.2)	-2.5
ASTP	09:01:28	ACDR	44	182.9 (72)	76.9 (169.5)	77.6 (171.1)	.7 (1.6)	.9
		CMP	51	179.1 (70.5)	74.8 (165)	72.8 (160.5)	-2.0 (-4.5)	-2.7
		DMP	44	180.3 (71)	80.2 (176.8)	77.6 (171.1)	-2.6 (-5.7)	-3.2

[b]Designated crewmen spent period at 1/6 g; all other crewmen remained in weightlessness throughout mission.

TABLE A-2.- WEIGHT CHANGES OF U.S.S.R. COSMONAUTS

Flight	Flight duration, days:hr	Crewman	Weight, kg		Weight change	
			Preflight	Postflight	kg	Percent
Vostok 1	00:02	Gagarin	NA[a]	NA	NA	[b,c]-0.7
Vostok 2	01:01	Titov	NA	NA	NA	[b,c]-3.9
Vostok 3	03:22	Nikolayev	NA	NA	NA	[b,c]-2.5
Vostok 4	02:23	Popovich	NA	NA	NA	[b,c]-2.7
Vostok 5	04:23	Bykovskiy	NA	NA	NA	[c]-3.5
Vostok 6	02:23	Tereshkova	NA	NA	NA	[c]-3.2
Voskhod 1	00:24	Komarov et al.	NA	NA	[b,d]-2.5 to -3	NA
Voskhod 2	01:02	C-Belyayev	NA	NA	[b]-1.0	NA
		A-Leonov	NA	NA	[b] -.9	NA
[e]Soyuz 3	03:23	Beregovoy	NA	NA	-2.4	NA
[e]Soyuz 4	02:23	Shatalov	NA	NA	-4.0	NA
	[f]02:00	Yeliseyev	NA	NA	-2.0	NA
	[f]02:00	Krunov	NA	NA	-2.0	NA
[e]Soyuz 5	03:46	Volynov	NA	NA	-2.4	NA
[e]Soyuz 6	04:23	Shonin	NA	NA	-2.4	NA
		Kubasov	NA	NA	-2.1	NA
[e]Soyuz 7	04:23	Filipchenko	NA	NA	-3.9	NA
		Gorbatko	NA	NA	-2.0	NA
		Volkov	NA	NA	-2.4	NA
[e]Soyuz 8	04:23	Shatalov	NA	NA	-2.2	NA
		Yeliseyev	NA	NA	-3.6	NA
Soyuz 9	17:16	Nikolayev	65.0	62.3	-2.7	[g]-4.15
	17:16	Sevast'yanov	68.0	64.5	-3.5	[g]-5.14
Soyuz 11/Salyut	24:00	Dobrovol'skiy	81.0	77.1	-3.9	[g]-4.8
		Volkov	83.3	80.56	-2.74	[g]-3.3
		Patsayev	74.6	70.87	-3.73	[g]-5.0

[a]NA = not available.
[b]Measured 24 hours after flight.
[c]Source: unpublished report.
[d]Range of losses.
[e]Source: Kakurin (1971).
[f]Crewmen launched on Soyuz 5 and returned on Soyuz 4.
[g]Source: Parin et al. (1974).

TABLE A-3.- DAILY BODY WEIGHTS OF SKYLAB CREWMAN

(a) SL-2

DOY	Date, 1973	MD	Weight, kg (lb)		
			CDR	SPT	PLT
			Preflight		
[a]115	Apr. 25	F - 30	62.8 (138.5)	78.6 (173.3)	81.4 (179.5)
116	Apr. 26	F - 29	62.5 (137.8)	78.5 (173.0)	81.3 (179.3)
117	Apr. 27	F - 28	62.5 (137.8)	78.4 (172.8)	81.0 (178.5)
118	Apr. 28	F - 27	62.5 (137.8)	78.4 (172.8)	81.0 (178.5)
119	Apr. 29	F - 26	62.1 (137.0)	77.8 (171.5)	80.7 (178.0)
120	Apr. 30	F - 25	62.1 (137.0)	77.9 (171.8)	80.9 (178.3)
121	May 1	F - 24	62.8 (138.5)	77.8 (171.5)	80.9 (178.3)
122	May 2	F - 23	62.8 (138.5)	78.0 (171.9)	80.3 (177.0)
123	May 3	F - 22	62.3 (137.3)	77.8 (171.5)	80.3 (177.0)
124	May 4	F - 21	62.0 (136.8)	77.6 (171.0)	80.2 (176.8)
125	May 5	F - 20	61.8 (136.3)	77.5 (170.9)	79.9 (176.3)
126	May 6	F - 19	62.8 (138.5)	78.2 (172.5)	80.2 (176.8)
127	May 7	F - 18	62.6 (138.0)	77.8 (171.5)	79.9 (176.3)
128	May 8	F - 17	62.5 (137.8)	78.2 (172.5)	79.8 (176.0)
129	May 9	F - 16	61.9 (136.5)	77.5 (170.8)	79.2 (174.5)
130	May 10	F - 15	61.9 (136.5)	77.9 (171.8)	79.6 (175.5)
131	May 11	F - 14	62.3 (137.3)	77.6 (171.0)	79.6 (175.5)
132	May 12	F - 13	62.3 (137.3)	77.5 (170.8)	79.7 (175.8)
133	May 13	F - 12	62.1 (137.0)	77.8 (171.5)	79.4 (175.0)
134	May 14	F - 11	62.0 (136.8)	77.6 (171.0)	79.4 (175.0)
135	May 15	F - 10	61.6 (135.8)	77.2 (170.3)	N.D.[b]
136	May 16	F - 9	62.0 (136.8)	77.6 (171.0)	79.6 (175.5)
137	May 17	F - 8	62.1 (137.0)	N.D.	79.7 (175.8)
138	May 18	F - 7	61.6 (135.8)	77.8 (171.5)	79.7 (175.8)
139	May 19	F - 6	62.0 (136.8)	78.4 (172.8)	80.3 (177.0)
140	May 20	F - 5	62.0 (136.8)	78.1 (172.3)	80.1 (176.5)
141	May 21	F - 4	62.5 (137.8)	78.4 (172.8)	81.0 (178.5)
142	May 22	F - 3	N.D.	N.D.	N.D.
143	May 23	F - 2	61.7 (136.0)	77.5 (170.8)	80.3 (177.0)
144	May 24	F - 1	62.0 (136.8)	77.7 (171.3)	79.7 (175.8)
145	May 25	1	61.9 (136.5)	77.2 (170.3)	79.7 (175.8)

[a]Start controlled diet.

[b]N.D. = not done.

TABLE A-3.- Continued

(a) Concluded

DOY	Date, 1973	MD	Weight, kg (lb)		
			CDR	SPT	PLT
			In-flight		
145	May 25	1	61.9 (136.5)	77.2 (170.3)	79.7 (175.8)
146	May 26	2	N.D.	N.D.	N.D.
147	May 27	3	N.D.	N.D.	N.D.
148	May 28	4	N.D.	N.D.	N.D.
149	May 29	5	61.4 (135.4)	75.6 (166.6)	79.4 (175.1)
150	May 30	6	61.2 (135.0)	75.2 (165.9)	79.2 (174.6)
151	May 31	7	62.1 (136.8)	76.1 (167.7)	78.9 (173.9)
152	June 1	8	61.1 (134.8)	75.3 (166.1)	79.0 (174.2)
153	June 2	9	61.7 (136.0)	75.5 (166.4)	78.6 (173.2)
154	June 3	10	61.6 (135.8)	75.9 (167.2)	78.0 (172.0)
155	June 4	11	61.2 (134.9)	75.9 (167.3)	78.8 (173.8)
156	June 5	12	61.6 (135.8)	75.3 (166.0)	79.1 (174.5)
157	June 6	13	60.5 (133.4)	74.7 (164.6)	79.1 (174.4)
158	June 7	14	60.1 (132.4)	75.3 (166.1)	78.5 (173.0)
159	June 8	15	60.7 (133.7)	74.9 (165.1)	78.1 (172.2)
160	June 9	16	61.0 (134.4)	76.0 (167.5)	78.6 (173.4)
161	June 10	17	61.4 (135.3)	76.0 (167.6)	78.4 (172.9)
162	June 11	18	61.1 (134.7)	75.7 (166.9)	78.0 (172.0)
163	June 12	19	61.2 (134.9)	75.9 (167.4)	78.6 (173.2)
164	June 13	20	61.3 (135.2)	75.4 (166.2)	78.2 (172.4)
165	June 14	21	60.7 (133.9)	76.1 (167.7)	77.9 (171.8)
166	June 15	22	61.3 (135.2)	75.7 (167.0)	78.3 (172.6)
167	June 16	23	61.1 (134.7)	75.6 (166.6)	77.3 (170.5)
168	June 17	24	61.3 (135.1)	75.7 (166.9)	77.7 (171.2)
169	June 18	25	N.D.	N.D.	N.D.
170	June 19	26	60.6 (133.6)	75.0 (165.3)	77.3 (170.3)
171	June 20	27	60.4 (133.1)	75.0 (165.4)	77.4 (170.6)
172	June 21	28	60.5 (133.3)	74.9 (165.2)	77.2 (170.3)
173	June 22	R + 0	60.8 (134.0)	74.5 (164.2)	76.5 (168.7)
			Postflight		
173	June 22	[c]R + 0	60.2 (132.8)	74.3 (163.8)	76.0 (167.5)
174	June 23	R + 1	60.6 (133.5)	73.8 (162.8)	76.4 (168.5)
175	June 24	R + 2	60.7 (133.8)	75.1 (163.5)	78.1 (172.3)
176	June 25	R + 3	61.0 (134.5)	N.D.	77.1 (170.0)
177	June 26	R + 4	61.2 (135.0)	74.6 (164.5)	77.3 (170.5)
178	June 27	R + 5	61.9 (136.5)	74.8 (165.0)	77.1 (170.0)
179	June 28	R + 6	61.7 (136.0)	75.1 (165.5)	77.6 (171.0)
180	June 29	R + 7	61.9 (136.5)	N.D.	77.5 (170.8)
181	June 30	R + 8	61.7 (136.0)	75.1 (165.5)	77.5 (170.8)
182	July 1	R + 9	N.D.	N.D.	N.D.
183	July 2	R + 10	61.5 (135.5)	74.8 (165.0)	77.7 (171.3)
184	July 3	R + 11	60.8 (134.0)	75.2 (165.8)	77.6 (171.0)
185	July 4	R + 12	60.8 (134.0)	N.D.	77.8 (171.5)
186	July 5	R + 13	60.8 (134.0)	75.0 (165.3)	77.2 (170.3)
187	July 6	R + 14	61.0 (134.5)	74.8 (165.0)	77.5 (170.8)
188	July 7	R + 15	N.D.	N.D.	77.5 (170.8)
[d]189	July 8	R + 16	N.D.	N.D.	77.6 (171.0)

[c]First shipboard weights.

[d]Stop controlled diet.

TABLE A-3.- Continued

(b) SL-3

DOY	Date, 1973	MD	Weight, kg (lb) CDR	Weight, kg (lb) SPT	Weight, kg (lb) PLT
			Preflight		
188[a]	July 7	F - 21	69.3 (152.8)	62.9 (138.8)	89.0 (196.3)
189	July 8	F - 20	68.4 (150.8)	62.5 (137.8)	86.7 (191.3)
190	July 9	F - 19	68.2 (150.3)	61.7 (136.0)	88.1 (194.3)
191	July 10	F - 18	68.8 (151.8)	62.1 (137.0)	87.9 (193.8)
192	July 11	F - 17	68.5 (151.0)	61.7 (136.0)	87.7 (193.3)
193	July 12	F - 16	68.0 (150.0)	61.5 (135.5)	87.1 (192.0)
194	July 13	F - 15	68.6 (151.3)	62.1 (137.0)	87.7 (193.3)
195	July 14	F - 14	68.9 (152.0)	61.6 (135.8)	88.5 (195.0)
196	July 15	F - 13	68.6 (151.3)	61.7 (136.0)	88.6 (195.3)
197	July 16	F - 12	68.3 (150.6)	61.5 (135.5)	88.1 (194.3)
198	July 17	F - 11	68.5 (151.0)	62.4 (137.5)	87.8 (193.5)
199	July 18	F - 10	68.7 (151.5)	62.0 (136.8)	87.8 (193.5)
200	July 19	F - 9	68.9 (152.0)	62.1 (137.0)	88.2 (194.5)
201	July 20	F - 8	68.6 (151.3)	61.6 (135.8)	88.3 (194.8)
202	July 21	F - 7	68.6 (151.3)	61.3 (135.3)	88.1 (194.3)
203	July 22	F - 6	68.0 (150.0)	61.7 (136.0)	87.4 (192.8)
204	July 23	F - 5	68.5 (151.0)	61.9 (136.5)	87.7 (193.3)
205	July 24	F - 4	68.8 (151.8)	62.5 (137.8)	88.5 (195.0)
206	July 25	F - 3	69.1 (152.3)	62.3 (137.3)	89.0 (196.3)
207	July 26	F - 2	68.6 (151.3)	61.1 (134.8)	88.8 (195.8)
208	July 27	F - 1	68.6 (151.3)	61.2 (135.0)	88.2 (194.5)
209	July 28	1	68.5 (151.0)	61.8 (136.3)	88.3 (194.8)
			In-flight		
209	July 28	1	68.5 (151.0)	61.8 (136.3)	88.3 (194.8)
210	July 29	2	67.1 (147.8)	60.5 (133.5)	[e]86.5 (190.6)
211	July 30	3	66.9 (147.5)	59.5 (131.2)	[e]84.2 (185.5)
212	July 31	4	66.3 (146.1)	59.4 (130.9)	[e]85.6 (188.6)
213	Aug. 1	5	66.4 (146.3)	59.4 (131.0)	85.3 (188.0)
214	Aug. 2	6	65.9 (145.4)	59.5 (131.2)	85.7 (189.0)
215	Aug. 3	7	65.7 (144.8)	59.5 (131.2)	85.3 (188.1)
216	Aug. 4	8	65.9 (145.3)	59.4 (131.0)	85.8 (189.1)
217	Aug. 5	9	66.1 (145.6)	59.3 (130.8)	86.0 (189.7)
218	Aug. 6	10	66.3 (146.2)	59.3 (130.7)	85.8 (189.3)
219	Aug. 7	11	66.0 (145.6)	58.7 (129.4)	85.8 (189.1)
220	Aug. 8	12	65.7 (144.8)	59.1 (130.3)	85.8 (189.3)
221	Aug. 9	13	66.1 (145.6)	59.4 (130.9)	86.1 (189.9)
222	Aug. 10	14	66.5 (146.6)	59.4 (130.9)	85.6 (188.8)
223	Aug. 11	15	66.3 (146.2)	59.0 (130.1)	86.0 (189.7)
224	Aug. 12	16	66.1 (145.8)	59.2 (130.4)	85.8 (189.3)
225	Aug. 13	17	66.0 (145.5)	59.1 (130.2)	85.8 (189.3)
226	Aug. 14	18	65.8 (145.1)	58.7 (129.4)	85.8 (189.1)
227	Aug. 15	19	66.1 (145.7)	59.2 (130.6)	86.0 (189.5)
228	Aug. 16	20	66.2 (146.0)	59.1 (130.3)	85.4 (188.3)
229	Aug. 17	21	66.4 (146.4)	58.9 (129.9)	85.6 (188.8)
230	Aug. 18	22	66.4 (146.3)	58.6 (129.3)	86.1 (189.8)
231	Aug. 19	23	66.5 (146.6)	58.7 (129.3)	85.8 (189.1)
232	Aug. 20	24	65.9 (145.3)	59.1 (130.4)	86.3 (190.2)
233	Aug. 21	25	66.3 (146.2)	59.1 (130.2)	85.6 (188.8)

[a]Start controlled diet.

[e]BMMD readings very scattered; measurements unreliable.

TABLE A-3.- Continued

(b) Continued

DOY	Date, 1973	MD	Weight, kg (lb) CDR	SPT	PLT
			In-flight		
234	Aug. 22	26	66.5 (146.5)	58.8 (129.6)	85.7 (188.8)
235	Aug. 23	27	66.1 (145.7)	58.6 (129.3)	85.5 (188.6)
236	Aug. 24	28	66.1 (145.7)	59.2 (130.5)	85.3 (188.1)
237	Aug. 25	29	65.8 (145.1)	58.7 (129.5)	85.6 (188.6)
238	Aug. 26	30	66.0 (145.6)	58.6 (129.2)	85.2 (187.8)
239	Aug. 27	31	66.4 (146.4)	58.9 (129.9)	85.7 (188.8)
240	Aug. 28	32	66.5 (146.7)	58.8 (129.7)	85.9 (189.3)
241	Aug. 29	33	66.3 (146.1)	58.9 (129.9)	85.7 (189.0)
242	Aug. 30	34	66.6 (146.8)	58.6 (129.3)	85.9 (189.4)
243	Aug. 31	35	66.4 (146.3)	58.6 (129.1)	85.7 (188.8)
244	Sept. 1	36	66.4 (146.3)	58.7 (129.4)	85.7 (189.0)
245	Sept. 2	37	66.3 (146.1)	58.7 (129.3)	85.3 (188.1)
246	Sept. 3	38	66.6 (146.8)	58.8 (129.5)	85.3 (188.1)
247	Sept. 4	39	66.3 (146.1)	58.5 (128.9)	85.6 (188.7)
248	Sept. 5	40	66.4 (146.4)	59.0 (130.0)	85.4 (188.2)
249	Sept. 6	41	66.2 (145.8)	58.3 (128.5)	85.6 (188.7)
250	Sept. 7	42	66.4 (146.5)	58.3 (128.5)	85.9 (189.3)
251	Sept. 8	43	66.5 (146.7)	58.7 (129.4)	85.3 (188.1)
252	Sept. 9	44	[f]66.6 (146.8)	58.9 (129.8)	85.6 (188.7)
253	Sept. 10	45	66.7 (147.1)	58.1 (128.0)	85.7 (189.0)
254	Sept. 11	46	66.0 (145.4)	58.2 (128.2)	86.1 (189.9)
255	Sept. 12	47	66.3 (146.1)	58.6 (129.1)	85.7 (188.8)
256	Sept. 13	48	65.5 (144.5)	58.4 (128.6)	85.7 (188.8)
257	Sept. 14	49	65.8 (145.1)	58.3 (128.5)	85.4 (188.3)
258	Sept. 15	50	66.0 (145.5)	58.3 (128.6)	85.6 (188.8)
259	Sept. 16	51	66.2 (146.0)	58.3 (128.6)	85.3 (188.1)
260	Sept. 17	52	65.9 (145.4)	58.5 (129.0)	85.7 (188.8)
261	Sept. 18	53	65.8 (145.1)	58.2 (128.2)	85.3 (188.1)
262	Sept. 19	54	66.0 (145.6)	58.5 (129.0)	85.7 (189.0)
263	Sept. 20	55	66.2 (145.8)	58.5 (128.9)	85.5 (188.5)
264	Sept. 21	56	65.8 (145.0)	59.0 (130.0)	85.2 (187.7)
265	Sept. 22	57	65.4 (144.3)	58.6 (129.1)	85.3 (188.0)
266	Sept. 23	58	65.3 (143.9)	58.0 (127.9)	85.1 (187.7)
267	Sept. 24	59	65.0 (143.4)	58.2 (128.3)	84.7 (186.6)
268	Sept. 25	R + 0	64.6 (142.4)	58.2 (128.4)	84.1 (185.5)

[f]Measurement made after breakfast; mass of breakfast deducted.

C-2

TABLE A-3.- Continued

(b) Concluded

DOY	Date, 1973	MD	Weight, kg (lb)		
			CDR	SPT	PLT
			Postflight		
268	Sept. 25	[c]R + 0	64.6 (142.5)	58.7 (129.5)	84.1 (185.5)
269	Sept. 26	R + 1	64.2 (141.5)	58.3 (128.5)	84.1 (185.5)
270	Sept. 27	R + 2	64.5 (142.3)	58.9 (129.8)	84.6 (186.5)
271	Sept. 28	R + 3	N.D.	60.2 (132.8)	N.D.
272	Sept. 29	R + 4	[f]66.8 (147.3)	60.0 (132.3)	87.1 (192.0)
273	Sept. 30	R + 5	66.5 (146.5)	[f]60.2 (132.8)	87.0 (191.8)
274	Oct. 1	R + 6	66.7 (147.0)	60.0 (132.3)	87.1 (192.0)
275	Oct. 2	R + 7	67.0 (147.8)	60.1 (132.5)	87.2 (192.3)
276	Oct. 3	R + 8	66.8 (147.3)	60.4 (133.3)	86.2 (190.0)
277	Oct. 4	R + 9	66.8 (147.3)	60.3 (133.0)	86.7 (191.3)
278	Oct. 5	R + 10	66.9 (147.5)	60.6 (133.5)	87.8 (193.5)
279	Oct. 6	R + 11	67.1 (148.0)	61.0 (134.5)	87.8 (193.5)
280	Oct. 7	R + 12	67.0 (147.8)	60.7 (133.8)	87.5 (193.0)
281	Oct. 8	R + 13	67.1 (148.0)	61.1 (134.8)	87.7 (193.3)
282	Oct. 9	R + 14	67.1 (148.0)	61.1 (134.8)	87.8 (193.5)
283	Oct. 10	R + 15	67.4 (148.5)	61.0 (134.5)	88.1 (194.3)
284	Oct. 11	R + 16	67.6 (149.0)	61.1 (134.8)	88.7 (195.5)
285	Oct. 12	R + 17	67.5 (148.8)	60.8 (134.0)	88.2 (194.5)
[d]286	Oct. 13	R + 18	N.D.	61.0 (134.5)	N.D.
287	Oct. 14	R + 19	N.D.	N.D.	N.D.
288	Oct. 15	R + 20	N.D.	N.D.	N.D.
289	Oct. 16	R + 21	68.9 (152.0)	N.D.	N.D.
290	Oct. 17	R + 22	68.7 (151.5)	62.0 (136.8)	N.D.
291	Oct. 18	R + 23	68.5 (151.0)	61.6 (135.8)	N.D.
292	Oct. 19	R + 24	68.5 (151.0)	61.0 (134.5)	N.D.
293	Oct. 20	R + 25	68.4 (150.8)	60.9 (134.3)	N.D.
294	Oct. 21	R + 26	68.9 (152.0)	61.2 (135.0)	N.D.
295	Oct. 22	R + 27	68.9 (152.0)	61.8 (136.3)	N.D.
296	Oct. 23	R + 28	69.2 (152.5)	61.3 (135.3)	N.D.
297	Oct. 24	R + 29	69.4 (153.0)	61.8 (136.3)	88.0 (194.0)
298	Oct. 25	R + 30	69.3 (152.8)	N.D.	N.D.
299	Oct. 26	R + 31	69.6 (152.5)	61.0 (134.5)	N.D.
300	Oct. 27	R + 32	N.D.	61.6 (135.8)	N.D.
301	Oct. 28	R + 33	N.D.	61.8 (136.3)	N.D.
302	Oct. 29	R + 34	N.D.	61.9 (136.5)	N.D.

[c]First shipboard weights.

[d]Stop controlled diet.

[f]Measurement made after breakfast; mass of breakfast deducted.

TABLE A-3.- Continued

(c) SL-4

DOY	Date	MD	Weight, kg (lb) CDR	SPT	PLT
			Preflight		
281	Oct. 8, 1973	F - 39	N.D.	70.5 (155.5)	N.D.
282	Oct. 9, 1973	F - 38	N.D.	70.3 (155.0)	N.D.
283	Oct. 10, 1973	F - 37	N.D.	71.4 (157.5)	N.D.
284	Oct. 11, 1973	F - 36	N.D.	71.2 (157.0)	N.D.
285	Oct. 12, 1973	F - 35	67.8 (149.5)	71.1 (156.8)	N.D.
286	Oct. 13, 1973	F - 34	66.7 (147.0)	71.3 (157.1)	67.2 (148.3)
287	Oct. 14, 1973	F - 33	66.5 (146.5)	71.8 (158.3)	67.4 (148.5)
288	Oct. 15, 1973	F - 32	66.2 (146.0)	72.3 (159.5)	67.5 (148.8)
289	Oct. 16, 1973	F - 31	67.8 (149.5)	71.9 (158.5)	67.6 (149.0)
290	Oct. 17, 1973	F - 30	67.2 (148.3)	71.0 (156.6)	67.6 (149.0)
291	Oct. 18, 1973	F - 29	66.6 (146.8)	71.3 (157.3)	67.8 (149.5)
292	Oct. 19, 1973	F - 28	66.3 (146.3)	71.0 (156.3)	68.0 (150.0)
[a]293	Oct. 20, 1973	F - 27	67.4 (148.5)	71.8 (158.3)	67.7 (149.3)
294	Oct. 21, 1973	F - 26	67.1 (148.0)	72.0 (158.8)	67.6 (149.0)
295	Oct. 22, 1973	F - 25	67.2 (148.3)	72.5 (159.8)	67.8 (149.5)
296	Oct. 23, 1973	F - 24	67.1 (148.0)	71.4 (157.5)	67.9 (149.8)
297	Oct. 24, 1973	F - 23	67.6 (149.0)	71.7 (158.0)	67.6 (149.0)
298	Oct. 25, 1973	F - 22	67.2 (148.3)	72.0 (158.8)	67.6 (149.0)
299	Oct. 26, 1973	F - 21	67.6 (149.0)	71.4 (157.5)	67.8 (149.5)
300	Oct. 27, 1973	F - 20	67.6 (149.0)	71.2 (157.0)	67.8 (149.5)
301	Oct. 28, 1973	F - 19	68.0 (150.0)	71.4 (157.5)	67.7 (149.3)
302	Oct. 29, 1973	F - 18	67.8 (149.5)	71.1 (156.8)	67.6 (149.0)
303	Oct. 30, 1973	F - 17	67.5 (148.8)	71.3 (157.3)	67.4 (148.5)
304	Oct. 31, 1973	F - 16	67.7 (149.3)	71.3 (157.3)	67.7 (149.3)
305	Nov. 1, 1973	F - 15	67.2 (148.3)	71.6 (157.8)	67.6 (149.0)
306	Nov. 2, 1973	F - 14	67.7 (149.3)	71.0 (156.5)	67.2 (148.3)
307	Nov. 3, 1973	F - 13	67.9 (149.8)	71.2 (157.0)	67.4 (148.5)
308	Nov. 4, 1973	F - 12	67.7 (149.3)	71.4 (157.5)	67.6 (149.0)
309	Nov. 5, 1973	F - 11	68.2 (150.3)	71.4 (157.5)	67.4 (148.5)
310	Nov. 6, 1973	F - 10	68.0 (150.0)	71.7 (158.0)	67.7 (149.3)
311	Nov. 7, 1973	F - 9	68.0 (150.0)	71.7 (158.0)	67.8 (149.5)
312	Nov. 8, 1973	F - 8	68.2 (150.3)	72.2 (159.3)	68.0 (150.0)
313	Nov. 9, 1973	F - 7	67.7 (149.3)	71.7 (158.0)	67.9 (149.8)
314	Nov. 10, 1973	F - 6	68.2 (150.3)	71.6 (157.8)	67.5 (148.8)
315	Nov. 11, 1973	F - 5	68.0 (150.0)	71.0 (156.5)	67.1 (148.0)
316	Nov. 12, 1973	F - 4	68.5 (151.0)	71.2 (157.0)	67.6 (149.0)
317	Nov. 13, 1973	F - 3	68.0 (150.0)	71.3 (157.3)	67.8 (149.5)
318	Nov. 14, 1973	F - 2	67.8 (149.5)	71.7 (158.0)	67.6 (149.0)
319	Nov. 15, 1973	F - 1	68.0 (150.0)	71.2 (157.0)	67.0 (147.8)
320	Nov. 16, 1973	1	67.9 (149.8)	71.2 (157.0)	67.6 (149.0)

[a]Start controlled diet.

TABLE A-3.- Continued

(c) Continued

DOY	Date	MD	Weight, kg (lb) CDR	SPT	PLT
			In-flight		
321	Nov. 17, 1973	2	N.D.	N.D.	N.D.
322	Nov. 18, 1973	3	66.7 (147.1)	70.8 (156.0)	65.7 (144.8)
323	Nov. 19, 1973	4	67.0 (147.8)	70.5 (155.4)	65.9 (145.4)
324	Nov. 20, 1973	5	67.1 (147.9)	70.5 (155.5)	65.4 (144.2)
325	Nov. 21, 1973	6	67.1 (147.9)	70.4 (155.3)	65.5 (144.4)
326	Nov. 22, 1973	7	67.1 (147.9)	70.2 (154.7)	65.3 (144.0)
327	Nov. 23, 1973	8	67.3 (148.3)	70.1 (154.6)	65.8 (145.1)
328	Nov. 24, 1973	9	66.9 (147.5)	69.8 (153.8)	64.9 (143.0)
329	Nov. 25, 1973	10	67.1 (147.9)	69.5 (153.3)	65.6 (144.6)
330	Nov. 26, 1973	11	67.2 (148.1)	69.0 (152.0)	65.1 (143.6)
331	Nov. 27, 1973	12	66.8 (147.3)	69.3 (152.7)	65.2 (143.7)
332	Nov. 28, 1973	13	67.3 (148.4)	69.4 (153.0)	65.6 (144.6)
333	Nov. 29, 1973	14	66.9 (147.5)	69.6 (153.5)	65.3 (144.0)
334	Nov. 30, 1973	15	67.4 (148.6)	69.7 (153.6)	65.6 (144.6)
335	Dec. 1, 1973	16	67.2 (148.1)	69.9 (154.1)	65.7 (144.8)
336	Dec. 2, 1973	17	67.2 (148.2)	69.6 (153.4)	65.9 (145.4)
337	Dec. 3, 1973	18	67.0 (147.7)	69.5 (153.3)	65.8 (145.0)
338	Dec. 4, 1973	19	67.3 (148.4)	69.0 (152.2)	66.0 (145.6)
339	Dec. 5, 1973	20	67.3 (148.4)	69.4 (153.0)	65.7 (144.8)
340	Dec. 6, 1973	21	67.3 (148.4)	69.1 (152.3)	65.6 (144.7)
341	Dec. 7, 1973	22	67.4 (148.7)	69.1 (152.3)	65.9 (145.3)
342	Dec. 8, 1973	23	67.4 (148.7)	68.9 (151.9)	65.8 (145.0)
343	Dec. 9, 1973	24	67.7 (149.2)	69.0 (152.2)	65.6 (144.6)
344	Dec. 10, 1973	25	67.6 (149.1)	68.7 (151.5)	65.6 (144.6)
345	Dec. 11, 1973	26	67.9 (149.7)	69.8 (153.8)	65.9 (145.3)
346	Dec. 12, 1973	27	67.5 (148.8)	69.0 (152.2)	65.8 (145.0)
347	Dec. 13, 1973	28	67.8 (149.5)	69.1 (152.4)	65.9 (145.2)
348	Dec. 14, 1973	29	67.5 (148.9)	69.3 (152.7)	65.4 (144.2)
349	Dec. 15, 1973	30	67.4 (148.6)	69.1 (152.3)	65.7 (144.8)
350	Dec. 16, 1973	31	67.7 (149.2)	69.1 (152.4)	65.5 (144.5)
351	Dec. 17, 1973	32	67.5 (148.8)	69.1 (152.4)	65.5 (144.3)
352	Dec. 18, 1973	33	67.7 (149.3)	69.1 (152.4)	65.7 (144.8)
353	Dec. 19, 1973	34	67.4 (148.7)	68.8 (151.6)	66.0 (145.4)
354	Dec. 20, 1973	35	67.8 (149.4)	69.0 (152.0)	66.0 (145.6)
355	Dec. 21, 1973	36	67.7 (149.4)	68.6 (151.3)	66.1 (145.7)
356	Dec. 22, 1973	37	67.7 (149.4)	68.8 (151.7)	66.2 (146.0)
357	Dec. 23, 1973	38	67.5 (148.8)	68.9 (151.9)	65.8 (145.0)
358	Dec. 24, 1973	39	67.1 (148.0)	69.2 (152.5)	65.9 (145.4)
359	Dec. 25, 1973	40	67.0 (147.8)	68.6 (151.3)	66.0 (145.6)
360	Dec. 26, 1973	41	67.6 (149.1)	68.6 (151.2)	65.9 (145.3)
361	Dec. 27, 1973	42	67.7 (149.4)	69.4 (153.0)	66.0 (145.4)
362	Dec. 28, 1973	43	67.9 (149.6)	69.1 (152.4)	66.2 (146.0)
363	Dec. 29, 1973	44	67.8 (149.4)	68.7 (151.5)	65.7 (144.9)
364	Dec. 30, 1973	45	67.9 (149.6)	68.9 (151.9)	65.9 (145.3)
365	Dec. 31, 1973	46	67.7 (149.2)	68.6 (151.3)	66.1 (145.8)

TABLE A-3.- Continued

(c) Continued

DOY	Date	MD	Weight, kg (lb) CDR	SPT	PLT
			In-flight		
1	Jan. 1, 1974	47	67.3 (148.4)	68.9 (151.8)	65.7 (144.9)
2	Jan. 2, 1974	48	67.0 (147.6)	68.6 (151.3)	65.4 (144.2)
3	Jan. 3, 1974	49	67.9 (149.8)	68.8 (151.7)	65.4 (144.2)
4	Jan. 4, 1974	50	67.5 (148.9)	69.4 (153.0)	65.6 (144.6)
5	Jan. 5, 1974	51	67.5 (148.9)	68.6 (151.2)	65.2 (143.7)
6	Jan. 6, 1974	52	67.8 (149.5)	68.6 (151.3)	65.1 (143.5)
7	Jan. 7, 1974	53	67.4 (148.6)	69.0 (152.2)	65.6 (144.5)
8	Jan. 8, 1974	54	67.7 (149.2)	69.6 (153.5)	65.8 (145.0)
9	Jan. 9, 1974	55	67.7 (149.3)	68.6 (151.3)	66.0 (145.4)
10	Jan. 10, 1974	56	67.3 (148.3)	68.0 (150.0)	65.4 (144.2)
11	Jan. 11, 1974	57	67.4 (148.6)	69.3 (152.7)	65.9 (145.4)
12	Jan. 12, 1974	58	68.0 (149.8)	69.7 (153.6)	66.0 (145.6)
13	Jan. 13, 1974	59	67.8 (149.4)	69.0 (152.2)	65.8 (145.2)
14	Jan. 14, 1974	60	67.6 (149.0)	68.8 (151.6)	66.1 (145.8)
15	Jan. 15, 1974	61	67.8 (149.5)	68.8 (151.7)	66.2 (146.0)
16	Jan. 16, 1974	62	67.8 (149.5)	69.1 (152.3)	66.4 (146.5)
17	Jan. 17, 1974	63	67.8 (149.4)	69.2 (152.6)	66.3 (146.1)
18	Jan. 18, 1974	64	67.8 (149.5)	69.2 (152.6)	65.8 (145.2)
19	Jan. 19, 1974	65	67.7 (149.4)	69.6 (153.4)	65.7 (144.8)
20	Jan. 20, 1974	66	67.9 (149.6)	69.6 (153.4)	66.0 (145.6)
21	Jan. 21, 1974	67	67.6 (149.0)	69.0 (152.2)	66.1 (145.8)
22	Jan. 22, 1974	68	67.8 (149.5)	69.5 (153.1)	65.9 (145.3)
23	Jan. 23, 1974	69	67.7 (149.2)	69.0 (152.2)	65.7 (144.8)
24	Jan. 24, 1974	70	68.3 (150.6)	68.9 (151.8)	66.6 (146.9)
25	Jan. 25, 1974	71	68.1 (150.1)	69.3 (152.9)	66.3 (146.1)
26	Jan. 26, 1974	72	67.6 (149.1)	68.9 (152.0)	66.3 (146.1)
27	Jan. 27, 1974	73	67.7 (149.3)	70.0 (154.4)	66.2 (145.8)
28	Jan. 28, 1974	74	67.7 (149.2)	69.9 (154.2)	66.0 (145.5)
29	Jan. 29, 1974	75	67.3 (148.4)	70.0 (154.4)	66.1 (145.8)
30	Jan. 30, 1974	76	67.4 (148.6)	69.7 (153.6)	66.5 (146.7)
31	Jan. 31, 1974	77	67.4 (148.7)	69.3 (152.8)	66.2 (145.9)
32	Feb. 1, 1974	78	67.9 (149.8)	69.8 (153.9)	66.7 (147.1)
33	Feb. 2, 1974	79	68.1 (150.1)	69.9 (154.1)	66.2 (145.9)
34	Feb. 3, 1974	80	67.6 (149.1)	69.7 (153.7)	66.4 (146.4)
35	Feb. 4, 1974	81	67.5 (148.9)	69.8 (153.8)	66.6 (146.9)
36	Feb. 5, 1974	82	67.5 (148.8)	69.9 (154.0)	66.6 (146.9)
37	Feb. 6, 1974	83	67.4 (148.6)	69.3 (152.7)	66.4 (146.4)
38	Feb. 7, 1974	84	67.1 (147.9)	69.3 (152.8)	66.6 (146.9)
39	Feb. 8, 1974	R + 0	67.9 (149.7)	69.8 (153.8)	66.2 (145.9)

TABLE A-3.- Concluded

(c) Concluded

DOY	Date	MD	Weight, kg (lb) CDR	SPT	PLT
			Postflight		
39	Feb. 8, 1974	[c]R + 0	67.8 (149.5)	68.6 (151.3)	66.1 (145.8)
40	Feb. 9, 1974	R + 1	67.1 (148.0)	69.4 (153.0)	66.8 (147.3)
41	Feb. 10, 1974	R + 2	67.9 (149.8)	70.1 (154.5)	67.0 (147.8)
42	Feb. 11, 1974	R + 3	67.6 (149.0)	71.0 (156.5)	67.6 (149.0)
43	Feb. 12, 1974	R + 4	67.9 (149.8)	70.8 (156.0)	67.4 (148.5)
44	Feb. 13, 1974	R + 5	68.5 (151.0)	71.1 (156.8)	67.0 (147.8)
45	Feb. 14, 1974	R + 6	68.4 (150.8)	71.7 (158.0)	67.4 (148.5)
46	Feb. 15, 1974	R + 7	68.4 (150.8)	71.6 (157.8)	67.9 (149.8)
47	Feb. 16, 1974	R + 8	N.D.	71.0 (156.5)	67.7 (149.3)
48	Feb. 17, 1974	R + 9	68.4 (150.8)	71.1 (156.8)	67.9 (149.8)
49	Feb. 18, 1974	R + 10	68.3 (150.5)	71.8 (158.3)	67.0 (147.8)
50	Feb. 19, 1974	R + 11	68.8 (151.8)	71.7 (158.0)	67.5 (148.8)
51	Feb. 20, 1974	R + 12	68.6 (151.3)	71.6 (157.8)	67.6 (149.0)
52	Feb. 21, 1974	R + 13	68.6 (151.3)	71.8 (158.3)	67.5 (148.8)
53	Feb. 22, 1974	R + 14	68.7 (151.5)	71.4 (157.5)	67.6 (149.0)
54	Feb. 23, 1974	R + 15	68.8 (151.8)	71.3 (157.3)	67.5 (148.8)
55	Feb. 24, 1974	R + 16	68.5 (151.0)	71.2 (157.0)	67.6 (149.0)
56	Feb. 25, 1974	R + 17	68.6 (151.3)	71.7 (158.0)	67.7 (149.3)
57	Feb. 26, 1974	R + 18	68.4 (150.8)	71.4 (157.5)	67.2 (148.3)
[d]58	Feb. 27, 1974	R + 19	67.9 (149.8)	71.2 (157.0)	68.0 (150.0)
59	Feb. 28, 1974	R + 20	68.9 (152.0)	72.5 (159.8)	69.3 (152.8)
60	Mar. 1, 1974	R + 21	69.6 (153.5)	71.4 (157.5)	69.3 (152.8)
61	Mar. 2, 1974	R + 22	69.6 (153.5)	72.2 (159.3)	69.4 (153.0)
62	Mar. 3, 1974	R + 23	68.5 (151.0)	72.7 (160.3)	70.1 (154.5)
63	Mar. 4, 1974	R + 24	68.8 (151.8)	73.7 (162.5)	69.4 (153.0)
64	Mar. 5, 1974	R + 25	68.6 (151.3)	72.8 (160.5)	69.6 (153.5)
65	Mar. 6, 1974	R + 26	68.9 (152.0)	72.8 (160.5)	69.9 (154.0)
66	Mar. 7, 1974	R + 27	69.4 (153.0)	72.1 (159.0)	69.9 (154.0)
67	Mar. 8, 1974	R + 28	69.2 (152.5)	N.D.	69.6 (153.5)
68	Mar. 9, 1974	R + 29	68.9 (152.0)	N.D.	70.3 (155.0)
69	Mar. 10, 1974	R + 30	69.2 (152.5)	73.7 (162.5)	69.9 (154.0)
70	Mar. 11, 1974	R + 31	69.2 (152.5)	74.2 (163.5)	69.4 (153.0)
71	Mar. 12, 1974	R + 32	68.9 (152.0)	73.0 (161.0)	69.6 (153.5)
72	Mar. 13, 1974	R + 33	68.6 (151.3)	73.8 (162.8)	69.7 (153.8)
73	Mar. 14, 1974	R + 34	69.3 (152.8)	74.2 (163.5)	70.3 (155.0)
74	Mar. 15, 1974	R + 35	68.8 (151.8)	73.8 (162.8)	69.9 (154.0)
75	Mar. 16, 1974	R + 36	68.5 (151.0)	73.0 (161.0)	70.9 (156.3)
76	Mar. 17, 1974	R + 37	68.7 (151.5)	74.2 (163.5)	71.4 (157.5)
77	Mar. 18, 1974	R + 38	70.2 (154.8)	73.9 (163.0)	70.6 (155.8)
78	Mar. 19, 1974	R + 39	70.0 (154.3)	N.D.	69.9 (154.0)
79	Mar. 20, 1974	R + 40	69.3 (152.8)	N.D.	N.D.
80	Mar. 21, 1974	R + 41	69.2 (152.5)	N.D.	N.D.
81	Mar. 22, 1974	R + 42	68.5 (151.0)	N.D.	70.4 (155.3)
82	Mar. 23, 1974	R + 43	68.5 (151.0)	N.D.	70.3 (155.0)
83	Mar. 24, 1974	R + 44	69.5 (153.3)	N.D.	N.D.
84	Mar. 25, 1974	R + 45	70.4 (155.3)	N.D.	N.D.
85	Mar. 26, 1974	R + 46	69.2 (152.5)	N.D.	N.D.

[c]First shipboard weights.

[d]Stop controlled diet.

APPENDIX B

HEIGHT MEASUREMENTS OF SKYLAB 4 CREWMEN

Height and change-in-height (Δ height) measurements of the Skylab 4 (SL-4) crewmen are contained in tables B-1 to B-3. The crewman designations are commander (CDR), science pilot (SPT), and pilot (PLT). Preflight measurements were taken with the crewmen in an erect standing position, and postflight measurements were taken with the crewmen in both erect and supine positions. In-flight measurements were taken in the morning and afternoon on mission day (MD) 21, MD-35, MD-57, MD-60, and MD-82. Recovery day is designated R + 0, R + 1 is 1 day after recovery, and so forth.

TABLE B-1.- HEIGHT AND CHANGE-IN-HEIGHT MEASUREMENTS OF SL-4 CDR

(a) Preflight measurements

Date	Erect height, cm (in.)
1966	172.2 (67.8)
1967	172.7 (68.0)
1968	172.5 (67.9)
1969	172.7 (68.0)
1970	172.7 (68.0)
1971	172.7 (68.0)
1972	173.0 (68.1)
[a]1972	[b]172.7 (68.0)

(b) In-flight measurements

Day	Height and Δ height					
	Morning			Afternoon		
	cm (in.)	Δ cm (Δ in.)	Δ percent	cm (in.)	Δ cm (Δ in.)	Δ percent
MD-21	177.3 (69.8)	4.6 (1.8)	2.7	177.5 (68.9)	4.8 (1.9)	2.8
MD-35	177.8 (70.0)	5.1 (2.0)	2.9	177.5 (69.9)	4.8 (1.9)	2.8
MD-57	177.8 (70.0)	5.1 (2.0)	2.9	176.8 (69.6)	4.1 (1.6)	2.4
MD-82	178.6 (70.3)	5.9 (2.3)	3.4	--	--	--
Mean	--	5.2 (2.03)	3.0	--	--	--

[a]Suit fit; other preflight measurements were from annual physical examinations.

[b]Baseline.

TABLE B-1.- Concluded

(c) Postflight measurements

Day	Height and Δ height					
	Erect			Supine		
	cm (in.)	Δ cm (Δ in.)	Δ percent	cm (in.)	Δ cm (Δ in.)	Δ percent
R + 0						
[c]01:42	--	--	--	176.8 (69.6)	4.1 (1.6)	2.4
[c]03:03	174.8 (68.8)	2.1 (0.8)	1.2	--	--	--
[c]05:43	174.0 (68.5)	1.3 (.5)	.7	--	--	--
R + 1						
Morning	175.3 (69.0)	2.6 (1.0)	1.5	--	--	--
Afternoon	173.4 (68.3)	.7 (.25)	.4	174.8 (68.8)	2.1 (.8)	1.2
R + 4	175.3 (69.0)	2.6 (1.0)	1.5	--	--	--
R + 5	173.7 (68.4)	1.0 (.4)	.6	176.0 (69.3)	3.3 (1.3)	1.9
R + 17	172.7 (68.0)	0 (0)	0	174.8 (68.8)	2.1 (.8)	1.2

[c]Time after recovery, hours:minutes.

TABLE B-2.- HEIGHT AND CHANGE-IN-HEIGHT MEASUREMENTS OF SL-4 SPT

(a) Preflight measurements

Date	Erect height, cm (in.)
1970	172.7 (68.0)
[a]1972	[b]173.0 (68.1)
1973	172.7 (68.0)
[c]1973	175.3 (69.0)

[a]Suit fit.
[b]Baseline.
[c]35 days before lift-off.

TABLE B-2.- Concluded

(b) In-flight measurements

Day	Height and Δ height					
	Morning			Afternoon		
	cm (in.)	Δ cm (Δ in.)	Δ percent	cm (in.)	Δ cm (Δ in.)	Δ percent
MD-21	177.8 (70.0)	4.8 (1.9)	2.8	177.8 (70.0)	4.8 (1.9)	2.8
MD-35	178.6 (70.3)	5.6 (2.2)	3.2	178.8 (70.4)	5.8 (2.3)	3.4
MD-60	177.8 (70.0)	4.8 (1.9)	2.8	178.0 (70.1)	5.0 (2.0)	3.0
MD-82	179.8 (70.8)	6.8 (2.7)	4.0	--	--	--
Mean	--	5.5 (2.18)	3.2	--	--	--

(c) Postflight measurements

Day	Height and Δ height					
	Erect			Supine		
	cm (in.)	Δ cm (Δ in.)	Δ percent	cm (in.)	Δ cm (Δ in.)	Δ percent
R + 0						
[d]01:53	--	--	--	178.8 (70.4)	5.8 (2.3)	3.4
[d]03:08	176.5 (69.5)	3.5 (1.4)	2.1	--	--	--
[d]07:43	175.0 (68.9)	2.0 (.8)	1.2	--	--	--
R + 1						
Morning	175.3 (69.0)	2.3 (.9)	1.3	--	--	--
Afternoon	174.0 (68.5)	1.0 (.4)	1.0	176.0 (69.3)	3.0 (1.2)	1.8
R + 4	174.0 (68.5)	1.0 (.4)	1.0	--	--	--
R + 5	174.8 (68.8)	1.8 (.7)	1.0	176.5 (69.5)	3.5 (1.4)	2.1
R + 17	174.5 (68.7)	1.5 (.6)	.9	176.5 (69.5)	3.5 (1.4)	2.1

[d]Time after recovery, hours:minutes.

TABLE B-3.- HEIGHT AND CHANGE-IN-HEIGHT MEASUREMENTS OF SL-4 PLT

(a) Preflight measurements

Date	Erect height, cm (in.)
1966	173.0 (68.1)
1969	173.5 (68.3)
[a]1972	[b]173.2 (68.2)
[c]1973	173.5 (68.3)

(b) In-flight measurements

Day	Height and Δ height					
	Morning			Afternoon		
	cm (in.)	Δ cm (Δ in.)	Δ percent	cm (in.)	Δ cm (Δ in.)	Δ percent
MD-21	178.8 (70.4)	5.6 (2.2)	3.2	179.1 (70.5)	5.6 (2.3)	3.4
MD-35	178.6 (70.3)	5.4 (2.1)	3.1	178.6 (70.3)	5.1 (2.1)	3.1
MD-57	177.8 (70.0)	4.6 (1.8)	2.6	176.8 (69.6)	3.3 (1.4)	2.1
MD-82	179.3 (70.6)	6.1 (2.4)	3.5	—	—	—
Mean	—	5.4 (2.13)	3.1	—	—	—

[a]Suit fit.
[b]Baseline.
[c]15 days before lift-off.

TABLE B-3.- Concluded

(c) Postflight measurements

Day	Height and Δ height					
	Erect			Supine		
	cm (in.)	Δ cm (Δ in.)	Δ percent	cm (in.)	Δ cm (Δ in.)	Δ percent
R + 0						
[d]01:26	--	--	—	177.5 (69.9)	5.9 (1.7)	2.5
[d]03:53	175.0 (68.9)	1.8 (0.7)	1.0	—	—	--
R + 1						
Morning	174.0 (68.5)	.8 (.3)	.4	--	--	--
Afternoon	173.5 (68.3)	.3 (.1)	.1	175.0 (68.9)	1.8 (.7)	1.0
R + 17	173.7 (68.4)	.5 (.2)	.3	175.3 (69.0)	5.8 (.8)	1.2

[d]Time after recovery, hours:minutes.

APPENDIX C

TRUNCAL, NECK, AND LIMB GIRTH MEASUREMENTS OF U.S. SPACE-FLIGHT CREWMEN

Truncal, neck, and limb girth measurements of Skylab and Apollo crewmen made before, during, and after various flights are presented in this appendix. Table C-1 contains data on truncal, neck, and arm girth of the Skylab 3 (SL-3) commander (CDR), science pilot (SPT), and pilot (PLT) obtained before flight, in flight (on mission day (MD) 38 and MD-54), and after flight (on recovery day (R + 0) and on the 1st, 2nd, and 4th days after recovery (days R + 1, R + 2, and R + 4, respectively)). Change-in-girth values (Δ girth) (with the preflight measurement as the baseline value) are also provided. All measurements were made in the anatomical position.

In table C-2, truncal and neck girth measurements of SL-4 crewmen made 30 and 15 days before lift-off (days F - 30 and F - 15, respectively), during flight, and after flight are compared to the preflight measurement made 4 days before lift-off (day F - 4), the baseline value in each case.

Tables C-3 to C-5 contain detailed circumference measurements of the left (L) and right (R) legs of SL-4 crewmen. Daily volumes for both the left and the right leg of each crewman are given, together with preflight means and standard deviations.

Table C-6 contains data on individual calf circumference and lower-limb volume from preflight and postflight measurements of the CDR, the command module pilot (CMP), and the lunar module pilot (LMP) of selected Apollo missions, in a resting, supine position. Preflight individual means and standard deviations and preflight and postflight group means and standard deviations are given, together with other statistical indicators.

The upper-limb volumes and changes in upper-limb volumes of Skylab crewmen shown in table C-7 were computed from girth segments every 3 cm from wrist to shoulder of both arms.

All truncal and neck girth measurements were made in the anatomical position.

TABLE C-1.- TRUNCAL, NECK, AND ARM GIRTH MEASUREMENTS

OF SL-3 CREWMEN

(a) CDR

Measurement	Preflight	MD-38	MD-54	R + 0	R + 1	R + 2	R + 4
Left biceps, cm	30.8	28.1	29.0	28.2	29.8	29.8	30.2
Δ girth, cm		-2.7	-1.8	-2.6	-1.0	-1.0	-0.6
Δ girth, percent		-8.8	-5.8	-8.4	-3.2	-3.2	-1.9
Right biceps, cm	30.8	28.8	30.0	29.2	29.8	31.7	31.4
Δ girth, cm		-2.0	-0.8	-1.6	-1.0	-0.9	0.6
Δ girth, percent		-6.5	-2.6	-5.2	-3.2	2.9	1.9
Chest, inspiratory (insp.), cm	96.0	--	--	95.2	96.5	95.9	97.5
Δ girth, cm		--	--	-0.8	0.5	-0.1	1.5
Δ girth, percent		--	--	-0.8	0.5	-0.1	1.6
Chest, expiratory (exp.), cm	91.1	88.9	--	89.5	90.8	90.5	92.1
Δ girth, cm		-2.2	--	-1.6	-0.3	-0.6	1.0
Δ girth, percent		-2.4	--	-1.8	-0.3	-0.7	1.1
Abdomen, cm	82.1	76.3	76.3	78.7	79.7	79.7	--
Δ girth, cm		-5.8	-5.8	-3.4	-2.4	-2.4	--
Δ girth, percent		-7.1	-7.1	-4.1	-2.9	-2.9	--
Neck, cm	38.1	37.1	37.3	38.4	37.1	39.0	38.1
Δ girth, cm		-1.0	-0.8	0.3	-1.0	0.9	0
Δ girth, percent		-2.6	-2.1	0.8	-2.6	2.4	0

TABLE C-1.- Continued

(b) SPT

Measurement	Preflight	MD-38	MD-54	R + 0	R + 1	R + 2	R + 4
Left biceps, cm	28.7	26.1	28.0	27.0	27.6	27.9	27.3
Δ girth, cm		-2.6	-0.7	-1.7	-1.1	-0.8	-1.4
Δ girth, percent		-9.0	-2.4	-5.9	-3.8	-2.8	-4.9
Right biceps, cm	28.9	27.6	29.3	29.5	28.9	29.5	28.9
Δ girth, cm		-1.3	0.4	0.6	0	0.6	0
Δ girth, percent		-4.5	1.4	2.1	0	2.1	0
Chest, insp, cm	90.0	--	86.8	89.2	88.9	88.9	88.9
Δ girth, cm		--	-3.2	-0.8	-1.1	-1.1	-1.1
Δ girth, percent		--	-3.6	-0.9	-1.2	-1.2	-1.2
Chest, exp., cm	84.2	84.0	83.4	83.2	81.3	--	--
Δ girth, cm		-0.2	-0.8	-1.0	-2.9	--	--
Δ girth, percent		-0.2	-0.9	-1.2	-3.4	--	--
Abdomen, cm	79.2	71.1	72.0	74.9	76.2	75.9	--
Δ girth, cm		-8.1	-7.2	-4.3	-3.0	-3.3	--
Δ girth, percent		-10.0	-9.1	-5.4	-3.8	-4.2	--
Neck, cm	35.9	--	34.9	34.6	34.9	35.2	35.9
Δ girth, cm		--	-1.0	-1.3	-1.0	-0.7	0
Δ girth, percent		--	-2.8	-3.6	-2.8	-1.9	0

TABLE C-1.- Concluded

(c) PLT

Measurement	Preflight	MD-38	MD-54	R + 0	R + 1	R + 2	R + 4
Left biceps, cm	33.6	31.7	33.0	32.4	33.0	33.0	33.0
Δ girth, cm		-1.9	-0.6	-1.2	-0.6	-0.3	-0.6
Δ girth, percent		-5.6	-1.8	-3.6	-1.8	-0.9	-1.8
Right biceps, cm	34.4	32.8	33.5	32.4	34.3	34.6	33.3
Δ girth, cm		-1.6	-0.9	-2.0	-0.1	0.2	-1.1
Δ girth, percent		-4.6	-2.6	-5.8	-0.3	0.6	-3.2
Chest, insp. cm	107.2	--	104.8	106.7	106.7	106.7	107.0
Δ girth, cm		--	-2.4	-0.5	-0.5	-0.5	-0.2
Δ girth, percent		--	-2.2	-0.5	-0.5	-0.5	-0.2
Chest, exp., cm	100.8	--	97.6	97.5	100.9	101.9	--
Δ girth, cm		--	-3.2	-3.3	0.1	1.1	--
Δ girth, percent		--	-3.2	-3.3	0.1	1.1	--
Abdomen, cm	88.4	84.0	83.9	88.6	87.0	89.2	--
Δ girth, cm		-4.4	-4.5	0.2	-1.4	0.8	--
Δ girth, percent		-5.0	-5.1	0.2	-1.6	0.9	--
Neck, cm	40.6	41.0	40.9	41.6	41.3	41.9	41.3
Δ girth, cm		0.4	0.3	1.0	0.7	1.3	0.7
Δ girth, percent		1.0	0.7	2.5	1.7	3.2	1.7

TABLE C-2.- TRUNCAL AND NECK GIRTH MEASUREMENTS OF SL-4 CREWMEN

(a) CDR

Measurement	Preflight			In-flight				Postflight					
	F - 30	F - 15	F - 4	MD-3	MD-8	MD-31	MD-58	R + 0	R + 1	R + 2	R + 4	R + 5	R + 11
Abdomen, cm	83.8	82.5	83.5	78.0	78.0	79.6	79.1	81.7	84.5	83.6	83.1	82.3	82.9
Δ girth, cm	0.3	-1.0		-5.5	-5.5	-3.9	-4.4	-1.8	1.0	0.1	-0.4	-1.2	-0.6
Δ girth, percent . . .	0.3	-1.2		-6.6	-6.6	-4.7	-5.3	-2.2	1.2	0.1	-0.5	-1.4	-0.7
Chest, insp., cm	103.5	100	102.2	99.3	98.5	101.2	100.8	101.6	101.6	103.5	102.6	102.0	102.7
Δ girth, cm	1.3	-2.2		-2.9	-3.7	-1.0	-1.4	-0.6	-0.6	1.3	0.4	-0.2	0.5
Δ girth, percent . . .	1.3	-2.1		-2.8	-3.6	-1.0	-1.4	-0.6	-0.6	1.3	0.4	-0.2	0.5
Chest exp., cm	98.4	94.4	96.8	93.5	92.5	94.0	93.1	97.4	95.5	96.3	96.0	94.8	96.1
Δ girth, cm	1.6	-2.4		-3.3	-4.3	-2.8	-3.7	0.6	-1.3	-0.5	-0.8	-2.0	-0.7
Δ girth, percent . . .	1.6	-2.5		-3.4	-4.4	-2.9	-3.8	0.6	-1.3	-0.5	-0.8	-2.1	-0.7
Neck, cm	37.1	37.4	37.5	36.8	38.1	37.5	37.5	36.8	37.9	37.9	38.1	38.9	36.9
Δ girth, cm	-0.4	-0.1		-0.7	0.6	0	0	-0.7	0.4	0.4	0.6	1.4	-0.6
Δ girth, percent . . .	-1.1	-0.3		-1.9	1.6	0	0	-1.9	1.1	1.1	1.6	3.7	-1.6
Buttocks, cm	—	90.4	87.2	88.5	87.0	87.5	89.1	91.3	89.9	90.7	92	91.4	91.3
Δ girth, cm	—	3.2		1.3	-0.2	0.3	1.9	4.1	2.7	3.5	4.8	4.2	4.1
Δ girth, percent . . .	—	3.7		-1.5	-0.2	0.3	2.2	4.7	3.1	4.0	5.5	4.8	4.7

(b) SPT

Measurement	Preflight			In-flight				Postflight					
	F - 30	F - 15	F - 4	MD-3	MD-8	MD-37	MD-61	R + 0	R + 1	R + 2	R + 4	R + 5	R + 11
Abdomen, cm	86.0	84.0	83.3	82.7	77.7	79.2	76.8	81.0	81.5	83.4	82.5	81.1	82.9
Δ girth, cm	2.7	0.7		-0.6	-5.6	-4.1	-6.5	-2.3	-1.8	0.1	-0.8	-2.2	-0.4
Δ girth, percent . . .	3.2	0.8		-0.7	-6.7	-4.9	-7.8	-2.8	-2.2	0.1	-0.9	-2.6	-0.5
Chest, insp., cm	101.8	99.5	97.0	96.0	96.2	95.0	95.5	97.6	98.0	98.6	97.8	97.4	97.9
Δ girth, cm	4.8	2.5		-1.0	-0.8	-2.0	-1.5	0.6	1.0	1.6	0.8	0.4	0.9
Δ girth, percent . . .	4.9	2.6		-1.0	-0.8	-2.1	-1.5	0.6	1.0	1.6	0.8	0.4	0.9
Chest, exp., cm	91.1	89.8	90.6	90.0	88.0	88.5	90.5	91.5	91.0	90.1	92.9	89.5	91.2
Δ girth, cm	0.5	-0.8		-0.6	-2.6	-2.1	-0.1	0.9	0.4	-0.5	2.3	-1.1	0.6
Δ girth, percent . . .	0.5	-0.9		-0.7	-2.9	-2.3	-0.1	1.0	0.4	-0.5	2.5	-1.2	0.7
Neck, cm	38.3	39.0	37.5	38.5	38.1	37.4	38.0	38.5	39.4	39.2	38.1	39.0	38.4
Δ girth, cm	0.8	1.5		1.0	0.6	-0.1	0.5	1.0	1.9	1.7	0.6	1.5	0.9
Δ girth, percent . . .	2.1	4.0		2.7	1.6	-0.3	1.3	2.7	5.1	4.5	1.6	4.0	2.4
Buttocks, cm	—	97	92.4	--	89.3	89.0	90.0	96.4	96.2	97.2	97.3	97.2	96.6
Δ girth, cm	—	4.6		--	-3.1	-3.4	-2.4	4.0	3.8	4.8	4.9	4.8	4.2
Δ girth, percent . . .	—	5.0		--	-3.3	-3.7	-2.6	4.3	4.1	5.2	5.3	5.2	4.5

TABLE C-2.- Concluded

(c) PLT

Measurement	Preflight			In-flight			Postflight					
	F - 30	F - 15	F - 4	MD-8	MD-60	MD-31	R + 0	R + 1	R + 2	R + 4	R + 5	R + 11
Abdomen, cm	82.5	80.7	81.4	71.3	72.8	71	78.5	79.4	80.0	78.7	76.9	79.0
Δ girth, cm	1.1	-0.7		-10.1	-8.6	-10.4	-2.9	-2.0	-1.4	-2.7	-4.5	-2.4
Δ girth, percent . . .	1.3	-0.8		-12.4	-10.6	-12.8	-3.6	-2.4	-1.7	-3.3	-5.5	-2.9
Chest, insp., cm	101.6	99.4	99.1	98	98.2	97.0	99.0	98.9	99.1	99.3	99.1	—
Δ girth, cm	2.5	0.3		-1.1	-0.9	-2.1	-0.1	-0.2	0	0.2	0	—
Δ girth, percent . . .	2.5	0.3		-1.1	-0.9	-2.1	-0.1	-0.2	0	0.2	0	—
Chest, exp., cm	92.7	92.0	93.4	89.1	94.8	92.5	92.5	92.2	92.0	92.0	91.7	91.4
Δ girth, cm	-0.7	-1.4		-4.3	1.4	-0.9	-0.9	-1.2	-1.4	-1.4	-1.7	-2.0
Δ girth, percent . . .	-0.7	-1.5		-4.6	1.5	-1.0	-1.0	-1.3	-1.5	-1.5	-1.8	-2.1
Neck, cm	38.7	38.5	36.7	34.6	35.5	35.3	35.0	36.0	35.6	35.4	36.5	35.7
Δ girth, cm	2.0	1.8		-2.1	-1.2	-1.4	-1.7	-0.7	-1.1	-1.3	-0.2	-1.0
Δ girth, percent . . .	5.4	4.9		-5.7	-3.3	-3.8	-4.6	-1.9	-3.0	-3.5	-0.5	-2.7
Buttocks, cm	—	93.0	90.1	89.4	87.8	81.9	92.5	92.4	93.1	92.9	91.5	94.2
Δ girth, cm	—	2.9		-0.7	-2.3	-8.2	2.4	2.3	3.0	2.8	1.4	4.1
Δ girth, percent . . .	—	3.2		-0.8	-2.5	-9.1	2.7	2.5	3.3	3.1	1.5	4.5

TABLE C-3.- LEG MEASUREMENTS OF SL-4 CDR

(a) Preflight

Leg zone	F - 49 (Aug. 28, 1973)		F - 35 (Oct. 12, 1973)		F - 21 (Oct. 26, 1973)		F - 10 (Nov. 6, 1973)		F - 6 (Nov. 10, 1973)		Mean ± SD[a]	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	—	—	—	—	—	—	—	—	—	—	—	—
2	21.2	20.9	20.8	20.8	21.1	20.9	20.8	21.1	20.8	21.1	—	—
3	22.0	21.4	21.6	21.6	21.7	21.9	21.6	21.6	21.5	21.9	—	—
4	24.0	23.1	23.8	23.6	23.8	23.4	23.6	23.4	23.3	23.3	—	—
5	26.8	25.4	25.6	26.0	26.0	25.5	25.7	25.1	25.5	26.2	—	—
6	29.0	27.5	28.4	29.0	28.6	28.4	27.9	27.5	28.1	29.1	—	—
7	31.8	31.3	31.0	32.2	32.0	32.0	30.6	31.2	31.0	31.5	—	—
8	34.5	33.6	33.6	34.2	34.3	34.5	34.0	33.5	33.8	33.8	—	—
9	34.9	34.6	34.7	35.0	34.9	34.8	35.1	34.9	35.1	34.9	—	—
10	33.8	33.8	34.1	33.9	34.1	33.9	34.1	34.2	34.7	34.6	—	—
11	32.3	32.2	32.7	32.4	32.5	32.2	32.5	32.6	33.0	32.5	—	—
12	32.2	32.2	32.6	32.1	32.5	32.4	32.4	32.9	32.5	32.3	—	—
13	35.0	34.1	34.5	34.6	34.0	34.9	34.5	33.5	34.0	34.2	—	—
14	36.4	36.4	36.6	36.4	36.2	36.6	36.2	35.7	35.9	36.3	—	—
15	36.4	36.1	36.4	36.6	36.3	36.7	36.5	36.6	36.5	36.3	—	—
16	37.5	36.3	36.5	37.1	36.7	37.7	36.9	36.8	36.6	36.6	—	—
17	39.0	38.1	38.1	39.0	38.4	39.9	38.2	38.4	38.2	38.4	—	—
18	43.8	40.4	40.4	41.8	41.3	42.8	41.0	41.2	41.0	40.2	—	—
19	45.0	44.2	43.7	44.6	44.8	45.6	44.1	43.9	44.5	44.7	—	—
20	49.0	47.5	46.7	47.3	47.8	49.1	47.1	47.9	46.9	47.1	—	—
21	50.9	49.8	49.4	50.0	50.5	51.7	50.0	49.9	49.6	49.4	—	—
22	51.9	50.9	51.5	51.5	51.9	53.0	51.9	51.6	51.4	51.7	—	—
23	53.0	52.5	53.9	52.5	54.0	53.9	54.5	53.4	54.2	53.1	—	—
24	54.6	53.1	55.3	54.6	55.0	54.0	55.6	54.6	56.2	54.8	—	—
25	—	—	—	—	—	—	—	—	—	—	—	—
	Volume, ml											
	7691.05	7346.29	7445.68	7531.90	7573.36	7746.47	7515.17	7455.70	7496.63	7475.62	7544.38 ±93.84	7511.20 ±147.75

[a]SD = standard deviation.

TABLE C-3.- Continued

(b) In-flight

Leg zone	MD-3 (Nov. 18, 1973)		MD-5 (Nov. 20, 1973)		MD-8 (Nov. 23, 1973)		MD-31 (Dec. 16, 1973)		MD-57 (Jan. 11, 1974)	
	L	R	L	R	L	R	L	R	L	R
	Circumference, cm									
1	--	--	--	--	--	--	--	--	--	--
2	20.2	21.0	21.7	--	20.1	20.2	19.8	20.0	19.4	20.2
3	20.5	21.0	21.2	--	20.9	21.3	20.5	20.4	20.2	19.9
4	21.7	22.5	22.5	--	22.1	22.9	22.3	21.8	21.5	21.1
5	23.8	24.0	24.3	--	24.1	24.9	24.1	23.9	23.6	22.9
6	26.1	26.3	26.8	--	26.5	26.7	26.3	25.7	25.3	24.8
7	28.3	28.7	29.4	--	29.3	30.3	28.2	29.5	28.9	27.3
8	32.2	32.5	32.0	--	32.0	32.4	31.8	32.0	31.6	31.0
9	33.5	33.6	33.2	--	33.0	33.0	32.4	33.8	32.1	32.3
10	33.1	33.0	33.1	--	32.5	31.9	31.7	32.5	31.5	32.3
11	32.0	31.5	33.0	--	30.3	30.6	30.2	31.4	30.3	31.0
12	30.5	32.0	30.8	--	30.5	31.1	30.6	30.7	30.2	30.6
13	31.0	31.5	30.7	--	30.7	32.3	31.6	32.0	31.3	32.0
14	32.6	33.8	33.3	--	33.0	35.0	33.4	34.2	33.2	33.4
15	33.8	34.5	33.7	--	34.7	34.8	34.1	34.8	34.2	34.7
16	34.2	34.5	34.0	--	34.2	34.3	33.8	34.6	33.7	34.7
17	34.6	35.0	35.3	--	34.9	35.2	34.8	35.0	34.6	35.2
18	37.0	37.2	38.0	--	36.7	38.2	36.8	36.2	35.5	37.1
19	38.6	41.0	41.1	--	39.2	41.0	40.2	39.4	39.0	39.1
20	42.2	44.8	44.5	--	42.6	44.5	42.0	41.2	40.6	41.4
21	45.1	46.7	46.5	--	45.2	46.7	44.8	44.3	44.1	44.3
22	48.0	49.5	48.6	--	48.8	47.9	47.2	47.5	47.4	47.3
23	50.2	51.0	50.6	--	49.1	50.1	48.9	50.0	48.4	49.5
24	51.0	52.0	51.8	--	51.4	51.9	50.6	51.2	50.6	51.3
25	--	--	--	--	--	--	--	--	--	--
	Volume, ml									
	6370.33	6671.57	6625.43	--	6389.47	6646.43	6294.55	6388.72	6152.23	6265.95

TABLE C-3.- Continued

(c) Postflight, R + 0 to R + 4

Leg zone	R + 0 (Feb. 8, 1974)		R + 1 (Feb. 9, 1974)		R + 1 (Feb. 9, 1974)		R + 2 (Feb. 10, 1974)		R + 3 (Feb. 11, 1974)		R + 4 (Feb. 12, 1974)	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	—	—	—	—	—	—	—	—	—	—	—	—
2	20.2	20.2	21.2	21.0	20.5	20.7	21.0	21.2	20.8	20.6	20.7	20.9
3	20.8	20.8	21.8	21.5	21.5	20.9	21.8	21.7	21.4	21.4	21.5	21.4
4	22.3	22.3	23.8	23.0	22.6	22.3	24.0	23.3	23.3	22.5	23.1	23.1
5	24.1	23.9	25.6	24.6	24.4	24.4	26.1	25.2	25.3	24.6	24.7	25.4
6	26.1	26.4	28.0	27.5	27.0	26.3	28.6	26.4	28.0	27.3	27.6	27.6
7	29.3	29.6	31.2	30.2	29.4	29.8	32.7	30.5	30.6	29.5	30.2	30.8
8	31.6	32.3	33.7	32.6	32.5	32.2	33.7	33.0	32.9	32.1	32.7	33.4
9	32.8	32.8	34.1	33.3	33.2	32.6	34.5	34.3	33.9	33.4	34.0	34.3
10	32.2	32.1	33.2	32.6	32.8	31.8	33.8	33.5	33.4	33.0	33.8	32.6
11	31.3	31.2	32.1	31.5	32.7	31.1	32.4	32.0	32.4	31.8	32.8	32.3
12	31.3	31.4	32.2	31.5	31.7	31.7	32.5	31.8	32.1	31.6	32.2	32.1
13	32.9	33.4	34.2	33.8	33.5	34.2	34.3	33.8	33.7	33.5	33.5	35.4
14	35.3	35.7	36.1	36.2	35.5	35.7	36.9	36.5	36.2	36.2	36.0	36.6
15	36.0	36.7	36.6	36.5	35.7	35.8	37.1	37.2	36.7	36.9	36.6	37.1
16	35.9	35.7	36.8	36.7	35.3	35.5	37.0	37.0	36.4	36.4	36.7	37.2
17	37.7	36.9	37.7	38.0	36.4	36.7	37.6	38.0	37.4	37.5	37.6	38.7
18	39.5	39.2	40.4	40.5	38.6	38.8	40.0	37.8	39.4	40.5	37.7	40.5
19	42.4	42.6	43.1	44.2	41.5	42.6	43.2	43.1	42.3	42.8	42.7	44.0
20	45.4	45.7	46.1	46.6	44.4	45.4	46.2	45.4	45.3	45.5	45.7	46.4
21	48.0	48.6	48.9	48.8	47.0	47.6	48.7	48.6	48.1	49.0	48.3	47.8
22	50.1	49.9	51.0	50.6	49.5	51.2	51.2	50.6	51.0	50.8	51.3	51.5
23	53.1	51.9	53.8	52.9	52.7	52.8	53.2	52.5	53.2	52.4	53.0	53.4
24	55.6	54.3	56.0	54.0	54.5	54.6	55.0	54.1	55.8	54.5	55.0	54.6
25	—	—	—	—	—	—	—	—	—	—	—	—
	Volume, ml											
	6984.87	6967.05	7354.09	7220.17	6926.50	6989.14	7412.26	7225.64	7213.81	7143.41	7228.04	7431.75

TABLE C-3.- Concluded

(d) Postflight, R + 5 to R + 68

Leg zone	R + 5 (Feb. 13, 1974)		R + 7 (Feb. 15, 1974)		R + 11 (Feb. 19, 1974)		R + 17 (Feb. 25, 1974)		R + 31 (Mar. 11, 1974)		R + 68 (Apr. 17, 1974)	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	—	—	--	—	--	--	--	—	--	--	--	--
2	20.7	20.9	20.3	20.9	21.0	20.8	20.9	21.1	20.5	20.5	20.5	20.8
3	21.4	21.9	22.3	21.5	21.4	21.7	21.7	21.5	21.6	21.3	21.2	21.6
4	22.8	23.0	22.7	23.0	23.3	23.4	23.8	22.9	23.2	22.5	23.3	23.0
5	24.9	25.3	25.4	25.4	25.0	26.2	26.6	24.7	25.1	24.5	25.6	25.2
6	27.0	28.0	27.4	27.9	27.5	28.3	28.4	27.8	27.3	27.2	27.7	27.8
7	27.7	30.9	29.6	31.6	31.2	31.8	31.3	30.9	30.8	30.0	31.4	31.0
8	32.8	33.5	32.6	33.5	33.2	33.9	33.9	32.9	32.9	32.7	34.0	34.2
9	33.9	34.2	33.7	33.0	34.4	34.4	34.6	34.4	34.0	34.0	34.6	35.0
10	33.8	33.3	33.4	33.4	33.8	33.4	33.7	33.9	33.6	33.4	33.8	34.3
11	32.6	32.4	32.1	32.4	32.7	32.2	32.5	32.7	32.0	32.0	32.3	32.7
12	32.1	32.0	32.2	32.3	32.1	32.1	32.2	31.9	32.0	31.9	32.4	32.5
13	33.2	33.2	33.7	34.6	33.5	35.0	39.3	34.2	33.7	34.5	34.4	34.5
14	36.0	36.0	36.1	36.5	36.1	36.6	36.6	36.6	36.0	36.4	36.6	36.4
15	36.5	36.9	36.3	36.9	36.8	36.8	37.0	36.5	36.6	36.5	36.6	37.2
16	36.5	36.6	36.5	37.0	36.7	37.6	37.3	37.2	36.7	36.7	37.2	37.6
17	37.5	37.9	37.8	39.3	38.0	39.4	39.0	38.5	38.3	38.4	39.0	39.2
18	39.6	39.9	40.8	40.6	40.8	41.7	41.7	41.0	40.4	40.5	41.6	42.1
19	43.0	44.2	43.8	44.5	44.0	45.7	44.4	44.6	43.7	44.2	45.0	45.5
20	46.3	46.5	46.0	46.8	47.1	48.5	48.2	47.6	47.1	48.0	47.8	48.3
21	48.7	49.5	48.8	49.9	49.7	50.1	50.2	50.9	49.3	49.5	50.5	51.4
22	51.3	51.5	50.8	50.8	51.0	52.0	52.3	51.2	51.3	50.9	52.7	53.4
23	53.2	53.0	53.1	52.6	53.7	53.7	55.2	52.6	54.1	52.6	54.9	54.9
24	55.3	55.5	55.6	55.4	55.8	55.6	57.4	55.4	55.5	54.5	56.2	56.4
25	—	—	—	--	—	—	--	--	—	--	--	--
	Volume, ml											
	7227.94	7347.18	7261.31	7432.81	7419.02	7629.09	7664.57	7455.12	7359.80	7317.71	7622.30	7743.78

TABLE C-4.- LEG MEASUREMENTS OF SL-4 SPT

(a) Preflight

Leg zone	F - 46 (Aug. 31, 1973)		F - 35 (Oct. 12, 1973)		F - 21 (Oct. 26, 1973)		F - 10 (Nov. 6, 1973)		F - 6 (Nov. 10, 1973)		Mean ± SD	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	—	—	—	—	—	—	—	—	—	—	—	—
2	20.6	20.9	20.1	20.8	20.2	20.9	20.3	20.9	20.2	20.5	—	—
3	21.5	21.8	20.5	21.6	20.5	21.8	21.0	21.4	20.7	21.1	—	—
4	23.7	24.1	22.8	23.8	23.0	23.6	23.0	23.9	23.3	23.5	—	—
5	26.4	27.6	25.4	26.9	25.6	26.5	26.0	27.5	25.8	26.6	—	—
6	29.7	31.3	28.6	29.6	28.5	29.6	29.6	30.5	29.3	30.4	—	—
7	33.4	34.6	31.9	33.6	33.2	32.6	33.2	33.4	32.4	32.6	—	—
8	37.4	37.0	35.7	36.0	36.0	36.0	36.8	36.1	35.5	35.4	—	—
9	38.1	37.4	36.9	36.4	37.3	36.7	37.9	36.9	37.4	36.6	—	—
10	37.0	36.5	36.6	35.5	36.6	35.9	36.8	35.9	36.6	36.1	—	—
11	34.9	34.0	35.6	33.5	34.8	34.0	35.2	33.9	35.0	33.8	—	—
12	34.0	33.2	34.0	33.1	33.7	33.1	33.8	33.3	34.0	32.9	—	—
13	35.5	35.7	34.7	35.9	34.4	35.2	35.9	35.5	36.6	35.6	—	—
14	37.9	37.9	37.3	37.5	37.3	38.3	37.8	37.6	37.7	37.3	—	—
15	38.8	38.1	37.8	38.4	38.1	39.0	38.4	38.6	38.2	38.3	—	—
16	38.7	38.9	37.9	39.1	38.3	40.5	38.2	39.0	38.9	37.8	—	—
17	40.1	40.6	39.0	41.2	39.6	42.0	40.0	41.7	39.8	40.2	—	—
18	42.6	44.1	41.4	43.6	42.1	45.2	42.3	43.7	43.1	43.3	—	—
19	45.6	46.4	45.1	46.5	45.6	47.8	45.8	47.0	45.0	46.4	—	—
20	49.4	50.1	47.3	49.6	48.4	50.5	48.7	49.7	48.6	48.7	—	—
21	52.2	52.2	49.8	51.8	51.1	53.0	50.8	52.1	50.0	51.4	—	—
22	53.7	53.3	52.2	52.4	53.7	54.1	52.8	52.8	52.0	52.0	—	—
23	56.0	53.9	55.1	54.5	55.5	56.5	54.8	53.9	53.6	53.2	—	—
24	56.5	55.9	56.7	56.9	55.9	56.0	57.1	57.2	55.7	54.9	—	—
25	--	--	--	--	--	--	--	--	--	--	—	—
	Volume, ml											
	8237.85	8244.90	7829.16	8120.34	7995.12	8374.84	8085.53	8192.67	7935.98	7944.06	8016.73 ±154.76	8175.36 ±159.26

TABLE C-4.- Continued

(b) In-flight

Leg zone	MD-3 (Nov. 18, 1973)		MD-5 (Nov. 20, 1973)		MD-8 (Nov. 23, 1973)		MD-37 (Dec. 22, 1973)		MD-59 (Jan. 13, 1974)		MD-81 (Feb. 4, 1974)	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	--	--	--	--	--	--	--	--	--	--	--	--
2	19.1	19.5	19.1	--	19.3	19.5	18.7	--	19.1	--	18.9	--
3	20.2	21.0	20.5	--	19.4	20.8	19.4	--	20.1	--	19.7	--
4	21.4	23.0	22.5	--	22.0	22.8	22.2	--	22.3	--	22.7	--
5	24.0	25.5	25.0	--	24.0	25.8	24.8	--	24.5	--	25.2	--
6	27.5	28.5	27.5	--	26.6	28.2	27.8	--	28.0	--	28.0	--
7	31.2	31.5	31.5	--	29.4	32.5	31.0	--	32.1	--	31.3	--
8	35.0	34.5	35.5	--	33.5	34.0	33.6	--	34.7	--	34.0	--
9	36.0	35.9	36.5	--	35.6	35.0	34.0	--	35.0	--	34.2	--
10	35.6	34.5	35.7	--	35.0	33.8	32.5	--	33.5	--	33.0	--
11	33.1	33.0	34.5	--	34.2	32.1	31.5	--	32.0	--	32.1	--
12	33.2	31.5	33.5	--	32.2	32.1	31.0	--	31.7	--	31.3	--
13	32.6	34.0	33.6	--	32.8	33.9	33.0	--	33.4	--	33.0	--
14	34.6	35.8	36.0	--	34.6	35.6	35.0	--	35.8	--	35.8	--
15	35.9	36.0	36.5	--	36.2	36.7	34.8	--	37.0	--	35.5	--
16	35.7	36.0	36.4	--	35.5	35.9	35.2	--	35.6	--	35.4	--
17	37.0	37.0	37.5	--	36.0	36.8	36.8	--	36.8	--	37.3	--
18	39.1	39.5	39.2	--	38.5	38.9	39.5	--	38.4	--	41.0	--
19	42.4	41.5	42.9	--	40.9	42.0	42.7	--	42.1	--	41.7	--
20	44.6	44.1	45.0	--	43.5	45.1	45.0	--	45.8	--	45.0	--
21	48.0	47.0	47.5	--	45.8	48.5	46.8	--	47.6	--	48.1	--
22	50.5	50.0	50.0	--	49.0	52.0	48.5	--	49.1	--	50.9	--
23	51.5	52.0	51.5	--	51.0	51.3	49.5	--	50.8	--	51.0	--
24	52.7	52.2	52.2	--	51.5	52.5	50.0	--	52.2	--	52.1	--
25	--	--	--	--	--	--	--	--	--	--	--	--
	Volume, ml											
	7100.71	7106.30	7239.15	--	6834.52	7168.61	6793.60	--	7026.05	--	7039.81	--

TABLE C-4.- Continued

(c) Postflight, R + 0 to R + 4

Leg zone	R + 0 (Feb. 8, 1974)		R + 1 (Feb. 9, 1974)		R + 1 (Feb. 9, 1974)		R + 2 (Feb. 10, 1974)		R + 3 (Feb. 11, 1974)		R + 4 (Feb. 12, 1974)	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	--	—	--	--	--	--	--	—	—	--	--	--
2	19.5	19.7	20.3	20.6	20.6	19.7	20.2	20.8	20.0	20.6	20.3	20.8
3	20.4	20.4	20.4	20.8	20.3	20.4	20.8	21.3	20.5	20.9	20.7	21.4
4	22.7	22.5	22.5	23.0	22.4	23.0	23.3	23.5	23.2	23.1	23.5	24.0
5	26.0	25.2	24.8	25.4	24.6	25.1	25.3	26.7	25.5	26.2	25.7	26.7
6	28.2	28.1	27.9	29.0	27.0	27.6	28.3	29.1	28.9	29.4	28.8	29.6
7	32.1	31.2	31.1	31.4	31.1	31.2	31.7	32.4	32.0	31.6	32.7	33.0
8	34.1	33.0	34.6	33.8	34.0	33.4	34.8	34.8	35.3	34.5	35.4	35.2
9	34.8	34.1	36.2	34.7	35.8	34.3	36.0	35.5	36.2	35.3	36.4	36.0
10	34.3	33.5	36.1	34.5	35.5	33.7	35.6	34.6	35.7	34.6	35.7	35.6
11	32.9	32.3	34.7	33.2	33.4	32.4	34.2	33.2	34.4	33.2	34.0	33.5
12	32.5	31.8	33.5	32.5	33.1	32.2	33.7	32.6	33.4	32.5	33.8	33.0
13	35.6	35.0	34.5	34.5	34.5	34.3	35.2	35.4	35.2	34.5	36.0	36.1
14	37.0	36.9	37.2	36.2	36.9	36.2	37.9	37.5	37.7	36.8	37.9	38.1
15	37.3	32.3	38.2	37.8	37.5	37.2	38.1	38.0	38.2	38.5	38.5	38.7
16	37.0	36.8	38.0	38.0	37.4	36.7	38.2	38.2	38.2	38.1	38.6	38.9
17	39.0	38.9	38.9	38.9	39.4	38.3	39.1	34.5	39.1	39.6	40.8	41.0
18	41.3	41.6	41.4	41.3	41.0	40.8	41.0	42.0	41.6	41.6	43.1	43.7
19	44.4	43.6	44.3	44.5	44.4	43.6	44.2	45.1	42.2	44.5	46.3	46.3
20	48.2	46.3	47.2	46.4	48.6	47.1	47.8	48.1	47.5	48.4	47.3	49.5
21	49.5	49.1	50.0	49.0	49.9	49.2	49.7	50.5	50.0	50.5	51.5	51.3
22	51.3	50.9	51.1	50.6	51.3	51.2	52.3	52.2	52.2	51.0	53.1	53.1
23	53.5	51.0	54.6	51.9	53.5	54.0	53.2	53.1	54.4	53.9	55.2	55.6
24	56.1	53.2	56.5	55.1	55.8	55.2	55.2	54.5	57.6	54.9	57.5	56.5
25	—	—	--	--	--	--	--	--	—	—	--	--
	Volume, ml											
	7579.27	7300.78	7689.47	7457.96	7599.91	7394.23	7710.79	7747.60	7762.68	7684.15	8085.90	8124.33

TABLE C-4.- Concluded

(d) Postflight, R + 5 to R + 68

Leg zone	R + 5 (Feb. 13, 1974)		R + 7 (Feb. 15, 1974)		R + 11 (Feb. 19, 1974)		R + 17 (Feb. 25, 1974)		R + 31 (Mar. 11, 1974)		R + 68 (Apr. 17, 1974)	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	--	--	--	--	--	--	--	--	--	--	--	--
2	20.0	20.8	20.0	21.0	20.2	20.2	20.2	20.6	21.0	21.1	20.7	20.8
3	20.8	21.4	20.6	21.5	20.6	21.6	20.7	21.3	21.7	21.5	21.1	21.3
4	22.6	23.5	22.6	23.8	23.0	23.9	22.6	23.6	24.2	23.5	23.2	23.5
5	25.3	26.5	24.8	27.0	25.9	26.2	25.3	26.2	26.7	26.7	25.8	26.6
6	28.1	29.5	27.7	27.9	29.2	30.1	28.1	29.4	30.4	29.9	29.2	30.1
7	32.1	32.6	32.2	33.5	33.0	32.7	31.8	32.6	34.6	34.6	33.0	33.3
8	35.2	35.7	35.5	35.4	35.9	35.5	35.4	35.2	37.0	35.5	36.7	36.4
9	36.3	36.0	36.9	36.4	37.0	36.3	36.7	36.1	38.2	36.7	37.9	37.1
10	35.7	34.5	36.6	35.9	36.4	35.4	36.2	35.5	37.2	35.9	37.6	36.5
11	34.4	33.8	34.9	34.2	34.6	33.6	34.7	33.8	35.5	34.4	36.0	34.6
12	33.7	33.2	35.8	33.3	34.0	33.0	33.9	33.1	34.6	33.6	34.7	33.7
13	35.6	35.5	34.9	36.2	35.9	35.2	35.3	35.4	36.8	36.0	35.8	36.1
14	37.4	37.4	37.5	37.4	38.1	38.1	37.8	37.6	38.9	38.4	38.4	38.3
15	38.4	38.5	38.2	38.2	39.0	38.8	38.8	38.5	39.6	39.3	39.1	39.3
16	38.4	38.5	38.2	38.6	38.8	38.9	38.6	38.4	39.9	39.3	39.1	40.1
17	40.0	40.1	39.6	39.4	40.1	40.7	40.6	40.3	41.1	41.2	40.5	41.8
18	42.0	42.5	42.0	42.9	42.3	43.0	42.2	43.3	43.3	44.2	43.5	44.2
19	44.8	45.5	45.0	46.5	45.2	45.5	44.8	45.5	46.7	47.3	46.7	47.3
20	48.0	48.2	47.5	48.6	48.7	48.6	48.8	48.9	49.9	49.7	49.3	50.0
21	50.7	50.4	50.4	51.4	50.5	50.8	51.0	51.3	52.0	51.6	51.8	51.5
22	52.6	52.4	52.7	52.1	52.6	52.2	52.8	52.6	54.2	53.5	54.0	54.5
23	55.2	54.7	55.2	53.9	54.4	54.0	54.9	57.6	57.3	55.2	56.6	56.1
24	57.2	56.1	57.2	55.0	56.8	56.4	57.1	56.7	58.8	56.3	58.0	57.3
25	--	--	--	--	--	--	--	--	--	--	--	--
	Volume, ml											
	7902.50	7912.85	7885.98	7999.82	8015.23	7976.42	7966.28	7985.16	8522.03	8265.90	8342.41	8375.52

TABLE C-5.- LEG MEASUREMENTS OF SL-4 PLT

(a) Preflight

Leg zone	F - 46 (Aug. 31, 1973)		F - 35 (Oct. 12, 1973)		F - 21 (Oct. 26, 1973)		F - 10 (Nov. 6, 1973)		F - 6 (Nov. 10, 1973)		Mean ± SD	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	--	--	--	--	--	--	--	--	--	--	--	--
2	22.0	21.4	22.0	21.5	22.1	21.6	21.8	21.4	22.0	21.5	--	--
3	22.3	21.9	22.1	22.1	22.5	22.6	22.0	21.8	22.2	21.6	--	--
4	24.2	23.6	24.0	23.7	24.2	24.0	24.0	23.6	24.2	23.6	--	--
5	26.5	25.9	26.0	25.6	26.5	26.1	26.1	26.1	26.6	25.3	--	--
6	28.3	28.6	28.0	27.9	28.4	28.2	28.2	28.3	28.4	27.6	--	--
7	30.6	30.6	30.4	30.0	30.9	31.2	30.8	30.5	31.1	29.5	--	--
8	33.7	34.0	33.1	33.1	34.2	34.1	33.4	32.8	33.9	31.8	--	--
9	36.8	35.2	35.9	35.4	36.9	36.2	36.6	34.7	36.3	34.1	--	--
10	36.7	35.3	36.6	35.7	36.7	36.2	36.5	35.7	36.5	35.6	--	--
11	35.0	33.3	35.1	33.9	35.2	34.3	35.3	33.7	34.5	34.0	--	--
12	33.4	32.5	33.7	32.7	33.7	33.3	33.5	32.7	33.3	32.5	--	--
13	34.4	34.6	34.8	34.6	35.3	34.5	35.0	34.2	35.0	34.1	--	--
14	36.7	35.9	36.7	35.9	37.1	36.2	36.8	35.9	36.9	36.0	--	--
15	36.3	36.1	37.9	36.5	38.2	37.4	37.4	36.3	37.7	36.5	--	--
16	36.8	36.2	37.5	37.2	37.9	36.9	37.2	36.3	37.8	35.7	--	--
17	39.7	37.7	39.7	38.6	39.8	40.2	40.1	38.4	40.1	37.7	--	--
18	41.3	42.1	42.7	41.5	42.9	43.8	43.3	42.3	43.6	42.6	--	--
19	45.0	47.0	45.9	45.5	46.7	47.0	46.7	46.0	46.3	44.0	--	--
20	48.5	48.3	48.4	48.5	49.5	49.2	49.1	48.4	49.1	47.6	--	--
21	51.2	50.3	50.4	50.4	51.2	51.2	51.2	50.3	51.3	49.5	--	--
22	52.1	50.7	51.6	51.1	52.1	51.0	52.1	50.8	52.0	50.9	--	--
23	52.6	50.6	53.3	51.6	53.5	52.6	53.4	50.8	53.5	51.2	--	--
24	53.3	51.3	54.1	52.9	54.2	52	55.0	52.4	54.2	51.9	--	--
25	--	--	--	--	--	--	--	--	--	--	--	--
	Volume, ml											
	7717.19	7466.25	7768.02	7521.66	7948.18	7777.57	7881.69	7475.53	7894.18	7327.43	7841.85 ±95.69	7513.69 ±164.39

TABLE C-5.- Continued

(b) In-flight

Leg zone	MD-5 (Nov. 20, 1973)		MD-8 (Nov. 23, 1973)		MD-31 (Dec. 16, 1973)		MD-58 (Jan. 12, 1973)		MD-81 (Feb. 4, 1974)	
	L	R	L	R	L	R	L	R	L	R
Circumference, cm										
1	—	—	—	--	—	--	—	—	—	—
2	26.0	--	20.5	21.6	20.2	20.2	20.2	20.0	20.0	—
3	21.6	—	21.6	21.3	21.2	20.4	20.5	20.8	20.9	—
4	23.2	--	23.6	23.0	23.3	22.5	22.4	22.8	22.4	--
5	25.4	—	25.6	24.6	25.5	24.6	24.1	24.8	24.8	--
6	27.4	--	28.0	27.4	27.9	27.6	26.0	26.9	26.3	—
7	29.2	—	30.0	29.2	29.9	29.4	28.2	29.1	28.5	--
8	32.9	--	33.5	31.2	32.6	31.1	30.6	31.6	31.5	--
9	36.1	—	35.0	34.5	34.0	33.5	34.0	33.2	33.8	--
10	34.6	—	33.7	33.4	33.1	33.5	33.6	32.1	32.8	--
11	32.6	—	32.3	32.0	31.0	33.0	32.3	31.1	31.5	—
12	31.2	—	31.9	31.5	31.3	31.2	31.2	31.4	31.8	--
13	32.4	—	33.8	32.7	32.6	32.5	32.7	33.8	33.8	--
14	35.3	—	34.9	34.4	35.0	34.5	34.0	34.3	34.3	--
15	35.0	—	34.5	34.5	34.6	34.2	34.1	34.0	34.1	--
16	35.2	--	34.5	33.5	34.3	33.7	34.1	35.6	34.6	--
17	38.7	--	36.3	34.2	37.5	36.2	35.4	36.7	36.4	--
18	41.6	—	38.5	36.3	38.6	38.1	38.9	39.2	40.7	--
19	45.1	—	43.5	40.6	42.2	42.8	40.9	43.2	43.8	--
20	46.8	—	45.3	42.8	45.7	45.1	45.0	47.0	45.5	--
21	47.5	--	46.6	46.8	46.8	47.1	45.4	47.2	47.3	--
22	48.9	--	47.9	46.9	48.5	47.9	46.8	48.8	48.7	--
23	50.1	--	48.4	48.9	49.8	48.6	48.9	49.6	49.7	--
24	49.9	--	49.2	49.6	50.7	49.9	49.6	51.2	50.3	—
25	--	--	—	—	--	--	--	—	--	--
Volume, ml										
	7120.24	--	6832.74	6508.76	6805.97	6668.12	6518.33	6804.72	6795.45	—

TABLE C-5.- Continued

(c) Postflight, R + 0 to R + 4

Leg zone	R + 0 (Feb. 8, 1974)		R + 1 (Feb. 9, 1974)		R + 1 (Feb. 9, 1974)		R + 2 (Feb. 10, 1974)		R + 3 (Feb. 11, 1974)		R + 4 (Feb. 12, 1974)	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	—	—	—	—	--	--	--	--	--	—	—	--
2	20.8	20.5	21.5	20.8	21.4	20.5	21.8	21.4	21.3	20.9	21.9	21.4
3	21.2	20.9	21.3	21.1	21.2	20.8	22.0	21.7	21.5	21.1	21.9	21.7
4	23.0	23.8	23.2	22.6	22.8	22.9	23.9	23.2	23.3	22.9	23.6	23.5
5	24.5	24.8	25.2	24.5	24.8	24.4	25.4	25.3	25.2	24.8	25.4	25.0
6	26.6	27.1	27.2	26.7	26.6	26.0	27.4	27.4	27.0	27.3	27.0	27.6
7	28.7	28.9	29.4	28.7	29.4	28.3	29.8	29.8	29.3	29.6	29.6	29.7
8	31.5	31.4	31.9	31.0	31.9	31.2	32.5	33.0	32.2	31.9	32.5	32.2
9	33.9	33.0	34.5	33.2	33.9	33.6	35.2	33.9	34.8	33.3	35.1	34.5
10	33.3	32.9	34.8	34.0	34.2	32.9	35.2	34.6	34.8	34.0	35.7	34.5
11	32.7	31.9	33.9	33.2	33.0	31.8	33.9	33.3	33.7	32.5	34.3	33.0
12	32.1	31.4	32.7	32.1	32.3	31.3	32.8	32.7	32.5	31.8	33.3	32.3
13	33.3	33.7	34.3	33.4	33.3	33.3	34.6	34.6	34.0	33.6	34.7	34.4
14	35.7	35.1	36.4	35.5	35.6	34.9	37.1	35.7	36.4	35.5	37.0	35.8
15	36.6	35.7	37.5	36.4	36.2	35.4	37.6	36.5	39.7	36.2	37.9	36.5
16	36.3	35.4	37.6	35.9	36.5	35.4	37.1	36.7	36.8	36.1	37.7	36.3
17	38.6	37.6	39.7	38.2	38.5	37.5	39.9	37.7	38.9	38.1	40.0	38.2
18	41.2	40.8	41.5	40.2	42.3	39.8	42.3	41.2	42.8	40.1	41.7	41.0
19	44.2	44.6	44.9	43.6	44.0	45.2	45.4	43.9	44.9	44.5	45.4	44.1
20	46.8	46.8	41.8	46.8	46.9	46.8	48.2	47.5	47.6	47.0	48.0	46.7
21	49.2	48.6	49.5	49.5	48.8	49.0	50.0	49.0	49.3	48.7	49.9	49.0
22	50.2	49.6	50.9	49.9	50.0	49.6	51.2	49.6	51.2	49.7	51.6	50.2
23	51.5	50.8	51.6	50.7	50.9	49.9	52.3	50.7	52.5	49.9	52.1	51.5
24	53.2	51.8	53.0	57.9	52.6	50.4	53.0	51.3	54.9	51.9	53.6	51.9
25	--	—	—	—	--	--	—	--	—	—	--	—
	Volume, ml											
	7175.40	7032.22	7431.37	7084.29	7194.36	6945.49	7574.22	7233.25	7467.87	7091.50	7594.82	7250.68

TABLE C-5.- Concluded

(d) Postflight, R + 5 to R + 68

Leg zone	R + 5 (Feb. 13, 1974)		R + 7 (Feb. 15, 1974)		R + 11 (Feb. 19, 1974)		R + 17 (Feb. 25, 1974)		R + 31 (Mar. 11, 1974)		R + 68 (Apr. 17, 1974)	
	L	R	L	R	L	R	L	R	L	R	L	R
	Circumference, cm											
1	--	--	--	--	--	--	--	--	--	--	--	--
2	21.7	21.1	21.4	21.1	21.8	21.4	21.7	21.4	22.2	21.7	22.2	21.3
3	21.8	21.6	21.8	21.5	22.3	22.1	21.9	21.9	22.3	22.5	22.0	22.0
4	23.0	23.1	23.4	23.2	24.2	24.7	23.5	23.6	24.2	23.6	23.6	23.8
5	25.2	25.4	25.2	24.9	26.2	25.4	25.9	25.5	26.3	24.9	25.4	26.0
6	26.9	27.6	27.3	27.3	28.0	27.6	27.6	28.1	28.4	27.4	27.5	28.2
7	29.2	29.5	29.6	29.1	30.6	29.8	30.1	29.9	30.7	29.4	30.4	31.2
8	32.3	31.9	33.0	31.4	33.8	32.7	33.4	32.5	33.9	32.2	32.9	33.5
9	34.8	34.3	35.1	34.1	36.4	34.9	36.0	35.0	36.3	35.0	36.0	36.5
10	35.4	35.5	35.5	34.0	35.8	35.0	35.8	35.3	36.5	35.9	37.4	36.9
11	34.1	33.1	34.1	32.8	34.3	33.5	34.3	33.9	35.0	34.8	35.9	35.2
12	32.9	32.2	33.0	31.9	33.4	32.4	33.1	32.7	33.7	33.1	34.2	33.7
13	34.2	34.1	34.6	33.6	35.3	35.0	34.5	34.2	35.7	34.3	34.5	35.0
14	36.7	35.7	36.6	35.4	37.3	35.8	36.7	35.9	37.4	36.3	37.3	37.0
15	37.3	36.4	36.9	35.8	37.7	36.8	37.4	36.7	38.2	37.2	38.3	37.7
16	37.0	36.9	37.2	36.4	37.7	37.0	37.5	36.7	38.2	36.5	38.4	38.0
17	38.7	38.6	38.8	38.2	40.0	39.2	40.1	39.2	40.3	38.2	39.6	40.0
18	41.0	41.5	41.7	41.2	43.2	42.4	43.4	41.6	43.2	41.6	43.0	44.0
19	44.6	45.0	45.6	44.7	47.4	46.0	46.3	45.4	47.2	45.6	47.2	47.8
20	47.6	47.3	48.6	47.4	49.4	48.6	48.8	48.1	49.8	48.4	49.5	50.7
21	49.9	49.9	49.7	49.8	50.9	50.1	50.9	50.5	52.0	50.2	51.3	52.9
22	51.6	50.5	51.3	50.3	52.0	51.1	52.2	51.0	53.0	51.6	53.1	53.6
23	52.8	50.9	52.5	51.1	52.9	51.7	53.2	51.9	54.2	52.6	54.1	54.4
24	53.2	53.1	53.8	51.4	55.0	52.4	54.8	53.0	55.2	53.6	55.1	55.2
25	--	--	--	--	--	--	--	--	--	--	--	--
	Volume, ml											
	7465.08	7335.29	7547.38	7201.60	7879.95	7523.88	7777.29	7493.53	8043.86	7547.92	7964.81	8097.25

TABLE C-6.- CALF-CIRCUMFERENCE AND LOWER-LIMB-VOLUME DATA FOR INDIVIDUAL APOLLO CREWMEMBERS IN A RESTING, SUPINE POSITION[a]

Apollo mission	Crew-member	Preflight evaluations			Preflight summary		Postflight evaluations[b]			
		F - 30	F - 15	F - 5	Mean	±SD	First	Second	Third	Fourth
					Resting supine mean calf circumference, cm					
7	CDR	40.7	40.9	40.8	40.8	0.10	40.1 ↓	40.1 ↓	—	—
	CMP	35.9	35.9	35.9	35.9	.00	34.7	35.6	—	—
	LMP	36.6	36.9	36.1	36.5	.40	35.1 ↓	36.0	—	—
8	CDR	35.2	35.3	35.4	35.3	.10	34.9 ↓	35.2	34.4 ↓	—
	CMP	39.7	39.4	39.4	39.5	.17	39.1	39.1	39.1	—
	LMP	37.3	36.8	37.2	37.1	.26	36.8	36.7	37.2	—
9	CDR	37.0	37.0	36.8	36.9	.12	35.2 ↓	35.9 ↓	36.4 ↓	—
	CMP	40.5	40.2	40.1	40.3	.21	38.9 ↓	40.2	40.4	—
	LMP	36.4	—	36.2	36.3	.14	34.7 ↓	38.1 ↑	36.1	—
10	CDR	36.3	35.1	35.9	35.8	.61	34.6 ↓	35.6	—	—
	CMP	37.8	37.1	37.0	37.3	.44	36.2	37.1	—	—
	LMP	38.1	37.5	37.0	37.5	.55	35.6 ↓	36.5	—	—
11	CDR	36.6	36.0	36.2	36.3	.31	35.6	—	—	—
	CMP	37.2	36.8	38.1	37.4	.67	37.0	—	—	—
	LMP	37.9	38.3	37.6	37.9	.35	37.6	—	—	—
15	CDR	40.3	40.5	40.5	40.4	.12	39.3 ↓	39.4 ↓	40.1	40.8 ↑
	CMP	36.5	36.3	36.5	36.4	.12	35.6 ↓	35.1 ↓	35.9 ↓	35.9 ↓
	LMP	37.5	37.1	37.4	37.3	.21	36.0 ↓	36.5 ↓	36.7 ↓	36.3 ↓
18	CDR	38.1	37.9	38.0	38.0	.10	36.6 ↓	36.6 ↓	36.5 ↓	—
	CMP	34.4	34.4	34.8	34.5	.23	33.5 ↓	33.5 ↓	33.2 ↓	—
	LMP	36.3	36.3	36.3	36.3	.00	35.6	35.6	35.4	—
17	CDR	38.0	38.2	38.5	38.2	.25	37.3 ↓	36.6 ↓	38.1	37.3 ↓
	CMP	38.8	38.1	38.6	38.5	.36	37.0 ↓	37.0 ↓	38.1	37.0 ↓
	LMP	38.6	39.1	38.9	38.9	.25	37.4 ↓	37.5 ↓	38.1 ↓	37.6 ↓
Group mean		37.57	37.44	37.47	37.47		36.43	36.85	37.05	37.48
±SD		1.621	1.724	1.625	1.634		1.688	1.719	1.995	1.743
					t-test		$p < 0.05$	n.s.[c]	n.s.	n.s.
					Lower limb volume, ml					
16	CDR	15 929	15 485	15 669	15 694	223	14 108 ↓	14 146 ↓	13 770 ↓	13 812 ↓
	CMP	12 577	12 492	12 798	12 622	158	12 150 ↓	11 898 ↓	12 005 ↓	12 146 ↓
	LMP	14 556	14 794	14 741	14 697	125	14 482	14 033 ↓	14 068 ↓	13 806 ↓
17	CDR	17 265	17 685	17 991	17 647	364	16 772	16 427 ↓	17 238	16 706 ↓
	CMP	17 426	17 132	17 357	17 305	154	15 964 ↓	16 366 ↓	17 028	16 424 ↓
	LMP	17 944	18 542	18 030	18 172	323	17 084 ↓	17 692	17 878	17 189 ↓
Group mean		15 950	16 022	16 098	16 023		15 093	15 094	15 331	15 014
±SD		2 059	2 218	2 089	2 113		1 873	2 116	2 371	2 035
					t-test		n.s.	n.s.	n.s.	n.s.

[a]W. Hoffler and R. Johnson: Apollo flight Crew Cardiovascular Evaluations. Ch. 4 of Biomedical Results of Apollo. NASA SP-368, in press.

[b]Arrows indicate probability $p < 0.05$.

[c]n.s. - not significant.

TABLE C-7.- UPPER-LIMB VOLUMES AND CHANGES IN VOLUME OF SKYLAB CREWMEN

(a) SL-2

Day	Right arm			Left arm		
	Vol., ml	Δ vol., ml	Δ vol., percent	Vol., ml	Δ vol., ml	Δ vol., percent
CDR						
F - 6	[a]2209	--	--	[a]2288	--	--
F + 1	2236	27	1.2	2312	24	1.0
R - 2	2294	85	3.8	2370	-18	-.8
SPT						
F - 6	[a]2768	--	--	[a]2611	--	--
R + 1	--	--	--	--	--	--
R + 2	2698	-70	-2.5	2577	-34	-1.3
PLT						
F - 6	[a]2702	--	--	[a]2472	--	--
R + 1	2589	-113	-4.2	2412	-60	-2.4
R + 2	2693	-9	-.3	2463	-9	-.4

[a]Baseline.

TABLE C-7.- Continued

(b) SL-3

Day	Right arm			Left arm		
	Vol., ml	Δ vol., ml	Δ vol., percent	Vol., ml	Δ vol., ml	Δ vol., percent
			CDR			
F - 6	[a]3228	—	--	[a]2831	—	--
F - 5	3182	-46	-1.4	2861	30	1.1
R + 1	2967	-261	-8.1	2710	-121	-4.3
R + 2	2874	-354	-11.0	2476	-355	-12.5
R + 3	2850	-378	-11.7	2550	-281	-9.9
R + 4	2807	-421	-13.0	2492	-339	-12.0
			CPT			
F - 6	[a]2745	—	—	[a]2672	—	—
F - 5	2774	29	1.1	2669	-3	-0.1
R + 1	2580	-165	-6.0	2543	-129	-4.8
R + 2	2521	-224	-8.2	2667	-5	-.2
R + 3	2675	-70	-2.6	2506	-166	-6.2
R + 4	2656	-89	-3.2	2544	-128	-4.8
			PLT			
F - 6	[a]3073	--	--	[a]3494	--	—
F - 5	3026	-47	-1.5	3482	-12	-0.3
R + 1	3013	-60	-1.9	3534	40	1.1
R + 2	3135	62	2.0	3509	15	.4
R + 3	3134	61	2.0	3580	86	2.5
R + 4	2992	-81	-2.6	3424	-70	-2.0

[a]Baseline.

TABLE C-7.- Continued

(c) SL-4

Day	Right arm			Left arm		
	Vol., ml	Δ vol., ml	Δ vol., percent	Vol., ml	Δ vol., ml	Δ vol., percent
CDR						
F - 30	2498	65	2.7	2335	-2	-0.1
F - 15	2430	-3	-.1	2393	56	2.4
F - 4	[a]2433	—	—	[a]2337	—	--
MD-5	--	--	--	2352	15	.6
MD-8	2434	1	.04	2224	-113	-4.8
MD-31	2367	-66	-2.7	2256	-81	-3.5
MD-57	2439	6	.2	2234	-103	-4.4
R + 0	2432	-1	.04	2348	11	.5
R + 1	2467	34	1.4	2353	16	.7
R + 2	2465	32	1.3	2362	25	1.1
R + 4	2511	78	3.2	2391	54	2.3
R + 5	2505	72	2.9	2401	64	2.7
R + 11	2442	9	.4	2344	7	.3

[a]Baseline.

TABLE C-7.- Continued

(c) Continued

Mission date	Right arm			Left arm		
	Vol., ml	Δ vol., ml	Δ vol., percent	Vol., ml	Δ vol., ml	Δ vol., percent
			SPT			
F - 30	2786	81	3.0	2612	-90	-3.3
F - 15	2681	-24	-.9	2603	-99	-3.7
F - 4	[a]2705	—	--	[a]2702	--	—
MD-5	--	--	—	2644	-58	-2.1
MD-8	2768	63	2.3	2574	-128	-4.7
MD-31	—	—	—	2378	-324	-12.0
MD-57	—	—	--	2680	-22	-.8
R + 0	2659	-46	-1.7	2631	-71	-2.6
R + 1	2628	-77	-2.8	2644	-58	-2.1
R + 2	2718	13	.5	2618	-84	-3.1
R + 4	2703	-2	-.1	2652	-50	-1.9
R + 5	2693	-12	-.4	2691	-11	-.4
R + 11	2740	35	1.3	2671	-31	-1.1

[a]Baseline.

TABLE C-7.- Concluded

(c) Concluded

Mission date	Right arm			Left arm		
	Vol., ml	Δ vol., ml	Δ vol., percent	Vol., ml	Δ vol., ml	Δ vol., percent
			PLT			
F - 30	2547	42	1.7	2450	126	5.4
F - 15	2560	55	2.2	2333	9	.4
F - 4	[a]2505	—	--	[a]2324	—	--
MD-5	—	—	—	2371	47	2.0
MD-8	2568	63	2.5	2299	-25	-1.1
MD-31	2498	-7	-.3	2342	18	.8
MD-57	2518	13	.5	2307	-17	-.7
R + 0	2555	50	2.0	2399	75	3.2
R + 1	2572	67	2.7	2442	118	5.1
R + 2	2566	61	2.4	2468	144	6.2
R + 4	2580	75	3.0	2469	145	6.2
R + 5	2566	61	2.4	2402	78	3.3
R + 11	2583	78	3.1	2449	125	5.4

[a]Baseline.

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CHAPTER II
VARIABILITY IN HUMAN BODY SIZE

by
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A century ago, human engineering was a virtually unknown concept. In schools and homes, on assembly lines and military front lines, the item was paramount and its user secondary. If the operator could not be rammed into the workspace, then the operator was dispensible. Little notice was taken of the high cost in speed, efficiency, accuracy, endurance and safety which was paid in the use of tools and equipment ill-fitted to the hands, legs, eyes and backs of diverse operators. As late as World War II, the design of gun turrets for bombers was dictated so single-mindedly by the air frame configuration and performance requirements established for the aircraft that the number of men who could be found to fit into the turret was severely limited.

With the advent of ever more sophisticated technology, such a disregard for the human factor is no longer possible and a knowledge of man's size and its variability has become progressively more critical in the design of clothing, equipment and workspaces. Stresses involving posture, position and pressure imposed on an operator will result inevitably in an unhealthy body performing a far less than optimum job. We can no longer afford a random matching of men and machines; there are, after all, no dispensible operators on a space flight.

The problems of designing for a highly variable population are, of course, immense but not insuperable. The key to the solutions lies in a thorough acquaintance with the problem.

One has only to view a group of people to be struck by the range of diversity in the size and shape of mankind. This diversity, often visually aesthetic, can be a source of annoyance to the designer. For those involved in design problems, the human body seems to have an inordinate number of irregularly curved and angular depressions and projections, as well as an assortment of appendages, all of which tend to impede a straightforward design solution. Computer models have historically represented man as a series of cylinders, cones and spheroids, but ordinarily the designer should not.

Despite the quality of the subject material, the designer of equipment and systems must arrive at a design solution which will be adequate to accommodate the irregularities of size, shape and mobility of potential users. It is of value, therefore, to have as detailed a quantification of body size variability of the design population as possible.

One can, in general, classify the total human morphological variability into three broad categories: intra-individual, inter-individual, and secular variability. Intra-individual variability, as used here, pertains to those size changes or effective size changes that occur in an individual during his or her adult life. Some size changes such as those related to the aging process and nutrition occur slowly; others are temporary or transient such as those precipitated by movement or the environment. Intra-individual size variability also includes right side-left side asymmetry and the effect of personal protective clothing on functional body size. Of unique concern to the National Aeronautics and Space Administration (NASA) engineers are the changes which occur in the human body under zero-g and high-g conditions.

The differences between the sexes represent a major source of inter-individual variability with the female having, in general, a smaller overall body size, less strength and less rugged features than the male. A second source of such variability lies in ethnic and racial origins. The reader may obtain a general visual impression of the diversity of males and females of the three principal racial groups by examination of Figure 1. Although some artistic liberties have been taken in the figure, each representative body form was scaled to mean dimensional data utilized later in this chapter. Obviously a greater amount of difference could be demonstrated if extreme values had been used.

While all living people belong to a single biological species, the species, like other life forms, is not geographically uniform; it is differentiated into a number of local variants or breeding groups. These variants frequently differ in a number of morphological traits such as skin, eye and hair color, body size and proportions, with a particular trait often highly characteristic for a single variety. It is not necessary here to probe for the reasons behind these morphological differences between variants of man but only to acknowledge their existence and attempt to deal with them in terms of sizing and design requirements. This variability is of some importance here because of the many ethnic and racial groups that constitute the American population as well as the potential design population in the NASA space program.

For reasons that are not always very clear, dimensional differences also occur between persons of different occupations even in a single heterogeneous population. It is most commonly thought that selective pressures of a social, educational or physical nature act to produce the effect.

The third source of human variability which is here termed "secular" concerns changes which occur from generation to generation. Though not well understood this factor is of some importance in systems design. The lengthy lead time required for the production of modern spacecraft and systems is such that the crew members who may eventually use them are often not even of adult age when the design specifications are fixed. It is of more than casual interest, therefore, to estimate what the physical size and proportions of a particular design population will be at a given point in the future.

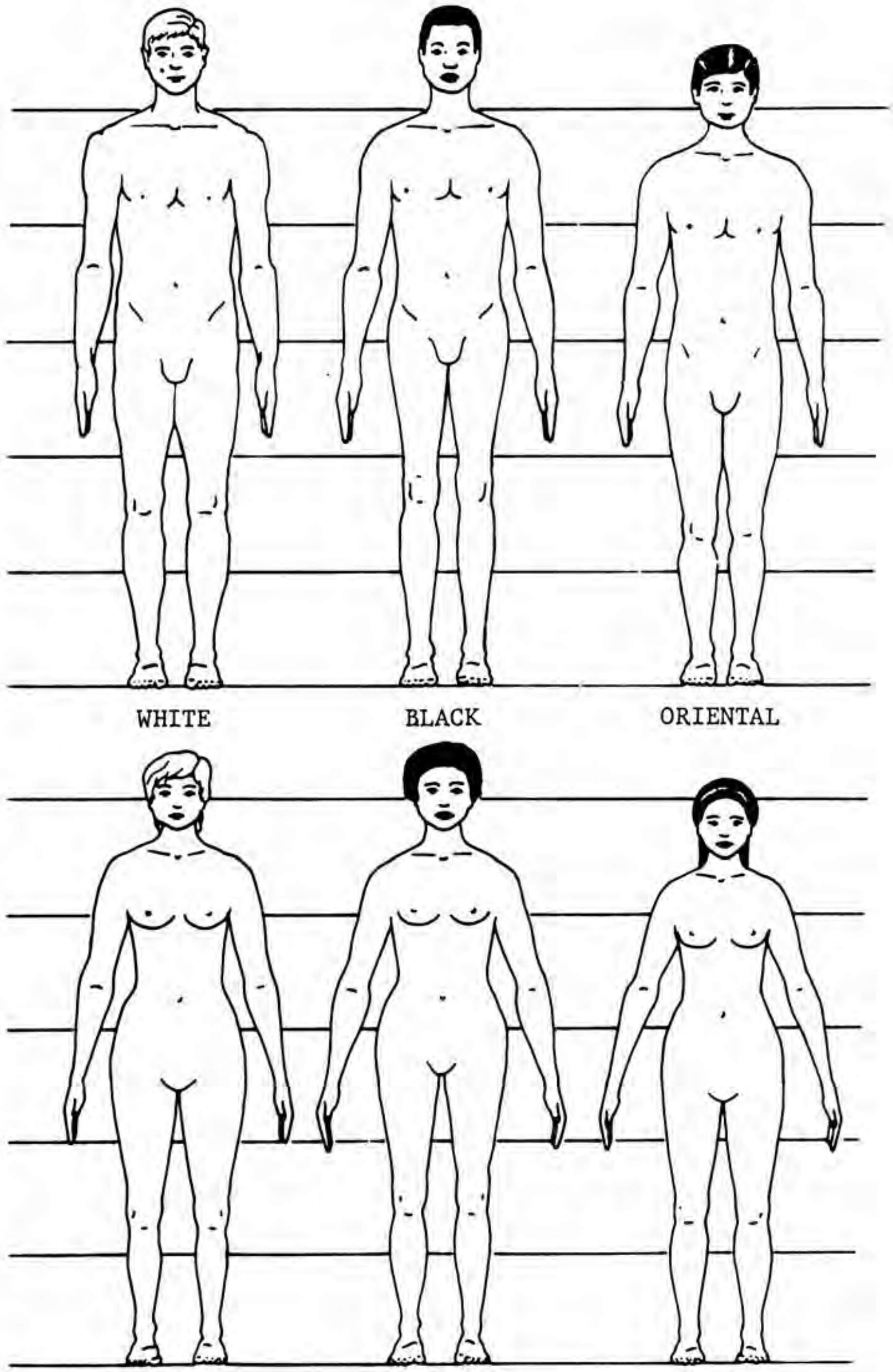

Figure 1. Body size comparisons of three principal racial groups: males and females.

Following a brief discussion of a few causes of size and shape variability of the individual we will offer in this chapter selected anthropometric data to guide the designer in statistically characterizing the variability of groups or populations as described above. Sections on the effects of aging, nutrition, right side-left side asymmetry, and transient changes in body size including day-to-day variations, the effect of posture and movement, and the effect of protective garments, will constitute the description of pertinent intra-individual variability. The effects of zero-g on body size, while noted in this chapter, have been covered in some detail in Chapter I. Variations between the sexes and among persons of different nationalities, racial groups and occupations will be discussed in sections on inter-individual variations. The concluding portions of this chapter will contain a discussion of secular changes recorded in the past century and suggest methods of predicting the size of astronauts and scientists a decade from now.

It should be assumed in all data presented that, unless otherwise noted we are dealing with adults for whom growth is complete. Obvious examples of extremes in size such as are found in Pygmy or Watusi populations have been ignored as have been pathogenetic examples of size extremes such as dwarfism or giantism. The data presented in this chapter represent "healthy" adults whose size variability (individually and in populations) reflect only the effects of "normal" genetic and environmental impact.

As we have attempted to do throughout this volume, an effort has been made to limit anthropometric data, wherever possible, to population surveys in which comparable measurement techniques and body landmarks were used. Obviously errors introduced by inter-anthropometrist differences cannot be altogether avoided and are endemic whenever comparative data presentations are made. Often, data presented in this chapter represents only selected dimensions for which more complete data from the same anthropometric survey is presented in more complete form elsewhere in the text.

Causes of Human Size Varability

No two individuals of a sexually reproducing species are exactly alike.* The statistical potential for individuality, in fact, verges on the incredible. Based on the weight of nucleotide pairs, Muller, the Nobel Prize winning geneticist, has estimated that there are $10^{2,400,000,000}$ possible combinations in the mass of DNA equivalent to that contained in the 46 human chromosomes (Dobzhansky 1962). Muller's staggering number would have to be further increased by unknown factors based on the number of possible combinations of environmental conditions which exert an influence on an individual's phenotypic expression.

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*Monozygotic or identical twins have the same genotype, but somatic mutations, the environment, etc., will act to produce dissimilarities in adults.

At conception, the genetic endowment composes the individual's genotype which directs the formulation of the distinctly human, distinctly individualized proteins from which a given person's cells are built. Instructions guide cellular differentiation into special organ systems, the size, if not the shape, of component organs and blends everything together into a distinctly human and a distinctly individual morphology. The resultant expression of genotype is called the phenotype, which includes those physical characteristics that can be observed, described or measured by the human biologist.

There is little direct evidence to describe the genetic impact upon the development of body dimensions. The inheritance of a number of body deforming syndromes (e.g., Marfan's syndrome, Laurence-Moon-Biedl syndrome) appear to be controlled by single genes; most continuously quantitative dimensional traits, on the other hand, are considered to be polygenic. With a number of genes acting as a "system," the resultant phenotypic expression becomes as varied as the number of mathematically possible combinations. The situation is made more complex by the potential for pleiotrophic effects (multiple effects of a single gene), mutations and both internal and external environmental effects.

Whether or not physical characteristics of differing humans, racial or otherwise, are adaptive or non-adaptive has not been completely settled by physical anthropologists. It is clear, however, that certain selected phenotypic characteristics find higher incidence in given environments. For example, the natural occurrence of black skin in tropical areas of the globe cannot be refuted.

Such factors as (1) climate, including temperature, amount of sunlight, and humidity, (2) altitude, (3) topography, and (4) soil type have been shown to be correlated with various physical traits. Of the meterological criteria, temperature is perhaps the factor most frequently related to types of people. Simply stated, man tends toward linearity in warmer climates and to be more spheric in colder climates. Related to this phenomenon are the so called rules of Bergman (warmer climates=smaller body size) and Allen (body protrusions and/or extremities shorter=colder climate). Both rules are interpreted to be adaptations to body heat exchange needs of a homeotherm. A compilation of stature-weight ratios for inhabitants of different parts of world is given in Table 1. Although not wholly consistent, the data tend to show a lower stature-weight ratio in cold areas of the world and a higher ratio in those that are hot.

Some other relationships between environment and various human traits which have been described include:

(1) lighter skin at higher altitudes.
(2) stockier build at higher altitudes, more linear at low.
(3) greater incidence of epicanthic fold at altitude.
(4) calf size greater in mountains than flat areas.
(5) low nasal index in cold-dry environments.
(6) high nasal index in hot-humid environments.
(7) basal metabolic rate increases as mean annual temperature decreases.

TABLE 1
STATURE, WEIGHT, AND STATURE:WEIGHT RATIO AMONG INHABITANTS
OF DIFFERENT PARTS OF THE WORLD (DOBZHANSKY, 1962, AFTER BLACK)*

MEAN VALUE

Population	Stature		Weight		Ratio
White					
Finland	171.0	(67.3)	70.0	(154.4)	2.44
United States (Army)	173.9	(68.5)	70.2	(154.8)	2.48
Iceland	173.6	(68.4)	68.1	(150.2)	2.55
France	172.5	(67.9)	67.0	(147.7)	2.57
England	166.3	(65.5)	64.5	(142.2)	2.58
Sicily	169.1	(66.6)	65.0	(143.3)	2.60
Morocco	168.9	(66.5)	63.8	(140.7)	2.65
Scotland	170.4	(67.1)	61.8	(136.3)	2.76
Tunisia	173.4	(68.3)	62.3	(137.4)	2.78
Berbers	169.8	(66.9)	59.5	(131.2)	2.85
Mahratta (India)	163.8	(64.5)	55.7	(122.8)	2.94
Bengal (India)	165.8	(65.3)	52.7	(116.2)	3.15
Black					
Yambasa	169.0	(66.5)	62.0	(136.7)	2.73
Kirdi	166.5	(65.6)	57.3	(126.4)	2.90
Baya	163.0	(64.2)	53.9	(118.9)	3.02
Batutsi	176.0	(69.3)	57.0	(125.7)	3.09
Kikuyu	164.5	(64.8)	51.9	(114.4)	3.17
Pygmies	142.2	(56.0)	39.9	(88.0)	3.56
Efe	143.8	(56.6)	39.8	(87.8)	3.61
Bushmen	155.8	(61.3)	40.4	(89.1)	3.86
Oriental					
Kazakh (Turkestan)	163.1	(64.2)	69.7	(153.7)	2.34
Eskimo	161.2	(63.5)	62.9	(138.7)	2.56
North China	168.0	(66.1)	61.0	(134.5)	2.75
Korea	161.1	(63.4)	55.5	(122.4)	2.90
Central China	163.0	(64.2)	54.7	(120.6)	2.98
Japan	160.9	(63.4)	53.0	(116.9)	3.04
Sundanese	159.8	(62.9)	51.9	(114.4)	3.08
Annamites	158.7	(62.5)	51.3	(113.1)	3.09
Hong Kong	166.2	(65.4)	52.2	(115.1)	3.18

*Data given in centimeters and kilograms with inches and pounds in parentheses.

Presented in the following sections are data which will alert the NASA engineer to the nature, extent and magnitude of human body size variability which will confront him in dealing with design problems for the astronauts of today and tomorrow and help him to solve some of the problems of designing for a range of users as potentially diverse as Japanese women and Scandinavian men. For a more complete presentation of specific dimensions for many populations the reader is referred to Volume II of this data book.

Intra-individual Variations in Size

The Effect of Aging

A number of physical and physiological changes occur in the adult body between the ages of 20 and 60 years as a result of the aging process. This phenomena has been recorded by Hooton and Dupertuis (1951) and a number of others. Among the changes of importance to the design engineer are the following:

(1) Stature increases up to the age of 25 and decreases after the age of 30 at a progressively increasing rate each decade.
(2) Body weight increases through 60 years (with the greatest increase among those between 30 and 40), then may decrease below the 30-year-old level.
(3) Chest circumference tends to increase at least through 60 years.
(4) Abdominal circumference tends to increase at least through 60 years.
(5) Strength decreases.

Certainly there are many additional changes that could be listed (i.e., body compositional changes such as an increasing percentage of body fat with a tendency to shift to the central body); however, many are not well documented by longitudinal studies and are of limited importance in engineering anthropometry. A summary of the average change for certain variables studied over 10 years for each decade between 20 and 60 years of age is given in Table 2.

TABLE 2
AVERAGE BODY CHANGES WHICH OCCUR WITH AGING
BASED ON GSELL (1967)*

Age in years	Body Length	Body Weight	Chest Circ. (minimum)	Abdominal Circ.
20-30	+ till age 25	---	+6.8 (2.7)	+5.4 (2.1)
30-40	- 0.6 (0.2)	+3.4 (7.5)	+2.4 (0.9)	+4.6 (1.8)
40-50	- 1.4 (0.6)	+2.5 (5.5)	+1.7 (0.7)	+3.2 (1.3)
50-60	- 1.7 (0.7)	+2.1 (4.6)	---	---

*Data given in kilograms and centimeters with pounds and inches in parentheses.

Perhaps more to the point for NASA designers are the differences which are found when 20-30 year-old persons are compared to 30-40 year-olds in the same population. One such study on men was reported by Fry and Churchill (1956). The authors analyzed dimensional differences for 132 measurements on pilots under 30 years old and over 30 years old as subgroups of the 1950 Air Force survey. A selected group of 17 measurements which had mean differences greater than 1 mm. (.04 in.) was analyzed to see what differences existed between the older and younger pilots at the 5th, 25th, 75th and 95th percentiles. Results are shown in Table 3. The majority of the measurements selected are clearance dimensions in which small variations may have marked effects on the design of personal equipment and clothing. The percentile values demonstrate that in addition to noting the differences in the mean values, it is also important to know where and to what extent the "large" and "small" men change with age.

The Effect of Nutrition

After growth is complete, nutrition may continue to play a role in body size. Overeating and starvation represent nutritional extremes which clearly affect a person's size. Slight dietary excesses and deficiencies probably occur from time to time in every adult lifetime. How much fluctuations in dietary substance such as trace elements and the like affect body size as one ages is unknown. However, generalized overeating over a period of time usually results in obesity. The obesity development associated with middle age in industrialized nations is well known and does not require documentation here. Experimentally controlled studies in obesity furnishing dimensional changes associated with a known diet are rare. In one study (Sims et al. 1968) nine subjects increased body weight by an average of 24.8% over a 300-day test period. These investigators found from 0.4 mm (.016 in.) (calf) to 3.0 mm (.12 in.) (lower abdomen) increase in body radii for each percent increase in body fat.

Perhaps the most outstanding illustration of the effect of starvation on body size is found in a study by Ivanovsky(1923), who reported dimensional changes occurring in over 2,000 Russian adults during a two-year famine following World War I. Of the measurements reported, the most outstanding change occurred in stature, with average decreases of 4.7 cm (1.9 in.) and 3.8 cm (1.5 in.) in the men and women respectively. So far as can be determined, these rather significant losses cannot be attributed to technique, since near original statures were regained within six months following restoration of normal diet. The decrement in stature in starvation was thought to be principally due to vertebral shrinkage.

In a controlled short-term study of semi-starvation, Brozek et al. (1957) reported girth decrements up to 9.5% over a 24-day period. Data reflecting the changes in circumference measured in the study are shown in Table 4. Mean weight loss in the Brozek group was 7.58 kg. (16.7 lbs.). The importance of dimensional change from nutritional excesses or deficiencies

TABLE 3
DIMENSIONAL DIFFERENCES AT SEVERAL PERCENTILE LEVELS BETWEEN USAF PILOTS AGED 20-30 YEARS AND USAF PILOTS AGED 30-40+ YEARS, BASED ON FRY AND CHURCHILL, 1956[1]
Older Pilots Minus Younger Pilots[2]

Dimension	5%	25%	50%	75%	95%
Weight	1.5 (3.2)	1.5 (3.2)	2.0 (4.4)*	1.7 (3.8)*	1.2 (2.6)
Stature	0.3 (0.1)	-0.5 (-0.2)	-0.5 (-0.2)	0.3 (0.1)	1.8 (0.7)
Nipple height	-0.5 (-0.2)	-0.3 (-0.1)	-0.5 (-0.2)	0.0 (0.0)	1.5 (0.6)
Crotch height	-1.8 (-0.7)**	-1.0 (-0.4)**	-0.3 (-0.1)	0.5 (0.2)	0.8 (0.3)
Buttock-knee length	0.0 (0.0)	0.0 (0.0)	-0.3 (-0.1)	0.3 (0.1)	0.8 (0.3)
Waist circ.	2.3 (0.9)*	2.5 (1.0)**	2.8 (1.1)**	2.8 (1.1)**	2.3 (0.9)
Chest circ.	1.5 (0.6)*	1.5 (0.6)**	1.8 (0.7)**	2.3 (0.9)**	2.3 (0.9)
Buttock circ.(sitting)	2.5 (1.0)**	1.8 (0.7)**	1.8 (0.7)**	1.3 (0.5)*	1.8 (0.7)
Buttock circ.(standing)	2.0 (0.8)**	1.5 (0.6)**	1.0 (0.4)*	0.8 (0.3)	-0.3 (-0.1)
Waist breadth	1.0 (0.4)**	0.5 (0.2)*	0.5 (0.2)**	0.5 (0.2)*	0.8 (0.3)
Chest breadth	0.0 (0.0)	0.3 (0.1)	0.5 (0.2)**	0.3 (0.1)	0.5 (0.2)
Hip breadth (sitting)	0.5 (0.2)	0.5 (0.2)**	0.3 (0.1)	0.3 (0.1)	0.3 (0.1)
Elbow-elbow breadth	1.3 (0.5)**	1.8 (0.7)**	1.5 (0.6)**	1.3 (0.5)**	1.8 (0.7)
Knee-knee breadth	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.3 (0.1)*	0.0 (0.0)
Shoulder breadth	0.0 (0.0)	0.3 (0.1)	0.3 (0.1)	0.5 (0.2)**	0.3 (0.1)
Waist depth	0.8 (0.3)**	0.8 (0.3)**	0.8 (0.3)**	0.8 (0.3)**	1.0 (0.4)
Chest depth	0.8 (0.3)**	0.8 (0.3)**	0.5 (0.2)**	0.8 (0.3)**	0.5 (0.2)

[1] Data given in kilograms and centimeters with pounds and inches in parentheses.
[2] Negative values (-) indicate younger group is larger.

* = Difference significant at 5% level ("Student's" t test)

** = Difference significant at 1% level ("Student's" t test)

TABLE 4
CHANGE IN BODY GIRTHS OF YOUNG MEN WITH SEMI-STARVATION
BASED ON BROZEK ET AL. 1957*

Body Part	Circ. at Start	S.D.	Change after 24 days: Intake=1010 kcal/day	% Change
Upper Arm	28.5 (11.2)	± 2.5 (± 1)	- 2.7 cm (1.1)	9.5%
Chest	92.5 (36.4)	± 7.9 (± 3.1)	- 4.4 (1.7)	4.8
Abdomen	80.3 (31.6)	± 7.4 (± 2.9)	- 7.1 (2.8)	8.8
Thigh	47.4 (18.7)	± 3.4 (± 1.3)	- 4.0 (1.6)	8.4
Calf	38.3 (15.1)	± 2.8 (± 1.1)	- 2.4 (0.9)	6.3

*Data given in centimeters with inches in parentheses.

for the designer is perhaps the fact that significant size changes can occur over a rather brief period of time although, unfortunately, such changes are highly individual.

Right Side-Left Side Asymmetry

People tend to believe that one side of their bodies is larger or longer than the other. Whether right side-left side asymmetry is real or imagined and therefore of any concern to the human engineer is the question. Laubach and McConville (1967) reported data for 21 paired measurements obtained from 42 to 117 young male subjects. Their data is summarized in Table 5. In 12 measurements the mean difference is less than one mm, well within the measurement error range. The authors question whether the statistically significant differences obtained in eight of the 21 measurements are of any practical significance.

A somewhat different study of right-left size variation was reported by Peters (1969), who measured some relaxed and erect, right and left side heights on 1166 women (German). A summary of this data is given in Table 6. Clearly in terms of work space (especially during seated desk work) the slumped versus erect differences are, on the whole, greater than the right-left differences.

TABLE 5

DIFFERENCES BETWEEN RIGHT SIDE AND LEFT SIDE MEASUREMENTS OF SELECTED DIMENSIONS
(BASED ON LAUBACH AND MCCONVILLE, 1967)*

Variable	Right Side Mean		Right Side S.D.		Left Side Mean		Left Side S.D.		RIGHT/LEFT DIFFERENCE	
Arm circ. at axilla	30.36	(11.95)	2.68	(1.06)	29.64	(11.67)	2.62	(1.03)	.72	(.28)
Biceps circ., relaxed	28.71	(11.30)	2.66	(1.05)	28.16	(11.09)	2.62	(1.03)	.55	(.22)
Biceps circ., flexed	31.56	(12.43)	2.59	(1.02)	30.82	(12.13)	2.59	(1.02)	.74	(.29)
Forearm circumference	26.54	(10.45)	1.54	(.61)	25.99	(10.23)	1.48	(.58)	.55	(.22)
Wrist circumference	16.72	(6.58)	.82	(.32)	16.58	(6.53)	.82	(.32)	.14	(.06)
Upper thigh circumference	55.28	(21.76)	4.54	(1.79)	55.22	(21.74)	4.55	(1.79)	.06	(.02)
Lower thigh circumference	38.41	(15.12)	2.55	(1.00)	38.45	(15.14)	2.74	(1.08)	.04	(.02)
Calf circumference	36.58	(14.40)	2.32	(.91)	36.50	(14.37)	2.54	(1.00)	.08	(.03)
Ankle circumference	22.41	(8.82)	1.30	(.51)	22.45	(8.84)	1.37	(.54)	.04	(.02)
Acromial height	143.57	(56.52)	5.98	(2.35)	144.19	(56.77)	5.87	(2.31)	.62	(.24)
Trochanteric height	92.69	(36.49)	4.42	(1.74)	92.60	(36.46)	4.38	(1.72)	.09	(.04)
Lower thigh circ. height	52.46	(20.65)	2.97	(1.17)	52.63	(20.72)	3.01	(1.19)	.17	(.07)
Tibiale height	48.21	(18.98)	2.50	(.98)	48.23	(18.99)	2.46	(.97)	.02	(.01)
Ankle height	13.79	(5.43)	1.15	(.45)	13.50	(5.31)	1.00	(.39)	.25	(.10)
Sphyrion height	7.46	(2.94)	.59	(.23)	7.48	(2.94)	.60	(.24)	.02	(.01)
Acromion-to-radiale length	33.44	(13.17)	1.80	(.71)	33.51	(13.19)	1.79	(.70)	.07	(.03)
Rad.-ulnar stylion length	25.56	(10.06)	1.37	(.54)	25.61	(10.08)	1.34	(.53)	.05	(.02)
Hand length	19.21	(7.56)	.98	(.39)	19.20	(7.56)	.97	(.38)	.01	0
Hand breadth	8.49	(3.34)	.55	(.22)	8.43	(3.32)	.52	(.20)	.06	(.02)
Humerus breadth	7.13	(2.81)	.38	(.15)	7.13	(2.81)	.39	(.15)	0	0
Femur breadth	9.91	(3.90)	.97	(.38)	9.86	(3.88)	.92	(.36)	.05	(.02)

*Data given in centimeters with inches in parentheses.

TABLE 6
RIGHT SIDE-LEFT SIDE DIMENSIONAL DIFFERENCES IN WOMEN IN ERECT AND RELAXED POSTURES
(BASED ON PETERS 1969)*

Measurement		Mean		S.D.		Diff. between erect & relax		Diff. between right & left	
Stature	(erect)	163.4	(64.33)	6.9	(2.7)				
	(relax)	163.2	(64.25)	4.6	(1.8)	0.2	(.08)		
Acromial ht.	(erect-R)	132.1	(52.01)	5.0	(2.0)				
	(erect-L)	132.4	(52.13)	3.9	(1.5)			0.3	(.1)
	(relax-R)	131.3	(51.69)	5.1	(2.0)	0.8	(.3)		
	(relax-L)	131.6	(51.81)	4.5	(1.8)	0.8	(.3)	0.3	(.1)
Elbow ht.	(erect-R)	100.1	(39.41)	4.6	(1.8)				
	(erect-L)	99.2	(39.06)	5.1	(2.0)			0.9	(.4)
	(relax-R)	99.4	(39.13)	3.4	(1.3)	0.7	(.3)		
	(relax-L)	99.2	(39.06)	4.2	(1.7)	0.0	0	0.2	(.08)
Sitting ht.	(erect)	83.7	(32.95)	2.6	(1.0)				
	(relax)	82.9	(32.64)	2.2	(0.9)	0.8	(.3)		
Eye ht. sitting	(erect)	74.2	(29.21)	3.7	(1.5)				
	(relax)	73.1	(28.78)	3.3	(1.3)	1.1	(.4)		
Acromial ht. sitting	(erect-R)	52.7	(20.75)	2.7	(1.1)				
	(erect-L)	52.9	(20.83)	1.4	(0.6)			0.2	(.08)
	(relax-R)	51.7	(20.35)	2.3	(0.9)	1.0	(.4)		
	(relax-L)	51.8	(20.39)	2.8	(1.1)	1.1	(.4)	0.1	(.04)
Elbow rest ht.	(erect-R)	20.3	(7.99)	2.3	(0.9)				
	(erect-L)	20.6	(8.11)	2.2	(0.9)			0.3	(.1)
	(relax-R)	19.3	(7.60)	2.5	(1.0)	1.0	(.4)		
	(relax-L)	19.6	(7.72)	2.4	(0.9)	1.0	(.4)	0.3	(.1)
Thigh diam. sitting	(R)	14.1	(5.55)	1.4	(0.6)				
	(L)	14.0	(5.51)	1.3	(0.5)			0.1	(.04)
Thigh ht. sitting	(R)	50.7	(19.96)	3.4	(1.3)				
	(L)	51.3	(20.20)	3.1	(1.2)			0.6	(.2)
Knee ht. sitting	(R)	39.3	(15.47)	2.3	(0.9)				
	(L)	39.6	(15.59)	2.3	(0.9)			0.3	(.1)

*Data given in centimeters with inches in parentheses.

Causes of Transient Body Size Change

While it is common knowledge that such long-term factors as aging, diet and disease have an effect on body size, it is much less well known that body dimensions fluctuate each day and that, wherever possible in the design of clothing and equipment, allowances for such changes should be made.

Many studies of day-to-day fluctuations in body weight have been conducted (Garrow, 1974; Khosla and Billewicz, 1964). Most such studies indicate that it is normal for weight to vary between 0.5 kg. (1.1 lb.) and 1.0 kg. (2.2 lb.) per day. This probably is largely the result of changes in total body water content during the day.

Decreases in stature occur during the course of a day as a result of compression of the fibrocartilaginous intervertebral disks and increased curvature of the spine as gravity and load-carrying strain the system. Loss in stature ranges from three to five cm. (1.2 to 2 inches) according to a number of investigators (Munipov and Zinchencko, 1970; DePuky, 1935; Ivanovsky, 1923) depending on the amount of standing, walking, or carrying which is done. In one study (Ivanovsky, 1923), stevedores were found to decrease 5 cm. (2 in.) by the end of the day. It is suggested that the best time to measure stature is at the beginning of the day, if "maximum" stature is critical to the problem at hand.

Normally stature, eye height and sitting height are greatly affected by posture. For example, the erecc versus "slumped" difference may range from 2 cm. (.75 in.) to 4.5 cm. (1.75 inches) for stature and sitting height respectively (Hertzberg, 1972). Anthropometrists conducting a survey of Women's Air Force personnel in 1968 recorded a difference of 1.3 cm. (.51 inches) between erect and relaxed sitting height. An average difference of 0.4 cm. (.15 in.) was found between two erect posture techniques (i.e., the British Morant method mean stature is greater than the U.S. method) when measurements were made of 2,000 RAF aircrewmen (Bolton et al. 1973). The higher figures are thought to be due to the straightening of the spine and tilting of the head which occurs when the subject is instructed to stretch to full height against a wall as he is in the Morant method. Damon (1964) found a stature difference ranging from .5 cm. (0.2 inches) to 2.0 cm. (0.8 inches) between subjects measured free standing versus those stretched against a wall. As expected, those measured against the wall were "taller." Head tilting (above the Frankfort plane) when subjects were backed against the wall added an average of 0.2 cm. (.08 inches) to the measurement.

All of the foregoing indicates the importance of controlled measurement conditions and suggests that users of such data should check, when possible, to determine by what means and under what conditions the measurements were made.

Obviously as a person moves within an imaginary three-dimensional static envelope which encompasses all possible body positions, size-related changes are constantly occurring. Considering that the spheroid envelope itself moves through space as the individual walks, runs, jumps, climbs and reaches, a truly dynamic analysis of body size changes would be extremely complex. There are, however, a number of dimensional changes which result from movement but which may be treated as static size changes when only the maximum "end of the range of change" is considered for design purposes.

The effect of erect or slumped posture and of different techniques on stature and sitting height measurements have already been mentioned. Related to these effects is the fact that standing height is less than prone or supine body length. Alexander and Clauser (1965) found supine length to average 2.59 cm (1 inch) more than stature. Buttock breadth and abdominal depth are examples of dimensions that increase from standing to sitting configurations of the body (Damon, Stoudt and McFarland, 1966). The chest, of course, moves and changes dimensions with each respiration. To some extent the abdomen will also change in girth during breathing. Although quite variable between individuals, especially between men and women, the abdominal wall may traverse a 2-3 cm (.79 to 1.2 inch) anterior-posterior distance with maximum breathing (Agostoni and Mead, 1964). Pregnancy, of course, results in significant dimensional changes on the torso of women.

One of the better known dimensional changes associated with movement is the increase in girth with flexion. What child has not been asked to "make a muscle" by flexing the biceps? Perhaps for this reason both relaxed and flexed biceps circumferences are frequently measured. A compilation of flexed-relaxed bicep measurements for U.S. and European military personnel is given in Table 7. The mean girth increase with flexion for the 11 male groups surveyed is 2.4 cm (0.95 in.). The single female sample averaged 1.18 cm (0.46 in.) increase, or approximately one half of the male value. The flexed-relaxed circumferences of the elbow and forearm for the same populations are also given in Table 7. The average of 18.8% increase in elbow circumference demonstrates why tightly fitting clothing may restrict motion or blood flow in the arm.

A dimensional change often overlooked is the increase or decrease in longitudinal dimensions on the convex and concave surfaces of joints during movement. Form fitting clothing, pressure suits, prosthetic devices, or anything that must allow a good range of body mobility requires consideration of these changes. Linear distance changes over the body surface resulting from various joint movements were studied by Emanuel and Barter (1957). A summary of the 49 measurements made on 30 subjects is given in Table 8. Measurements were made using a flexible tape. Two arbitrary points were marked on either side of a joint and distances between them measured, first in a neutral position and then in specified flexed, abducted, retracted or protruded positions. While there are definite and significant changes in bodily dimensions with joint movement, the authors found them to be "fairly constant in magnitude" and repeatable. The amount of change is fairly constant regardless of stature or weight of the person.

TABLE 7
DIFFERENCES (Δ) BETWEEN MEAN RELAXED ($\bar{X}_r$) AND MEAN FLEXED ($\bar{X}_f$)
BICEPS AND ELBOW CIRCUMFERENCE FOR SELECTED MILITARY POPULATIONS *

Population	Biceps Circumference				Elbow Circumference				Forearm Circumference			
	$\bar{X}_f$	$\bar{X}_r$	Δ_{f-r}	%↑**	$\bar{X}_f$	$\bar{X}_r$	Δ_{f-r}	%↑**	$\bar{X}_f$	$\bar{X}_r$	Δ_{f-r}	%↑**
USAF-'67	32.74 (12.89)	30.79 (12.12)	1.95 (.77)	6.3	31.24 (12.30)	27.67 (10.89)	3.57 (1.41)	12.9	29.77 (11.72)	28.16 (11.09)	1.61 (.63)	5.7
USAF-'65	31.05 (12.22)	27.90 (10.98)	3.15 (1.24)	11.3	31.02 (12.21)	26.11 (10.28)	4.91 (1.93)	18.8	28.82 (11.35)	26.93 (10.60)	1.89 (.74)	7.0
WAF	26.79 (10.55)	25.61 (10.08)	1.18 (.46)	4.6	26.98 (10.62)	-	-	-	24.98 (9.83)	23.48 (9.24)	1.50 (.59)	6.4
German AF	32.22 (12.69)	29.33 (11.55)	2.89 (1.14)	9.9	34.11 (13.43)	26.69 (10.51)	7.42 (2.92)	27.8	29.45 (11.59)	27.32 (10.76)	2.13 (.84)	7.8
NATO (military)	30.53 (12.02)	28.41 (11.19)	2.12 (.83)	7.5	30.63 (12.06)	25.96 (10.22)	4.67 (1.84)	18.0	28.63 (11.27)	26.86 (10.57)	1.77 (.70)	6.6
Turkish (military)	29.77 (11.72)	27.19 (10.70)	2.58 (1.02)	9.5	29.99 (11.81)	25.31 (9.96)	4.68 (1.84)	18.5	28.02 (11.03)	26.10 (10.28)	1.92 (.76)	7.4
Greek (military)	30.64 (12.06)	28.37 (11.17)	2.27 (.89)	8.0	30.19 (11.89)	25.86 (10.18)	4.33 (1.70)	16.7	28.64 (11.28)	26.97 (10.62)	1.67 (.66)	6.2
Italian (military)	30.95 (12.19)	29.27 (11.52)	1.68 (.66)	5.7	31.41 (12.37)	26.49 (10.43)	4.92 (1.94)	18.6	29.03 (11.43)	27.30 (10.75)	1.73 (.68)	6.3

*Data given in centimeters with inches in parentheses.

**Percentage change calculation based upon: $\frac{\Delta_{f-r}}{\bar{X}_r} \times 100$.

TABLE 8
LINEAR DISTANCE CHANGES OVER BODY JOINTS WITH MOVEMENT
(BASED ON EMANUEL AND BARTER, 1957)*

Measurement	Mean Difference		Standard Deviation	
ELBOW				
Flexion, Full	8.48	(3.34)	0.91	(0.36)
WRIST				
Dorsal Surface				
Volar Flexion	2.00	(0.80)	0.48	(0.19)
Dorsiflexion	-0.27	(-0.106)	0.74	(0.29)
Volar Surface				
Volar Flexion	-3.37	(-1.47)	0.74	(0.29)
Dorsiflexion	1.93	(0.76)	0.51	(0.20)
SHOULDER				
Anterior				
Suprasternale-Acromion				
Protrusion	-2.21	(-0.87)	0.66	(0.26)
Abduction, Horiz.	-1.22	(-0.48)	0.43	(0.17)
Sternum to Scye				
Protrusion	-2.88	(-1.13)	1.24	(0.49)
Retraction	2.79	(1.09)	1.09	(0.43)
Abduction, Horiz.	2.46	(0.97)	1.19	(0.47)
Scye to Mid-arm				
Protrusion	-0.84	(-0.33)	1.32	(0.52)
Retraction	1.83	(0.72)	0.51	(0.20)
Abduction, Horiz.	1.47	(0.58)	0.97	(0.38)
Posterior				
Cervicale to Acromion				
Protrusion	-0.53	(-0.21)	0.94	(0.37)
Retraction	-2.57	(-1.01)	1.27	(0.50)
Abduction, Horiz.	-4.93	(-1.94)	0.91	(0.36)
Abduction, Overhead	-8.74	(-3.44)	1.17	(0.46)
Vertebra to Scye				
Protrusion	-9.30	(-3.66)	1.65	(0.65)
Abduction, Horiz.	2.01	(0.79)	1.22	(0.48)
Abduction, Overhead	5.77	(2.27)	1.42	(0.56)
Posterior Scye to Mid-Arm				
Protrusion	4.78	(1.88)	0.97	(0.38)
Abduction, Horiz.	1.55	(0.61)	0.76	(0.30)
Abduction, Overhead	4.60	(1.81)	0.94	(0.37)
Lateral				
Acromion to Mid-Arm				
Protrusion	-3.18	(-1.25)	0.86	(0.34)
Retraction	-2.44	(-0.96)	0.64	(0.25)
Abduction, Horiz.	-3.71	(-1.46)	0.53	(0.21)
Abduction, Overhead	-5.72	(-2.25)	0.91	(0.36)

*Data given in centimeters with inches in parentheses.

TABLE 8 (continued)

Measurement	Mean Difference		Standard Deviation	
NECK				
Anterior				
Suprasternale to Menton				
Posterior Flexion	7.14	(2.81)	1.09	(0.43)
Posterior				
Vertebra at Scye Level to Inion				
Anterior Flexion	6.12	(2.41)	1.14	(0.45)
Lateral				
Acromion to Mastoid Tip				
Right Flexion	-5.05	(-1.99)	1.70	(0.67)
Left Flexion	3.02	(1.19)	0.91	(0.36)
HIP				
Anterior				
(Ant. Sup. Spine Level to 3/4 Thigh)				
Hyperextension	1.32	(0.52)	0.48	(0.19)
Hanging, Sitting, 90°	-6.71	(-2.64)	1.12	(0.44)
Posterior				
Flexion, Forced, Sitting	15.24	(6.00)	1.98	(0.78)
Hyperextension	-0.91	(0.36)	1.17	(0.46)
Hanging, Sitting, 90°	8.64	(3.40)	1.88	(0.74)
Lateral				
Abduction	-3.12	(-1.23)	1.47	(0.58)
KNEE				
Anterior				
(3/4 Thigh to Mid-Calf)				
Flexion, Forced	10.39	(4.09)	1.04	(0.41)
Flexion, 90°, Sitting	5.99	(2.36)	0.91	(0.36)
TRUNK				
(Coccyx Tip to Cervicale, Sitting)				
Flexion, Full Anterior	10.11	(3.98)	1.88	(0.74)
ANKLE				
Anterior				
(Mid-Calf Interphalangeal Joint I)				
Dorsiflexion	-1.75	(0.69)	0.97	(0.38)
Plantar Flexion	3.58	(1.41)	0.71	(0.28)
Posterior				
(Mid-Calf to Heel Line)				
Dorsiflexion	0.51	(0.20)	0.56	(0.22)
Plantar Flexion	-3.45	(-1.36)	0.81	(0.32)

Effects of Protective Garments on Body Size

Basic anthropometric dimensions are normally given for the nude or "shirt sleeved" conditions; however, in a number of situations personal protective garments or equipment which must be worn may grossly alter the effective size of the wearer. Not only may heavy winter clothing add over 9.1 kg. (20 lbs) to body weight, but it may also increase stature some 7 cm (2.8 in.) and will add up to 25 cm (10 in.) to other key dimensions. In addition to simple linear dimension increases, such clothing may significantly affect range of joint movement and thereby further complicate the design layout of work spaces. Therefore, modifications in body size and biomechanical characteristics of an individual should be given careful consideration by the designer in situations where special encumbering gear will be used.

The change in selected body dimensions for a variety of civilian clothing, U.S. Army uniforms and U.S. Air Force flight assemblies is given in Table 9. In a more recent study Alexander, Laubach and McConville (1976) obtained data on the effect of full flight clothing on body size. The incremental and percentage increases in five nude and suited body dimensions critical to aircraft ejection envelopes are given in Figure 2. Investigators also found that in order to maintain the eye reference point (the basic design datum for cockpits) at a constant level, the seat reference point would have to be lowered an average of 1.9 cm (.75 in.) when aircrew wear maximum flight assemblies.

As if the dimensional increases caused by ordinary protective clothing were not sufficient, even greater changes in dimensions are associated with full pressure suits. Pressure suits generally are anthropomorphic gas-tight bags, designed to protect a pilot or astronaut from the reduced atmospheric pressure of high altitudes or the vacuum of space. When pressure suits are inflated to operational pressure (usually about 1/3 atmosphere), they grow in size and become stiff, often making motion difficult. The effect of one type of pressure suit, both uninflated and inflated, on 33 body dimensions, was reported by Clauser and Hertzberg in 1964. Results can be seen in Table 10. Although many girths are increased significantly, the most outstanding increase is in knee-to-knee breadth. In a later study of a more advanced Air Force pressure suit (Alexander, et al. 1969) the greatest dimensional change was again found to be in knee-to-knee breadth. The mean incremental (uninflated to inflated) and percentage change in six dimensions when this pressure suit is worn is shown in Figure 3. As with the flight clothing, the legs are more dimensionally affected than are the arms.

During EVA (extra-vehicular activity) the astronaut must wear a pressure suit which may include a portable life support system (PLSS). (The total assembly has been termed by NASA an Extra-Vehicular Mobility Unit or EMU.) A number of functional envelope dimensions required for the fully suited 5th and 95th percentile astronaut carrying the PLSS and Backup Oxygen Supply (OPS) are given in Figure 4. The recommended design dimensions for access corridors, hatches and direction change for the suited astronaut* (Apollo EMU) are shown in Figure 5.

*Preliminary Design Requirements for Shuttle EVA/IVA Orbiter Support. NASA Internal Note MSC-EC-R-71-10, 1971.

ORIGINAL ... OF POOR QUALITY

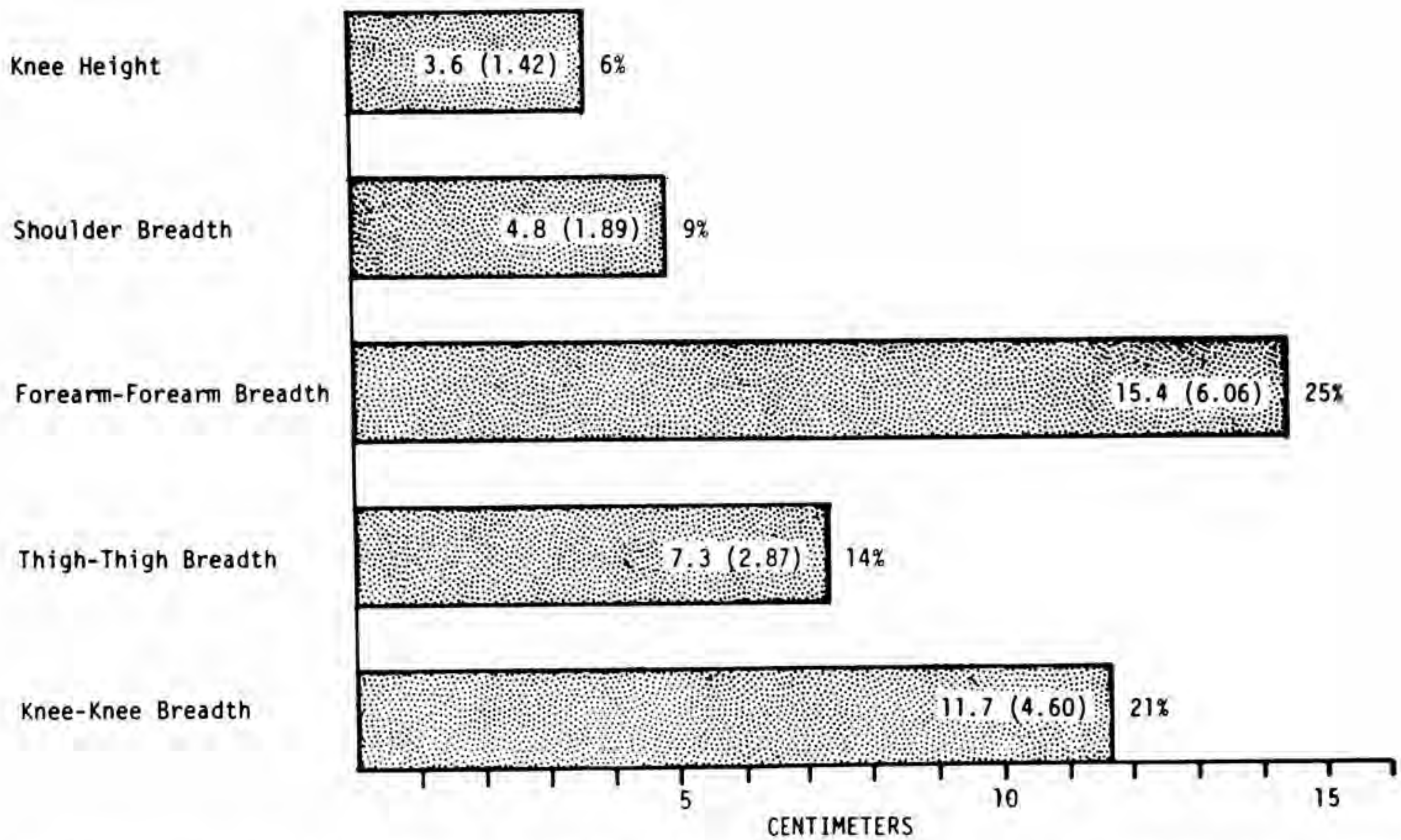
TABLE 9

INCREASE IN DIMENSIONS FROM CLOTHING (BASED ON CLAUSER AND HERTZBERG, 1964)*

	Civilian		Army				Air Force		
	Men Street Clothing	Women Street Clothing	Summer Uniform	Fall Uniform	Winter Uniform	Winter Combat	Full Flight Gear	Light Flight Assembly	Winter Flight Assembly
Weight	12.70 (5.00)	8.90 (3.50)	23.88 (9.40)	29.98 (11.80)	47.24 (18.60)	58.17 (22.90)			50.80 (20.00)
Stature	2.54 (1.00)	1.27-7.60 (.5-3.0)	6.60 (2.60)	6.73 (2.65)	6.73 (2.65)	6.99 (2.75)	-5.08 (-2.00)	8.38 (3.30)	4.83 (1.90)
Abdomen depth			2.39 (.94)	3.0 (1.18)	4.95 (1.95)	6.45 (2.54)	12.70 (5.00)		3.56 (1.40)
Arm reach anterior			.10 (.04)	.20 (.08)	.51 (.20)	.94 (.37)			1.02 (.40)
Buttock-knee length			.51 (.20)	.76 (.30)	1.37 (.54)	1.78 (.70)	5.08 (2.00)		1.27 (.50)
Chest breadth							6.35 (2.50)		1.52 (.60)
Chest depth			1.04 (.41)	2.44 (.96)	4.57 (1.80)	3.91 (1.54)	11.43 (4.50)	2.03 (.80)	3.56 (1.40)
Elbow breadth			1.42 (.56)	2.64 (1.04)	4.67 (1.84)	5.38 (2.12)	27.94 (11.00)		11.18 (4.40)
Eye level ht. sitting			.10 (.04)	.20 (.08)	.41 (.16)	.56 (.22)			1.02 (.40)
Foot breadth	.80 (.30)		.51 (.20)	.51 (.20)	.51 (.20)	.51 (.20)			3.05 (1.20)
Foot length	3.05 (1.20)		4.06 (1.60)	4.06 (1.60)	4.06 (1.60)	4.06 (1.60)			6.86 (2.70)
Hand breadth						.76 (.30)			1.02 (.40)
Hand length						.38 (.15)			.76 (.30)
Head breadth			7.11 (2.80)	7.11 (2.80)	7.11 (2.80)	7.11 (2.80)			1.02 (.40)
Head length			8.90 (3.50)	8.90 (3.50)	8.90 (3.50)	8.90 (3.50)			1.02 (.40)
Head height			3.43 (1.35)	3.43 (1.35)	3.43 (1.35)	3.68 (1.45)			.51 (.20)
Hip breadth			1.42 (.56)	1.93 (.76)	2.74 (1.08)	3.56 (1.40)			3.30 (1.30)
Hip breadth sitting			1.42 (.56)	1.93 (.76)	2.74 (1.08)	3.56 (1.40)	13.97 (5.50)	7.37 (2.90)	4.32 (1.70)
Knee breadth			1.22 (.48)	1.22 (.48)	1.83 (.72)	4.27 (1.68)	2.41 (9.50)		6.35 (2.50)
Knee height sitting			3.35 (1.32)	3.35 (1.32)	3.66 (1.44)	3.66 (1.44)			4.57 (1.80)
Shoulder breadth			.61 (.24)	2.24 (.88)	3.86 (1.52)	2.95 (1.16)	15.24 (6.00)	1.02 (.40)	3.30 (1.30)
Shoulder-elbow length			.36 (.14)	1.27 (.50)	2.39 (.94)	1.57 (.62)			.76 (.30)
Shoulder ht. sitting			.41 (.16)	1.47 (.58)	2.34 (.92)	2.03 (.80)			1.52 (.60)
Sitting ht.			3.53 (1.39)	3.63 (1.43)	4.09 (1.61)	4.24 (1.67)		5.33 (2.10)	1.52 (.60)

*Data given in centimeters with inches in parentheses.

Civilians, men: underwear, shirt, trousers, tie, socks, shoes.
Civilians, women: underwear, dress, or blouse or sweater and skirt, shoes.
Army, summer uniform: underwear, khakis or O.D.'s or fatigues, socks, shoes, helmet and liner.
Army, fall uniform: underwear, fatigues, field jacket, socks, shoes, helmet and liner.
Army, winter uniform: underwear, fatigues, field jacket, overcoat, socks, shoes, helmet and liner.
Army, winter combat: underwear, fatigues, combat suit, overcoat, socks, shoes, gloves, wool cap, helmet and liner.
Air Force, full flight gear: T-1 partial pressure suit, inflated; ventilation suit, deflated, MD-1 anti-exposure suit and MD-3A liner, long cotton underwear.
Air Force, light flight assembly: T-5 partial pressure suit, uninflated; K-1 pressure helmet and boots.
Air Force, winter flight assembly: Word War II heavy winter flying clothing, including jacket, trousers, helmet, boots and gloves.



*Increments computed from 95th percentile values. Data given in centimeters with inches in parentheses. Measurements were made on 32 subjects in winter over-land and over-water assemblies.

Figure 2. Incremental and percentage growth changes in body size due to the effects of protective clothing and equipment (based on Alexander et al. 1976).

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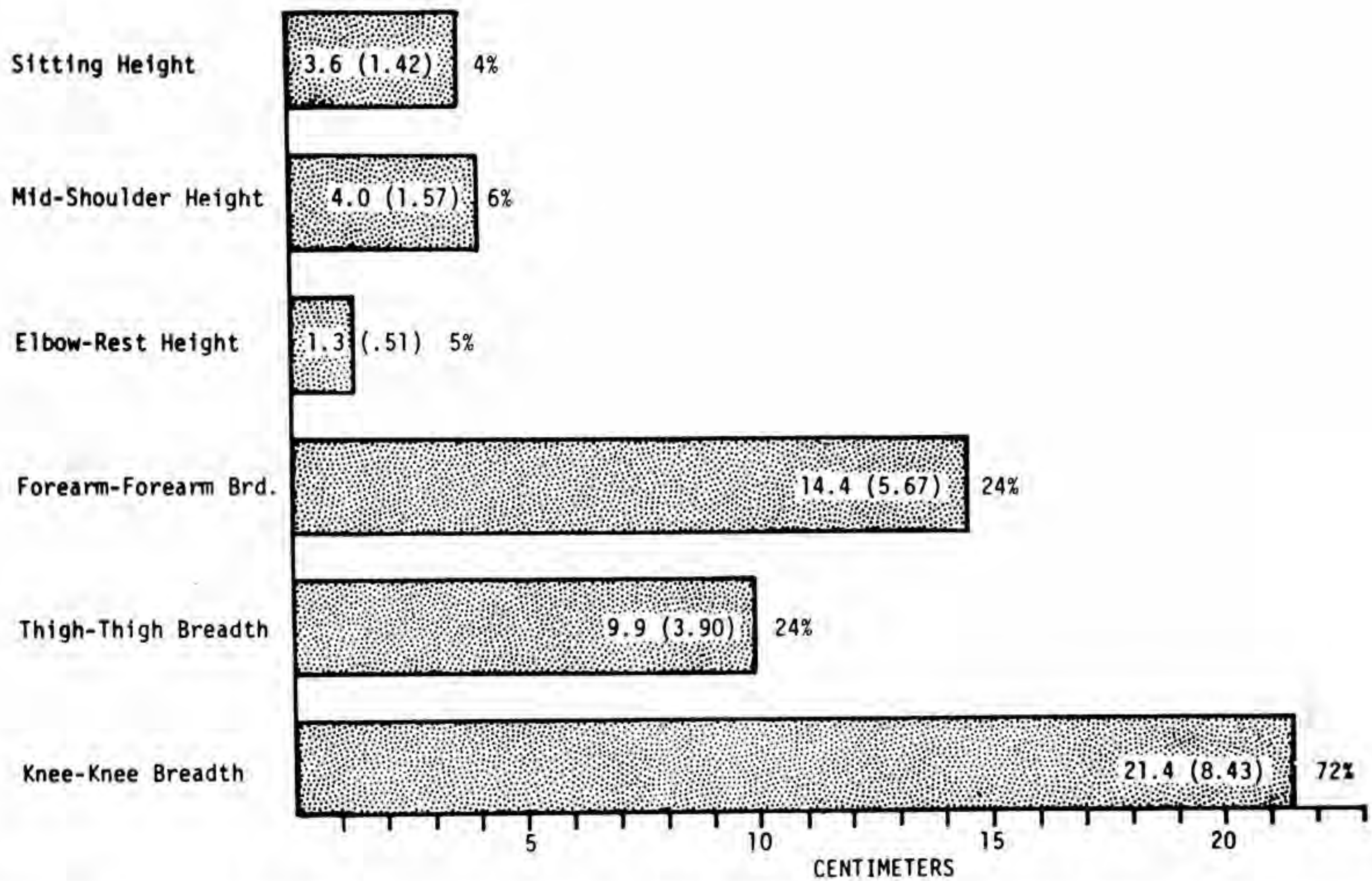
TABLE 10
INCREASE IN DIMENSIONS FROM PRESSURE SUIT
(BASED ON CLAUSER AND HERTZBERG 1964)*

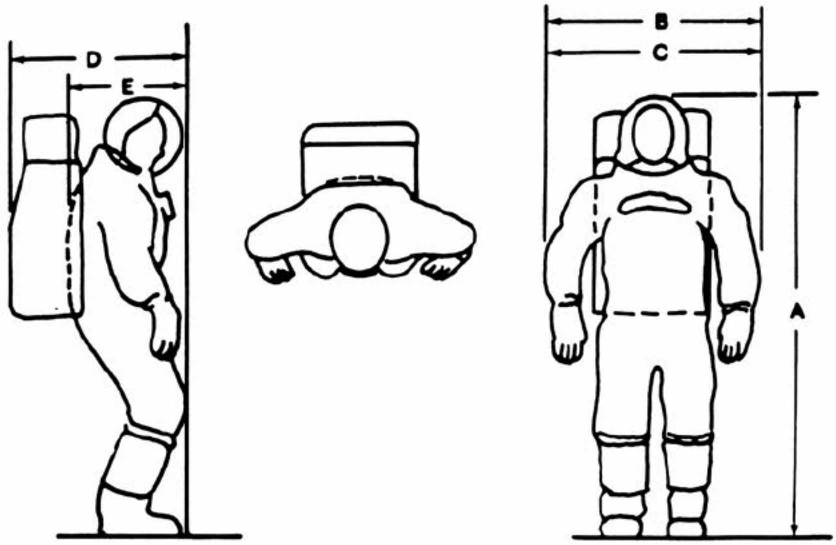
Measurement	Nude Median	Nude Range	Uninflated Median	Uninflated Range	Inflated Median	Inflated Range
Shoulder circumference	122.68 (48.3)	114.55-128.27 (45.1-50.5)	142.49 (56.1)	138.94-154.9 (54.7-61.0)	160.02 (63.0)	152.40-165.10 (60.0-65.0)
Chest circumference	100.58 (39.6)	95.76-107.19 (37.7-42.2)	122.68 (48.3)	121.92-132.08 (48.0-52.0)	133.35 (52.5)	128.27-137.67 (50.5-54.2)
Waist circumference	87.12 (34.3)	81.28-98.55 (32.0-38.8)	112.78 (44.4)	106.68-119.89 (42.0-47.2)	120.14 (47.3)	114.81-127.00 (45.2-50.0)
Upper thigh circumference	63.75 (25.1)	56.64-66.04 (22.3-26.0)	65.28 (25.7)	65.52-71.12 (25.8-28.0)	68.58 (27.0)	64.26-73.66 (25.3-29.0)
Lower thigh circumference	43.18 (17.0)	39.62-46.99 (15.6-18.5)	52.83 (20.8)	46.23-59.94 (18.2-23.6)	56.13 (22.1)	53.59-62.23 (21.1-24.5)
Calf circumference	37.85 (14.9)	36.83-43.18 (14.5-17.0)	42.93 (16.9)	41.15-49.28 (16.2-19.4)	46.48 (18.3)	42.93-50.55 (16.9-19.9)
Ankle circumference	23.37 (9.2)	22.61-26.67 (8.9-10.5)	30.73 (12.1)	28.96-34.54 (11.4-13.6)	30.73 (12.1)	30.48-35.05 (12.0-13.8)
Biceps circumference	34.29 (13.5)	32.26-36.83 (12.7-14.5)	37.59 (14.8)	35.56-41.40 (14.0-16.3)	41.15 (16.2)	37.85-43.18 (14.9-17.0)
Wrist circumference	17.78 (7.0)	16.76-18.29 (6.6-7.2)	20.57 (8.1)	20.07-21.34 (7.9-8.4)	22.86 (9.0)	21.08-23.37 (8.3-9.2)
Vertical trunk circumference	171.20 (67.4)	163.58-181.61 (64.4-71.5)	169.67 (66.8)	165.07-177.80 (65.0-70.0)		
Knee circumference	40.39 (15.9)	38.10-43.43 (15.0-17.1)	56.13 (22.1)	50.80-58.42 (20.0-23.0)	55.37 (21.8)	50.80-59.44 (20.0-23.4)
Vertical trunk circumference	163.07 (64.2)	161.80-171.45 (63.7-67.5)	168.9 (66.5)	165.10-176.78 (65.0-69.6)	170.94 (67.3)	167.64-178.82 (66.0-70.4)
Buttock circumference	106.68 (42.0)	99.31-115.57 (39.1-45.5)	118.62 (46.7)	115.06-129.54 (45.3-51.0)	126.75 (49.9)	120.14-129.54 (47.3-51.0)
Shoulder breadth	48.77 (19.2)	46.23-50.29 (18.2-19.8)	52.32 (20.6)	47.24-55.88 (18.6-22.0)	60.20 (23.7)	35.05-64.77 (13.8-25.5)
Chest breadth	33.02 (13.0)	27.69-32.77 (10.9-12.9)	35.05 (13.8)	32.26-38.35 (12.7-15.1)	37.34 (14.7)	36.58-39.62 (14.4-15.6)
Hip breadth	34.80 (13.7)	32.77-36.58 (12.9-14.4)	39.12 (15.4)	35.81-41.40 (14.1-16.3)	44.20 (17.4)	41.15-47.24 (16.2-18.6)
Hip depth	26.16 (10.3)	24.13-30.48 (9.5-12.0)	28.96 (11.4)	27.43-29.72 (10.8-11.7)	38.10 (15.0)	38.10 (15.0)
Chest depth	25.90 (10.2)	24.89-27.18 (9.8-10.7)	33.27 (13.1)	30.73-34.29 (12.1-13.5)	37.85 (14.9)	36.07-38.61 (14.2-15.2)
Elbow-elbow breadth	50.55 (19.9)	47.24-56.13 (18.6-22.1)	58.93 (23.2)	52.58-63.75 (20.7-25.1)	70.36 (27.7)	65.53-76.45 (25.8-30.1)
Knee-knee breadth	20.83 (8.2)	19.81-23.62 (7.8-9.3)	30.48 (12.0)	27.18-34.29 (10.7-13.5)	54.10 (21.3)	47.24-57.40 (18.6-22.6)
Sitting height	90.68 (35.7)	88.14-95.76 (34.7-37.7)	88.39 (34.8)	85.60-91.95 (33.7-36.2)	93.47 (36.8)	90.42-97.79 (35.6-38.5)
Eye height	79.25 (31.2)	75.18-83.82 (29.6-33.0)	77.22 (30.4)	72.14-80.52 (28.4-31.7)	79.50 (31.3)	74.68-81.79 (29.4-32.2)
Shoulder height	59.69 (23.5)	57.66-63.25 (22.7-24.9)	59.69 (23.5)	56.13-62.23 (22.1-24.5)	61.72 (24.3)	59.44-64.26 (23.4-25.3)
Knee height	55.63 (21.9)	54.10-57.91 (21.3-22.8)	59.18 (23.3)	57.40-60.71 (22.6-23.9)	60.96 (24.0)	58.17-62.48 (22.9-24.6)
Popliteal height	44.45 (17.5)	43.69-50.29 (17.2-19.8)	45.97 (18.1)	43.18-46.74 (17.0-18.4)	46.23 (18.2)	42.67-48.01 (16.8-18.9)
Elbow rest height	19.8 (7.8)	19.05-23.11 (7.5-9.1)	20.83 (8.2)	16.00-25.65 (6.3-10.1)	25.40 (10.0)	24.13-27.94 (9.5-11.0)
Shoulder elbow length	38.1 (15.0)	36.07-39.12) (14.2-15.4)	39.12 (15.4)	36.83-40.89 (14.5-16.1)	40.13 (15.8)	38.61-40.64 (15.2-16.0)
Forearm-hand length	48.77 (19.2)	46.99-50.80 (18.5-20.0)	49.28 (19.4)	48.01-51.56 (18.9-20.3)	50.55 (19.9)	47.24-52.58 (18.6-20.7)
Foot length	26.67 (10.5)	26.16-27.94 (10.3-11.0)	32.00 (12.6)	29.97-32.26 (11.8-12.7)	31.24 (12.3)	29.72-32.00 (11.7-12.6)
Hand length	19.56 (7.7)	19.05-21.59 (7.5-8.5)	19.05 (7.5)	18.29-19.56 (7.2-7.7)	18.03 (7.1)	17.27-19.05 (6.8-7.5)
Palm length	11.43 (4.5)	11.18-11.43 (4.4-4.5)	8.89 (3.5)	9.91-10.92 (3.9-4.3)	10.16 (4.0)	8.13-14.99 (3.2-5.9)
Crotch height (standing)	84.58 (33.3)	78.99-88.39 (31.1-34.8)	82.30 (32.4)	78.23-84.84 (30.8-33.4)		
Thigh clearance	16.51 (6.5)	13.97-18.03 (5.5-7.1)	16.26 (6.4)	15.49-17.78 (6.1-7.0)	20.57 (8.1)	19.30-20.83 (7.6-8.2)

*All measurements were taken on seated subject, except crotch height. These measurements were taken on six subjects wearing the MC-2 (X-15 type) full pressure suit. Data is given in centimeters with inches in parentheses.



*Increments computed from 95th percentile values. Data given in centimeters with inches in parentheses. Measurements were made on 34 subjects wearing A/P22S-2 pressure suits.

Figure 3. Incremental and percentage growth changes in body size due to the effects of inflated pressure suits (based on Alexander et al., 1969).*



DIMENSION	PERCENTILE MAN 5%	95%
A - Height	171.45 (67.5)	191.77 (75.5)
B - Maximum breadth at elbows (arms relaxed)	--- --	74.68 (29.4)
C - Maximum breadth at elbows (arms at side)	--- --	67.06 (26.4)
D** - Maximum depth with portable life support system (PLSS) and backup oxygen (OPS)	66.04 (26.0)	72.14 (28.4)
E** - Maximum depth without PLSS/OPS	39.37 (15.5)	45.47 (17.9)
Weight (lb), with PLSS/OPS	143.31 (316.0)	174.73 (385.3)
Weight (lb), without PLSS/OPS	86.30 (190.3)	117.73 (259.6)

* Measurements made on A7L pressure garment assembly, pressurized to 3.75 psig. Data given in centimeters and kilograms with inches and pounds in parentheses.

** To obtain envelope dimensions, 2 inches have been added to maximum chest depth of suited/pressurized crewman for PLSS control box.

Figure 4. Functional envelope dimensions of the fully suited astronaut based on NASA Habitability Data Handbook (1971).*

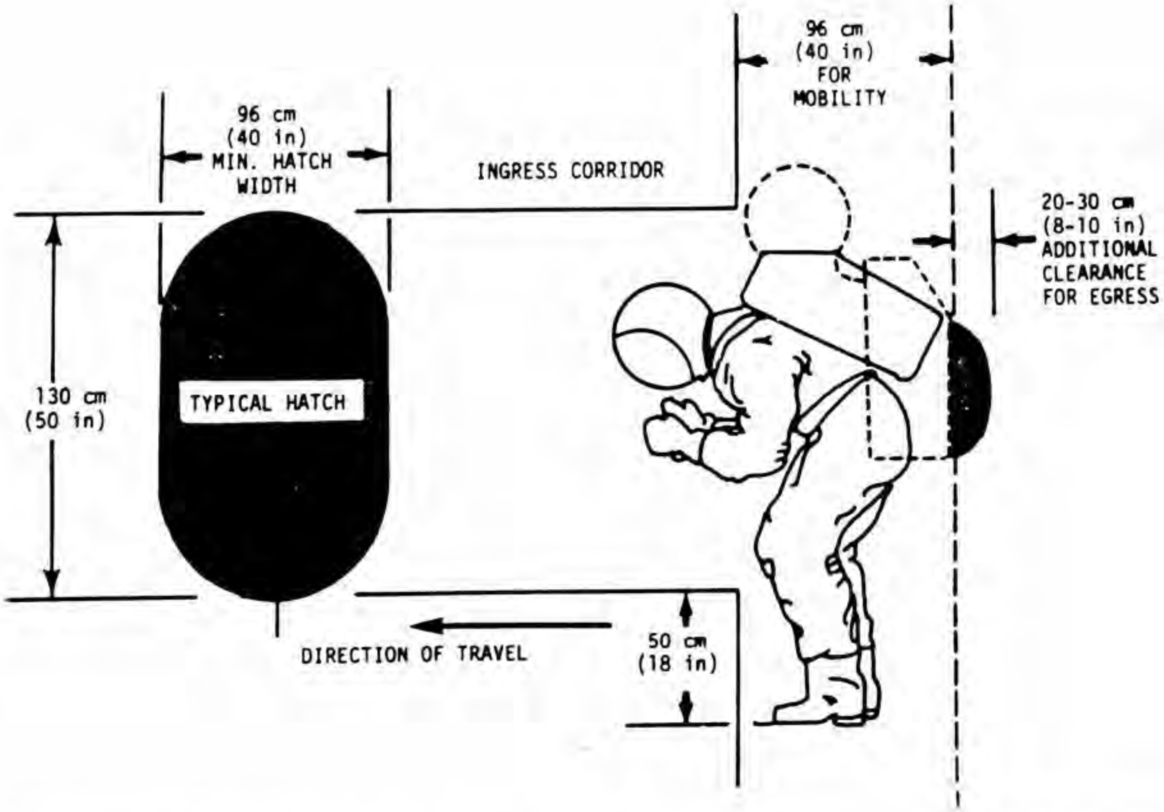


Figure 5. Recommended access corridor dimensions to accommodate fully suited astronaut (data obtained from NASA Internal Note MSC-EC-R-71-10, 1971).

It should be stressed, before leaving this subject, that body size changes caused by the addition of protective clothing, are suit-specific. Each suit or assemblage will result in somewhat different growth increments; the important point is that such growth is often significant and must be accommodated in the workspace design.

Effects of Zero-g on Body Size

Many features of man's form and structure resulted from having evolved in the earth's gravitational force (one-g). Our physiological functions are one-g adapted as are anatomical features related to our ability to maintain an erect posture. It is not surprising that when the force of gravity is removed for a period of time, changes in body size, shape, function and composition may occur since it is in opposing gravity that certain body features remain stable. Physicians since Hippocrates have known that immobility and disuse of the body (reduced dynamic opposition to gravity) result in tissue atrophy. Prolonged bedrest, a form of hypodynamism, also brings on a variety of deconditioning processes including muscular atrophy.

Not until space flight, however, were hypodynamic and hypogravic effects on body size of direct concern to the design engineer. Early concerns of medical specialists over the underlying pathology of body changes and the possibility of their progressive nature have largely been dispelled by the longer missions. The significance of zero-g body size changes for the design engineer is that many types of changes observed represent a class of intra-individual change not previously encountered. A pressure suit custom fitted at one-g may not be easily donned or comfortable for an astronaut "adjusted" to weightlessness. Work space carefully laid out and sized for "earthmen" may not be functional in space.

A discussion of the major anthropometric changes observed in astronauts during space flight can be found in Chapter I.

Inter-individual Variations in Size

Male-Female Size Differences

One of the primary sources of variability in size between individuals is the difference between the sexes, a matter of considerable importance to designers today since women are becoming more frequent participants in all forms of activity. Areas of design which a few years ago would not have required consideration of female size and strength no longer exist.

One need hardly point out that, in general, women tend to be smaller than men. In addition, the sexual tendency for females to deposit subcutaneous fat makes women more rounded. In attempting to assess quantitatively the size differences between men and women, care must be exercised in selection of data for comparison. Because of similarities in technique and proximity in time of completion of the studies, the best available data for comparison probably are from the 1967 male U.S. Air Force (AMRL unpublished) and the 1968 female Air Force (Clauser et al. 1972) surveys. The 5th and 95th percentile values for selected body dimensions are compared in Table 11 which shows that the male fliers are heavier and generally larger, as might be expected.

It has been an accepted rule of thumb that female measurements tend to average about 92% of comparable male values. The ratios shown in Table 12 indicate that for most linear measurements, the rule holds reasonably well for the general U.S. populations. A major exception is weight, a non-linear measurement. The table shows that women's weight is about three-quarters that of the men. To properly equate weight, an essentially three-dimensional quantity, with the linear measures, the cube roots of the weights should be computed. When this is done, the female to male ratio becomes 91.3%, a value clearly consistent with the 92% rule of thumb.

If male-female differences in the mean values for most body dimensions average only about 8%, what is their significance for designers? The answer to this question may be approached in several ways. One method is to examine the range of size differences, especially for dimensions commonly used in design, between a small female (5th percentile) and a large male (95th percentile). This is far from a merely academic exercise since persons representative of each extreme (in one or more dimensions) may be required to use or operate the same item or function in the same work space.

Examining again the data from the USAF surveys as shown in Table 11, it can be seen that the ratio of the 5th percentile females to the 95th percentile males for most dimensions is considerably lower (i.e., about 72%) than the ratio of the mean values. To illustrate the range of size difference, selected dimensions are graphed in Figure 6 to show not only the range of differences, but also the overlap of the 5th and 95th percentiles of each group. (The extreme range of differences, 40 cm. (16 in.) in waist circumference may be partially attributed to the age difference between the two groups. The women averaged 23.4 years and the men averaged 30 years of age.)

A second method that may be used to demonstrate the significance of sexual differences is through the use of bivariate distributions. When the distribution of the various height-weight combinations is plotted for the Air Force populations, two partially overlapping ellipses may be drawn which each encompass about 95% of their respective samples. Examination of Figure 7 will show that while there is considerable overlap, the two groups are nevertheless quite distinct in these two variables. Because of the well-known relationship of many other body dimensions to height and weight, it is apparent that the sexes are quite different in other aspects of body size as well.

TABLE 11
COMPARISON OF MALES AND FEMALES FOR SELECTED DIMENSIONS
5TH AND 95TH PERCENTILE VALUES*
(FROM 1967 USAF SURVEY UNPUBLISHED AND CLAUSER ET AL. 1972)

Variable	Males 5th%	Males 95th%	Females 5th%	Females 95th%	Ratio**
Weight	63.6 (140.2)	95.6 (210.8)	46.4 (102.3)	70.9 (156.3)	.49
Stature	167.2 (65.8)	187.7 (73.9)	152.4 (60.0)	172.1 (67.8)	.81
Sitting height	88.1 (34.7)	98.6 (38.8)	80.4 (31.7)	90.9 (35.8)	.82
Acromial height	135.7 (53.4)	154.8 (60.9)	123.0 (48.4)	141.1 (55.6)	.79
Waist height	98.7 (38.9)	114.3 (45.0)	93.1 (36.7)	107.9 (42.5)	.81
Crotch height	78.3 (30.8)	92.0 (36.2)	68.1 (26.8)	81.4 (32.0)	.74
Popliteal height	40.1 (15.8)	47.5 (18.7)	38.0 (15.0)	44.1 (17.4)	.80
Thigh clearance height	14.3 (5.6)	18.8 (7.4)	10.4 (4.1)	14.6 (5.7)	.55
Buttock-knee length	56.1 (22.1)	65.0 (25.6)	53.2 (20.9)	61.9 (24.4)	.82
Sleeve length	85.2 (33.5)	96.8 (38.1)	74.2 (29.2)	85.1 (33.5)	.77
Sleeve inseam	44.4 (17.5)	52.8 (20.8)	40.2 (15.8)	48.2 (19.0)	.76
Hand length	17.8 (7.0)	20.5 (8.1)	16.9 (6.7)	20.1 (7.9)	.82
Foot length	25.1 (9.9)	29.0 (11.4)	22.2 (8.7)	26.0 (10.2)	.77
Biacromial breadth	37.5 (14.8)	43.8 (17.2)	33.2 (13.1)	38.6 (15.2)	.76
Chest circ. (scye)	92.5 (36.4)	112.4 (44.3)	77.0 (30.3)	93.2 (36.7)	.69
Waist circ.	75.7 (29.8)	100.1 (39.4)	59.5 (23.4)	77.2 (30.4)	.59
Buttock circ. (sitting)	97.1 (38.2)	119.3 (47.0)	90.8 (35.7)	110.8 (43.6)	.76
Thigh circ.	51.5 (20.3)	66.2 (26.1)	48.7 (19.2)	62.6 (24.6)	.74
Calf circ.	33.3 (13.1)	40.6 (16.0)	30.6 (12.0)	38.1 (15.0)	.75
Hand circ.	20.0 (7.9)	23.1 (9.1)	16.8 (6.6)	19.8 (7.8)	.73
Head circ.	55.2 (21.7)	59.9 (23.6)	52.3 (20.6)	57.6 (22.7)	.87
Biceps circ. (flexed)	28.5 (11.2)	35.9 (14.1)	23.0 (9.1)	30.7 (12.1)	.64

*Data given in kilograms and centimeters with pounds and inches in parentheses.
**5th% Female/95th Male.

TABLE 12
SELECTED DIMENSIONS OF MALES AND FEMALES IN THE U.S. POPULATION
(BASED ON STOUDT ET AL. 1965)*

Variable	Males (25.5-34.5 years) Mean	Males S.D.	Females (18.5-24.5 years) Mean	Females S.D.	Ratio**
Arm circumference (biceps)	31.14 (12.26)	3.20 1.26	26.10 (10.28)	3.40 (1.34)	.84
Biacromial diameter	40.1 (15.79)	2.10 (.83)	35.50 (13.98)	1.90 (.75)	.89
Buttock-knee length	59.79 (23.54)	2.95 (1.16)	56.67 (22.31)	3.18 (1.25)	.95
Buttock-popliteal length	49.81 (19.61)	3.18 (1.25)	47.80 (18.82)	3.15 (1.24)	.96
Chest circumference	99.2 (39.06)	8.30 (3.27)	83.7 (32.95)	6.20 (2.44)	.84
Elbow-elbow breadth	41.55 (16.36)	4.52 (1.78)	33.66 (13.25)	4.11 (1.62)	.81
Elbow rest height	24.64 (9.70)	2.77 (1.09)	22.76 (8.96)	2.69 (1.06)	.92
Knee height	54.84 (21.59)	2.82 (1.11)	50.09 (19.72)	2.59 (1.02)	.90
Popliteal height	45.34 (17.85)	2.69 (1.06)	40.59 (15.98)	2.46 (.97)	.90
Seat breadth	35.46 (13.96)	2.87 (1.13)	35.10 (13.82)	3.28 (1.29)	.99
Sitting ht. (erect)	91.44 (36.0)	3.45 (1.36)	85.29 (33.58)	3.20 (1.26)	.92
Sitting ht. (relaxed)	87.12 (34.30)	3.58 (1.41)	82.37 (32.43)	3.45 (1.36)	.95
Stature	175.3 (69.02)	7.00 (2.76)	162.0 (63.78)	6.20 (2.44)	.93
Thigh clearance height	14.71 (5.79)	1.78 (.70)	13.46 (5.30)	1.68 (.66)	.92
Waist circumference	86.69 (34.13)	10.69 (4.21)	69.55 (27.38)	9.35 (3.68)	.80
Weight	77.4 (170.45)	13.10 (28.95)	58.9 (129.8)	11.00 (24.33)	.76

*Data given in centimeters and kilograms (for weight) with inches and pounds in parentheses.

**Female $\bar{X}$/Male $\bar{X}$.

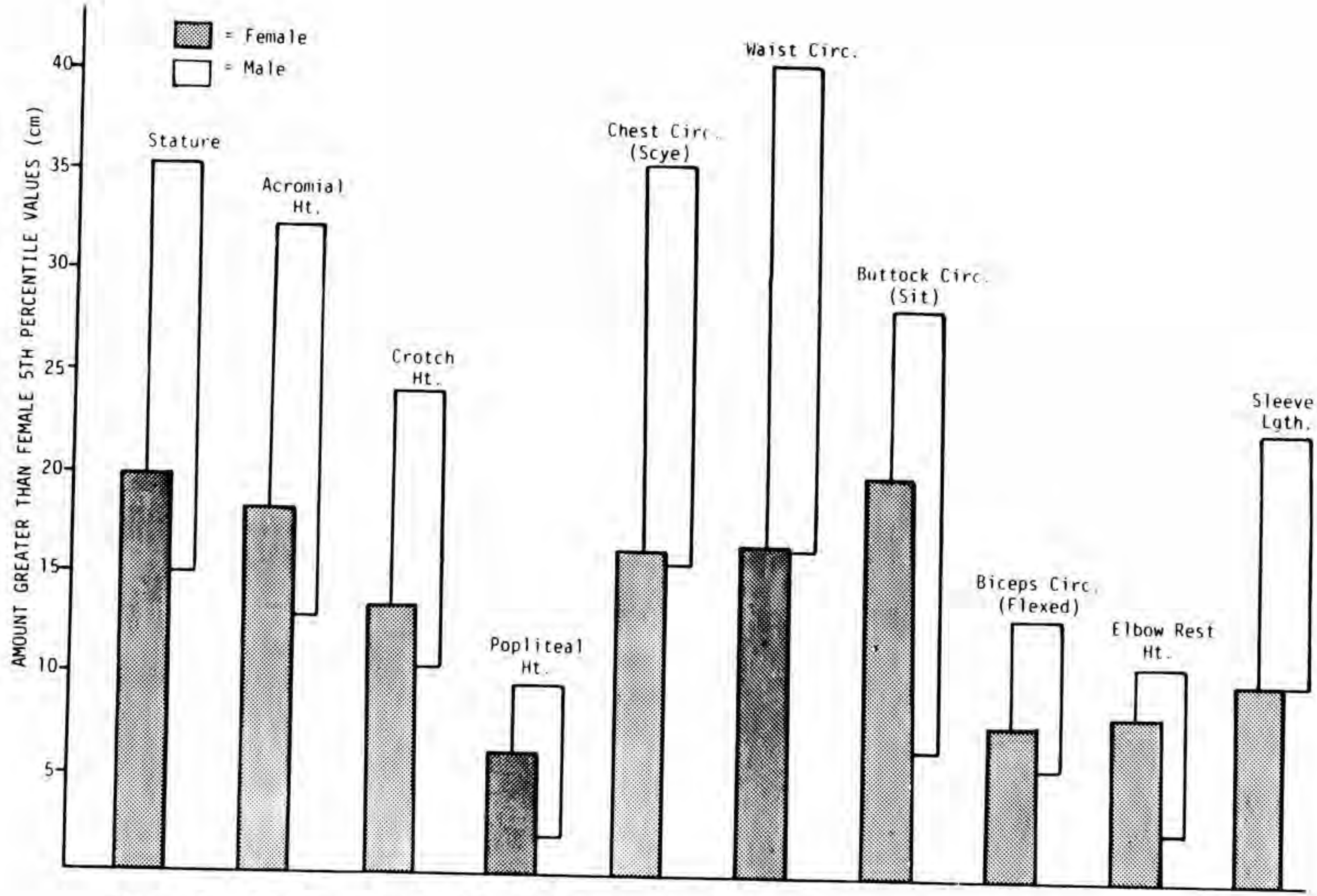
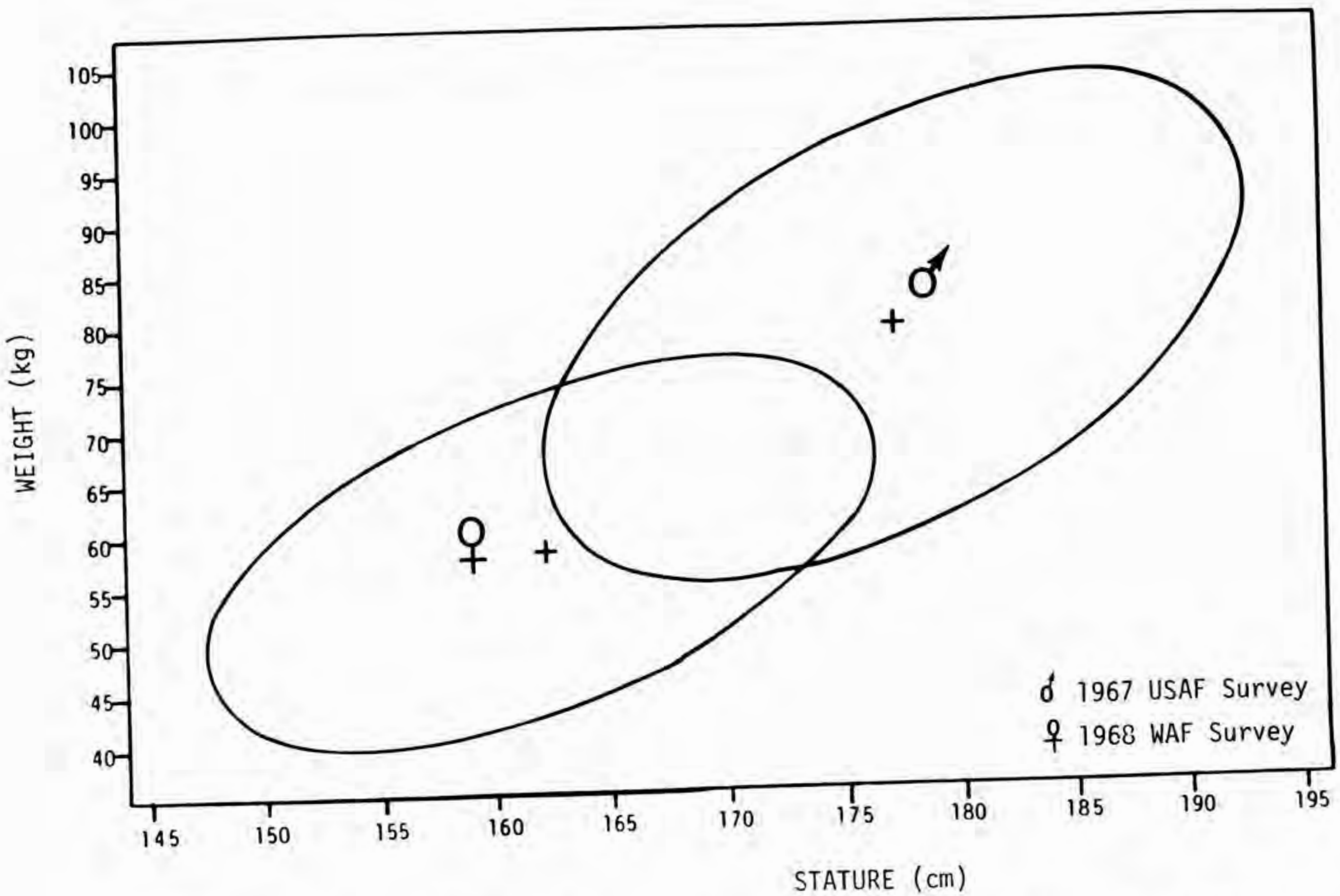


Figure 6. A comparison of 5th-95th percentile male and female values for selected dimensions showing the range of differences and overlap between the two groups.



* Approximately 95% of each group is contained within the appropriate ellipse.

Figure 7. Distributions of stature and weight for U.S. Air Force personnel - male and female.

Since the standard deviations of body size values, male or female, average about 5% of the mean, a difference of 8% would mean, in general, that the body size of females lying approximately one standard deviation above the female mean value would tend to match the body size of males lying approximately one standard deviation below the male mean value. From a design viewpoint this indicates that system or equipment specifications based on the anthropometry of male fliers, for example, would have to be modified if they are to accommodate the body size differences of female users.

Racial/Ethnic Variation in Body Size

To enter upon a lengthy discussion about the definition of "race" or "ethnic" is outside the purpose of this data book. The term "race" as used here will be equivalent to the subspecies usage although the conventional taxonomic names of Negro, Caucasian and Mongolian for the three major racial classes have been replaced by the more generalized terms, Black, White and Oriental respectively. We have included size data for selected examples of White, Black and Oriental populations. Only American Blacks have been considered. Whether they, as a population distinct from African Blacks, have formed or are forming a new race, has not been considered. "Ethnic" will refer chiefly to national origin of a subject or population.

Body size variability related to ethnic/racial groups is of considerable interest to Americans because of the broad spectrum of national origins that characterizes the American population. Some information on the ethnic and racial makeup of the U.S. population, as obtained from the 1970 census, is shown in Table 13 below.

TABLE 13
RACIAL/ETHNIC ORIGINS OF U.S. POPULATION*
(FROM CENSUS BUREAU DATA, APRIL 1970)

Group	Number in Thousands	Percent	
White	177,784	87.5	
Spanish Speaking	10,115		4.9
Black	22,580	11.1	
Other	2,883	1.4	
Indian	793		0.4
Japanese	591		0.3
Chinese	435		0.2
Filipino	343		0.2
Other	720		0.4

Racial/ethnic comparisons can be made by using the 1966 U.S. Army anthropometric survey data (White and Churchill). In this survey the subjects were asked to designate their ethnic derivation or national extraction. There were three categories in which national extraction was not otherwise specified: American White (29.3%); American Black (14.7%); and American Indian (1.8%). These categories represent approximately 45% of the total sample. The remainder of the sample was self-classified into 37 national origins. It is of some interest to compare these groups in terms of gross body size. Using only the dimensions of height and weight, such a comparison is given in Table 14. The table lists the mean and standard deviation for the total sample and shows the deviation of each group from these values. The sample sizes of some of the subsets are rather small, but they are adequate to indicate the diversity that exists in the various racial/ethnic components of the military population. These height-weight differences, while often quite large, still do not tell the complete story of body size differences.

Young adult males and females of the three principal races may be compared more broadly by examining the data presented in Tables 15 and 16 and Figures 8 and 9. The U.S. Air Force basic trainee survey of 1965 (Long and Churchill, 1968) and the Japanese Air Force survey of 1972 (Yokohori) are the sources of the male data. The female data are selected from measurements obtained from the 1968 survey of U.S. Air Force women (Clauser et al. 1972) and the Japanese civilian surveys of 1967-68 and 1972-73 (Yanagisawa 1974). In both cases the Black and White data are from the respective U.S. Air Force surveys. The mean values and standard deviations for selected measurements for the men and women are presented in Tables 15 and 16. Selected dimensions are plotted in Figures 8 and 9 in overlapping bar graphs to demonstrate the range of variation of the males and females of the three racial groups.

The 343 Black and White males that formed the comparative sample were selected from the total Air Force survey population (N=3,869) and matched on the basis of age, length of military service and region of birth; the females represent the total sample. Height and weight values for both racial groups are very similar Despite this, there are significant differences in the mean values for about three quarters of the measurements. The Blacks have legs, arms, hands and feet which, on the average, are longer than those of Whites; the reverse is true for measurements of the torso. The Blacks tend to have longer heads, wider faces, and less body fat.

The Oriental samples cannot be so rigorously compared to the others as the Blacks and Whites can be to each other, since the Japanese survey was performed seven years later. The measurement techniques used in each survey are thought to have been comparable, however. As might be expected, the data show that the Orientals are on the average somewhat smaller. Despite the fact that for these samples the Japanese average nearly 10 cm (3.9 in.) shorter in stature, the sitting heights of all three groups are nearly the same. The limb lengths, especially the legs, apparently account for the vast proportion of the longitudinal difference in size. (See Figure 1) The majority of the circumferences do not appear to be significantly different. The Whites tend to be the most variable of the three groups.

TABLE 14

HEIGHT AND WEIGHT OF U.S. MILITARY MALES WITH DEVIATIONS OF THE RACIAL/ETHNIC SUBGROUPS FROM THE TOTAL SAMPLE MEAN AND STANDARD DEVIATION (FROM U.S. ARMY SURVEY, 1966)*

Ethnic Group **	No.	Height X		SD		Weight X		SD	
Total Sample	6682	174.52	(68.71)	6.61	(2.60)	72.15	(159.09)	10.59	(23.35)
American White	1960	.58	(.23)	- .20	(- .08)	- .36	(- .80)	- .11	(- .24)
American Black	982	.02	(.01)	.04	(.02)	1.06	(2.34)	.28	(.62)
American Indian	120	- .08	(- .03)	0.00	0	- .89	(-1.97)	- .63	(-1.38)
Mexican	113	-4.05	(-1.59)	- .32	(-.13)	-1.28	(-2.82)	-1.31	(-2.89)
Puerto Rican	125	-6.09	(-2.40)	- .18	(-.07)	-5.95	(-13.11)	-1.28	(-2.82)
Spanish	74	-3.48	(-1.37)	- .02	(.01)	-3.55	(-7.83)	- .64	(-1.42
Filipino	13	-7.02	(-2.76)	1.40	(.55)	-3.84	(-8.47)	.47	(1.04)
Hawaiian	10	-1.25	(- .49)	- .40	(-.16)	4.69	(10.35)	1.90	(4.18)
Japanese	26	-5.75	(-2.26)	- .55	(-.22)	4.36	(-9.61)	-1.43	(-3.15)
English	558	.61	(.24)	- .20	(-.08)	.53	(1.17)	.16	(.35)
Irish	864	.68	(.27)	- .44	(-.17)	.18	(.39)	- .19	(- .41)
Scottish	169	.94	(.37)	- .18	(-.07)	1.51	(3.32)	.67	(1.48)
Welsh	21	.96	(.38)	- .42	(-.17)	- .84	(-1.85)	.44	(.96)
French	273	-.82	(- .32)	- .42	(-.17)	-1.48	(-3.26)	.70	(1.54)
German	1080	.68	(.27)	- .19	(-.07)	1.11	(2.44)	.40	(.88)
Austrian	14	-.91	(- .3)	- .37	(-.15)	-2.15	(-4.73)	.92	(2.02)
Polish	218	.43	(.17)	- .27	(-.11)	.84	(1.86)	- .31	(-.69)
Swedish	134	1.61	(.63)	- .18	(-.07)	1.25	(2.75)	- .14	(-.31)
Dutch	147	-.28	(- .11)	- .38	(-.15)	-1.21	(-2.66)	-1.04	(-2.29)
Italian	319	-2.04	(- .80)	- .47	(-.19)	- .15	(- .32)	- .82	(-1.80)

*Data given in centimeters and kilograms with inches and pounds in parentheses.

**Subgroup classification self-assigned.

TABLE 15

MEANS AND STANDARD DEVIATIONS OF SELECTED DIMENSIONS FOR YOUNG MILITARY MALES OF THREE RACIAL GROUPS
(BASED ON LONG AND CHURCHILL, 1968, AND YOKOHORI, 1972)*

Variable	Black (U.S.) Mean		S.D.		White (U.S.) Mean		S.D.		Oriental (Japan) Mean		S.D.	
Weight	68.39	(150.8)	9.16	(20.2)	68.07	(150.1)	10.84	(23.9)	60.59	(133.6)	6.49	(14.3)
Stature	175.1	(68.94)	6.6	(2.6)	175.2	(68.98)	6.9	(2.7)	165.9	(65.31)	5.31	(2.1)
Sitting height	88.2	(34.72)	3.1	(1.2)	91.6	(36.06)	3.6	(1.4)	90.4	(35.59)	2.8	(1.1)
Sitting eye height	77.1	(30.35)	3.0	(1.2)	80.3	(31.61)	3.3	(1.3)	78.6	(30.94)	2.8	(1.1)
Cervicale	149.8	(58.98)	6.3	(2.5)	149.6	(58.90)	6.5	(2.6)	140.3	(55.24)	4.9	(1.9)
Crotch height	86.1	(33.90)	4.7	(1.9)	83.0	(32.68)	4.4	(1.7)	73.9	(29.09)	3.7	(1.5)
Elbow rest height	20.5	(8.07)	2.4	(.9)	24.0	(9.45)	2.5	(1.0)	26.0	(10.24)	2.1	(.8)
Thigh clearance height	15.2	(5.98	1.3	(.5)	14.9	(5.87)	1.4	(.6)	13.5	(5.31)	1.3	(.5)
Buttock-knee length	62.0	(24.41)	3.0	(1.2)	60.0	(23.62)	3.0	(1.2)	55.3	(21.77)	2.6	(1.0)
Shoulder-elbow length	36.9	(14.53)	1.8	(.7)	36.3	(14.29)	1.8	(.7)	33.1	(13.03)	1.9	(.7)
Elbow-wrist length	30.0	(11.81)	1.5	(.6)	28.6	(11.26)	1.4	(.6)	-	-	-	-
Hand length	20.3	(7.99)	1.0	(.4)	19.5	(7.68)	1.0	(.4)	18.2	(7.17)	-	-
Functional reach	81.2	(31.97)	4.4	(1.7)	78.6	(30.94)	4.0	(1.6)	-	-	-	-
Foot length	27.6	(10.87)	1.3	(.5)	26.6	(10.47)	1.3	(.5)	24.7	(9.72)	1.0	(.4)
Chest circumference	90.1	(35.47)	5.7	(2.2)	91.6	(36.06)	6.7	(2.6)	88.6	(34.88)	4.5	(1.8)
Waist circumference	74.9	(29.49)	6.0	(2.4)	78.0	(30.71)	7.8	(3.1)	75.0	(29.53)	5.4	(2.1)
Buttock circumference	90.6	(35.67)	5.8	(2.3)	92.1	(36.26)	6.4	(2.5)	89.1	(35.08)	3.9	(1.5)
Thigh circumference	54.3	(21.38)	4.9	(1.9)	53.8	(21.18)	5.3	(2.1)	52.6	(20.71)	3.4	(1.3)
Calf circumference	35.9	(14.13)	2.6	(1.0)	36.0	(14.17)	2.7	(1.1)	35.5	(13.98)	2.1	(.8)
Scye	41.9	(16.50)	2.2	(.9)	41.7	(16.42)	2.5	(1.0)	41.4	(16.30)	2.3	(.9)
Biceps circumference	30.7	(12.09)	2.6	(1.0)	30.0	(11.81)	2.7	(1.1)	29.8	(11.73)	2.0	(.8
Forearm circumference	26.9	(10.59)	1.4	(.6)	26.3	(10.35)	1.6	(.6)	26.9	(10.59)	1.3	(.5)
Hand circumference	21.7	(8.54)	1.0	(.4)	21.3	(8.39)	1.0	(.4)	20.2	(7.95)	0.9	(.4)
Vert. trunk circumfer.	157.4	(61.97)	6.7	(2.6)	161.6	(63.62)	7.8	(3.1)	156.1	(61.46)	5.9	(2.3)
Sleeve inseam	51.2	(20.16)	2.6	(1.0)	49.4	(19.45)	2.5	(1.0)	-	-	-	-
Ankle circumference	22.5	(8.86)	1.4	(.6)	22.7	(8.94)	1.5	(.6)	21.4	(8.43)	1.1	(.4)
Head length	19.8	(7.80)	0.7	(.3)	19.5	(7.68)	0.7	(.3)	18.8	(7.40)	0.7	(.3)
Head breadth	15.1	(5.94)	0.5	(.2)	15.1	(5.94)	0.6	(.2)	15.8	(6.22)	0.6	(.2)
Vertex-menton height	23.2	(9.13)	1.0	(.4)	22.7	(8.94)	0.9	(.4)	23.4	(9.21)	1.1	(.4)
Bizygomatic breadth	13.6	(5.35)	0.6	(.2)	13.6	(5.35)	0.6	(.2)	12.8	(5.04)	0.9	(.4)
Head circumference	56.2	(22.13)	1.6	(.6)	55.8	(21.97)	1.6	(.6)	56.3	(22.17)	1.4	(.6)
Knee height sitting	56.6	(22.28)	2.6	(1.0)	55.1	(21.69)	2.7	(1.1)	49.4	(19.45)	2.1	(1.0)

*Data given in centimeters and kilograms with inches and pounds in parentheses.

TABLE 16
MEANS AND STANDARD DEVIATIONS OF SELECTED DIMENSIONS FOR YOUNG FEMALES OF THREE RACIAL GROUPS
(BASED ON CLAUSER ET AL. 1972)*

	Black (U.S.)		White (U.S.)		Oriental(Japan)	
Variable	Mean	S.D.	Mean	S.D.	Mean	S.D.
Age	20.9	3.9	20.3	3.6	25-39	(range)
Weight	56.4 (124.3)	7.1 (15.7)	57.1 (125.9)	7.0 (15.4)	51.3 (113.1)	7.0 (15.4)
Stature	161.3 (63.5)	5.8 (2.3)	161.9 (63.7)	5.9 (2.3)	153.2 (60.3)	4.8 (1.9)
Cervicale height	139.2 (54.8)	5.4 (2.1)	139.0 (54.7)	5.4 (2.1)		
Acromial height	131.7 (51.9)	5.4 (2.1)	131.7 (51.9)	5.4 (2.1)		
Sitting height	81.3 (32.0)	3.1 (1.2)	84.3 (33.2)	3.1 (1.2)		
Waist height	101.1 (39.8)	4.8 (1.9)	100.0 (39.4)	4.4 (1.7)	93.2 (36.7)	3.7 (1.5)
Crotch height	76.9 (30.3)	4.1 (1.6)	74.3 (29.3)	3.9 (1.5)	68.3 (26.9)	3.3 (1.3)
Tibiale height	42.8 (16.9)	2.4 (0.9)	41.9 (16.5)	2.3 (0.9)	38.6 (15.2)	1.8 (0.7)
Foot length	24.8 (9.8)	1.1 (0.4)	24.0 (9.4)	1.1 (0.4)	22.6 (8.9)	0.9 (0.4)
Hand length	19.2 (7.6)	0.9 (0.4)	18.3 (7.2)	0.9 (0.4)		
Head length	18.7 (7.4)	0.7 (0.3)	18.3 (7.2)	0.7 (0.3)		
Sleeve length	80.5 (31.7)	3.5 (1.4)	79.3 (31.2)	3.2 (1.3)	68.7 (27.0)	2.5 (1.0)
Head breadth	14.4 (5.7)	0.6 (0.2)	14.5 (5.7)	0.6 (0.2)		
Head circumference	55.8 (22.0)	1.5 (0.6)	54.6 (21.5)	1.6 (0.6)	54.5 (21.5)	1.4 (0.6)
Bust circumference	87.2 (34.3)	4.4 (1.7)	89.2 (35.1)	5.2 (2.0)	83.6 (32.9)	6.4 (2.5)
Waist circumference	66.4 (26.1)	4.7 (1.9)	66.9 (26.3)	5.0 (2.0)	67.1 (26.4)	6.3 (2.5)
Hip circumference	93.0 (36.6)	6.2 (2.4)	94.8 (37.3)	5.7 (2.2)	90.0 (35.4)	5.2 (2.0)
Thigh circumference	54.6 (21.5)	4.3 (1.7)	55.2 (21.7)	4.0 (1.6)	51.5 (20.3)	3.8 (1.5)
Knee circumference	36.1 (14.2)	2.3 (0.9)	36.2 (14.3)	2.1 (0.8)	33.5 (13.2)	2.2 (0.9)
Calf circumference	33.5 (13.2)	2.5 (1.0)	34.2 (13.5)	2.2 (0.9)	33.3 (13.1)	2.3 (0.9)
Ankle circumference	20.8 (8.2)	1.4 (0.6)	21.2 (8.3)	1.3 (0.5)		
Biceps circumference (relaxed)	25.0 (9.8)	2.2 (0.9)	25.4 (10.0)	2.1 (0.8)	26.7 (10.5)	2.5 (1.0)
Wrist circumference	15.0 (5.9)	0.8 (0.3)	15.0 (5.9)	0.7 (0.3)		
Vert trunk circumference	149.8 (59.0)	5.9 (2.3)	154.0 (60.6)	6.5 (2.6)	147.7 (58.1)	5.9 (2.3)

*Data given in kilograms and centimeters with pounds and inches in parentheses; age in years.

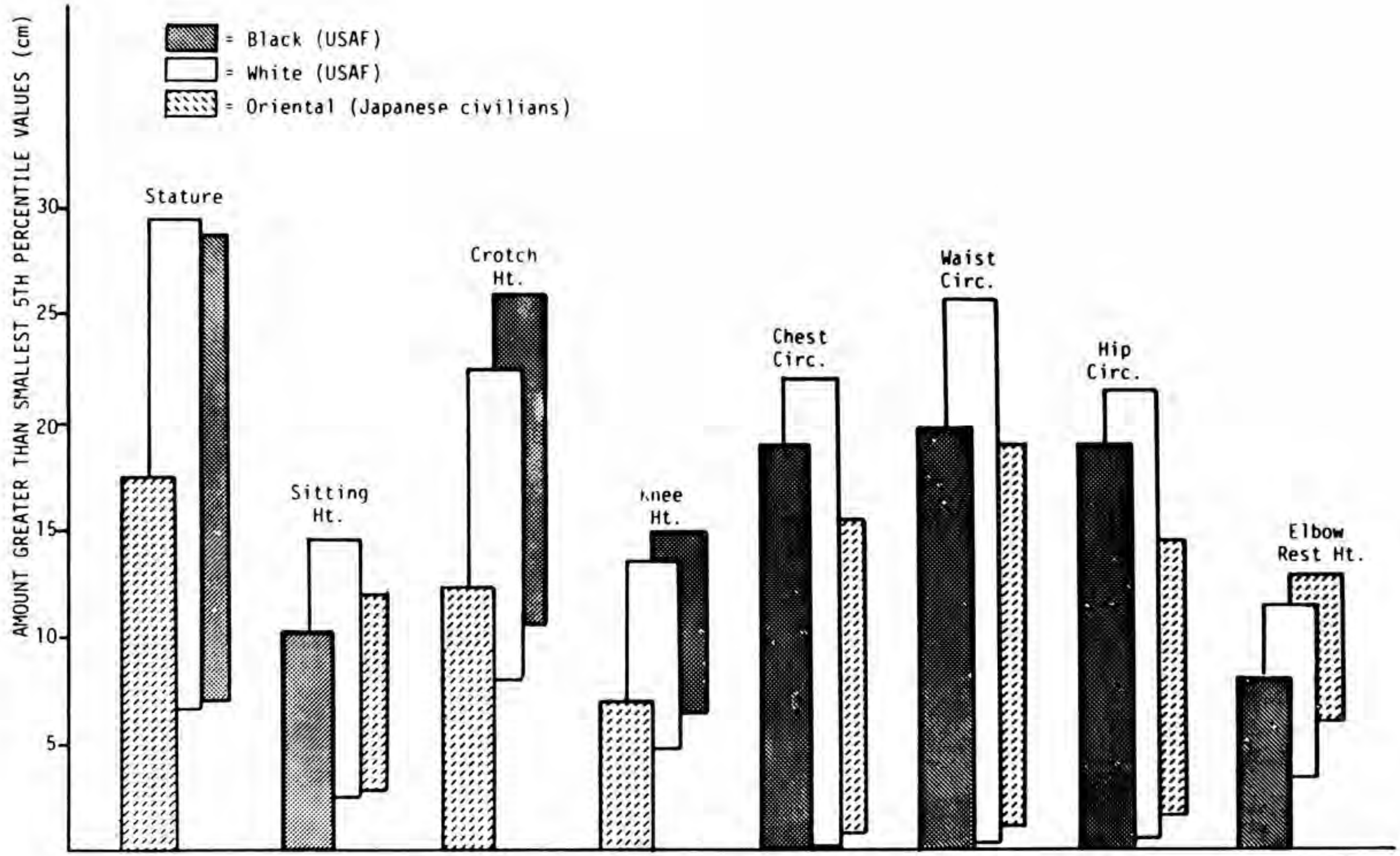


Figure 8. Range of variation between males of three racial groups for selected body dimensions (smallest 5th to largest 95th percentile).

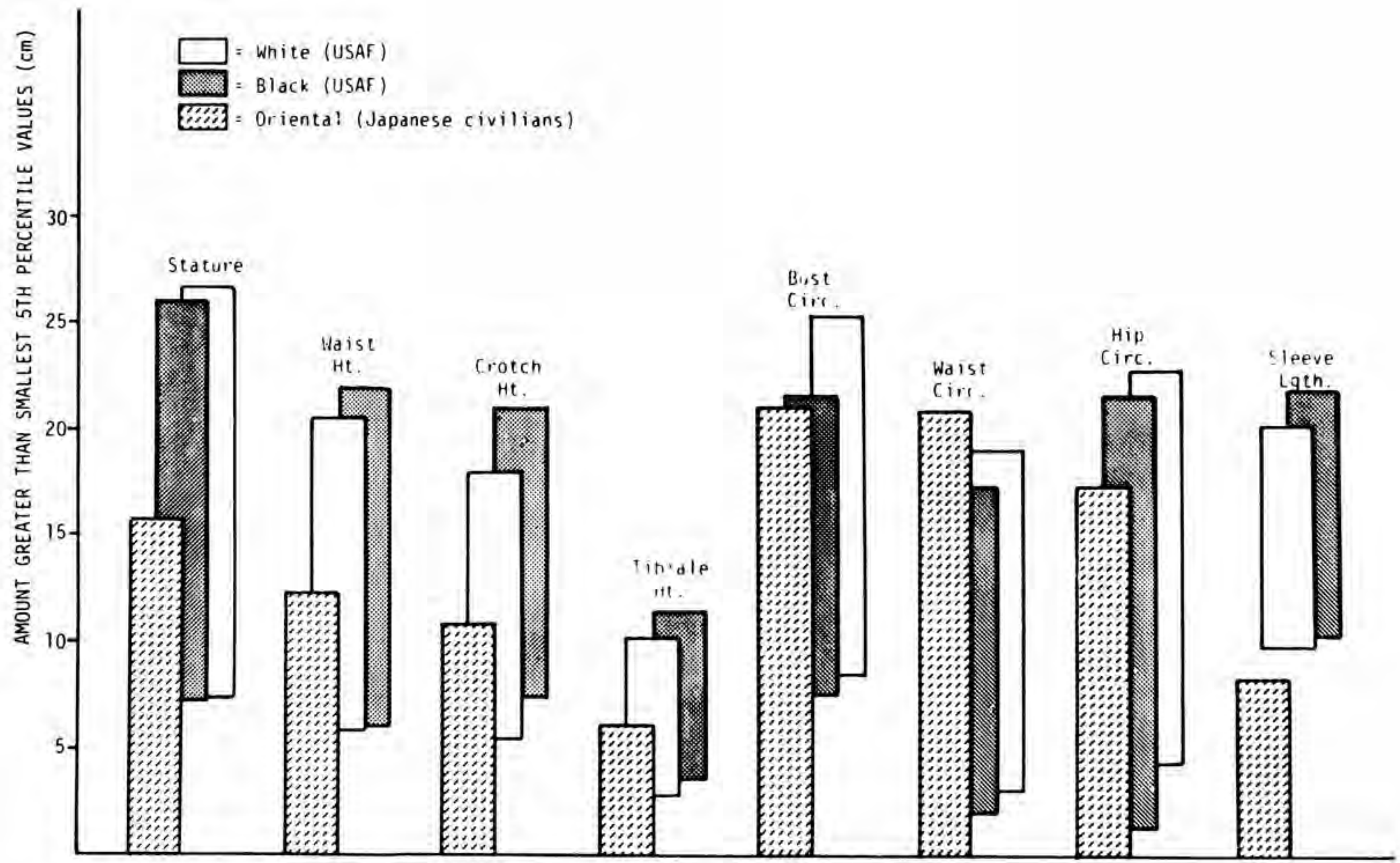


Figure 9. Range of variation between females of three racial groups for selected body dimensions (smallest 5th to largest 95th percentile).

While individual values for Whites and Blacks overlap to a large extent (partly as a result of greater variability in the White sample), the body size differences cited above are of sufficient magnitude to warrant consideration in the design of systems and equipment to be used by both Whites and Blacks.

National-Ethnic Size Variability

Without regard to racial composition of a given nation, there are demonstrable differences in body size when specific intra- or international groups are compared. This fact is easily ascertained by examination of the tables in Chapter III and the data in Volume II of this book. Selected portions of that material is presented graphically here in order to demonstrate national-ethnic variability. For convenience and brevity eleven common dimensions, as measured on the same 12 populations selected for presentation in Chapter III, have been chosen for presentation here. The 5th and 95th percentile range for each population (where available) are shown in Figures 10 through 20. The graphs clearly demonstrate the range of variability between subjects of different national origin and between groups of subjects of the same national origin (i.e., U.S. civilians and U.S. military personnel).

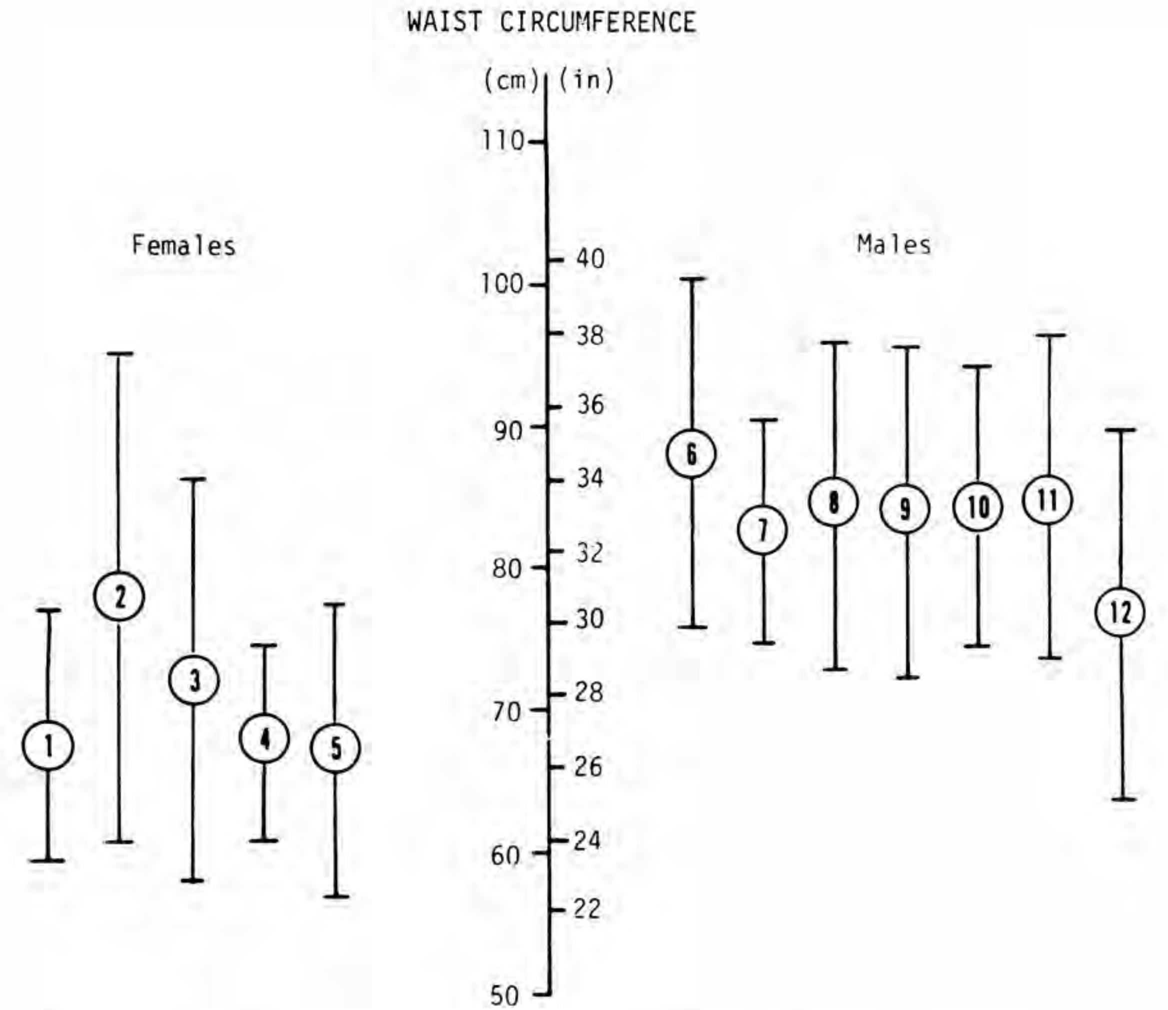
Size Differences Between Persons in Different Occupations

As noted above, dimensional differences are observed when anthropometric data from various vocational-professional populations are compared to data representing the general population. Utilizing the U.S. Health Examination Survey (HES) data (Stoudt et al. 1965) as a base, and data from surveys of several vocational-professional populations for comparison, Tables 17 and 18 were developed for males and females respectively. In comparing data, it should be remembered that the HES was performed somewhat earlier in time and the average age of the subjects was greater. It is recommended therefore that rigorous comparisons not be made. The purpose of this presentation is rather to alert the design engineer to the fact that if the user of the end item can be classed into a specific occupation, size data from the same or a similar population should be used wherever possible.

In comparing the male populations, the police are clearly larger than other individuals. The Air Force trainees are generally smaller but are also significantly younger. The group of stewardesses tends to be taller and slimmer than the other female groups. Again, the age of the HES population must be considered to affect dimensions such as waist circumference and elbow-elbow breadth.

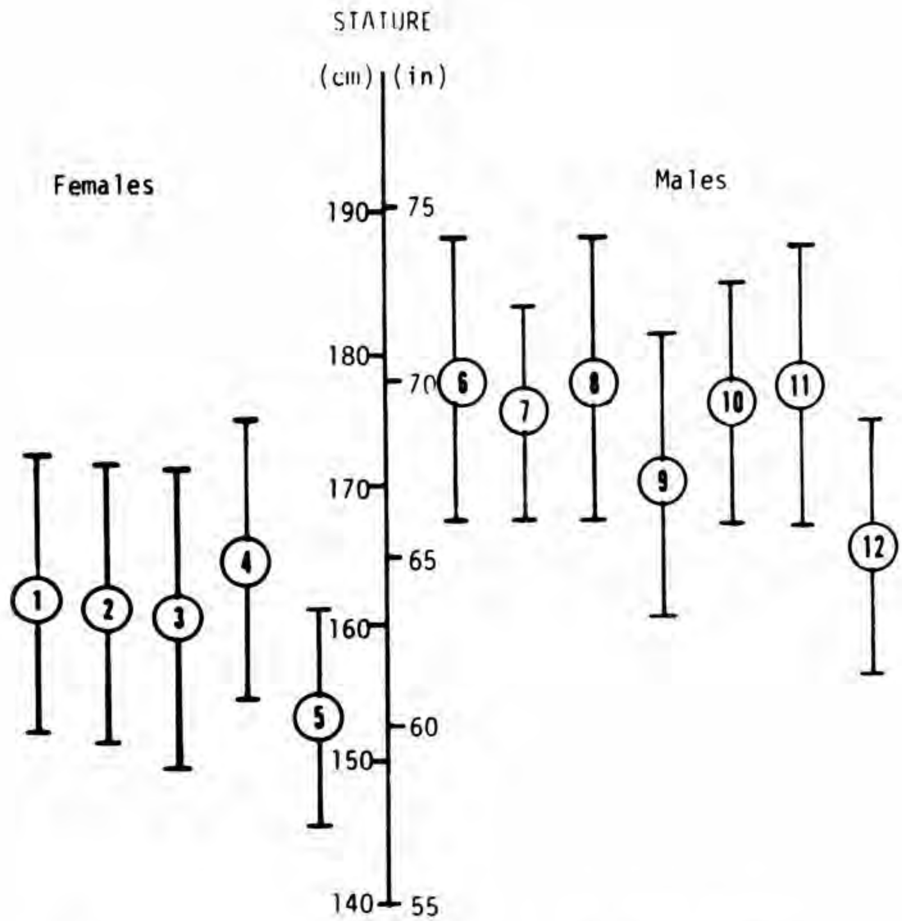
Secular Changes in Adult Body Size

The fact that the size of the adult human body is thought to be increasing over time probably comes as no surprise. The man on the street will tell you that people are getting taller; older members of a community will recall "when people were smaller." Evidence shows that today's children



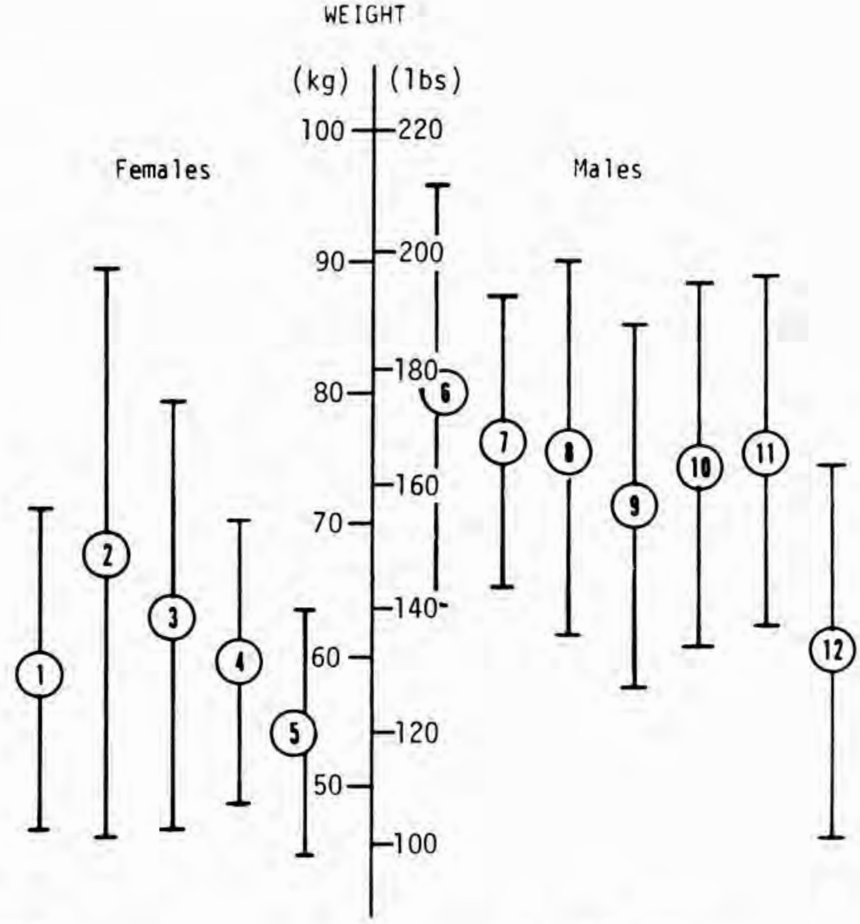
1. USAF
2. U. S. HEW civilians
3. British civilians
4. Swedish civilians
5. Japanese civilians
6. USAF fliers
7. NASA astronauts
8. British fliers
9. Italian military
10. French fliers
11. German Air Force
12. Japanese civilians

Figure 10. Range of variability (5th-95th percentile) in waist circumference for selected populations.



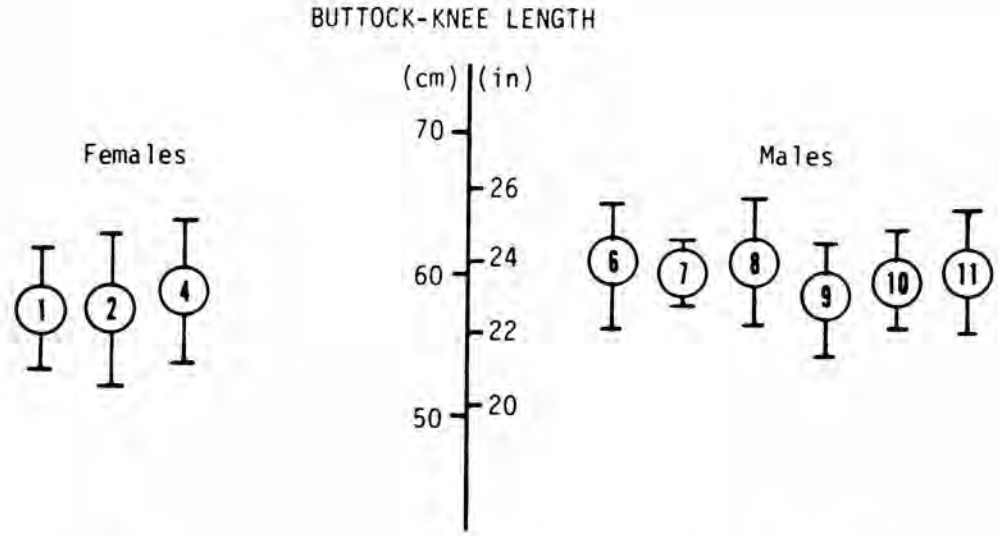
1. USAF
2. U. S. HEW civilians
3. British civilians
4. Swedish civilians
5. Japanese civilians
6. USAF fliers
7. NASA astronauts
8. British fliers
9. Italian military
10. French fliers
11. German Air Force
12. Japanese civilians

Figure 11. Range of variability (5th-95th percentile) in stature for selected populations.



1. USAF
2. U. S. HEW civilians
3. British civilians
4. Swedish civilians
5. Japanese civilians
6. USAF fliers
7. NASA astronauts
8. British fliers
9. Italian military
10. French fliers
11. German Air Force
12. Japanese civilians

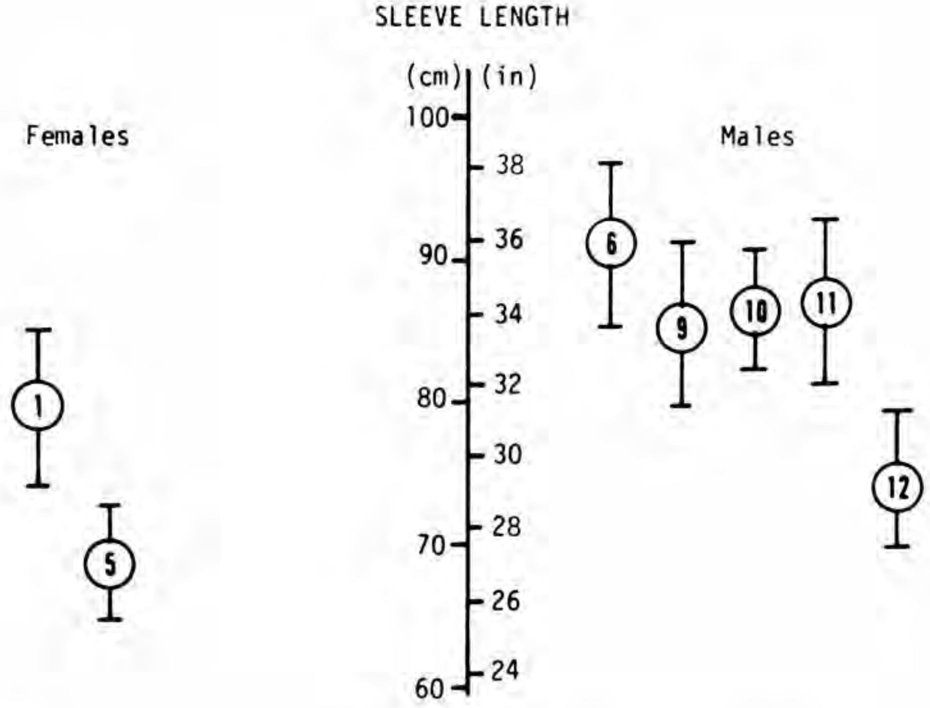
Figure 12. Range of variability (5th-95th percentile) in weight for selected populations.



1. USAF
2. U. S. HEW civilians
4. Swedish civilians

6. USAF fliers
7. NASA astronauts
8. British fliers
9. Italian military
10. French fliers
11. German Air Force

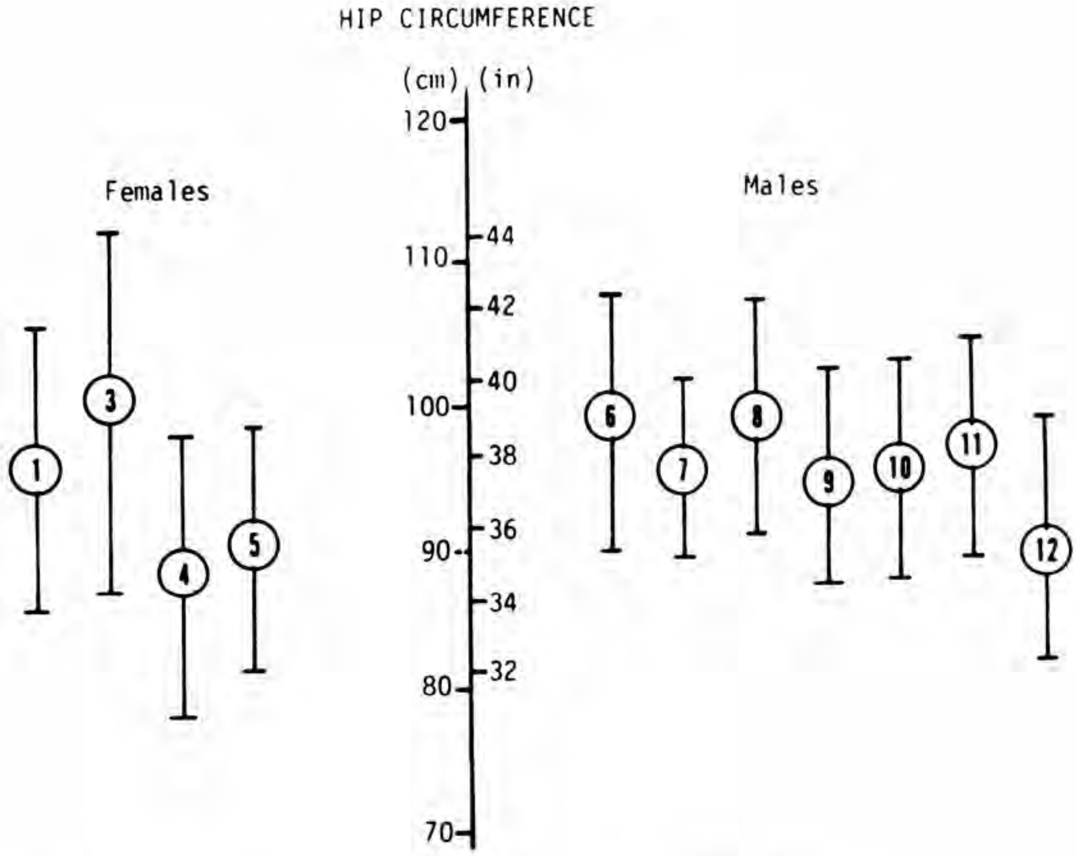
Figure 13. Range of variability (5th-95th percentile) in buttock-knee length for selected populations.



1. USAF
5. Japanese civilians

6. USAF fliers
9. Italian military
10. French fliers
11. German Air Force
12. Japanese civilians

Figure 14. Range of variability (5th-95th percentile) in sleeve length for selected populations.



1. USAF
3. British civilians
4. Swedish civilians
5. Japanese civilians

6. USAF fliers
7. NASA astronauts
8. British fliers
9. Italian military
10. French fliers
11. German Air Force
12. Japanese civilians

Figure 15. Range of variability (5th-95th percentile) in hip circumference for selected populations.

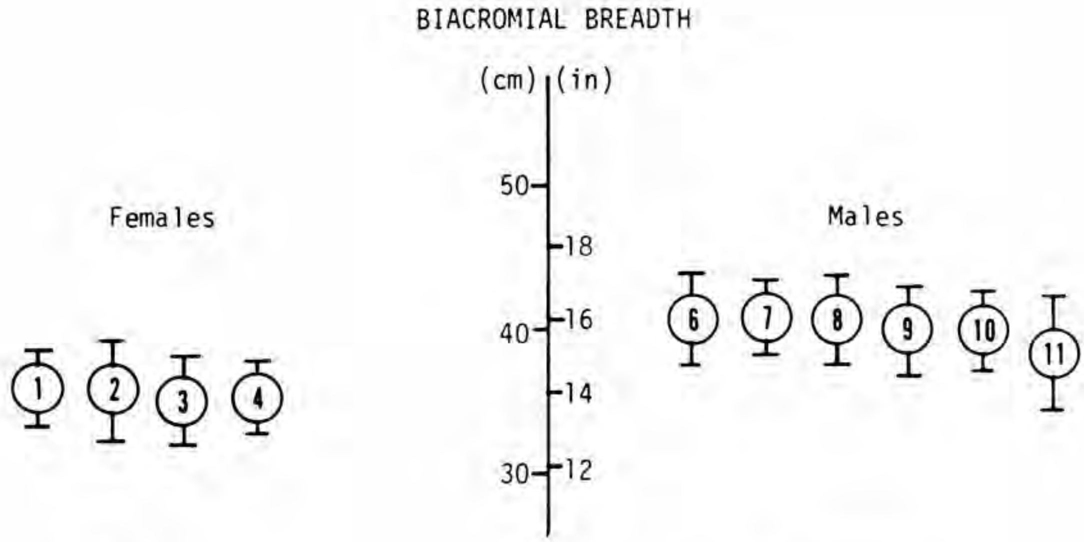
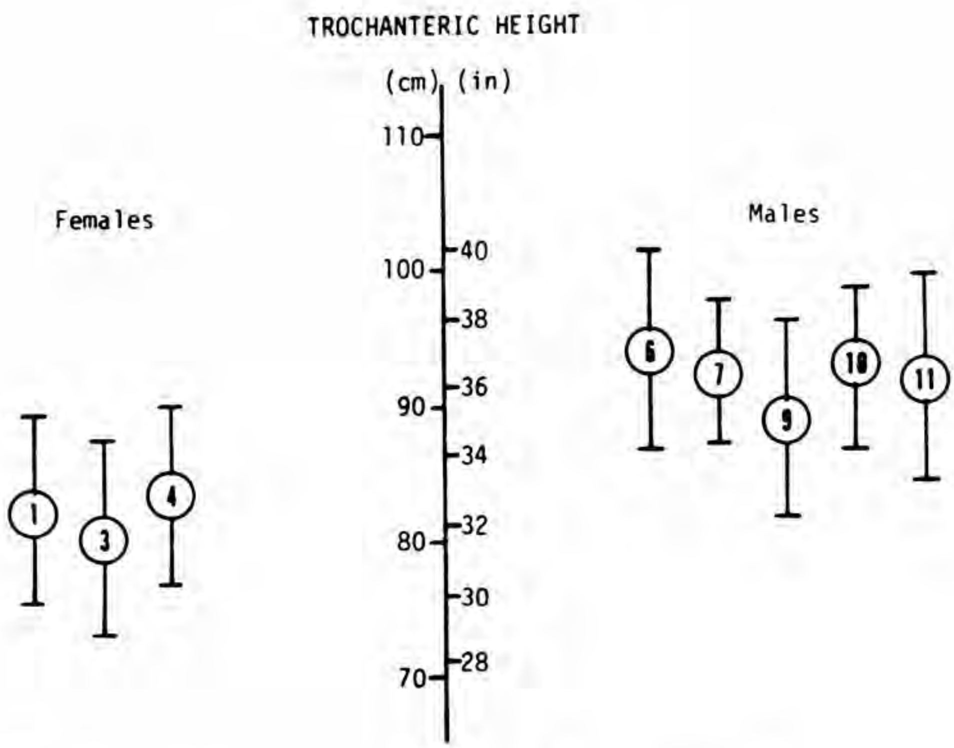


Figure 16. Range of variability (5th-95th percentile) in biacromial breadth for selected populations.



1. USAF
3. British civilians
4. Swedish civilians

6. USAF fliers
7. NASA astronauts
9. Italian military
10. French fliers
11. German Air Force

Figure 17. Range of variability (5th-95th percentile) in trochanteric height for selected populations.

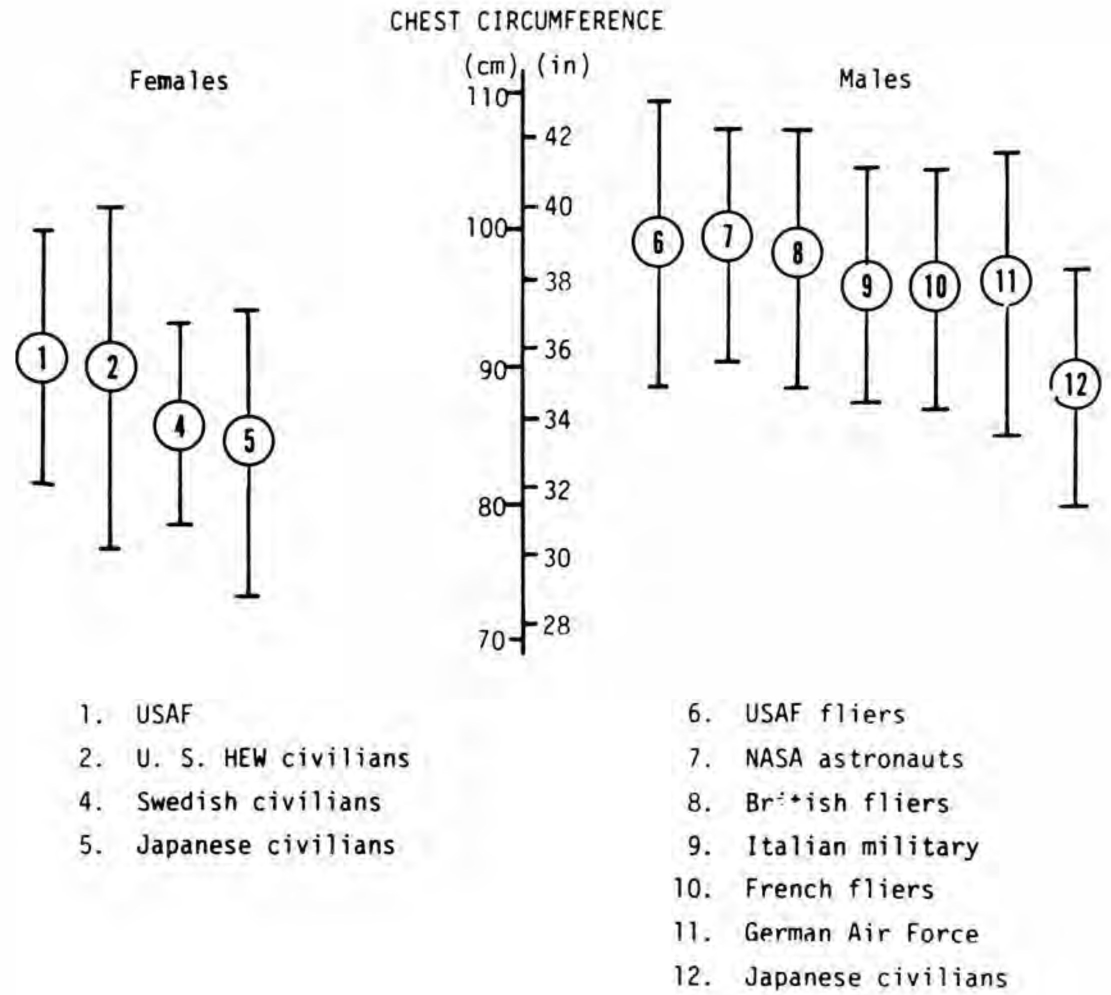
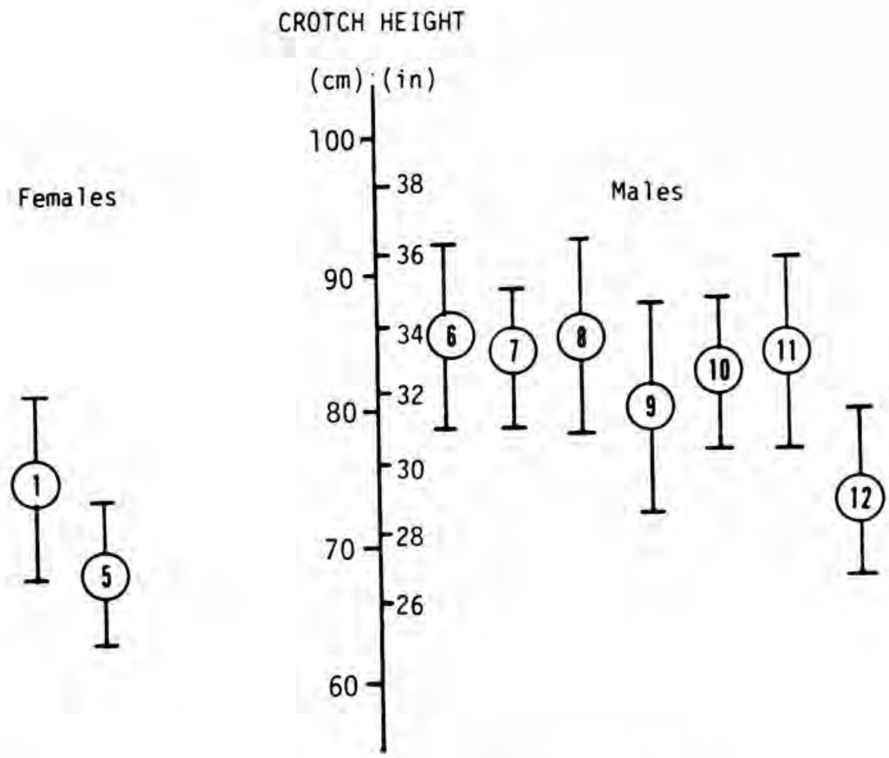


Figure 18. Range of variability (5th-95th percentile) in chest circumference for selected populations.



1. USAF
5. Japanese civilians

6. USAF fliers
7. NASA astronauts
8. British fliers
9. Italian military
10. French fliers
11. German Air Force
12. Japanese civilians

Figure 19. Range of variability (5th-95th percentile) in crotch height for selected populations.

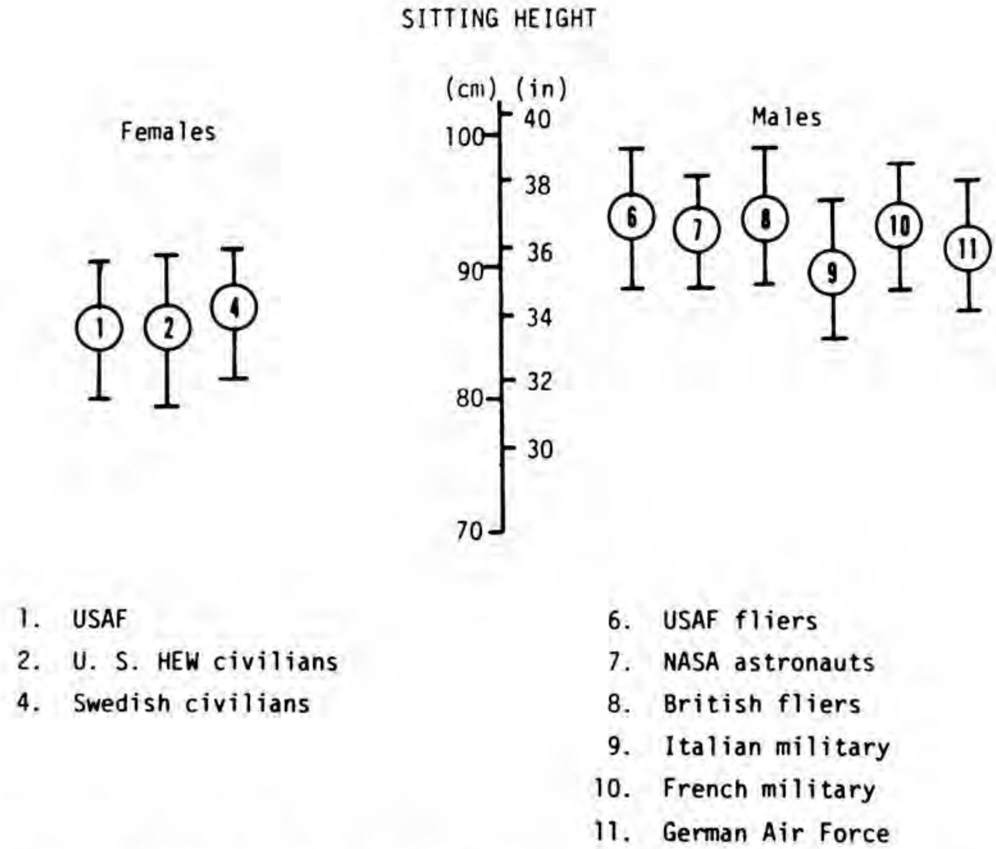


Figure 20. Range of variability (5th-95th percentile) in sitting height for selected populations.

TABLE 17
SELECTED DIMENSIONS OF DIFFERENT VOCATIONAL-PROFESSIONAL GROUPS OF U.S. MALES [1]

Variable	HES [2]		'67 USAF [3]		'75 POLICE [4]		'65 AF TRAINEES [5]		'55 BUS DRIVER [6]		ASTRONAUTS [7]	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Age	43.2	15.5	30.0	6.3	30.7	8.7	19.3	1.3	37.0	8.2	28-43	(range)
Weight	75.9 (167.3)	12.6 (27.8)	78.7 (173.5)	9.7 (21.4)	83.3 (183.6)	12.0 (26.5)	68.7 (151.4)	10.2 (22.5)	75.9 (167.3)	12.7 (27.9)	74.5 (164.2)	6.9 (15.2)
Height	173.2 (68.2)	6.8 (2.7)	177.3 (69.8)	6.2 (2.4)	178.1 (70.1)	5.8 (2.3)	175.1 (68.9)	6.5 (2.6)	173.6 (68.3)	6.6 (2.6)	176.4 (69.4)	4.7 (1.9)
Biacromial breadth	39.6 (15.6)	2.0 (0.8)	40.7 (16.0)	1.9 (0.7)	- -	- -	39.7 (15.6)	1.9 (0.7)	40.0 (15.7)	1.6 (0.6)	40.5 (15.9)	1.7 (0.7)
Biceps circ.	30.7 (12.1)	3.3 (1.3)	30.8 (12.1)	2.3 (0.9)	- -	- -	27.3 (10.7)	2.6 (1.0)	- -	- -	- -	- -
Chest circ.	99.3 (39.1)	8.4 (3.3)	98.6 (38.8)	6.4 (2.5)	102.2 (40.2)	7.9 (3.1)	91.8 (36.1)	1.6 (0.6)	97.8 (38.5)	8.2 (3.2)	97.1 (38.2)	4.8 (1.9)
Waist circ.	88.6 (34.9)	11.4 (4.5)	87.6 (34.5)	7.4 (2.9)	90.6 (35.7)	9.4 (3.7)	78.0 (30.7)	7.5 (3.0)	- -	- -	82.1 (32.3)	4.5 (1.8)
Sitting height	90.4 (35.6)	3.8 (1.5)	93.2 (36.7)	3.2 (1.3)	92.2 (36.3)	3.4 (1.3)	91.1 (35.9)	3.5 (1.4)	92.0 (36.2)	3.3 (1.3)	92.4 (36.4)	2.6 (1.0)
Knee height	54.1 (21.3)	2.8 (1.1)	55.8 (22.0)	2.5 (1.0)	55.9 (22.0)	2.5 (1.0)	55.4 (21.8)	2.6 (1.0)	55.0 (21.7)	3.3 (1.3)	- -	- -
Popliteal height	43.9 (17.3)	2.8 (1.1)	43.7 (17.2)	2.3 (0.9)	- -	- -	44.8 (17.6)	2.4 (0.9)	- -	- -	- -	- -
Thigh clearance height	14.3 (5.6)	1.8 (0.7)	16.5 (6.5)	1.4 (0.6)	- -	- -	15.0 (5.9)	1.4 (0.6)	- -	- -	- -	- -
Buttock-knee length	59.2 (23.3)	3.0 (1.2)	60.4 (23.8)	2.7 (1.1)	61.5 (24.2)	2.7 (1.1)	60.3 (23.7)	2.9 (1.1)	60.3 (23.7)	3.3 (1.3)	60.4 (23.8)	1.5 (0.6)
Seat breadth	35.3 (13.9)	2.8 (1.1)	37.8 (14.9)	2.3 (0.9)	- -	- -	35.3 (13.9)	2.5 (1.0)	37.0 (14.6)	3.3 (1.3)	- -	- -
Elbow-elbow breadth	42.0 (16.5)	4.6 (1.8)	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
Elbow rest height	24.1 (9.5)	3.0 (1.2)	25.2 (9.9)	2.6 (1.0)	- -	- -	23.5 (9.3)	2.8 (1.1)	- -	- -	- -	- -
Buttock-popliteal length	49.3 (19.4)	3.0 (1.2)	50.4 (19.8)	2.6 (1.0)	- -	- -	49.4 (19.4)	2.7 (1.1)	- -	- -	- -	- -

[1] Data given in kilograms and centimeters with pounds and inches in parentheses; age in years.

[2] Stoudt et al. 1965.

[3] Unpublished data.

[4] Martin et al. 1975.

[5] Long and Churchill 1968.

[6] Damon and McFarland 1955.

[7] Roth 1968.

TABLE 18

SELECTED DIMENSIONS OF DIFFERENT VOCATIONAL-PROFESSIONAL GROUPS OF U.S. FEMALES[1]

Variable	HES[2] Mean	HES[2] S.D.	STEWARDESSES[3] Mean	STEWARDESSES[3] S.D.	'68 WAF[4] Mean	'68 WAF[4] S.D.
Age	42.6	15.4	22.1	1.6	23.4	6.4
Weight	64.7 (142.6)	13.8 (30.4)	52.8 (116.4)	4.3 (9.5)	57.7 (127.2)	7.5 (16.5)
Height	160.3 (63.1)	6.6 (2.6)	166.2 (65.4)	4.8 (1.9)	162.1 (63.8)	6.0 (2.4)
Biacromial breadth	35.3 (13.9)	2.0 (0.8)	35.0 (13.8)	1.5 (0.6)	35.8 (14.1)	1.6 (0.6)
Biceps circumference	28.7 (11.3)	4.3 (1.7)	23.3 (9.2)	1.3 (0.5)	25.6 (10.1)	2.3 (0.9)
Chest circumference	88.1 (34.7)	8.1 (3.2)	85.6 (33.7)	4.0 (1.6)	89.7 (35.3)	5.7 (2.2)
Waist circumference	76.7 (30.2)	11.9 (4.7)	62.2 (24.5)	2.8 (1.1)	67.2 (26.5)	5.5 (2.2)
Sitting ht. (erect)	84.6 (33.3)	3.5 (1.4)	87.0 (34.3)	2.8 (1.1)	85.6 (33.7)	3.2 (1.3)
Knee ht. (sitting)	49.8 (19.6)	2.8 (1.1)	51.9 (20.4)	2.2 (0.9)	- -	- -
Popliteal height	39.6 (15.6)	2.5 (1.0)	43.5 (17.1)	2.1 (0.8)	41.0 (16.1)	1.9 (0.7)
Thigh clearance height	13.7 (5.4)	1.8 (0.7)	- -	- -	12.4 (4.9)	1.2 (0.5)
Buttock-knee height	56.9 (22.4)	3.0 (1.2)	57.5 (22.6)	2.3 (0.9)	57.4 (22.6)	2.6 (1.0)
Buttock-popliteal length	48.0 (18.9)	3.0 (1.2)	48.2 (19.0)	2.5 (1.0)	47.7 (18.8)	2.8 (1.1)
Seat breadth (hip)	36.6 (14.4)	3.8 (1.5)	36.8 (14.5)	1.8 (0.7)	33.7 (13.3)	2.1 (0.8)
Elbow-elbow breadth	38.9 (15.3	5.3 (2.1)	33.0 (13.0)	2.3 (0.9)	- -	- -
Elbow rest height	23.1 (9.1)	2.8 (1.1)	24.1 (9.5)	2.5 (1.0)	22.7 (8.9)	2.5 (1.0)

[1] Data given in kilograms and centimeters with pounds and inches in parentheses.

[2] Stoudt et al. 1965.

[3] Snow et al. 1975.

[4] Clauser et al. 1972.

reach peak height velocity earlier in adolescence and each decade sees them reach puberty four to five months earlier than the last (Tanner, 1962). Growth tends to be completed at an earlier age today than it was at the turn of the century.*

This type of human variation, occurring from generation to generation over time is usually referred to as secular change by anthropologists. Whether the effect results from better nutrition, improved health care or some biological selection process has not been determined and is, in any case, of no practical significance to design engineers who need to know how much rather than why. The lengthy lead time required for the design and production of spacecraft, aircraft and other sophisticated devices is such that the persons who will eventually use them are, for the most part, only children when the design specifications are fixed. It is of more than casual interest, therefore, to anticipate the dimensions of physical size and body proportion which will exist at a given point in the future.

Records for height and weight for many of the nations of Western Europe go back as far as 200 years ago. Most of the early data was collected on military recruits and is therefore for young adult men only. Udjus (1964) has reviewed stature changes in Norwegian recruits over the past 200 years and Harbeck (1960) has accumulated stature data for a number of European countries and Japan extending back to the first half of the 19th century. The data from both sources are presented in Figure 21 which illustrates that the trend over time, although somewhat variable, has been for young adult men to become taller. The rate of increase in stature since 1900 in the European nations surveyed has ranged from .87 cm (.34 inches) to 1.29 cm (.51 inches) per decade in France and Switzerland respectively.

The demonstration of secular change in stature in the U.S. population, particularly for men, must also rely on military data. Height and weight data were collected on Union army personnel during the Civil War (Baxter, 1875; Gould, 1869). Since that time, military surveys of increasing complexity and accuracy have been conducted with increasing frequency. The mean stature and weight of U.S. soldiers at four points in time are listed in Table 19. The data indicate that there was little change in stature in the young American male between 1863 and 1919. In fact, data for recruits between 1906 and 1915 indicate that men were slightly shorter at that time than they were in the 1860's. Davenport (1921) suggests that this apparent reversal in the trend to increase in stature over time resulted from the influx of shorter Southern European immigrants into the U.S. population during the intervening period. Whether Davenport's suggestion is valid or not, it serves to point out the dangers in comparing temporally and technically disjointed data. Measurement techniques change, measurement personnel are different, military selection pressures vary and transient environmental factors affecting growth and development may be involved in influencing the data obtained at any given time. All these variables notwithstanding, the mean stature values for U.S. males since 1860 have shown a substantial increase, particu-

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*A recent publication of the National Center for Health Statistics (Hamill et al. 1976) concludes that the secular growth trend appears to have stopped in American children born after 1955-56.

TABLE 19
MEAN STATURE, WEIGHT AND AGE OF U.S. ARMY SOLDIERS*

	Stature	Weight	Age
Northern Civil War Recruits (1863)	171.45 (67.5)	61.68 (136.0)	--
Northern Civil War Veterans (1865)	171.96 (67.7)	63.04 (139.0)	--
World War I Veterans (1919)	171.45 (67.5)	64.17 (141.5)	--
World War II Veterans (1942)	173.74 (68.4)	70.20 (154.8)	22.2
U.S. Army (1966)	174.50 (68.7)	72.15 (159.1)	24.3

*Data given in centimeters and kilograms with inches and pounds in parentheses.

TABLE 20
AVERAGE VALUES FOR SELECTED BODY MEASUREMENTS OF U.S. FEMALES BORN 1903 to 1933 [1]

Year of birth	1903 - 4 [2]	1927	1933 [3]
Age	36 yrs.	41 yrs.	40 yrs.
Weight	60.5	63.3	63.7
	(133.5)	(139.5)	(140.4)
Height	160.5	163.1	163.6
	(63.2)	(64.2)	(64.4)
Hip Circumference	98.6	98.6	100.1
	(38.8)	(38.8)	(39.4)
Waist Circumference	74.2	74.7	76.4
	(29.2)	(29.4)	(30.1)
Mid-Thigh Circumference	49.8	50.6	-
	(19.6)	(19.9)	-
Knee Circumference	35.6	36.6	37.1
	(14.0)	(14.4)	(14.6)
Calf Circumference	34.3	34.5	35.1
	(13.5)	(13.6)	(13.8)
Ankle Circumference	21.1	21.3	21.6
	(8.3)	(8.4)	(8.5)
Waist Height	102.0	-	102.9
	(40.2)	-	(40.5)
Crotch Height	72.4	-	76.5
	(28.5)	-	(30.1)
Foot Length	-	24.1	24.6
	-	(9.5)	(9.7)

[1] Data given in centimeters and kilograms with inches and pounds in parentheses.

[2] Data from O'Brien (1941).

[3] Data from Cullipher and Delate (1974).

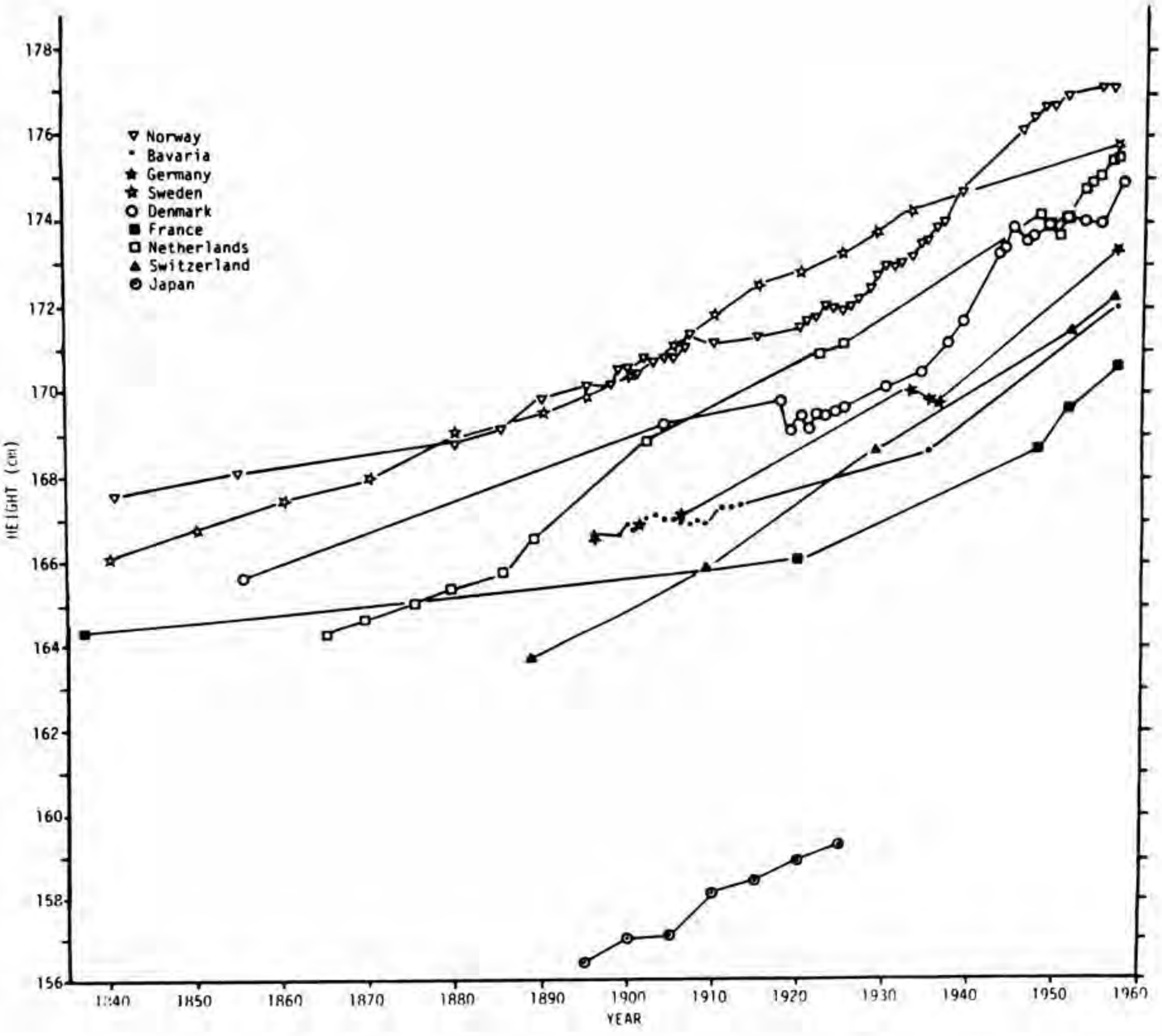

Figure 21. Secular increase in stature of young European and Japanese males: 1840-1960. After: Udjus (1964), and Harbeck (1960).

larly since the 1900's, and it is safe to assume that the trend is a real rather than artifactual one. Stature data for major U.S. surveys (male) are plotted in Figure 22. The rate of increase in stature since 1920 is nearly 1.0 cm (.4 in.) per decade, a finding which agrees fairly well with the European data.

Because most large surveys have historically been associated with the military, and because women were never drafted and rarely recruited until World War II, long term secular trends for women are more difficult to establish. Several dimensions obtained on fairly large and reasonably comparable samples of adult U.S. women are listed in Table 20. The survey covered a birth year period of 42 years (1903-1945) corresponding with the period during which U.S. men showed the most rapid increase in stature. The general trend is for today's women to be slightly larger for the dimensions listed, when women of the same age are compared.

Whatever the trend, the secular changes in body size are shown by the military surveys to be significant in systems and equipment design. As Kennedy (1972) noted, the USAF flying personnel measured in 1967 differed in a number of important respects from those measured in 1950, and, as a result, the "...Seat Reference Point to the cockpit eye line, as specified in MIL-STD-1333 (Cockpit Geometry, Department of Defense, 1969a), and MIL-STD-33574,5, and 6 (Basic Cockpit Dimensions, Department of Defense, 1969 b, c, d) was increased by 0.5 inches, from 31.0 inches to 31.5 inches. Such dimensions as sitting height, buttock-knee length, and knee height, sitting, to name just a few, are extremely critical in determining the basic vertical and fore-and-aft ejection clearance dimensions in the aircraft cockpit."

In summary, it is essential to recognize that body size, at least of military populations, is in a dynamic state, and that body size changes must be documented continuously if systems and equipment requiring long lead times are to be designed effectively.

Projection of Future Body Size

The chief application of data on secular changes is, of course, in predicting the size of a future design population. As noted above, the long lead time required for designing and building complex machines necessitates predicting size change in the human operator well in advance. Recognizing the importance of secular size variation and the consequences of ignoring such change, NASA recently asked the Aerospace Medical Research Laboratory (AMRL) at Wright Patterson Air Force Base to conduct a study to make predictions of body size through 1985.

The initial assumption of the AMRL study was that it could best be done by predicting the size of USAF pilots who will be in their mid-thirties in 1985 and accepting these predictions as being suitable for astronauts as well. Data from a half dozen past anthropometric surveys of flying personnel were analyzed to establish a trend for the stature and weight predictions while values for close to 200 additional dimensions were estimated by combining the height/weight data with appropriate regression equations. (For more complete data on projected anthropometry of 1985 flying personnel, see Chapter III, Appendix B).

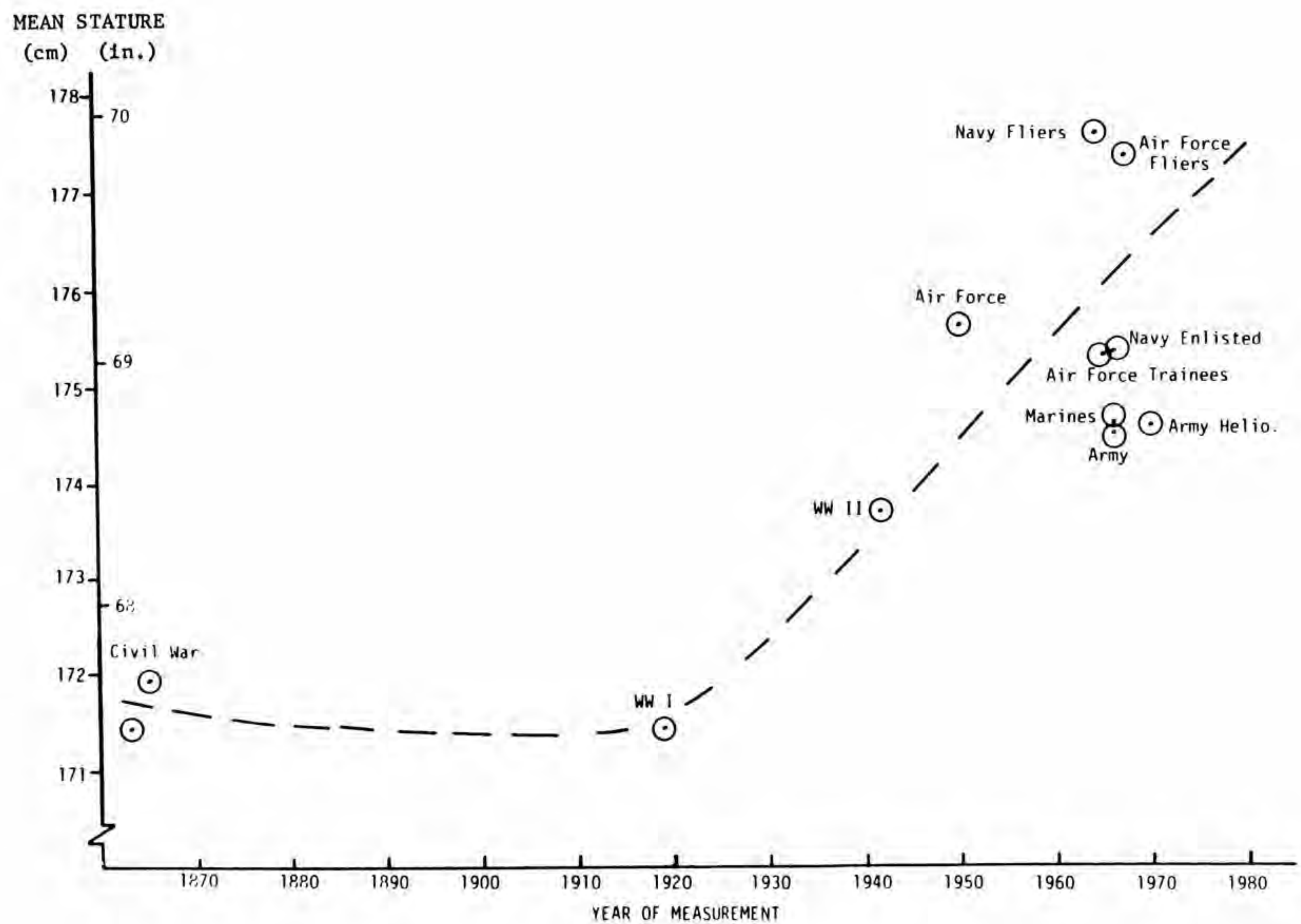

Figure 22. Secular trend in stature for young U.S. males: 1870-1980.

While analysis of past trends is a reasonable way for determining the dimensions of future astronauts, the process is both time-consuming and fraught with all the pitfalls that usually attend the manipulation of complex data. It could be pointed out, for example, that the rate of human "growth" since the turn of the century is not expected to continue indefinitely and, as noted above, there is some evidence that the trend toward earlier maturity and increased adult size is leveling off (Hamill et al. 1976).

One simple strategy, however, is available for predicting stature of air and space crews of the near future. In estimating astronaut statures for a decade hence, it can be assumed that the concern is with men who will be at least in their early and mid-thirties at that time, if not older. In a sense, it is not necessary to estimate these men's statures; one can go out and measure them. Men with appropriate birth years are already participating in USAF pilot and navigator training and other advanced military and space programs and can be measured at any given moment in time. In 1973 such a survey was carried out at two training bases. Statures and other data were quickly obtained for about 500 men, 23 to 27 years old, men, that is, with full growth who would be from 30 to 34 in 1980 and from 35 to 39 in 1985.

Summary

Invariably, a superior product will result if sizing factors related to the human operator are injected early in the design process. At present, anthropometric data are by far the best source of sizing information available to the designer. Once the relevant sizing factors and the target design population have been identified, the designer must ascertain whether reliable and recent anthropometric data are available for that population (See Volume II). If such data are available, the designer, armed with some understanding of statistical forms, must apply them knowledgeably to his problem. If such data are not available and an immediate survey of the population cannot be performed, the designer must adjust available data according to the types of size variability described in this chapter. While the various categories of variation dealt with here have been treated as though they were of equal importance, it must, of course, be remembered that each design problem is unique. Not all sources of human body size variability are equally relevant to every design task but none of them should be dismissed without careful consideration.

Although we have attempted to cover major areas of human size variability relevant to NASA designers, it is not possible in one chapter to cover exhaustively all sources of such variation. Thus it will be necessary from time to time for the design engineer to be innovative in the application of body size data. On occasion the designer will have to interpolate and extrapolate data provided here as well as in other chapters and volumes of this data book. It has been the aim of this chapter to provide the design engineer with a sufficient background to stimulate greater awareness of the sources of body size variability and to guide his approach to the solutions of design problems. In the design of space flight hardware and equipment, consideration of human factors is not just important--it may be critical.

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CHAPTER III
ANTHROPOMETRY

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Anthropometry, the practice of measuring the parts and proportions of the human body, encompasses a variety of techniques for determining an almost limitless number of dimensions. Each user of anthropometric data has his own list of dimensions that he considers essential for his purposes. Unfortunately, the list of one user seldom coincides with the list preferred by another. As a consequence, the literature of anthropometry contains many tabulations of data that are unique to a particular investigation, survey or design situation. At the same time, as the number of measured variables grows it becomes increasingly difficult to tabulate them in any usable fashion. In 1942 the young Army Air Force anthropology group included 55 measurements in its anthropometric survey of the body size of aircrewmen (Randall et al. 1946). In the next major USAF survey, conducted in 1950, the number of measurements had grown to 132 (Hertzberg et al. 1954), and in the most recent such survey, conducted in 1967, the number of variables had reached a total of 190 (Churchill et al. 1977). When the anthropometric data available on worldwide populations is compiled, with each survey contributing a few unique dimensions, the task of collation and presentation becomes formidable.

In Volume II of this book we have collected and tabulated the anthropometric data from every survey available to us, making it probably as comprehensive a reference book as has ever been compiled on the subject. A condensed and summarized version of this material appears in this chapter. Data on 59 variables, selected for their relevance to NASA design problems, are tabulated for 12 U.S. and foreign populations which represent countries involved in the space shuttle program (see Table 1).

Appendix B contains predicted body-size dimensions for the U.S. astronaut population of 1985. Data includes estimated measurements of the same 59 dimensions for average, 5th and 95th percentile men and women based on a projection of data from military surveys conducted in the past several decades.

As a further aid to NASA engineers involved in crew station design, Appendix C describes the most up-to-date two-dimensional drawing board manikins currently available and provides information on how to obtain plans for fabricating the models.* Actual patterns for simplified versions

* USAF 2-D manikins developed by Kenneth W. Kennedy, Aerospace Medical Research Laboratories, Wright Patterson Air Force Base, Ohio.

TABLE I

A SUMMARY OF THE ANTHROPOMETRIC DATA AVAILABLE FOR TWELVE SAMPLE POPULATIONS

	U.S.A.F. Females 1968	U.S.A. HEW Civ Females 1960-62	British Civ. Females 1957	Swedish Civ. Females 1968	Japanese Civ. Females 1967-68 & 1972-73	U.S.A.F. Fliers 1967	NASA Astro-nauts Dates Vary	British Fliers 1970-71	Italian Military 1960	French Fliers 1973	German Air Force 1975	Japanese Civ. 1967-68 1972-73
Weight	x	x	x	x	x	x	x	x	x	x	x	x
Stature	x	x	x	x	x	x	x	x	x	x	x	x
Acromial Height (Shoulder Height)	x			x		x	x		x	x	x	
Waist Height	x			x	x	x	x	x	x		x	x
Crotch Height	x				x	x	x	x	x	x	x	x
Trochanteric Height	x		x	x		x	x		x	x	x	
Tibiale Height	x		x	x	x		x			x		x
Calf Height						x			x		x	
Ankle Height	x					x			x			
Radiale Height (Elbow Height)						x			x		x	
Stylion Height (Wrist Height)						x			x		x	
Sitting Height	x	x		x		x	x	x	x	x	x	
Eye Height, Sitting	x					x	x		x	x	x	
Midshoulder Height, Sitting	x					x			x		x	
Elbow Rest Height, Sitting	x	x		x		x		x	x	x	x	
Knee Height, Sitting		x				x		x	x	x	x	
Popliteal Height, Sitting	x	x				x			x	x	x	
Shoulder-Elbow Length						x	x		x	x	x	
Forearm-Hand Length				x			x	x				
Buttock-Popliteal Length	x	x				x			x	x	x	
Buttock-Knee Length	x	x		x		x	x	x	x	x	x	
Thumb-Tip Reach	x					x		x	x		x	
Thigh Clearance Height, Sitting	x	x		x		x		x	x	x	x	
Biacromial Breadth	x	x	x	x		x	x	x	x	x	x	
Bideltoid Breadth (Shoulder Breadth)	x					x	x	x	x	x	x	
Hip Breadth, Sitting		x				x	x	x	x	x		
Chest (Bust) Depth	x					x	x		x	x	x	
Chest (Bust) Breadth	x			x		x	x		x	x	x	
Hip Breadth, Standing	x					x	x		x		x	
Neck Circumference	x		x		x	x	x	x	x	x	x	x
Shoulder Circumference	x					x	x		x	x	x	
Chest (Bust) Circumference	x	x	x	x	x	x	x	x	x	x	x	x
Waist Circumference	x	x	x	x	x	x	x	x	x	x	x	x
Hip Circumference, Maximum	x		x	x	x	x	x	x	x	x	x	x
Upper Thigh Circumference	x			x	x	x	x	x	x	x	x	x
Knee Circumference	x		x		x	x	x		x		x	x
Calf Circumference	x		x	x	x	x	x	x	x	x	x	x
Arm Circumference at Scye	x		x			x	x		x	x	x	
Biceps Circumference, Flexed	x					x	x		x	x	x	
Biceps Circumference, Relaxed	x	x	x	x	x	x			x	x	x	x
Forearm Circumference, Flexed	x					x	x		x	x	x	
Wrist Circumference	x			x		x	x	x	x	x	x	
Vertical Trunk Circumference	x				x	x	x	x	x	x	x	x
Sleeve Length	x				x	x			x	x	x	x
Waist Front Length						x	x		x		x	
Waist Back Length	x		x		x	x	x		x		x	x
Shoulder Length	x					x			x		x	
Interscye	x		x			x	x		x		x	
Head Length	x					x	x	x	x	x	x	
Head Breadth	x					x	x	x	x	x	x	
Head Circumference	x				x	x	x	x	x	x	x	x
Hand Length	x			x		x	x		x	x	x	
Hand Breadth	x			x		x			x	x	x	
Hand Circumference	x					x	x		x	x	x	
Foot Length	x			x	x	x		x	x	x	x	x
Foot Breadth	x			x		x	x	x	x	x	x	
Foot Circumference						x		x	x	x	x	
Face Length	x					x			x	x	x	
Face Breadth	x					x			x	x	x	

of these manikins are provided in the Appendix for the designer who does not require the full capabilities of the more complicated USAF 2-D manikin. Detailed instructions are given to enable the user to trace, cut out and assemble serviceable quarter-scale 5th, 50th and 95th percentile manikins.

Measurement Techniques

It is difficult to document the numerous subtle differences in the techniques of measurement, landmark definition or interpretation inherent in data from such a wide variety of sources as is presented here. Although in many instances these differences are of little practical significance, in some cases they may be important to the design engineer. Certainly it is essential that he be aware that such variations exist when he compares anthropometric data from different sources.

Traditionally in the United States, anthropometric studies have employed a set of instruments like those shown in Figure 1. The anthropometer (A and B), the basic tool of the anthropometrist, is used to measure all linear dimensions. The detached upper half (A) forms a beam caliper to measure breadths, depths and segment lengths. The smaller sliding (C) and spreading (D) calipers are used primarily to measure dimensions of the head, face, hands and feet. The steel tape (E) is used for body circumferences.

Despite periodic attempts to develop worldwide standardization of anthropometric procedures (Papillault, 1906; Stewart, 1947; Hertzberg, 1968; Tanner et al. 1969) other instruments and techniques are sometimes used in other countries. During World War II Morant and Gilson (1945) developed an anthropometric procedure in England which is still widely used by British military establishments in body size surveys and by many of the military groups in British Commonwealth countries.

In the most recent anthropometric survey of RAF aircrew (Bolton et al. 1973), a modified Morant rig was used to make the measurements. In order to compare techniques, four measurements were retaken using the instruments and methods normally employed by USAF anthropometrists. The data, analyzed and reported by Turner (1974), indicate that the differences are statistically significant for three of the four measurements (stature, sitting height and bideltoid breadth) and not significant for buttock-knee length. Comparisons are illustrated in Table 2.

Turner concluded, however, that the magnitude of the individual differences between values obtained by the two techniques were on the level of experimental error, that is, equivalent to the variation in results obtained by repeated measurements of the same subject and thus, for all practical purposes, there were no differences between the four measurements studied.

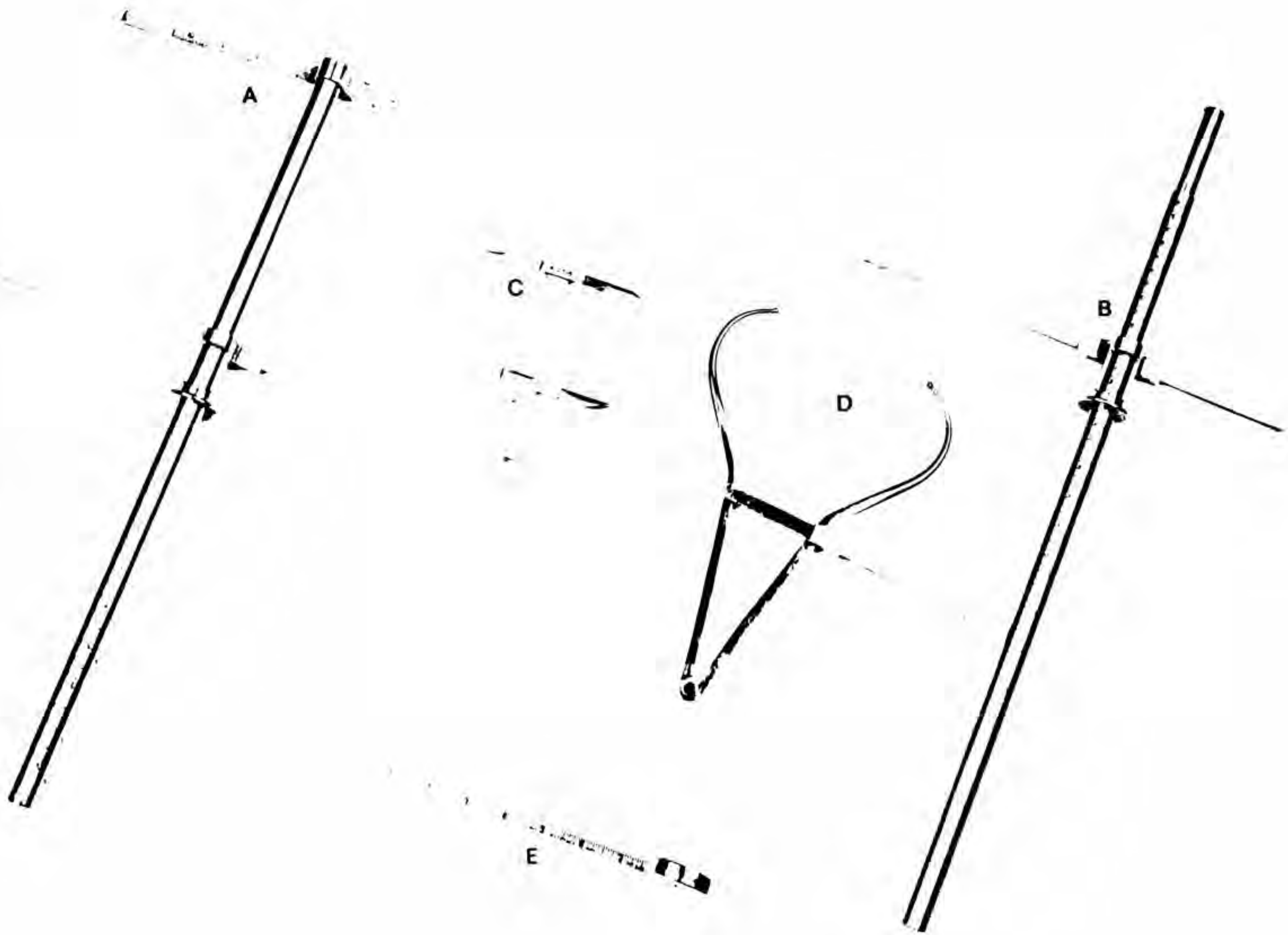


Figure 1. Anthropometric instruments.

TABLE 2
COMPARISON OF UK AND USAF MEASURING TECHNIQUES*

Dimension	UK	USAF	Δ	Significance	Δ%	r
Stature	1774.4	1770.0	-4.4	$p<0.050$	0.25	.996
Sitting height	936.0	929.6	-6.4	$p<0.001$	0.68	.956
Buttock-knee length	607.6	607.3	-0.3	NS	0.05	.930
Bideltoid breadth	465.8	469.8	4.0	$p<0.001$	0.86	.909

*Mean values in mm.

Not all such comparisons, however, result in such comforting conclusions. Damon (1964) described the differences between two standard methods of measuring adult stature. In one, the subject stands against a wall and is measured with a right-angled device; in the other, he is measured free-standing, with an anthropometer. The differences in technique gave mean results that ranged from 0.2 to 0.8 inches for four groups of men measured under various conditions, with the wall measurement giving the average greater stature.

A number of new methods, aimed at measuring man in three dimensions, are in various stages of development and show much promise for future anthropometric studies. Andrometry is a photographic technique for obtaining three-dimensional coordinates of bodily feature for purposes of accurately determining the size and location of the human operator's anatomy in three-dimensional space (Chaffee 1961). In stereophotogrammetry two or more cameras are used to provide an image from which can be obtained accurate measures of three-dimensional size and shape. While both these methods are well advanced in the experimental stages, no body of anthropometric data has yet resulted. Various other forms of stereometry involving ultrasonics, infra red imagery and laser beams have been conceived for recording precise images for anthropometric uses but as yet these are untried.

While none of the data reported in this book were obtained by any of the three-dimensional techniques described above, much of it was generated by anthropometrists in different times and places using variations of the classic methods. When we found serious discrepancies resulting from differences in technique, we either re-assigned data to another variable which we felt more accurately described the measurement, or deleted the data altogether if we found it incomprehensible. We do not, however, claim that all the remaining data in these volumes are absolutely comparable. The user must make the judgement, within the framework of a particular design problem, about whether differences in instruments, measuring techniques or landmarks will be of practical significance. If small differences will affect his results, it is incumbent upon the user to consult the original survey and make his own assessment or to refer to the excellent two-volume study, A Collation of Anthropometry by Garrett and Kennedy (1971), in which anthropometric data from some 47 sources have been reviewed and collated to determine the degree of equivalence in measurement techniques.

Variations in positioning subjects is another potential source of artifactual variance in anthropometric measurements. In many studies, subject posture has been standardized to assure that the variation found in body size within a group is truly that associated with body size and not a compounding of this variance by differences in body stance.

For the measurements made on the body standing erect, the subject's body weight is evenly distributed on both feet, heels together as closely as possible, legs and torso straight without stiffness and head erect with the line of vision parallel to the floor. The arms hang straight but loosely at the sides with the palms alongside but not touching the thighs. This posture is similar to the position of military attention but without the stiffness or bracing often associated with it.

To assume the standard posture in sitting erect, the subject sits on a cushionless flat surface, feet on an adjustable footrest so that the knees are flexed to 90 degrees, the long axis of the thighs parallel. The trunk is erect without stiffness and the head is also erect with the path of vision parallel to the plane of the floor. The upper arms are hanging loosely at the sides with elbows flexed at 90 degrees while forearms and hands are held at right angles to the body. Once more, the user is cautioned to consult the original source if comparative data suggests that techniques have not been comparable and if the resulting differences will be significant in the design.

The anthropometric data assembled here and in Volume II are for the nude or lightly clothed body in a standardized posture. Increments for clothing and variations in body posture must be estimated or ascertained. A number of approximations for various clothing and personal protective equipment assemblages have been detailed in Chapter II. Every possible combination of body covering has not, of course, been studied with regard to its effect on body sizing and it rests with the designer either to ascertain what these increments will be for a particular design situation or to select the best available approximation from the incremental data given in Chapter II.

The Data

The 59 dimensions tabulated on the following data pages are believed to be those most relevant to current design problems and the populations selected for inclusion are judged to be those most representative of persons likely to participate in shuttle missions. The complete references to the selected sample populations are listed below:

USAF Women: Clauser, Charles E., Pearl E. Tucker, John T. McConville, E. Churchill, Lloyd L. Laubach, and Joan A. Reardon. 1972. AMRL-TR-70-5, Anthropometry of Air Force Women, Aerospace Medical Research Laboratories, Wright Patterson Air Force Base, Ohio.

U.S. HEW Civ: (Men & Women) Stoudt, Howard W., Albert Damon, Ross McFarland, and Jean Roberts. 1965. Weight, Height, and Selected Body Dimensions of Adults, Washington, D.C.: National Center for Health Statistics, Series 11, Number 8, U.S. Department of Health, Education and Welfare.

Stoudt, Howard W., Albert Damon, Ross A. McFarland, and Jean Roberts. 1970. Skinfolds, Body Girths, Biacromial Diameter, and Selected Anthropometric Indices of Adults, Washington, D.C.: National Center for Health Statistics, Series 11, Number 35, U.S. Department of Health, Education and Welfare.

British Civ: (Women) Kemsley, W. F. F. 1957. Women's Measurements and Sizes. Cheltenham Press Ltd., Cheltenham, England.

Swedish Civ: (Women) Ingelmark, B. E., and Thord Lewin. 1968. "Anthropometrical Studies on Swedish Women," Acta Morphologica, Vol. VII, No. 2, pp. 145-178.

Japanese Civ: (Men & Women) Yanagisawa, Sumiko. 1974. About Japanese Physique and Body Girth (in Japanese), Tokyo, Japan: Department of Home Economics, Ochanomizu Institute, Women's University, Bunkyo-Ku.

USAF Flying Personnel: (Men) Unpublished United States Air Force Systems Command Anthropometric Data of Flying Personnel, furnished to Webb Associates Inc., Yellow Springs, Ohio by the Aerospace Medical Research Laboratories, Wright Patterson Air Force Base, Ohio, 1967.

NASA Astronauts: (Men) Unpublished National Aeronautics and Space Administration - Astronaut Anthropometric Data, furnished to Webb Associates, Inc., Yellow Springs, Ohio by John T. Jackson, NASA Lyndon B. Johnson Space Center, Man-Machine Engineering Section, Houston, Texas, 1976.

Roth, E. M., "Anthropometry and Temporo-Spatial Environment," Volume III, Section 16 in Compendium of Human Responses to the Aerospace Environment. 1968. Washington, D.C.: National Aeronautics and Space Administration, NASA CR-1205(III).

RAF Flying Personnel: (Male) Bolton, C. B., M. Kenward, R. E. Simpson, and G. M. Turner. 1973. An Anthropometric Survey of 2000 Royal Air Force Aircrew, 1970/1971, Royal Aircraft Establishment Technical Report 73083, Procurement Executive, Ministry of Defense, Farnborough, Hants, England.

Italian Military: (Men)	Hertzberg, H. T. E., Edmund Churchill, C. Wesley Dupertuis, Robert M. White, and Albert Damon. 1963. Anthropometric Survey of Turkey, Greece and Italy, New York: The Macmillan Company.
French Fliers: (Men)	Anonymous. 1973. Etude Anthropometrique des Personnels Militaires des Armees (French text). Anthropologie Appliquee, 45 rue des Saints-Peres, Paris 6e, France.
German Air Force: (Men)	Grunhofer, H. J., and G. Kroh (eds.). 1975. A Review of Anthropometric Data of German Air Force and United States Air Force Flying Personnel 1967-1968, AGARDograph No. 205, Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, Neuilly sur Seine, France.

It should be noted that the publication date of the reference does not always coincide with the survey date (e.g., the anthropometric data on USAF women were measured during the spring and summer months of 1968, but the report was published in 1970). When we were able to ascertain the survey date, it has been included on each individual data page.

It will readily become apparent to the user of the anthropometric data that we do not have information on every anthropometric dimension for each of our selected 12 samples. As has been noted, every survey is planned around a somewhat different set of dimensions, and seldom if ever do such lists coincide. Table 1 summarizes the anthropometric data available for the sample populations.

On each of the 59 data pages, the text supplies the name of the dimension, an illustrative sketch, a brief description of the measurement and a guide to its possible applications. Data tabulated for each dimension include: the date of the study, the sample size, the age range of the sample, and the mean, standard deviation and 5th and 95th percentile values in both centimeters and inches for that dimension.

Measurement of the body requires the use of landmarks and anatomical terminology that may not be familiar to the user of this handbook. A glossary of such terms has, therefore, been included as Appendix A to this chapter. The reader is referred to Volume II for data on a much expanded list of dimensions and populations.

Drawings in the following section are illustrative; where there appears to be any discrepancy between the drawing and the measurement definition the written definition should be considered the more accurate.

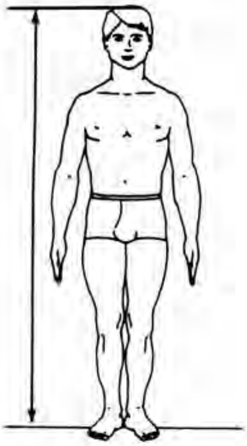
WEIGHT

Definition: Nude body weight as measured on physician's scales.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout;
Body linkage and models;
Equipment design: structural support for seats, platforms, couches, and body-restraint systems and harness rigging.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	57.73 (127.27)	7.52 (16.58)	46.4 (102.3)	70.9 (156.3)
U.S. HEW Civ.	1960-62	1165	25-40	62.38 (137.52)	14.26 (31.44)	46.0 (101.4)	89.4 (197.1)
British Civ.	1957	4989	18-55+	60.40 (133.15)	10.00 (22.05)	46.6 (102.7)	79.4 (175.0)
Swedish Civ.	1968	210	20-49	59.26 (130.64)	6.65 (14.66)	48.3 (106.5)	70.2 (154.8)
Japanese Civ.	1967-68 1972-73	1622	25-39	51.30 (113.09)	7.00 (15.43)	39.8 (87.7)	62.8 (138.4)
MALES							
USAF Flying Personnel	1967	2420	21-50	78.74 (173.58)	9.72 (21.43)	63.6 (140.2)	95.6 (210.8)
NASA Astronauts	Dates Vary	59	28-43	74.51 (164.26)	6.92 (15.26)	65.1 (143.5)	87.3 (192.5)
RAF Flying Personnel	1970-71	1998	18-45	75.04 (165.43)	8.81 (19.42)	61.4 (135.4)	90.3 (199.1)
Italian Military	1960	1342	18-59	70.25 (154.87)	8.42 (18.56)	57.6 (127.0)	85.1 (187.6)
French Fliers	1973	65	27-32	74.0 (163.1)	8.10 (17.9)	60.6 (133.6)	88.3 (194.7)
German AF	1975	1004	Not Reported	74.73 (164.74)	8.10 (17.86)	62.2 (137.1)	88.8 (195.8)
Japanese Civ.	1967-68 1972-73	1870	25-39	60.20 (132.71)	8.60 (18.96)	46.1 (101.6)	74.3 (163.8)

*Data given in kilograms with pounds in parentheses.



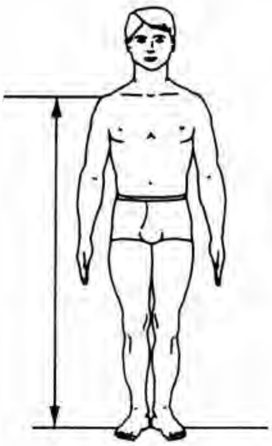
STATURE

Definition: The vertical distance from the standing surface to the top of the head. The subject stands erect and looks straight ahead.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout-specifically, clearances;
Body linkage and models;
Equipment design: vertical clearances of workspaces and living quarters as well as prone or supine clearance of beds, litters, etc.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	162.1 (63.8)	6.0 (2.4)	152.4 (60.0)	172.1 (67.8)
U.S. HEW Civ.	1960-62	1165	25-40	161.7 (63.7)	6.3 (2.5)	151.3 (59.6)	171.9 (67.7)
British Civ.	1957	4995	18-55+	160.1 (63.0)	6.6 (2.6)	149.5 (58.9)	171.2 (67.4)
Swedish Civ.	1968	215	20-49	164.7 (64.8)	6.1 (2.4)	154.6 (60.9)	174.7 (68.8)
Japanese Civ.	1967-68 1972-73	1622	25-39	153.2 (60.3)	4.8 (1.9)	145.3 (57.2)	161.1 (63.4)
MALES							
USAF Flying Personnel	1967	2420	21-50	177.3 (69.8)	6.2 (2.4)	167.2 (65.8)	187.7 (73.9)
NASA Astronauts	Dates Vary	60	28-43	176.4 (69.4)	4.7 (1.9)	167.4 (65.9)	182.8 (72.0)
RAF Flying Personnel	1970-71	2000	18-45	177.4 (69.8)	6.2 (2.4)	167.3 (67.4)	187.8 (73.9)
Italian Military	1960	1342	18-59	170.8 (67.2)	6.2 (2.4)	160.2 (63.1)	180.8 (71.2)
French Fliers	1973	65	27-32	175.6 (69.1)	5.3 (2.1)	166.9 (65.7)	184.6 (72.7)
German AF	1975	1004	Not Reported	176.7 (69.6)	6.2 (2.4)	166.8 (65.7)	187.1 (73.7)
Japanese Civ.	1967-68 1972-73	1870	25-39	165.3 (65.1)	5.8 (2.3)	155.8 (61.3)	174.8 (68.8)

*Data given in centimeters with inches in parentheses.



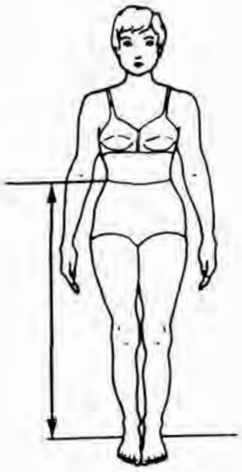
ACROMIAL (SHOULDER) HEIGHT

Definition: The vertical distance from the standing surface to the most lateral point of the acromial process of the scapula. The subject stands erect and looks straight ahead.

Application: General body description; Workspace layout; Body linkage models.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	131.9 (51.9)	5.5 (2.2)	123.0 (48.4)	141.1 (55.6)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	215	20-49	133.8 (52.7)	4.5 (1.8)	126.4 (49.8)	141.1 (55.6)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	145.2 (57.2)	5.8 (2.3)	135.7 (53.4)	154.8 (60.9)
NASA Astronauts	Dates Vary	53	28-43	144.2 (56.8)	4.3 (1.7)	136.7 (53.8)	150.9 (59.4)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	138.9 (54.7)	5.7 (2.2)	129.4 (50.9)	148.2 (58.3)
French Fliers	1973	65	27-32	144.7 (57.0)	5.0 (2.0)	136.3 (53.7)	152.5 (60.0)
German AF	1975	1004	Not Reported	147.2 (58.0)	5.8 (2.3)	137.6 (54.2)	156.9 (61.8)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



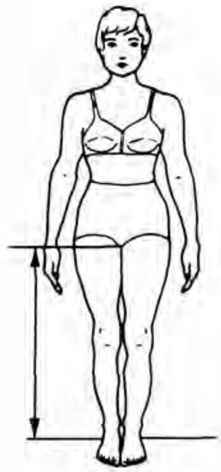
WAIST HEIGHT

<u>Definition:</u> The vertical distance from the standing surface to the waist landmark. The subject stands erect and looks straight ahead.

<u>Application:</u> General body description;
Sizing of clothing and personal protective equipment;
Workspace layout;
Equipment design: height of work surface for standing operation.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	100.3 (39.5)	4.5 (1.8)	93.1 (36.7)	107.9 (42.5)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	214	20-49	98.2 (38.7)	4.1 (1.6)	91.5 (36.0)	104.8 (41.3)
Japanese Civ.	1967-68 1972-73	1622	25-39	93.2 (36.7)	3.7 (1.5)	87.1 (34.3)	99.3 (39.1)
MALES							
USAF Flying Personnel	1967	2420	21-50	106.5 (41.9)	4.7 (1.9)	98.7 (38.9)	114.3 (45.0)
NASA Astronauts	Dates Vary	57	28-43	106.8 (42.0)	3.7 (1.5)	100.7 (39.6)	113.8 (44.8)
RAF Flying Personnel	1970-71	1662	18-45	107.4 (42.3)	5.1 (2.0)	99.2 (39.1)	116.1 (45.7)
Italian Military	1960	1342	18-59	101.3 (39.9)	4.9 (1.9)	93.0 (36.6)	109.2 (43.0)
French Fliers							
German AF	1975	1004	Not Reported	106.6 (42.0)	4.8 (1.9)	98.9 (38.9)	114.6 (45.1)
Japanese Civ.	1967-68 1972-73	1870	25-39	96.2 (37.9)	4.1 (1.6)	89.5 (35.2)	102.9 (40.5)

*Data given in centimeters with inches in parentheses.



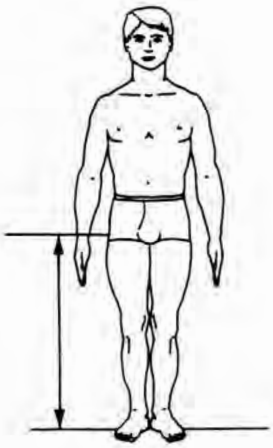
CROTCH HEIGHT

Definition: The vertical distance from the standing surface up into the crotch until light contact is made. The subject stands erect, heels approximately 10 cm. apart, and weight distributed equally on both feet.

Application: Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	74.5 (29.3)	4.0 (1.6)	68.1 (26.8)	81.4 (32.0)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.	1967-68 1972-73	1622	25-39	68.3 (26.9)	3.3 (1.3)	62.9 (24.8)	73.7 (29.0)
MALES							
USAF Flying Personnel	1967	2420	21-50	85.1 (33.5)	4.2 (1.7)	78.3 (30.8)	92.0 (36.2)
NASA Astronauts	Dates Vary	60	28-43	83.5 (32.9)	3.0 (1.2)	78.6 (30.9)	88.7 (34.9)
RAF Flying Personnel	1970-71	2000	18-45	85.4 (33.6)	4.3 (1.7)	78.4 (30.9)	92.5 (36.4)
Italian Military	1960	1342	18-59	80.7 (31.8)	4.2 (1.7)	73.6 (29.0)	87.6 (34.5)
French Fliers	1973	65	27-32	81.8 (32.2)	3.3 (1.3)	76.9 (30.3)	87.8 (34.6)
German AF	1975	1004	Not Reported	83.8 (33.0)	4.2 (1.7)	76.9 (30.3)	90.8 (35.7)
Japanese Civ.	1967-68 1972-73	1870	25-39	73.6 (29.0)	3.7 (1.5)	67.5 (26.6)	79.7 (31.4)

*Data given in centimeters with inches in parentheses.



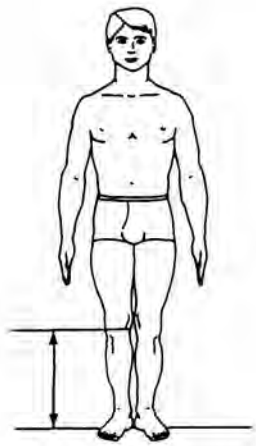
TROCHANTERIC HEIGHT

Definition: The vertical distance from the standing surface to the most superior point of the greater trochanter of the femur. The subject stands erect looking straight ahead, heels together and weight distributed equally on both feet.

Application: Body linkage and models.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	82.7 (32.6)	4.3 (1.7)	75.7 (29.8)	89.8 (35.4)
U.S. HEW Civ.							
British Civ.	1957	4995	18-55+	80.4 (31.7)	4.4 (1.7)	73.3 (28.9)	87.7 (34.5)
Swedish Civ.	1968	215	20-49	83.6 (32.9)	4.0 (1.6)	77.0 (30.3)	90.2 (35.5)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	94.0 (37.0)	4.4 (1.7)	86.9 (34.2)	101.3 (39.9)
NASA Astronauts	Dates Vary	56	28-43	92.0 (36.2)	3.3 (1.3)	87.1 (34.3)	97.8 (38.5)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	88.8 (35.0)	4.4 (1.7)	81.5 (32.1)	96.0 (37.8)
French Fliers	1973	65	27-32	92.2 (36.3)	3.6 (1.4)	86.6 (34.1)	98.5 (38.8)
German AF	1975	1004	Not Reported	91.8 (36.1)	4.6 (1.8)	84.2 (33.)	99.5 (39.2)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



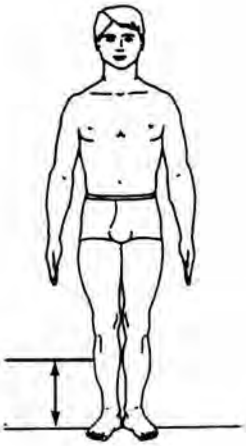
TIBIALE HEIGHT

Definition: The vertical distance from the standing surface to the proximal medial margin of the tibia. The subject stands erect, heels together and weight distributed equally on both feet.

Application: Body linkage and models.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	42.0 (16.5)	2.4 (0.9)	38.2 (15.0)	46. (18.)
U.S. HEW Civ.							
British Civ.	1957	4995	18-55+	43.0 (16.9)	2.7 (1.1)	38.7 (15.2)	47.5 (18.7)
Swedish Civ.	1968	214	20-49	43.9 (17.3)	4.6 (1.8)	36.4 (14.3)	51.4 (20.2)
Japanese Civ.	1967-68 1972-73	1622	25-39	38.6 (15.2)	1.8 (0.7)	35.6 (14.0)	41.6 (16.4)
MALES							
USAF Flying Personnel							
NASA Astronauts	Dates Vary	24	28-43	46.6 (18.3)	1.7 (0.7)	43.8 (17.2)	49.4 (19.4)
RAF Flying Personnel							
Italian Military							
French Fliers	1973	65	27-32	46.2 (18.2)	2.0 (0.8)	42.8 (16.9)	49.0 (19.3)
German AF							
Japanese Civ.	1967-68 1972-73	1870	25-39	42.1 (16.6)	2.0 (0.8)	38.8 (15.3)	45.4 (17.9)

*Data given in centimeters with inches in parentheses.



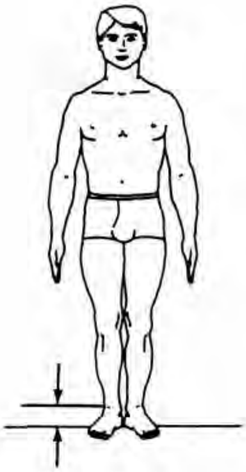
CALF HEIGHT

Definition: The vertical distance from the standing surface to the maximum posterior protrusion of the gastrocnemius. The subject stands erect, heels together and weight distributed equally on both feet.

Application: Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES USAF Women							
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES USAF Flying Personnel	1967	2420	21-50	35.6 (14.0)	2.2 (0.9)	32.0 (12.6)	39.3 (15.5)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	34.6 (13.6)	2.1 (0.8)	31.2 (12.3)	38.1 (15.0)
French Fliers							
German AF	1975	1004	Not Reported	35.1 (13.8)	2.4 (0.9)	31.2 (12.3)	39.3 (15.5)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



ANKLE HEIGHT

Definition: The vertical distance from the standing surface to the level of the minimum circumference of the ankle. The subject stands with his weight equally distributed on both feet.

Application: Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	11.2 (4.4)	1.4 (0.6)	9.2 (3.6)	13.6 (5.4)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	13.7 (5.4)	1.2 (0.5)	12.0 (4.7)	15.8 (6.2)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	12.9 (5.1)	0.6 (0.2)	11.9 (4.7)	13.9 (5.5)
French Fliers							
German AF							
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

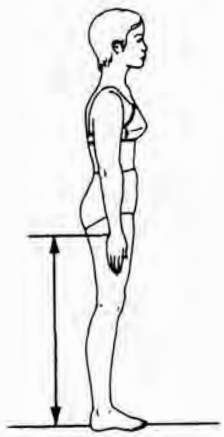
ELBOW HEIGHT

Definition: The vertical distance from the standing surface to the depression at the elbow between the humerus and the radius. The subject stands erect with his arms hanging naturally at his sides.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout;
Body linkage and models.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women							
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	112.3 (44.2)	4.6 (1.8)	104.8 (41.3)	120.0 (47.2)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	106.1 (41.8)	4.6 (1.8)	98.5 (38.8)	113.7 (44.8)
French Fliers							
German AF	1975	1004	Not Reported	110.9 (43.7)	4.5 (1.8)	103.6 (40.8)	118.6 (46.7)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



WRIST HEIGHT

Definition: The vertical distance from the standing surface to the most distal point of the ulna. The subject stands erect with his arms hanging naturally at his sides.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout;
Body linkage and models.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X	SD	5%ile	95%ile
FEMALES							
USAF Women							
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	86.6 (34.1)	3.9 (1.5)	80.2 (31.6)	93.3 (36.7)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	81.5 (32.1)	3.7 (1.5)	75.4 (29.7)	87.6 (34.5)
French Fliers							
German AF	1975	1004	Not Reported	87.2 (34.3)	4.0 (1.6)	80.6 (31.7)	94.0 (37.0)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

SITTING HEIGHT

Definition: The vertical distance from the sitting surface to the top of the head. The subject sits erect, looking straight ahead.

Application: General body description; Workspace layout; Body linkage and models; Equipment design: minimum vertical clearance from the seat surface of the seated operator.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	85.6 (33.7)	3.2 (1.3)	80.4 (31.7)	90.9 (35.8)
U.S. HEW Civ.	1960-62	1165	25-40	85.6 (33.7)	3.3 (1.3)	79.9 (31.5)	91.4 (36.0)
British Civ.							
Swedish Civ.	1968	214	20-49	87.3 (34.4)	3.0 (1.2)	82.3 (32.4)	92.2 (36.3)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	93.2 (36.7)	3.2 (1.3)	88.1 (34.7)	98.6 (38.8)
NASA Astronauts	Dates Vary	28	28-43	92.4 (36.4)	2.6 (1.0)	88.1 (34.7)	96.7 (38.1)
RAF Flying Personnel	1970-71	2000	18-45	93.6 (36.9)	3.1 (1.2)	88.4 (34.8)	98.6 (38.8)
Italian Military	1960	1342	18-59	89.7 (35.3)	3.2 (1.3)	84.3 (33.2)	94.8 (37.3)
French Fliers	1973	65	27-32	93.2 (36.7)	3.0 (1.2)	88.3 (34.8)	97.3 (38.3)
German AF	1975	1004	Not Reported	91.3 (35.9)	3.1 (1.2)	86.1 (33.9)	96.5 (38.0)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

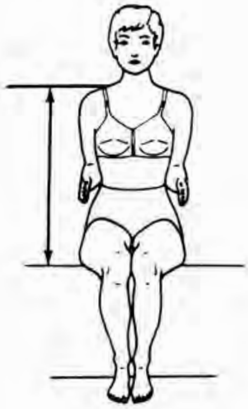
EYE HEIGHT, SITTING

Definition: The vertical distance from the sitting surface to the outer corner (external canthus) of the eye. The subject sits erect and looks straight ahead.

Application: General body description; Workspace layout; Body linkage and models; Equipment design: vertical distance from the seat surface to operator's eye position for optimum vision of workspace.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	73.7 (29.0)	3.1 (1.2)	68.7 (27.0)	78.8 (31.0)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	81.0 (31.9)	3.0 (1.2)	76.2 (30.0)	86.1 (33.9)
NASA Astronauts	Dates Vary	24	28-43	80.7 (31.8)	2.9 (1.1)	75.9 (29.9)	85.5 (33.7)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	78.0 (30.7)	3.0 (1.2)	73.1 (28.8)	82.9 (32.6)
French Fliers	1973	65	27-32	83.4 (32.8)	3.2 (1.3)	77.5 (30.5)	87.7 (34.5)
German AF	1975	1004	Not Reported	80.0 (31.5)	3.1 (1.2)	74.7 (29.4)	84.9 (33.4)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



MIDSHOULDER HEIGHT, SITTING

Definition: The vertical distance from the sitting surface to a point on the upper surface of the shoulder midway between the acromiale and the neck. The subject sits erect with his upper arms hanging relaxed and forearms and hands extended forward horizontally.

Application: Sizing of clothing;
Personal protective equipment;
Workspace layout;
Equipment design: placement of upper torso restraint for seated operator.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	58.0 (22.8)	2.7 (1.1)	53.7 (21.1)	62.5 (24.6)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	64.6 (25.4)	2.7 (1.1)	60.2 (23.7)	69.2 (27.2)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	61.3 (24.1)	2.6 (1.0)	57.1 (22.5)	65.6 (25.8)
French Fliers							
German AF	1975	1004	Not Reported	62.3 (24.5)	2.8 (1.1)	57.5 (22.6)	66.8 (26.3)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

ELBOW REST HEIGHT

Definition: The vertical distance from the sitting surface to the bottom of the elbow. The subject sits erect with his upper arms hanging relaxed and forearms and hands extended forward horizontally.

Application: Workspace layout; Equipment design: vertical distance from the seat surface to the top of the arm rest for the seated operator.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	22.7 (8.9)	2.5 (1.0)	18.7 (7.4)	26.9 (10.6)
U.S. HEW Civ.	1960-62	1165	25-40	23.6 (9.3)	2.8 (1.1)	18.9 (7.4)	28.4 (11.2)
British Civ.							
Swedish Civ.	1968	212	20-49	23.0 (9.1)	2.3 (0.9)	19.2 (7.6)	26.7 (10.5)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	25.2 (9.9)	2.6 (1.0)	20.9 (8.2)	29.5 (11.6)
NASA Astronauts							
RAF Flying Personnel	1970-71	2000	18-45	24.8 (9.8)	2.5 (1.0)	20.7 (8.1)	28.9 (11.4)
Italian Military	1960	1342	18-59	22.5 (8.9)	2.3 (0.9)	18.8 (7.4)	26.2 (10.3)
French Fliers	1973	65	27-32	25.6 (10.1)	2.2 (0.9)	22.0 (8.7)	28.8 (11.3)
German AF	1975	1004	Not Reported	23.9 (9.4)	2.7 (1.1)	19.3 (7.6)	28.4 (11.2)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

KNEE HEIGHT, SITTING

Definition: The vertical distance from the floor to the uppermost point on the knee. The subject sits erect with his knees and ankles at right angles.

Application: Workspace layout; Equipment design: vertical clearance from the floor to the underside of work surfaces and consoles for the seated operator.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women							
U.S. HEW Civ.	1960-62	1165	25-40	50.0 (19.7)	2.7 (1.1)	45.5 (17.9)	54.6 (21.5)
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	55.8 (22.0)	2.5 (1.0)	51.7 (20.4)	59.9 (23.6)
NASA Astronauts							
RAF Flying Personnel	1970-71	2000	18-45	55.9 (22.0)	2.5 (1.0)	51.9 (20.4)	60.3 (23.7)
Italian Military	1960	1342	18-59	53.4 (21.0)	2.6 (1.0)	49.2 (19.4)	57.9 (22.8)
French Fliers	1973	65	27-32	55.4 (21.8)	1.9 (0.7)	52.5 (20.7)	58.1 (22.9)
German AF	1975	1004	Not Reported	54.5 (21.5)	2.5 (1.0)	50.6 (19.9)	58.8 (23.1)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

POPLITEAL HEIGHT

Definition: The vertical distance from the floor to the underside of the thigh immediately behind the knee. The subject sits erect with his knees and ankles at right angles.

Application: Workspace layout; Equipment design: vertical distance from the floor to the top forward edge of the seat pan for the seated operator.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	41.1 (16.2)	1.9 (0.7)	38.0 (15.0)	44.1 (17.)
U.S. HEW Civ.	1960-62	1165	25-40	40.0 (15.7)	2.6 (1.0)	35.8 (14.1)	44.3 (17.4)
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	43.7 (17.2)	2.3 (0.9)	40.1 (15.8)	47.5 (18.7)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	40.3 (15.9)	2.3 (0.9)	36.6 (14.4)	44.2 (17.4)
French Fliers	1973	65	27-32	45.6 (18.0)	1.5 (0.6)	42.6 (16.8)	47.7 (18.8)
German AF	1975	1004	Not Reported	43.8 (17.2)	2.1 (0.8)	40.4 (15.9)	47.4 (18.7)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

SHOULDER-ELBOW LENGTH

Definition: The distance from the top of the acromion process to the bottom of the elbow. The subject sits erect with his upper arms vertical and forearms and hands extended forward horizontally.

Application: Workspace layout;
Body linkage and models;
Equipment design: used in conjunction with shoulder height and shoulder height sitting to establish the vertical placement of work surfaces and controls.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women							
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	36.0 (14.2)	1.7 (0.7)	33.2 (13.1)	38.8 (15.3)
NASA Astronauts	Dates Vary	57	28-43	36.5 (14.4)	1.5 (0.6)	34.5 (13.6)	39.5 (15.6)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	35.6 (14.0)	1.7 (0.7)	32.9 (13.0)	38.5 (15.2)
French Fliers	1973	65	27-32	32.2 (12.7)	1.7 (0.7)	30.0 (11.8)	34.7 (13.7)
German AF	1975	1004	Not Reported	36.6 (14.4)	2.1 (0.8)	33.1 (13.0)	39.9 (15.7)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

FOREARM-HAND LENGTH

<u>Definition</u>: The distance from the tip of the elbow to the tip of the longest finger. The subject sits erect with his upper arms vertical and forearms and hands extended forward horizontally.

<u>Application</u>: Workspace layout;
Body linkage and models;
Equipment design: a minimum fingertip reach distance for workplace layout with the upper arm restrained.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women							
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	215	20-49	44.2 (17.4)	2.5 (1.0)	40.2 (15.8)	48.2 (19.0)
Japanese Civ.							
MALES							
USAF Flying Personnel							
NASA Astronauts	Dates Vary	28	28-43	47.6 (18.7)	2.0 (0.8)	44.3 (17.4)	50.9 (20.0)
RAF Flying Personnel	1970-71	1999	18-45	48.0 (18.9)	2.0 (0.8)	44.7 (17.6)	51.4 (20.2)
Italian Military							
French Fliers							
German AF							
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

BUTTOCK-POPLITEAL LENGTH

Definition: The horizontal distance from the most posterior aspect of the right buttock to the back of the lower leg at the knee. The subject sits erect with his knees and ankles at right angles.

Application: Workspace layout;
Body linkage and models;
Equipment design: horizontal distance from the rear to the front edge of the seat pan to accommodate the thigh length of the seated operator.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	47.7 (18.8)	2.8 (1.1)	43.5 (17.1)	52.6 (20.7)
U.S. HEW Civ.	1960-62	1165	25-40	48.1 (18.9)	3.1 (1.2)	43.0 (16.9)	53.6 (21.1)
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	50.4 (19.8)	2.6 (1.0)	46.1 (18.1)	54.6 (21.5)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	48.0 (18.9)	2.5 (1.0)	44.1 (17.4)	52.2 (20.6)
French Fliers	1973	65	27-32	49.0 (19.3)	2.0 (0.8)	46.3 (18.2)	52.0 (20.5)
German AF	1975	1004	Not Reported	48.9 (19.3)	2.5 (1.0)	44.8 (17.6)	53.0 (20.9)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

BUTTOCK-KNEE LENGTH

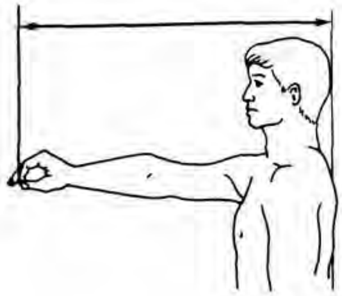
Definition: The horizontal distance from the most posterior aspect of the right buttock to the most anterior aspect of the right kneecap. The subject sits erect with his knees and ankles at right angles.

Application: Workspace layout;
Body linkage and models;
Equipment design: horizontal clearance from the front surface of the seat back rest to accommodate the upper leg length of the seated operator.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	57.4 (22.6)	2.6 (1.0)	53.2 (20.9)	61.9 (24.4)
U.S. HEW Civ.	1960-62	1165	25-40	57.1 (22.5)	3.1 (1.2)	52.0 (20.5)	62.8 (24.7)
British Civ.							
Swedish Civ.	1968	215	20-49	58.6 (23.1)	3.1 (1.2)	53.6 (21.1)	63.6 (25.0)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	60.4 (23.8)	2.7 (1.1)	56.1 (22.1)	65.0 (25.6)
NASA Astronauts	Dates Vary	23	28-43	60.4 (23.8)	1.5 (0.6)	57.9 (22.8)	62.9 (24.8)
RAF Flying Personnel	1970-71	2000	18-45	60.8 (23.9)	2.7 (1.1)	56.4 (22.2)	65.2 (25.7)
Italian Military	1960	1342	18-59	58.2 (22.9)	2.6 (1.0)	54.1 (21.3)	62.6 (24.6)
French Fliers	1973	65	27-32	59.5 (23.4)	2.2 (0.9)	56.3 (22.2)	63.1 (24.8)
German AF	1975	1004	Not Reported	60.2 (23.7)	2.6 (1.0)	56.0 (22.0)	64.6 (25.4)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

THUMB-TIP REACH



<u>Definition</u>: The horizontal distance from the wall to the tip of the thumb, measured with the subject's back against the wall, his arm extended forward, and his index finger touching the tip of his thumb.

<u>Application</u>: Workspace layout; Equipment design: a minimum forward thumbtip reach distance with shoulder and torso restrained.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	74.1 (29.2)	3.9 (1.5)	67.7 (26.7)	80.5 (31.7)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	80.3 (31.6)	4.0 (1.6)	73.9 (29.1)	87.0 (34.3)
NASA Astronauts							
RAF Flying Personnel	1970-71	1997	18-45	80.2 (31.6)	3.6 (1.4)	74.4 (29.3)	85.1 (33.5)
Italian Military	1960	1342	18-59	75.3 (29.6)	3.7 (1.5)	69.3 (27.3)	81.6 (32.1)
French Fliers							
German AF	1975	1004	Not Reported	80.0 (31.5)	4.3 (1.7)	73.1 (28.8)	87.1 (34.3)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

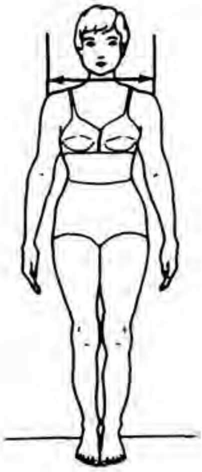
THIGH CLEARANCE

<u>Definition:</u> The vertical distance from the sitting surface to the highest point on the right thigh. The subject sits erect with his knees and ankles at right angles.

<u>Application:</u> Workspace layout; Equipment design: vertical clearance from the top of the seat surface to the underside of work tables and consoles for the seated operator.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	12.4 (4.9)	1.3 (0.5)	10.4 (4.1)	14.6 (5.7)
U.S. HEW Civ.	1960-62	1165	25-40	13.9 (5.5)	1.9 (0.7)	10.7 (4.2)	17.8 (7.0)
British Civ.							
Swedish Civ.	1968	214	20-49	15.4 (6.1)	1.3 (0.5)	13.2 (5.2)	17.5 (6.9)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	16.5 (6.5)	1.4 (0.6)	14.3 (5.6)	18.8 (7.4)
NASA Astronauts							
RAF Flying Personnel	1970-71	588	18-45	15.8 (6.2)	1.2 (0.5)	13.9 (5.5)	17.8 (7.0)
Italian Military	1960	1342	18-59	16.1 (6.3)	1.1 (0.4)	14.4 (5.7)	18.0 (7.1)
French Fliers	1973	65	27-32	14.5 (5.7)	1.1 (0.4)	12.7 (5.0)	16.4 (6.5)
German AF	1975	1004	Not Reported	15.5 (6.1)	1.5 (0.6)	13.2 (5.2)	18.0 (7.1)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



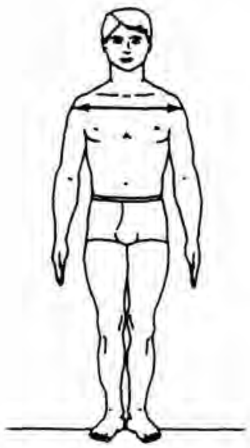
BIACROMIAL BREADTH

Definition: The horizontal distance across the body between the acromial landmarks. The subject stands erect with arms hanging naturally at her sides.

Application: General body description; Sizing of clothing and personal protective equipment; Workspace layout; Body linkage and models.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	35.8 (14.1)	1.6 (0.6)	33.2 (13.1)	38.6 (15.2)
U.S. HEW Civ.	1960-62	1165	25-40	35.7 (14.1)	1.9 (0.7)	32.3 (12.7)	39.1 (15.4)
British Civ.	1957	4995	18-55+	35.1 (13.8)	1.9 (0.7)	32.0 (12.6)	38.1 (15.0)
Swedish Civ.	1968	215	20-49	35.4 (13.9)	1.5 (0.6)	32.9 (13.0)	37.8 (14.9)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	40.7 (16.0)	1.9 (0.7)	37.5 (14.8)	43.8 (17.2)
NASA Astronauts	Dates Vary	52	28-43	40.5 (15.9)	1.7 (0.7)	38.0 (15.0)	43.5 (17.1)
RAF Flying Personnel	1970-71	2000	18-45	40.7 (16.0)	1.9 (0.7)	37.5 (14.8)	43.8 (17.2)
Italian Military	1960	1342	18-59	39.8 (15.7)	1.8 (0.7)	36.8 (14.5)	42.8 (16.9)
French Fliers	1973	65	27-32	39.9 (15.7)	1.8 (0.7)	37.0 (14.6)	42.6 (16.8)
German AF	1975	1004	Not Reported	38.5 (15.2)	2.4 (0.9)	34.3 (13.5)	42.3 (16.7)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



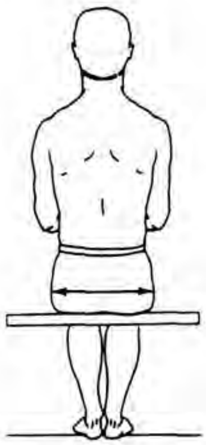
BIDELTOID (SHOULDER) BREADTH

Definition: The horizontal distance across the body at the level of the deltoid landmarks. The subject stands erect with his arms hanging naturally at his sides.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout;
Body linkage and models;
Equipment design: clearance dimension of crawlway, hatches, and the like, and minimum breadth of cockpits and other workspaces.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	41.9 (16.5)	2.3 (0.9)	38.2 (15.0)	45.9 (18.1)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	48.2 (19.0)	2.6 (1.0)	44.1 (17.4)	52.6 (20.7)
NASA Astronauts	Dates Vary	56	28-43	48.0 (18.9)	1.9 (0.7)	44.6 (17.6)	51.0 (20.1)
RAF Flying Personnel	1970-71	1993	18-45	46.6 (18.3)	2.1 (0.8)	43.2 (17.0)	50.1 (19.7)
Italian Military	1960	1342	18-59	46.2 (18.2)	2.2 (0.9)	42.8 (16.9)	49.9 (19.6)
French Fliers	1973	65	27-32	47.6 (18.7)	2.1 (0.8)	43.4 (17.1)	50.6 (19.9)
German AF	1975	1004	Not Reported	46.2 (18.2)	2.4 (0.9)	42.4 (16.7)	50.2 (19.8)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



HIP BREADTH, SITTING

Definition: The maximum horizontal distance across the thighs. The subject sits erect, upper arms relaxed, forearms and hands extended forward horizontally, thighs completely supported by the sitting surface, and the long axis of the thighs parallel.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout;
Body linkage and models;
Equipment design: horizontal breadth of sitting support surfaces.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women							
U.S. HEW Civ.	1960-62	1165	25-40	36.4 (14.3)	3.7 (1.5)	31.1 (12.2)	43.3 (17.0)
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	37.8 (14.9)	2.3 (0.9)	34.2 (13.5)	41.8 (16.5)
NASA Astronauts	Dates Vary	27	28-43	36.5 (14.4)	1.5 (0.6)	34.0 (13.4)	39.0 (15.4)
RAF Flying Personnel	1970-71	2000	18-45	36.8 (14.5)	2.0 (0.8)	33.7 (13.3)	40.0 (15.7)
Italian Military	1960	1342	18-59	35.7 (14.1)	1.8 (0.7)	32.7 (12.9)	38.7 (15.2)
French Fliers	1973	65	27-32	36.8 (14.5)	1.9 (0.7)	33.9 (13.3)	39.5 (15.6)
German AF							
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

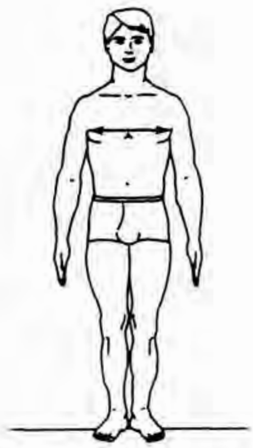
CHEST (BUST) DEPTH

Definition: The horizontal depth of the trunk at the level of the nipples. The subject stands erect, looking straight ahead, heels together, and weight distributed equally on both feet.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	23.6 (9.3)	1.9 (0.7)	20.9 (8.2)	27.2 (10.7)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	24.5 (9.6)	1.9 (0.7)	21.3 (8.4)	27.7 (10.9)
NASA Astronauts	Dates Vary	28	28-43	24.0 (9.4)	(1.6 (0.6)	21.4 (8.4)	26.6 (10.5)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	23.8 (9.4)	1.7 (0.7)	21.1 (8.3)	26.8 (10.6)
French Fliers	1973	65	27-32	25.1 (9.9)	1.7 (0.7)	22.7 (8.9)	28.0 (11.0)
German AF	1975	1004	Not Reported	23.2 (9.1)	2.0 (0.8)	20.1 (7.9)	26.7 (10.5)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



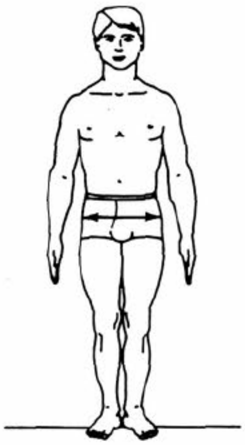
CHEST BREADTH

<u>Definition:</u> The horizontal distance across the trunk at the level of the nipples. The subject stands erect, looking straight ahead, with his arms slightly abducted.

<u>Application:</u> General body description;
Sizing of clothing and personal protective equipment;
Workspace layout;
Equipment design: clearance breadth of torso-worn personal protective equipment such as respirator packs, rigid body armor, and back packs.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics * X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	28.0 (11.0)	1.9 (0.7)	25.1 (9.9)	31.4 (12.4)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	213	20-49	25.3 (10.0)	1.2 (0.5)	23.3 (9.2)	27.4 (10.8)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	32.8 (12.9)	2.1 (0.8)	29.5 (11.6)	36.5 (14.4)
NASA Astronauts	Dates Vary	57	28-43	32.1 (12.6)	1.9 (0.7)	29.3 (11.5)	35.6 (14.0)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	31.8 (12.5)	1.8 (0.7)	29.0 (11.4)	34.9 (13.7)
French Fliers	1973	65	27-32	32.1 (12.6)	1.9 (0.7)	29.0 (11.4)	35.7 (14.1)
German AF	1975	1004	Not Reported	31.3 (12.3)	2.3 (0.9)	27.7 (10.9)	35.4 (13.9)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



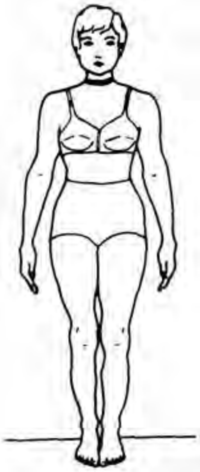
HIP BREADTH

Definition: The maximum horizontal distance across the hips. The subject stands erect, heels together and weight distributed equally on both feet.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	35.0 (13.8)	2.2 (0.9)	31.6 (12.4)	38.8 (15.3)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	35.3 (13.9)	1.9 (0.7)	32.3 (12.7)	38.5 (15.2)
NASA Astronauts	Dates Vary	56	28-43	34.7 (13.7)	1.7 (0.7)	31.7 (12.5)	37.6 (14.8)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	34.2 (13.5)	1.7 (0.7)	31.5 (12.4)	37.1 (14.6)
French Fliers							
German AF	1975	1004	Not Reported	35.2 (13.9)	1.8 (0.7)	32.3 (12.7)	38.3 (15.1)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



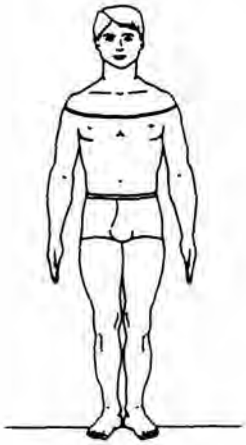
NECK CIRCUMFERENCE

Definition: The maximum circumference of the neck at a point just inferior to the bulge of the thyroid cartilage. The subject sits erect, head in the Frankfort plane.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	33.8 (13.3)	1.7 (0.7)	31.1 (12.2)	36.7 (14.4)
U.S. HEW Civ.							
British Civ.	1957	4995	18-55+	38.4 (15.1)	2.0 (0.8)	35.3 (13.9)	41.7 (16.4)
Swedish Civ.							
Japanese Civ.	1967-68 1972-73	1622	25-39	37.1 (14.6)	1.7 (0.7)	34.3 (13.5)	39.9 (15.7)
MALES							
USAF Flying Personnel	1967	2420	21-50	38.3 (15.1)	1.9 (0.7)	35.4 (13.9)	41.7 (16.4)
NASA Astronauts	Dates Vary	50	28-43	38.2 (15.0)	1.8 (0.7)	35.0 (13.8)	41.1 (16.2)
RAF Flying Personnel	1970-71	2000	18-45	38.2 (15.0)	1.7 (0.7)	35.5 (14.0)	41.0 (16.1)
Italian Military	1960	1342	18-59	37.6 (14.8)	1.7 (0.7)	35.2 (13.9)	40.7 (16.0)
French Fliers	1973	65	27-32	37.9 (14.9)	2.0 (0.8)	34.9 (13.7)	41.0 (16.1)
German AF	1975	1004	Not Reported	38.1 (15.0)	1.7 (0.7)	35.4 (13.9)	41.2 (16.2)
Japanese Civ.	1967-68 1972-73	1870	25-39	36.0 (14.2)	1.9 (0.7)	32.9 (13.0)	39.1 (15.4)

*Data given in centimeters with inches in parentheses.



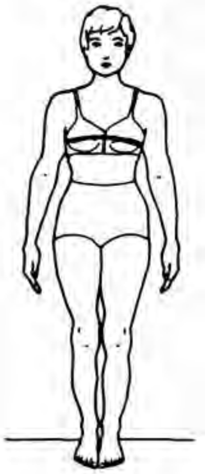
SHOULDER CIRCUMFERENCE

Definition: The horizontal circumference of the body over the deltoid muscles. The subject stands erect, looking straight ahead, arms relaxed at the sides, heels together, and weight distributed equally on both feet.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	100.4 (39.5)	5.1 (2.0)	92.6 (36.5)	109.4 (43.1)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	117.7 (46.3)	5.8 (2.3)	108.4 (42.7)	127.6 (50.2)
NASA Astronauts	Dates Vary	56	28-43	116.2 (45.7)	4.3 (1.7)	109.7 (43.2)	123.8 (48.7)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	112.8 (44.4)	5.0 (2.0)	105.0 (41.3)	121.4 (47.8)
French Fliers	1973	65	27-32	115.6 (45.5)	5.2 (2.0)	106.4 (41.9)	122.7 (48.3)
German AF	1975	1004	Not Reported	115.7 (45.6)	5.6 (2.2)	106.7 (42.0)	125.3 (49.3)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



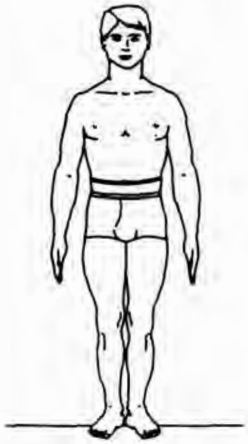
CHEST CIRCUMFERENCE

Definition: The horizontal circumference of the chest at the level of the nipples. The subject stands erect, looking straight ahead, heels together, and weight distributed equally on both feet.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout;
Equipment design: upper torso restraint systems and rigging.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	89.7 (35.3)	5.7 (2.2)	81.6 (32.1)	100.2 (39.4)
U.S. HEW Civ.	1960-62	1165	25-40	86.6 (34.1)	7.9 (3.1)	76.6 (30.2)	101.8 (40.1)
British Civ.	1957	4995	18-55+	92.7 (36.5)	8.7 (3.4)	81.5 (32.1)	109.6 (43.1)
Swedish Civ.	1968	215	20-49	86.0 (33.9)	4.6 (1.8)	78.5 (30.9)	93.4 (36.8)
Japanese Civ.	1967-68 1972-73	1622	25-39	83.6 (32.9)	6.4 (2.5)	73.1 (28.8)	94.1 (37.0)
MALES							
USAF Flying Personnel	1967	2420	21-50	98.6 (38.8)	6.4 (2.5)	88.6 (34.9)	109.4 (43.1)
NASA Astronauts	Dates Vary	53	28-43	97.1 (38.2)	4.8 (1.9)	90.1 (35.5)	107.1 (42.2)
RAF Flying Personnel	1970-71	1999	18-45	97.2 (38.3)	5.7 (2.2)	88.3 (34.8)	107.1 (42.2)
Italian Military	1960	1342	18-59	94.9 (37.4)	5.2 (2.0)	87.0 (34.3)	104.0 (40.9)
French Fliers	1973	65	27-32	96.0 (37.8)	5.8 (2.3)	86.6 (34.1)	104.1 (41.0)
German AF	1975	1004	Not Reported	94.7 (37.3)	6.3 (2.5)	84.7 (33.3)	105.3 (41.5)
Japanese Civ.	1967-68 1972-73	1870	25-39	88.1 (34.7)	5.3 (2.1)	79.4 (31.3)	96.8 (38.1)

*Data given in centimeters with inches in parentheses.



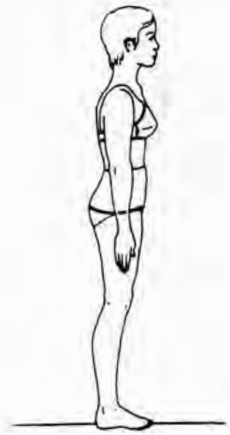
WAIST CIRCUMFERENCE

Definition: The horizontal circumference of the trunk at the level of the waist landmarks. Subject stands erect, looking straight ahead, heels together and weight distributed equally on both feet.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	67.2 (26.5)	5.5 (2.2)	59.5 (23.4)	77.2 (30.4)
U.S. HEW Civ.	1960-62	1165	25-40	73.6 (29.0)	11.0 (4.3)	60.9 (24.0)	95.1 (37.4)
British Civ.	1957	4995	18-55+	68.3 (26.9)	8.9 (3.5)	58.1 (22.9)	86.2 (33.9)
Swedish Civ.	1968	215	20-49	67.7 (26.7)	4.2 (1.7)	60.8 (23.9)	74.6 (29.4)
Japanese Civ.	1967-68 1972-73	1622	25-39	67.1 (26.4)	6.3 (2.5)	56.7 (22.3)	77.5 (30.5)
MALES							
USAF Flying Personnel	1967	2420	21-50	87.6 (34.5)	7.4 (2.9)9	75.7 (29.8)	100.1 (39.4)
NASA Astronauts	Dates Vary	59	28-43	82.1 (32.3)	4.5 (1.8)	74.7 (29.4)	90.2 (35.5)
RAF Flying Personnel	1970-71	1662	18-45	85.7 (33.7)	7.0 (2.8)	74.7 (29.4)	97.8 (38.5)
Italian Military	1960	1342	18-59	82.4 (32.4)	7.1 (2.8)	72.3 (28.5)	95.3 (37.5)
French Fliers	1973	65	27-32	84.8 (33.4)	6.3 (2.5)	74.4 (29.3)	94.0 (37.0)
German AF	1975	1004	Not Reported	84.0 (33.1)	6.8 (2.7)	73.5 (28.9)	96.1 (37.8)
Japanese Civ.	1967-68 1972-73	1870	25-39	76.5 (30.1)	7.9 (3.1)	63.5 (25.0)	89.5 (35.2)

*Data given in centimeters with inches in parentheses.



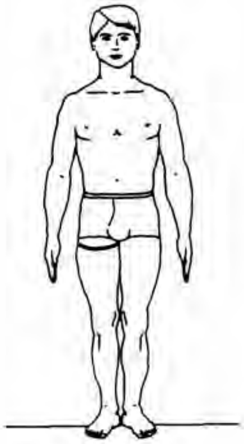
BUTTOCK CIRCUMFERENCE

Definition: The circumference of the hips at the level of the maximum posterior protrusion of the buttocks. The subject stands erect, looking straight ahead, heels together, and weight distributed equally on both feet.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	95.3 (37.5)	6.0 (2.4)	85.8 (33.8)	105.6 (41.6)
U.S. HEW Civ.							
British Civ.	1957	4994	18-55+	97.6 (38.4)	7.9 (3.1)	87.0 (34.3)	112.4 (44.3)
Swedish Civ.	1968	214	20-49	88.1 (34.7)	6.1 (2.4)	78.1 (30.7)	98.0 (38.6)
Japanese Civ.	1967-68 1972-73	1622	25-39	90.0 (35.4)	5.2 (2.0)	81.4 (32.0)	98.6 (38.8)
MALES							
USAF Flying Personnel	1967	2420	21-50	98.6 (38.8)	5.5 (2.2)	89.7 (35.3)	107.9 (42.5)
NASA Astronauts	Dates Vary	58	28-43	96.1 (37.8)	4.0 (1.6)	89.5 (35.2)	102.8 (40.5)
RAF Flying Personnel	1970-71	1999	18-45	98.9 (38.9)	5.0 (2.0)	90.8 (35.7)	107.3 (42.2)
Italian Military	1960	1342	18-59	95.1 (37.4)	4.9 (1.9)	87.3 (34.4)	103.4 (40.7)
French Fliers	1973	65	27-32	96.5 (38.0)	5.0 (2.0)	87.8 (34.6)	104.0 (40.9)
German AF	1975	1004	Not Reported	96.6 (38.0)	4.7 (1.9)	89.1 (35.1)	104.5 (41.1)
Japanese Civ.	1967-68 1972-73	1870	25-39	90.3 (35.6)	5.2 (2.0)	81.7 (32.2)	98.9 (38.9)

*Data given in centimeters with inches in parentheses.



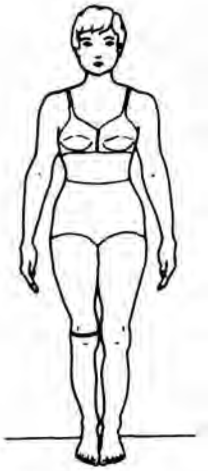
THIGH CIRCUMFERENCE

Definition: The circumference of the thigh at the level of the gluteal furrow. The subject stands erect, heels approximately 10 cm. apart, and weight distributed equally on both sides.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	55.5 (21.9)	4.2 (1.7)	48.7 (19.2)	62.6 (24.6)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	215	20-49	56.3 (22.2)	4.7 (1.9)	48.7 (19.2)	64.0 (25.2)
Japanese Civ.	1967-68 1972-73	1622	25-39	51.5 (20.3)	3.8 (1.5)	45.2 (17.8)	57.8 (22.8)
MALES							
USAF Flying Personnel	1967	2420	21-50	58.8 (23.1)	4.4 (1.7)	51.5 (20.3)	66.2 (26.1)
NASA Astronauts	Dates Vary	57	28-43	56.9 (22.4)	2.9 (1.1)	52.3 (20.6)	61.8 (24.3)
RAF Flying Personnel	1970-71	2000	18-45	57.0 (22.4)	3.9 (1.5)	50.6 (19.9)	63.3 (24.9)
Italian Military	1960	1342	18-59	54.5 (21.5)	3.5 (1.4)	48.8 (19.2)	60.3 (23.7)
French Fliers	1973	65	27-32	55.8 (22.0)	3.8 (1.5)	48.2 (19.0)	62.0 (24.4)
German AF	1975	1004	Not Reported	55.9 (22.0)	3.5 (1.4)	50.3 (19.8)	61.7 (24.3)
Japanese Civ.	1967-68 1972-73	1870	25-39	50.3 (19.8)	3.9 (1.5)	43.9 (17.3)	56.7 (22.3)

*Data given in centimeters with inches in parentheses.



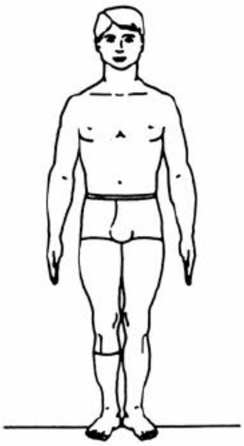
KNEE CIRCUMFERENCE

Definition: The circumference of the knee at the level of the midpatella landmark. The subject stands erect, heels approximately 10 cm. apart, and weight distributed equally on both feet.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* X	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	36.3 (14.3)	2.3 (0.9)	32.8 (12.9)	40.2 (15.8)
U.S. HEW Civ.							
British Civ.	1957	4994	18-55+	35.5 (14.0)	2.6 (1.0)	31.7 (12.5)	40.0 (15.7)
Swedish Civ.							
Japanese Civ.	1967-68 1972-73	1622	25-39	33.5 (13.2)	2.2 (0.9)	29.9 (11.8)	37.1 (14.6)
MALES							
USAF Flying Personnel	1967	2420	21-50	38.7 (15.2)	2.1 (0.8)	35.4 (13.9)	42.2 (16.6)
NASA Astronauts	Dates Vary	52	28-43	39.5 (15.6)	2.1 (0.8)	37.0 (14.6)	43.3 (17.0)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	38.1 (15.0)	1.9 (0.7)	35.1 (13.8)	41.5 (16.3)
French Fliers							
German AF	1975	1004	Not Reported	38.0 (15.0)	1.9 (0.7)	35.0 (13.8)	41.0 (16.1)
Japanese Civ.	1967-68 1972-73	1870	25-39	34.6 (13.6)	2.0 (0.8)	31.3 (12.3)	37.9 (14.9)

*Data given in centimeters with inches in parentheses.



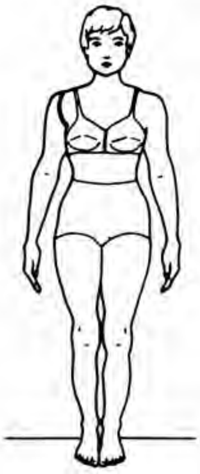
CALF CIRCUMFERENCE

Definition: The maximum horizontal circumference of the calf. The subject stands erect, heels approximately 10 cm. apart, and weight distributed equally on both feet.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	34.1 (13.4)	2.3 (0.9)	30.6 (12.0)	37.9 (14.9)
U.S. HEW Civ.							
British Civ.	1957	4994	18-55+	34.6 (13.6)	2.6 (1.0)	30.6 (12.0)	39.1 (15.4)
Swedish Civ.	1968	212	20-49	35.4 (13.9)	2.6 (1.0)	31.1 (12.2)	39.7 (15.6)
Japanese Civ.	1967-68 1972-73	1622	25-39	33.3 (13.1)	2.3 (0.9)	29.5 (11.6)	37.1 (14.6)
MALES							
USAF Flying Personnel	1967	2420	21-50	37.2 (14.6)	2.3 (0.9)	33.5 (13.2)	41.0 (16.1)
NASA Astronauts	Dates Vary	57	28-43	38.3 (15.1)	2.1 (0.8)	34.8 (13.7)	41.7 (16.4)
RAF Flying Personnel	1970-71	2000	18-45	36.7 (14.4)	2.2 (0.9)	33.2 (13.1)	40.3 (15.9)
Italian Military	1960	1342	18-59	36.5 (14.4)	2.2 (0.9)	33.3 (13.1)	40.4 (15.9)
French Fliers	1973	65	27-32	36.8 (14.5)	2.2 (0.9)	32.4 (12.8)	40.0 (15.7)
German AF	1975	1004	Not Reported	37.1 (14.6)	2.2 (0.9)	33.5 (13.2)	40.7 (16.0)
Japanese Civ.	1967-68 1972-73	1870	25-39	34.9 (13.7)	2.6 (1.0)	30.6 (12.0)	39.2 (15.4)

*Data given in centimeters with inches in parentheses.



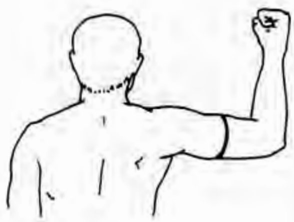
SCYE CIRCUMFERENCE

Definition: The circumference of the scye, passing through the axilla over the anterior and posterior vertical scye landmarks and over the acromial landmark. The subject stands erect, looking straight ahead, with the right arm slightly abducted.

Application: Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	37.1 (14.6)	2.3 (0.9)	33.6 (13.2)	41.1 (16.2)
U.S. HEW Civ.							
British Civ.	1957	4995	18-55+	39.8 (15.7)	3.3 (1.3)	35.2 (13.9)	45.9 (18.1)
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	48.4 (19.1)	2.8 (1.1)	43.8 (17.2)	53.0 (20.9)
NASA Astronauts	Dates Vary	53	28-43	45.8 (18.0)	2.0 (0.8)	42.9 (16.9)	49.2 (19.4)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	44.8 (17.6)	2.5 (1.0)	40.8 (16.1)	49.0 (19.3)
French Fliers	1973	65	27-32	43.3 (17.0)	2.1 (0.8)	39.9 (15.7)	47.0 (18.5)
German AF	1975	1004	Not Reported	45.9 (18.1)	3.6 (1.4)	40.4 (15.9)	52.2 (20.6)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



BICEPS CIRCUMFERENCE, FLEXED

Definition: The circumference of the arm at the level of the biceps landmark. The subject stands with his elbow bent at 90 degrees and the biceps maximally flexed.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* X	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	26.8 (10.6)	2.3 (0.9)	23.3 (9.2)	30.8 (12.1)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	32.7 (12.9)	2.3 (0.9)	29.1 (11.5)	36.6 (14.4)
NASA Astronauts	Dates Vary	56	28-43	33.3 (13.1)	1.8 (0.7)	30.8 (12.1)	36.9 (14.5)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	31.0 (12.2)	2.1 (0.8)	27.8 (10.9)	34.8 (13.7)
French Fliers	1973	65	27-32	31.9 (12.6)	2.0 (0.8)	28.3 (11.1)	35.1 (13.8)
German AF	1975	1004	Not Reported	32.2 (12.7)	2.2 (0.9)	28.6 (11.3)	35.9 (14.1)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

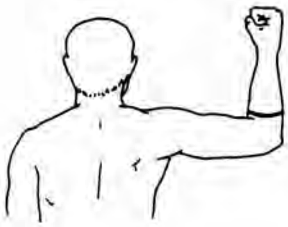
BICEPS CIRCUMFERENCE, RELAXED

Definition The circumference of the arm at the level of the biceps landmark. The subject stands with his arm slightly abducted.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	25.6 (10.1)	2.3 (0.9)	22.2 (8.7)	29.7 (11.7)
U.S. HEW Civ.	1960-62	1165	25-40	28.1 (11.1)	4.2 (1.7)	22.6 (8.9)	36.4 (14.3)
British Civ.	1957	4995	18-55+	28.6 (11.3)	3.2 (1.3)	24.1 (9.5)	34.5 (13.6)
Swedish Civ.	1968	214	20-49	27.7 (10.9)	3.0 (1.2)	22.8 (9.0)	32.5 (12.8)
Japanese Civ.	1967-68	1622	25-39	26.7 (10.5)	2.5 (1.0)	22.6 (8.9)	30.8 (12.1)
MALES							
USAF Flying Personnel	1967	2420	21-50	30.8 (12.1)	2.3 (0.9)	27.0 (10.6)	34.7 (13.7)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	29.3 (11.5)	2.2 (0.9)	26.0 (10.2)	33.0 (13.0)
French Fliers	1973	65	27-32	29.5 (11.6)	2.0 (0.8)	26.0 (10.2)	33.1 (13.0)
German AF	1975	1004	Not Reported	29.3 (11.5)	2.0 (0.8)	25.9 (10.2)	32.7 (12.9)
Japanese Civ.	1967-68 1972-73	1870	25-39	27.5 (10.8)	2.4 (0.9)	23.6 (9.3)	31.4 (12.4)

*Data given in centimeters with inches in parentheses.



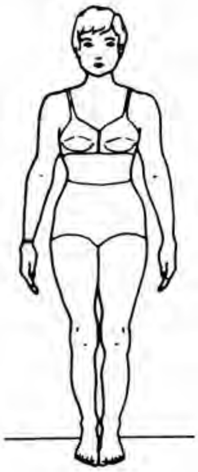
FOREARM CIRCUMFERENCE, FLEXED

Definition: The circumference of the arm at the level of the forearm landmark. The subject stands with his upper arm raised so that its long axis is horizontal, elbow flexed 90 degrees and fist tightly clenched.

Application: Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	25.0 (9.8)	1.5 (0.6)	22.6 (8.9)	27.5 (10.8)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	29.8 (11.7)	1.6 (0.6)	27.2 (10.7)	32.4 (12.8)
NASA Astronauts	Dates Vary	55	28-43	29.2 (11.5)	1.6 (0.6)	26.6 (10.5)	31.7 (12.5)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	29.0 (11.4)	1.6 (0.6)	26.4 (10.4)	31.7 (12.5)
French Fliers	1973	65	27-32	28.2 (11.1)	1.1 (0.4)	26.3 (10.4)	29.8 (11.7)
German AF	1975	1004	Not Reported	29.5 (11.6)	2.0 (0.8)	26.3 (10.4)	32.9 (13.0)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



WRIST CIRCUMFERENCE

<u>Definition</u>: The minimum circumference of the wrist at the level of the stylion landmark. The subject stands with the arm slightly abducted.

<u>Application</u>: Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	15.0 (5.9)	0.7 (0.3)	13.8 (5.4)	16.2 (6.4)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	215	20-49	16.3 (6.4)	0.9 (0.4)	14.8 (5.8)	17.7 (7.0)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	17.6 (6.9)	0.9 (0.4)	16.2 (6.4)	19.2 (7.6)
NASA Astronauts	Dates Vary	57	28-43	17.3 (6.8)	0.8 (0.3)	16.0 (6.3)	18.7 (7.4)
RAF Flying Personnel	1970-71	1999	18-45	17.4 (6.9)	1.0 (0.4)	15.9 (6.3)	19.1 (7.5)
Italian Military	1960	1342	18-59	17.4 (6.9)	0.9 (0.4)	16.0 (6.3)	18.9 (7.4)
French Fliers	1973	65	27-32	16.9 (6.7)	0.8 (0.3)	15.8 (6.2)	18.5 (7.3)
German AF	1975	1005	Not Reported	17.8 (7.0)	0.9 (0.4)	16.4 (6.5)	19.4 (7.6)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

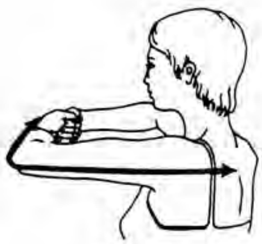
VERTICAL TRUNK CIRCUMFERENCE

Definition: The circumference of the trunk measured by passing a tape between the legs, over the protrusion of the right buttock, and up the back to lie over the midshoulder landmark. The other end of the tape is brought up over the right nipple to the midshoulder landmark. The subject stands with the legs slightly apart.

Application: Sizing of clothing and personal protective equipment;
Equipment design: length of straps and webbing for restraint systems and rigging.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	154.4 (60.8)	6.9 (2.7)	143.5 (56.5)	166.3 (65.5)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.	1967-68 1972-73	1622	25-39	147.7 (58.1)	5.9 (2.3)	138.0 (54.3)	157.4 (62.0)
MALES							
USAF Flying Personnel	1967	2420	21-50	168.1 (66.2)	7.2 (2.8)	156.7 (61.7)	180.2 (70.9)
NASA Astronauts	Dates Vary	58	28-43	168.4 (66.3)	7.1 (2.8)	157.6 (62.0)	181.0 (71.3)
RAF Flying Personnel	1970-71	2000	18-45	162.5 (64.0)	6.6 (2.6)	151.8 (59.8)	173.4 (68.3)
Italian Military	1960	1342	18-59	160.5 (63.2)	6.3 (2.5)	150.5 (59.3)	171.2 (67.4)
French Fliers	1973	65	27-32	159.5 (62.8)	6.4 (2.5)	149.7 (58.9)	169.2 (66.6)
German AF	1975	1004	Not Reported	165.5 (65.2)	6.9 (2.7)	154.7 (60.9)	177.4 (69.8)
Japanese Civ.	1967-68 1972-73	1870	25-39	158.9 (62.6)	7.4 (2.9)	146.7 (57.8)	171.1 (67.4)

*Data given in centimeters with inches in parentheses.



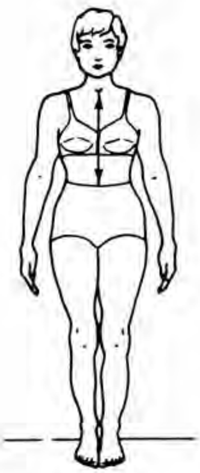
SPINE-TO-WRIST LENGTH (SLEEVE LENGTH)

Definition: The surface distance from the spine to the wrist landmark. The subject stands, arms horizontal, elbows flexed about 60 degrees, fists clenched and touching, and shoulders relaxed.

Application: Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	79.6 (31.3)	3.3 (1.3)	74.2 (29.2)	85.1 (33.5)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.	1967-68 1972-73	1622	25-39	68.7 (27.0)	2.5 (1.0)	64.6 (25.4)	72.8 (28.7)
MALES							
USAF Flying Personnel	1967	2420	21-50	90.8 (35.7)	3.5 (1.4)	85.2 (33.5)	96.8 (38.1)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	85.3 (33.6)	3.5 (1.4)	79.6 (31.3)	91.1 (35.9)
French Fliers	1973	65	27-32	86.6 (34.1)	2.8 (1.1)	82.1 (32.3)	90.7 (35.7)
German AF	1975	1004	Not Reported	87.4 (34.4)	3.8 (1.5)	81.2 (32.0)	93.7 (36.9)
Japanese Civ.	1968-68 1972-73	1870	25-39	74.6 (29.4)	2.9 (1.1)	69.8 (27.5)	79.4 (31.3)

*Data given in centimeters with inches in parentheses.



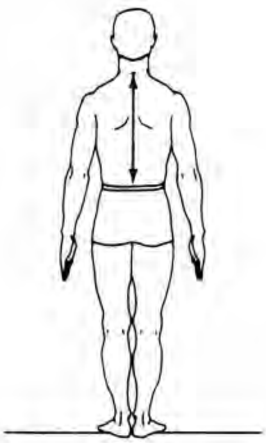
WAIST FRONT

Definition: The surface distance from the suprasternale landmark to the anterior waist landmark. The subject stands erect, looking straight ahead.

Application: Sizing of clothing and personal protective equipment;
Equipment design: length of personal equipment to be worn on the torso such as respirator packs and rigid body armor.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* X̄	SD	5%ile	95%ile
FEMALES							
USAF Women							
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	40.4 (15.9)	2.2 (0.9)	36.9 (14.5)	44.2 (17.4)
NASA Astronauts	Dates Vary	50	28-43	38.2 (15.0)	2.6 (1.0)	34.4 (13.5)	42.4 (16.7)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	38.9 (15.3)	2.0 (0.8)	35.9 (14.1)	42.5 (16.7)
French Fliers							
German AF	1975	1004	Not Reported	39.0 (15.4)	2.1 (0.8)	35.8 (14.1)	42.7 (16.8)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



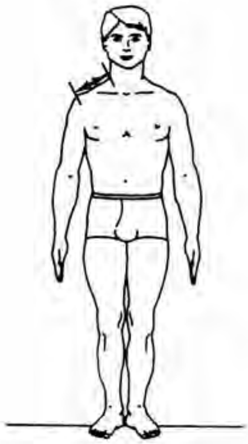
WAIST BACK

Definition: The surface distance along the spine from the cervicale landmark to the posterior waist landmark. The subject stands erect, with his head in the Frankfort plane.

Application: Sizing of clothing and personal protective equipment;
Equipment design: length of personal equipment to be worn on the torso such as respirator packs and rigid body armor.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	40.5 (15.9)	2.2 (0.9)	37.0 (14.6)	44.3 (17.4)
U.S. HEW Civ.							
British Civ.	1957	4995	18-55+	38.0 (15.0)	2.3 (0.9)	34.2 (13.5)	41.9 (16.5)
Swedish Civ.							
Japanese Civ.	1967-68 1972-73	1622	25-39	37.7 (14.8)	1.7 (0.7)	34.9 (13.7)	40.5 (15.9)
MALES							
USAF Flying Personnel	1967	2420	21-50	46.9 (18.5)	2.4 (0.9)	43.1 (17.0)	50.9 (20.0)
NASA Astronauts	Dates Vary	50	28-43	46.6 (18.3)	2.2 (0.9)	43.5 (17.1)	50.5 (19.9)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	45.5 (17.9)	2.2 (0.9)	41.7 (16.4)	49.1 (19.3)
French Fliers							
German AF	1975	1004	Not Reported	45.6 (18.0)	2.6 (1.0)	41.3 (16.3)	50.1 (19.7)
Japanese Civ.	1967-68 1972-73	1870	25-39	46.0 (18.1)	2.5 (1.0)	41.9 (16.5)	50.1 (19.7)

*Data given in centimeters with inches in parentheses.



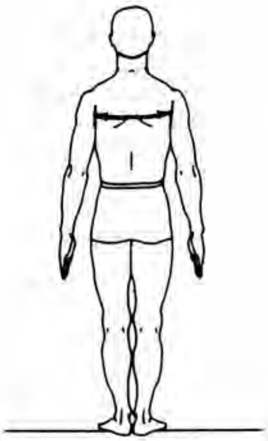
SHOULDER LENGTH

Definition: The surface distance along the top of the shoulder from the right lateral neck landmark to the right acromial landmark. The subject stands erect, looking straight ahead.

Application: Sizing of clothing and body personal protective equipment;
Equipment design: width of webbing and straps of restraint systems and suspension for packs and harnesses.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	14.7 (5.8)	1.0 (0.4)	13.0 (5.1)	16.4 (6.5)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	16.6 (6.5)	1.3 (0.5)	14.6 (5.7)	18.7 (7.4)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	16.8 (6.6)	1.2 (0.5)	14.9 (5.9)	18.6 (7.3)
French Fliers							
German AF	1975	1004	Not Reported	14.2 (5.6)	1.7 (0.7)	11.2 (4.4)	16.7 (6.6)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



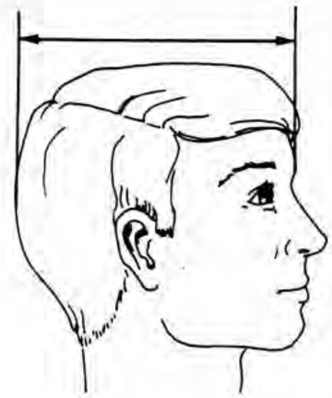
INTERSCYE

Definition: The horizontal distance across the back between the posterior scye point landmarks. The subject stands erect with the arms relaxed.

Application: Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	35.1 (13.8)	2.4 (0.9)	31.2 (12.3)	39.2 (15.4)
U.S. HEW Civ.							
British Civ.	1957	4994	18-55+	33.9 (13.3)	2.9 (1.1)	29.4 (11.6)	38.9 (15.3)
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	38.8 (15.3)	3.8 (1.5)	32.5 (12.8)	45.0 (17.7)
NASA Astronauts	Dates Vary	52	28-43	36.4 (14.3)	2.3 (0.9)	32.6 (12.8)	40.2 (15.8)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	39.4 (15.5)	2.6 (1.0)	35.3 (13.9)	44.1 (17.4)
French Fliers							
German AF	1975	1004	Not Reported	43.3 (17.0)	3.8 (1.5)	37.1 (14.6)	49.6 (19.5)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



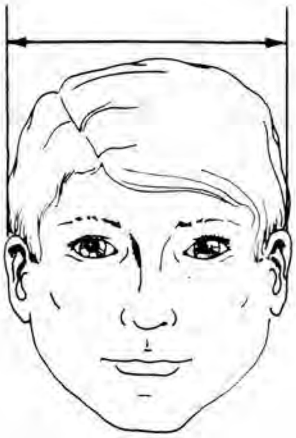
HEAD LENGTH

Definition: The maximum length of the head between the glabella and the occiput in the midsagittal plane.

Application: General body description; Sizing of clothing and personal protective equipment; Equipment design: protective head gear and equipment suspension systems for head and face.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	18.4 (7.2)	0.7 (0.3)	17.3 (6.8)	19.5 (7.7)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	19.9 (7.8)	0.7 (0.3)	18.8 (7.4)	21.0 (8.3)
NASA Astronauts	Dates Vary	28	28-43	20.0 (7.9)	0.5 (0.2)	19.2 (7.6)	20.8 (8.2)
RAF Flying Personnel	1970-71	2000	18-45	19.9 (7.8)	0.6 (0.2)	18.8 (7.4)	20.9 (8.2)
Italian Military	1960	1342	18-59	19.3 (7.6)	0.7 (0.3)	18.2 (7.3)	20.4 (8.0)
French Fliers	1973	65	27-32	19.5 (7.7)	0.6 (0.2)	18.6 (7.2)	20.5 (8.1)
German AF	1975	1004	Not Reported	19.2 (7.6)	0.8 (0.3)	17.7 (7.0)	20.4 (8.0)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



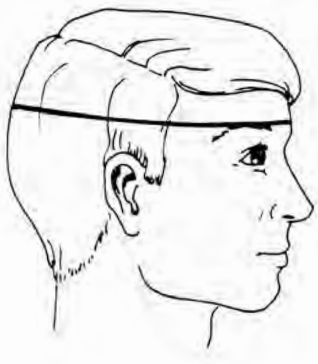
HEAD BREADTH

Definition: The maximum horizontal breadth of the head above the level of the ears.

Application: General body description; Sizing of clothing and personal protective equipment; Equipment design: protective head gear and equipment suspension systems for head and face.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	14.5 (5.7)	0.6 (0.2)	13.5 (5.3)	15.5 (6.1)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	15.6 (6.1)	0.5 (0.2)	14.7 (5.8)	16.5 (6.5)
NASA Astronauts	Dates Vary	28	28-43	15.6 (6.1)	0.6 (0.2)	14.6 (5.7)	16.6 (6.5)
RAF Flying Personnel	1970-71	2000	18-45	15.8 (6.2)	0.5 (0.2)	14.9 (5.9)	16.6 (6.5)
Italian Military	1960	1342	18-59	15.5 (6.1)	0.6 (0.2)	14.6 (5.7)	16.5 (6.5)
French Fliers	1973	65	27-32	15.4 (6.1)	0.5 (0.2)	14.6 (5.7)	16.2 (6.4)
German AF	1975	1004	Not Reported	15.7 (6.2)	0.6 (0.2)	14.7 (5.8)	16.7 (6.6)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



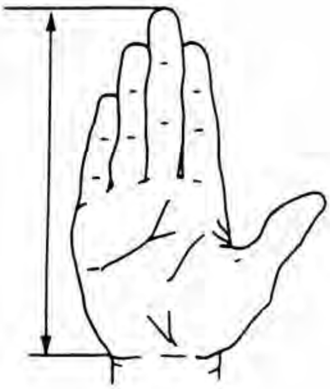
HEAD CIRCUMFERENCE

Definition: The maximum circumference of the head passing above the brow ridges.

Application: General body description; Sizing of clothing and personal protective equipment; Equipment design: protective head gear and equipment suspension systems for head and face.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	54.9 (21.6)	1.6 (0.6)	52.3 (20.6)	57.6 (22.7)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.	1967-68 1972-73	1622	25-39	54.5 (21.5)	1.4 (0.6)	52.2 (20.6)	56.8 (22.4)
MALES							
USAF Flying Personnel	1967	2420	21-50	57.5 (22.6)	1.4 (0.6)	55.2 (21.7)	59.9 (23.6)
NASA Astronauts	Dates Vary	57	28-43	57.6 (22.7)	1.3 (0.5)	55.3 (21.8)	59.7 (23.5)
RAF Flying Personnel	1970-71	2000	18-45	57.7 (22.7)	1.4 (0.6)	55.5 (21.9)	59.9 (23.6)
Italian Military	1960	1342	18-59	56.5 (22.2)	1.4 (0.6)	54.2 (21.3)	58.8 (23.1)
French Fliers	1973	65	27-32	56.8 (22.4)	1.5 (0.6)	54.5 (21.5)	59.2 (23.3)
German AF	1975	1004	Not Reported	57.0 (22.4)	1.4 (0.6)	54.7 (21.5)	59.5 (23.4)
Japanese Civ.	1967-68 1972-73	1870	25-39	56.5 (22.2)	1.5 (0.6)	54.0 (21.3)	59.0 (23.2)

*Data given in centimeters with inches in parentheses.



HAND LENGTH

Definition: The distance from the wrist landmark to dactylion. The subject sits with the hand flat on a table, palm up, with fingers together and straight.

Application: General body description; Sizing of clothing and personal protective equipment; Body linkage and models.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	18.4 (7.2)	1.0 (0.4)	16.9 (6.7)	20.1 (7.9)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	162	20-49	17.9 (7.0)	1.0 (0.4)	16.3 (6.4)	19.6 (7.7)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	19.1 (7.5)	0.8 (0.3)	17.8 (7.0)	20.5 (8.1)
NASA Astronauts	Dates Vary	25	28-43	19.0 (7.5)	1.3 (0.5)	16.9 (6.7)	21.1 (8.3)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	19.0 (7.5)	0.9 (0.4)	17.6 (6.9)	20.4 (8.0)
French Fliers	1973	65	27-32	19.2 (7.6)	0.8 (0.3)	17.7 (7.0)	20.4 (8.0)
German AF	1975	1004	Not Reported	18.9 (7.4)	0.9 (0.4)	17.4 (6.9)	20.3 (8.0)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

HAND BREADTH

<u>Definition:</u> The breadth of the hand between metacarpal-phalangeal joints II and V. The subject sits with the hand flat on a table, palm down, with the fingers together and straight.

<u>Application:</u> General body description; Sizing of clothing and body personal protective equipment; Equipment design: width of grasping surface for controls, handholds, and handles.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	7.6 (3.0)	0.4 (0.2)	6.9 (2.7)	8.2 (3.2)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	214	20-49	7.7 (3.0)	0.4 (0.2)	7.1 (2.8)	8.3 (3.3)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	8.9 (3.5)	0.4 (0.2)	8.2 (3.2)	9.6 (3.8)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	8.9 (3.5)	0.4 (0.2)	8.2 (3.2)	9.6 (3.8)
French Fliers	1973	65	27-32	8.7 (3.4)	0.4 (0.2)	8.1 (3.2)	9.4 (3.7)
German AF	1975	1004	Not Reported	8.6 (3.4)	0.4 (0.2)	7.9 (3.1)	9.3 (3.7)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

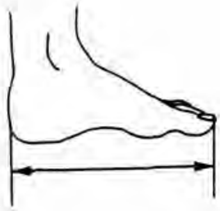
HAND CIRCUMFERENCE

Definition: The circumference of the hand passing over the metacarpal-phalangeal joints II and V. The subject sits with the hand flat on a table, palm down, fingers extended, and thumb abducted.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	18.3 (7.2)	0.9 (0.4)	16.8 (6.6)	19.8 (7.8)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	21.6 (8.5)	0.9 (0.4)	20.0 (7.9)	23.1 (9.1)
NASA Astronauts	Dates Vary	33	28-43	21.2 (8.3)	3.0 (1.2)	16.2 (6.4)	26.2 (10.3)
RAF Flying Personnel							
Italian Military	1960	1342	18-59	21.6 (8.5)	1.0 (0.4)	20.0 (7.9)	23.2 (9.1)
French Fliers	1973	65	27-32	21.7 (8.5)	1.0 (0.4)	20.2 (8.0)	23.4 (9.2)
German AF	1975	1004	Not Reported	21.3 (8.4)	1.3 (0.5)	19.1 (7.5)	23.5 (9.3)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



FOOT LENGTH

Definition: The distance, parallel to the long axis of the foot, from the back of the heel to the tip of the most protruding toe. The subject stands with weight equally distributed on both feet.

Application: General body description;
Sizing of clothing and personal protective equipment;
Workspace layout;
Body linkage and models.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	24.1 (9.5)	1.1 (0.4)	22.2 (8.7)	26.0 (10.2)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	210	20-49	24.6 (9.7)	1.1 (0.4)	22.8 (9.0)	26.3 (10.4)
Japanese Civ.	1967-68 1972-73	1622	25-39	22.6 (8.9)	0.9 (0.4)	21.1 (8.3)	24.1 (9.5)
MALES							
USAF Flying Personnel	1967	2420	21-50	27.0 (10.6)	1.2 (0.5)	25.1 (9.9)	29.1 (11.5)
NASA Astronauts							
RAF Flying Personnel	1970-71	2000	18-45	26.6 (10.5)	1.2 (0.5)	24.7 (9.7)	28.6 (11.3)
Italian Military	1960	1342	18-59	26.5 (10.4)	1.1 (0.4)	24.6 (9.7)	28.4 (11.2)
French Fliers	1973	65	27-32	26.5 (10.4)	1.1 (0.4)	24.7 (9.7)	28.5 (11.2)
German AF	1975	1004	Not Reported	26.4 (10.4)	1.2 (0.5)	24.5 (9.6)	28.5 (11.2)
Japanese Civ.	1967-68 1972-73	1870	25-39	24.4 (9.6)	1.0 (0.4)	22.8 (9.0)	26.0 (10.2)

*Data given in centimeters with inches in parentheses.

FOOT BREADTH

Definition: The maximum horizontal distance across the foot, at right angles to the long axis. The subject stands with weight equally distributed on both feet.

Application: General body description; Sizing of clothing and personal protective equipment; Workspace layout.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	8.9 (3.5)	0.5 (0.2)	8.0 (3.1)	9.8 (3.9)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.	1968	210	20-49	9.5 (3.7)	0.7 (0.3)	8.4 (3.3)	10.5 (4.1)
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	9.8 (3.9)	0.5 (0.2)	9.0 (3.5)	10.6 (4.2)
NASA Astronauts	Dates Vary	27	28-43	10.3 (4.1)	0.5 (0.2)	9.5 (3.7)	11.1 (4.4)
RAF Flying Personnel	1970-71	1998	18-45	9.5 (3.7)	0.4 (0.2)	8.8 (3.5)	10.3 (4.1)
Italian Military	1960	1342	18-59	10.2 (4.0)	0.5 (0.2)	9.4 (3.7)	11.0 (4.3)
French Fliers	1973	65	27-32	10.3 (4.1)	0.5 (0.2)	9.5 (3.7)	11.3 (4.4)
German AF	1975	1004	Not Reported	10.1 (4.0)	0.6 (0.2)	9.2 (3.6)	11.0 (4.3)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

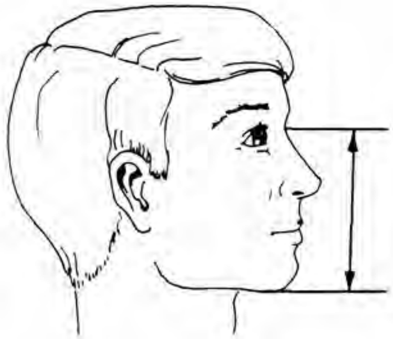
BALL OF FOOT CIRCUMFERENCE

Definition: The circumference of the foot over the distal ends of the metatarsal bones. The subject stands with his feet slightly apart and weight distributed equally on both feet.

Application: General body description; Sizing of clothing and personal protective equipment.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* $\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women							
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	24.8 (9.8)	1.2 (0.5)	22.9 (9.0)	27.0 (10.6)
NASA Astronauts							
RAF Flying Personnel	1970-71	2000	18-45	25.0 (9.8)	1.2 (0.5)	23.1 (9.1)	27.0 (10.6)
Italian Military	1960	1342	18-59	25.2 (9.9)	1.2 (0.5)	23.2 (9.1)	27.1 (10.7)
French Fliers	1973	65	27-32	25.2 (9.9)	1.2 (0.5)	23.0 (9.1)	27.0 (10.6)
German AF	1975	1004	Not Reported	25.0 (9.8)	1.3 (0.5)	22.9 (9.0)	27.2 (10.7)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



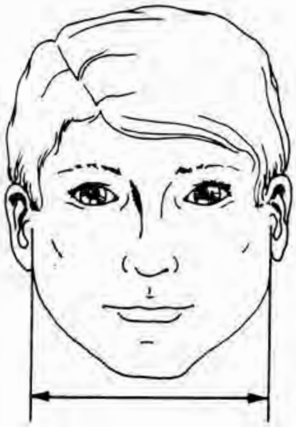
MENTON-SELLION (FACE) LENGTH

Definition: The distance from the menton landmark to the deepest point of the nasal root depression. The subject sits with mouth closed and jaw relaxed.

Application: General body description; Sizing of clothing and personal protective equipment; Equipment design: length of oral-nasal oxygen mask and respirator face pieces.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics* X̄	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	10.6 (4.2)	0.6 (0.2)	9.6 (3.8)	11.7 (4.6)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	12.0 (4.7)	0.6 (0.2)	11.0 (4.3)	13.0 (5.1)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	11.9 (4.7)	0.6 (0.2)	11.0 (4.3)	12.9 (5.1)
French Fliers	1973	65	27-32	12.7 (5.0)	0.6 (0.2)	11.8 (4.6)	13.7 (5.)
German AF	1975	1004	Not Reported	12.0 (4.7)	0.7 (0.3)	10.9 (4.3)	13.2 (5.2)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.



BIZYGOMATIC (FACE) BREADTH

Definition: The maximum horizontal breadth of the face between the zygomatic arches.

Application: General body description; Sizing of clothing and personal protective equipment; Equipment design: respirator face pieces and face shields.

Sample & Reference	Survey Date	No. of Subj.	Age Range	Descriptive Statistics*			
				$\bar{X}$	SD	5%ile	95%ile
FEMALES							
USAF Women	1968	1905	18-56	12.9 (5.1)	0.6 (0.2)	11.9 (4.7)	13.8 (5.4)
U.S. HEW Civ.							
British Civ.							
Swedish Civ.							
Japanese Civ.							
MALES							
USAF Flying Personnel	1967	2420	21-50	14.2 (5.6)	0.5 (0.2)	13.4 (5.3)	15.1 (5.9)
NASA Astronauts							
RAF Flying Personnel							
Italian Military	1960	1342	18-59	14.3 (5.6)	0.5 (0.2)	13.5 (5.3)	15.2 (6.0)
French Fliers	1973	65	27-32	14.2 (5.6)	0.5 (0.2)	13.5 (5.3)	14.8 (5.8)
German AF	1975	1004	Not Reported	13.3 (5.2)	0.8 (0.3)	11.9 (4.7)	14.7 (5.8)
Japanese Civ.							

*Data given in centimeters with inches in parentheses.

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APPENDIX A

A GLOSSARY OF ANATOMICAL AND ANTHROPOMETRIC TERMS

A

abdominal extension level -- the most anterior point on the curve of the abdomen in the midsagittal plane.

abduct -- to move away from the axis of the body or one of its parts.

acromion -- the most lateral point of the lateral edge of the spine of the scapula. Acromial height is usually equated with shoulder height.

anterior -- pertaining to the front of the body; as opposed to posterior.

auricular -- pertaining to the external ear.

axilla -- the armpit.

B

bi -- a prefix denoting connection with or relation to each of two symmetrically paired parts.

biceps brachii -- the large muscle on the anterior surface of the upper arm.

biceps femoris -- a large posterior muscle of the thigh.

brow ridges -- the bony ridges of the forehead that lie above the orbits of the eye.

bustpoint -- the most anterior protrusion of the right bra pocket.

buttock protrusion -- the maximum posterior protrusion of the right buttock.

C

calcaneus -- the heel bone.

canthus -- a corner or angle formed by the meeting of the eyelids.

carpus -- the wristbones, collectively.

cervicale -- the protrusion of the spinal column at the base of the neck caused by the tip of the spine (q.v.) of the 7th cervical vertebra.

cheilion -- the corners of the mouth formed by the juncture of the lips.

coronal plane -- any vertical plane at right angles to the midsagittal plane.

crinion -- the point in the midplane where the hairline meets the forehead.

cutaneous lip -- the area between the upper lip and the nose.

D

dactylion -- the tip of the middle finger.

deltoid muscle -- the large muscle on the lateral border of the upper arm in the shoulder region.

distal -- the end of a body segment farthest from the head, as opposed to proximal.

E

ectocanthus (also external canthus) -- the outside corner or angle formed by the meeting of the eyelids.

endocanthus -- the inside corner or angle formed by the meeting of the eyelids.

epicondyle -- the bony eminence at the distal end of the humerus, radius, and femur.

extend -- to move adjacent segments so that the angle between them is increased, as when the leg is straightened; as opposed to flex.

external -- away from the central long axis of the body; the outer portion of a body segment.

F

femoral epicondyles -- the bony projections on either side of the distal end of the femur.

femur -- the thigh bone.

flex -- to move a joint in such a direction as to bring together the two parts which it connects, as when the elbow is bent; as opposed to extend.

fossa -- a depression, usually somewhat longitudinal in shape, in the surface of a part, as in a bone.

Frankfort plane -- the standard horizontal plane or orientation of the head. The plane is established by a line passing through the right tragion (approximate earhole) and the lowest point of the right orbit (eye socket).

G

gastrocnemius -- the largest muscle in the calf of the leg.

glabella -- the most anterior point of the forehead between the brow ridges in the midsagittal plane.

gluteal furrow -- the furrow at the juncture of the buttock and the thigh.

gonial angle -- the angle at the back of the lower jaw formed by the intersection of the vertical and horizontal portions of the jaw.

H

helix -- the rolled outer part of the ear.

humerus -- the bone of the upper arm.

humeral epicondyles -- the bony projections on either side of the distal end of the humerus.

hyperextend -- to overextend a limb or other part of the body.

I

iliac crest -- the superior rim of the pelvic bone.

inferior -- below, in relation to another structure; lower.

inion -- the summit of the external occipital protuberance; the most posterior bony protuberance on the back of the head.

inseam -- a term used in tailoring to indicate the inside length of a sleeve or trouser leg. It is measured on the medial side of the arm or leg.

internal -- near the central long axis of the body; the inner portion of a body segment.

interpupillary -- between the centers of the pupils of the eyes.

J-K

knuckle -- the joint formed by the meeting of a finger bone (phalanx) with a palm bone (metacarpal).

L

lateral -- lying near or toward the sides of the body; as opposed to medial.

lateral malleolus -- the lateral bony protrusion of the ankle.

larynx -- the cartilaginous box of the throat that houses the voice mechanism. The "Adam's apple" is the most noticeable part of the larynx.

lip prominence -- the most anterior protrusion of either the upper or the lower lip.

M

malleolus -- a rounded bony projection in the ankle region. There is one on both the lateral and the medial side of the leg.

mandible -- the lower jaw.

mastoid process -- a bony projection on the inferior lateral surface of the temporal bone behind the ear.

medial -- lying near or toward the midline of the body; as opposed to lateral.

menton -- the point of the tip of the chin in the midsagittal plane.

metacarpal -- pertaining to the long bones of the hand between the carpus and the phalanges.

midaxillary line -- a vertical line passing through the center of the axilla.

midpatella -- a point one-half the distance between the superior and the inferior margins of the right patella.

midsagittal plane -- the vertical plane which divides the body into right and left halves.

midshoulder -- a point one-half the distance between the neck and the right acromion.

N

nasal root depression -- the area of greatest indentation where the bridge of the nose meets the forehead.

nasal septum -- the cartilaginous wall separating the right nostril from the left.

navicular bone -- the small bone of the hand just distal to the bend of the wrist on the thumb side.

nuchale -- the lowest point in the midsagittal plane of the occiput that can be palpated among the muscles in the posterior-superior part of the neck. This point is often visually obscured by hair.

O

ocular -- pertaining to the eye.

occipital bone -- a curved bone forming the back and part of the base of the skull.

olecranon -- the proximal end of the ulna (the medial forearm bone).

omphalion -- the center point of the navel.

orbit -- the eye socket.

P

patella -- the kneecap.

phalanges -- the bones of the fingers and toes (singular, phalanx).

philtrum -- the vertical groove that runs from the upper lip to the base of the nasal septum.

plantar - pertaining to the sole of the foot.

popliteal -- pertaining to the ligament behind the knee or to the part of the leg back of the knee.

posterior -- pertaining to the back of the body; as opposed to anterior.

pronasale -- the most anterior point on the nose.

proximal -- the end of a body segment nearest the head; as opposed to distal.

Q-R

radiale -- the uppermost point on the lateral margin of the proximal end of the radius.

radius -- the bone of the forearm on the thumb side of the arm.

ramus -- the vertical portion of the lower jaw bone (mandible).

S

sagittal -- pertaining to the anteroposterior median plane of the body, or to a plane parallel to the median.

scapula -- the shoulder blade.

scye -- a tailoring term to designate the armhole of a garment. Refers here to landmarks which approximate the lower level of the axilla.

sellion -- the point of greatest indentation of the nasal root depression.

septum -- a dividing wall between two cavities; the nasal septum is the fleshly partition between the two nasal cavities.

sphyrion -- the most distal extension of the tibia on the medial side of the foot.

spine (or spinal process) of vertebrae -- the posterior prominences of the vertebrae.

sternum -- the breastbone.

stomion -- the point of contact in the midsagittal plane between the upper and lower lip.

stylion -- the most distal point on the styloid process of the radius.

styloid process -- a long, spinelike projection of a bone.

sub -- a prefix designating below or under.

submandibular -- below the mandible or lower jaw.

subnasale -- the point where the base of the nasal septum meets the philtrum.

substernale -- the point located at the middle of the lower edge of the breastbone.

superior -- above, in relation to another structure; higher.

supra -- prefix designating above or on.

suprasternale -- the lowest point in the notch in the upper edge of the breastbone.

surface distance -- a measurement that follows the general contours of the surface of the body.

T

tarsus -- the collection of bones in the ankle joint, at the distal end of the tibia.

temporal crest -- a narrow bony ridge along the side of the head above the ear level that serves as a point of attachment for the temporal muscles.

temporal muscles -- the muscles of the temple region.

thyroid cartilage -- the bulge of the cartilage on the anterior surface of the throat; in men, the Adam's apple.

tibia -- the medial bone of the leg (shin bone).

tibiale -- the uppermost point of the medial margin of the tibia.

tragion -- the point located at the notch just above the tragus of the ear.

trapezius muscle -- the large muscle on each side of the back of the neck and shoulders, the action of which moves the shoulders.

triceps -- the muscle mass of the posterior upper arm.

trochanterion -- the tip of the bony lateral protrusion of the proximal end of the femur.

U

ulna -- one of the bones of the forearm on the little finger side of the arm.

V

vertex -- the top of the head.

W-X-Y-Z

zygomatic arch -- the bony arch below the orbit of the skull extending horizontally along the side of the head from the cheekbone (the zygomatic bone) nearly to the external ear.

ILLUSTRATED GLOSSARY

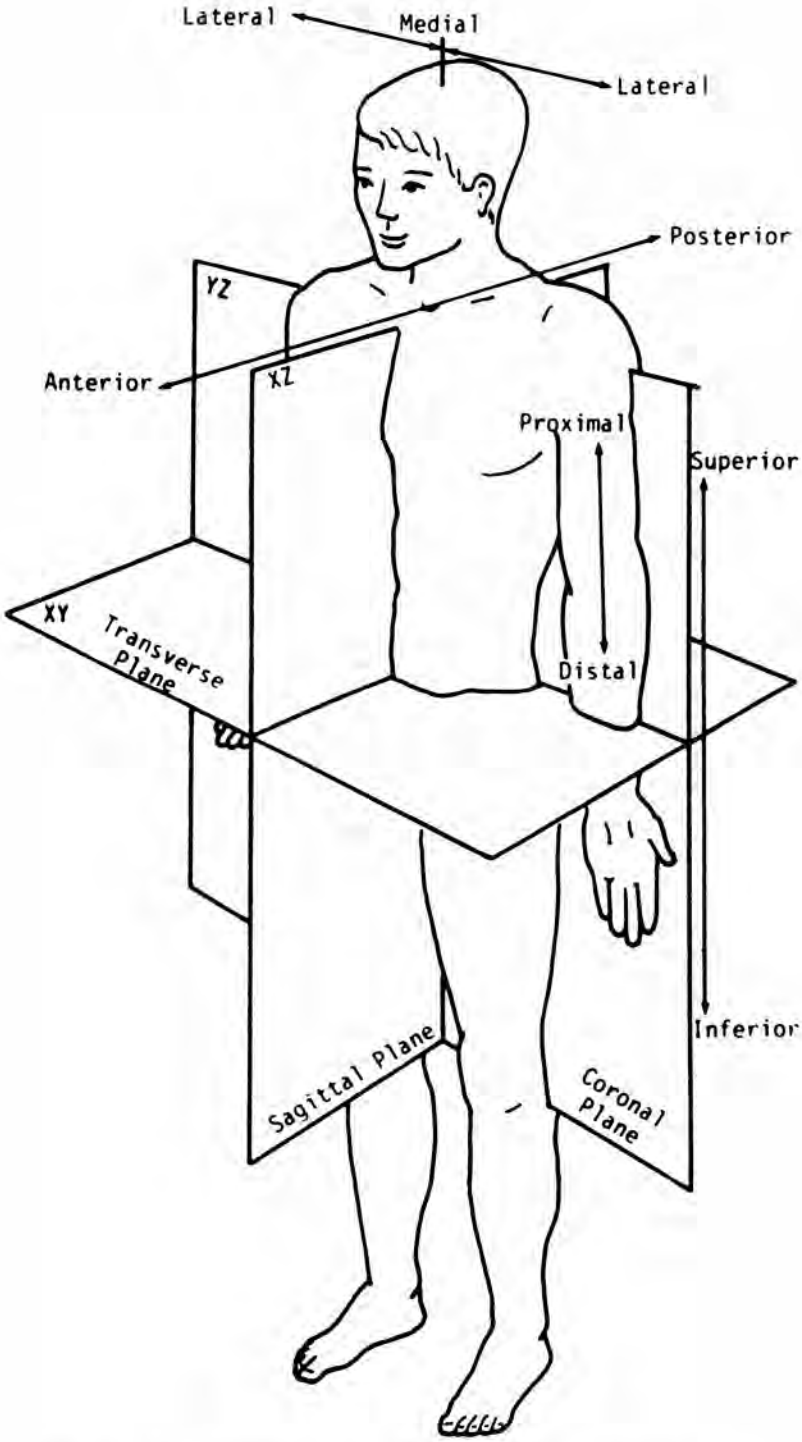


Figure 1. Anatomical planes and orientations.

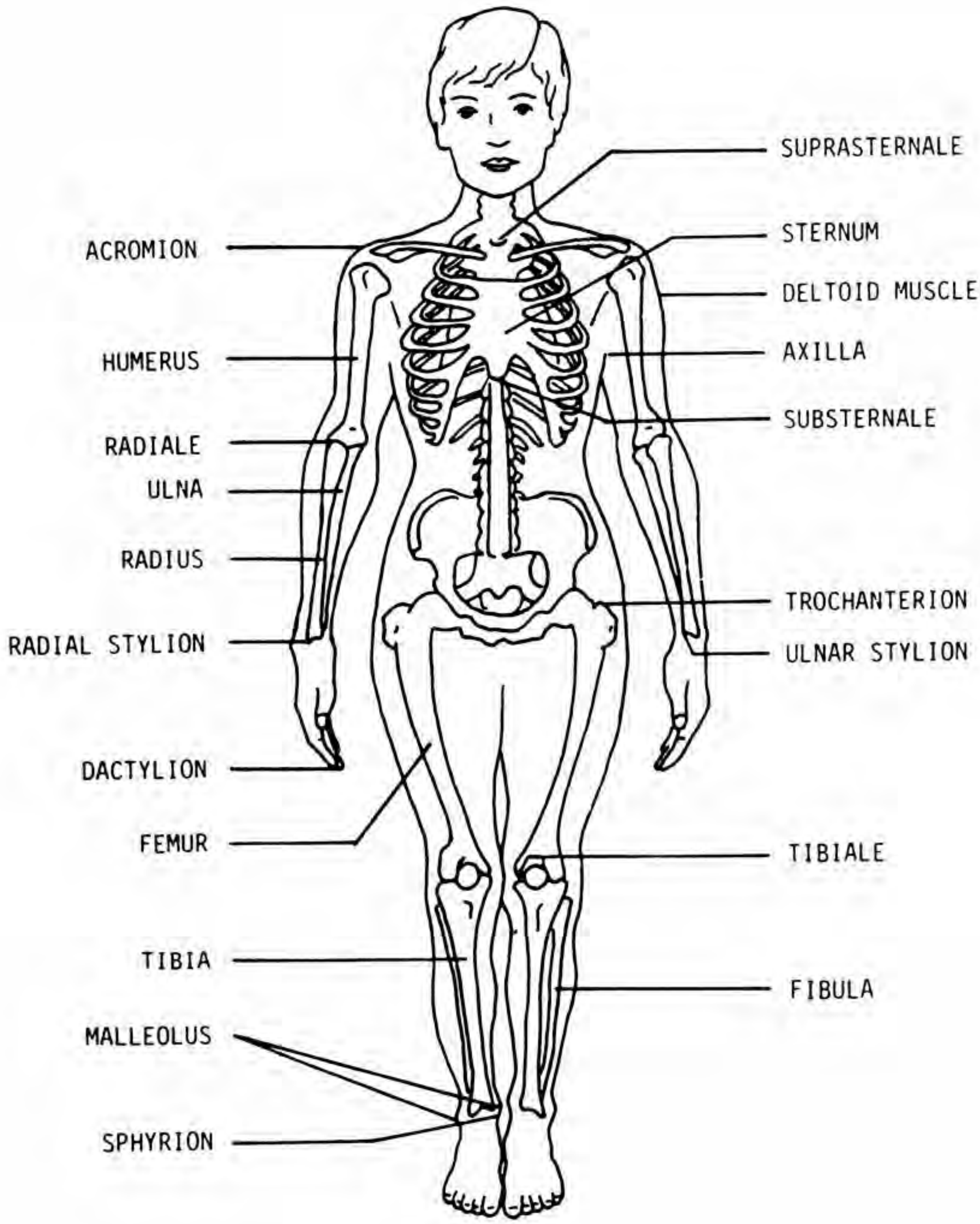


Figure 2. Anatomical and anthropometric landmarks.

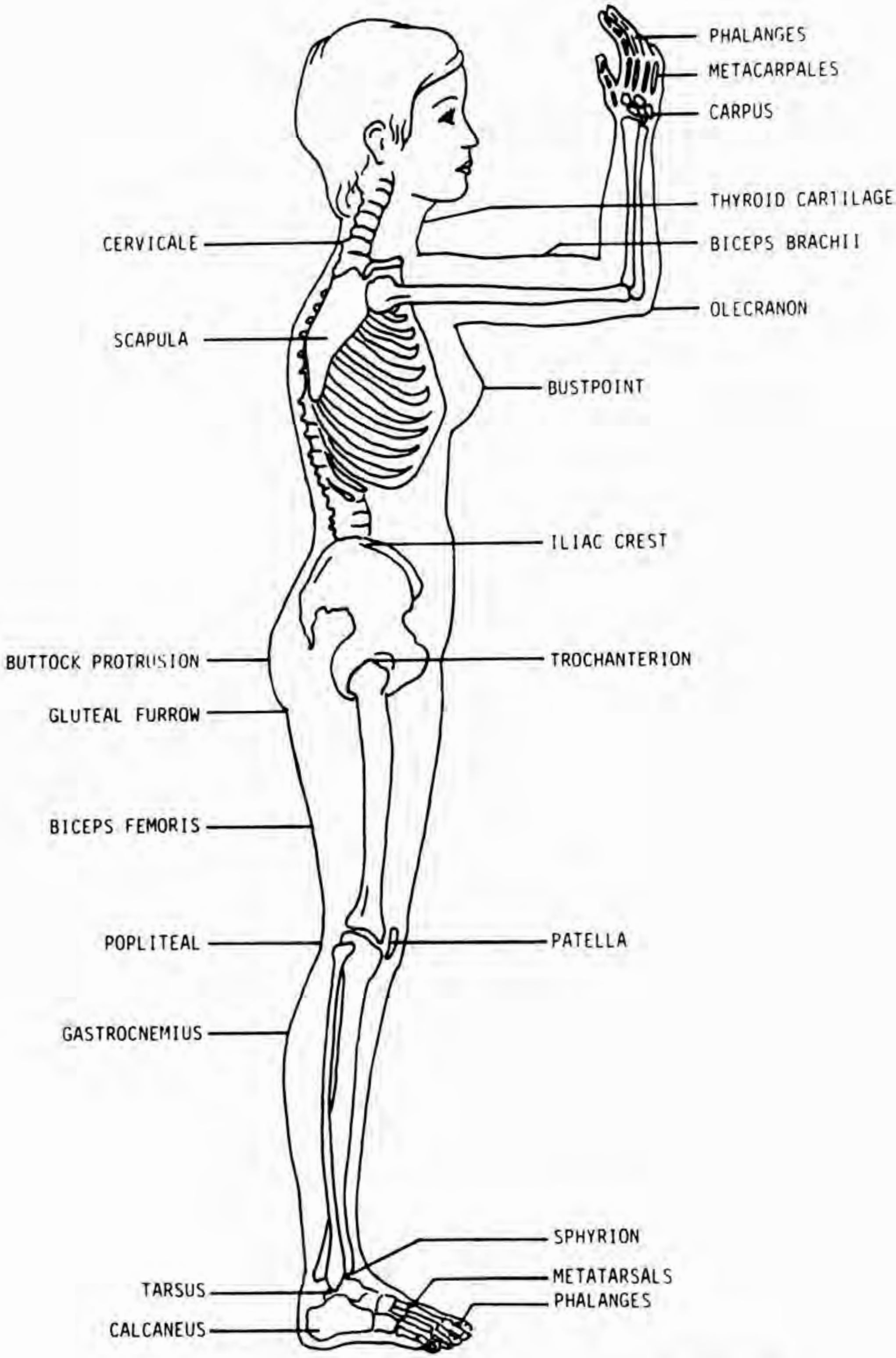


Figure 3. Anatomical and anthropometric landmarks.

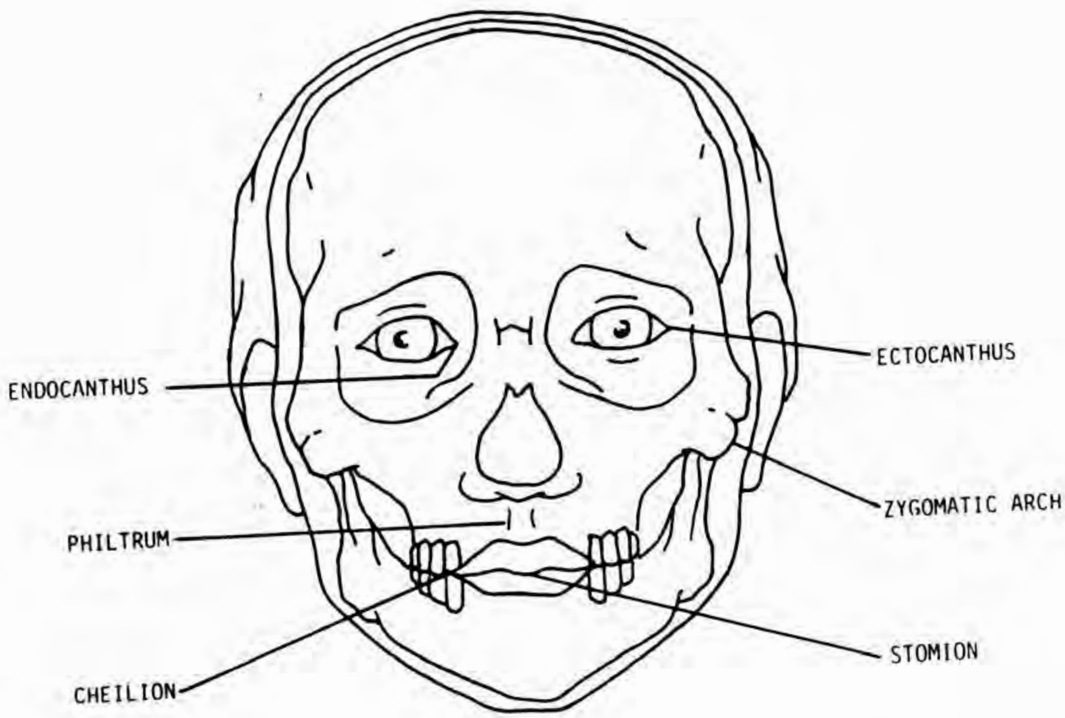


Figure 4. Anthropometric landmarks of the head and face.

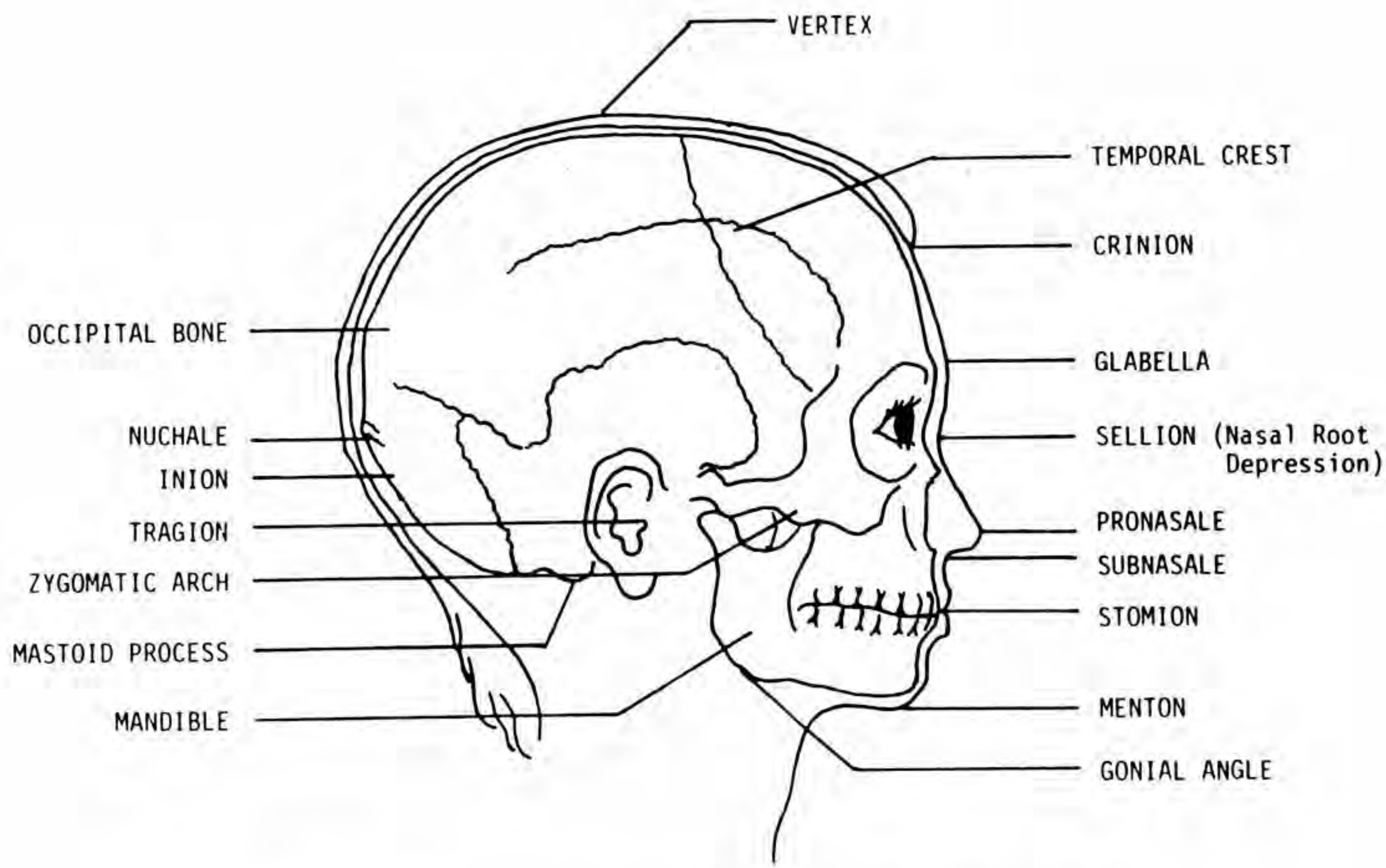


Figure 5. Anthropometric landmarks of the head and face.

APPENDIX B

PROJECTED 1985 BODY SIZE DATA

PROJECTED 1985 BODY SIZE DATA

As man/machine systems become increasingly more complex, the research and development cycle from concept to ultimate end product is continually lengthened. The more complex the system, the more time is involved in the establishment of system requirements and design parameters, mock up, prototype fabrication, testing and evaluation prior to the production of the system. This research and development cycle can become so lengthy that the anticipated users of a particular system such as a fighter aircraft, for example, may still be adolecents at the time the basic system requirements are being established. The designer must therefore think in terms of the requirements of users projected five to 15 years in the future.

In Chapter II, sources of human body size variability are described and quantified. There, particular attention was paid to secular changes in the body size of populations over time. To relieve the NASA design engineer of the burden of extrapolating data to the 1980-1990 time frame, the following anthropometric data have been developed for selected body dimensions projected to 1985. The dimensions chosen for inclusion here are the same 59 variables charted in the main body of this chapter and were selected for their general all-around usefulness to NASA engineers.

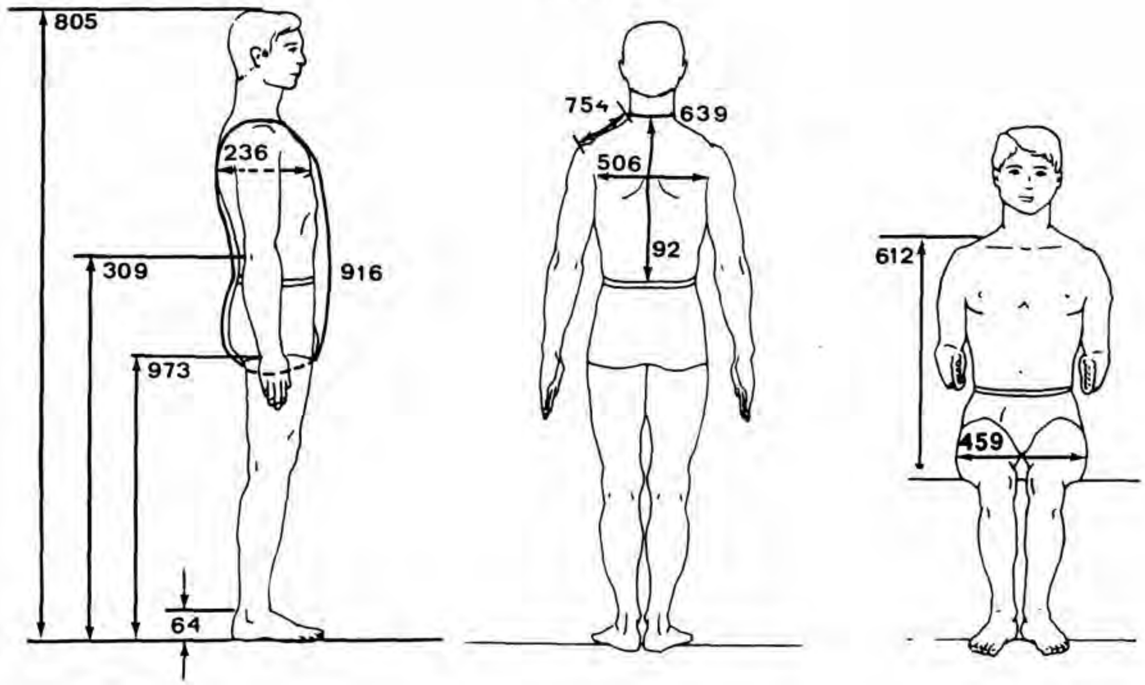
The male extrapolations were made on the basis of data from a number of surveys of USAF and U.S. Navy flying personnel conducted between 1950 and 1973. The data used were restricted to those from commissioned officers in the 23-35 year age range. Estimates were made for stature and for weight for astronauts aged 35 in 1985; estimates for other bodily dimensions were then computed by modifying the USAF '67 flying personnel data to reflect the anticipated increases in stature and weight.

Stature was assumed to be solely dependent on year of birth and statistics for stature were computed, year by year, for men born in each year from 1915 to 1950. Regression lines fitted to the means, 5th percentiles and 95th percentiles of these data suggested a continuing increase in all three statistics of about 8 mm (1/3 inch) per decade. Since the men who will be 35 years old in 1985 were born in 1950, 12-13 years later than the average member of the '67 flying personnel survey, an increase of about one centimeter (0.4 inch) was postulated.

Weight was considered as being primarily related to age and, for purposes of projection, it was assumed that the ponderal index (stature divided by the cube root of weight) was independent of birth year but was a linear function of age. On this basis, a value for the ponderal index for men of 35 was derived. The projected weight was then established by determining the weight which, with the anticipated 1985 stature, corresponded to this index. Unlike the values of stature, the projected increases in weight increased substantially from the low end to the high end of the body size distribution: 5th %ile, 1.6 kg (3.5 lb); 10th %ile, 1.7 kg (3.7 lb); mean, 1.9 kg (4.2 lb); 90th %ile, 2.1 kg (4.6 lb); 95th %ile, 2.2 kg (4.9 lb).

Because no correspondingly large group of surveys on which to study secular changes in the dimensions of female officers exists and because of the small size of the changes in the men's values, the data for the officers' subseries measured in the 1968 Air Force Women's survey have been accepted as the most satisfactory basis from which estimates were made.

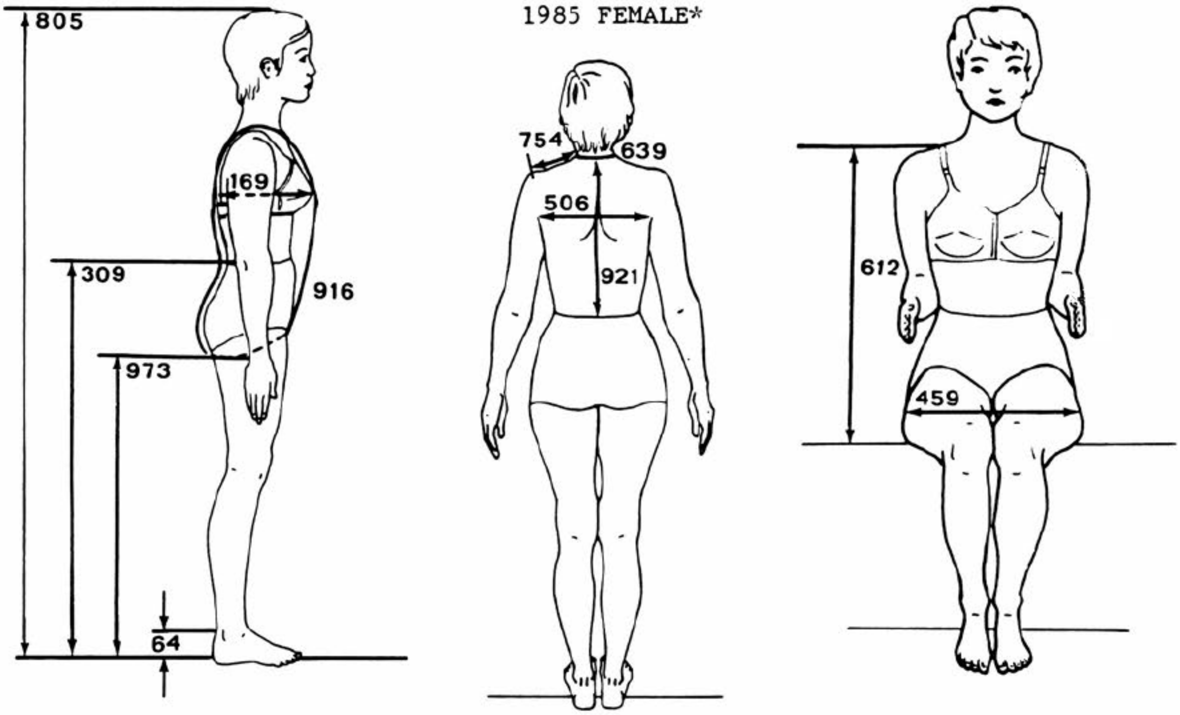
1985 MALE*



No.	Dimension	5%ile	Mean	95%ile
805	Stature	168.2 (66.2)	178.4 (70.2)	188.6 (74.3)
973	Wrist height	80.7 (31.8)	87.1 (34.3)	93.9 (37.0)
64	Ankle height	12.1 (4.8)	13.8 (5.4)	15.8 (6.2)
309	Elbow height	105.5 (41.5)	113.0 (44.5)	120.9 (47.6)
236	Chest depth	21.5 (8.5)	24.6 (9.7)	27.8 (10.9)
916	Vertical trunk circumference	157.4 (62.0)	169.0 (66.5)	180.9 (71.2)
612	Midshoulder height, sitting	60.6 (23.9)	65.0 (25.6)	69.6 (27.4)
459	Hip breadth, sitting	34.4 (13.5)	38.1 (15.0)	42.2 (16.6)
921	Waist back	43.3 (17.0)	47.2 (18.6)	51.1 (20.1)
506	Interscye	32.6 (12.8)	38.9 (15.3)	45.2 (17.8)
639	Neck circumference	35.5 (14.0)	38.5 (15.2)	41.8 (16.5)
754	Shoulder length	14.7 (5.8)	16.7 (6.6)	18.9 (7.4)

*Data given in centimeters with inches in parentheses.

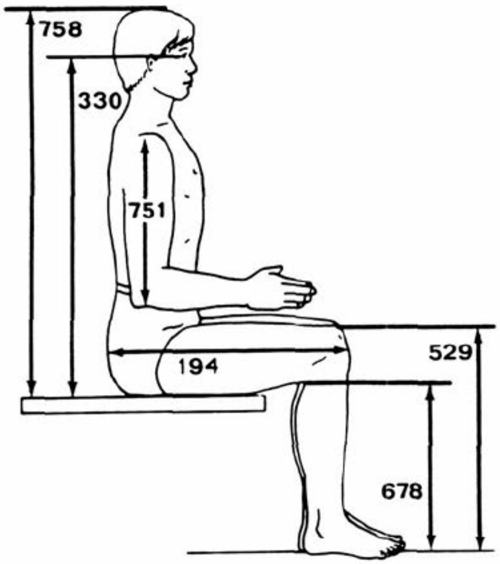
1985 FEMALE*

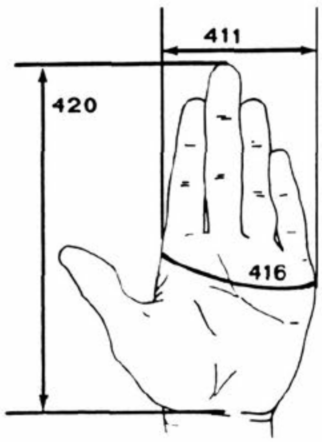


No.	Dimension	5%ile	Mean	95%ile
805	Stature	152.3 (60.0)	162.8 (64.1)	172.8 (68.0)
973	Wrist height**	73.5 (28.9)	79.4 (31.3)	85.3 (33.6)
64	Ankle height	9.1 (3.6)	11.2 (4.4)	13.6 (5.4)
309	Elbow height**	96.5 (38.0)	102.6 (40.4)	108.7 (42.8)
169	Bust depth	21.1 (8.3)	24.2 (9.5)	28.2 (11.1)
916	Vertical trunk circumference	145.3 (57.2)	156.6 (61.7)	169.0 (66.5)
612	Midshoulder height, sitting	54.2 (21.3)	58.5 (23.0)	63.1 (24.8)
459	Hip breadth, sitting	35.4 (13.9)	38.5 (15.2)	41.6 (16.4)
921	Waist back	36.8 (14.5)	40.5 (15.9)	44.5 (17.5)
506	Interscye	31.4 (12.4)	35.6 (14.0)	39.9 (15.7)
639	Neck circumference	31.3 (12.3)	34.0 (13.4)	37.3 (14.7)
754	Shoulder length	13.1 (5.2)	14.7 (5.8)	16.5 (6.5)

*Data given in centimeters with inches in parentheses.
**Estimated from regression equations.

1985 MALE*

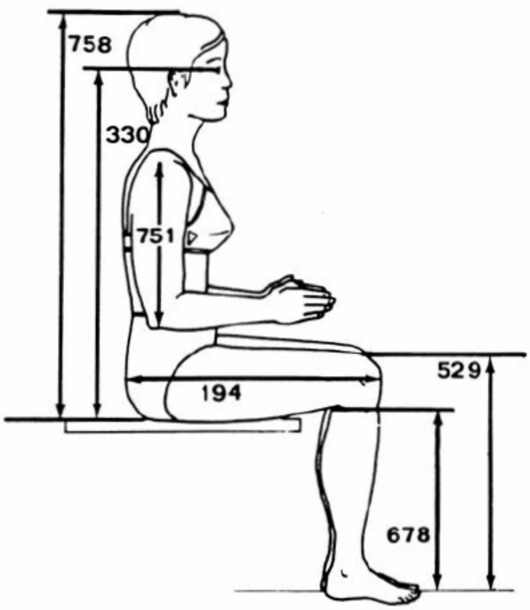


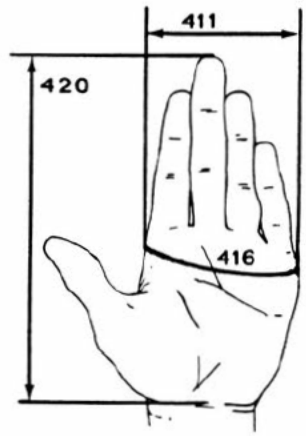


No.	Dimension	5%ile	Mean	95%ile
758	Sitting height	88.5 (34.8)	93.6 (36.9)	99.0 (39.0)
330	Eye height, sitting	76.4 (30.1)	81.3 (32.0)	86.5 (34.1)
529	Knee height, sitting	52.1 (20.5)	56.1 (22.1)	60.3 (23.7)
678	Popliteal height	40.4 (15.9)	44.0 (17.3)	47.8 (18.8)
751	Shoulder-elbow length	33.3 (13.1)	36.1 (14.2)	38.9 (15.3)
194	Buttock-knee length	56.4 (22.2)	60.8 (23.9)	65.4 (25.7)
420	Hand length	17.9 (7.0)	19.2 (7.6)	20.6 (8.1)
411	Hand breadth	8.3 (3.3)	8.9 (3.5)	9.6 (3.8)
416	Hand circumference	20.1 (7.9)	21.6 (8.5)	23.2 (9.1)

*Data given in centimeters with inches in parentheses.

1985 FEMALE*

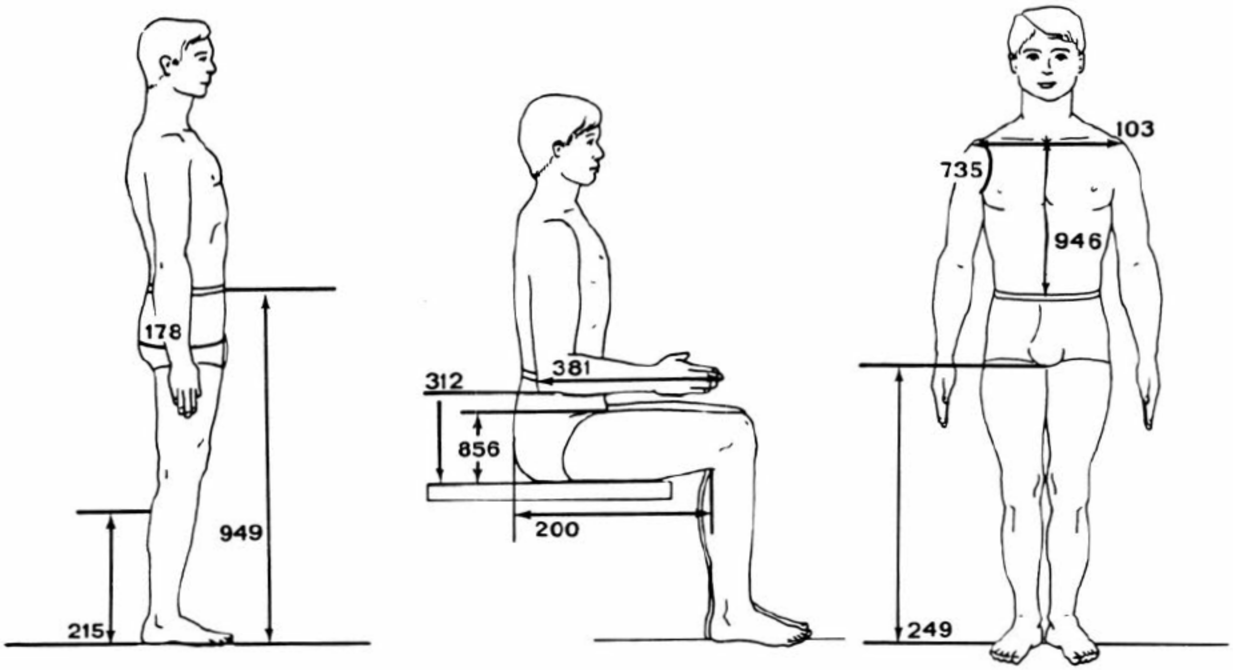




No.	Dimension	5%ile	Mean	95%ile
758	Sitting height	81.2 (32.0)	86.2 (33.9)	91.5 (36.0)
330	Eye height, sitting	69.5 (27.4)	74.4 (29.3)	79.6 (31.3)
529	Knee height, sitting**	46.7 (18.4)	50.5 (19.9)	54.3 (21.4)
678	Popliteal height	37.8 (14.9)	41.0 (16.1)	44.2 (17.4)
751	Shoulder-elbow length**	30.6 (12.0)	33.2 (13.1)	35.8 (14.1)
194	Buttock-knee length	53.3 (21.0)	57.6 (22.7)	62.0 (24.4)
420	Hand length	17.0 (6.7)	18.4 (7.2)	20.1 (7.9)
411	Hand breadth	6.9 (2.7)	7.6 (3.0)	8.3 (3.3)
416	Hand circumference	16.7 (6.6)	18.3 (7.2)	19.9 (7.8)

*Data given in centimeters with inches in parentheses.
**Estimated from regression equations.

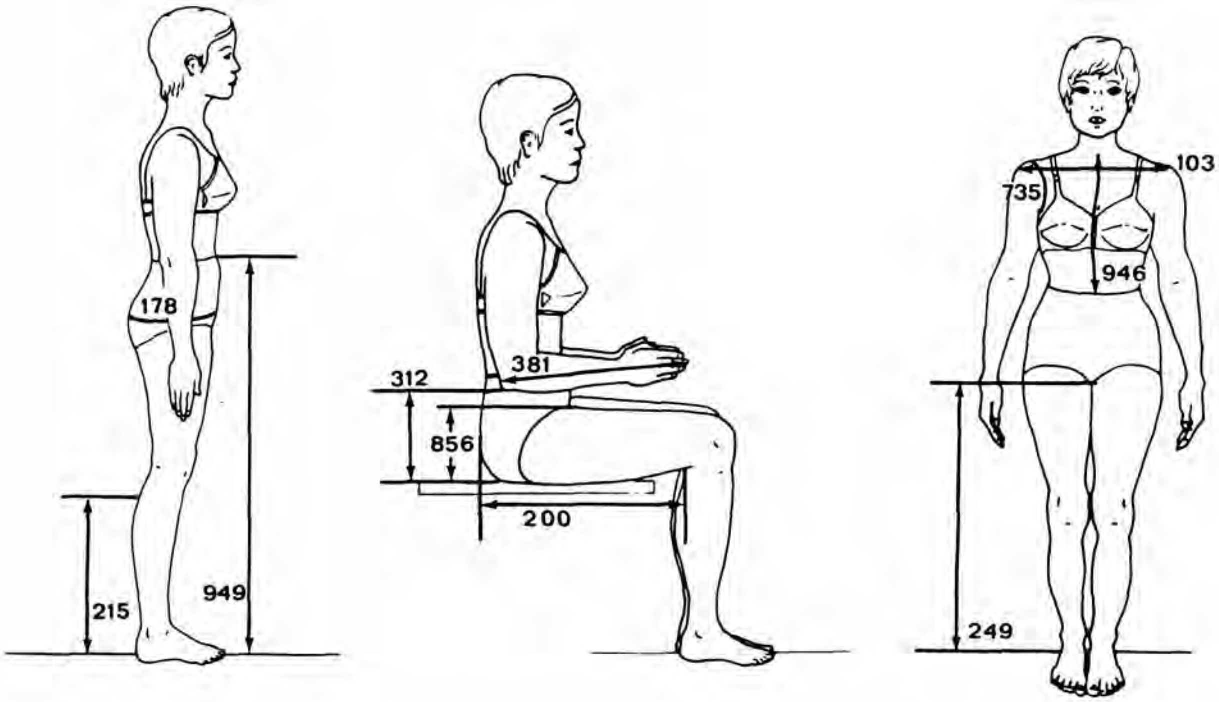
1985 MALE*



No.	Dimension	5%ile	Mean	95%ile
949	Waist height	99.4 (39.1)	107.2 (42.2)	114.8 (45.2)
249	Crotch height	78.9 (31.1)	85.7 (33.7)	92.6 (36.5)
215	Calf height	32.3 (12.7)	35.8 (14.1)	39.6 (15.6)
103	Biacromial breadth	37.6 (14.8)	40.9 (16.1)	44.0 (17.3)
946	Waist front	37.1 (14.6)	40.6 (16.0)	44.2 (17.4)
735	Scye circumference	44.2 (17.4)	48.7 (19.2)	53.3 (21.0)
178	Buttock circumference	90.3 (35.6)	99.5 (39.2)	108.9 (42.9)
312	Elbow rest height	21.0 (8.3)	25.3 (10.0)	29.7 (11.7)
856	Thigh clearance	14.5 (5.7)	16.8 (6.6)	19.1 (7.5)
381	Forearm-hand length**	45.7 (18.0)	49.1 (19.3)	52.6 (20.7)
200	Buttock-popliteal length	46.4 (18.3)	50.8 (20.0)	55.1 (21.7)

*Data given in centimeters with inches in parentheses.
**Estimated from regression equations.

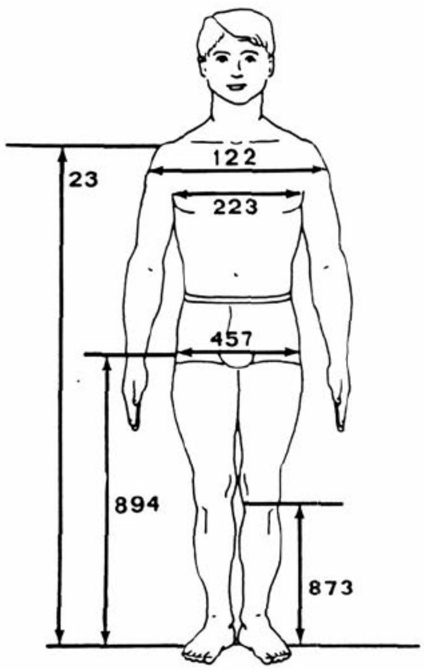
1985 FEMALE*



No.	Dimension	5%ile	Mean	95%ile
949	Waist height	93.1 (36.7)	100.7 (39.6)	108.1 (42.6)
249	Crotch height	67.7 (26.7)	74.4 (29.3)	81.3 (32.0)
215	Calf height**	28.7 (11.3)	33.1 (13.0)	37.5 (14.8)
103	Biacromial breadth	33.4 (13.1)	36.1 (14.2)	38.8 (15.3)
946	Waist front	30.4 (12.0)	33.7 (13.3)	37.1 (14.6)
735	Scye circumference	34.1 (13.4)	37.8 (14.9)	41.9 (16.5)
178	Buttock circumference	86.0 (33.9)	95.1 (37.4)	106.6 (42.0)
312	Elbow rest height	19.2 (7.6)	22.9 (9.0)	27.1 (10.7)
856	Thigh clearance	10.4 (4.1)	12.5 (4.9)	14.9 (5.9)
381	Forearm-hand length**	39.7 (15.6)	42.8 (16.9)	45.9 (18.1)
200	Buttock-popliteal length	43.7 (17.2)	47.9 (18.9)	52.7 (20.7)

*Data given in centimeters with inches in parentheses.
**Estimated from regression equations.

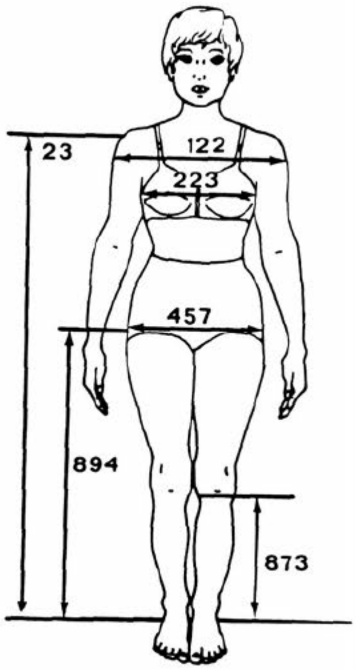
1985 MALE*



No.	Dimension	5%ile	Mean	95%ile
957	Weight (not pictured) kg. (lbs.)	65.2 (143.7)	81.5 (179.7)	97.7 (215.4)
23	Acromial (shoulder) height	136.5 (53.7)	146.1 (57.5)	155.7 (61.3)
894	Trochanteric height	87.5 (34.4)	94.6 (37.2)	101.8 (40.1)
873	Tibiale height	44.8 (17.6)	48.9 (19.3)	53.0 (20.9)
122	Bideltoid (shoulder) breadth	44.4 (17.5)	48.6 (19.1)	52.9 (20.8)
223	Chest breadth	29.7 (11.7)	33.0 (13.0)	36.7 (14.4)
457	Hip breadth	32.5 (12.8)	35.5 (14.0)	38.8 (15.3)
165	Bizygomatic (face) breadth	13.4 (5.3)	14.3 (5.6)	15.1 (5.9)
427	Head breadth	14.7 (5.8)	15.6 (6.1)	16.6 (6.5)

*Data given in centimeters with inches in parentheses.

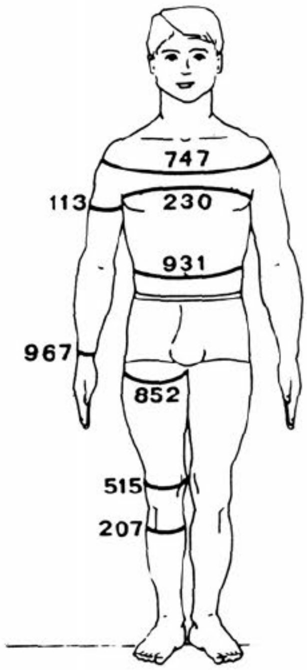
1985 FEMALE*

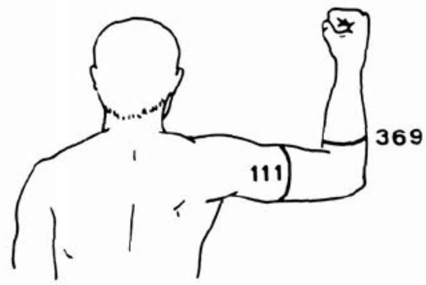


No.	Dimension	5%ile	Mean	95%ile
957	Weight (not pictured) kg. (lbs.)	47.4 (104.5)	59.7 (131.6)	74.9 (165.1)
23	Acromial (shoulder) height	122.9 (48.4)	132.4 (52.1)	141.4 (55.7)
894	Trochanteric height	75.6 (29.8)	82.8 (32.6)	90.1 (35.5)
873	Tibiale height	38.1 (15.0)	42.1 (16.6)	46.4 (18.3)
122	Bideltoid (shoulder) breadth	38.6 (15.2)	42.4 (16.7)	46.8 (18.4)
223	Chest breadth	25.3 (10.0)	28.5 (11.2)	32.3 (12.7)
457	Hip breadth**	32.0 (3.9)	35.5 (4.3)	39.6 (4.6)
165	Bizygomatic (face) breadth	12.0 (4.7)	13.0 (5.1)	14.0 (5.5)
427	Head breadth	13.7 (5.4)	14.7 (5.8)	15.7 (6.2)

*Data given in centimeters with inches in parentheses.
**Estimated from regression equations.

1985 MALE*

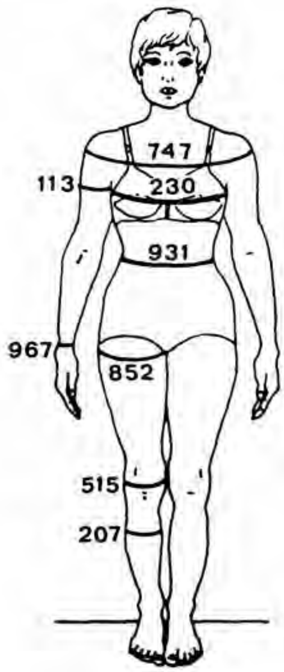


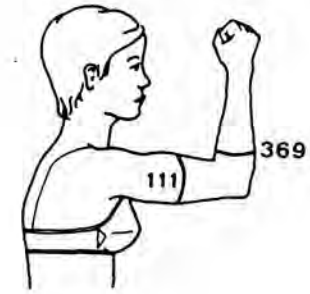


No.	Dimension	5%ile	Mean	95%ile
747	Shoulder circumference	109.0 (42.9)	118.5 (46.7)	128.4 (50.6)
230	Chest circumference	89.1 (35.1)	99.1 (39.0)	109.8 (43.2)
931	Waist circumference	76.4 (30.1)	88.4 (34.8)	100.7 (39.6)
852	Thigh circumference	52.1 (20.5)	59.5 (23.4)	67.1 (26.4)
515	Knee circumference	35.6 (14.0)	39.0 (15.4)	42.7 (16.8)
207	Calf circumference	33.8 (13.3)	37.5 (14.8)	41.3 (16.3)
113	Biceps circumference, relaxed	27.2 (10.7)	31.1 (12.2)	35.0 (13.8)
967	Wrist circumference	16.2 (6.4)	17.6 (6.9)	19.3 (7.6)
111	Biceps circumference, flexed	29.4 (11.6)	33.1 (13.0)	36.9 (14.5)
369	Forearm circumference, flexed	27.4 (10.8)	30.0 (11.8)	32.6 (12.8)

*Data given in centimeters with inches in parentheses.

1985 FEMALE*

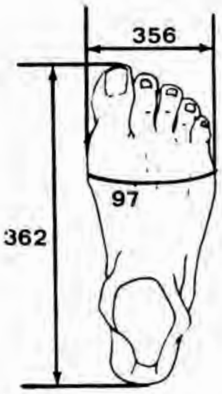


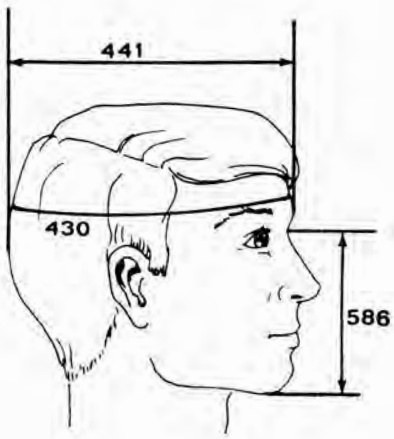


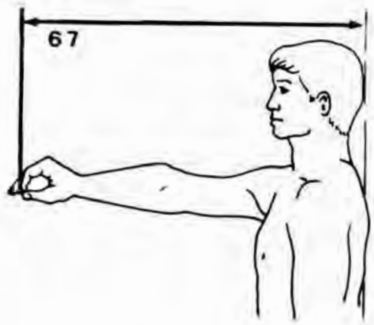
No.	Dimension	5%ile	Mean	95%ile
747	Shoulder circumference	93.3 (36.7)	101.7 (40.0)	111.8 (44.0)
230	Chest circumference	82.2 (32.4)	91.6 (36.1)	103.6 (40.8)
931	Waist circumference	59.4 (23.4)	68.2 (26.9)	80.4 (31.7)
852	Thigh circumference	49.2 (19.4)	56.3 (22.2)	64.1 (25.2)
515	Knee circumference	33.0 (13.0)	36.7 (14.4)	41.1 (16.2)
207	Calf circumference	30.7 (12.1)	34.3 (13.5)	38.4 (15.1)
113	Biceps circumference, relaxed	22.8 (9.0)	26.3 (10.4)	30.9 (12.2)
967	Wrist circumference	13.8 (5.4)	15.0 (5.9)	16.3 (6.4)
111	Biceps circumference, flexed	23.9 (9.4)	27.5 (10.8)	32.0 (12.6)
369	Forearm circumference, flexed	22.7 (8.9)	25.2 (9.9)	27.8 (10.9)

*Data given in centimeters with inches in parentheses.

1985 MALE*



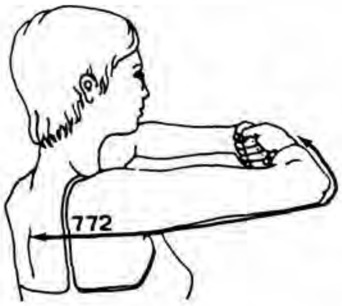


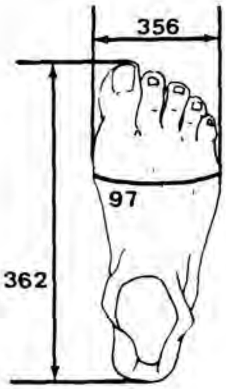


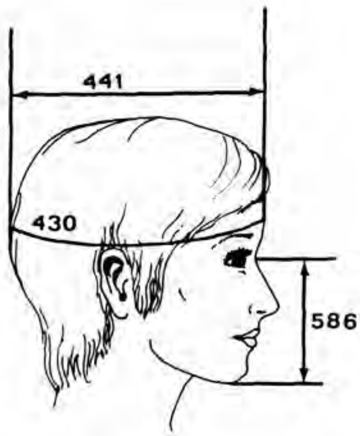
No.	Dimension	5%ile	Mean	95%ile
67	Thumb-tip reach	74.3 (29.3)	80.7 (31.8)	87.4 (34.4)
772	Sleeve length	85.7 (33.7)	91.3 (35.9)	97.3 (38.3)
441	Head length	18.8 (7.4)	19.9 (7.8)	21.0 (8.3)
430	Head circumference	55.3 (21.8)	57.6 (22.7)	60.0 (23.6)
586	Menton-sellion (face) length	11.1 (4.4)	12.0 (4.7)	13.0 (5.1)
362	Foot length	25.3 (10.0)	27.2 (10.7)	29.2 (11.5)
356	Foot breadth	9.0 (3.5)	9.8 (3.9)	10.7 (4.2)
97	Ball of foot circumference	23.0 (9.1)	25.0 (9.8)	27.0 (10.6)

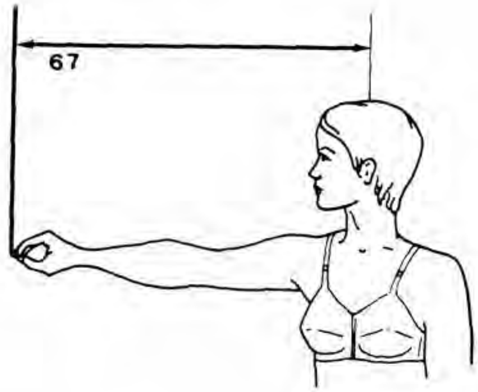
*Data given in centimeters with inches in parentheses.

1985 FEMALE*









No.	Dimension	5%ile	Mean	95%ile
67	Thumb-tip reach	67.7 (26.7)	74.3 (29.3)	80.6 (31.7)
772	Sleeve length	74.2 (29.2)	80.0 (31.5)	85.2 (33.5)
441	Head length	17.5 (6.9)	18.6 (7.3)	19.7 (7.8)
430	Head circumference	52.6 (20.7)	55.2 (21.7)	57.9 (22.8)
586	Menton-sellion (face) length	12.6 (9.8)	14.0 (10.8)	15.6 (11.8)
362	Foot length	22.2 (8.7)	24.1 (9.5)	26.1 (10.3)
356	Foot breadth	8.0 (3.1)	8.8 (3.5)	9.7 (3.8)
97	Ball of foot circumference**	21.3 (8.4)	23.3 (9.2)	25.3 (10.0)

*Data given in centimeters with inches in parentheses.
**Estimated from regression equations.

APPENDIX C

DRAWING BOARD MANIKINS

Two-dimensional drawing board manikins are among the most important aids used by the designer in making preliminary as well as fairly complete crew station drawings. The most up-to-date and accurate such manikins are those developed by Kenneth W. Kennedy of the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. Acting on a request from the Lyndon B. Johnson Space Center, NASA, Kennedy developed a 5th, 50th and 95th percentile drawing board manikin based on the anticipated 1980-1990 body size distribution of USAF fliers. These manikins provide not only accurate body size dimensions but body length links, segmental centers of rotation and joint range limits. As well, they incorporate adjustments for changes in body size dimensions for sitting and standing design postures.

Figures 1 and 2 illustrate the new manikins (patents applied for). They are designed to represent the USAF rated officers of the 1980-90 time period. Figure 1 is a photograph of one variation, the 5th percentile, with the arm detached to permit an uncluttered view of its parts. Fifth, 50th, and 95th percentile manikins have been designed. A variant of the same manikin, provided with a boot and helmet, is pictured in Figure 2 in the fetal position to illustrate the manikin's mobility and natural body profile in such an extreme position.

The manikins are accurate in at least 25 body size dimensions important in the layout of crew stations. Chief among these are:

Stature
Sitting height
Eye height, sitting
Functional reach
Functional reach, extended
Elbow to grip distance
Buttock knee length
Knee height, sitting
Chest depth
Waist depth
Hand, head and foot dimensions

Alternate limbs have been designed and sized to allow the designer to consider variability in body proportions as well as body size in the design of crew stations. Each percentile torso is equipped with three sets of limbs representing the design range. Thus, a 50th percentile manikin could be fitted either with 50th percentile limbs or with a set of arms and legs representing the largest or smallest generally found on that size torso.

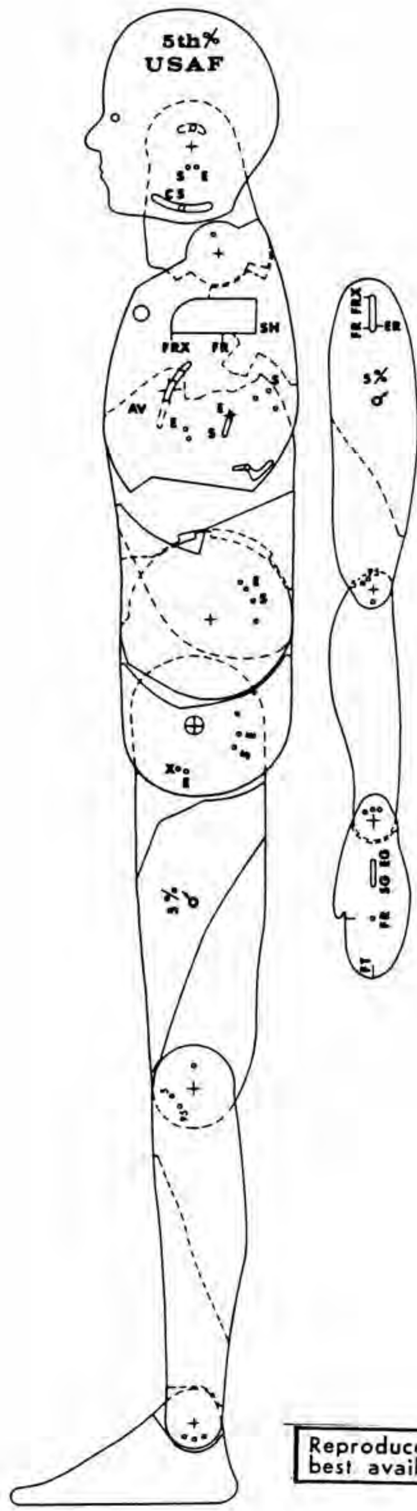


Figure 1. USAF two-dimensional manikin.

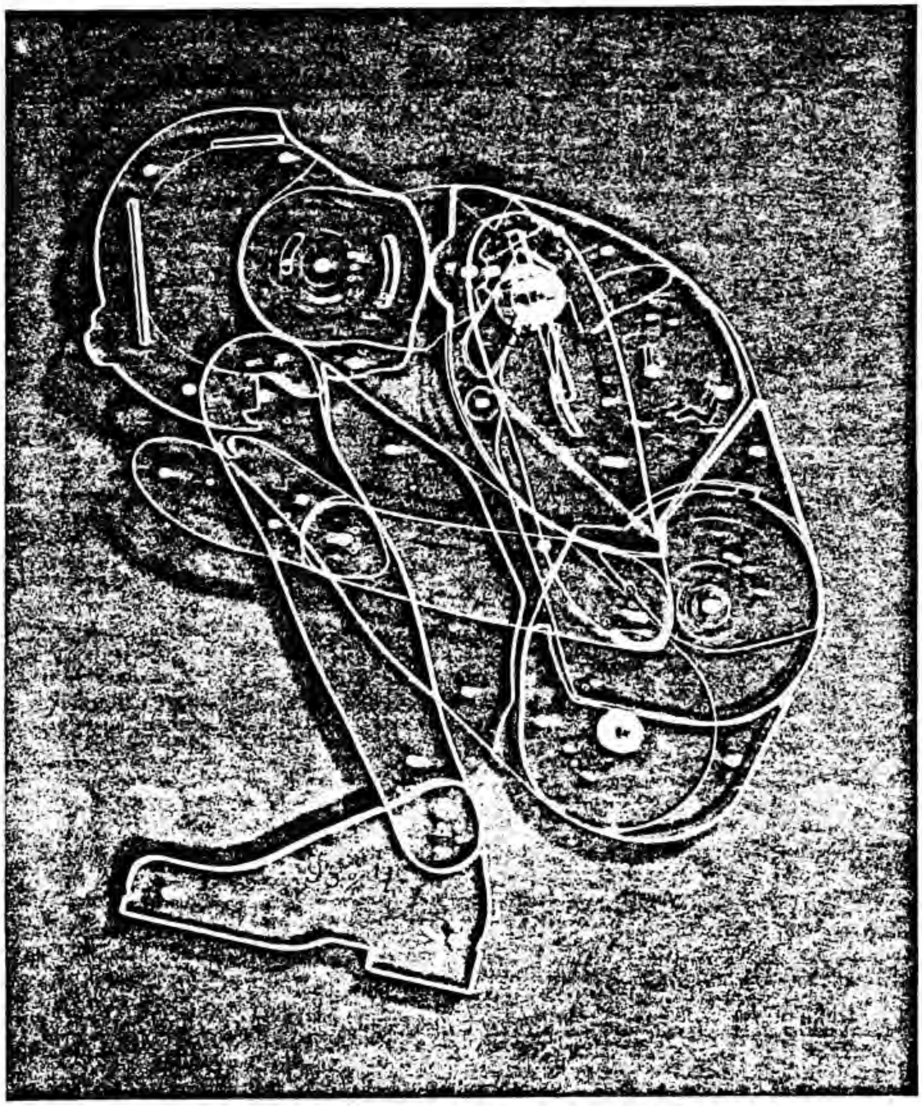


Figure 2. USAF two-dimensional manikin in fetal position.

The manikins are obviously useful in laying out the geometry of crew stations. They are also valuable in evaluating a crew station in terms of tolerance to G forces because they provide the capability to track the positions of the eye, the carotid sinuses, and the aortic valves. The heights of the eye-heart and carotid sinus-heart columns can be calculated.

To provide the USAF manikin with the desired features and to provide for realistic intra-torso mobility and the greatest possible stability on the drawing board, it was necessary to design the manikin in three layers. With this design, the head, torso, and legs on each side can be uniplanar. Since the convention is to design cockpits and other vehicle driving stations "face left," the symbology has been designed for that direction. The arm is fastened to the manikin's left side. Should the occasion arise to design face right, the arm can be removed and fastened to the other side.

The plans for this manikin are not simple, nor can useful models be made with cardboard and scissors. They require precise and rather skilled care in their fabrication to assure the desired results. Although somewhat expensive to fabricate, a well-made manikin is an extremely useful and valuable design tool. Plans may be obtained from:

6570 Aerospace Medical Research Laboratory
ATTN: Mr. Kenneth W. Kennedy
Wright-Patterson AFB, Ohio 45433

For the casual user and for the designer who does not need the full capabilities of the more complicated USAF 2-D manikins, a simpler design has been prepared and is presented in Figures 3, 4 and 5. While the pictured patterns do not embody all the features of the more complicated manikins, they are much less costly to produce and still provide accurate body dimensional and mobility data readily useful to the designer. These illustrations are accurate as presented to allow the user to duplicate the patterns, cut them out, and actually make up serviceable 1/4 scale, 5th, 50th, and 95th percentile manikins.

For users who wish to assemble the cut-out manikins, the following symbology should be understood:

A target, ⌖, indicates a joint center and should be drilled in accordance with available fasteners.

Two targets connected by a straight line, such as in the upper torso and upper arm, represent a slot of a convenient diameter to permit slippage of the fastener. This slot permits the arm to be placed in both the functional reach and functional reach, extended positions.

Index hole = • ; Adjustment hole = o .

"E," which appears adjacent to adjustment holes in the head, neck, torso, and lower limb, indicates adjustment holes for the erect body position, both standing and seated. When the index holes (•) are aligned with the adjustment hole (o) marked "E," the manikin is adjusted to a normal erect body position. When the index holes are aligned with the other holes, the joint in consideration is at an extreme of its motion capability.

It is extremely important to follow instructions when fabricating these manikins. With the manikins in the standing erect position (as illustrated), the following instructions apply.

Joint A (Head):

Drill index hole through both top and bottom pieces.
Drill adjustment holes through bottom piece only.
Scribe "E" on bottom piece.

Joint B (Neck):

Drill index hole through both pieces.
Drill adjustment holes through bottom piece.
Scribe "E" on bottom piece.

Joint C (Mid-chest--below arm attachment slot):

Drill index hole through both pieces.
Drill adjustment holes through top piece.
Scribe "E" on top piece.

Joint D (Abdomen):

Drill index hole through both pieces.
Drill adjustment holes through bottom piece.
Scribe "E" on bottom piece.

Joint E (Hip):

Drill index hole through both pieces.
Drill adjustment holes through bottom piece.
Scribe "E"s and "X" on bottom piece.

Joint F (Knee):

Drill index hole through both pieces.
Drill adjustment holes through bottom piece.
Scribe "E", "5" and "95" on bottom piece.

Joint G (Ankle):

Drill index hole through top piece only.
Drill adjustment holes through bottom piece.

Joint H (Elbow):

Drill index hole through both pieces.
Drill adjustment holes through top piece.
Scribe "5" and "95" on top piece.

Joint I (Wrist):

Drill index hole through top piece only .
Drill adjustment holes through bottom piece.

When the manikin is in use, functional reach ("FR" mark on hand) and finger tip reach ("FT" mark on hand) can be accurately simulated by aligning "FR" in the slot in the upper arm with "FR" in the slot in the upper torso, with the arm straight and extended forward. Functional reach extended ("FRX" mark on the hand) and finger tip reach can be simulated by similarly aligning "FRX" on the torso and arm.

When the index hole is aligned with "5" or "95" at the knee or elbow, 5th and 95th percentile knee and elbow flexion, respectively, are achieved. When in the "E" position, the joint is fully extended.

When the index hole at the hip is adjusted to one of the two "E" adjustment holes, that joint is in the seated or standing erect position; when adjusted to "X", the hip is hyperextended. When at one of the remaining two adjustment holes, the hip is either normally extended or flexed.

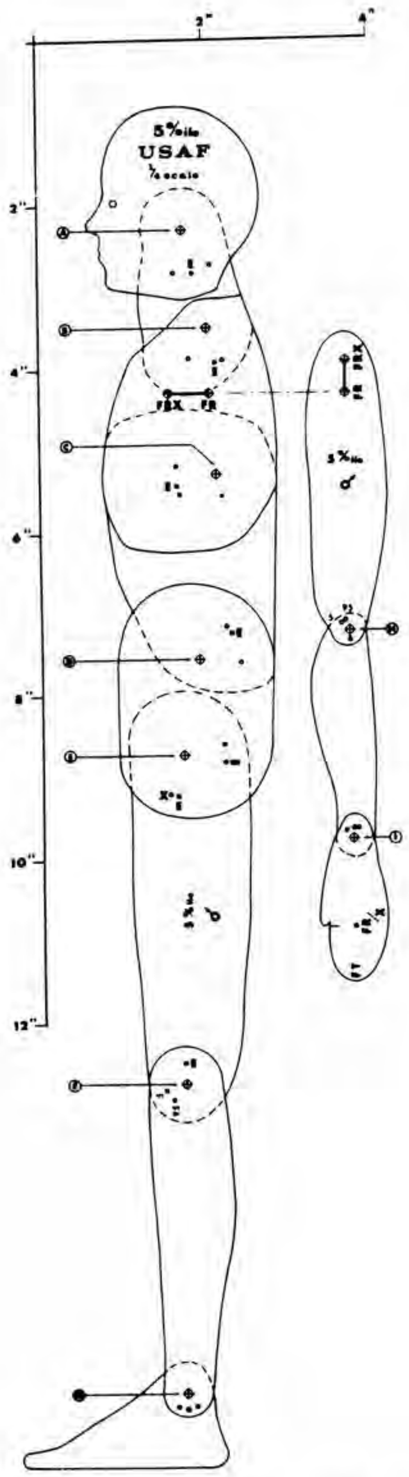


Figure 3. Two-dimensional 5%ile USAF manikin (simplified version).

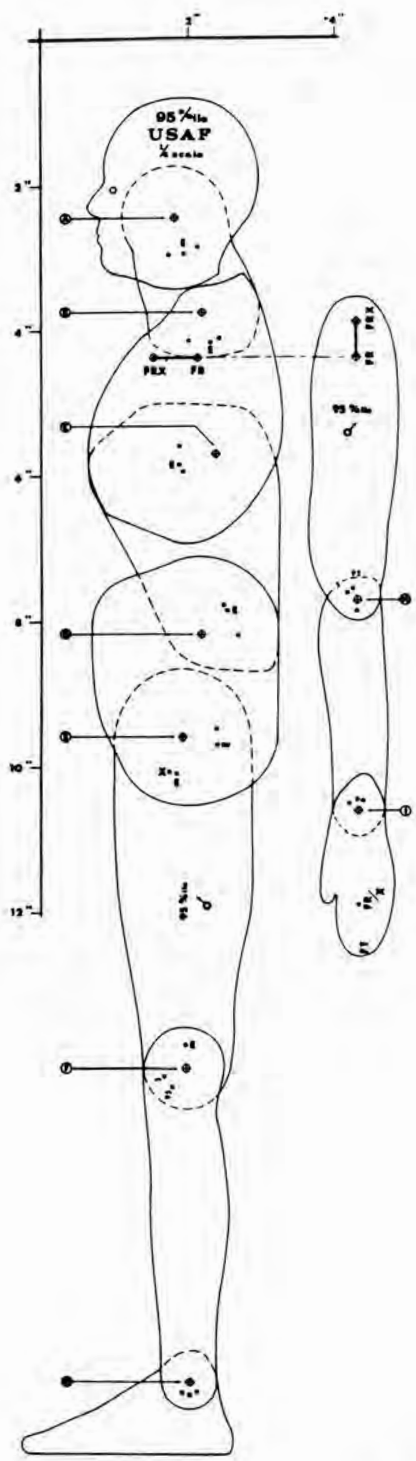


Figure 4. Two-dimensional 50%ile USAF manikin (simplified version).

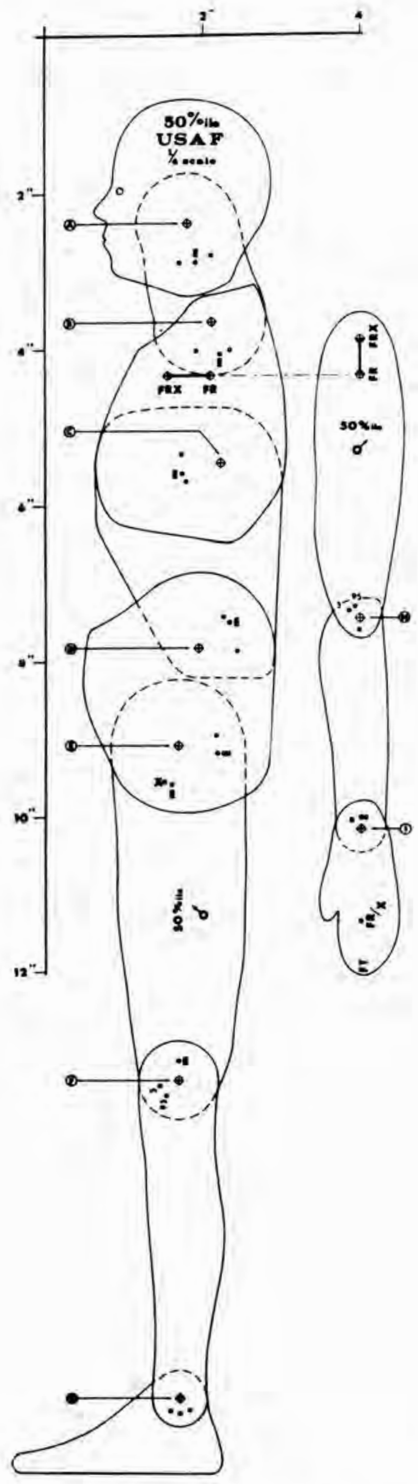


Figure 5. Two-dimensional 95%ile USAF manikin (simplified version).

N79-11738

CHAPTER IV
THE INERTIAL PROPERTIES OF THE BODY AND ITS SEGMENTS

by
Herbert M. Reynolds
The University of Michigan

The purpose of this chapter is to present a user-oriented summary of the current state of knowledge on the mass distribution properties of the adult human body. Design engineers, the most common users of such data, have two sources of information for establishing human biomechanical limitations relevant to their design product. These are directly measured data and output from mathematical models. Empirical data are obviously the more desirable but are often either unavailable or unattainable on living subjects so the output from mathematical models becomes the sole source of design information. These models have, in the past, been based upon the properties of geometric analogues of body segments. While this approach serves a useful purpose in examining population problems where the variation in the population is greater than the error in the model, it does not provide a design engineer with the needed sensitivity to design equipment for a highly selected group of astronauts.

Collected here for the first time are all the known data describing the mass distribution properties of the body presented in such a manner that mathematical models can be highly individualized. This material, which includes data for living whole bodies in static positions and segment data obtained from cadaver studies, will provide both direction for constructing mass distribution models and a range of values by which the model output can be evaluated.

Mass distribution properties will be discussed in terms of the musculoskeletal linkage system, axes systems, mass, volume, center of mass, and inertial properties. In the following sections data and prediction equations or coefficients suitable for modeling these properties are provided.

Predictive formulas presented in this chapter and suitable for both the whole body and its segments will employ, primarily, total body weight and stature as the independent variables. While some computations have been completed and presented here, the user may be interested in computing for a different population. In this case either an individual's measured height and weight could be used or the appropriate population statistics (See Chapter III) could be substituted.

While the prediction equations and resulting estimates will be of use in the preliminary analysis of the design problem for a population, they will not be sensitive to individual variations which may be of significance in designing for a specific astronaut or scientist. For this purpose the reader will be referred to various tables in Appendix B in which data and computation techniques for estimating the biomechanical properties of the individual appear. Equations provided in this Appendix are aimed at describing segments of the body in such a way that differences between individuals can be observed and will help the designer determine the range and extent to which a particular piece of equipment needs to be personalized. These data also provide biomechanical input for individualized models useful in solving workspace design problems or analyzing dynamic environments.

Data Sources and Limitations

The data and prediction equations presented in this chapter are based, in general, on small samples of living and cadaveric subjects typical of the White European male. In the very few cases where data were available on males and females of other races, the information has been reviewed and incorporated in the appropriate table or prediction equations. However, the fact that most of the data were collected on white European males presents an undeniable problem to the design engineer concerned with a population whose range in size goes from the fifth percentile Oriental woman to the 95th percentile Caucasoid male.

Many different techniques have been utilized for measuring the mass distribution properties of the whole body. Hay (1973) gives an excellent review of these studies and points out the two major difficulties in studies of the living; (1) fluid and tissue shifts in the measurement procedure and (2) the static, or position-dependent, nature of the measured locations. When a whole body is measured, the data are completely valid only when applied to a body in that position. Thus, in order to determine the location of the center of mass for any given body, it is necessary to measure either every possible body position or to measure the location of the center of mass in each body segment and model the whole body from the sum of its segments. The latter approach has been emphasized in the present chapter since it provides information on a wider range of body types and body positions.

The segment model approach has been a recent development and most of the data are derived from European and U.S. studies of cadavers (Harless, 1860; Braune and Fischer, 1889, 1892; Fischer, 1906; Dempster, 1955; Clauser et al. 1969; and Chandler et al. 1975). Two additional studies by Mori and Yamamoto (1959) and Fujikawa (1963) provide some data on the mass distribution of twelve Japanese cadavers. Although the total sample size from all the above-mentioned studies is limited, it probably provides a better estimate for the desired biomechanical properties than do the present geometric models.

Measurements on the body segments of living subjects have usually relied upon indirect methods. Segment weight has been estimated by measuring segment volume (Drillis and Contini, 1966) and by measuring the reaction change on a weight board due to segment displacement (Bernstein et al. 1931). Segment center of mass measurements have used volumetric estimates

(Bernstein et al. 1931; Cleaveland, 1955).Inertial data have been collected almost exclusively on the links using indirect measurement techniques to estimate a single moment of inertia about a joint center of rotation (Fenn, Brody, and Petrilli, 1931; Fenn, 1938; Hill, 1940; Bouisset and Pertuzon, 1968, Allum and Young, 1976). These techniques, in general, assume knowledge of segment density, segment center of mass, and joint centers of rotation depending upon the variable under investigation. A promising indirect technique for measuring the mass distribution properties of the living human body appears to be stereophotogrammetric measures of volume as developed by Herron et al. (1976).

In addition to the lack of complete population data, there are no data on the effect of the secular increase in size on the mass distribution properties of the human body. It has been assumed that these changes will be proportional, thus making a linear solution to any problem possible. For example, if an increase in stature of 0.5% occurs in the next 10 years it is assumed that there would be a corresponding increase in link length. Furthermore, the assumption is made that statistical relationships would remain the same, e.g., the correlation coefficient between acromion-radiale length and stature would remain constant. The design engineer and modeler should be alerted to these kinds of assumptions (which we make, for example, in combining linkage data from Dempster, 1955, and Snyder, Chaffin, and Schultz, 1972) so that he can assess the data within his tolerance limits and decide on the extent to which these data can be relied upon.

Two further limitations of the basic data should be mentioned before proceeding.

First, the relationship between data collected from living subjects and data based on cadaver studies has never been defined. This means that it is not yet known how accurately data garnered from a cadaver can be applied to the living. In addition, the error in estimating data from indirect measurements made on living subjects has also not been defined.

Secondly, all data so far collected were measured at one-g and the changes which a zero-g environment effect on an individual were not considered. One means of dealing with this problem is discussed in following sections on linkage and mass.

The Anatomical Framework

The human body is often compared to a machine. Persuaded by this concept, one is easily led to rely on mechanical concepts to describe the geometry and motion of the body in the biomechanical framework. However, one must recognize that the present mechanical treatment of the human anatomy with mechanical analogies is only an approximation of a highly complex and variable system. As a first step in clarifying the construction of the human body, an anatomical description of joint centers of rotation, axes systems, and body linkages is given in great detail in Appendix A. The user of this chapter is strongly urged to read this Appendix and obtain some grasp of the anatomical structure that underlies all these biomechanical data. Without a thorough understanding, the user is likely to go astray in applying the data.

In the study of anatomy, three planes--sagittal, frontal, and transverse--have been hypothetically superimposed on the body to describe the relative location of its anatomical features. The usual directional notation system used to describe locations relative to these planes is as follows with the corresponding, right-hand rule axis system nomenclature in parenthesis:

Anterior--towards the front (+X)
Posterior--towards the rear (-X)
Lateral--towards the side: Left (+Y), Right (-Y)
Medial--towards the middle: Left (-Y), Right (+Y)
Superior--towards the head (+Z)
Inferior--towards the feet (-Z)

With the body in the standard anatomical position, the sagittal plane is defined by the X- and Z-axes; the frontal, or coronal, plane is defined by the Y- and Z-axes; and the transverse, or horizontal, plane is defined by the X- and Y-axes (See Figure 1). This superstructure of intersecting planes has not traditionally been anchored to any single location in the body. For biokinematic research and engineering hardware design a whole body axis system should be fixed (rather than "floating") through use of specific anatomical or anthropometric landmarks. The axes proposed in this chapter use three definable landmarks selected so that they form a plane approximately parallel to one of the cardinal anatomical planes of the body. A right-handed, orthogonal axis system is then constructed using the anthropometric plane of orientation, a perpendicular plane and a plane normal to the other two planes. Thus, the axis system will be defined by the intersection of three orthogonal planes of reference and a defined point of origin.

Although a number of axes systems have been proposed (Santschi et al. 1963; Ignazi et al. 1972; and Chandler et al. 1975; Panjabi et al. 1974; Thomas et al. 1975) the whole body axis system which appears at this time to be best suited for biomechanical models is one centered on the pelvis (See Figure 1).

There are several reasons for choosing this system. First, the center of mass of the whole body in every position is approximately at the site of the pelvis. Second, the pelvis can be treated as a rigid body. Third, the human body in its most elemental form is hinged at the pelvis. In other words, a major controlling factor in attitude and motion of the body is the spatial orientation and location of the pelvis.

Therefore, it is recommended that a frontal plane (YZ) be established using symphysion and the right and left anterior superior iliac spines. The transverse (XY) plane is constructed as a perpendicular to the YZ plane while passing through the right and left anterior superior iliac spines. The sagittal (XZ) plane is constructed as a normal to the YZ and XY planes while pass-

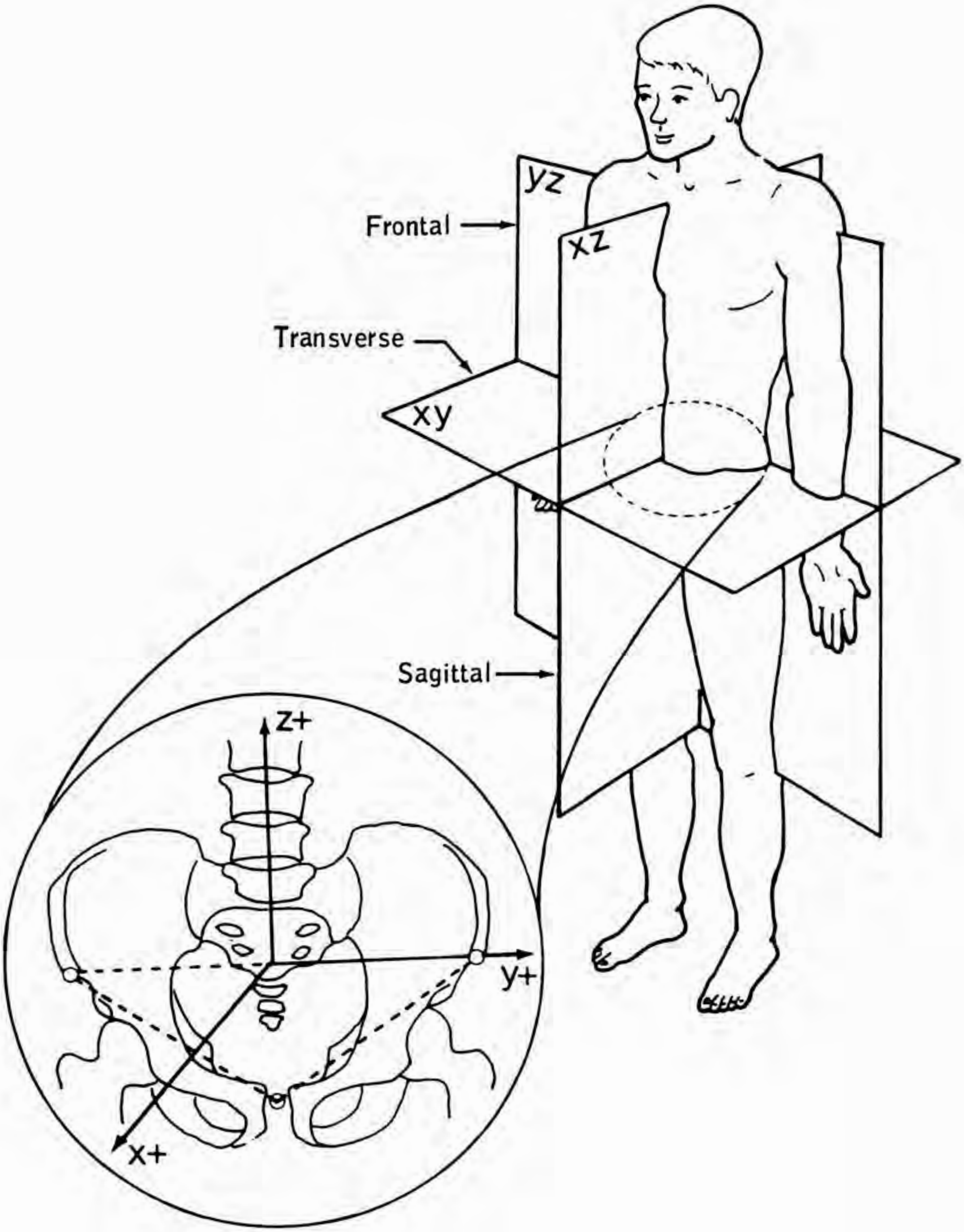


Figure 1. Whole body axis system centered on the pelvis.

ing through symphysion. The coordinate axis system origin will lie on a line passing through the right and left anterior superior iliac spines approximately at the midpoint of bispinous diameter. The +X axis will pass anteriorly along the intersection of the XY and XZ planes; the +Y axis will pass laterally along the intersection of the XY and YZ planes; and the +Z axis will pass superiorly along the intersection of the XZ and YZ planes.

Similar frames of reference have been provided for body segments (See Appendix A). Theoretically, a biomechanical segment of the body is the largest dimensional mass which, when moved, will maintain a constant geometry. Thus, body segments are defined as the mass which lies between two adjacent segmentation surfaces which pass through their respective joint centers of rotation. For example, the forearm is a biomechanical body segment since it has a mass that lies between the wrist and elbow joint centers of rotation. It is, in other words, a body link--a term borrowed from rigid body mechanics which is used frequently to refer to the straight-line distance between two adjacent joint centers of rotation.

In general, the principal body segments are easily identified although the specific segmentation planes and their locations are not as easily determined. The number of principal body segments differ in the literature, particularly with respect to the torso which has been segmented into individual vertebral sections (Liu and Wickstrom, 1973) and left intact as one mass (Chandler et al. 1975). Other segmentation schemes utilized in mass distribution studies have been described in Reynolds et al. (1975). In addition, there are differences in segmentation planes between studies conducted on living subjects and cadavers (See Figure 2).

For the present chapter, the segmentation planes will follow the rationale first presented by Braune and Fischer (1892) and simulated in subsequent studies. This scheme segments the body at the level of joint centers of rotation thereby providing data correlated with the linkage system of the body. Dempster (1955) and Snyder et al. (1972) have provided the basic data we will use here in describing the linkage system and its spatial description.

This chapter is a result of sorting through numerous alternatives to arrive at an anatomical framework most suitable for biomechanical research. The data reflect this approach but without a thorough appreciation of the implications of a mechanical model upon the anatomical reality, costly mistakes and misinterpretations can occur. Therefore the user is once again encouraged to become familiar with Appendix A for a full appreciation of the information contained in this chapter.

The Body Linkage System

A description of the body as a linkage system provides a biomechanical framework that can be used to undertake a rigorous analysis of its kinematics. Without this basic model, the study of the motion of the body and its respective segments would be extremely difficult, if not impossible.

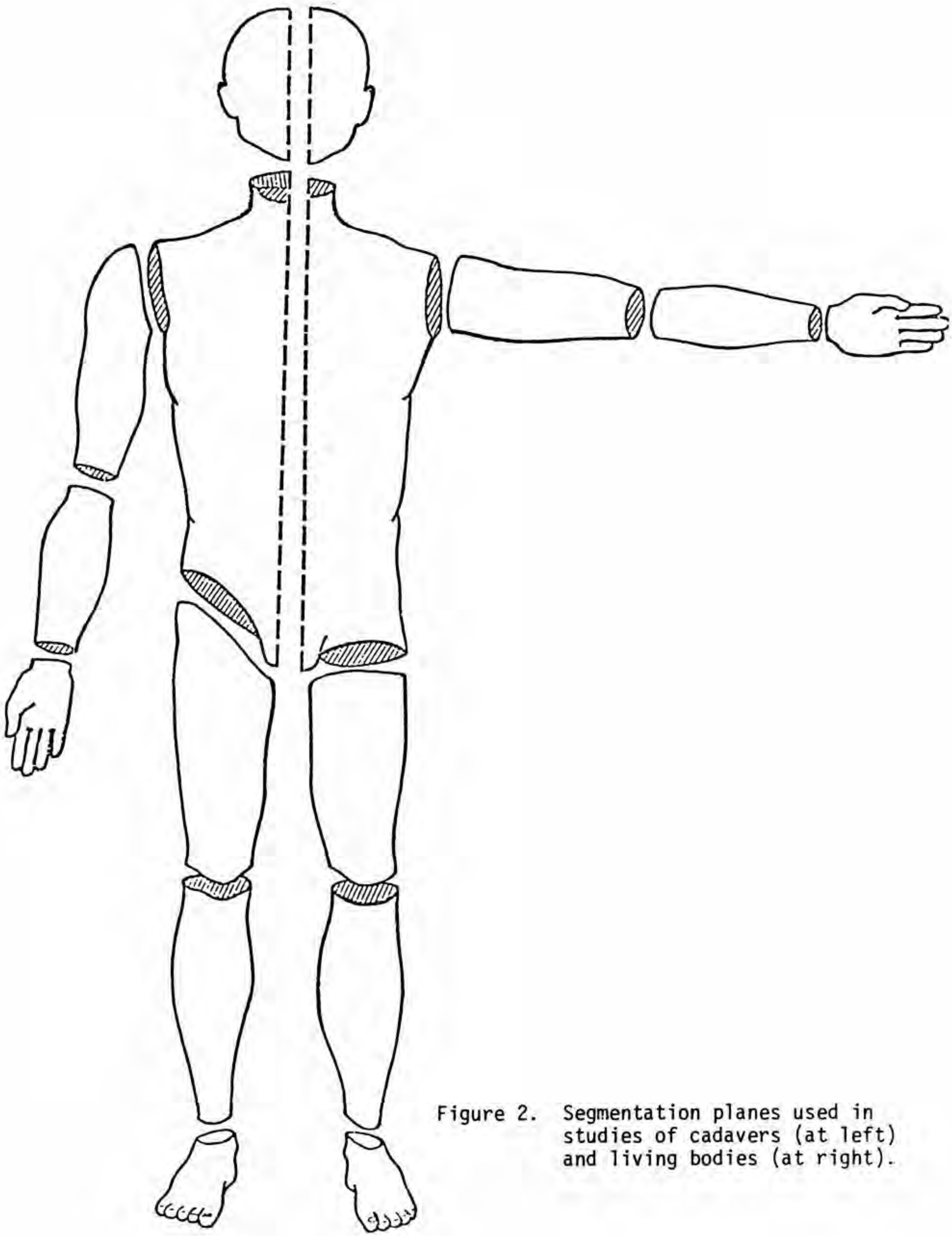


Figure 2. Segmentation planes used in studies of cadavers (at left) and living bodies (at right).

It should be noted, before proceeding, that the concepts of body segments and body links must be handled carefully. The concept of a body segment is useful in describing mass distribution; the concept of a body link is used when describing body motion. When dealing with the limbs, segments and links generally correspond. The torso, however, has such complex motion capabilities that its various segments often contain more than one link.*

For the purposes of this chapter, the body is composed of 20 links: head, neck, thoracic, thoraco-sternum assemblage** (right and left transthoracic and transternum), right and left clavicular, right and left scapular, lumbar, pelvic assemblage** (right and left ilio-pelvic and transpelvic), right and left upper arm, right and left forearm, right and left thigh, right and left shank, right and left foot. These links are illustrated in Figure 3 and defined in Appendix A.

Theoretically, links are pure straight line distances between centers of joint rotation. In fact, due to the complex nature of actual joint motion, the link is an average straight-line distance calculated from points at the mid-range of joint mobility. For a more complete discussion of the body linkage system and the underlying anatomical assumptions, the reader is referred to Dempster's "Space Requirements of the Seated Operator" (1955).

Limb Links

The first step in determining the length of links in the arms and legs is to determine lengths of the relevant long bones, which in turn can be estimated from stature. Then, using coefficients which have been derived as a ratio of link length to bone length, link lengths are determined by multiplying bone lengths by the link/bone coefficients. A step-by-step description of these procedures follows:

The four limb links and their associated bones are: upper arm (humerus), forearm (radius and ulna), thigh (femur), and shank (tibia and

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* Insufficient research has been conducted to resolve in a logical and consistent manner the apparent conflict between torso links and segments.

** Both of these linkage assemblages are closed systems composed of three straight-line distances and three joint centers of rotation. They are considered assemblages, at present, since no one straight-line distance in an assemblage can move independently of the other two.

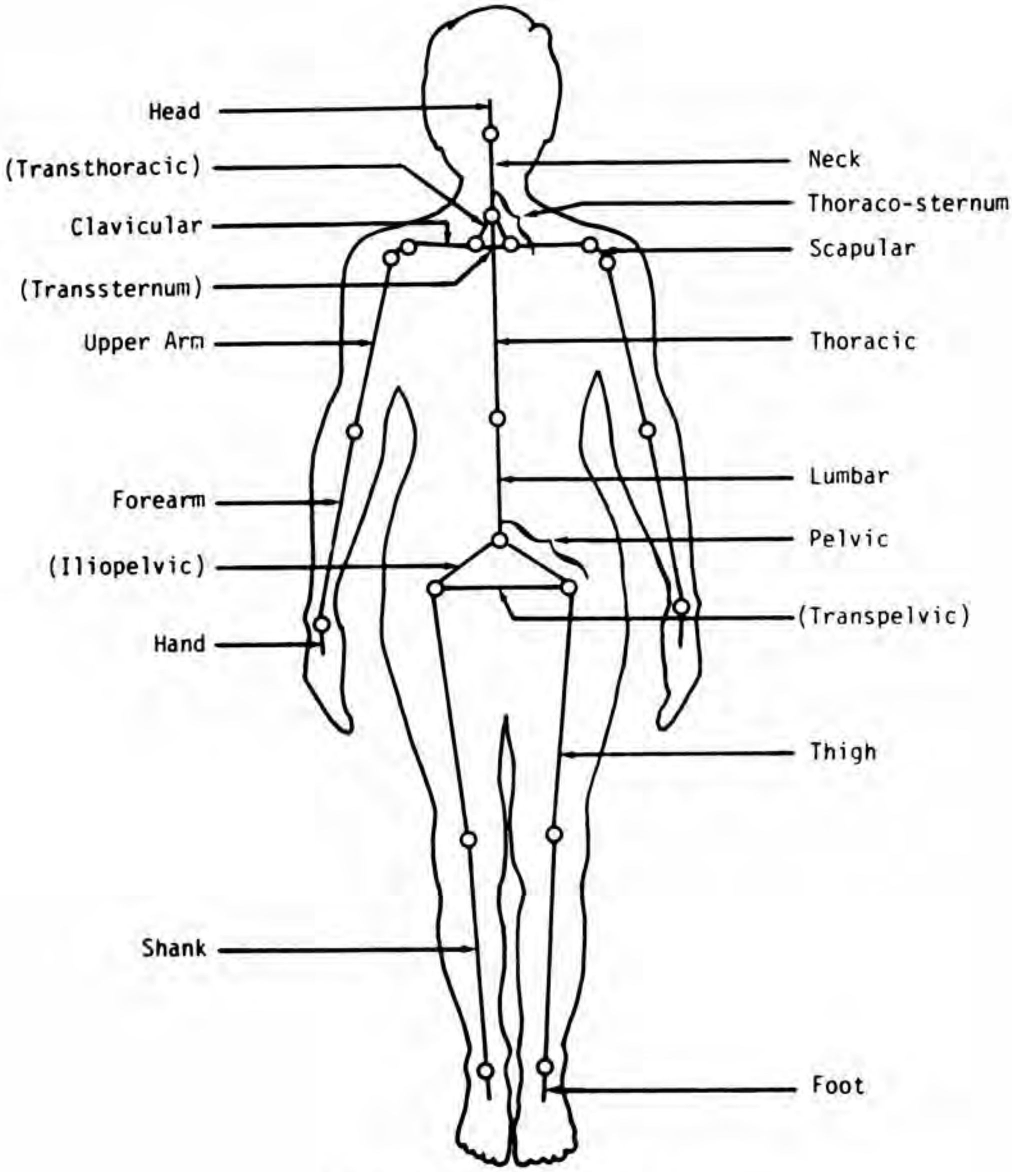

Figure 3. Linkage system.

fibula). In the following discussion and accompanying tables it will be noted that the shank link is presented for tibia length only, whereas the forearm link is described relative to either the radius or ulna. This discrepancy in treatment between the shank and forearm, both of which have two long bones, probably arises as a result of past practice among anthropometrists to measure tibial length rather than fibula length and to measure either of the long bones in the forearm. Design engineers may use either ratio for the forearm or choose to average the relatively small differences between them.

Link lengths in this chapter have been obtained by combining data from two studies: Trotter and Gleser (1958) who measured long bones in the arms and legs using standard osteological techniques, and Dempster. Sherr and Priest (1964) who developed coefficients and regression equations for predicting bone and link lengths.

First the bone length and stature for the sex and race groups in Trotter and Gleser (1958) were normalized in the following manner:

$$\frac{\text{Bone Length - Mean Bone Length}}{\text{Bone Length Standard Deviation}} \qquad (1)$$

and,

$$\frac{\text{Stature - Mean Stature}}{\text{Stature Standard Deviation}} \qquad (2)$$

Next, a linear relationship between the two normalized variables was assumed and the following equation was constructed using the correlation coefficient as the regression coefficient, or slope, with an intercept equal to zero:

$$\frac{\text{Bone Length - Mean Bone Length}}{\text{Bone Length Standard Deviation}} = \text{Corr. Coef.} \ \frac{\text{Stature - Mean Stature}}{\text{Stature Standard Deviation}} \qquad (3)$$

with

$$Se_{est} = \text{Bone Standard Deviation} \sqrt{1 - (\text{Corr. Coef.})^2} \qquad (4)^*$$

By substituting the appropriate variables from Trotter and Gleser (1958) into equation #3 and solving for the dependent and independent variables, the standard regression equation is generated in the form:

$$y = bx + a^{**} \qquad (5)$$

*The derivation of these equations can be found in Croxton (p. 175-176, 1959).

**Where y=bone length, x=stature, b=slope and a=intercept.

with an accompanying standard error of the estimate (equation #4). Table 1 presents the regression equations derived to predict bone lengths from stature for white and black American females and white American, black American, and Oriental males.

To use these equations, an appropriate value for stature is selected and inserted into the equation which is then solved for the appropriate bone length. The same stature value is used for all bone lengths to describe a particular individual or group of individuals. Table 2 presents values derived from the equations in Table 1 for 5th, 50th, and 95th percentile stature data predicted for white males and females in 1985 (See Chapter III, Appendix B).

For these bone length estimates, Dempster, Sherr, and Priest (1964) have provided coefficients to estimate the corresponding link length. Table 3 presents these coefficients which have been derived as a ratio of link length to bone length.

To compute link lengths, the coefficients presented in Table 3 are multiplied by the bone lengths calculated from equations in Table 1. In the present case, the data in Table 2 have been multiplied by the appropriate coefficients in Table 3 to generate the link lengths presented in Table 4. It is interesting to note that the coefficients in Table 3 were computed from data on male whites only and yet the results in Table 4 appear, on the basis of the forearm link, to estimate the link lengths of females with better correspondence between estimates than for males.

Dempster, Sherr and Priest (1964) also derived regression equations to estimate link lengths directly from anthropometric measures of bone length (See Appendix B, Table 1). When bone length data are available for individual astronauts, for example, these equations can be used to estimate individual link lengths more precisely.

Link lengths for the hands and feet are calculated from the wrist and ankle joint centers to the respective centers of mass. These data are presented in the next section in which the segment centers of mass are discussed. However, Dempster (1955) provides two coefficients to estimate hand and foot links. The hand link is estimated as 20.6% of humerus length (See Table 1); the foot link is estimated as 30.6% of foot length (See Chapter III).

Head and Torso

The torso with its unique characteristics of motion and the complex spatial relationships of its parts is the most difficult part of the body to describe within the linkage framework. While a number of approaches are possible, the input parameters used to describe the kinematic properties of the torso in this chapter will be relative to three links for the spinal column (neck, thorax, and lumbar), a link assemblage for the pelvic girdle

TABLE 1
REGRESSION EQUATIONS FOR ESTIMATING LIMB LENGTHS*

						Se_{est}
Female						
a) White						
Humerus Length	=	0.1855	stature	+	0.771	(±1.03)
Radius Length	=	0.130	stature	+	1.273	(±0.76)
Ulna Length	=	0.139	stature	+	1.708	(±0.89)
Femur Length	=	0.289	stature	-	3.516	(±1.30)
Tibia Length	=	0.242	stature	-	4.870	(±1.15)
Fibula Length	=	0.243	stature	-	4.695	(±1.13)
b) Black						
Humerus Length	=	0.181	stature	+	1.699	(±1.05)
Radius Length	=	0.143	stature	+	0.580	(±1.14)
Ulna Length	=	0.130	stature	+	4.535	(±0.99)
Femur Length	=	0.310	stature	-	6.214	(±1.27)
Tibia Length	=	0.265	stature	-	7.221	(±1.25)
Fibula Length	=	0.261	stature	-	6.471	(±1.22)
Male						
a) White						
Humerus Length	=	0.185	stature	+	1.338	(±1.17)
Radius Length	=	0.137	stature	+	1.467	(±0.89)
Ulna Length	=	0.140	stature	+	2.688	(±0.93)
Femur Length	=	0.281	stature	-	1.902	(±1.44)
Tibia Length	=	0.268	stature	-	8.369	(±1.33)
Fibula Length	=	0.257	stature	-	6.490	(±1.22)
b) Black						
Humerus Length	=	0.202	stature	-	0.969	(±1.13)
Radius Length	=	0.157	stature	-	0.599	(±1.02)
Ulna Length	=	0.158	stature	-	1.013	(±1.06)
Femur Length	=	0.314	stature	-	9.740	(±1.49)
Tibia Length	=	0.288	stature	-	9.740	(±1.40)
Fibula Length	=	0.266	stature	-	6.129	(±1.32)
c) Oriental						
Humerus Length	=	0.213	stature	-	4.028	(±1.22)
Radius Length	=	0.160	stature	-	2.364	(±0.98)
Ulna Length	=	0.158	stature	-	0.244	(±1.03)
Femur Length	=	0.303	stature	-	6.621	(±1.48)
Tibia Length	=	0.292	stature	-	12.951	(±1.14)
Fibula Length	=	0.303	stature	-	14.659	(±1.14)

*All values are given in centimeters. To convert to inches, multiply by .3937.

TABLE 2
BONE LENGTH VALUES ESTIMATED FOR 1985 POPULATION*

Limb	Male White 5th	Male White 50th	Male White 95th	Female White 5th	Female White 50th	Female White 95th
Humerus	32.03 (12.61)	34.08 (13.42)	36.16 (14.24)	29.23 (11.51)	31.12 (12.25)	32.96 (12.98)
Radius	24.20 (9.53)	25.72 (10.13)	27.25 (10.73)	21.22 (8.35)	22.54 (8.87)	23.83 (9.38)
Ulna	25.91 (10.20)	27.47 (10.81)	29.04 (11.43)	23.03 (9.07)	24.45 (9.63)	25.82 (10.17)
Femur	44.72 (17.61)	47.84 (18.83)	50.98 (20.07)	40.82 (16.07)	43.76 (17.23)	46.63 (18.36)
Tibia	36.09 (14.21)	39.07 (15.38)	42.07 (16.56)	32.25 (12.70)	34.72 (13.67)	37.12 (14.61)
Fibula	36.15 (14.23)	39.00 (15.35)	41.88 (16.49)	32.58 (12.83)	35.06 (13.80)	37.47 (14.75)

*Data given in centimeters with inches in parentheses.

TABLE 3
RATIOS OF LINK LENGTH TO BONE LENGTH
(After Dempster, et al. 1964)

Ratio of Lengths	N	Mean	Standard Deviation
Upper Arm Link/ Humerus Length	32	89.44%	1.59%
Forearm Link/Ulna Length	32	98.70	2.66
Forearm Link/Radius Length	26	107.09	3.53
Thigh Link/Femur Length	32	90.34	0.88
Shank Link/Tibia Length	33	107.76	1.81

TABLE 4
LINK LENGTH VALUES ESTIMATED FOR 1985 POPULATION*

Limb	Male White 5th %tile	Male White 50th %tile	Male White 95th %tile	Female White 5th %tile	Female White 50th %tile	Female White 95th %tile
Upper Arm Link	28.65 (11.28)	30.48 (12.00)	32.34 (12.73)	26.14 (10.29)	27.83 (10.96)	29.48 (11.61)
Forearm Link (Ulna)	25.57 (10.07)	27.11 (10.67)	28.66 (11.28)	22.73 (8.95)	24.13 (9.50)	25.48 (10.03)
Forearm Link (Radius)	25.92 (10.20)	27.54 (10.84)	29.18 (11.49)	22.72 (8.94)	24.13 (9.50)	25.52 (10.05)
Thigh Link	40.40 (15.91)	43.22 (17.02)	46.06 (18.13)	36.88 (14.52)	39.53 (15.56)	42.13 (16.59)
Shank Link	38.89 (15.31)	42.10 (16.57)	45.33 (17.85)	34.75 (13.68)	37.41 (14.73)	40.00 (15.75)

*Data given in centimeters with inches in parentheses.

(right and left ilio-pelvic and transpelvic), and five links for the shoulder girdle (thoraco-sternum assemblage, right and left clavicular, and right and left scapular). These links are defined in Appendix A and illustrated in Figure 3.

A fairly complete discussion of some of these links can be found in Dempster (1955). He provides coefficients based on cadaver data for estimating the clavicular and transpelvic links. The clavicular link is estimated as 35.2% of biacromial breadth (See Chapter III); the transpelvic link is estimated as 37.2% of femur length (See Table 1). He did not provide coefficients for estimating any of the remaining links in the torso. Thus, with the publication of Dempster's work on the linkage system of the human body, the links in the appendages were defined quantitatively, the links in the shoulder and pelvic girdles were identified and the links in the spinal column were as yet unstudied.

In 1961, S. P. Geoffrey attempted to establish the spatial relationship between the hip joint center and the shoulder joint center. This is the only extant quantitative description of the distance between the shoulder and hip joint centers of rotation. Geoffrey studied twelve men to locate these joint centers radiographically in the sagittal plane for the purpose of constructing a two-dimensional design manikin. The average distance between the shoulder joint center and the hip joint center is 47.4 cm (18.67 in.)

which is representative of the average joint center-to-joint center dimension in the erect seated position for a 50th percentile 1985 male.

The next attempt to examine the torso linkage system was made in 1972 by Snyder, Chaffin, and Schutz. Their report contains a prediction model of torso mobility relative to two reach envelopes for the right elbow. Their data define the configuration of a collection of discrete skeletal landmarks for a specific elbow reach position; the data do not describe interrelationships between these landmarks which would define the torso linkage system. We will not attempt here to synthesize their model or to draw conclusions from it. Rather, we will encourage the reader to refer to the original publication.

A computer model developed for this chapter has produced the illustrations in Figures 4, 5, 6, and 7. These stick figure drawings depict a 50th percentile 1985 male in a seated reach configuration typically encountered in work environments. This model is based upon equations developed in the Snyder et al. study, as well as equations for the limbs presented in Table 1. As can be observed in the illustrations, there are spatial data on a large number of skeletal landmarks. These landmarks represent typical candidates in the spinal column for joint centers of rotation from which a linkage system of the spinal column could be developed. The Snyder report contains data on almost all the vertebra in the spinal column, but additional analysis is required to determine the minimum number and location of the links necessary to describe motion in the torso.

At this point, some observations with respect to a general statement concerning our knowledge of the link system is necessary. Dempster has provided us with sufficient information on the linkage system of the appendages to establish useable population estimates. Geoffrey established a dimension for the relationship between the shoulder and hip joint centers but his data are insufficient for population estimates. The most recent attempt by Snyder et al. considers the torso linkage system within the general context of a workspace reach problem. Therefore, there are data available which provide a generalized understanding of the body linkage system, but quantitative population estimates are, at present, unavailable.

In order to complete the current linkage model of the body, substantial information is needed on the pelvic assemblage. Furthermore, subsequent data must be collected relative to standard body dimensions taken in an initial body position used in traditional anthropometry. In summary, a linkage system of the body has been proposed and modeled but not completely validated for any body positions.

The Torso in Zero-Gravity

The torso linkage system discussed above represents the body configuration under one-g conditions (e.g. terrestrial environment) and, for space applications, must be modified to conform with the current understanding of the changes that occur under zero-gravity conditions.

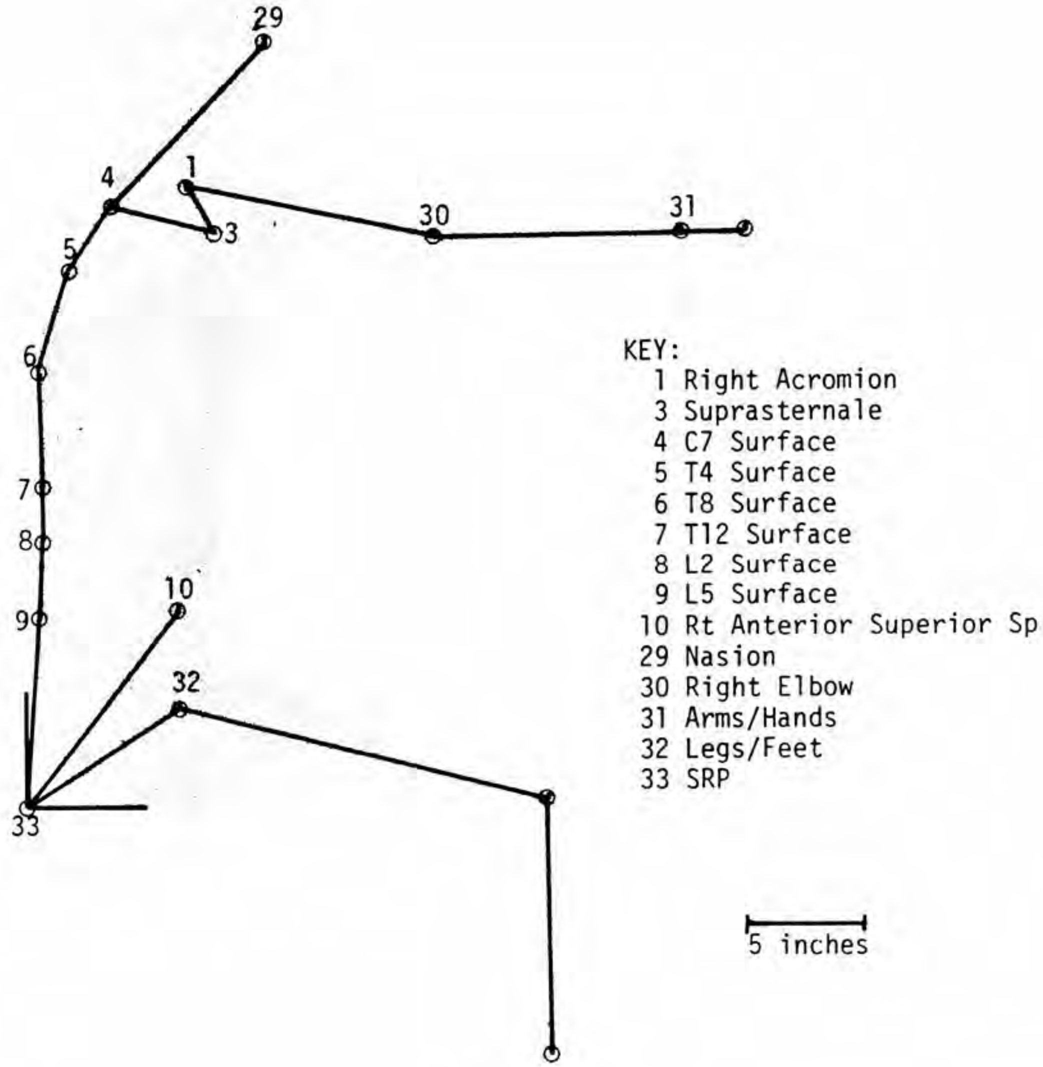

Figure 4. A computer model of body linkage: 50th percentile 1985 man with extended elbow.

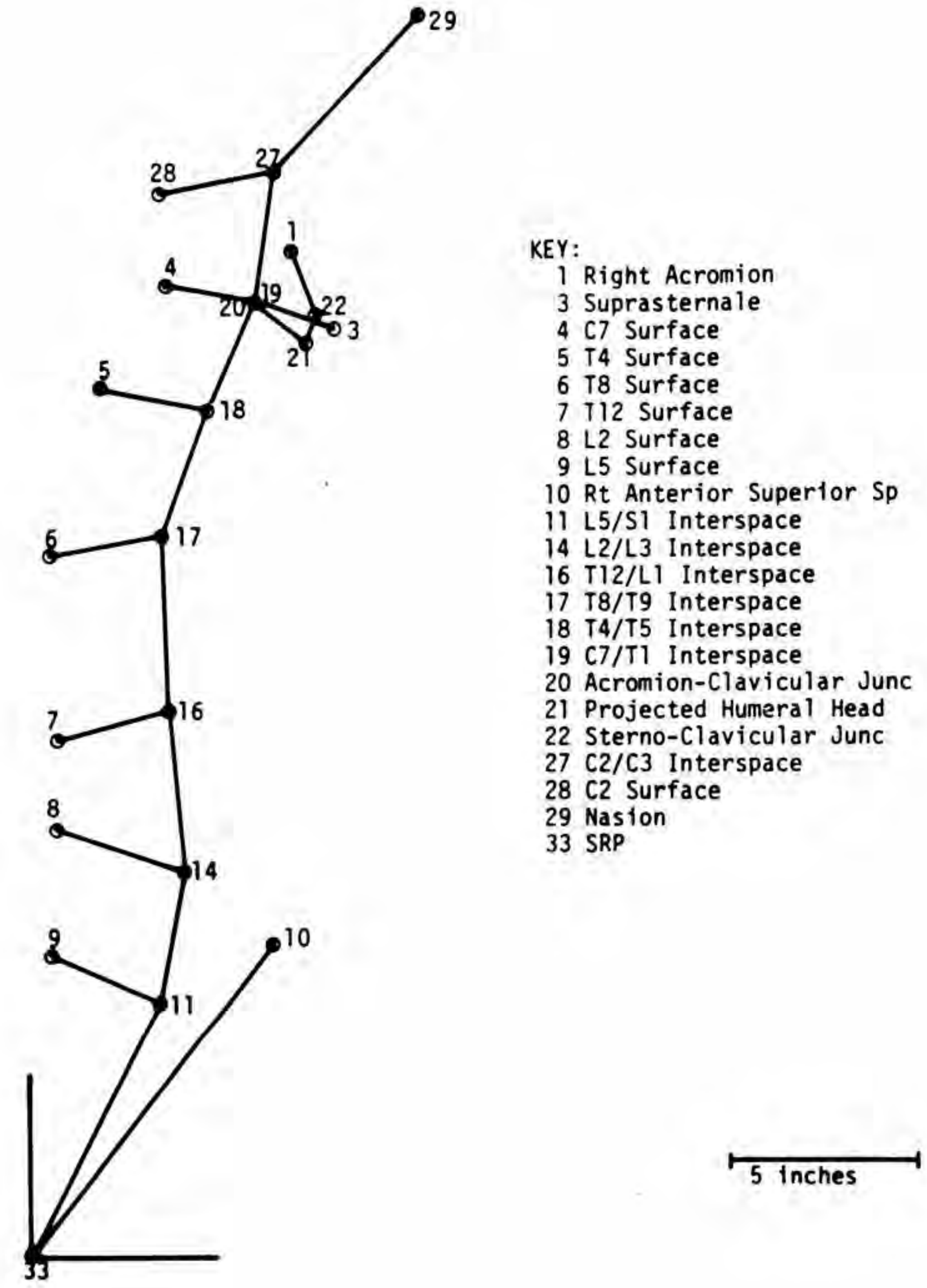

Figure 5. Internal anatomical landmarks of the torso for body position depicted in Figure 4.

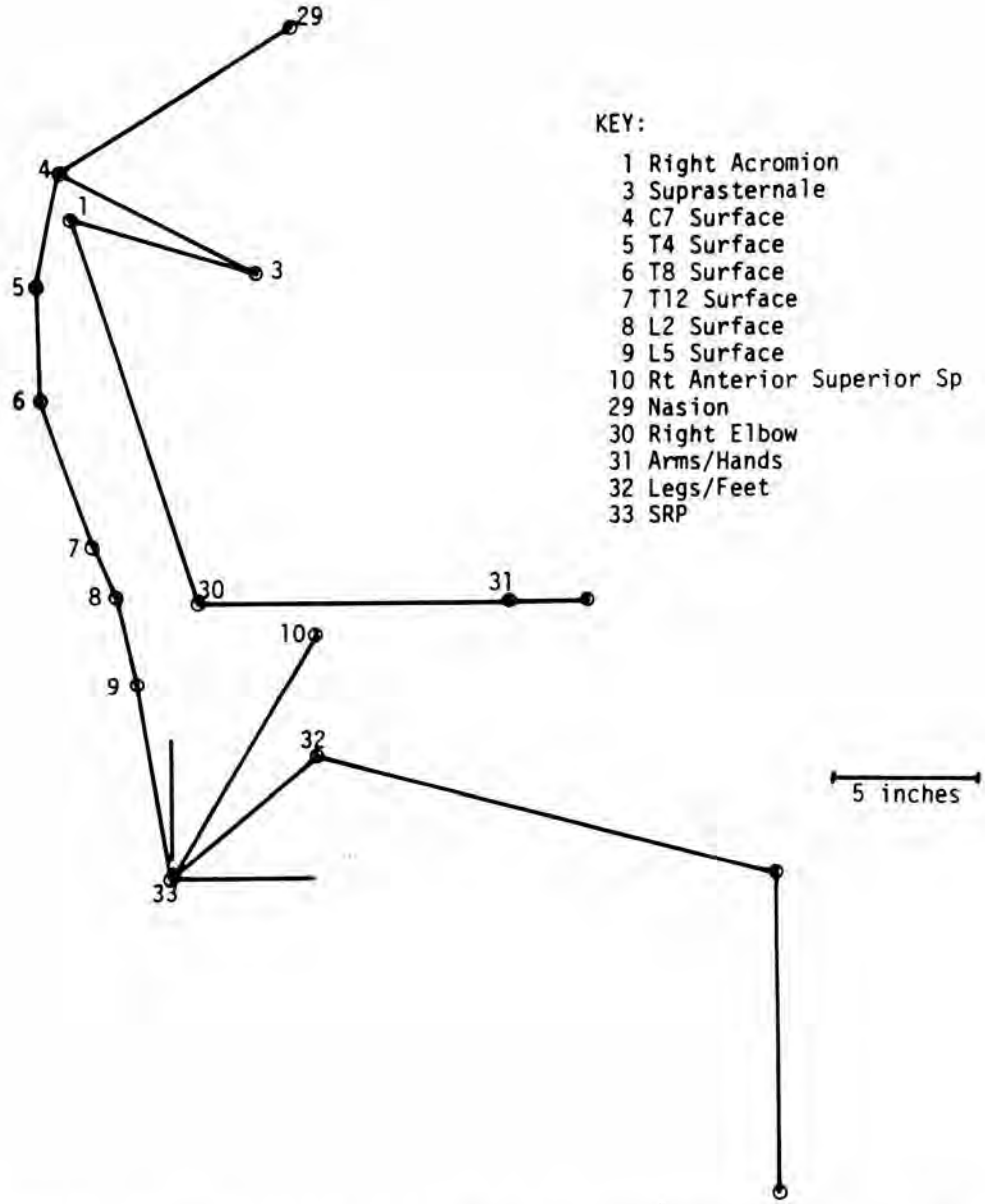

Figure 6. Computer model of body linkage: 50th percentile 1985 man in resting one-g seated position.

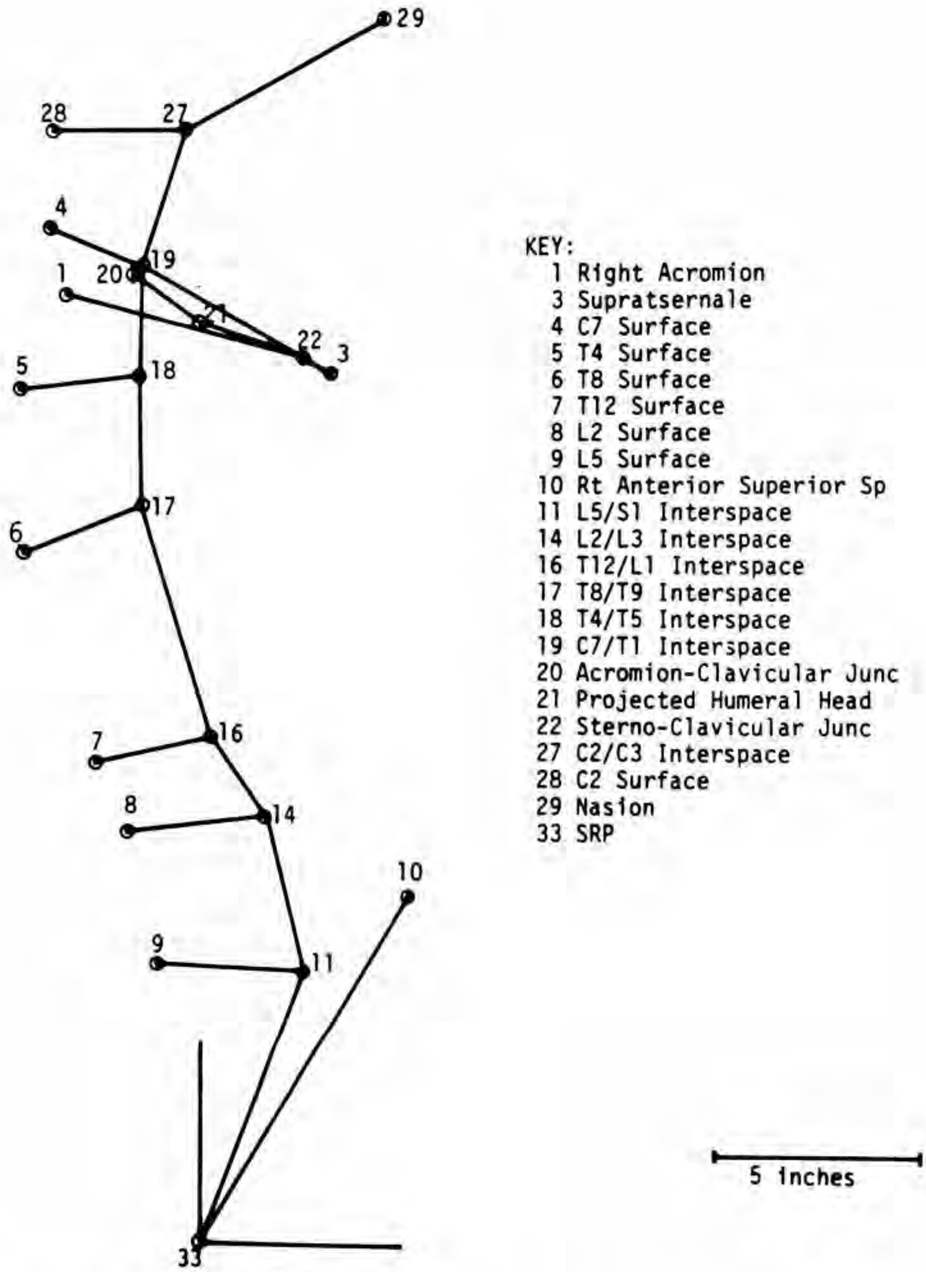

Figure 7. Internal anatomical landmarks of the torso for body position depicted in Figure 6.

It has been reported (Thornton et al., 1974) by astronauts that their stature increases by as much as two inches in space. This increase probably occurs primarily in the torso and only slightly in the lower limbs (knee and ankle joints).

The upright stance of the human body on earth is achieved by means of an S-shaped adaptation in the spinal column which begins as a single continuous curve at birth. In the zero-g environment, gravity no longer acts to compress the spinal column; and the typical lordosis and kyphosis curves in the spine are no longer a functional requirement for upright posture. Figure 8 illustrates the typical relaxed "weightless" posture assumed in the zero-g environment (Jackson, Bond and Gunderson, 1975).

To reflect the elimination of gravitational pull, torso link data must be elongated and straightened. Table 5, based on an analysis of vector distances and angles for all one-g positions reported on in Snyder et al. (1972), portrays the effects of modifying the link data. By allowing for a 5% intervertebral expansion factor and straightening the curved spinal column, approximately 3.7 cm (1.5 inches) of "growth" can be explained. This growth will obviously be subject to individual variations in both expansion among the vertebrae and straightening of the thoraco-lumbar spinal column.

TABLE 5
VALUES COMPUTED FROM SNYDER ET AL. (1972) DATA DEMONSTRATING POSSIBLE SOURCE OF ZERO-GRAVITY TORSO "GROWTH"

Intervertebral Links	Link Length (1-g)	5% Expansion Factor (0-g)
(Expansion)		
L5/S1 - L4/L5	3.66 (1.44)	.18 (0.07)
L4/L5 - L3/L4	3.63 (1.43)	.18 (0.07)
L3/L4 - L2/L3	3.86 (1.52)	.20 (0.08)
L2/L3 - L1/L2	3.63 (1.43)	.18 (0.07)
L1/L2 - T12/L1	3.66 (1.44)	.18 (0.07)
T12/L1 - T8/T9	11.28 (4.44)	.56 (0.22)
T8/T9 - T4/T5	9.47 (3.73)	.48 (0.19)
T4/T5 - C7/T1	8.91 (3.51)	.46 (0.18)
	Subtotal	2.42 (0.95)
(Straightening)		
L5/S1 - C7/T1	46.41 (18.27)	1.30 (0.51)
	Total "Growth"	3.72 (1.46)

*Data given in centimeters with inches in parentheses.

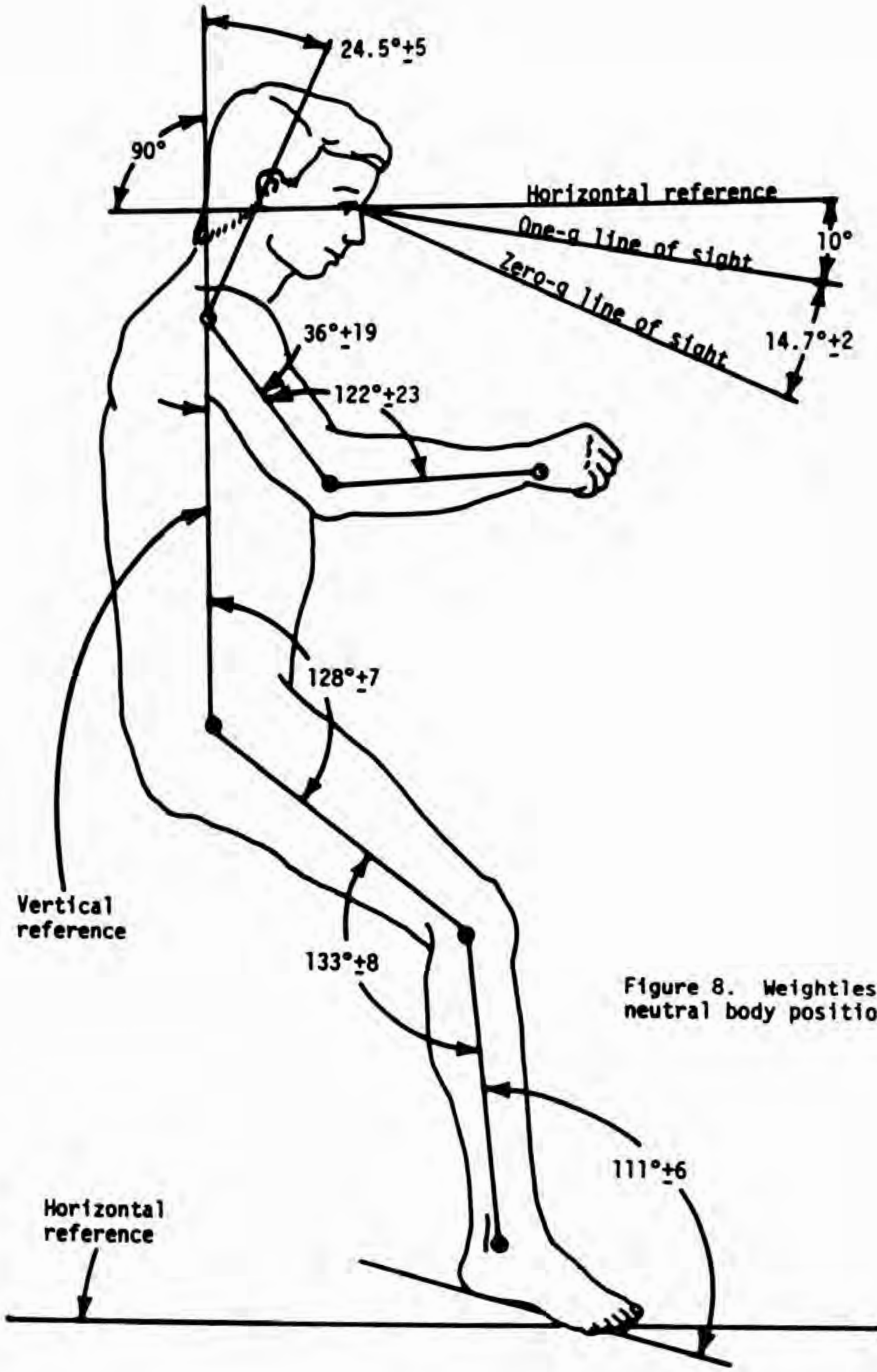

Figure 8. Weightless neutral body position.

Center of Mass

This section will serve as a general guide for locating the whole body center of mass.* The center of mass of the whole body is best predicted from individualized models in which the center of mass is computed from the sum of segments. Measurements of living subjects under one-g conditions have established that the center of mass of the whole body is always in close proximity to the pelvis and appears to remain, regardless of body configuration, at the approximate level of the anterior superior iliac spines. This relationship evidently changes under zero-gravity conditions. Data on the location of the center of mass in static whole bodies and predictive equations for body segments locations will be given in this section.

Most of the whole body center of mass locations have been measured with the body in either a standing or sitting position. Since both living subjects and cadavers have been measured in these studies, comparisons between the two sets of data can be made.

In all of the investigations cited, measurements have been taken with the body in a static position under one-g environmental conditions. As has already been noted, one effect of zero-gravity on the torso is to extend the vertebral column. Another effect is a shift in body fluids, reducing them in the limbs and increasing them in the torso. These conditions, which have the effect of moving the center of mass toward the head, generally describe embalmed cadavers, particularly those stored in the supine position. With the force of gravity acting on the supine body, the vertebral column tends to straighten, thereby extending the torso length. This phenomenon has been noted for the living when, upon rising in the morning, the body is approximately .5 to .75 inches taller than it is at night (Backman, 1924; Damon, 1964). In addition, body fluids in embalmed cadavers tend to pool in the head and torso, since they are generally at the lowest level of the body in the supine position and have a volume of unfilled space greater than other parts of the body. Thus, while the causes of an extension of the vertebral column and a shift in body fluids are not the same in cadavers and living persons in a zero-g environment, the effects are similar.

Much of the data in the following tables have been measured on embalmed cadavers. If the design engineer accepts the assumption that the mass distribution of the zero-gravity astronaut is more analogous to embalmed cadavers than living subjects on earth, then relevant cadaver coefficients and equations should be utilized. There do exist some alternative data from studies in which the location of the center of mass of body segments for living subjects were measured indirectly using volumetric or reaction change techniques. Engineers using these data should be aware of an underlying assumption in this case too, namely, that these results assume constant density throughout the body part measured, thus equating center of mass with center of volume.

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*The center of mass measured under zero-gravity conditions and the center of gravity measured under one-g conditions are considered for practical purposes to be the same. The major difference occurs as a result of the force of gravity distorting living tissues and redistributing fluids in the body.

Whole Body

In general, the center of mass in living adult males and females in the standing position is 55% of stature as measured from the floor (Crosky et al. 1922; Cotton, 1931; Hellebrandt et al. 1937; Ignazi et al. 1972; Page, 1974). The center of mass in adult male cadavers is slightly higher at 59% of stature (Clauser et al. 1969; Chandler et al. 1975). Ignazi et al. (1972), confirming that the center of mass is at 55% of stature, further pinpointed the measurement at 97.2% of anterior superior iliac spine height (measuring from the floor), at 50% of bicristal breadth in the y-axis, and 31.7% of a line perpendicular to two parallel lines tangent to the heel and toes (measured from the heel) on the x-axis.

In 1962 Swearingen measured the location of the center of mass of the whole body in 67 positions. His sample consisted of five adult men with an average weight of 163.85 lbs (113.25-225.1 lbs) and an average stature of 68.8 inches (64.75-72.0 inches). Swearingen attempted to define the maximum displacement of the center of mass of the whole body relative to the pelvis.

Swearingen first located the center of gravity for each of his subjects in an initial erect standing body position. All body appendages, including the upper torso were then moved around the pelvis which remained in the same position relative to the measurement device. For example, to determine maximum displacement in an anterior direction, the center of gravity was first located for an erect standing position relative to the position of the pelvis in the measurement device. Keeping the pelvis fixed, the body parts were moved anteriorly to determine the maximum displacement possible. Table 6 defines the spatial envelope within which the location of centers of gravity for most of the common body positions will fall.

On the following pages we present the results of three studies aimed at locating the center of mass in living subjects. The results in all three studies have been reported using different axes systems. However, when the data are examined using comparable axes systems, the differences disappear, or become negligible. (To avoid confusion, the data are reported and illustrated here in their original axis systems.) In all cases, individualized data are presented in the report and if a user needs design information for a specific individual, he is encouraged to utilize the original report and match his subject on the basis of height and weight rather than using the sample summaries reported herein.

In the first study, Santschi, DuBois, and Omoto (1963) measured the location of the center of mass in three axes for eight positions depicted in Figure 9. A summary of their data appears in Table 7 which is presented relative to a right-handed orthogonal axis system. The x-axis shown in the illustration accompanying Table 7 is measured posteriorly to the back plane (YZ). The y-axis is measured as one-half of bispinous diameter in the midsagittal plane (XZ). The z-axis is measured superiorly to vertex as a perpendicular to a transverse plane (XY). The average location of the center of mass for this sample of 66 male subjects represents that found in an

TABLE 6
SUMMARY OF MAXIMUM DISPLACEMENT OF CENTER OF GRAVITY FOR VARIOUS BODY POSITIONS DESCRIBED BY SWEARINGEN (1962)*

Distance	CG Measured From	Direction	Initial Position	Max. Displacement
29.2 (11.5)	Ischium	Towards the head	Erect standing	Seated, arms extended overhead and legs extended and raised maximally towards the head.
25.4 (10.0)	Ischium	Towards the feet	Erect standing	Standing, torso flexed at waist with hands touching floor.
20.3 (8.0)	Back plane	Anteriorly	Erect standing	Sitting with arms and legs parallel, fully extended, and in maximum reach position in the horizontal plane.
11.4 (4.5)	Abdomen plane	Posteriorly	Erect standing	Resting on abdomen with torso flexed posteriorly, arms and legs in maximum posterior reach position.
11.4 (4.5)	Mid-sagittal plane	Laterally	Erect standing	Torso flexed laterally and all body parts moved laterally as far as possible in para-sagittal planes.

*Data given in centimeters with inches in parentheses.

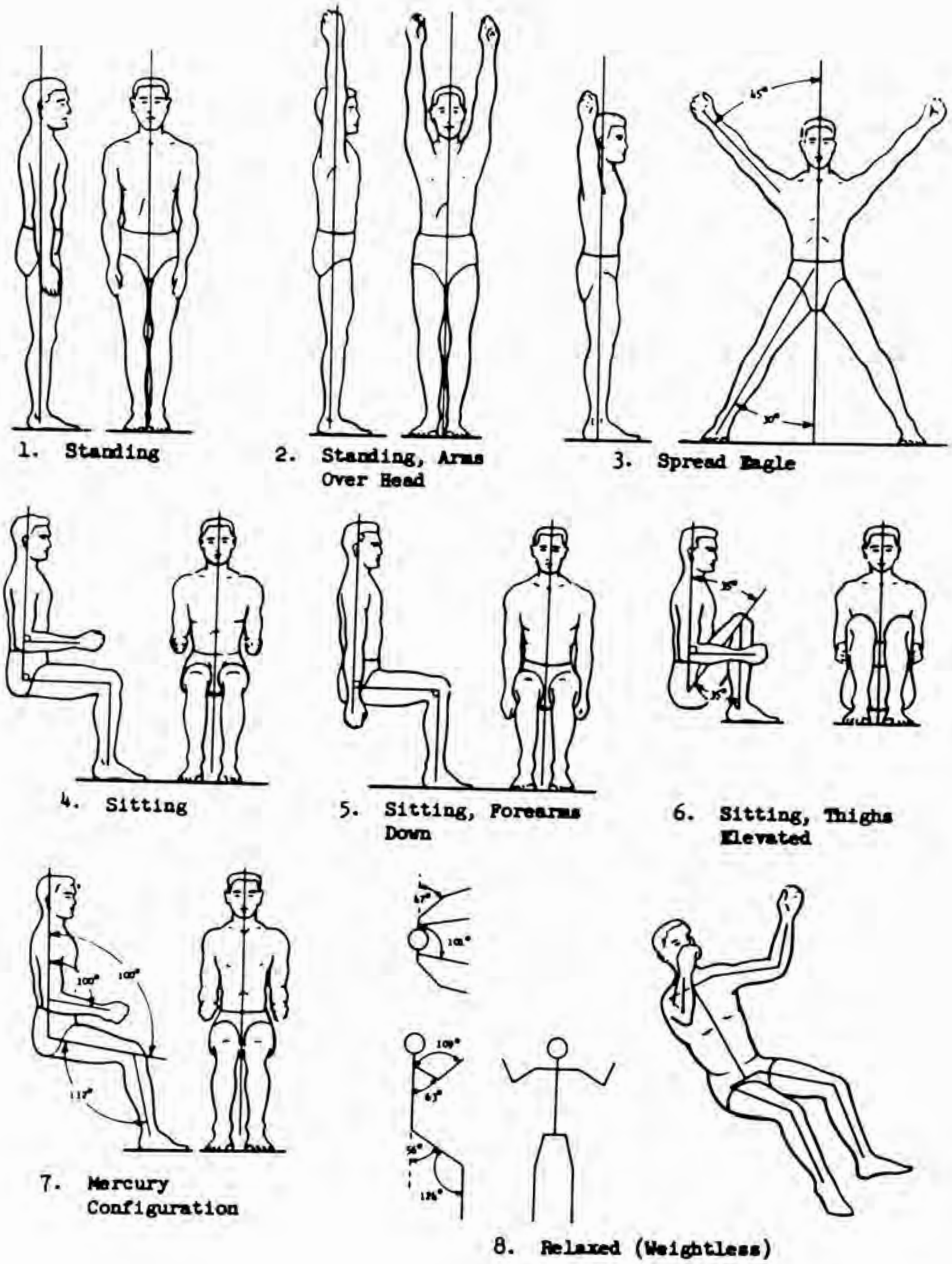
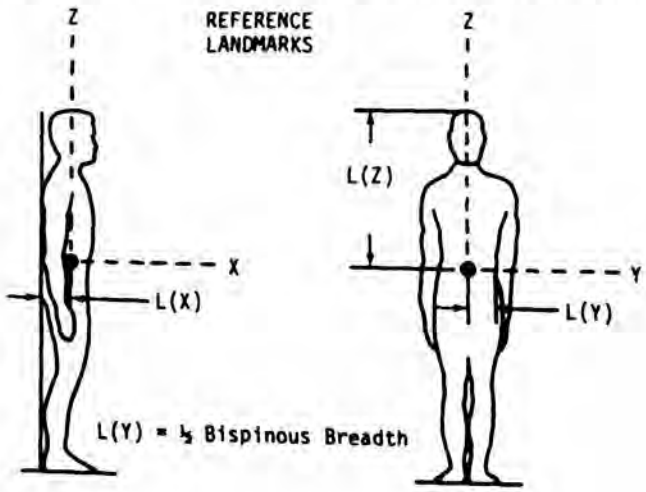


Figure 9. Centers of mass in eight body positions (from Santschi et al. 1963).

TABLE 7
LOCATION OF CENTER OF GRAVITY BASED ON SANTSCHI ET AL. (1963)*

		Mean	S.D.
1. Standing	x	8.89 (3.5)	0.51 (0.20)
	y	12.19 (4.8)	0.99 (0.39)
	z	78.74 (31.0)	3.68 (1.45)
2. Standing, arms over head	x	8.89 (3.5)	0.56 (0.22)
	y	12.19 (4.8)	0.99 (0.39)
	z	72.64 (28.6)	3.38 (1.33)
3. Spread eagle	x	8.38 (3.3)	0.48 (0.19)
	y	12.19 (4.8)	0.99 (0.39)
	z	72.39 (28.5)	4.83 (1.90)
4. Sitting	x	20.07 (7.9)	0.91 (0.36)
	y	12.19 (4.8)	0.99 (0.39)
	z	67.31 (26.5)	2.90 (1.14)
5. Sitting, fore-arms down	x	19.56 (7.7)	0.86 (0.34)
	y	12.19 (4.8)	0.99 (0.39)
	z	68.07 (26.8)	2.95 (1.16)
6. Sitting, thighs ele-vated	x	18.29 (7.2)	0.94 (0.37)
	y	12.19 (4.8)	0.99 (0.39)
	z	58.67 (23.1)	1.98 (0.78)
7. Mercury con-figuration	x	20.07 (7.9)	0.86 (0.34)
	y	12.19 (4.8)	0.99 (0.39)
	z	68.83 (27.1)	2.90 (1.14)
8. Relaxed (weightless)	x	18.54 (7.3)	0.84 (0.33)
	y	12.19 (4.8)	0.99 (0.39)
	z	69.85 (27.5)	3.66 (1.44)

*Data given in centimeters with inches in parentheses.



individual slightly smaller than the 50th percentile of the 1985 white European male population.

DuBois et al. (1964) extended the 1963 study to measure the centers of gravity in the sitting and relaxed positions for the nude, unpressurized, and pressurized male wearing the A/P22s-2 full pressure garment. The results are presented in Table 8. It can be noted that the nude data for the x- and y- axes are very similar to the Santschi data; the location of the center of gravity along the z-axis, however, was measured superiorly to the seat pan rather than inferiorly from vertex.

Ignazi et al. (1972) report the only recent European data on the whole body.* Their data are summarized in Table 9. Here, too, the axis system differs somewhat from Santschi's in the z direction since measurements were taken from the floor rather than from center of gravity to vertex. A quick calculation reveals that the z-axis measured from center of gravity to vertex in the Ignazi study averages 31.10 inches compared to 31.0 inches in the Santschi study.

The most rigorous study of the location of the whole body center of gravity can be found in Chandler et al. (1975) which reports the results of an investigation into the inertial properties of six adult male cadavers. Their data locate the center of gravity in three dimensions for three embalmed, cadavers frozen in the standing position and for three embalmed, cadavers frozen in the seated position. These measurements were made on rigid bodies, fixed within a three-dimensional inertial frame of reference, thereby avoiding some of the methodological problems of repositioning living subjects. Furthermore, this study reports measurements of the center of gravity in the y-axis rather than assuming symmetry.

Using the same axis system as utilized by Santschi, a comparison between cadaver and living subject data was made in Reynolds et al. (1975). This comparison reveals that for subjects matched on the basis of stature and weight, differences in the locations of the whole body center of gravity can be ignored for practical purposes. Except in connection with the x-axis in the standing position, differences can be explained by reference to the previously discussed changes in the body of the cadaver stored in a supine position. In general, the differences in mass distribution between a cadaver and a living human reflect shifts in tissue and fluids and a change in spinal configuration.

The magnitude and direction of these differences can be observed in Table 10 which reports the percentage differences between the cadavers in the Chandler et al. (1975) study and living subjects, matched for height

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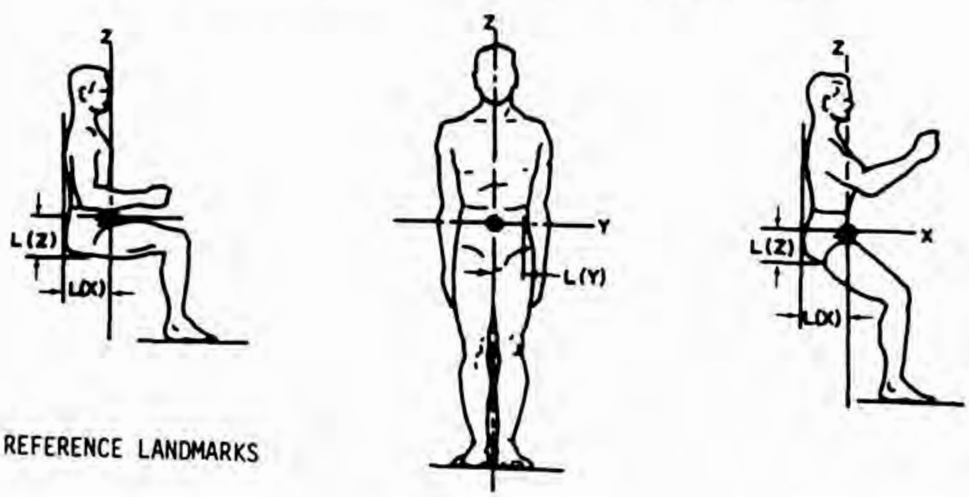
*Despite the differences in average body weight between the Ignazi and Santschi samples, a careful comparison of matched subjects reveals no significant differences in their mass distribution properties. Thus, the differences in the sample means probably reflect sampling differences of statistical origin.

TABLE 8
LOCATION OF CENTER OF GRAVITY BASED ON DUBOIS ET AL. (1964)*

			Mean	S.D.
Sitting	Nude	x	20.04 (7.89)	1.04 (0.41)
		y	12.17 (4.79)	0.69 (0.27)
		z	23.27 (9.16)	0.74 (0.29)
	Unpressurized	x	21.16 (8.33)	0.99 (0.39)
		y	12.17 (4.79)	0.69 (0.27)
		z	24.79 (9.76)	0.76 (0.30)
	Pressurized	x	21.89 (8.62)	0.97 (0.38)
		y	12.17 (4.79)	0.69 (0.27)
		z	24.64 (9.70)	0.71 (0.28)
Relaxed (Weightless)	Nude	x	18.64 (7.34)	0.97 (0.38)
		y	12.17 (4.79)	0.69 (0.27)
		z	18.77 (7.39)	1.07 (0.42)
	Unpressurized	x	19.84 (7.81)	0.76 (0.30)
		y	12.17 (4.79)	0.69 (0.27)
		z	19.96 (7.86)	1.14 (0.45)
	Pressurized	x	20.52 (8.08)	0.74 (0.29)
		y	12.17 (4.79)	0.69 (0.27)
		z	19.84 (7.81)	1.22 (0.48)

*Data given in centimeters with inches in parentheses.



REFERENCE LANDMARKS

TABLE 9
LOCATION OF CENTER OF GRAVITY BASED ON IGNAZI ET AL. (1972)*

	Mean	S.D.	C.V.	Min.	Max.	Range
x-axis	15.09 (5.94)	1.31 (0.52)	8.71 (3.43)	13.40 (5.28)	17.70 (6.97)	4.30 (1.69)
y-axis	8.83 (3.48)	0.62 (0.24)	6.99 (2.75)	7.60 (2.99)	9.70 (3.82)	2.10 (0.83)
z-axis	96.49 (37.99)	4.25 (1.67)	4.40 (1.73)	86.90 (34.21)	101.10 (39.80)	14.30 (5.63)

*Data given in centimeters with inches in parentheses.

REFERENCE LANDMARKS

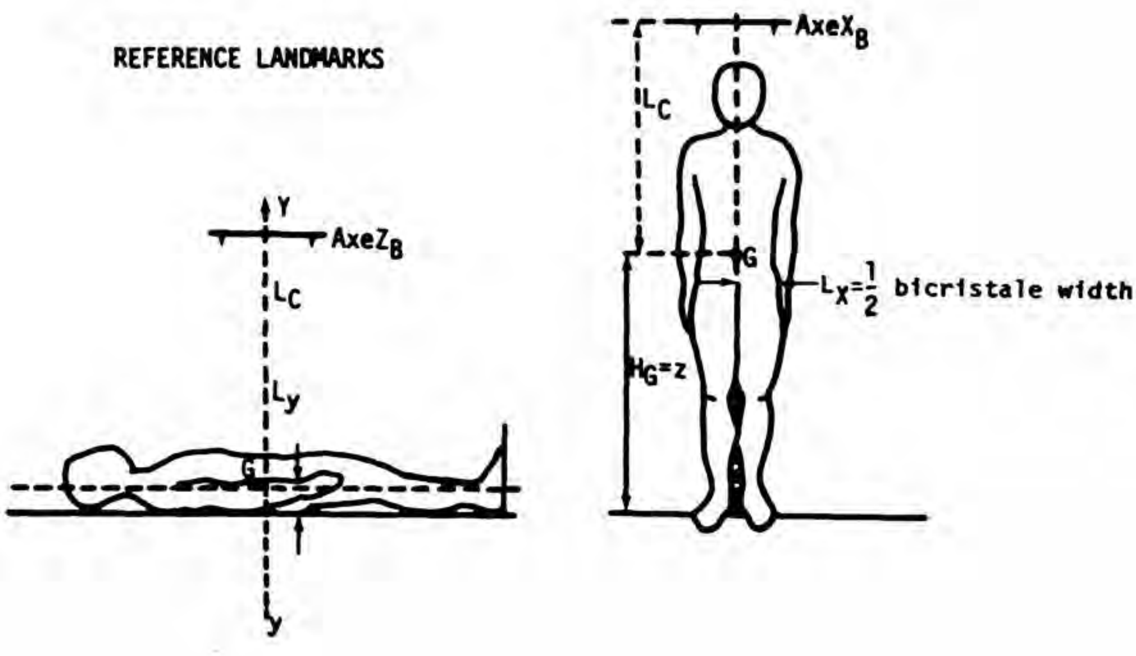


TABLE 10
COMPARISON OF CHANDLER ET AL. (1975) AND SANTSCHI ET AL. (1963) LOCATION OF CENTER OF GRAVITY FOR THE WHOLE BODY IN SUBJECTS MATCHED ON BASIS OF HEIGHT AND WEIGHT

	Standing			Sitting		
Subject (Chandler & Santschi)	(1 & 19)	(2 & 1)	(3 & 17)	(4 & 26)	(5 & 16)	(6 & 39)
Stature	-2.3%	-1.0%	-0.7%	0.3%	-1.4%	-0.8%
Weight	0.5%	-2.2%	-2.4%	-17.4%	-14.5%	-1.2%
Center of Gravity						
x	14.1%	10.3%	11.3%	-17.0%	-13.5%	-5.2%
y	*	*	*	*	*	*
z	-10.9%	-10.8%	-8.1%	-1.7%	-2.7%	-8.7%

*Santschi assumes body symmetry for the location of the center of gravity along the y-axis.

and weight in the Santschi et al. (1963) study. A negative percentage means that the Chandler cadaver subjects had a lower value than the Santschi subjects. The differences in the locations of the center of gravity indicate a posterior movement of the center of gravity in the x-axis sitting position and a cephalad movement in the z-axes for both standing and sitting positions. Since the y-axis is the axis of symmetry, changes there are negligible. This latter observation can be verified in the results reported by Reynolds et al. (1975).

The standing x-axis location is difficult to measure on the living since variation in the dimension approaches the tolerance magnitude in most measurement systems. In the present instance, the apparent contradiction in the cadaver data with the changes which usually take place in embalmed cadavers is probably due to several differences between the two studies--back plane definition and subject head position are likely candidates. The average difference in percentage appears large but the average absolute difference is 1.2 cm (.47 in) which in most man-machine systems would probably be imperceptible.

Therefore, the cephalad shift in the location of the center of mass along the z-axis in zero gravity can be approximated by reducing the distance of the center of mass from vertex by a factor of 10%. The y-axis is best approximated by the assumption of symmetry, and the x-axis appears to be inconsistent. At present, the user must determine first the sensitivity of the system to shifts in the location of the center of mass along the x-axis before using cadaver data. In general, it would appear reasonable to assume that changes in segment position would affect the location more than tissue and fluid shifts but this is a problem that needs more extensive research.

Segments

The location of the center of mass in the limbs has traditionally been presented as a percent of link length. The torso presents a unique problem since it has been measured as a composite segment without attempting to separate it into individual links, an approach which does not satisfy the requirements of most three-dimensional models. Furthermore, the data contain no information on the changing location of the center of mass caused by fluid and organ shifts.

Most of the usable segment data have been collected from cadavers. Table 11 presents a summary of these data as a function of the ratio of segment length to distance of the center of mass along a longitudinal axis from some known landmark. These data have been used to generate the best estimate of the location of the center of mass given in Table 12. The coefficients for the x-axis (head and torso, primarily) should be multiplied by an anthropometric dimension measured from the back plane. The coefficients for the y-axis, which are always .5, assume segment symmetry. The coefficients for the z-axis should be multiplied by an anthropometric dimension measured from the most proximal joint in the limbs, suprasternale in the torso, and tragion-vertex height in the head. In all cases, the axis system is assumed to be orthogonal and relative to the geometric shape of the segment. (Coefficients were calculated using the average of data from the appropriate reports listed in Table 11.)

Clauser, McConville, and Young (1969) derived regression equations to estimate the center of mass of segments. These equations, which appear in Appendix B, Table 2, are derived from anthropometric input for the independent variables and locate centers of mass in two dimensions (in general, along the x- and z-axes). They have a relatively small standard error of the estimate. Data derived from these equations will be more appropriate for individualized models of the body if the individual's anthropometric information is available. In the event that individual dimensions are unknown the coefficients given in Table 12 can be used.

Segment Weight

A total of 65 cadavers and 273 living subjects have been used in mass distribution studies reported since 1860 but data on segment weights remain scarce. The little data that have been recorded are difficult to compare since definitions of segments differ. By and large, cadaver data are the most accurate since they can be measured directly. Extrapolation of segment weights for the living from embalmed cadavers assumes comparable densities and there are no data to support these assumptions under one-g conditions. Under zero-g conditions, however, observations made by the astronauts suggest that changes in the body are more analogous to the mass distribution measured in cadavers than to that indirectly measured on living subjects. Thus, the assumption of comparable density may provide reasonable estimates of the segment weights of astronauts in a zero-gravity environment.

TABLE 11
LOCATION OF THE CENTER OF MASS (CM)[1]

Segments	Chandler et al. (1975)			Clauser, McConville & Young (1969)			Becker (1972)			Dempster (1955)	Braune & Fischer (1889)
	x	y	z	x	y	z	x	y	z		
Head	0.02 (0.00)	-0.20 (-0.08)	2.67 (1.05)	-2.72 (-1.07)	Assuming symmetry	1.12 (0.44)	1.31 (0.52)	-0.10 (-0.04)	2.52 (0.99)	In the sphenoid sinus[2] approximately 4mm beyond the anterior-inferior margin of the sella turcica.	Fossa Tarini[2] Clivus
Torso	CM-Suprasternale 21.20 (8.35)			CM-Suprasternale 22.02 (8.67)			NM[4]			NM	Level of L1
	Location of CM as a Percentage of the Distance from Proximal Joint Length to Total Link Length										
Upper arm	50.92%			51.30%			NM			43.6%	46.8% Rt. 45.1 Lt.
Forearm	41.42			38.96			NM			43.0	42.0 Rt. 42.0 Lt.
Hand	51.75			18.02[3]			NM			50.6	5.6 cm[5] Rt. 5.4 cm[5] Lt.
Thigh	39.33			37.19			NM			43.3	44.7% Rt. 44.7 Lt.
Shank	41.75			37.05			NM			43.3	42.2 Rt. 42.0 Lt.
Foot	43.83			44.85			NM			43.8	42.9 Rt. 43.9 Lt.

[1] Data given in centimeters with inches in parentheses.

[2] These locations are bony landmarks in the interior base of the skull that lie in the mid-sagittal plane approximately 2-3 cm in front of and slightly above the Tragion-Tragion axis.

[3] Reported as CM-Meta III/Stylion-Meta III length.

[4] Not measured.

[5] Distance from proximal joint center.

TABLE 12
LOCATION OF BODY SEGMENTS' CENTER OF MASS

Head	x = Tragion to wall depth y = .5 bitragion breadth z = .17 tragion to vertex height
Torso	x = .44 waist depth at omphalion y = .5 waist breadth at omphalion z = .42 suprasternale to trochanterion
Upper Arm	x = Assume symmetry y = Assume symmetry z = .48 link length (Tables 1 & 3)
Forearm	x = Assume symmetry y = Assume symmetry z = .41 link length (Tables 1 & 3)
Hand	x = Assume symmetry of palm at z-axis location y = Assume symmetry of palm at z-axis location z = .51 palm length
Thigh	x = Assume symmetry y = Assume symmetry z = .41 link length (Tables 1 & 3)
Shank	x = Assume symmetry y = Assume symmetry z = .44 link length (Tables 1 & 3)
Foot	x = Assume symmetry of foot at z-axis location y = Assume symmetry of foot at z-axis location z = .44 foot length (from heel)

The weight of the body segments has been estimated in a number of ways. In 1957, Barter developed regression equations for predicting segment weight using total body weight as the independent variable from data reported by Braune and Fischer (1889), Fischer (1906), and Dempster (1955). Barter's equations, based on a sample of 12 cadavers, predicted the weight of seven segments and various combinations of segments. In order to update Barter's work with additional data and provide estimates for more individual segments, the equations in Table 13 were prepared. These equations are based on Barter's original sample with the addition of head and neck data

TABLE 13
PREDICTION EQUATIONS TO ESTIMATE SEGMENT WEIGHT BASED ON REANALYSIS OF CADAVER DATA*

Segment	Equation	R	Se_{est}
Head	.0306 (TBW) + 2.46 (5.42)	.626	± .43 (.95)
Head & neck	.0534 (TBW) + 2.33 (5.14)	.726	± .60 (1.32)
Neck	.0146 (TBW) + .60 (1.32)	.666	± .21 (.46)
Head, neck & torso	.5940 (TBW) - 2.20 (4.85)	.949	± 2.01 (4.43)
Neck & torso	.5582 (TBW) - 4.26 (9.39)	.958	± 1.72 (3.79)
Total arm	.0505 (TBW) + .01 (.02)	.829	± .35 (.77)
Upper arm	.0274 (TBW) - .01 (.02)	.826	± .19 (.42)
Forearm & hand	.0233 (TBW) - .01 (.02)	.762	± .20 (.44)
Forearm	.0189 (TBW) - .16 (.35)	.783	± .15 (.33)
Hand	.0055 (TBW) + .07 (.15)	.605	± .07 (.15)
Total leg	.1582 (TBW) + .05 (.11)	.847	± 1.02 (2.25)
Thigh	.1159 (TBW) - 1.02 (2.25)	.859	± .71 (1.57)
Shank & foot	.0452 (TBW) + .82 (1.81)	.750	± .41 (.90)
Shank	.0375 (TBW) + .38 (.84)	.763	± .33 (.73)
Foot	.0069 (TBW) + .47 (1.04)	.552	± .11 (.24)

*Data given in kilograms with pounds in parentheses.

from Walker et al. (1973), and head, torso, arms, and legs data from Clauser et al. (1969) and Chandler et al. (1975). The segments are defined in accordance with the definitions provided in Appendix A and only those segments in each study which closely matched those definitions were used in the segment samples. Prediction equations for estimating segment weight were also developed by Clauser et al. (1969) in their study of 13 cadavers. These later equations utilize anthropometric dimensions as the independent variables and are thus more sensitive to individual variations. The Clauser et al. equations appear in Appendix B, Table 3.

A third method (referred to in the literature as the method of coefficients) makes use of percentages of total body weight to estimate segment weights. Most of the available information on this subject appears in Table 14 and has been further refined for use by engineers and modellers in Table 15. Studies by Liu and Wickstrom (1973) and Walker et al. (1973), who used eight cadavers in common, provided additional input for the torso and neck data which appears in Table 15. This table is for use in determining the mean population estimates of segment weights, and for determining the weight of torso segments not given by the regression equations. Table 16 provides estimates of segment weights for selected total body weights using the regression equations in Table 13 and the torso coefficients in Table 15.

TABLE 14
SEGMENTAL WEIGHT/BODY WEIGHT RATIOS FROM CADAVER STUDIES [1]

Source	Harless (1860)	Braune & Fischer (1889)	Fischer (1906)	Dempster [2] (1955)	Clauser et al. (1969)	Walker et al. (1973)	Chandler et al. (1975)	Mori & Yamamoto (1959)		Fujikawa (1963)
Sample	2M	3M	1M	8 M	13 M	20M	6M	3M	3F	6M&F
Head and neck	7.6%	7.0%	8.8%	8.1%	7.3%	9.0%	6.1%	12.6%	11.1%	8.2%
Trunk	44.2	46.1	45.2	49.7	50 7		52.2	53.7	53.4	53.6
Total arm	5.7	6.2	5.4	5.0	4.9	-	-	4.4	4.9	4.7
Upper arm	3.2	3.3	2.8	2.8	2.6	-	2.9	2.8	2.6	2.6
Forearm & hand	2.6	2.9	2.6	2.2	2.3	-	-	1.6	2.3	2.2
Forearm	1.7	2.1	-	1.6	1.6	-	1.7	1.1	1.6	1.4
Hand	0.9	0.8	-	0.6	0.7	-	0.6	0.5	0.7	0.8
Total leg	18.4	17.2	17.6	16.1	16.1	-	-	12.4	13.0	14.5
Thigh	11.9	10.7	11.0	9.9	10.3	-	10.2	7.4	7.5	9.4
Shank & foot	6.6	6.5	6.6	6.1	5.8	-	-	5.0	5.3	5.0
Shank	4.6	4.8	4.5	4.6	4.3	-	4.1	3.4	3.5	3.3
Foot	2.0	1.7	2.1	1.4	1.5	-	1.3	1.6	1.6	1.7
Total body weight [3]	55.53 (122.44)	63.85 (140.79)	44.06 (97.15)	59.72 (131.68)	65.61 (144.67)	68.40 (150.82)	65.17 (143.70)	31.57 (69.61)	37.57 (82.84)	50.30 110.91

[1] Data presented for right side of body rather than average of right and left sides.
[2] Values adjusted by Clauser et al. 1969.
[3] Data given in kilograms with pounds in parentheses.

TABLE 15
PERCENTAGE DISTRIBUTION OF TOTAL BODY WEIGHT ACCORDING TO DIFFERENT SEGMENTATION PLANS

Grouped Segments Percent of Total Body Weight		Individual Segments Percent of Grouped Segments Weight	
Head and neck	= 8.4%	Head	= 73.8%
		Neck	= 26.2%
Torso	= 50.0%	Thorax	= 43.8%
		Lumbar	= 29.4%
		Pelvis	= 26.8%
Total arm	= 5.1%	Upper arm	= 54.9%
		Forearm	= 33.3%
		Hand	= 11.8%
Total leg	= 15.7%	Thigh	= 63.7%
		Shank	= 27.4%
		Foot	= 8.9%

There are two further methods available for estimating segment weights of living subjects, both of which incorporate an unknown error factor. Bernstein et al. (1931) developed a technique by which a segment weight could be estimated from a change in a lever arm moment due to the angular displacement of discrete body segments. This technique, however, assumes knowledge of the location of both the center of mass and joint center of rotation and these points are difficult to locate on the living subject. The method is further predicated on the assumption that center of mass is equivalent to center of volume and subsequent assessment of this assumption (by Clauser et al. 1969) revealed a systematic error in Bernstein's technique.

A sounder method is to calculate segment weights from segment volumes as percentages of total body volumes, correcting for density. The volume measurement technique described most frequently in the literature is underwater displacement, but other methods exist and the use of stereophotogrammetry is a promising new tool for measuring the mass distribution properties of the living body.

The majority of subjects used thus far have been males; only a few studies of females have ever been conducted. Presented in Table 17 are the data for segment volumes as percentages of total body volume for male cadavers and living subjects; comparable data for living female subjects appear in Table 18. It should be remembered that different segmentation planes for the upper arm and upper leg for cadavers and living subjects (see Figure 2) affect the results of calculations for the relevant limbs as well as for the torso. When the average segment volume percentages of

TABLE 16
SEGMENT WEIGHT DESIGN VALUES DERIVED FROM REGRESSION EQUATIONS IN TABLE 13*

Segment						
TOTAL BODY WEIGHTS	45.37 (100)	54.45 (120)	63.52 (140)	72.59 (160)	81.67 (180)	90.74 (200)
Head	3.87 (8.47)	4.12 (9.08)	4.40 (9.70)	4.68 (10.32)	4.95 (10.91)	5.23 (11.53)
Head & neck	4.75 (10.47)	5.24 (11.55)	5.72 (12.61)	6.20 (13.67)	6.69 (14.75)	7.17 (15.81)
Neck	1.27 (2.80)	1.40 (3.09)	1.53 (3.37)	1.66 (3.66)	1.80 (3.97)	1.93 (4.26)
Neck & torso	21.06 (46.44)	26.13 (57.62)	31.19 (68.77)	36.26 (79.95)	41.33 (91.13)	46.39(102.29)
Thorax**	9.30 (20.51)	11.62 (25.62)	13.94 (30.74)	16.26 (35.85)	18.58 (40.97)	20.90 (46.08)
Lumbar**	5.48 (12.08)	6.85 (15.10)	8.22 (18.13)	9.58 (21.12)	10.95 (24.14)	12.31 (27.14)
Pelvis**	5.01 (11.05)	6.26 (13.80)	7.50 (16.54)	8.75 (19.29)	10.00 (22.05)	11.25 (24.81)
Head, neck & torso	24.75 (54.57)	30.14 (66.46)	35.53 (78.34)	40.92 (90.23)	46.31(102.11)	51.70(114.00)
Total arm	2.30 (5.07)	2.76 (6.09)	3.21 (7.08)	3.67 (8.09)	4.13 (9.11)	4.59 (10.12)
Upper arm	1.23 (2.71)	1.48 (3.26)	1.73 (3.81)	1.98 (4.37)	2.23 (4.92)	2.48 (5.47)
Forearm & hand	1.05 (2.31)	1.26 (2.78)	1.47 (3.24)	1.68 (3.70)	1.89 (4.17)	2.10 (4.63)
Forearm	0.70 (1.54)	0.87 (1.92)	1.04 (2.29)	1.22 (2.69)	1.39 (3.06)	1.56 (3.44)
Hand	0.32 (0.71)	0.37 (0.82)	0.42 (0.93)	0.47 (1.04)	0.52 (1.15)	0.57 (1.26)
Total leg	7.23 (15.94)	8.66 (19.09)	10.10 (22.27)	11.53 (25.42)	12.97 (28.60)	14.40 (31.75)
Thigh	4.24 (9.35)	5.29 (11.66)	6.34 (13.98)	7.39 (16.29)	8.45 (18.63)	9.50 (20.95)
Shank & foot	2.87 (6.33)	3.28 (7.23)	3.69 (8.14)	4.10 (9.04)	4.51 (9.94)	4.92 (10.85)
Shank	2.08 (4.59)	2.42 (5.34)	2.76 (6.09)	3.11 (6.86)	3.45 (7.61)	3.79 (8.36)
Foot	0.78 (1.72)	0.85 (1.87)	0.91 (2.01)	0.97 (2.14)	1.03 (2.27)	1.10 (2.43)

*Data given in kilograms with pounds in parentheses.

**The weights of these segments are computed as a percentage of torso weight reported in Table 15.

TABLE 17
MALE SEGMENT VOLUME AS PERCENT OF TOTAL BODY VOLUME

Subjects	Cadaver			Living				
Studies	Clauser et al. (1969)	Chandler et al. (1975)	Average	Dempster (1955)	Cleaveland (1955)	Drillis et al. (1966)	Katch & Waltman (1975)	Average
Head		5.4%						
Head & neck	7.0%				7.0%		7.4%	7.2%
Torso					48.1		46.2	47.2
Neck & torso	51.9	56.9	54.4%					
Upper arm	2.6	2.7	2.7	3.5%	3.1	3.5%		3.4
Forearm	1.5	1.5	1.5	1.5	1.6	1.7		1.6
Upper & forearm	4.1	4.2	4.2	5.0	4.7	5.2	5.6	5.1
Hand	0.6	0.5	0.6	0.6	0.5	0.6	0.7	0.6
Total arm	4.7	4.7	4.7	5.6	5.2	5.8	6.3	5.7
Thigh	10.3	9.4	9.9	14.2	11.2	9.2		11.5
Shank	4.2	3.6	3.9	4.9	4.4	4.1		4.5
Thigh & shank	14.5	13.0	13.8	19.1	15.6	13.3	15.2	15.8
Foot	1.4	1.1	1.3	1.4	1.3	1.3	1.7	1.4
Total leg	15.9	14.1	15.0	20.5	16.9	14.6	16.9	17.2
Total body	100.1%	99.9%	100.0%		99.3%		100.0%	
N	13	6	-	39	12	11	24	
Stature*	172.7	172.1	172.4	174.5	175.8	176.0	176.9	175.8
Weight*	65.6	65.17	65.4	75.6	71.5	73.42	76.2	73.9
Age	49.3	54.3	51.9	20.6	27.2	20.8	21.2	22.5
TB volume*	62.99	69.61	66.3	71.32**	66.73	69.26**	71.89**	69.8

*Stature is reported in centimeters, weight in kilograms and total body volume in liters.
**Total body volume computed as weight ÷ 1.06.

TABLE 18
FEMALE SEGMENT VOLUME AS PERCENT OF TOTAL BODY VOLUME

	Katch & Weltman (1975)	Kjeldsen (1972)
Head & neck	8.3%	8.8%
Torso		(50.7%)
Upper torso		16.4%
Lower torso		34.3%
Upper arm		2.8%
Lower arm		1.4%
Upper & lower arm	4.5%	(4.2%)
Hand	0.6%	0.5%
Thigh		9.4%
Thigh & shank	15.4%	(14.4%)
Foot	1.6%	1.2%
N	23	12

total body volume are compared with the percentages for weight, the differences are small, reflecting the close correlation between volume and weight. Thus, to estimate segment weight, the percentages from either Table 17 or Table 18 can be used. To estimate segment volume, regression equations appearing in Appendix B, Table 4 can also be used.

If segment volume is available for an individual or for a population, the density data in Table 19 will provide the necessary values for estimating weight from volume. These values are based on cadaveric data and have the same bias which is present in the actual segment weights of cadavers. Therefore, whether segment weights for astronauts are estimated via regression equations or measured segment volume, the engineer must assume that cadaver data is only an approximation of these properties in the living body. The accuracy with which these data reflect living body weight distribution is essentially unknown, but they are the best approximations available.

Moments of Inertia

This section will serve as a guide to the inertial properties of the whole body and its segments. Its purpose is to present the available empirical data for estimating moments of inertia and to present methods of estimating these properties for specific populations.

The inertial properties of the whole body and its segments have been reported in a variety of ways: as moments of inertia; as a momental ellipsoid of inertia; and as an inertia tensor. All three describe the

TABLE 19
SEGMENT DENSITY FOR MALE CADAVERS
(Values in grams/cm^3)

	Dempster (1955)	Clauser et al. (1969)	Chandler et al. (1975)	Average
Head			1.06	1.06
Head & neck	1.11	1.07		1.09
Torso				
Neck & torso		1.02	0.85	0.94
Head, neck, & torso	1.03	1.03		1.03
Upper arm	1.07	1.06	1.00	1.04
Lower arm	1.13	1.10	1.05	1.09
Hand	1.16	1.11	1.08	1.12
Thigh	1.05	1.04	1.02	1.04
Shank	1.09	1.08	1.07	1.08
Foot	1.10	1.08	1.07	1.08

inertial properties of an individual but are based on different assumptions or data analysis methods.

Moments of inertia are defined about an axis of rotation which, in most studies, is defined as passing through the center of gravity, but occasionally is defined as passing through an estimated joint center of rotation. All the moments reported in this section are about axes passing through centers of gravity. In the studies of living subjects, the measured moments of inertia are reported about three orthogonal axes defined by the researcher. In recent studies using cadaver specimens, moments about six or more axes were measured in order to determine an inertial tensor which was used to derive the principal moments of inertia about the principal axes of inertia.

As with other mass distribution properties, data on the whole body are obtained primarily from measurements of living subjects and data on segments come primarily from measurements of cadavers. A comparison has been made on the following pages which will clarify the differences between methods used in studies of cadavers and that used in the study of living subjects.

Whole Body

Measurements of whole body moments of inertia are position-dependent data since they describe the mass distribution in a particular position assumed by the subject during the measurement procedure. As soon as any of the segments change position, the magnitude and direction of the moments of inertia are changed. The only reasonable approach for data on the whole body is to measure moments of inertia for common positions of the body. Three such studies, covering a range of positions for the moments of inertia relative to an inertial "anatomical" axis system located at the center of gravity of the living body, have been undertaken.

The first direct measures of moments of inertia of the whole body were made by Santschi et al. (1963) on 66 subjects representative of the U.S. Air Force flying personnel. Using a compound pendulum with the body in the eight positions depicted in Figure 9, investigators measured three moments of inertia about three axes passing through the center of gravity of the body. The data, summarized in Table 20, give the moments of inertia for U.S. males and include regression equations which predict the moments of inertia about an "anatomical" axis system defined by the intersection of the three cardinal anatomical planes with an origin at the center of gravity for the whole body (See Figure 1).

Table 21 presents values computed from the regression equations in Table 20 for small, medium and large white males in the standing, sitting and relaxed (weightless) positions. These estimates are appropriate for the U.S. white male population projected for 1985 as are the following data from DuBois.

Using the same measurement techniques, DuBois et al. (1964), enlarged on the Santschi study by measuring three moments of inertia about the same axes on 19 male subjects wearing full-pressure suits. The subjects assumed only two positions (sitting and relaxed) but were measured in three dress conditions: nude, unpressurized suit, and pressurized suit (See Figure 10). The suit sizes ranged from small-regular to extra-large-long. Table 22 presents the summary statistics and regression equations and Table 23 contains values computed from the regression equations in Table 22.

There has been one French study in which the inertial properties of living subjects were measured. Ignazi et al. (1972) measured three moments of inertia on eleven standing male subjects using a method similar to that used in the U.S. studies. Table 24 presents the summary statistics for height, weight, and the moments of inertia for the x-, y- and z-axes as well as multiple regression equations for predicting the moments of inertia and center of mass from anthropometric dimensions. This study represents the only source of whole body inertial information on European subjects.

The above-described studies are based on the assumption that the "anatomical" axis system (as depicted in Figure 1) reasonably approximates the principal axes of inertia. The basic difference between them is that the "anatomical" axis system is a hypothetical construction imposed on the body by the investigator while the principal axes of inertia are inherent in the body or its parts. The former is unaffected by the dynamics of the body while the latter change as the body configuration and mass distribution change in time and space.

TABLE 20

MEANS, STANDARD DEVIATIONS, AND REGRESSION EQUATIONS FOR WHOLE BODY MOMENTS OF INERTIA FROM SANTSCHI ET AL. (1963)

	Axis	Moment of Inertia[1] Mean	S.D.	$R_{i \cdot sw}$ [2]	$Se_{est.}$	I_o Regression Equations[3]
1. Standing	x	115.0	19.3	0.98	4.18	3.77S + 0.512W - 232.0
	y	103.0	17.9	0.96	5.27	3.43S + 0.460W - 212.0
	z	11.3	2.2	0.93	0.84	-0.098S + 0.112W - 0.604
2. Standing, arms over head	x	152.0	26.1	0.98	5.63	5.36S + 0.652W - 328.0
	y	137.0	25.3	0.96	6.89	5.34S + 0.589W - 332.0
	z	11.1	1.9	0.89	0.87	-0.085S + 0.094W + 1.4
3. Spread eagle	x	151.0	27.1	0 98	4.90	5.63S + 0.677W - 353.0
	y	114.0	21.3	0.96	6.24	4.30S + 0.516W - 270.0
	z	36.6	7.9	0.93	2.82	1.52S + 0.191W - 101.0
4. Sitting	x	61.1	10.3	0.92	4.01	1.43S + 0.322W - 91.6
	y	66.6	11.6	0.92	4.51	2.26S + 0.268W - 135.0
	z	33.5	5.8	0.97	1.45	0.76S + 0.201W - 52.8
5. Sitting, forearms down	x	62.4	9.7	0.91	3.98	1.29S + 0.309W - 78.7
	y	68.1	12.0	0.92	4.67	2.05S + 0.321W - 127.0
	z	33.8	5.9	0.97	1.36	0.765S + 0.206W - 53.7
6. Sitting, thighs elevated	x	39.1	6.0	0.89	2.79	0.543S + 0.212W - 33.8
	y	38.0	5.8	0.77	3.66	0.434S + 0.180W - 22.2
	z	26.3	5.1	0.92	2.00	0.328S + 0.204W - 30.4
7. Mercury configuration	x	65.8	10.3	0.93	3.75	1.57S + 0.308W - 94.3
	y	75.2	14.0	0.94	4.96	2.85S + 0.318W - 175.0
	z	34.2	5.6	0.96	1.64	0.668S + 0.197W - 45.0
8. Relaxed (weightless)	x	92.2	13.3	0.96	3.71	1.77S + 0.452W - 106.0
	y	88.2	13.3	0.94	4.54	2.43S + 0.352W - 139.0
	z	35.9	5.4	0.96	1.54	0.776S + 0.176W - 47.2

[1] Values for I_o are given in lb.in.sec.^{2}. For conversion to other units, see Appendix C.

[2] Multiple correlation coefficient of stature and weight with the independent variables.

[3] (Stature) in inches
(Weight) in pounds

TABLE 21
WHOLE BODY MOMENTS OF INERTIA FOR MALE WHITES COMPUTED FROM TABLE 20*

		Small: 5th %ile 168.2 cm. (66.2 in.) 65.2 kg. (143.7 lb.)		Medium: 50th %ile 178.4 cm. (70.2 in.) 81.5 kg. (180.0 lb.)		Large: 95th %ile 188.6 cm. (74.3 in.) 97.7 kg. (215.3 lb.)	
		lb.-in.sec^2	gm-cm^2(x10^6)	lb.-in.sec.^{2}	gm-cm^2(x10^6)	lb.-in.sec.^{2}	gm-cm^2(x10^6)
Standing	x	91.148	103.065	124.814	141.132	158.345	179.047
	y	81.168	91.780	111.586	126.175	141.887	160.438
	z	9.003	10.180	12.676	14.333	16.228	18.350
Sitting	x	49.337	55.787	66.746	75.473	83.976	94.955
	y	53.124	60.070	71.892	81.291	90.618	102.466
	z	26.396	29.847	36.732	41.534	49.943	56.473
Relaxed	x	76.126	86.079	99.164	112.638	122.827	138.886
	y	72.448	81.920	94.946	107.359	117.335	132.676
	z	29.462	33.314	38.955	44.048	48.350	54.671

*For conversion to other units, see Appendix C.

Nude

Unpressurized

Pressurized

1. Sitting

Nude

Unpressurized

Pressurized

2. Relaxed (Weightless)

Figure 10. Mean centers of gravity in nude and suited subjects (from DuBois et al., 1964).

TABLE 22

MEANS, STANDARD DEVIATIONS, AND REGRESSION EQUATIONS FOR WHOLE BODY MOMENTS OF INERTIA FROM DUBOIS ET AL. (1964)

	Axis	Moment of Inertia[1] Mean	Moment of Inertia[1] S.D.	$R_{1.sw}$ [2]	$Se_{est.}$	I_o Regression Equation[3]
Sitting						
Nude	x	56.3	8.22	0.95	2.67	1.59S + 0.317W - 105.0
	y	66.5	9.98	0.91	4.07	2.10S + 0.344W - 135.0
	z	28.3	5.10	0.97	1.17	0.923S+ 0.212W - 70.4
Unpressurized	x	67.5	9.16	0.93	3.42	1.82S + 0.337W - 114.0
	y	82.8	11.30	0.97	2.77	2.96S + 0.362W - 181.0
	z	33.6	5.72	0.97	1.47	1.09S + 0.229W - 79.5
Pressurized	x	68.8	8.70	0.93	3.24	2.06S + 0.281W - 120.0
	y	82.4	11.30	0.94	3.79	2.54S + 0.389W - 157.0
	z	34.0	5.72	0.96	1.53	1.07S + 0.230W - 78.1
Relaxed (Weightless)						
Nude	x	99.2	14.20	0.97	3.30	2.88S + 0.556W - 191.0
	y	89.8	15.20	0.95	4.60	4.04S + 0.461W - 265.0
	z	31.2	5.04	0.94	1.75	0.567S+ 0.231V - 46.0
Unpressurized	x	118.0	15.30	0.95	4.62	3.19S + 0.574W - 197.0
	y	114.0	15.00	0.96	4.38	3.59S + 0.506W - 217.0
	z	36.2	5.03	0.96	1.33	0.801S+ 0.217W - 54.8
Pressurized	x	118.0	15.20	0.97	3.93	3.42S + 0.550W - 208.0
	y	114.0	15.70	0.96	4.44	4.18S + 0.482W - 254.0
	z	36.1	4.85	0.96	1.36	0.720S+ 0.214W - 48.7

[1] Values for I_o are given in lb.in.sec.^{2}. For conversion to other units, see Appendix D.

[2] Multiple correlation coefficient of stature and weight with the independent variables.

[3] S (Stature) in inches.
W (Weight) in pounds.

TABLE 23
WHOLE BODY MOMENTS OF INERTIA FOR MALE WHITES COMPUTED FROM TABLE 22*

		Small: 5th %ile		Medium: 50th %ile		Large: 95th %ile	
		168.2 cm. (66.2 in.) 65.2 kg. (143.7 lb.)		178.4 cm. (70.2 in.) 81.5 kg. (180.0 lb.)		188.6 cm. (74.3 in.) 97.7 kg. (215.3 lb.)	
		lb.-in.sec.^{2}	gm-cm^2(x10^6)	lb.-in.sec.^{2}	gm-cm^2(x10^6)	lb.-in.sec.^{2}	gm-cm^2(x10^6)
Sitting							
Unpressurized	x	54.911	62.104	74.424	84.174	93.782	106.067
	y	66.971	75.744	91.952	103.998	116.867	132.177
	z	25.565	28.914	38.238	43.247	50.791	57.445
Pressurized	x	56.752	64.187	75.192	85.042	93.557	105.813
	y	67.047	75.830	91.328	103.292	115.474	130.601
	z	25.785	29.163	38.414	43.446	50.920	57.591
Relaxed							
Unpressurized	x	96.662	109.325	130.258	147.030	163.599	185.030
	y	93.370	105.601	126.098	142.617	158.679	179.466
	z	29.409	33.262	40.490	45.794	51.434	58.172
Pressurized	x	97.439	110.204	131.084	148.256	164.521	186.073
	y	91.979	104.028	126.196	142.728	160.349	181.355
	z	29.716	33.609	43.364	49.045	50.870	57.534

*For conversion to other units, see Appendix C.

TABLE 24
MEANS, STANDARD DEVIATIONS AND REGRESSION EQUATIONS FOR WHOLE BODY MOMENTS OF INERTIA FROM IGNAZI ET AL. (1972)

Axis[1]	Moment of Inertia[2] Mean	S.D.	$R_{i \cdot sw}$[3]	$Se_{est.}$	I_o Regression Equation[4]
x	11.51	1.99	.980	0.396	0.136W + 0.119S - 18.874
y	12.38	2.03	.985	0.351	0.106W + 0.172S - 25.211
z	1.12	0.29	.963	0.079	0.033W - 0.006S - 2.135

[1] See axis system definition in Table 9.

[2] Values are given in $kg.m^2$. For conversion to other units, see Appendix D.

[3] Multiple correlation coefficient of stature and weight with the independent variables.

[4] S (Stature) in centimeters
W (Weight) in kilograms

Chandler et al. (1975) conducted the first study to determine the principal moments of inertia about the principal axes of inertia in the whole body. The subjects were six embalmed cadavers. The principal moments of inertia are presented in Table 25 relative to a right-handed orthogonal axis system located at the whole body center of gravity. These moments were determined about the principal axes according to a technique described by Winstandley et al. (1968) and further discussed in the Chandler et al. report.

Inertial data from the Chandler study can be used to examine the assumption that the "anatomical" axis system (about which the three previous investigators measured their data) approximates the principal axes of inertia. This "anatomical" axis system has been treated as an inertial frame of reference defined in the standard anatomical position. The axis system about which the principal moments of inertia in the Chandler study were determined, defines the momental ellipsoid of inertia (Synge and Griffith, 1942). Table 26 presents a comparison of the Chandler data with data from the Santschi study for subjects individually matched for height and weight.

In general, the percentage differences are small for the principal moments of inertia in the standing position indicating that the "anatomical" axis system closely approximates the principal axes of the momental ellipsoid of inertia in that position. It will be noted that the z-axes in the sitting position are significantly different. These differences are attributed to the displacement of the appendages away from the cardinal anatomical planes. As a general rule for symmetrical displacements of the appendages relative to the torso, moments of inertia about the x-axis and y-axis will most closely approximate the principal moments of inertia measured about the "anatomical" axis. The z-axis will have the poorest approximation since it is the major axis of the ellipsoid and hence the most sensitive.* The two studies by Chandler et al. (1975) and Becker (1972) in which moments of inertia were measured about principal axes result in more reliable data except for unresolved differences between them concerning head data.

All available data were measured under one-g conditions and therefore incorporate the effect of gravity on the tissues and fluids of the body. Although some raw data on inertial properties under zero-g conditions have been collected, they have not been analyzed, so there are, as yet, no guidelines for adjusting values for moments of inertia in the zero-g environment.

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*The magnitude of the axes in a momental ellipsoid is given by the square root of the inverse of a moment of inertia. Therefore, for a typical ellipsoid, the major axis passes through the centroid and a point on the surface defined by a tangent to the greatest rate of curvature. Therefore the major axis is the most sensitive to minor changes in the mass distribution of the body.

TABLE 25
PRINCIPAL MOMENTS OF INERTIA FROM CHANDLER ET AL. (1975)

Subject	Standing			Sitting				
	1	2	3	4	5	6	X	SD
Age	65	45	47	58	61	50	54.3	7.4
Weight*	58.7 (129.43)	76.15 (167.91)	89.15 (196.58)	50.62 (111.62)	58.08 (128.07)	58.34 (128.64)	65.17 (143.70)	13.21 (29.13)
Stature*	167.8 (66.06)	181.7 (71.54)	174.2 (68.58)	175.9 (69.25)	168.8 (66.46)	164.5 (64.76)	172.15 (67.78)	5.75 (2.26)
Principal Moments of Inertia ($\times 10^3$ gm - cm^2)								
I_{xx} (Standing)	98,807	150,886	169,127	---	---	---	133,967.0	45,391.4
(Seated)	---	---	---	70,858	64,125	66,937	67,306.7	3,087.0
I_{yy} (Standing)	89,223	125,580	141,888	---	---	---	118,897.0	24,611.9
(Seated)	---	---	---	66,023	69,801	60,726	65,516.7	4,161.4
I_{zz} (Standing)	11,644	17,424	22,388	---	---	---	17,152.0	4,908.7
(Seated)	---	---	---	11,385	17,445	15,825	14,885.0	2,864.1

*Data given in kilograms and centimeters with pounds and inches in parentheses.

TABLE 26
COMPARISON OF MOMENTS OF INERTIA BETWEEN CHANDLER ET AL. (1975)
AND SANTSCHI ET AL. (1963)

	Standing			Sitting		
Subject #	1/19	2/1	3/17	4/26	5/16	6/39
Ix*	-4.05%	0.84%	7.04%	14.67%	4.15%	10.76%
Iy*	-2.69%	-7.17%	2.82%	-3.03%	-5.16%	-10.54%
Iz*	18.10%	14.94%	21.42%	-183.33%	-91.95%	-107.59%

*Deviation as percent of cadaver value.

Segments

Table 27 presents a summary of the data from four cadaver studies. Although the sample sizes are too small to permit definitive conclusions for the population, these are the only data of their kind available and may be used with caution. It should also be noted when using this table that some differences between the samples are attributable to differing definitions of the segments and the resultant variations in segment mass.

As can be observed from the table, Chandler et al. (1975) and Becker (1972) measured the principal moments of inertia about three principal axes of inertia. The results of both studies confirm that, for our purposes, moments of inertia about the "anatomical" axes closely approximate the principal moments of inertia determined about the principal axes of inertia for body segments.

For the modeler, there are three approaches which can be used to predict the principal moments of inertia of body segments. Table 28 presents the first and simplest approach by providing coefficients from the data in the Chandler study for the radii of gyration (K = I/M) expressed as a ratio, or percentage, of segment length. To estimate the radius of gyration, multiply the segment length (or link length) by the appropriate coefficient found in Table 28. The resulting product is multiplied by the appropriate segment weight (see Table 13) to obtain the principal moments of inertia for each segment. Table 29 presents some sample calculations for small (5th percentile), medium (50th percentile) and large (95th percentile) 1985 males.

The torso in Table 28 corresponds to the segmentation plan followed in the Chandler study which combined the neck, thorax, abdomen and pelvis segments into one. Geometric models, based on segment weight estimates in Table 15, can be used to calculate inertial properties of these four segments.

TABLE 27

SEGMENT MOMENTS OF INERTIA (10^3 $gm\text{-}cm^2$) THROUGH THE CENTER OF MASS [1]

		Chandler, et al. (1975)			Becker (1972)			Dempster (1955)	Braune & Fischer (1892)			
									Cadaver 1		Cadaver 2	
		I_{xx}	I_{yy}	I_{zz}	I_{xx}	I_{yy}	I_{zz}	I_{x-y} [2]	I_{x-y}	I_z	I_{x-y}	I_z
Head		174.0	164.4	202.9	198.5	221.0	133.8	NM [3]	---	---	179.94	
Torso		16,193.7	10,876.3	3,785.1		NM [3]		NM	---	---	5,574.6	
Upper arm	Rt.	135.0	132.7	20.1		NM		142.0	101.0	---	75.56	9.66
	Lt.	152.1	137.7	22.8		NM		139.0	121.0	18.0	75.98	9.40
Forearm	Rt.	66.9	64.5	8.8		NM		56.0	130.0 [4]	---	121.5 [4]	8.45 [4]
	Lt.	64.7	63.0	8.6		NM		55.0	142.0 [4]	---	152.2 [4]	8.85 [4]
Hand	Rt.	7.54	6.15	2.15		NM		5.0				
	Lt.	6.84	5.57	1.79		NM		4.5				
Thigh	Rt.	1137.3	1157.9	224.9		NM		1100.0	684.0	19.0	589.1	100.61
	Lt.	1151.4	1221.2	212.5		NM		1080.0	818.0	21.0	628.4	100.02
Shank	Rt.	391.3	392.8	29.1		NM		430.0	257.0	---	173.68	20.15
	Lt.	394.9	389.6	28.6		NM		416.0	271.0	---	176.37	17.58
Foot	Rt.	32.10	31.08	7.04		NM		31.0	36.0	---	34.785	35.093
	Lt.	33.13	30.43	7.54		NM		29.0	38.0	---	32.433	35.433
Head & neck		---	---	---	359.1	452.2	257.6	294.0	---	---	---	---
Head & torso		---	---	---	---	---	---	18,400.0	9,417.00	---	10,571.5	---

[1] For conversion to other units, see Appendix D.

[2] This axis is undefined except to say that it is perpendicular to the long axis and passes through the center of mass.

[3] NM = Not Measured.

[4] Forearm and hand measured together.

TABLE 28
THE RADIUS OF GYRATION (K) AS A PERCENT OF SEGMENT LENGTH

		L	K/L
Head	x	Head length	31.6%
	y		30.9%
	z		34.2%
Torso	x	Torso length	43.0%
	y	(Suprasternale hgt.	35.2%
	z	-trochanterion hgt.)	20.8%
Upper arm	x	Acromion-radiale l.	26.1%
	y		25.4%
	z		10.4%
Forearm	x	Radiale-stylion l.	29.6%
	y		29.2%
	z		10.8%
Hand	x	Hand breadth	50.4%
	y		45.6%
	z		26.6%
Thigh	x	Trochanterion hgt.	27.9%
	y	-fibular hgt.	28.4%
	z		12.2%
Shank	x	Fibular hgt.	28.2%
	y		28.2%
	z		7.6%
Foot	x	Foot length	26.1%
	y		24.9%
	z		12.2%

A second method of predicting the principal moments of inertia is to use regression equations based on body weight, segment weight or segment volume. These equations were computed in the Chandler study and are given in Appendix B, Table 5. The same segmentation plan as that used in Table 28 must be followed but the equations are based on a slightly different set of independent data.

A third method by which a design engineer can estimate the principal moments of inertia of body segments is to use geometric models. There are several current models which utilized geometric estimates, including those developed by Bartz and Gianotti (1973), Hanavan (1964) and Tieber and Lindemuth (1965). These models share some common assumptions which are well known but are not inherent in the two previously reported methods. First,

TABLE 29

SEGMENT MOMENTS OF INERTIA AS COMPUTED FROM THE COEFFICIENTS IN TABLE 28

		Small: 5th %ile 168.2 cm. (66.2 in.) 65.2 kg. (143.7 lb.)		Medium: 50th %ile 178.4 cm. (70.2 in.) 81.5 kg. (180.0 lb.)		Large: 95th %ile 188.6 cm. (74.3 in.) 97.7 kg. (215.3 lb.)	
		$kg\text{-}cm^2$ 9	$lb.in.sec^2$	$kg\text{-}cm^2$	$lb.in.sec^2$	$kg\text{-}cm^2$	$lb.in.sec^2$
Head	x	156.9	0.139	195.7	0.173	240.3	0.213
	y	150.0	0.133	187.2	0.166	229.7	0.203
	z	183.8	0.163	229.3	0.203	281.5	0.249
Torso	x	14604.0	12.916	20219.2	17.882	21837.2	19.313
	y	9786.5	8.655	13549.2	11.983	14632.9	12.941
	z	3417.5	3.022	4731.0	4.184	5109.3	4.519
Upper arm	x	111.1	0.098	166.0	0.147	233.7	0.207
	y	99.9	0.088	157.2	0.139	221.3	0.196
	z	17.6	0.016	26.3	0.023	37.1	0.033
Forearm	x	57.7	0.051	88.5	0.078	127.6	0.113
	y	56.1	0.050	86.1	0.076	124.2	0.110
	z	7.7	0.007	11.8	0.010	17.0	0.015
Hand	x	7.4	0.007	10.4	0.009	14.3	0.013
	y	6.1	0.005	8.5	0.008	11.7	0.010
	z	2.1	0.002	2.9	0.003	4.0	0.003
Thigh	x	1123.9	0.994	1666.6	1.474	2334.9	2.065
	y	1164.5	1.030	1726.8	1.527	2419.5	2.140
	z	214.9	0.190	318.7	0.282	446.5	0.395
Shank	x	369.3	0.327	534.3	0.473	736.9	0.652
	y	369.3	0.327	534.3	0.473	736.9	0.652
	z	26.8	0.024	38.8	0.034	53.5	0.047
Foot	x	40.1	0.035	52.1	0.046	66.6	0.059
	y	36.5	0.032	47.4	0.042	60.6	0.054
	z	8.8	0.008	11.4	0.010	14.5	0.013

geometric models assume rigid homogeneous bodies of unknown density usually estimated to be 1.0. Second, they assume the shape of these bodies to be best approximated by symmetrical geometric shapes. As a consequence, they further assume that the principal "geometric" axes are the same as the principal "inertial" axes. Based on empirical data collected thus far, the last assumption appears to have some validity although it must be pointed out that the only comparison presently possible is between data collected on six embalmed cadavers and the geometric models.

The first two methods described above are derived from directly measured data which suggests that they are more accurate and more individualized than the older method which relies on geometric models. However, computer programs, which do exist for the geometric models, have not yet been written for the newer empirical equations, so the ultimate decision concerning which method to employ must be made by the user who will examine his requirements and select accordingly.

The reader of this chapter will have noted, perhaps with some impatience, the number of reservations and cautionary statements surrounding much of the material presented here, the number of alternative approaches offered and the frequency with which the lack of hard data has been pointed out. This is an inevitable consequence of any attempt to assemble a usable and up-to-date body of knowledge in an area in which verified data are still so sparse and in which so much research and validation remains to be done. We are still on the frontiers of understanding the inertial properties of the human body.

Nevertheless, despite the limitations and deficiencies of the published data, material in this chapter provides the user for the first time with a means of estimating the mass distribution properties of the human body from empirical data rather than solely from the traditional geometrical models. This is a major step toward a fuller understanding of the biomechanical behavior of the human body.

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APPENDIX A
THE ANATOMICAL FRAMEWORK

Joint Centers of Rotation and Linkage and Axis Systems for Body Segments

1. Joint Centers of Rotation

Head/Neck	-Midpoint of the interspace between the occipital condyles and the first cervical vertebra.
Neck/Thorax	-Midpoint of the interspace between the 7th cervical and 1st thoracic vertebral bodies.*
Thorax/ Lumbar	-Midpoint of the interspace between the 12th thoracic and 1st lumbar vertebral bodies.*
Lumbar/Sacral	-Midpoint of the interspace between the 5th lumbar and 1st sacral vertebral bodies.*
Sternoclavicular	-"Midpoint position of the palpable junction between the proximal end of clavicle and the sternum at the upper border (jugular notch) of the sternum." (Dempster, p. 123, 1955)
Claviscapular	-"Midpoint of a line between the coracoid tuberosity of the clavicle (at the posterior border of the bone) and the acromioclavicular articulation (or the tubercle at the lateral end of the clavicle); the point, however, should be visualized as on the underside of the clavicle."(Dempster, p. 123, 1955)
Glenohumeral	-"Midregion of the palpable bony mass of the head and tuberosities of the humerus; with the arm abducted about 45° relative to the vertebral margin of the scapula, a line dropped perpendicular to the long axis of the arm from the outermost margin of the acromion will approximately bisect the joint." (Dempster, p. 125, 1955)

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*These locations are defined relative to the last and first vertebrae of each of the major anatomical vertebrae groups. Thus, there are occasionally missing or additional vertebrae which would not change the functional definition of these links.

Elbow -"Midpoint on a line between (1) the lowest palpable point the medial epicondyle of the humerus, and (2) a point 8mm above the radiale (radiohumeral junction)." (Dempster p. 125, 1955)

Wrist -"On the palmar side of the hand, the distal wrist crease at the palmaris longus tendon, or the midpoint of a line between the radial styloid and the center of the pisiform bone; on the dorsal side of the hand, the palpable groove between the lunate and capitate bones, on a line with metacarpal bone III." (Dempster p. 125, 1955)

Hip -"(Lateral aspect of the hip). A point at the tip of the femoral trochanter 0.4 inch anterior to the most laterally projecting part of the femoral trochanter." (Dempster, p. 125, 1955)

Knee -"Midpoint of a line between the centers of the posterior convexities of the femoral condyles." (Dempster, p. 125, 1955)

Ankle -"Level of a line between the tip of the lateral malleolus of the fibula and a point 5mm distal to the tibial malleolus." (Dempster, p. 125, 1955).

2. Body Segments: Recommended Links and Axis Systems

Head

Link: The straight line between the occipital condyle/C1 interspace center and the center of mass of the head.

Axis System: Formed relative to the Frankfort Plane which is the standard anthropometric measurement position parallel to the transverse (XY) plane. The Frankfort Plane (XY) is established by left infra-orbitale and right and left ear holes. The YZ plane will be perpendicular to the XY plane passing through the left and right ear holes. The XZ-plane will be constructed as a normal to the XY and YZ -planes passing through nasion in the mid-sagittal plane. Thus, the point of origin will be at the mid-point of the biporion axis. The +X-axis will pass anteriorly along the intersection of the XZ- and XY-planes; the +Y axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes. This axis closely approximates the system used in Chandler et al. (1975).

Neck

Link: The straight line between the occipital condyle/C1 and C7/T1 vertebral interspace joint centers.

Axis-System: Formed relative to the mid-sagittal plane (XZ) defined by the occipital condyle/C1 and C7/T1 vertebrae interspace centers and the most anterior chin/neck intersect point. The YZ-plane will be constructed as a perpendicular to the XZ-plane passing through the occipital condyle/C1 and C7/T1 vertebral interspace centers. The XY-plane will be constructed as a normal to the XZ and YZ-planes passing through the most anterior chin/neck intersect point. Thus, the point of origin will be at the intersection of the three planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Torso

Link: The straight line distance from the occipital condyle/C1 interspace joint center to the midpoint of a line passing through the right and left hip joint center.

Axis System: Formed relative to the mid-sagittal (XZ) plane defined by suprasternale and occipital condyle/C1 interspace and the hip joint centers midpoint. The YZ-plane will be formed as a perpendicular to the mid-sagittal plane passing through the occipital condyle/C1 interspace and the hip joint centers midpoint. The XY-plane will be constructed as a normal to the XZ- and YZ-planes passing through suprasternale. Thus, the point of origin will be close to the C7/T1 interspace of the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection passing through the hip knee joint centers of rotation. The XY- plane will be constructed as a normal to the XZ- and YZ-planes passing through the anterior surface point. Thus, the point of origin will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Thorax

Links: <u>Thoraco-sternum</u> - A closed linkage system composed of three links. The right and left transthorax are straight line distances from the C7/T1 interspace to the right and left sternoclavicular joint centers of rotation. The transternum link is a straight line distance between the right and left sternoclavicular joint centers of rotation.
<u>Clavicular</u> - The straight line between the sternoclavicular and the claviscapular joint centers.
<u>Scapular</u> - The straight line between the claviscapular and glenohumeral joint centers.
<u>Thoracic</u> - The straight line between C7/T1 and T12/L1 vertebral body interspace joint centers.

Axis System: Formed relative to the mid-sagittal (XZ) plane defined by suprasternale and center of the vertebral body interspaces of C7/T1 and T12/L1. The YZ-plane will be formed as a perpendicular to the mid-sagittal plane passing through the C7/T1 interspace. The XY-plane will be constructed as a normal to the XZ- and YZ-planes passing through the C7/T1 interspace. Thus, the point of origin will be at the C7/T1 interspace. The +X-axis will pass anteriorly along the intersection of the XY- and YZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Lumbar

Link: The straight line between the T12/L1 and L5/S1 vertebrae interspace joint centers.

Axis System: Formed relative to the mid-sagittal plane (XZ) defined by the T12/L1 and L5/S1 joint centers and umbilicus. The YZ-plane will be formed perpendicular to the XZ-plane passing through the T12/L1 and L5/S1 joint centers. The XY-plane will be formed as a normal to the XZ- and YZ-planes passing through L5/S1. Thus, the point of origin will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Pelvis

Links: The pelvis is treated as a closed-loop linkage system composed of three links. The right and left iliopelvic links are straight lines between the L5/S1 interspace joint center and a hip joint center. The transpelvic link is a straight line between the right and left hip joint centers.

Axis System: A frontal plane (YZ) will be established using symphysion and the right and left anterior superior iliac spines. The XY-plane will be constructed as a perpendicular to the YZ plane passing through the right and left anterior superior iliac spines. The XZ-plane will be constructed as a normal to the XY and YZ-planes passing through symphysion. The point of origin will lie on a line passing through the right and left anterior superior iliac spines approximately at the midpoint of the bispinous diameter. The +X-axis will pass anteriorly along the intersection of the XY- and YZ-planes. The +Y-axis will pass laterally along the intersection of the XY- and YZ-planes and the +Z axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Upper Arm

Link: The straight line between the glenohumeral and elbow joint centers of rotation.

Axis System: A para-sagittal plane (XZ) will be constructed with the arm in the extended anatomical position using the glenohumeral and elbow joint centers of rotation and a point on the anterior surface of the skin overlying the maximum protrusion of the <u>biceps brachii muscle</u> approximately at the middle of the upper arm. The YZ-plane will be established perpendicular to the XZ-plane passing through the glenohumeral and elbow joint centers of rotation. The XY-plane will be constructed as a normal to the XZ- and YZ-planes passing through the anterior surface point. Thus, the origin of the axis system will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Forearm

Link: The straight line between the elbow and wrist joint centers of rotation.

Axis System: A para-sagittal plane (XZ) will be established with the arm in the extended anatomical position using the elbow and wrist joint centers of rotation and a point on the anterior surface of the skin mid-way along the length of the forearm. The YZ-plane will be established as a perpendicular to the XZ-plane passing through the elbow and wrist joint centers. The XY-plane will be constructed as a normal to the XZ- and YZ-planes passing through the anterior surface point. Thus, the origin will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Hand

Link: The straight line between the wrist joint center of rotation and the center of mass of the hand.

Axis System: Formed relative to a para-sagittal plane (XZ) with the arm and hand in the extended anatomical position using the wrist joint center of rotation, the most dorsal point on metacarpal III and the most distal point at the tip of phalanx III. The YZ-plane will be established as a perpendicular to the XZ-plane and will pass through the wrist joint center and the phalanx III distal point. The XY-plane will be formed as a normal to the XZ- and YZ-planes passing through the metacarpale III landmark. Thus, the point of origin of the axis system will lie at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Thigh

Link: The straight line between the hip and knee joint center of rotation.

Axis System: Formed relative to a para-sagittal plane (XZ) with the leg in the extended anatomical position using the hip and knee joint centers of rotation and a point on the anterior surface of the thigh lying approximately at mid-segment. The YZ-plane will be established as a perpendicular to the XZ-plane passing through the knee and hip joint centers of rotation. The XY-plane will be established as a normal to the YZ- and XZ-planes passing through the anterior surface point. Thus, the origin of the axis system will be at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y axis will pass laterally along the intersection of the XZ- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Shank

Link: The straight line between the knee and ankle joint centers of rotation.

Axis System: Formed relative to a para-sagittal plane (XZ) with the leg in the extended anatomical position using the knee and ankle joint centers and a point on the anterior surface approximately at mid-segment. The YZ-plane will be constructed as a perpendicular to the XZ-plane passing through the knee and ankle joint centers of rotation. The XY-plane will be formed as a normal to the XZ- and YZ-planes passing through the anterior surface landmark. Thus, the point of origin of the axis system will lie at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-planes; the +Y-axis will pass along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

Foot

Link: The straight line between the ankle joint center of rotation and the center of mass of the foot.

Axis System: Formed relative to a para-sagittal plane (XZ) with leg in the extended anatomical position using the ankle joint center, the most posterior point on the heel, and most anterior point on the tip of the second toe. The YZ-plane is constructed perpendicular to the XZ-plane passing through the most posterior and anterior points of the foot. The XY-plane is formed as a normal to the XZ- and YZ-planes passing through the ankle joint center. Thus, the point of origin of the axis system lies at the intersection of the three orthogonal planes. The +X-axis will pass anteriorly along the intersection of the XY- and XZ-axis; and the +Y-axis will pass laterally along the intersection of the XY- and YZ-planes; and the +Z-axis will pass superiorly along the intersection of the XZ- and YZ-planes.

APPENDIX B

REGRESSION EQUATIONS

APPENDIX B

REGRESSION EQUATIONS

Tables 2, 3 and 4, regression equations for estimating center of mass, weight and volume of body segments, present a series of two- and three-step equations for predicting individual segment centers of mass, weight and volume from anthropometry. The regression equations are relatively simple to use but are given here in a form which differs somewhat to the customary form

The first entry in Table 2 is for predicting the location of the center of mass of the head and trunk as a distance from the top of the head (vertex). The equation is to be read as:

CM of Head and trunk from vertex = .859 Bicristal breadth + 23.539 ($\pm$1.20)

The two and three-step equations are correspondingly to be read as:

CM of Head and trunk from vertex = .491 Bicristal breadth + .408 Head-trunk length + 1.313 ($\pm$1.01)

CM of Head and trunk from vertex = .621 Bicristal breadth + .582 Head-trunk length - .181 Stature + 14.050 ($\pm$0.75)

As the number of anthropometric variables in the equation increases, the correlation coefficient increases and the standard error of estimate decreases.

For the Head and trunk, the CM is located only as a distance from vertex (Z axis); for the majority of the other segments, the CM is located both in the Z axis and at a distance from the anterior surface of the segment (X axis). The location of the CM in the Y axis was assumed in this study to lie in the medial-lateral center of the segment.

TABLE 1
REGRESSION EQUATIONS FOR ESTIMATING LINK LENGTHS DIRECTLY FROM ANTHROPOMETRIC MEASURES OF BONE LENGTHS FROM DEMPSTER, SHERR AND PRIEST (1964)

Empirical Equation	Standard Error of Estimate	Correlation Coefficient
Ulna Length = 23.7922 + (0.9810 x Radius Length)	4.58	.94
Humerus Length = 64.4829 + (0.9683 x Radius Length)	9.97	.81
Forearm-Link Length = 1.0709 x Radius Length	--	--
Arm-Link Length = 58.0752 + (0.9646 x Radius Length)	8.92	.94
Radius Length = 7.9728 + (0.9002 x Ulna Length)	4.39	.94
Humerus Length = 74.0856 + (0.9688 x Ulna Length)	11.07	.76
Forearm-Link Length = 0.9870 x Ulna Length	--	--
Arm-Link Length = 66.2621 + (0.8665 x Ulna Length)	9.90	.94
Femur Length = 125.6879 + (0.9067 x Tibia Length)	18.39	.73
Fibula Length = 31.3653 + (0.9252 x Tibia Length)	5.28	.97
Shank-Link Length = 1.0776 x Tibia Length	--	--
Thigh-Link Length = 132.8253 + (0.8172 x Tibia Length)	16.57	.73
Femur Length = 101.8815 + (0.9629 x Fibula Length)	11.45	.87
Tibia Length = 8.6266 + (1.0110 x Fibula Length)	5.53	.97
Shank-Link Length = 8.2184 + (1.0904 x Fibula Length)	5.95	.97
Thigh-Link Length = 92.0397 + (0.8699 x Fibula Length)	10.34	.87

TABLE 2
REGRESSION EQUATIONS TO ESTIMATE CENTER OF MASS OF BODY SEGMENTS FROM CLAUSER, ET AL. (1969)[1]

Segment	CM Measured from	Independent Regression Variables			Constant	R	Se_{est}
		Bicristal breadth[2]	Head-torso length	Stature			
Head & trunk	Top of head	.859			+ 23.539	.897	1.20
		.491	+ .402		+ 1.313	.935	1.01
		.621	+ .582	- .181	+ 14.050	.968	.75
		Tibiale height	Calf circumference	Upper thigh circumference			
Total leg	Trochanterion	.518			+ 11.016	.638	1.52
		.534	+ .099		+ 7.235	.650	1.57
		.562	+ .404	- .264	+ 9.061	.721	1.50
		AP at CM[3]	Weight	Iliac crest skinfold			
Total leg	Anterior aspect	.530			+ 1.212	.695	.62
		.795	- .053		+ 1.499	.817	.52
		.935	- .054	- .050	+ 0.408	.894	.43
		B humerus-rad. length[4]	Forearm circumference	Arm circumference (axillary)			
Total arm	Acromion	.966			+ 2.336	.684	1.67
		.947	+ .391		- 7.353	.729	1.64
		.963	+ .918	- .571	- 4.909	.842	1.35
		Head circumference	Height of head				
Head	Top of head	.293			- 5.573	.704	.55
		.246	+ .159		- 6.711	.731	.55
		Head circumference	Head breadth				
Head	Back of head	.158			- 1.039	.468	.55
		.238	- .570		+ 3.376	.541	.55
		Bi-spinous breadth	Iliac crest skinfold	Trunk length			
Trunk	Suprasternale	.578			+ 8.102	.846	.79
		.622	- .066		+ 7.741	.900	.68
		.471	- .058	+ .166	+ 1.683	.926	.61
		Trochanterion height	Knee breadth (bone)	Iliac crest			
Thigh	Trochanterion	.250			- 5.902	.841	.68
		.214	+ .902		- 11.660	.918	.52
		.227	+ .989	- .033	- 13.362	.934	.49
		AP at CM[4]					
Thigh	Anterior aspect	.595			- .956	.838	.69
		Tibiale height	Calf circumference				
Shank & foot	Tibiale	.360			+ 5.226	.789	.68
		.335	- .159		+ 11.267	.871	.57
		AP at CM[4]	Calf length				
Shank & foot	Anterior aspect	.539			- 1.731	.782	.40
		.646	+ .114		- 7.044	.850	.35

[1] All dimensions are given in centimeters except skinfolds which are given in millimeters.

[2] For a precise definition of all dimensions, see Clauser, et al. (1969).

[3] Anterior-posterior

[4] Ball of humerus-radiale length.

TABLE 2 - Concluded

Segment	CM Measured from	Independent Regression Variables			Constant	R	Se_{est}
		Tibiale height	Knee breadth (bone)				
Shank	Tibiale	.276			+ 1.709	.800	.50
		.309	- .558		+ 5.786	.872	.43
		AP at CM [2]	Calf length				
Shank	Anterior aspect	.455			- 0.301	.665	.53
		.503	+ .101		- 4.688	.725	.51
		Foot length	Ankle circumference	Lateral malleolus height			
Foot	Heel	.217			+ 5.729	.566	.33
		.233	+ .135		+ 2.627	.712	.29
		.153	+ .137	+ .444	+ 1.403	.827	.25
		Arch circumference					
Foot	Sole	.325			- 4.639	.672	0.47
		B humerus-rad. length [1]	Arm Circumference (axillary)	Elbow Breadth (bone)			
Upper arm	Acromion	.707			- 4.563	.689	1.21
		.710	- .045		- 3.333	.691	1.26
		.329	- .250	+ 2.827	- 6.168	.918	.72
		AP at CM [2]					
Upper arm	Anterior aspect	.444			+ .665	.874	.23
		Wrist breadth (bone)	Radiale-stylion length	Forearm Circumference			
Forearm & hand	Radiale	2.765			+ .405	.764	.72
		1.962	+ .379		- 4.822	.847	.62
		1.617	+ .585	- .331	+ .510	.929	.46
		AP at CM [2]	Elbow breadth (bone)	Styl.-meta. III length [4]			
Forearm & hand	Anterior aspect	.890			- 2.355	.913	.25
		.900	- .280		- .385	.936	.23
		.890	- .313	- .229	- 2.153	.974	.16
		Radiale-stylion length	Wrist breadth (bone)				
Forearm	Radiale	.537			- 3.808	.788	.53
		.440	+ .761		- 5.645	.821	.51
		AP at CM [2]					
Forearm	Anterior aspect	.790			- 2.295	.843	.35
		Wrist breadth (bone)	Hand circumference				
Hand	Metacarpale III	.358			- .415	.272	.39
		.657	- .202		+ 2.130	.486	.37
		Wrist breadth (bone)	Hand breadth				
Hand	Medial aspect	1.224			- 2.226	.769	.32
		1.038	+ .248		- 3.271	.810	.30

[4] Stylion-Metacarpale III length.

TABLE 3
REGRESSION EQUATIONS FOR ESTIMATING SEGMENT WEIGHTS
FROM CLAUSER, MCCONVILLE AND YOUNG (1969)*

Segment	Independent Regression Variables			Constant	R	$S_{e\ est}$
	Body Weight	Trunk length**	Chest depth	Constant		
Head & trunk	.580			+ .009	.968	1.36
	.521	+ .362		- 17.077	.980	1.11
	.491	+ .504	+ .370	- 31.122	.987	.93
	Body Weight	Calf circumference	Upper thigh circumference			
Total leg	.161			- .000	.919	.62
	.115	+ .221		- 3.792	.954	.50
	.094	+ .146	+ .113	- 5.455	.964	.46
	Body Weight	Wrist circumference	Biceps circumference			
Total arm	.047			+ .132	.883	.23
	.031	+ .186		- 1.894	.929	.19
	.014	+ .182	+ .083	- 3.041	.952	.16
	Head circumference	Weight				
Head	.148			- 3.716	.814	.20
	.104	+ .015		- 2.189	.875	.17
	Body Weight	Trunk length	Chest circumference			
Trunk	.551			- 2.837	.966	1.33
	.494	+ .347		- 19.186	.979	1.11
	.349	+ .423	+ .229	- 35.460	.986	.92
	Body Weight	Upper thigh circumference	Iliac crest skinfold			
Thigh	.120			- 1.123	.893	.54
	.074	+ .138		- 4.641	.933	.45
	.074	+ .123	+ .027	- 4.216	.944	.43
	Calf circumference	Tibiale height	Ankle circumference			
Shank & foot	.165			- 1.279	.934	.16
	.172	+ .051		- 3.824	.971	.11
	.130	+ .058	+ .103	- 4.915	.982	.09
	Calf circumference	Tibiale height	Ankle circumference			
Shank	.135			- 1.318	.933	.14
	.141	+ .042		- 3.421	.971	.09
	.111	+ .047	+ .074	- 4.208	.979	.08
	Body Weight	Ankle circumference	Foot length			
Foot	.009			+ .369	.810	.06
	.005	+ .033		- .030	.882	.05
	.003	+ .048	+ .027	- .869	.907	.04
	Body Weight	Arm circumference (axillary)	Acromion-rad. length			
Upper arm	.030			- .238	.879	.14
	.019	+ .060		- 1.280	.931	.12
	.007	+ .092	+ .050	- 3.101	.961	.09
	Wrist circumference	Forearm circumference	Radiale-stylion length			
Forearm & hand	.168			- 1.295	.874	.10
	.132	+ .049		- 1.987	.919	.09
	.103	+ .046	+ .043	- 2.343	.940	.08
	Wrist circumference	Forearm circumference				
Forearm	.119			- .913	.827	.09
	.081	+ .052		- 1.650	.920	.06
	Wrist circumference	Wrist breadth (bone)	Hand breadth			
Hand	.051			- .418	.863	.03
	.038	+ .080		- .660	.917	.03
	.029	+ .075	+ .031	- .746	.942	.02

*Weight is given in kilograms, skinfolds in millimeters and all other dimensions in centimeters.

**For a precise definition of all dimensions, see Clauser, et al. (1969).

TABLE 4
REGRESSION EQUATIONS TO ESTIMATE SEGMENT VOLUME
FROM CLAUSER, ET AL. (1969)*

Segment	Independent Regression Variables			Constant	R	Se est
	Body Weight	Chest circumference**	Trunk length			
Head & trunk	.563			+ .187	.951	1.65
	.358	+ .353		- 19.331	.970	1.35
	.228	+ .450	+ .448	- 45.797	.988	.90
	Body Weight	Upper thigh circumference				
Total leg	.157			- .345	.924	.58
	.105	+ .157		- 4.370	.955	.47
	Body Weight	Wrist circumference	Biceps circumference			
Total arm	.047			- .106	.907	.20
	.032	+ .165		- 1.850	.945	.16
	.015	+ .161	+ .080	- 2.913	.968	.13
	Head circumference	Weight				
Head	.173			- 5.453	.883	.17
	.139	+ .012		- 4.301	.912	.16
	Body Weight	Waist breadth	Chest circumference			
Trunk	.534			- 2.343	.949	1.59
	.389	+ .476		- 7.392	.968	1.33
	.179	+ .502	+ .347	- 26.817	.988	.86
	Body Weight	Upper thigh circumference	Iliac crest skinfold			
Thigh	.116			- 1.149	.888	.54
	.073	+ .128		- 4.390	.924	.47
	.073	+ .106	+ .039	- 3.760	.950	.40
	Shank circumference	Tibiale height	Ankle circumference			
Shank & foot	.148			- 1.056	.911	.17
	.155	+ .050		- 3.555	.955	.13
	.103	+ .059	+ .127	- 4.910	.975	.10
	Shank circumference	Tibiale height	Ankle circumference			
Shank	.123			- 1.170	.908	.15
	.130	+ .044		- 3.396	.956	.11
	.090	+ .051	+ .097	- 4.427	.973	.09
	Body Weight	Ankle circumference	Foot length			
Foot	.008			+ .360	.810	.05
	.005	+ .029		- .025	.875	.04
	.003	+ .043	+ .025	- .794	.901	.04
	Body Weight	Arm circumference (axillary)	Acromion-rad. length			
Upper arm	.030			- .330	.886	.14
	.018	+ .070		- 1.600	.953	.10
	.008	+ .098	+ .044	- 3.234	.976	.07
	Wrist circumference	Forearm circumference	Radiale-stylion length			
Forearm & hand	.153			- 1.181	.890	.09
	.117	+ .048		- 1.847	.943	.07
	.093	+ .045	+ .035	- 2.278	.960	.06
	Wrist circumference	Forearm circumference				
Forearm	.111			- .875	.842	.08
	.072	+ .053		- 1.622	.954	.05
	Wrist circumference	Wrist breadth (bone)	Hand breadth			
Hand	.048			- .410	.885	.03
	.036	+ .071		- .617	.935	.02
	.028	+ .066	+ .027	- .686	.958	.02

*Weight is given in kilograms, skinfolds in millimeters and all other dimensions in centimeters.

**For a precise definition of all dimensions, see Clauser, et al. (1969).

TABLE 5

REGRESSION EQUATIONS FOR PREDICTING PRINCIPAL MOMENTS OF INERTIA ($Gm\text{-}cm^2$) FROM CHANDLER ET AL. (1975)

	R	Se_{est}
Head		
I_{xx} = 2.129 Body Wgt. + 32030	.72	33217
I_{yy} = 1.676 Body Wgt. + 54818	.64	32598
I_{zz} = 3.186 Body Wgt. + 6846	.75	45033
I_{xx} = 61.333 Seg. Wgt. - 73825	.75	28310
I_{yy} = 50.190 Seg. Wgt. - 36367	.70	27066
I_{zz} = 108.133 Seg. Wgt. - 234457	.94	20880
I_{xx} = 71.289 Seg. Vol. - 99078	.72	33413
I_{yy} = 67.587 Seg. Vol. - 91812	.77	27265
I_{zz} = 133.055 Seg. Vol. - 302860	.93	24479
Torso		
I_{xx} = 296.900 Body Wgt. - 3156034	.96	1379345
I_{yy} = 284.493 Body Wgt. - 7664879	.94	1698612
I_{zz} = 102.507 Body Wgt. - 2895524	.98	335637
I_{xx} = 559.413 Seg. Wgt. - 2823363	.98	1065961
I_{yy} = 538.593 Seg. Wgt. - 7432970	.96	1404515
I_{zz} = 189.523 Seg. Wgt. - 2657654	.98	353958
I_{xx} = 621.812 Seg. Vol. - 8456005	.99	733465
I_{yy} = 601.400 Seg. Vol. -12964208	.97	1100318
I_{zz} = 205.205 Seg. Vol. - 4349563	.94	448759
Upper Arm (Right and Left)		
I_{xx} = 1.315 Body Wgt. + 56859	.65	21982
I_{yy} = 1.006 Body Wgt. + 69616	.67	16355
I_{zz} = .484 Body Wgt. - 9094	.91	3139
I_{xx} = 76.750 Seg. Wgt. - 577	.76	18907
I_{yy} = 51.383 Seg. Wgt. + 39365	.68	16149
I_{zz} = 26.025 Seg. Wgt. - 26122	.98	1644
I_{xx} = 74.063 Seg. Vol. + 4887	.77	18635
I_{yy} = 49.456 Seg. Vol. + 43236	.68	18039
I_{zz} = 24.846 Seg. Vol. - 23785	.98	1646
Forearm (Right and Left)		
I_{xx} = 1.084 Body Wgt. - 4812	.84	9973
I_{yy} = 1.062 Body Wgt. - 3444	.87	8652
I_{zz} = .271 Body Wgt. - 9020	.96	1090
I_{xx} = 63.300 Seg. Wgt. - 3888	.87	9219
I_{yy} = 60.290 Seg. Wgt. - 2628	.87	8647
I_{zz} = 15.760 Seg. Wgt. - 8683	.99	691
I_{xx} = 63.515 Seg. Vol. - 365	.86	9484
I_{yy} = 60.844 Seg. Vol. + 172	.87	8750
I_{zz} = 16.038 Seg. Vol. - 8091	.99	373
Hand (Right and Left)		
I_{xx} = .106 Body Wgt. + 294	.77	1279
I_{yy} = .117 Body Wgt. - 1760	.86	1206
I_{zz} = .056 Body Wgt. - 1703	.72	793
I_{xx} = 21.162 Seg. Wgt. - 977	.92	795
I_{yy} = 21.495 Seg. Wgt. - 2453	.94	668
I_{zz} = 11.414 Seg. Wgt. - 2443	.87	563
I_{xx} = 22.560 Seg. Vol. - 880	.92	798
I_{yy} = 23.091 Seg. Vol. - 2417	.95	632
I_{zz} = 12.216 Seg. Vol. - 2408	.87	558
Thigh (Right and Left)		
I_{xx} = 22.206 Body Wgt. - 302878	.93	131640
I_{yy} = 22.410 Body Wgt. - 270933	.88	176759
I_{zz} = 7.333 Body Wgt. - 259219	.86	63057
I_{xx} = 174.770 Seg. Wgt. - 17732	.96	103026
I_{yy} = 178.913 Seg. Wgt. - 70	.92	145457
I_{zz} = 58.390 Seg. Wgt. - 169540	.90	54426
I_{xx} = 177.458 Seg. Vol. - 14973	.95	104278
I_{yy} = 181.809 Seg. Vol. + 1809	.92	145763
I_{zz} = 59.315 Seg. Vol. - 168797	.90	54587
Shank (Right and Left)		
I_{xx} = 5.934 Body Wgt. + 6359	.83	58521
I_{yy} = 5.345 Body Wgt. + 49951	.84	49951
I_{zz} = .955 Body Wgt. - 33393	.86	8078
I_{xx} = 133.207 Seg. Wgt. + 36264	.80	62315
I_{yy} = 125.929 Seg. Wgt. + 53889	.85	47940
I_{zz} = 22.252 Seg. Wgt. - 30775	.87	7950
I_{xx} = 145.497 Seg. Vol. + 27035	.82	59030
I_{yy} = 136.580 Seg. Vol. + 47599	.87	45097
I_{zz} = 23.493 Seg. Vol. - 30273	.86	8092
Foot (Right and Left)		
I_{xx} = .432 Body Wgt. + 4481	.65	7229
I_{yy} = .359 Body Wgt. + 7328	.72	5081
I_{zz} = .141 Body Wgt. - 1915	.80	1542
I_{xx} = 60.816 Seg. Wgt. - 18255	.94	3202
I_{yy} = 47.772 Seg. Wgt. - 9206	.97	1693
I_{zz} = 15.950 Seg. Wgt. - 6051	.92	990
I_{xx} = 49.804 Seg. Vol. - 7647	.75	6288
I_{yy} = 37.130 Seg. Vol. + 736	.74	4910
I_{zz} = 15.035 Seg. Vol. - 4864	.85	1356

APPENDIX C

CONVERSION TABLE OF MOMENTS OF INERTIA

APPENDIX C

TABLE 1

CONVERSION TABLE OF MOMENTS OF INERTIA

	lb-in^2	lb-ft^2	oz-in^2	Gm-cm^2	kg-cm^2	kg-M^2	oz-in-sec^2	lb-in-sec^2	lb-ft-sec^2	kg-M-sec^2	Gm-M-sec^2	Gm-cm-sec^2
lb-in^2	---	6.947 (10^{-3})	1.600 (10^{1})	2.929 (10^{3})	2.929 (10^{1})	2.929 (10^{-4})	4.145 (10^{-3})	2.591 (10^{-3})	2.159 (10^{-4})	2.993 (10^{-5})	2.993 (10^{-2})	2.993 (10^{1})
lb-ft^2	1.440 (10^{2})	---	2.304 (10^{3})	4.217 (10^{5})	4.217 (10^{2})	4.217 (10^{-2})	5.967 (10^{1})	3.729 (10^{-1})	3.108 (10^{-2})	4.308 (10^{-3})	4.308 (10^{1})	4.308 (10^{2})
oz-in^2	6.248 (10^{-2})	4.341 (10^{-4})	---	1.830 (10^{2})	1.830 (10^{-1})	1.830 (10^{-5})	2.590 (10^{-3})	1.619 (10^{-4})	1.349 (10^{-5})	1.870 (10^{-6})	1.870 (10^{-3})	1.870 (10^{-1})
Gm-cm^2	3.414 (10^{-4})	2.371 (10^{-6})	5.463 (10^{-3})	---	10^{-3}	10^{-7}	1.415 (10^{-5})	8.844 (10^{-7})	7.370 (10^{-8})	1.022 (10^{-8})	1.022 (10^{-5})	1.022 (10^{-3})
kg-cm^2	3.414 (10^{-1})	2.371 (10^{-3})	5.463 (10^{1})	10^{3}	---	10^{-4}	1.415 (10^{-2})	8.844 (10^{-4})	7.370 (10^{-5})	1.022 (10^{-5})	1.022 (10^{-2})	1.022 (10^{1})
kg-M^2	3.414 (10)	2.371 (10^{1})	5.463 (10^{4})	10^{7}	10^{4}	---	1.415 (10^{2})	8.844 (10^{1})	7.370 (10^{-1})	1.022 (10^{-1})	1.022 (10^{2})	1.022 (10^{4})
oz-in-sec^2	2.413 (10^{1})	1.676 (10^{-1})	3.861 (10^{2})	7.067 (10^{4})	7.067 (10^{1})	7.067 (10^{-3})	---	6.250 (10^{-2})	5.208 (10^{-3})	7.220 (10^{-4})	7.220 (10^{-1})	7.220 (10^{1})
lb-in-sec^2	3.860 (10^{2})	2.681 (10^{1})	6.178 (10^{3})	1.131 (10^{6})	1.131 (10^{3})	1.131 (10^{-1})	1.600 (10^{1})	---	8.333 (10^{-2})	1.155 (10^{-2})	1.155 (10^{1})	1.155 (10^{3})
lb-ft-sec^2	4.632 (10^{3})	3.218 (10^{1})	7.413 (10^{4})	1.357 (10^{7})	1.357 (10^{4})	1.357 (10^{1})	1.920 (10^{2})	1.200 (10^{1})	---	1.386 (10^{-1})	1.386 (10^{2})	1.386 (10^{4})
kg-M-sec^2	3.341 (10^{4})	2.321 (10^{2})	5.347 (10^{5})	9.788 (10^{7})	9.788 (10^{4})	9.788 (10^{1})	1.385 (10^{3})	8.656 (10^{1})	7.214 (10^{1})	---	10^{3}	10^{5}
Gm-M-sec^2	3.341 (10^{1})	2.321 (10^{-1})	5.347 (10^{2})	9.788 (10^{4})	9.788 (10^{1})	9.788 (10^{-3})	1.385 (10^{1})	8.656 (10^{-2})	7.214 (10^{-3})	10^{-3}	---	10^{-5}
Gm-cm-sec^2	3.341 (10^{-1})	2.321 (10^{-3})	5.347 (10^{1})	9.788 (10^{2})	9.788 (10^{-1})	9.788 (10^{-5})	1.385 (10^{-2})	8.656 (10^{-4})	7.214 (10^{-5})	10^{-5}	10^{-2}	---

CHAPTER V
ARM-LEG REACH AND WORKSPACE LAYOUT

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This chapter presents information on functional reach measurements relevant to the design and layout of workspaces in the Space Shuttle and Spacelab programs. Most of the existing data described in the following review have been taken under standard gravity conditions on the earth's surface, with specific workspace constraints, i.e., subject usually in a seated position, with fixed backrest and seat surface angles, and lap and upper torso restraint systems that may severely limit the amount of body movement. The measurements were also made on populations anthropometrically selected to be representative of the appropriate user group. In short, the intent was always to gain reach data that would be applicable under a given set of design conditions for one group of people with specifically defined reaches. As a result, functional reach data that are immediately and directly applicable to space vehicles in a zero-g environment, for all practical purposes, do not presently exist.

In the present NASA project we are concerned with potentially very different sorts of workspace conditions, i.e., standing, or "free-floating" in the neutral body position in a state of weightlessness, where there may normally be no restraints on body position or movement. In order to stabilize body position in a zero-g environment, some form of mechanical restraint such as handholds, waist belts, or fixed shoes, must be utilized. Even with restraints, however, there will probably be considerably more body movement possible than that encountered in any one-g reach study to date and greater freedom of body movement implies greater reach distances.

In addition, the potential Space Shuttle-Spacelab population differs anthropometrically from those groups on which functional reach data are currently available. We are no longer dealing with a precisely defined "U.S. Air Force" population, or even with "U.S. drivers," but rather with a potentially worldwide population that varies markedly in body size and reach, from perhaps 5th percentile Oriental females to 95th percentile U.S. or Northwestern European males. In addition, since the space vehicles presently envisioned may be operational through the period 1980-1990, and since secular changes in body size are known to be taking place in many populations, it will be necessary to take into account possible increases in functional reaches during that time period.

In this chapter each of the above variables will be discussed as necessary, and the most appropriate basic reach data will be presented along with recommendations for applying correction factors to adjust for differences in (1) workspace, task, and body position; (2) environmental conditions-primarily g forces; and (3) anthropometric characteristics of various populations.

Review of Existing Data on Functional Reach Measurements

Static Reach Measurements

Traditional measurements of anatomic arm length, such as shoulder-elbow or elbow-fingertip lengths, or of anatomic leg length such as buttock-knee length, have long been included in the battery of dimensions taken in many anthropometric surveys. Such "static" measurements, however, have generally been of relatively little use to those concerned with how far a person can reach and perform some specified task.

In attempting to deal with this problem, some anthropometric surveys have included limited kinds of arm reach measurements, usually two or three dimensions on the outstretched arm. Hertzberg et al. (1954), for example, includes such measurements as "arm reach from wall," a wall-to-fingertip dimension taken with both shoulders against a vertical surface and the arm extended horizontally. Similar reach measurements have also been included in more recent anthropometric surveys (Clauser et al. 1972; White and Churchill, 1971) but ultimately they are of limited utility in equipment or workspace design since they describe a specific reach to a single point immediately in front of, or directly above, the subject. These dimensions tell us nothing of what other reaches might be to almost innumerable other points surrounding the subject, though crude extrapolations can be made in some cases. Nor can static reach measurements accurately describe the effects of body movement. For this purpose, different kinds of reach measurements, specifically "functional" reach measurements, are required.

Functional Reach Measurements

All measurements of functional reach are more difficult to obtain and to present in a meaningful way than are static measurements. The more important factors contributing to this problem are: a) variations in body position including, if seated, seat height above the floor and angulation of seat surface and of backrest; b) the presence or absence of restraint systems for the body; c) anatomical locations of such restraint systems; d) the kind of reach to be made, or the task to be performed; and e) finally and most importantly in the present case, the presence or absence of g forces.

One of the earliest attempts to deal systematically with the measurement of functional arm reach was that of King, Morrow and Vollmer (1947) who measured 139 naval personnel to determine the boundaries of the maximum area for the operation of manual controls. In this study the subjects were seated in a standard pilot's seat with a locked lap belt and shoulder harness and kept their backs against the backrest cushion. A later publication extrapolated the values of these reaches that would be possible with 18 inches of forward shoulder movement permitted (King, 1948). A similar approach was utilized by Emanuel and Dempsey (1955) in an Air Force study of the effects on arm reach of a partial pressure flying suit. Ely, Thomson and Orlansky (1963) developed graphic presentations of functional arm reach which have some utility as very rough guides or indicators of reach, but are lacking specificity and are difficult to apply, especially since the means of determining the data were not specified, nor were the physical characteristics of the population on which they were measured.

Dempster and his associates (Dempster, 1955; Dempster, Gabel and Felts, 1959) have presented an excellent theoretical and methodological approach to the problem of functional reaches and "kinetospheres", but they were not primarily concerned with obtaining reach data on specific populations for specific applications. The data again are of limited practical utility. A somewhat different device and technique for obtaining arm reaches was described by Wright (1964), but also without applicable data.

These earlier data have been largely superseded by the work of Kennedy (1964), who determined the outer boundaries of grasping-reach envelopes for a shirt-sleeved operator by making measurements at a total of 24 vertical planes intersecting with 12 horizontal planes, resulting in 288 measurements for each of 20 subjects.

Stoudt et al. (1970) obtained functional arm reach measurements on 100 subjects, 50 males and 50 females, selected to approximate the general U.S. adult driving population in height and weight. The purpose was to provide data to assist in establishing the outer limits for the location of controls in motor vehicles. One hundred and twenty arm reach points were defined for each subject.

Other studies on functional arm reaches relative to U.S. automotive design, have been conducted for the industry by Woodson et al. (1971), and within the industry by, among others, Chaffee and associates (1968), and by Hammond and Roe (1972) for the Society of Automotive Engineers. In the European automotive industry, arm reach studies have been conducted by, for example, Rebiffe et al. (1969).

The discussion so far has related only to arm reaches. Leg reaches may also be important in workspace layout and design, though perhaps somewhat less so in a space environment. Data on functional leg reaches are unfortunately even more imperfectly known than are arm reach data. Thorough rigorous studies comparable to those made on arm reaches are non-existent. Leg reach has been investigated primarily from the point of view of range of motion at the joints of the leg, and of leg strength exertable at different leg positions and angles, rather than from a concern about spatial limits for operation of foot controls. The single exception is some new, limited, information, as yet unpublished, by Laubach and Alexander (n.d.). Perhaps the single best effort relative to layout of foot controls is that of Ely et al. (1963). However, the lack of specificity of the anthropometric data upon which it was based, and the rather tentative nature of the somewhat overly generalized recommendations, make the study difficult to use except as a very rough guideline.

The major difficulty with all functional reach studies described above, is that they have been conducted under very specific workspace conditions, usually seated with a given restraint system, always in a one-g environment, and on specially defined populations in terms of physical and anthropometric characteristics. In attempting to utilize these data under other conditions such as weightlessness, or for other populations, serious problems of extrapolation arise.

With regard to functional reach studies designed to determine capabilities in a space environment, both the General Electric Space Division (1969), and the Martin Marietta Corporation (Lenda, Rosener, and Stephenson, 1972) have carried out experiments under water, with neutral buoyancy conditions simulating a state of weightlessness. These data have been summarized in Man/System Design Criteria for Manned Orbiting Payload, Section 5.Anthropometry/Crew Capability (National Aeronautics and Space Administration, 1974).

These studies are quite useful in that they indicate for the first time, in a definitive way, how functional reaches differ in a neutral buoyancy environment simulating zero-g conditions. Unfortunately, because of the small numbers of subjects involved and their lack of representativeness of the anthropometric range of the future spacelab populations, the data are of very limited direct applicability in determining functional reach areas and workspace layouts. As the NASA report states, these data "...should be used only as guideline information. The design of a crew station shall assure that all tasks required at the station are located so that all of the user population can perform the task. This means that all tasks must be located well within the reach envelopes shown...so that the tasks can be performed by a 5th percentile woman". (National Aeronautics and Space Administration, 1974). Unfortunately, the phrase "located well within" is so general as to be of little utility in establishing any specific guidelines for the maximum permissible reach distances in the layout of workspaces.

The best, though far from fully satisfactory, solution to this dilemma, is to select those reach studies made under one-g conditions that appear to be most useful for NASA purposes, and to present those data (with all their limitations) with accompanying extrapolation factors for different environmental conditions, specifically utilizing and integrating those data and information available on zero-g, or simulated zero-g, reaches. Selected arm reach data and instructions for extrapolation appear in the last two sections of this chapter.

Comparability of Data from Reach Studies

Each functional arm reach study has utilized a different population for its subjects. The earliest, and some of the most rigorous studies, were made on military pilots, (e.g., King et al., 1947; Kennedy, 1964) and hence represent the arm reaches of a rather highly selected, exclusively male, fairly young, anthropometrically relatively large, and healthy, United States population. More recently, comparable data have become available on a United States female population (Kennedy, 1976).

Later studies have dealt with the United States general civilian driving population and, as such, included both males and females over a fairly wide age range (Stoudt et al., 1970; Chaffee, 1968; Hammond and Roe, 1972).

Functional arm reach studies on non-United States populations are considerably more limited. One of the few available was done by Bullock (1974) on Australian pilots, both male and female. Subjects were selected on the basis of height and weight to be anthropometrically representative of the parent population. Comparable kinds of functional arm reach data on non-European/American populations are not generally available.

Where data are not available, extrapolation from the measured to the unmeasured (for functional reach) groups becomes necessary. Fortunately, functional arm reaches are closely related to overall body size. Fairly good indications of the reach of different ethnic or national populations can therefore be achieved by selecting certain percentiles of United States data to be the equivalent of different percentiles of other populations. For example, the 5th percentile reach on a United States population may be the equivalent of the 10th or 20th percentile reach on another, anthropometrically smaller, national or ethnic population. While this does present some problems and potential pitfalls in the interpolation process, they are relatively small as compared to the difficulties inherent in extrapolating from one set of workspace measuring conditions to another.

A second source of variance between studies is difference in measuring techniques. Functional reach data have been obtained by a variety of means and through use of different basic reference points from which the reach measurements are indexed. Regardless of which basic reference points, measuring systems, or techniques of recording the dimensions are used, the data are employed to serve a common purpose, namely to define the outer boundaries of a workspace to which the subjects can reach, given the specific conditions under which the measurements were taken. The problem is not primarily one of lack of comparability of measuring systems or techniques; if the measurements are taken properly, regardless of which system is used for a given set of conditions, the results should be generally comparable. The major source of difficulty arises when the conditions under which the measurements are taken, vary. The most important of these conditions is probably body position, i.e., standing or seated; if seated, backrest angle, type of restraint system, etc. The major challenge is to find the best way of extrapolating, or converting, functional arm reach measurements taken under one set of conditions, to measurements that will, as accurately as possible, describe the functional reaches under a different set of physical workspace conditions.

Data Presentation

Percentiles are the single most effective way of presenting anthropometric data, including functional reaches, for purposes of workspace design and layout--provided they are properly understood and utilized.

Obviously, the 50th percentile (which usually approximates the average), in functional reach, means that one half of the subjects in a given population have reaches shorter than that value, and one half have longer reaches. In similar manner, the value of the 95th percentile reach is usually that of a fairly large, or long-armed person; only 5% of all the people in that population have longer arm reaches. However, what is generally more important for establishing workspace layouts and central locations are the values of the lower percentiles, i.e., the people in the population with the shortest reaches. For example, 5th percentile reaches are sometimes given as the values for establishing the lower limits of reach; 95% of the population can reach beyond the 5th percentile; only 5% of all the people in that population have shorter arm reaches.

The practical problem here is that if it concerns the locations of a presumably important item, then it may be totally unacceptable for fully 5% (or one out of 20) of the population to be unable to attain that reach. This might well be true in a spacecraft. From this point of view, the 1st percentile value of reach would be better--only 1 percent could not reach this far. Ideally, if everyone must be able to achieve a given reach, then the smallest reach in the entire population must be used--this would necessitate the use of the minimum, or single smallest reach value. In practice, this may not be always necessary, since most reach values usually contain a built in "safety factor." That is, under normal conditions, a 5th percentile reach might be achievable by someone of the 4th, 3rd, 2nd or perhaps even 1st percentiles of "normal" reaches with extra effort or body repositioning. Similarly a 1st percentile reach might well be attained by all of the smaller percent of the population if there were no really aberrantly small members of the group as presumably there would not be in a spacecraft population.

Workspace Design as Based on Functional Reach Measurements

As noted above, a prime requirement in the layout of any workspace is that all controls or tasks that are in any way related to manual or pedal operation, be located so that they can be reached and operated or performed satisfactorily by all members of that workspace population. To achieve this, measurements are needed that define just how far given percentages of that population can reach under the conditions anticipated for that workspace. This can be most effectively accomplished by selecting a representative (both anthropometrically, and for other variables related to reach) sample, determining their functional arm reaches, and defining an overall, three-dimensional "reach envelope" that specifies both the maximum permissible outer limits, and sometimes optimum location, for the placement of all relevant items or tasks within the workspace.

This ideal procedure has not always been carried out in practice. Sometimes interpolations and extrapolations must be made from existing data, and sometimes reach locations and outer limits must be established on the basis of "guestimate", perhaps supported by brief trials involving only a few subjects. This may be relatively easy to do and can be an acceptable procedure where the reach locations in the area surrounding the operator are limited in number and complexity, and can be checked rather easily for adequacy. However, potential difficulties may arise where a number of controls or tasks must be located within a given area, and all clearly cannot be placed in the area immediately surrounding the operator where they can be easily reached. When some items must be located in less appropriate areas on the outer periphery of the workspace, it becomes essential to know exactly where the outer boundaries are for the accommodation of all persons in the population.

A considerable amount of information relative to the layout of workspaces in terms of functional reach is available, though of variable quality, and variable relevancy to the present concerns of zero-g conditions in Space Shuttle-Spacelab. It should be noted that these are not only studies of functional reach per se (i.e., King et al., 1947; Kennedy, 1964; Stoudt et al., 1970) but also are studies that make recommendations for workspace layout and design dimensions to accommodate the functional anthropometric capabilities, whether known or assumed, of the intended occupants or operators.

General guidelines for the layout to workspaces can be found in the first edition of the Human Engineering Guide to Equipment Design (Ely, Thomson, and Orlansky, 1963; Damon, Stoudt, and McFarland, 1963), as well as in Damon, Stoudt, and McFarland (1966), Van Cott and Kinkade (1972), McCormick (1970), and Roebuck, Kroemer and Thomson (1975). Though these studies (with the exception of the latter) do not present specific design recommendations directly applicable to the zero-g condition--nor was this their intent--they are all useful in terms of background, methodology, and approach.

The first aerospace study dealing with anthropometric data and aircraft design was carried out during World War II by Randall et al. (1946). The study included, in addition to body dimensions of Army Air Force pilots, certain aspects of cockpit design and spatial accommodation in fighter and bomber aircraft. Arm reach measurements were limited, as were related design specifications. More recently, design specifications for military aircraft relative to control location can be found in the human engineering section of a U.S. Air Force Systems Command Manual (1972). The reach-related dimensions treated here concern spatial location and travel of throttle handles, and foot pedal location and adjustments, all relative to a neutral seat reference point.

A more detailed study for control location based on arm reach is that of Garrett, Alexander and Matthews (1970) which defined reach envelopes for the outer boundaries of controls in a series of positions with different conditions of clothing and equipment, and body restraints. For each position and condition, a design dimension was specified as follows, e.g.,: "to manipulate with the right hand a rotary knob located 60° to the right of center and 18" above the deck the knob must be placed no further than 30" from the Seat Reference Point". All such data were taken in the seated position, under one g, and with a degree of specificity regarding workspace conditions that makes extrapolation to the zero-g, Space Shuttle environment extremely difficult.

In spacecraft, on the basis of astronaut zero-g Skylab experience, some specific dimensions relative to workspace layout and dimensions have been made. These concern the optimum work surface height and change in eye position, both relative to foot restraint position, and, most importantly, changes in functional reach.

Certain general design features of the Space Shuttle and Spacelab relative to functional reach considerations appear to be fairly well established. For example, the Space Shuttle is designed to carry a crew of seven, including pilot, co-pilot, mission specialist, and other scientific or technical personnel. The primary flight stations are organized in the usual pilot-co-pilot relationship, with other personnel to the rear. The g forces involved here in launch and re-entry will require traditional seated positions, probably with lap and torso restraints, a factor which must be considered in control layouts for these locations.

The Space Shuttle will also provide accommodations for all crew members including food, waste management, sleeping and personal hygiene. For these functions zero-g conditions will apply, as they will for all Spacelab operations. Preliminary indications are that the basic Spacelab design will be similar to that shown in Figure 1. Some form of foot restraint will be used in Spacelab for body stabilization, which will considerably increase the potential range of different body positions from which arm reaches can be made, as suggested in Figure 2.

These features and other factors affecting functional reach capability are outlined and described below.

Biological Factors Affecting Functional Reaches

A wide variety of different factors influence the distances that people can reach. Many of these are related to the innate characteristics of the individual, such as age, sex, race, health status, physical condition, etc. These biological variables are, for the most part, either unalterable or relatively difficult to alter. Selection of individuals in terms of the specific biological characteristics related to given kinds of functional reach is, generally speaking, the only way in which such variables can be "controlled". The effects of the more important biological variables

TOP: Core module cross section showing workbench and console station.
BOTTOM: Typical internal rack arrangement.

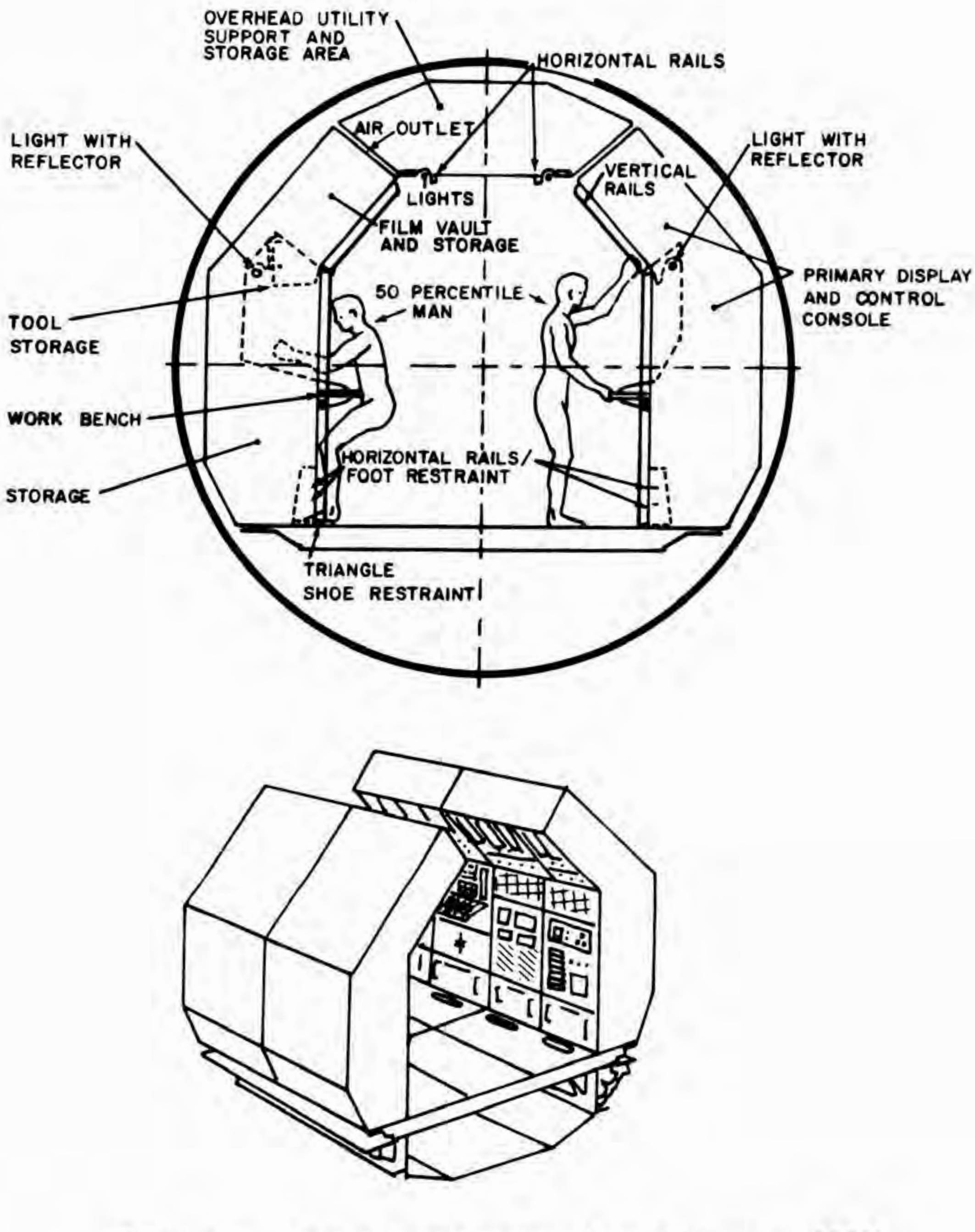


Figure 1. Spacelab workspaces (from Thompson, 1975).

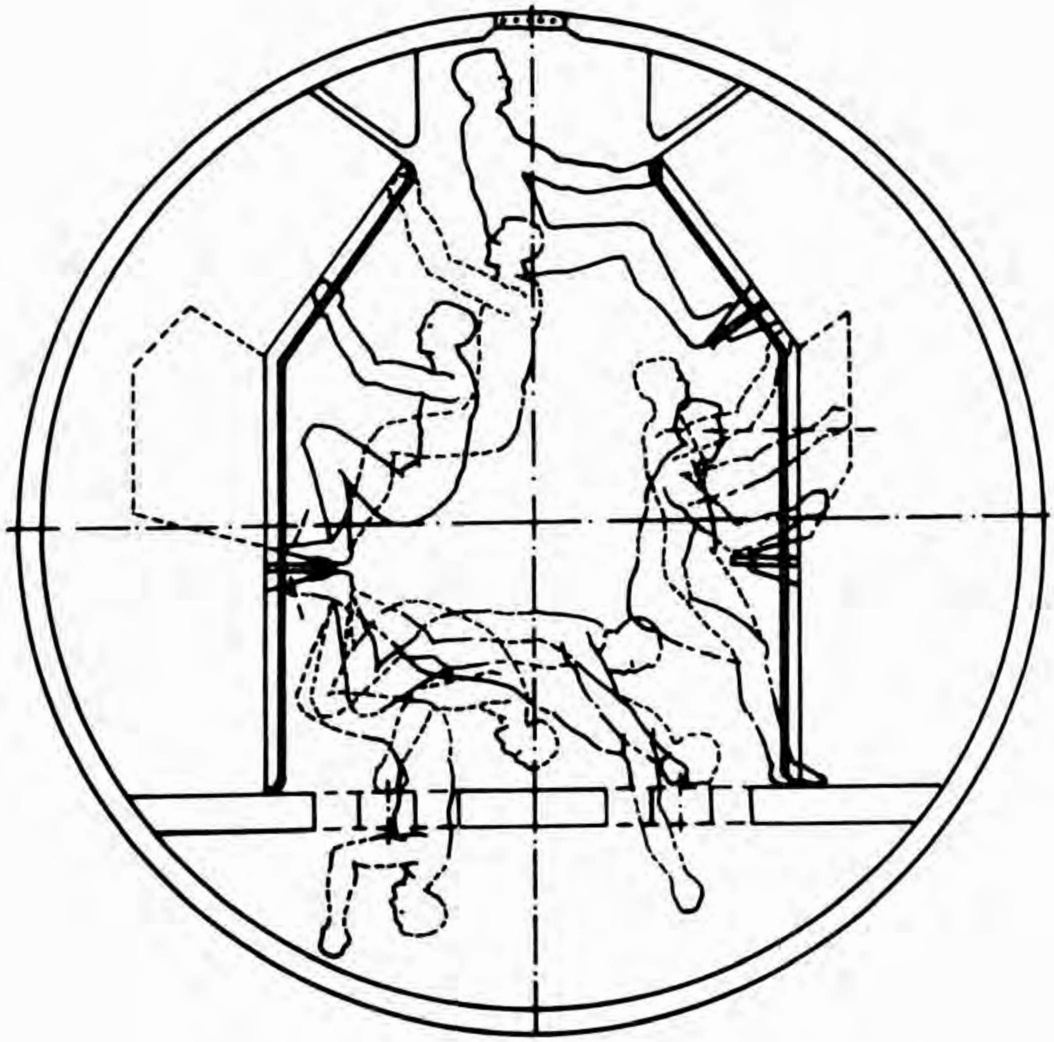


Figure 2. Portable foot restraint positions (from Thompson, 1975).

related to functional reach in the projected Space Shuttle-Spacelab environment are summarized below. A discussion of environmental variables follows in the next section.

Age

Functional reach is closely related to overall body size. For all practical purposes, full growth and maximum body size (except for weight-related dimensions) are achieved by about age 20 in males and about 17 in females. Since the Spacelab population will be all adult, this aspect of the aging process should not be a factor in the functional reaches of this group, although there may be slightly reduced body sizes in middle-aged and older groups, and, in addition, some reduction in functional reaches may occur because of certain degenerative or arthritic type conditions which are more prevalent with increasing age.

Sex

Differences in overall body size, and therefore in functional reach, are both marked and significant between the sexes. For example, men, on the average, are roughly five and a half inches (14 cm.) taller than women, and about 30 pounds (13.6 kg.) heavier. In static forward arm reach, perhaps more accurately described as arm length, women's average values are three inches (7.6 cm.) less than those for men.

Such sex differences also apply to functional reaches, and it is therefore necessary to take the sex distribution of a group into account in designing and laying out workspaces. Any workspace designed around, and adequate for, a given male population may well be inadequate for some percentage, perhaps substantial, of a female population.

Race-Ethnicity

There is a fairly wide range in overall body size, and therefore in associated reach dimensions, among the various races, ethnic and national groups of the world. U.S. and Northwest European populations tend to have the largest body sizes, with Southern and Southeastern Europeans somewhat smaller, and Orientals or Asiastics generally, though not always, smaller still. (See Chapter II, Human Body Size Variability, for detailed comparative data.)

Secular changes in body size, i.e., an evolutionary trend towards larger body size over time may account for relatively small differences between these groups, since they were measured at different times over the past 20 years. However, by far the larger part of the differences is due to the innate biological variability in body size between racial, national, ethnic, and socio-economic, groups. For present purposes, the extremes of such variability in body size, and therefore in functional arm reach, to be considered are U.S. (male) populations at the upper, or larger, end, and Asiatics (female) at the lower, or smaller, end.

Health-Physical Condition

Since it is reasonable to assume that all persons involved in the Space Shuttle-Spacelab program will be considerably above average in health status and that they will also be at least average or above, for their age, in physical condition, the changes in static and functional body dimensions that could result from these variables should not be relevant here.

Secular Trends

There appears to be a tendency towards an evolutionary increase in body size over time. People have been "getting taller". Projections from the Aerospace Medical Research Laboratory (n.d) show, for example, that a U.S. Air Force male population comparable to the 1967 measured population would be expected to be 0.65 inches taller in 1980. Detailed data on secular growth trends to date and indications that such "growth" may have slowed down for at least one population, can be found in Chapter II.

Environmental Factors Affecting Functional Reaches

The other, and equally important, class of variables related to functional reaches are those of an environmental nature. These are usually concerned with the physical characteristics and constraints of the workspace itself, or with the type of task that is to be carried out within that workspace. Present examples of the former are the effects of a zero-g environment, workspace layout and design including body restraints, body position in the workspace, and clothing and equipment. While the effects of weightlessness cannot be changed, most other characteristics of the environment, workspace and task lend themselves to at least some modification.

Gravity

All definitive studies of both static anthropometry and functional reach have been made on the earth's surface under conditions of standard gravity. However, a zero-g environment will affect both static anthropometry and, to a considerably greater extent, functional reach measurements. As has been noted in previous chapters, for static dimensions intervertebral spinal pressures will decrease, resulting in an apparent increase in erect and seated body heights. Such changes, plus a concomitant body fluid redistribution will tend to shift the center of mass of the whole body headward. Since the pull of gravity on the arms will be eliminated, the shoulders will tend to move upward, and the elbows upward and akimbo (Roebuck et al. 1975).

Functional reach dimensions will increase even more markedly under such conditions. This will result in an increase in usable working space and increased reach areas--if the operator is either unrestrained, or only partially restrained, in regard to body movement (Parker and West, 1973). The basic question is, how much will functional reaches increase in a state of weightlessness? A precise answer is difficult because of the many variables affecting functional reach under these conditions, including not only body restraints, but working position, clothing and equipment worn, and type of task to be performed. These factors are discussed below.

Information on zero-g reaches, or on conditions affecting these reaches have been obtained by: (1) observations of films of astronauts' experiences in zero g, (2) astronauts' reports of their own zero-g experiences, and (3) by measurements of simulated zero-g reaches. The latter studies have been made with very small numbers of subjects (five or less) and the results therefore cannot give a clear picture of the range of reaches attainable by any specific, anthropometrically defined, population. However, both sorts of data do give some clear indications of the kinds of differences in functional reach that can be expected under zero g. For example, "downward" reaches are more difficult; there is no gravity assist. Similarly, "upward" reaches will seem easier. Reaches to the rear of the body, with the body anchored at the feet by a shoe restraint, exceeds reach to the front. In a zero-g environment, ankle extension, knee flexion and vertebral extension are more effective, in terms of maximum reach, than the opposite joint movements in the forward direction (General Electric Space Division, 1969). Again, a major factor in zero-g reaches is the fact that it is totally unnecessary, or even desirable, to "sit" at a work location.

Finally, it should be remembered that, while zero-g conditions may be the constant mode for Spacelab operations, for the Space Shuttle there will be forces up to 3-g during launch, and up to 1.5-g during a typical re-entry (National Aeronautics and Space Administration, 1975 b). Consequently, any controls or workspace items that must be reached and operated during these times cannot be positioned on the basis of the greater reach capabilities possible under zero g.

Working Positions

The normal working position of the body in a zero-g environment differs substantially from that in a one-g environment. The seated position is for all practical purposes eliminated, since the sitting posture is not a natural one under these conditions (Johnson, 1975). Seats, with lap belts or other restraints to anchor the occupants are both unnecessary, uncomfortable, and undesirable.

The "standing" position of the body in a state of weightlessness has been found to gradually change from initial erectness, with a straightened spine, to a forwardly bent, semi-erect position. This has been called the neutral body position of weightlessness, and has been defined as that position which the body tends to naturally assume when completely relaxed and acted upon by no external forces. It is a semi-crouched, neither sitting nor standing posture as shown in Chapter IV, Figure 8. It will also be noted that the normal one-g line of sight is depressed about 10° below the horizontal. Under zero-g conditions, because of the natural tendency of the head and neck to incline downward, there is an additional depression of the line of sight, of about 15° (Jackson, Bond, and Gundersen, 1975).

The neutral body position then, is the basic posture that should be used in establishing workspace layout and design. Unfortunately, no adequate body of functional reach measurements exists which have been measured from the neutral body position. Extrapolation from one-g studies, usually in the seated, restrainted position, will be necessary.

Body Restraints

While the absence of g forces will usually facilitate rather than restrict body movement, orientation, or positioning, this same lack of gravitational stabilization will leave the individual without any contrathrust platform. Thus some sort of artificial body restraint system will be necessary to provide an energy sink, or device or place for disposing of energy (General Electric Space Division, 1969).

To accomplish this, three basic types of body restraint or stabilizing devices have been tested either under neutral buoyancy conditions on earth, and/or actual zero-g conditions in space. These are handhold, waist, and foot restraints (See Figure 3). In the former, the individual is stabilized by holding on to a handgrip with one hand and performing the reach or task with the other. This restraint affords a fairly wide range of functional reaches, but body control is difficult, and body stability is poor. In addition, the use of the handhold restraint has been found to be quite fatiguing. For this reason, it is not recommended for any work station that is to be used for any extended period of time.

A waist restraint (for example a belt around the waist in either the seated, erect, or neutral body position) affords good body control and stabilization, but seriously limits the range of motion and reach distances attainable. It could therefore be used for workspaces in which only fairly restricted arm reaches are necessary, but would not be appropriate where longer reaches or frequent body movement, or repositioning, is required.

The third basic system restrains the individual by the feet, either through "Dutch Shoes", a toe-rail, a cleated shoe which interlocks with a "floor" grid, or by suction cups attached to the sole and heel. Shoe restraints, generally, have been found to be definitely superior with regard to range of motion, body control, and lack of fatigue. In neutral buoyancy tests, the shoe restraints were judged to be excellent in "performance,

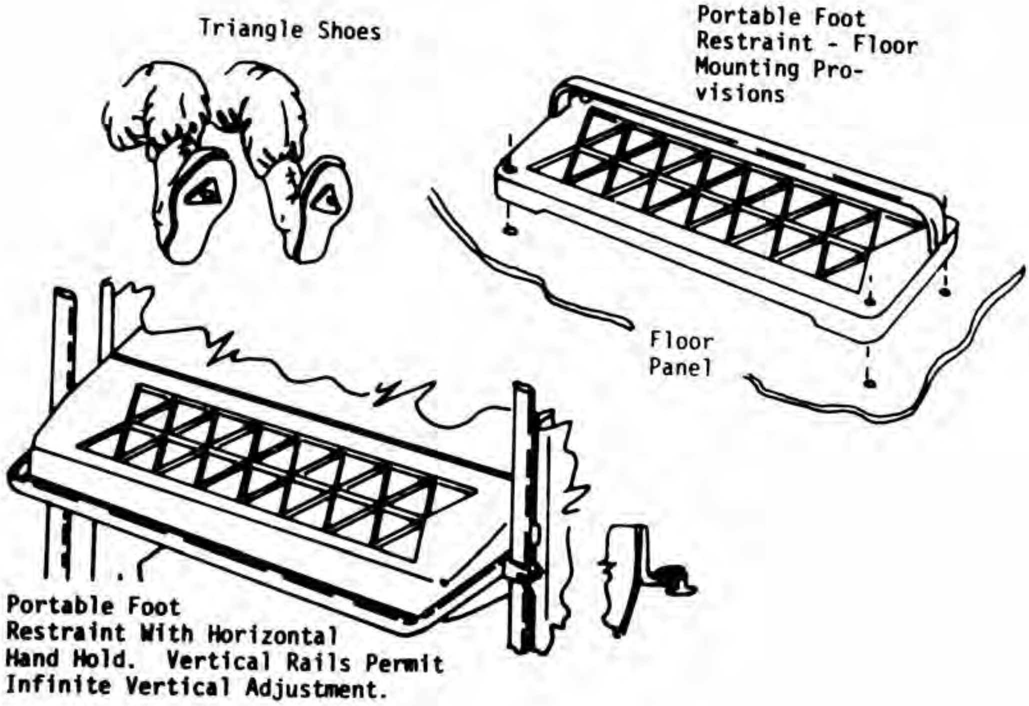


Figure 3. Foot restraint system (from Thompson, 1975).

stability, and deliberateness...as evidenced by the subjects' ability to draw continuous and steady curves". (General Electric Space Division, 1969).

Clothing and Personal Equipment

Clothing and personal equipment worn on the body can influence functional reach measurements. The effect is most commonly a decrease in reach which can sometimes be considerable if the clothing or equipment is especially bulky or cumbersome. Most data on functional reaches have been gathered under so-called "shirt-sleeve" conditions, (light indoor clothing) which do not appreciably affect the measurements. Exceptions are a study by Garrett et al. (1970) who presented data on the functional reach capabilities of military aircrew wearing light weight coveralls (longest reaches), and full pressure suits, both uninflated, and inflated (shortest reaches). In addition, Laubach and Alexander (1975) measured functional reaches on a group of Air Force pilots, first shirt-sleeved with inertia reel unlocked, and then wearing complete winter flying assembly with inertia reel locked. Differences were substantial. Under the very worst conditions for example, it was found that 5th percentile reaches with flying clothing and inertia reel may only be about 60% of shirt-sleeve reaches. More commonly the difference ranges between 70% and 90%, clearly a very significant and practical difference.

If space suits were required during any phase of the Space Shuttle-Spacelab intravehicular operations, this would probably necessitate a substantial reduction in any design reach dimensions established for shirt-sleeve operations. The extent of these differences would have to be determined from "with-and-without" studies using the specific space suits and gear to be employed in that mission. For example, in the underwater, neutral buoyancy tests of functional reach (General Electric Space Division, 1969), measurements were made with the NASA Gemini Spacesuit, but the experimenters noted that direct "interpolation of the values for pressure-suit access volumes is inappropriate unless suits with the same dynamic characteristics are utilized."

For extravehicular activity, the problem of functional reach dimensions would presumably be of relatively little consequence because of body mobility. And, since normal intravehicular activity and operations for both Space Shuttle and Spacelab are planned for pressurized non space-suited conditions (Anonymous, 1975), it should be possible to utilize shirt-sleeved functional reach dimensions for design purposes in these vehicles. There are, it is true, some differences between clothing worn in aerospacecraft in zero g and one g. Zero-g clothing has more and larger pockets--to temporarily store and carry small articles. This should not affect functional arm reach to any appreciable extent. Special restraint shoes, oxygen pack and mask, and communications equipment might be worn (National Aeronautics and Space Administration, 1974), but again, these should not substantially affect functional arm reach (though the suction cup shoe restraint would likely add one to two inches to stature). Special areas requiring the use of space suits, or emergency conditions may, of course, necessitate other provisions.

Task to Be Performed

The length of a functional arm reach is clearly dependent upon the kind of task or operation to be performed by that reach. For example, tasks requiring only finger-tip pressure on a push button could be located at or near the outer limits of arm reach as defined by the finger tip. This would be, essentially, absolute maximum attainable functional reach. However, another task may require rotation of a control knob between thumb and forefinger; this would result in a reduction of the above maximum attainable functional reach of about 2.5 inches (6.4 cm.). Full hand grasp of a control level would reduce maximum reach even more, perhaps by 5 inches (12.7 cm.). Where two-handed operation, or greater precision, or continuous operation, are required, the task must be located still closer to the operator, and maximum functional reach will decrease accordingly.

It should be noted that the maximum reaches referred to above, are those made to the outer limits of the workspace. They represent the farthest distance at which a control or task can be located if necessary and still be operated or performed by the person(s) with the smallest functional reaches in the group. These are not necessarily the optimum locations for such placements, which may well be closer in to the body.

These considerations apply equally well in zero g as to one g, though some minor differences in reach and performance have been reported. For example, any "downward" reach or reach involving bending at the waist will be judged more difficult (though only slightly so) in zero g because of the absence of gravity assist in "pulling" the arm or body down. "Upward" reaches would similarly be judged easier. The general concensus of astronaut Skylab experience was that most manual tasks were performed as easily, or more easily, in a zero-g environment (when foot restraints were used) because of the greater flexibility in body positioning, and the increased efficiency in handling large masses (National Aeronautics and Space Administration, 1975c).

The Data: Functional Reach Measurements

Considerations in Data Selection

There is no single study, or body of data, or functional reach measurement that is immediately and directly applicable to the design of workspaces for the specific environmental conditions and populations anticipated for Space Shuttle and Spacelab through the year 1990. As noted in the discussions above, functional reach studies are always made under a certain set of prescribed conditions for a given population. The intent is to obtain data that can be used in the design of one specific kind of workspace, under conditions and with populations similar to those for which the reach data were obtained.

After review of all available functional arm reach studies that might be applicable to the present design situation, the single most appropriate set of data was determined to be that of Kennedy for both men (1964) and women (1976). Reasons for the selection of these data are as follows: (1) the experimental design, measuring apparatus, and data analysis and presentation were as carefully planned and well controlled as those of any other functional reach study and better than most; (2) they are the only studies which present separate, but comparable, data for both male and female populations; (3) while the number of subjects, 20 for males and 30 for females, is fairly small, they were specially selected anthropometrically to accurately represent the size range of the parent populations. Certain disadvantages of the Kennedy study for present purposes, i.e., seated position with specific seat back and seat pan angles, shoulder restraints, etc., are considerable, but are common to almost all other functional reach studies that might have been selected except for the underwater neutral buoyancy tests. Although the latter were intended to simulate zero-g conditions, the subject population was too small and too anthropometrically atypical to be of any real utility here.

Arm Reach Data - Males

The Kennedy data were obtained on 20 subjects selected to be anthropometrically representative of the U.S. Air Force population. Their dimensions, and those of the female subjects, are presented in Table 1. All functional reach measurements were taken with the subject on a hard, unyielding seat with a backrest angle of 103^{o}, and a seat angle of 6^{o}. The reach task was to grasp with the right hand a small knob between the thumb and forefinger and push away until the arm was fully extended, with the shoulders still in contact with the seat back. Subjects wore light indoor clothing that did not appreciably restrict their reach.

The measurements of reach was as follows. Reaches were made to a series of vertical planes emanating from the seat reference point (intersection of planes of seat and backrest surfaces in seat midline), starting at 0^{o}, or straight ahead, and at 15^{o} increments to the right and left to 180^{o}, or directly to the rear. At each of these angles, reaches were made to a series of horizontal planes, at 5 inch (12.7 cm.) intervals, starting at the seat reference point to 45 inches (114.3 cm.) above this point. All reach dimensions presented in the following tables describe the horizontal distance between the two points defined by (1) the position of a knob being grasped by the thumb and forefinger, and (2) the seat reference vertical, (SRV), or vertical line through the seat reference point (SRP). See Figures 4-13 accompanying the tabular data for further clarification.

In the following tables the "minimum" value column presents the single shortest reach made in the sample of 20 subjects. It is very roughly equivalent to a 1st percentile value, but since it is based on only one individual, the values may be somewhat variable. The 5th percentile value is that of the individual who had the next to shortest reach (or 19th of the 20 in rank). The 50th percentile is the arithmetic mean of the 10th and 11th values, and the 95th percentile is that of the individual with the second longest reach.

Arm Reach Data - Females

These data were obtained on 30 subjects selected to be anthropometrically representative of the U.S. Air Force female population. The subjects' dimensions are presented in Table 1. Conditions of measurement for the functional reaches were comparable in equipment and technique to those for the male subjects, i.e., taken with the subject on a hard, unyielding seat with a backrest angle of 103^o, and a seat angle of 6^o. The reach task and the unrestrictive nature of the clothing worn by the female subjects were also the same as the men's. Reaches were made for a series of vertical planes emanating from the seat reference point, starting at 0^o, or straight ahead, and at 15^o increments to the right and left to 180^o, or directly to the rear. At each of these angles, reaches were made to a series of horizontal planes at 6 inch (15.2 cm.) intervals starting at the seat reference point to 42 inches (106.7 cm.) above the point. In this latter regard the women's study varied slightly from the men's in which reaches were measured at 5 inch (12.7 cm.) intervals and extended to 45 inches (114.3 cm.) above SRP. Recording of "minimum" values was omitted in the women's study.

Conversion Technique for Different Workspace Conditions

As noted, the above data on functional arm reach for males and females were taken under standardized conditions, i.e., seated position, hard seat, 103^o backrest, 9^o seat angle, shoulders in contact with backrest during reach, and a one-g environment. These data can therefore be expected to apply directly only to seated workspaces with similar configurations.

Gravity Conditions - Body Movement Restrained

For the Space Shuttle (as opposed to Spacelab) design, the seated position for flight crew, mission specialist, and other scientific or technical personnel during the g forces of launch and re-entry, will be the workspace conditions to which the present data are most directly applicable. If seat configurations are generally similar to those of the simulated U.S. Air Force pilots' seat used in determining the present arm reach data (Tables 2-19), then the latter may be used directly in establishing the layout of these workspaces and control locations--subject only to possible adjustment because of different sized operator groups which is discussed in the next section on conversion techniques for different populations.

TABLE 1
ANTHROPOMETRIC DIMENSIONS OF THE MALE AND FEMALE SUBJECTS UTILIZED IN THE FUNCTIONAL ARM REACH STUDIES*

Dimension (inches)	Males (N=20)		Females (N=30)	
	Mean	S.D.	Mean	S.D.
Age (years)	(27.9)	(5. 1)	(20.8)	(4.03)
Stature	176.8 (69.6)	6.7 (2.63)	162.8 (64.1)	5.74 (2.26)
Weight	75.2 (165.8)	9.35 (20.62)	56.37(124.3)	5.56 (12.26)
Sitting height	92.2 (36.3)	3.45 (1.36)	86.4 (34.0)	2.64 (1.04)
Eye height, sitting	-	-	73.7 (29.0)	2.64 (1.04)
Acromion height, sitting	61.5 (24.2)	3.05 (1.20)	55.6 (21.9)	2.51 (0.99)
Functional reach	81.3 (32.0)	3.86 (1.52)	71.9 (28.3)	3.53 (1.39)
Arm reach from wall	86.9 (34.2)	3.63 (1.43)	-	-
Maximum reach from wall	97.0 (38.2)	3.91 (1.54)	-	-
Shoulder-elbow length	36.6 (14.4)	1.57 (0.62)	32.5 (12.8)	1.68 (0.66)
Forearm-hand length	48.3 (19.0)	1.88 (0.74)	42.4 (16.7)	1.98 (0.78)
Hand length	19.3 (7.6)	0.58 (0.23)	-	-
Buttock-knee length	-	-	57.4 (22.6)	2.16 (0.85)
Biacromial breadth	39.9 (15.7)	1.91 (0.75)	36.3 (14.3)	1.55 (0.61)
Shoulder breadth	-	-	41.9 (16.5)	1.98 (0.78)

*Anthropometric data from Kennedy, 1964, 1976. For definitions of measurements see Kennedy, 1964, Hertzberg et al., 1954, or Damon et al., 1966. Data given in centimeters and kilograms with inches and pounds in parentheses.

TABULATED ARM REACH DATA:

MEN AND WOMEN

TABLE 2

MEN'S RIGHT HAND GRASPING REACH TO A PLANE THROUGH THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV*
See Figure 4

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90								
L 75								
L 60								
L 45								
L 30								
L 15								
0								
R 15								
R 30			44.5	(17.5)	52.6	(20.7)	63.5	(25.0)
R 45	41.1	(16.2)	49.5	(19.5)	55.1	(21.7)	66.0	(26.0)
R 60	44.5	(17.5)	52.1	(20.5)	56.4	(22.2)	66.5	(26.2)
R 75	43.7	(17.2)	50.8	(20.0)	56.4	(22.2)	66.0	(26.0)
R 90	43.2	(17.0)	49.5	(19.5)	56.4	(22.2)	64.8	(25.5)
R 105	41.1	(16.2)	47.5	(18.7)	55.9	(22.0)	64.0	(25.2)
R 120	38.1	(15.0)	46.2	(18.2)	52.6	(20.7)	62.2	(24.5)
R 135	33.0	(13.0)	41.9	(16.5)	48.3	(19.0)	59.7	(23.5)
R 150			35.6	(14.0)	41.9	(16.5)	51.3	(20.2)
R 165					33.0	(13.0)	43.2	(17.0)
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

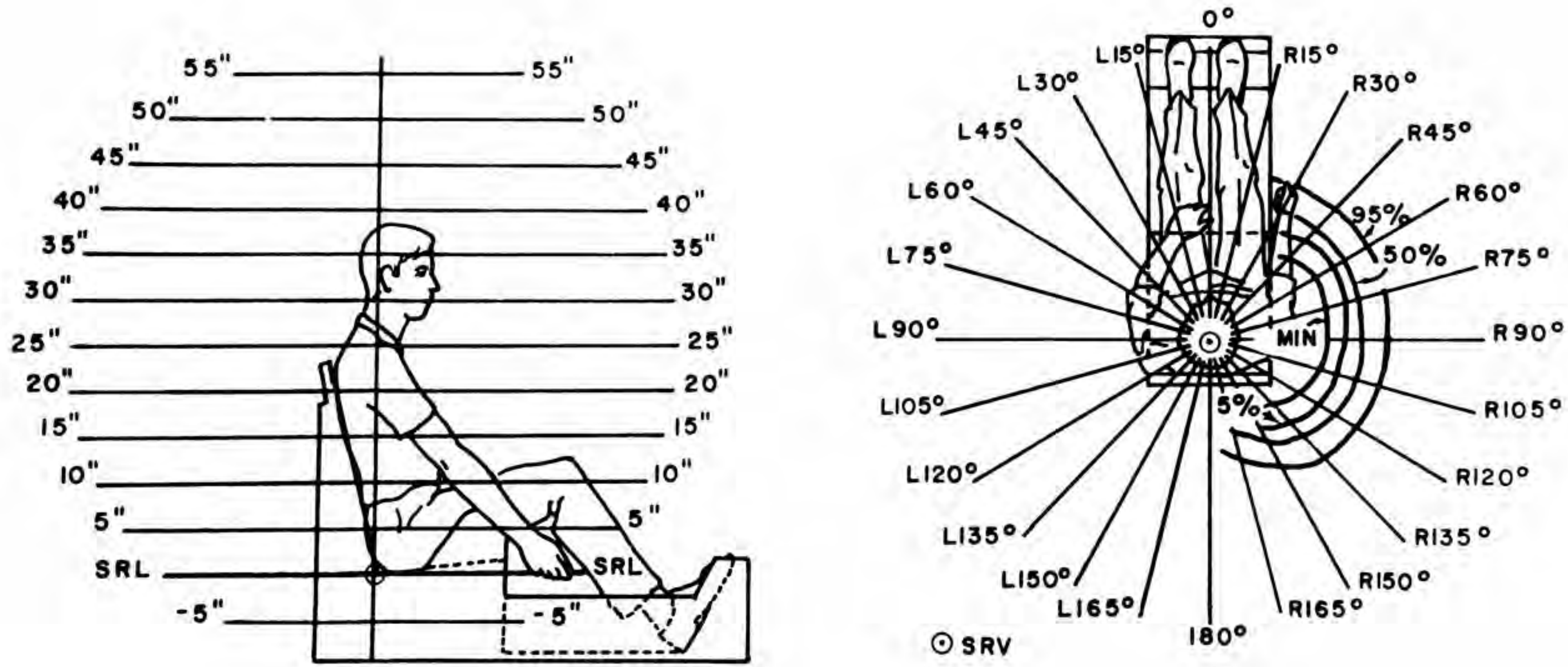


Figure 4. Men's grasping reach to a horizontal plane through the seat reference point.

TABLE 3
MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE 12.5 CENTIMETERS (5 in.) ABOVE THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV*
See Figure 5

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90								
L 75								
L 60								
L 45								
L 30								
L 15								
0								
R 15								
R 30	55.9	(22.0)	60.2	(23.7)	66.0	(26.0)	74.9	(29.5)
R 45	59.7	(23.5)	64.0	(25.2)	69.1	(27.2)	76.2	(30.0)
R 60	60.2	(23.7)	65.3	(25.7)	70.4	(27.7)	76.2	(30.0)
R 75	61.0	(24.0)	65.3	(25.7)	69.9	(27.5)	76.7	(30.2)
R 90	61.0	(24.0)	65.3	(25.7)	69.9	(27.5)	78.0	(30.7)
R 105	60.2	(23.7)	64.0	(25.2)	68.6	(27.0)	76.2	(30.0)
R 120	58.4	(23.0)	62.2	(24.5)	67.3	(26.5)	73.7	(29.0)
R 135	54.6	(21.5)	57.7	(22.7)	63.5	(25.0)	71.1	(28.0)
R 150					56.4	(22.2)	65.3	(25.7)
R 165					48.8	(19.2)	53.8	(21.2)
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

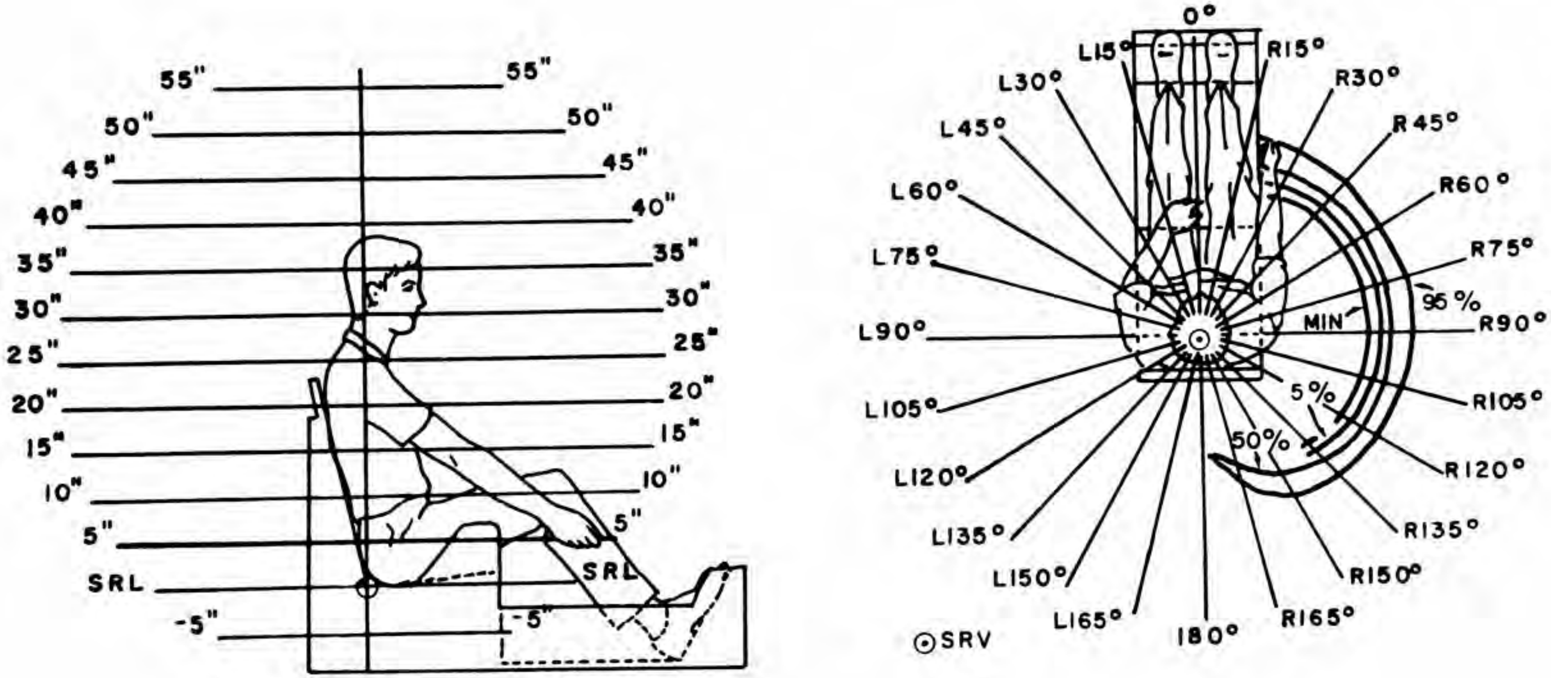


Figure 5. Men's grasping reach to a horizontal plane 5 inches above the seat reference point.

TABLE 4

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
25.4 CENTIMETERS (10 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 6

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90							34.3	(13.5)
L 75							43.7	(17.2)
L 60					41.9	(16.5)	53.3	(21.0)
L 45					49.5	(19.5)	58.9	(23.2)
L 30					53.3	(21.0)	62.7	(24.7)
L 15					55.9	(22.0)	66.5	(26.2)
0								
R 15								
R 30	66.5	(26.2)	68.6	(27.0)	74.2	(29.2)	83.8	(33.0)
R 45	69.1	(27.2)	71.6	(28.2)	77.5	(30.5)	85.6	(33.7)
R 60	71.1	(28.0)	73.7	(29.0)	78.0	(30.7)	85.1	(33.5)
R 75	71.6	(28.2)	74.2	(29.2)	78.0	(30.7)	85.1	(33.5)
R 90	71.6	(28.2)	74.2	(29.2)	78.7	(31.0)	85.1	(33.5)
R 105	70.4	(27.7)	72.9	(28.7)	77.5	(30.5)	83.1	(32.7)
R 120	67.8	(26.7)	70.4	(27.7)	75.4	(29.7)	80.0	(31.5)
R 135			66.5	(26.2)	71.6	(28.2)	78.0	(30.7)
R 150					64.0	(25.2)	72.9	(28.7)
R 165								
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

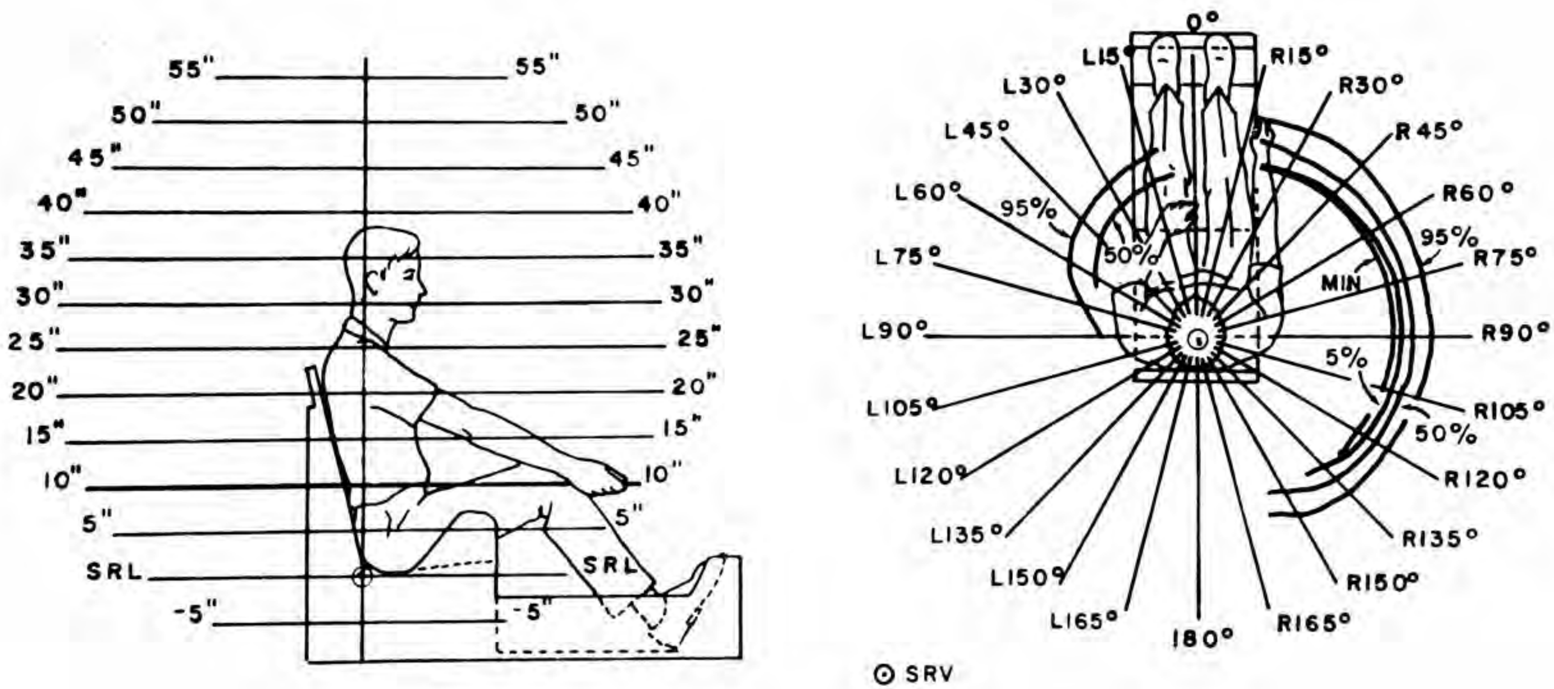


Figure 6. Men's grasping reach to a horizontal plane 10 inches above the seat reference point.

TABLE 5

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
38.1 CENTIMETERS (15 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 7

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90							44.5	(17.5)
L 75							50.8	(20.0)
L 60					48.8	(19.2)	58.4	(23.0)
L 45			48.3	(19.0)	54.6	(21.5)	65.3	(25.7)
L 30	53.3	(21.0)	55.1	(21.7)	61.0	(24.0)	69.1	(27.2)
L 15	57.2	(22.5)	58.9	(23.2)	66.0	(26.0)	72.9	(28.7)
0	61.5	(24.2)	62.7	(24.7)	72.9	(28.7)	78.7	(31.0)
R 15	66.0	(26.0)	67.3	(26.5)	77.5	(30.5)	86.4	(34.0)
R 30	71.6	(28.2)	72.4	(28.5)	80.0	(31.5)	88.9	(35.0)
R 45	74.9	(29.5)	76.2	(30.0)	83.1	(32.7)	90.2	(35.5)
R 60	76.2	(30.0)	78.7	(31.0)	82.6	(32.5)	88.1	(34.7)
R 75	76.2	(30.0)	80.0	(31.5)	82.6	(32.5)	88.1	(34.7)
R 90	76.7	(30.2)	78.7	(31.0)	82.6	(32.5)	88.1	(34.7)
R 105	76.2	(30.0)	78.0	(30.7)	81.8	(32.2)	87.6	(34.5)
R 120	73.7	(29.0)	74.9	(29.5)	81.3	(32.0)	85.6	(33.7)
R 135					76.2	(30.0)	82.6	(32.5)
R 150							74.9	(29.5)
R 165								
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

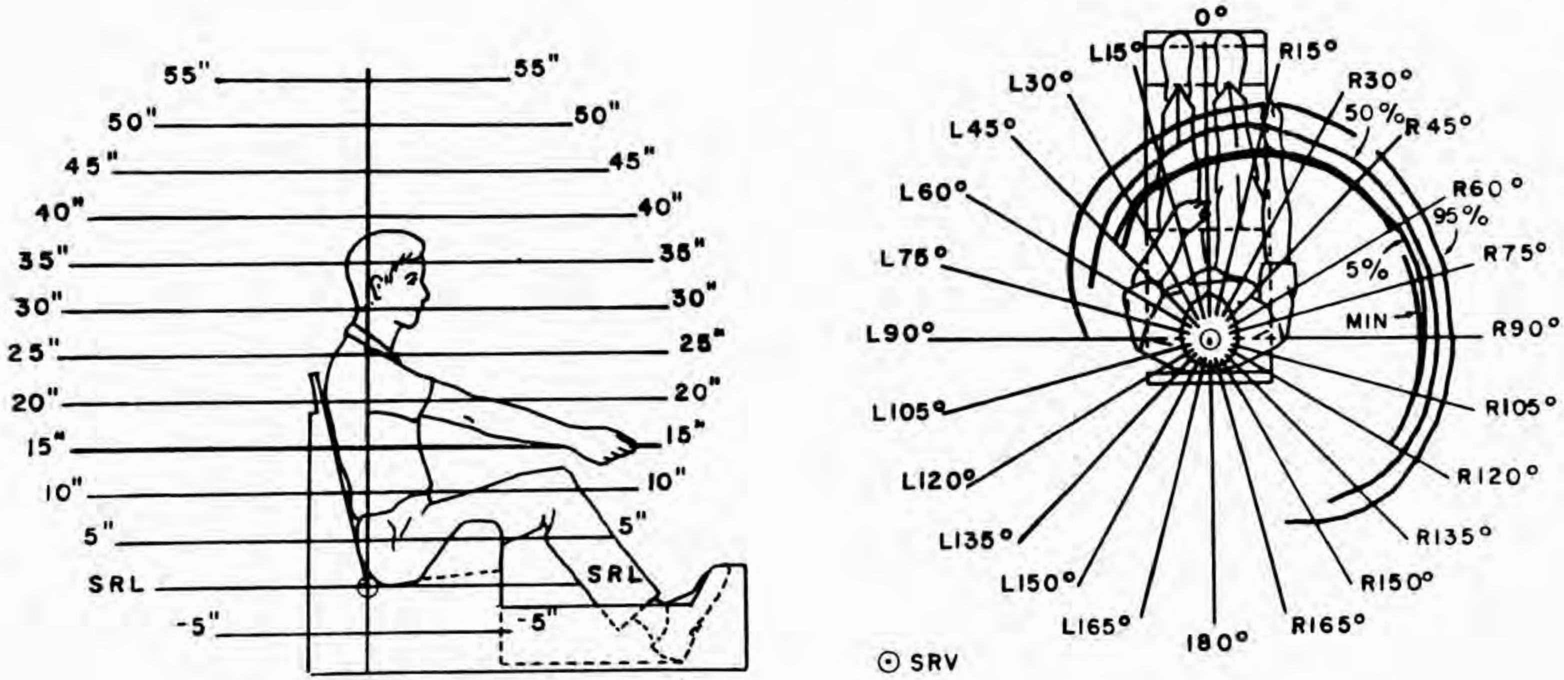


Figure 7. Men's grasping reach to a horizontal plane 15 inches above the seat reference point.

TABLE 6

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
50.8 CENTIMETERS (20 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 8

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90					35.6	(14.0)	47.5	(18.7)
L 75					45.7	(18.0)	54.6	(21.5)
L 60	43.2	(17.0)	44.5	(17.5)	52.1	(20.5)	62.2	(24.5)
L 45	46.2	(18.2)	49.5	(19.5)	57.7	(22.7)	67.8	(26.7)
L 30	51.3	(20.2)	54.6	(21.5)	62.7	(24.7)	71.6	(28.2)
L 15	57.2	(22.5)	59.7	(23.5)	67.8	(26.7)	75.4	(29.7)
0	63.5	(25.0)	64.8	(25.5)	72.9	(28.7)	80.5	(31.7)
R 15	69.1	(27.2)	71.1	(28.0)	77.5	(30.5)	86.4	(34.0)
R 30	73.7	(29.0)	76.2	(30.0)	81.3	(32.0)	90.7	(35.7)
R 45	77.5	(30.5)	78.7	(31.0)	85.1	(33.5)	91.9	(36.2)
R 60	80.0	(31.5)	81.3	(32.0)	85.6	(33.7)	91.9	(36.2)
R 75	80.0	(31.5)	81.8	(32.2)	86.4	(34.0)	92.7	(36.5)
R 90	80.5	(31.7)	81.8	(32.2)	86.4	(34.0)	91.4	(36.0)
R 105	80.0	(31.5)	80.5	(31.7)	85.1	(33.5)	90.7	(35.7)
R 120			77.5	(30.5)	83.8	(33.0)	90.2	(35.5)
R 135							87.6	(34.5)
R 150								
R 165								
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

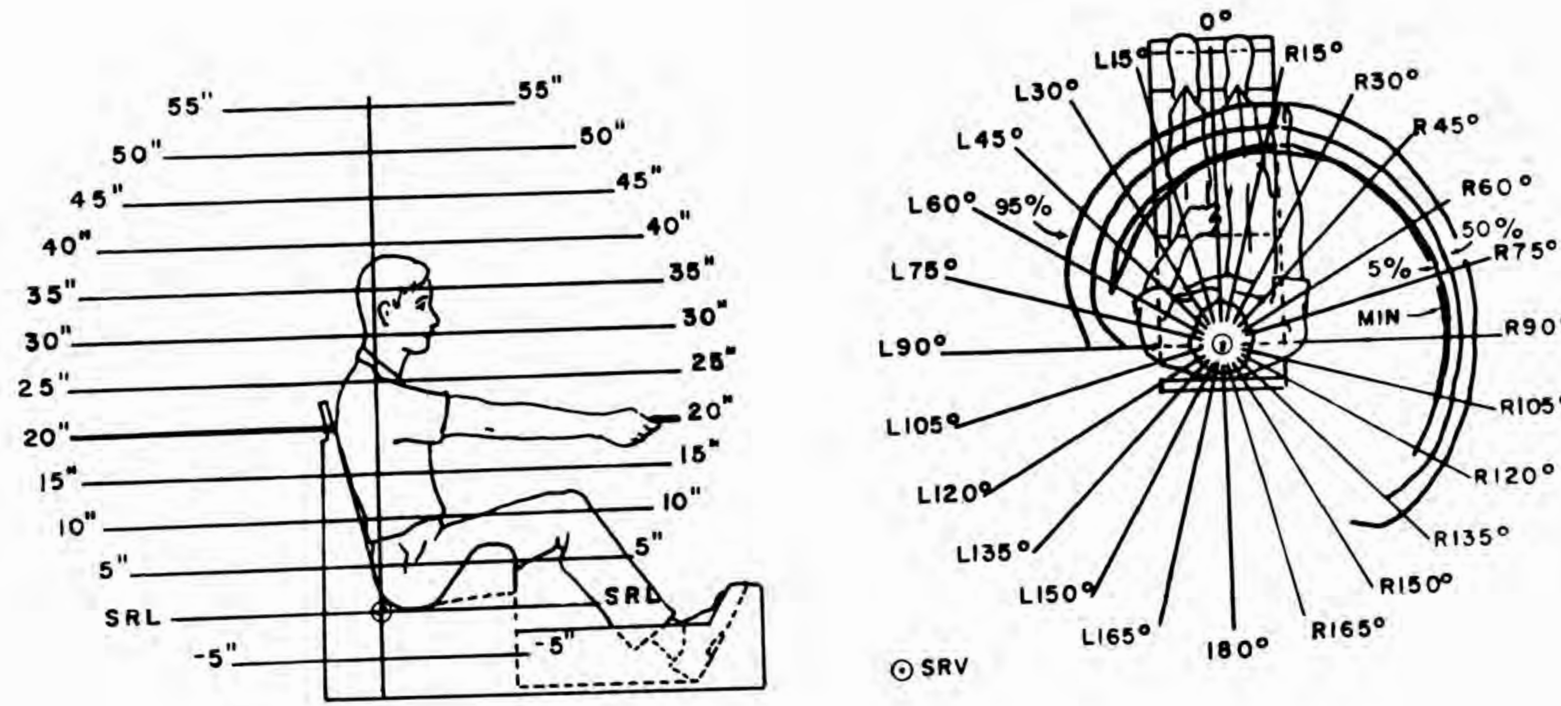


Figure 8. Men's grasping reach to a horizontal plane 20 inches above the seat reference point.

TABLE 7

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
63.5 CENTIMETERS (25 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 9

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105							45.0	(17.7)
L 90					39.9	(15.7)	51.3	(20.2)
L 75					48.8	(19.2)	56.4	(22.2)
L 60	45.0	(17.7)	46.2	(18.2)	54.6	(21.5)	62.7	(24.7)
L 45	48.8	(19.2)	50.8	(20.0)	58.9	(23.2)	69.1	(27.2)
L 30	54.6	(21.5)	57.2	(22.5)	63.5	(25.0)	72.4	(28.5)
L 15	58.9	(23.2)	61.0	(24.0)	68.6	(27.0)	75.4	(29.7)
0	63.5	(25.0)	66.5	(26.2)	72.4	(28.5)	80.0	(31.5)
R 15	69.1	(27.2)	71.6	(28.2)	76.7	(30.2)	85.1	(33.5)
R 30	74.2	(29.2)	76.7	(30.2)	82.6	(32.5)	89.4	(35.2)
R 45	77.5	(30.5)	78.7	(31.0)	85.1	(33.5)	90.7	(35.7)
R 60	78.7	(31.0)	80.0	(31.5)	85.6	(33.7)	94.0	(37.0)
R 75	80.0	(31.5)	81.3	(32.0)	85.1	(33.5)	92.7	(36.5)
R 90	80.5	(31.7)	81.8	(32.2)	85.6	(33.7)	91.9	(36.2)
R 105	79.2	(31.2)	80.0	(31.5)	85.1	(33.5)	91.4	(36.0)
R 120			77.5	(30.5)	84.3	(33.2)	90.2	(35.5)
R 135							88.9	(35.0)
R 150								
R 165								
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

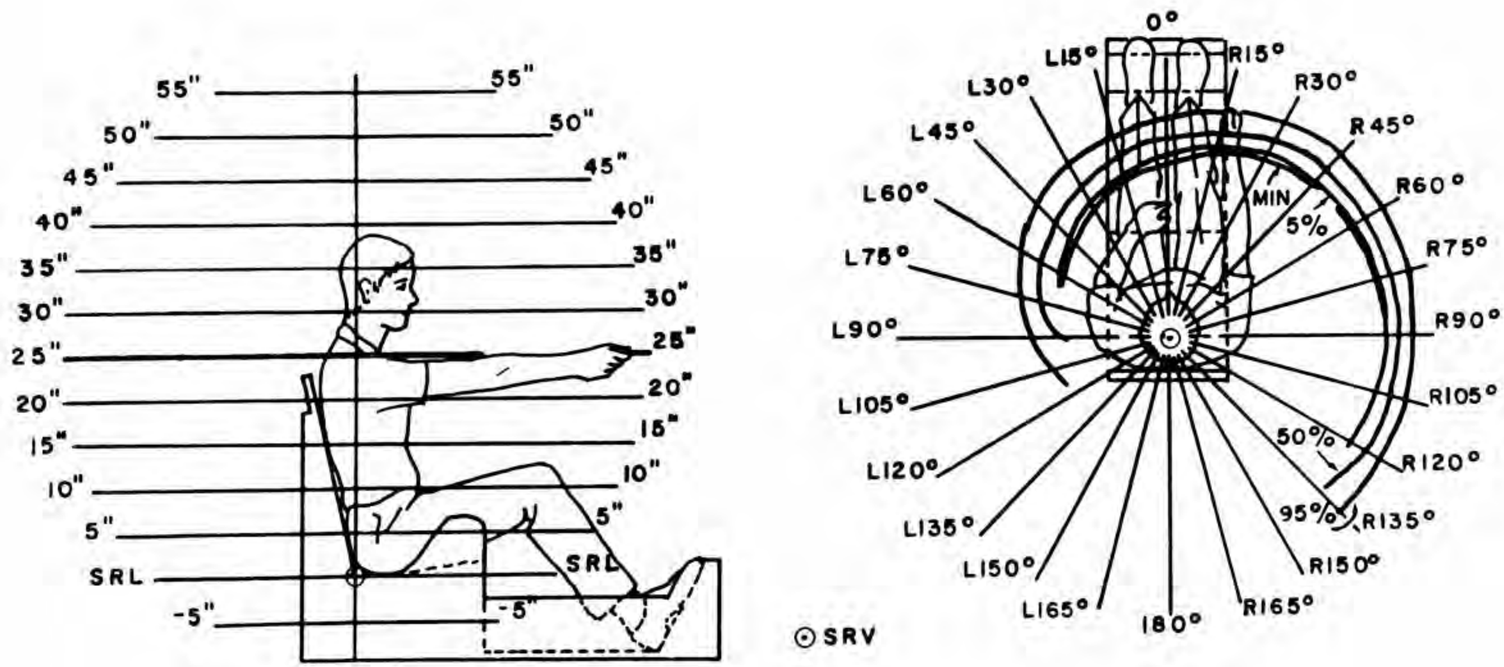


Figure 9. Men's grasping reach to a horizontal plane 25 inches above the seat reference point.

TABLE 8

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE 76.2 CENTIMETERS (30 in.) ABOVE THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV.*

See Figure 10

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165							47.5	(18.7)
L 150							48.8	(19.2)
L 135							50.8	(20.0)
L 120							47.5	(18.7)
L 105							48.3	(19.0)
L 90					42.4	(16.7)	52.6	(20.7)
L 75					47.5	(18.7)	57.2	(22.5)
L 60	43.2	(17.0)	43.7	(17.2)	52.6	(20.7)	62.2	(24.5)
L 45	46.2	(18.2)	48.3	(19.0)	57.2	(22.5)	67.3	(26.5)
L 30	50.0	(19.7)	54.6	(21.5)	62.2	(24.5)	71.6	(28.2)
L 15	55.9	(22.0)	60.2	(23.7)	67.8	(26.7)	74.9	(29.5)
0	60.2	(23.7)	64.8	(25.5)	72.4	(28.5)	78.7	(31.0)
R 15	66.0	(26.0)	69.1	(27.2)	75.4	(29.7)	83.8	(33.0)
R 30	70.4	(27.7)	73.7	(29.0)	80.0	(31.5)	86.9	(34.2)
R 45	72.9	(28.7)	76.7	(30.2)	81.8	(32.2)	88.1	(34.7)
R 60	76.2	(30.0)	78.7	(31.0)	83.1	(32.7)	90.7	(35.7)
R 75	78.0	(30.7)	79.2	(31.2)	83.8	(33.0)	90.2	(35.5)
R 90	78.7	(31.0)	79.2	(31.2)	84.3	(33.2)	90.7	(35.7)
R 105	78.0	(30.7)	78.7	(31.0)	83.8	(33.0)	89.4	(35.2)
R 120			76.7	(30.2)	82.6	(32.5)	88.1	(34.7)
R 135							87.6	(34.5)
R 150								
R 165							49.5	(19.5)
180							51.3	(20.2)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

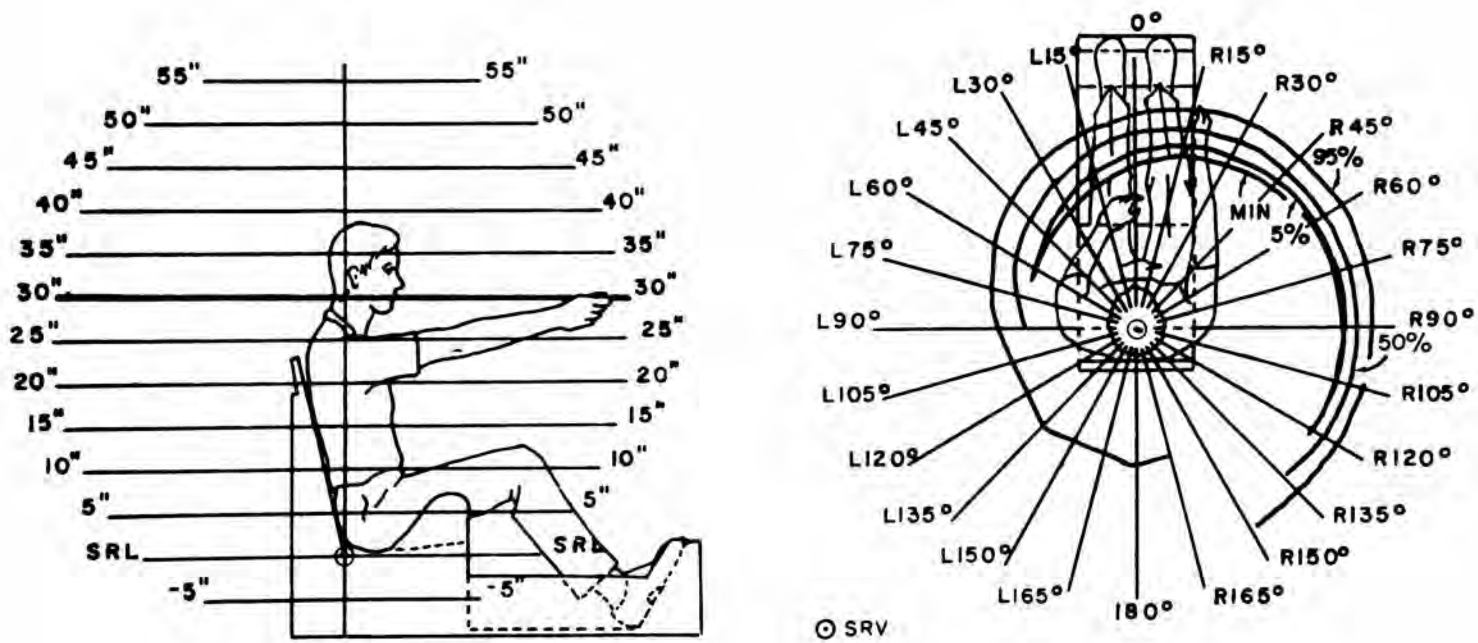


Figure 10. Men's grasping reach to a horizontal plane 30 inches above the seat reference point.

TABLE 9

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
88.9 CENTIMETERS (35 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 11

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165					37.3	(14.7)	53.3	(21.0)
L 150					34.8	(13.7)	50.8	(20.0)
L 135					33.5	(13.2)	48.3	(19.0)
L 120			27.2	(10.7)	33.5	(13.2)	47.5	(18.7)
L 105			31.0	(12.2)	35.6	(14.0)	47.5	(18.7)
L 90	32.3	(12.7)	34.8	(13.7)	39.4	(15.5)	50.8	(20.0)
L 75	36.1	(14.2)	38.1	(15.0)	43.7	(17.2)	53.3	(21.0)
L 60	38.6	(15.2)	40.6	(16.0)	47.5	(18.7)	54.6	(21.5)
L 45	41.1	(16.2)	43.7	(17.2)	52.1	(20.5)	62.7	(24.7)
L 30	45.7	(18.0)	48.8	(19.2)	57.2	(22.5)	66.5	(26.2)
L 15	48.8	(19.2)	53.3	(21.0)	62.7	(24.7)	68.6	(27.0)
0	52.6	(20.7)	56.4	(22.2)	67.3	(26.5)	72.4	(28.5)
R 15	57.7	(22.7)	62.7	(24.7)	70.4	(27.7)	78.7	(31.0)
R 30	62.2	(24.5)	67.8	(26.7)	74.2	(29.2)	83.1	(32.7)
R 45	67.8	(26.7)	71.6	(28.2)	77.5	(30.5)	85.6	(33.7)
R 60	71.1	(28.0)	73.7	(29.0)	78.7	(31.0)	85.6	(33.7)
R 75	72.9	(28.7)	74.9	(29.5)	79.2	(31.2)	86.4	(34.0)
R 90	73.7	(29.0)	75.4	(29.7)	79.2	(31.2)	85.1	(33.5)
R 105	73.7	(29.0)	75.4	(29.7)	80.0	(31.5)	85.1	(33.5)
R 120	72.4	(28.5)	73.7	(29.0)	78.7	(31.0)	85.1	(33.5)
R 135					72.39	(28.5)	85.1	(33.5)
R 150							80.0	(31.5)
R 165							55.1	(21.7)
180					41.9	(16.5)	56.4	(22.2)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

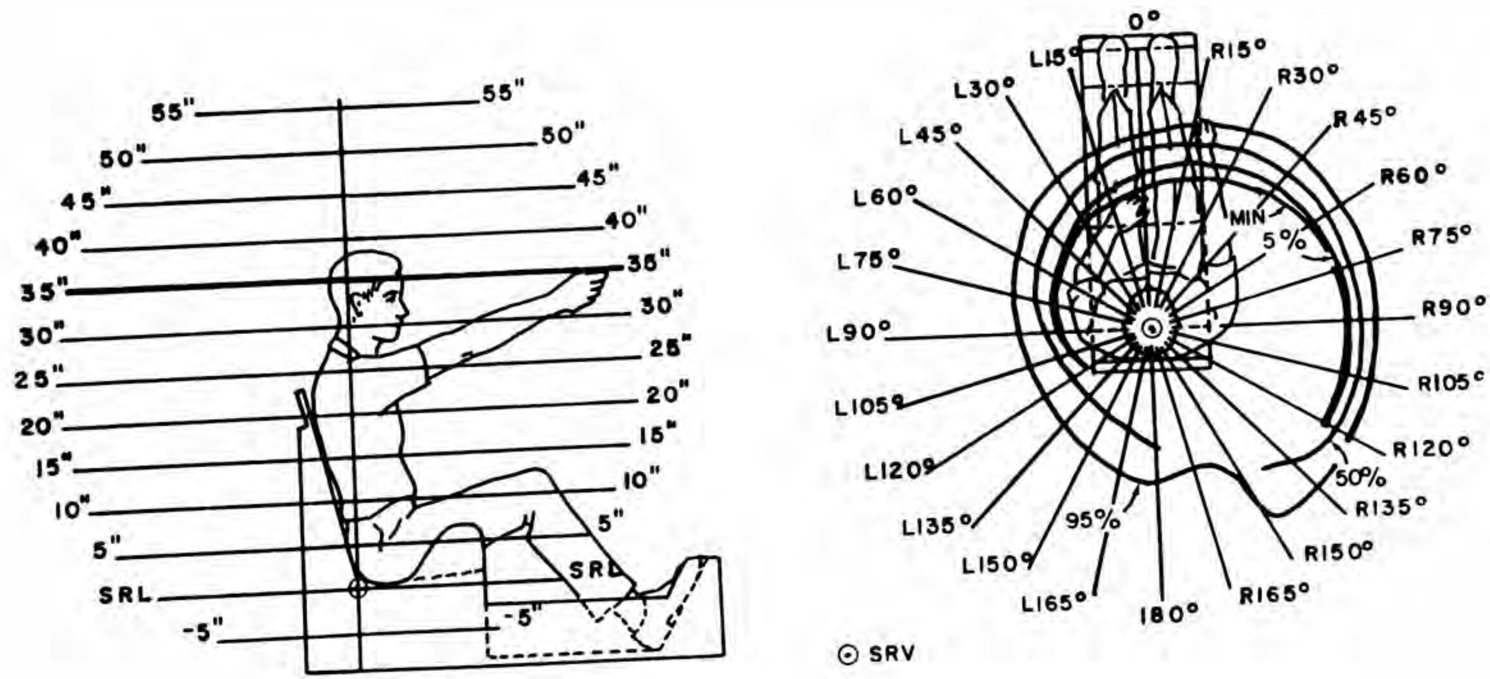


Figure 11. Men's grasping reach to a horizontal plane 35 inches above the seat reference point.

TABLE 10

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
101.6 CENTIMETERS (40 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 12

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165					39.4	(15.5)	54.6	(21.5)
L 150					37.3	(14.7)	50.8	(20.0)
L 135					35.6	(14.0)	48.8	(19.2)
L 120			28.4	(11.2)	33.5	(13.2)	47.0	(18.5)
L 105			29.7	(11.7)	33.5	(13.2)	46.2	(18.2)
L 90	30.5	(12.0)	31.0	(12.2)	34.8	(13.7)	46.2	(18.2)
L 75	31.0	(12.2)	31.8	(12.5)	38.1	(15.0)	47.5	(18.7)
L 60	31.8	(12.5)	33.5	(13.2)	41.1	(16.2)	50.8	(20.0)
L 45	33.0	(13.0)	35.6	(14.0)	45.0	(17.7)	54.6	(21.5)
L 30	34.8	(13.7)	39.4	(15.5)	49.5	(19.5)	59.7	(23.5)
L 15	38.6	(15.2)	43.2	(17.0)	53.8	(21.2)	62.2	(24.5)
0	43.2	(17.0)	48.3	(19.0)	58.4	(23.0)	65.3	(25.7)
R 15	47.5	(18.7)	53.3	(21.0)	62.2	(24.5)	72.4	(28.5)
R 30	53.3	(21.0)	57.7	(22.7)	66.5	(26.2)	77.5	(30.5)
R 45	58.9	(23.2)	62.7	(24.7)	70.4	(27.7)	80.0	(31.5)
R 60	61.5	(24.2)	64.8	(25.5)	71.1	(28.0)	79.2	(31.2)
R 75	63.5	(25.0)	66.0	(26.0)	71.1	(28.0)	80.0	(31.5)
R 90	63.5	(25.0)	66.5	(26.2)	71.6	(28.2)	80.0	(31.5)
R 105	65.3	(25.7)	67.8	(26.7)	72.4	(28.5)	80.5	(31.7)
R 120			66.5	(26.2)	72.9	(28.7)	80.0	(31.5)
R 135					68.6	(27.0)	78.7	(31.0)
R 150							74.2	(29.2)
R 165					42.4	(16.7)	60.2	(23.7)
180					45.0	(17.7)	59.7	(23.5)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

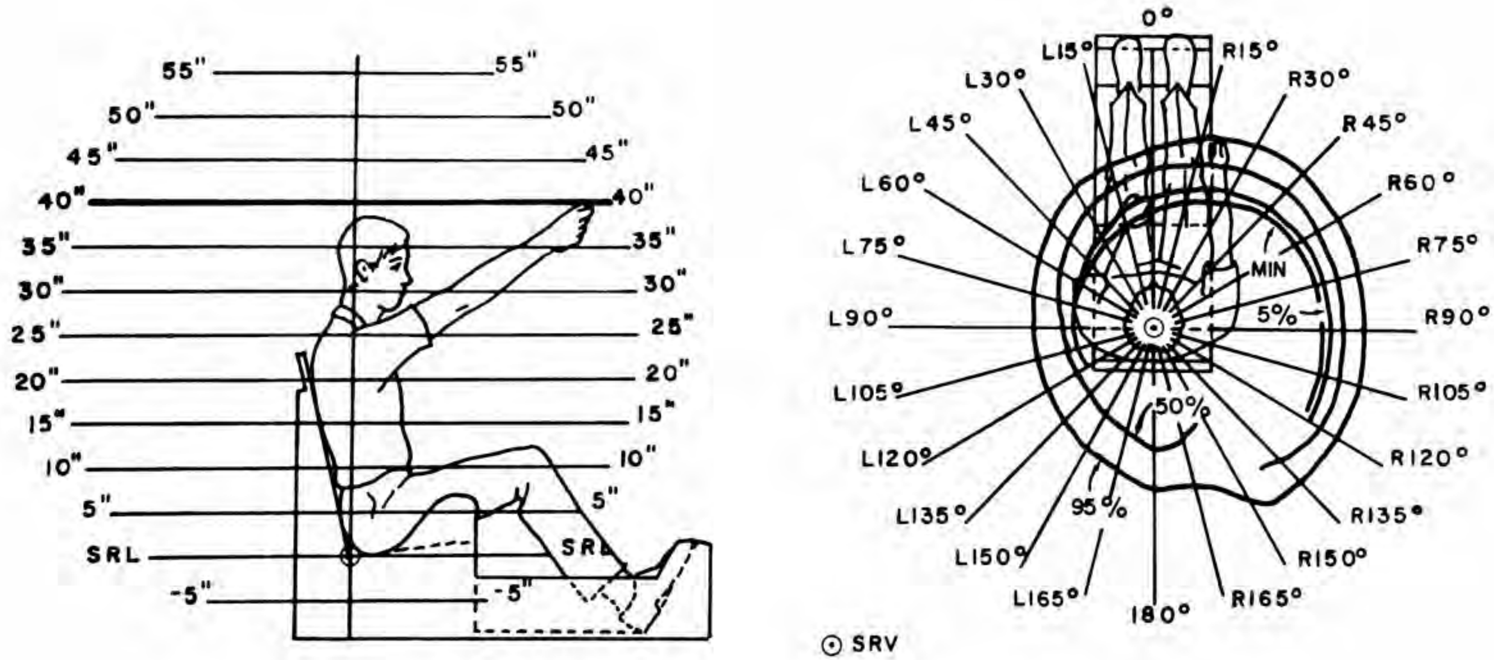


Figure 12. Men's grasping reach to a horizontal plane 40 inches above the seat reference point.

TABLE 11
MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
114.3 CENTIMETERS (45 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 13

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165			26.7	(10.5)	35.6	(14.0)	50.8	(20.0)
L 150	21.6	(8.5)	22.1	(8.7)	31.0	(12.2)	46.2	(18.2)
L 135	19.1	(7.5)	19.6	(7.7)	27.9	(11.0)	42.4	(16.7)
L 120	17.8	(7.0)	19.1	(7.5)	26.7	(10.5)	39.4	(15.5)
L 105	17.0	(6.7)	18.3	(7.2)	25.9	(10.2)	38.1	(15.0)
L 90	17.0	(6.7)	18.3	(7.2)	26.7	(10.5)	38.1	(15.0)
L 75	17.0	(6.7)	19.1	(7.5)	27.9	(11.0)	38.6	(15.2)
L 60	17.8	(7.0)	19.6	(7.7)	30.5	(12.0)	41.1	(16.2)
L 45	19.1	(7.5)	21.6	(8.5)	34.3	(13.5)	46.2	(18.2)
L 30	21.6	(8.5)	24.1	(9.5)	38.1	(15.0)	50.0	(19.7)
L 15	25.4	(10.0)	27.9	(11.0)	41.9	(16.5)	53.8	(21.2)
0	28.4	(11.2)	32.3	(12.7)	46.2	(18.2)	57.7	(22.7)
R 15	33.0	(13.0)	39.4	(15.5)	50.8	(20.0)	62.7	(24.7)
R 30	37.3	(14.7)	44.5	(17.5)	55.9	(22.0)	66.5	(26.2)
R 45	43.7	(17.2)	48.3	(19.0)	59.7	(23.5)	68.6	(27.0)
R 60	48.8	(19.2)	52.1	(20.5)	61.0	(24.0)	69.1	(27.2)
R 75	49.5	(19.5)	52.1	(20.5)	61.0	(24.0)	69.9	(27.5)
R 90	50.0	(19.7)	53.3	(21.0)	61.5	(24.2)	70.4	(27.7)
R 105	51.3	(20.2)	54.6	(21.5)	62.2	(24.5)	71.1	(28.0)
R 120	50.0	(19.7)	53.8	(21.2)	62.2	(24.5)	70.4	(27.7)
R 135	47.5	(18.7)	50.8	(20.0)	58.9	(23.2)	70.4	(27.7)
R 150			39.4	(15.5)	52.6	(20.7)	66.0	(26.0)
R 165			37.3	(14.7)	45.7	(18.0)	57.7	(22.7)
180			32.3	(12.7)	41.9	(16.5)	54.6	(21.5)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

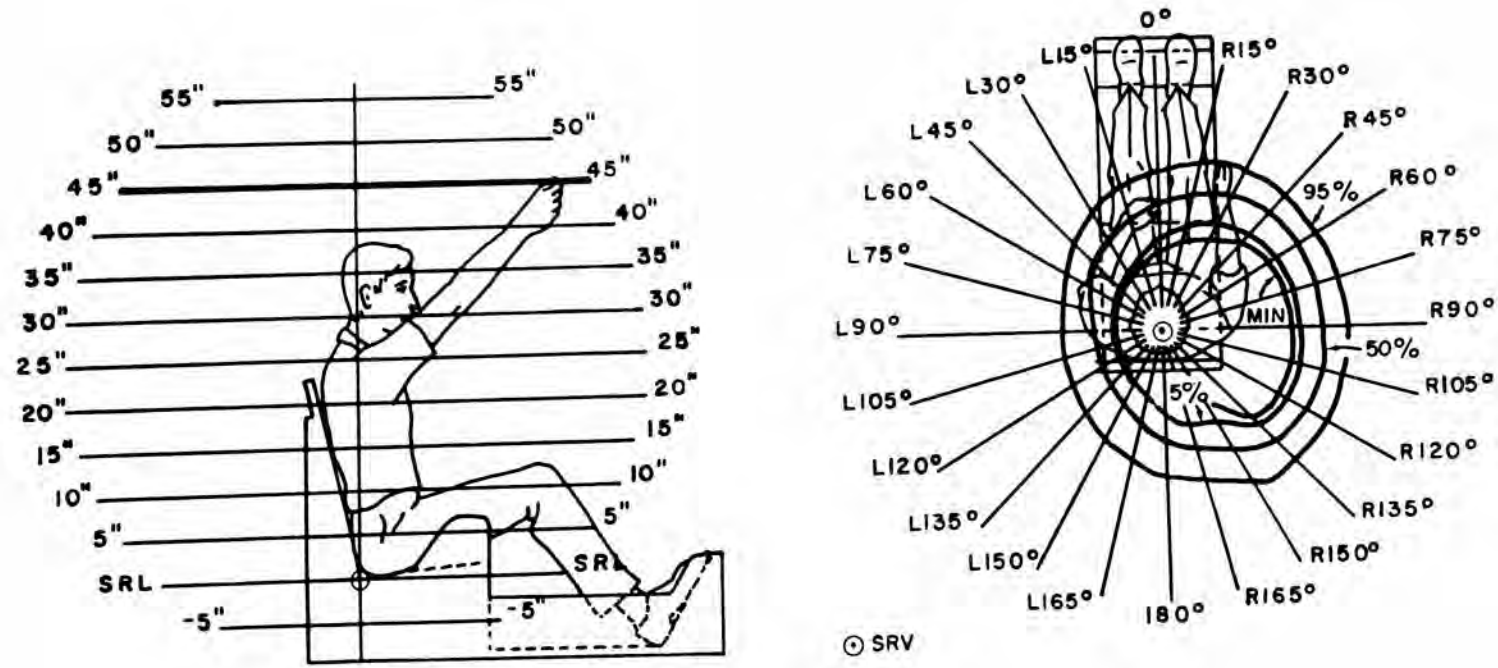


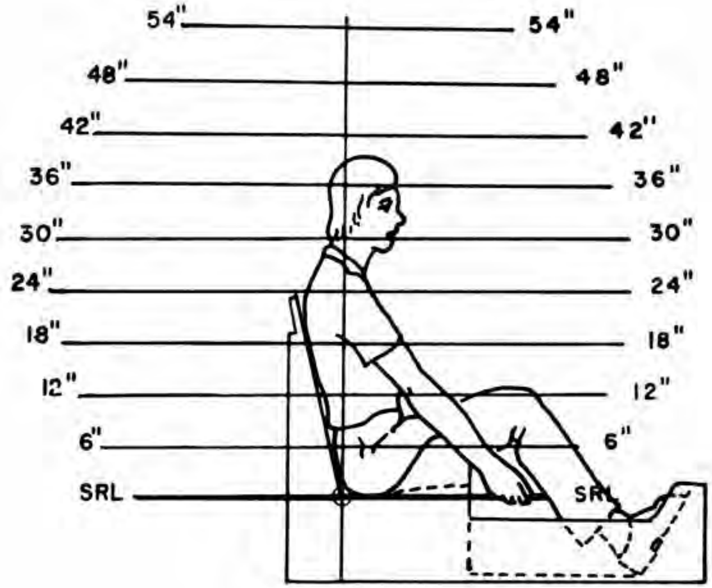
Figure 13. Men's grasping reach to a horizontal plane 45 inches above the seat reference point.

TABLE 12
WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
THROUGH THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 14

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165							
L 150							
L 135							
L 120							
L 105							
L 90							
L 75							
L 60							
L 45							
L 30							
L 15							
0							
R 15						55.9	(22.0)
R 30				41.1	(16.2)	55.1	(21.7)
R 45		35.6	(14.0)	44.5	(17.5)	56.4	(22.2)
R 60		38.6	(15.2)	47.5	(18.7)	58.4	(23.0)
R 75		41.1	(16.2)	48.3	(19.0)	60.2	(23.7)
R 90		42.4	(16.7)	49.5	(19.5)	60.2	(23.7)
R 105		40.6	(16.0)	48.3	(19.0)	58.4	(23.0)
R 120		38.6	(15.2)	46.2	(18.2)	55.9	(22.0)
R 135		33.0	(13.0)	41.9	(16.5)	52.1	(20.5)
R 150				33.0	(13.0)	47.5	(18.7)
R 165						39.9	(15.7)
180							

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.



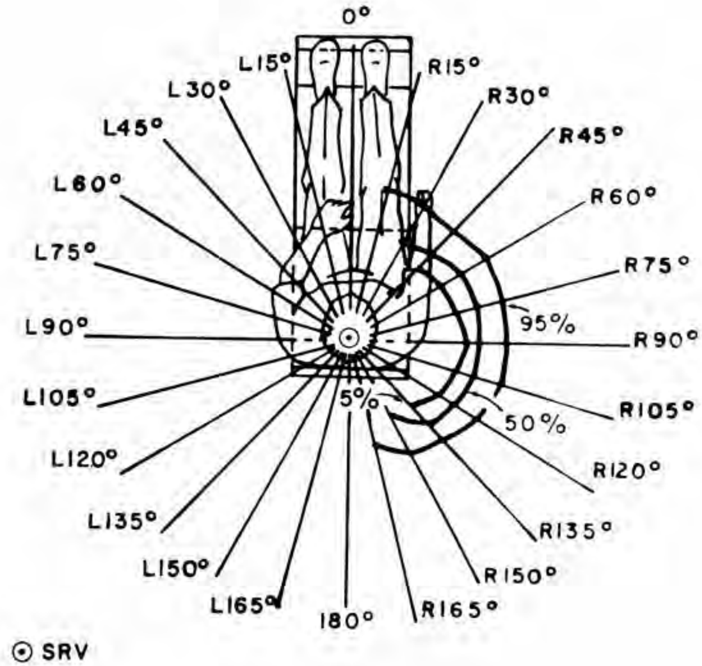


Figure 14. Women's grasping reach to a horizontal plane through the seat reference point.

TABLE 13

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
15.2 CENTIMETERS (6 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 15

Angle to Left or Right	Minimum	Percentiles 5	50	95
L 165				
L 150				
L 135				
L 120				
L 105				26.7 (10.5)
L 90				29.2 (11.5)
L 75				36.8 (14.5)
L 60				40.6 (16.0)
L 45				45.7 (18.0)
L 30				50.8 (20.0)
L 15				
0				
R 15		50.8 (20.0)	57.2 (22.5)	67.3 (26.5)
R 30		53.3 (21.0)	58.4 (23.0)	69.9 (27.5)
R 45		54.6 (21.5)	60.2 (23.7)	71.1 (28.0)
R 60		58.9 (23.2)	63.5 (25.0)	71.1 (28.0)
R 75		60.2 (23.7)	63.5 (25.0)	72.4 (28.5)
R 90		60.2 (23.7)	64.0 (25.2)	72.4 (28.5)
R 105		58.9 (23.2)	63.5 (25.0)	70.4 (27.7)
R 120		55.9 (22.0)	61.0 (24.0)	66.5 (26.2)
R 135		52.6 (20.7)	58.4 (23.0)	64.8 (25.5)
R 150			50.8 (20.0)	61.0 (24.0)
R 165			41.1 (16.2)	53.3 (21.0)
180				

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

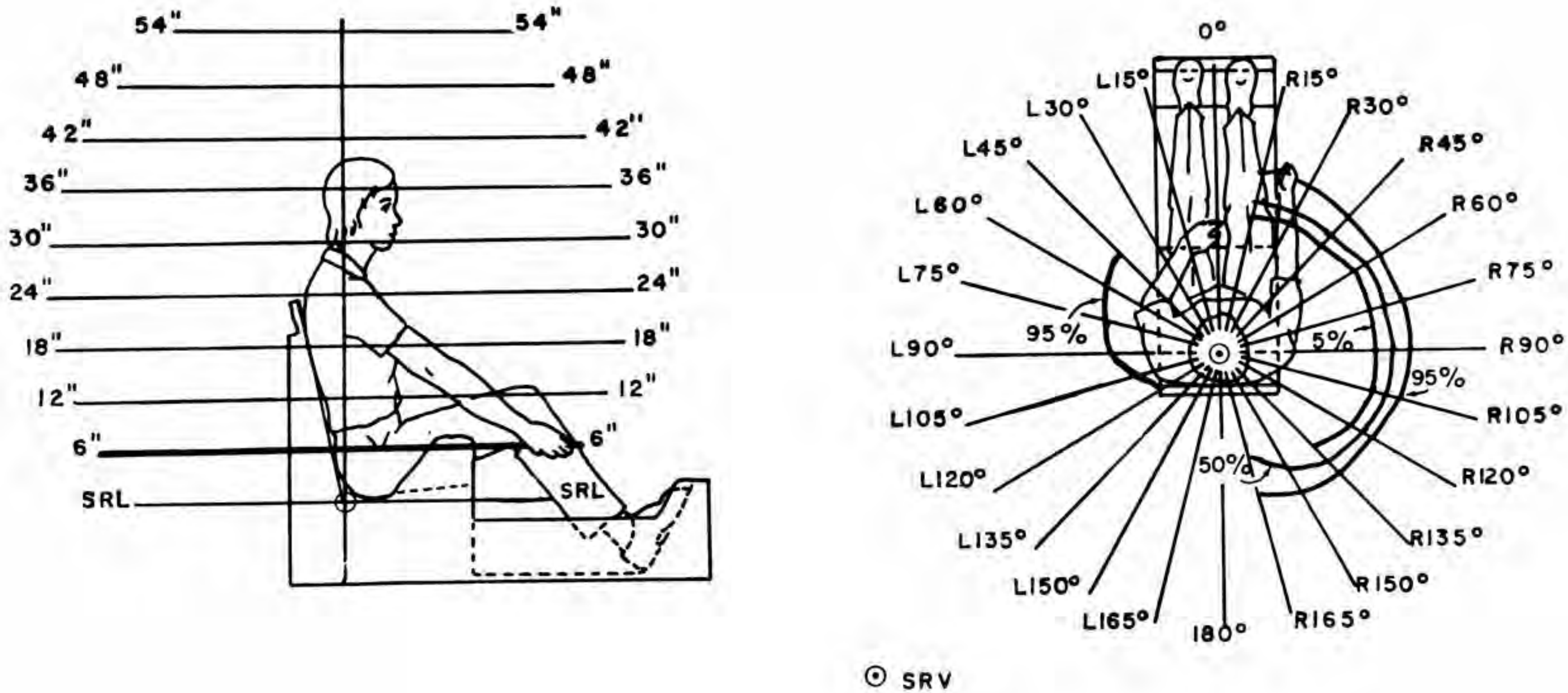


Figure 15. Women's grasping reach to a horizontal plane 6 inches above the seat reference point.

TABLE 14

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE 30.5 CENTIMETERS (12 in.) ABOVE THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV.*

See Figure 16

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165							
L 150							
L 135							
L 120						32.3	(12.7)
L 105						35.6	(14.0)
L 90				27.9	(11.0)	39.4	(15.5)
L 75				33.0	(13.0)	44.5	(17.5)
L 60		31.0	(12.2)	38.1	(15.0)	50.8	(20.0)
L 45		36.8	(14.5)	45.0	(17.7)	54.6	(21.5)
L 30		41.9	(16.5)	50.8	(20.0)	57.7	(22.7)
L 15		48.3	(19.0)	55.1	(21.7)	62.2	(24.5)
0		54.6	(21.5)	59.7	(23.5)	66.0	(26.0)
R 15		58.4	(23.0)	63.5	(25.0)	71.1	(28.0)
R 30		61.0	(24.0)	66.0	(26.0)	74.2	(29.2)
R 45		64.8	(25.5)	69.1	(27.2)	76.2	(30.0)
R 60		67.3	(26.5)	71.6	(28.2)	78.0	(30.7)
R 75		67.8	(26.7)	71.6	(28.2)	78.7	(31.0)
R 90		69.1	(27.2)	72.4	(28.5)	78.7	(31.0)
R 105		67.3	(26.5)	72.4	(28.5)	78.7	(31.0)
R 120				69.9	(27.5)	74.9	(29.5)
R 135				64.8	(25.5)	71.6	(28.2)
R 150				48.3	(19.0)	63.5	(25.0)
R 165						57.2	(22.5)
180							

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

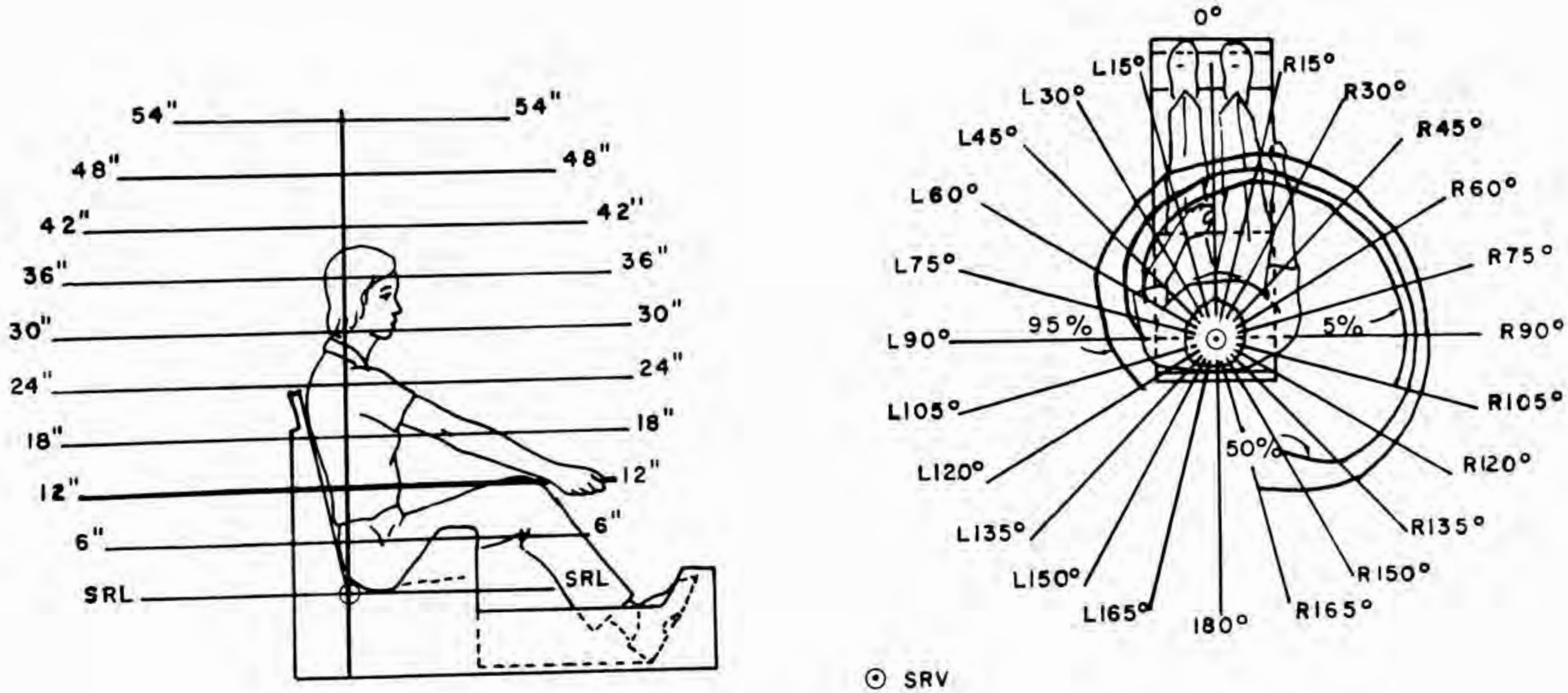


Figure 16. Women's grasping reach to a horizontal plane 12 inches above the seat reference point.

TABLE 15

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE 45 CENTIMETERS (18 in.) ABOVE THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 17

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165							
L 150							
L 135							
L 120						35.6	(14.0)
L 105				27.9	(11.0)	39.4	(15.5)
L 90		26.7	(10.5)	33.0	(13.0)	43.7	(17.2)
L 75		29.7	(11.7)	38.1	(15.0)	50.0	(19.7)
L 60		35.6	(14.0)	45.0	(17.7)	53.3	(21.0)
L 45		42.4	(16.7)	50.0	(19.7)	58.4	(23.0)
L 30		47.5	(18.7)	54.6	(21.5)	61.5	(24.2)
L 15		50.8	(20.0)	58.4	(23.0)	66.0	(26.0)
0		57.2	(22.5)	62.7	(24.7)	69.9	(27.5)
R 15		61.5	(24.2)	66.5	(26.2)	74.9	(29.5)
R 30		64.8	(25.5)	69.9	(27.5)	76.7	(30.2)
R 45		67.8	(26.7)	72.9	(28.7)	78.7	(31.0)
R 60		70.4	(27.7)	74.9	(29.5)	81.3	(32.0)
R 75		70.4	(27.7)	75.4	(29.7)	81.3	(32.0)
R 90		71.1	(28.0)	76.2	(30.0)	80.5	(31.7)
R 105		69.9	(27.5)	76.7	(30.2)	81.8	(32.2)
R 120				72.9	(28.7)	78.7	(31.0)
R 135						71.6	(28.2)
R 150						38.1	(15.0)
R 165							
180							

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

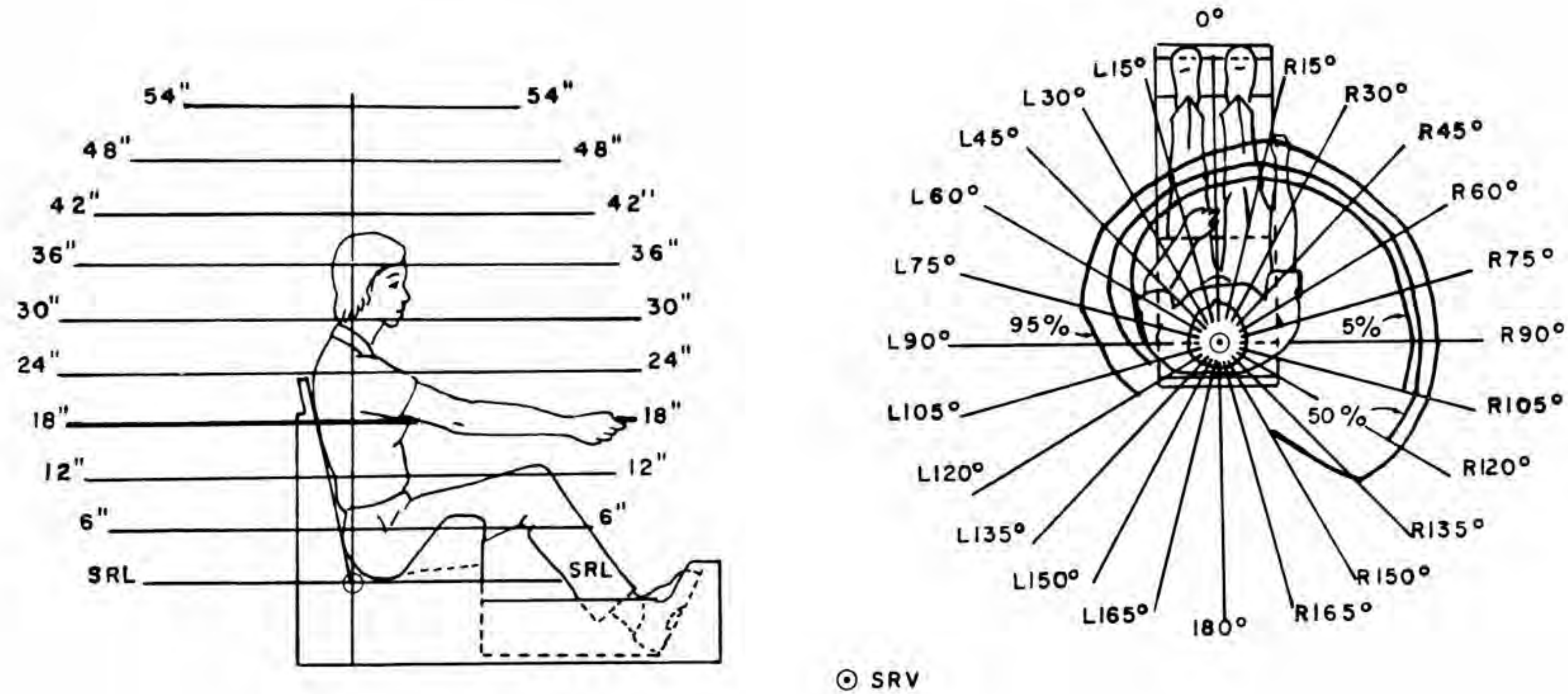


Figure 17. Women's grasping reach to a horizontal plane 18 inches above the seat reference point.

TABLE 16

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
61 CENTIMETERS (24 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 18

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165				22.9	(9.0)	38.1	(15.0)
L 150				22.9	(9.0)	40.6	(16.0)
L 135				27.2	(10.7)	35.6	(14.0)
L 120				25.4	(10.0)	42.4	(16.7)
L 105		20.3	(8.0)	31.0	(12.2)	48.3	(19.0)
L 90		25.4	(10.0)	37.3	(14.7)	45.0	(17.7)
L 75		29.2	(11.5)	40.6	(16.0)	53.3	(21.0)
L 60		36.1	(14.2)	47.0	(18.5)	54.6	(21.5)
L 45		43.2	(17.0)	50.8	(20.0)	59.7	(23.5)
L 30		48.3	(19.0)	55.1	(21.7)	62.7	(24.7)
L 15		52.1	(20.5)	58.4	(23.0)	66.0	(26.0)
0		55.9	(22.0)	63.5	(25.0)	71.1	(28.0)
R 15		59.7	(23.5)	66.5	(26.2)	74.9	(29.5)
R 30		63.5	(25.0)	69.9	(27.5)	76.7	(30.2)
R 45		66.5	(26.2)	72.4	(28.5)	78.7	(31.0)
R 60		67.8	(26.7)	74.2	(29.2)	81.3	(32.0)
R 75		68.6	(27.0)	76.2	(30.0)	81.3	(32.0)
R 90		69.9	(27.5)	77.5	(30.5)	81.3	(32.0)
R 105		69.1	(27.2)	76.7	(30.2)	81.8	(32.2)
R 120		33.0	(13.0)	72.4	(28.5)	78.7	(31.0)
R 135		27.9	(11.0)	35.6	(14.0)	68.6	(27.0)
R 150		22.9	(9.0)	30.5	(12.0)	55.9	(22.0)
R 165		20.8	(8.2)	28.4	(11.2)	45.7	(18.0)
180				27.9	(11.0)	40.6	(16.0)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

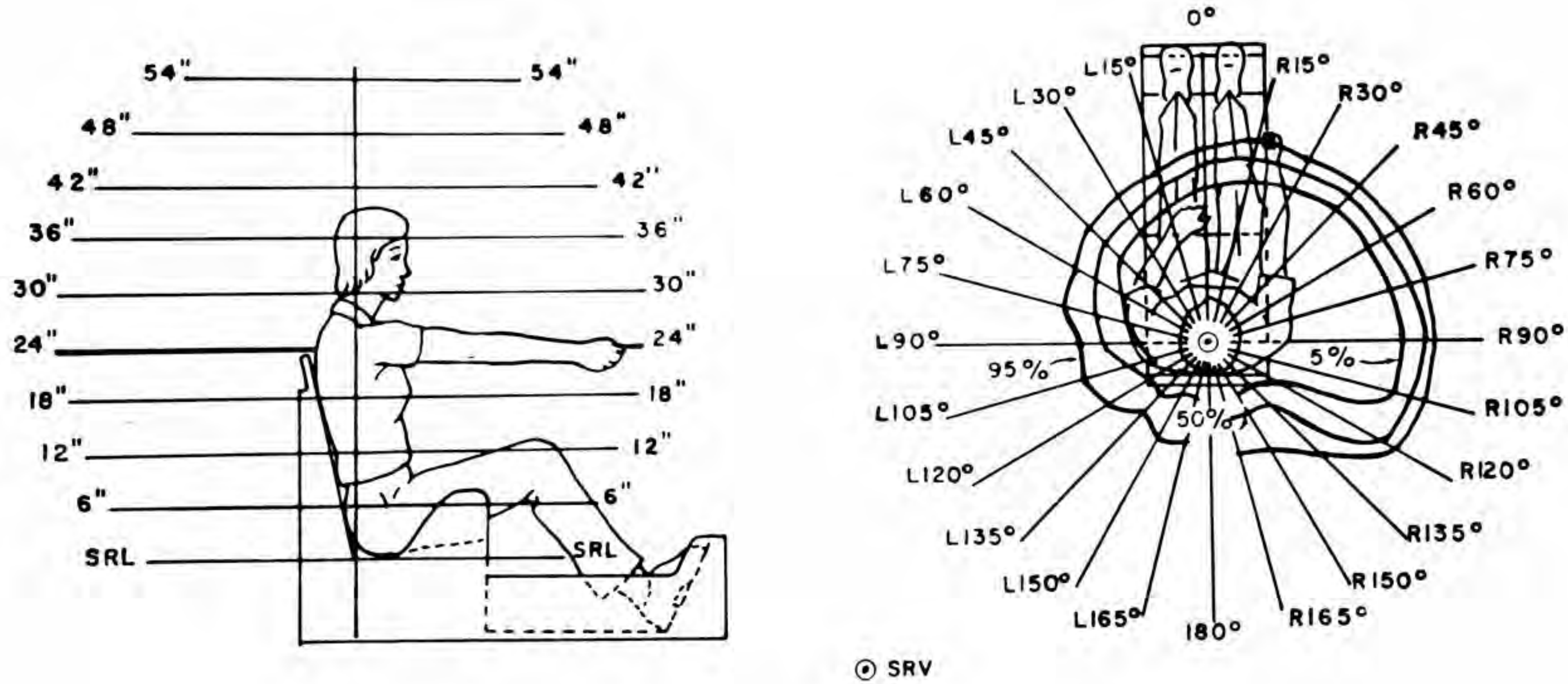


Figure 18. Women's grasping reach to a horizontal plane 24 inches above the seat reference point.

TABLE 17

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
76.2 CENTIMETERS (30 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 19

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165		18.3	(7.2)	31.8	(12.5)	48.8	(19.2)
L 150		15.7	(6.2)	30.5	(12.0)	41.9	(16.5)
L 135		17.0	(6.7)	22.1	(8.7)	38.6	(15.2)
L 120		17.8	(7.0)	27.2	(10.7)	43.2	(17.0)
L 105		16.5	(6.5)	30.5	(12.0)	45.7	(18.0)
L 90		22.1	(8.7)	33.0	(13.0)	43.7	(17.2)
L 75		25.4	(10.0)	39.4	(15.5)	50.8	(20.0)
L 60		33.0	(13.0)	44.5	(17.5)	53.3	(21.0)
L 45		38.1	(15.0)	48.3	(19.0)	55.9	(22.0)
L 30		43.2	(17.0)	52.1	(20.5)	61.5	(24.2)
L 15		46.2	(18.2)	55.9	(22.0)	64.0	(25.2)
0		50.8	(20.0)	58.4	(23.0)	68.6	(27.0)
R 15		54.6	(21.5)	62.2	(24.5)	71.6	(28.2)
R 30		57.2	(22.5)	65.3	(25.7)	73.7	(29.0)
R 45		58.9	(23.2)	69.9	(27.5)	75.4	(29.7)
R 60		62.2	(24.5)	70.4	(27.7)	77.5	(30.5)
R 75		64.0	(25.2)	72.4	(28.5)	76.7	(30.2)
R 90		65.3	(25.7)	72.9	(28.7)	78.7	(31.0)
R 105		66.0	(26.0)	73.7	(29.0)	78.7	(31.0)
R 120		41.1	(16.2)	66.5	(26.2)	74.9	(29.5)
R 135		32.3	(12.7)	49.5	(19.5)	69.9	(27.5)
R 150		27.9	(11.0)	41.1	(16.2)	59.7	(23.5)
R 165		26.7	(10.5)	39.4	(15.5)	55.9	(22.0)
180		24.1	(9.5)	38.1	(15.0)	50.8	(20.0)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

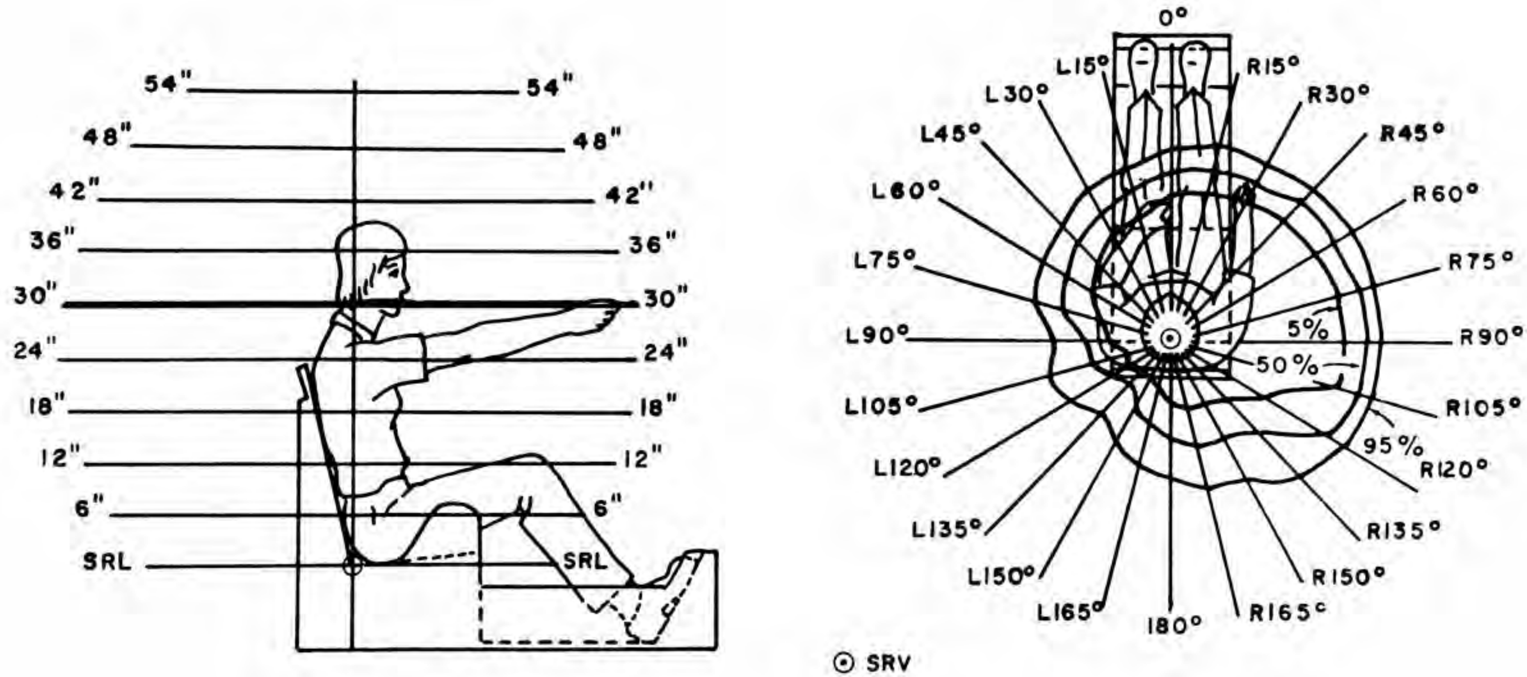


Figure 19. Women's grasping reach to a horizontal plane 30 inches above the seat reference point.

TABLE 18

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
91.4 CENTIMETERS (36 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 20

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165		22.9	(9.0)	33.0	(13.0)	49.5	(19.5)
L 150		20.3	(8.0)	29.2	(11.5)	45.0	(17.7)
L 135		18.3	(7.2)	25.9	(10.2)	40.6	(16.0)
L 120		18.3	(7.2)	25.4	(10.0)	39.4	(15.5)
L 105		18.3	(7.2)	26.7	(10.5)	38.6	(15.2)
L 90		19.6	(7.7)	29.2	(11.5)	40.6	(16.0)
L 75		20.8	(8.2)	33.0	(13.0)	43.7	(17.2)
L 60		25.4	(10.0)	36.1	(14.2)	45.7	(18.0)
L 45		29.2	(11.5)	39.4	(15.5)	49.5	(19.5)
L 30		33.5	(13.2)	43.7	(17.2)	54.6	(21.5)
L 15		36.1	(14.2)	48.3	(19.0)	57.7	(22.7)
0		41.1	(16.2)	52.1	(20.5)	61.0	(24.0)
R 15		44.5	(17.5)	54.6	(21.5)	62.7	(24.7)
R 30		47.0	(18.5)	57.2	(22.5)	66.0	(26.0)
R 45		48.8	(19.2)	61.0	(24.0)	68.6	(27.0)
R 60		52.6	(20.7)	63.5	(25.0)	70.4	(27.7)
R 75		53.3	(21.0)	64.8	(25.5)	71.1	(28.0)
R 90		56.4	(22.2)	66.5	(26.2)	72.9	(28.7)
R 105		53.8	(21.2)	66.5	(26.2)	72.9	(28.7)
R 120		46.2	(18.2)	63.5	(25.0)	70.4	(27.7)
R 135		31.8	(12.5)	48.3	(19.0)	65.3	(25.7)
R 150		25.4	(10.0)	43.7	(17.2)	59.7	(23.5)
R 165		25.9	(10.2)	40.6	(16.0)	55.9	(22.0)
180		24.1	(9.5)	38.6	(15.2)	53.8	(21.2)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

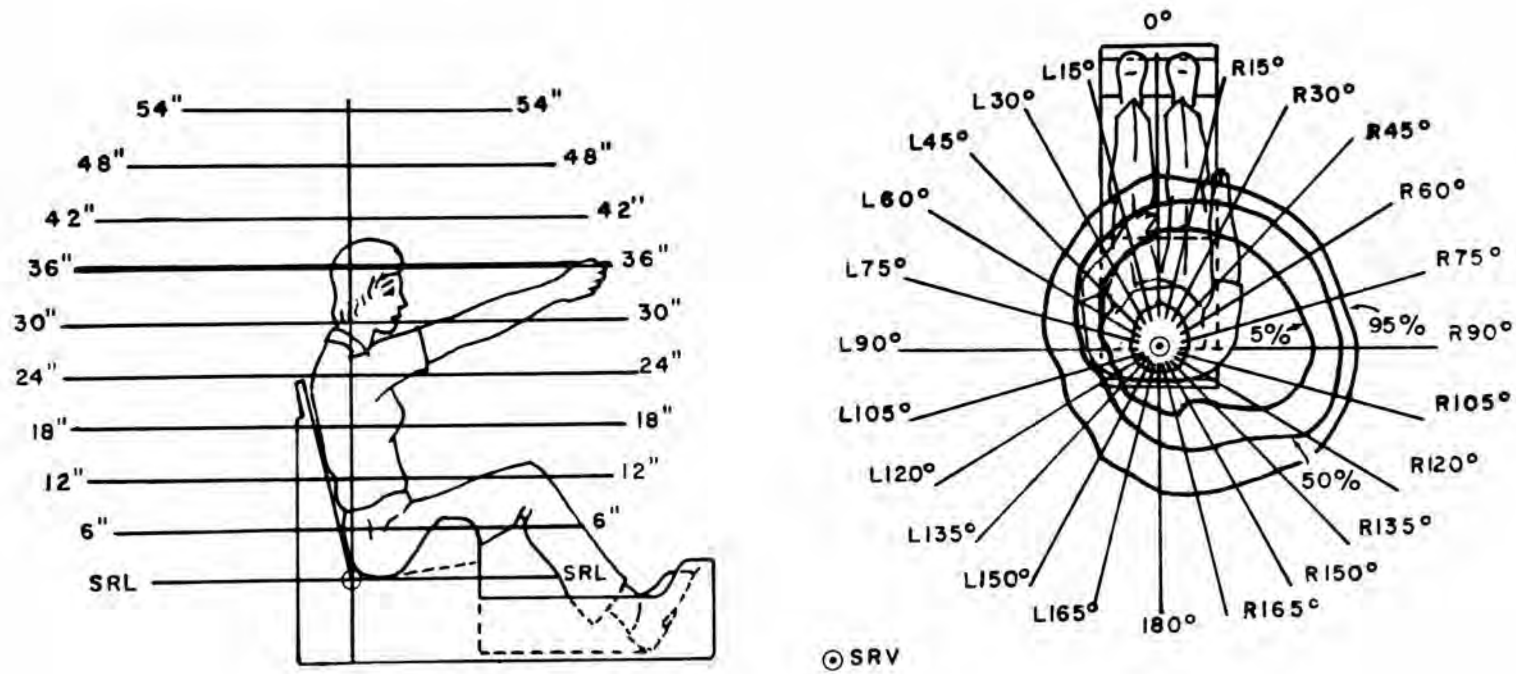


Figure 20. Women's grasping reach to a horizontal plane 36 inches above the seat reference point.

TABLE 19

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE 106.7 CENTIMETERS (42 in.) ABOVE THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV.*

See Figure 21

Angle to Left or Right	Minimum	Percentiles					
		5		50		95	
L 165		12.7	(5.0)	25.9	(10.2)	43.2	(17.0)
L 150		10.7	(4.2)	22.9	(9.0)	38.1	(15.0)
L 135		9.4	(3.7)	21.6	(8.5)	34.8	(13.7)
L 120		8.9	(3.5)	20.3	(8.0)	33.0	(13.0)
L 105		8.1	(3.2)	20.3	(8.0)	31.8	(12.5)
L 90		8.9	(3.5)	20.3	(8.0)	33.0	(13.0)
L 75		9.4	(3.7)	22.1	(8.7)	36.8	(14.5)
L 60		10.2	(4.0)	24.1	(9.5)	41.1	(16.2)
L 45		11.9	(4.7)	26.7	(10.5)	40.6	(16.0)
L 30		14.0	(5.5)	29.2	(11.5)	43.2	(17.0)
L 15		16.5	(6.5)	31.8	(12.5)	45.0	(17.7)
0		19.1	(7.5)	35.6	(14.0)	47.0	(18.5)
R 15		22.9	(9.0)	40.6	(16.0)	48.3	(19.0)
R 30		25.4	(10.0)	43.2	(17.0)	52.1	(20.5)
R 45		28.4	(11.2)	44.5	(17.5)	55.9	(22.0)
R 60		30.5	(12.0)	48.3	(19.0)	57.2	(22.5)
R 75		33.0	(13.0)	50.8	(20.0)	59.7	(23.5)
R 90		35.6	(14.0)	50.8	(20.0)	61.0	(24.0)
R 105		35.6	(14.0)	52.1	(20.5)	61.0	(24.0)
R 120		30.5	(12.0)	47.0	(18.5)	59.7	(23.5)
R 135		23.4	(9.2)	39.4	(15.5)	53.8	(21.2)
R 150		19.1	(7.5)	35.6	(14.0)	50.0	(19.7)
R 165		16.5	(6.5)	31.0	(12.2)	48.3	(19.0)
180		14.0	(5.5)	27.9	(11.0)	47.5	(18.7)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

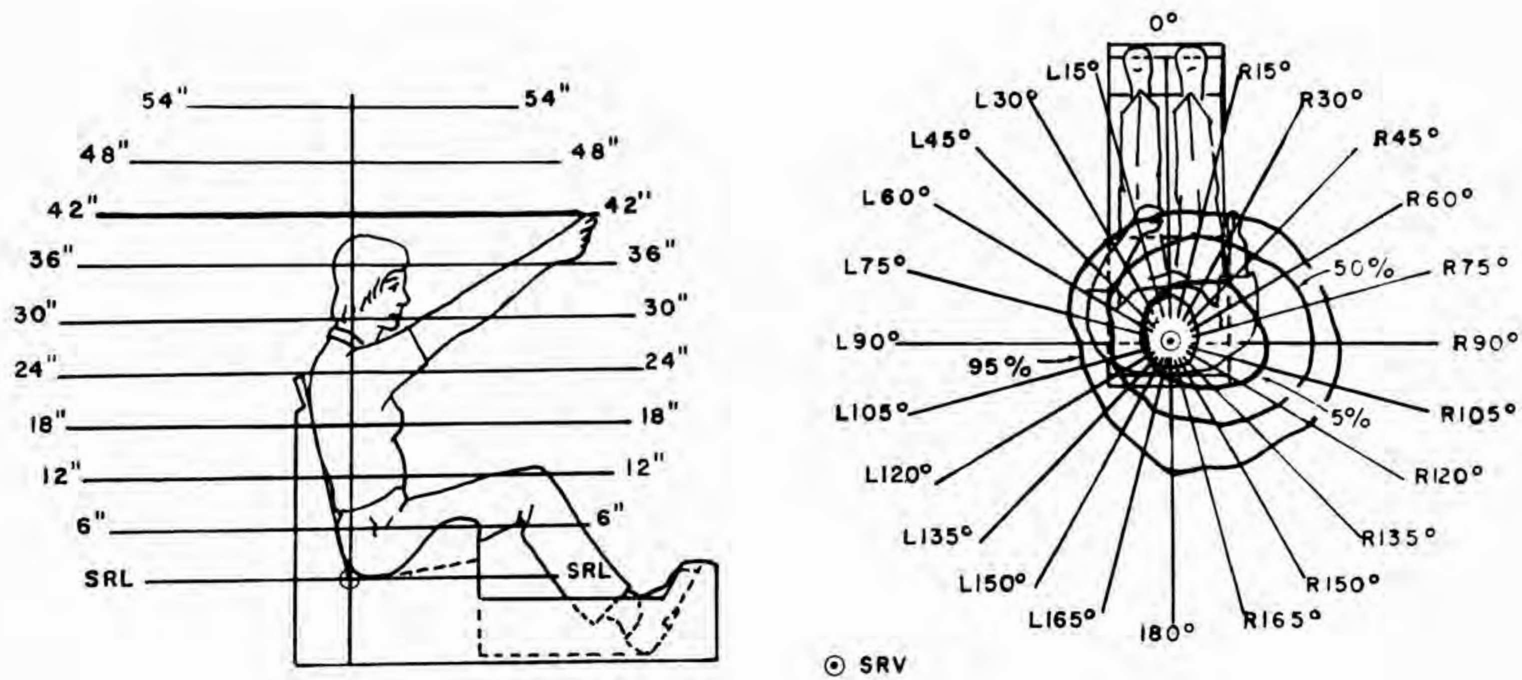


Figure 21. Women's grasping reach to a horizontal plane 42 inches above the seat reference point.

When backrest angles are changed, however, there will be corresponding changes in the functional reaches attainable--assuming other factors remain constant. As the angle of the backrest increases from 103° the shoulders will move rearward, and forward reach distances will be correspondingly reduced; as the backrest assumes a more vertical position, forward reaches will be increased. Both Ely, Thomson and Orlansky (1963) and Bullock (1974) have dealt with the question of changes in reach as a function of changes in backrest angle. Data from the first of these reports indicate that a change in backrest angle from 103° to the vertical (or 90°) results in an increase in directly forward functional reach of about 5 inches (12.7 cm.), or approximately 0.4 inches (1.0 cm.) for each one degree of backrest change. This holds for the area at shoulder height to about 11 inches (27.9 cm.) below this level. This study did not report data for reaches other than straight ahead.

The Bullock study did investigate changes in other angular reaches as a function of changes in backrest angle. Here, it was reported that at a level of 14 inches (35.6 cm.) above the SRP, reaches to the side, or 90° from the midline, were affected least. Differences in reach with backrest change were maximal in the area around 15° from the right of the midline, thereafter decreasing to both the right and left. Changes with a decrease in backrest angle (towards the vertical) were not determined by Bullock, but extrapolation from the above data indicates that, with a vertical backrest, maximal functional forward reaches would be increased above those taken at 103° by about 5.0 inches (12.7 cm.) in reaches made directly to the front, a value that agrees with that of Ely et al. Combining the results of the two studies, we show in Table 20, the increments or decrements, in functional arm reaches that would be expected to result from each one degree of change in backrest angle from the 103° conditions under which the date in Tables 2-19 were obtained. As an example, a change in backrest from 103° to 90° (vertical), would increase 45° angular reach by 13 x 0.37 inches or 4.8 inches (12.2 cm.). It should be noted that these correction factors are expected to be reasonably accurate except for reaches to the highest levels, where the increments will become smaller, with the least change for reach directly overhead.

When shoulders are not kept in contact with the backrest, differences are difficult to quantify because of the great variability in arm reaches afforded by free body movement and by the variability of restrictions caused by different clothing and equipment assemblies. Basic functional reach data are those that are taken under conditions of torso restraints, as in the present Tables 2-19. Here, with the use of the factors in Table 20, corrections may be made to convert the data to vertical backrest conditions--which is the equivalent of defining the arm reach from a vertical plane in back of the shoulder, a useful concept. For example, adding approximately 5 inches (12.7 cm.) to any 0° degree arm reach in Tables 2-19 will give a back-of-the-shoulder-to-finger-grasp reach dimension.

In any event, the practical problems suggested by such differences in backrest angle and body movement clearly indicate the need for further, definitive studies to more accurately determine the best means of transforming existing data in such a way that they will have applicability under differing kinds of conditions.

Zero-G Conditions - Unrestrained or Partially Restrained Body Movement

Another consideration in utilizing the present arm reach data relates to the changes in working conditions in a zero-g environment, where we are normally dealing with the operator in a neutral body position. Here the body may be either totally unrestrained, or partially restrained--in the latter case probably by means of a foot restraint system.

When the body is totally unrestrained, or "free-floating", problems of design layout relative to functional reach would appear to be minimal. With no restraints on body movement, anyone, regardless of body size or related functional reach, should be able to reach to virtually any physically accessible location in or around the workspace with a minimum of difficulty.

With the body restrained or anchored at the feet, zero-g experience in Skylab has led to the observation that for body size in general and arm reach in particular "...the (design) limitations of work stations to 38 inches (96.5 cm.) width...and the use of foot restraints that can be positioned to any height will provide for all possible sizes of 5th to 95th percentile populations" (Thompson, 1975). It is quite true that the ability to position the feet of the operator at any of a variety of positions for body restraint in a zero-g environment lends a dimension of adjustability to the workspace that is not normally found under terrestrial conditions. As a consequence, the much greater flexibility that is afforded for body positioning makes the layout of workspaces and controls on the basis of functional arm reaches considerably easier under zero-g conditions. Deficiencies in arm reach resulting from even markedly smaller body size can be compensated for by the simple expedient of moving the foot restraint position up or down, in or out.

In addition, as a result of zero-g experience in Skylab, it has been stated that the neutral body posture at console stations enables a crewman to "reach approximately 0.4 meter (15.7 inches) beyond his normal seated reach" (Johnson, 1975). Granted that this is an approximation, and that this value would not necessarily apply equally to all reach positions within a workspace, it nevertheless gives a clear indication of the very substantial increases in functional reach that can be expected as part of the normal zero-g working conditions. Adding 15.7 inches (39.9 cm.), or even somewhat less to allow for a "safety factor", to the reach dimensions in Tables 2-19, will greatly simplify the task of providing workspace and control accessibility in Space Shuttle-Spacelab, especially in conjunction with the greatly expanded reach capability afforded by body repositioning through adjustable foot restraint positions.

For these reasons, it would seem that workspace layout and control locations for weightlessness operations should present relatively few problems to the designer. Nevertheless, there may be occasions in which it is necessary to estimate certain reach dimensions with the body in a fixed position. Here the data in Tables 2-19 may again be used. The first correction, as before, should be to change the data from a 103° backrest to a vertical one; reach dimensions can then be assumed to start, functionally, from the back of the shoulder (instead of from the seat reference vertical - SRV). Specific examples are as follows: From Table 20 the appropriate increments can be added to accomplish this purpose, i.e., 5.2 inches (13.2 cm.) to the tabular data for direct forward reach (13° x 0.40); 6.5 inches (16.5 cm.) at 15° ; 5.8 inches (14.7 cm.) at 30°; 4.8 inches (12.2 cm.) at 45° ; 3.3 inches (8.4 cm.) at 60°; 1.8 inches (4.6 cm.) at 75°; and 1.3 inches (3.3 cm.) at 90°. Thus, if a fixed position of the shoulder is assumed, functional reaches can be estimated on the above basis.

Shoulder position will, of course, be dependent in large part upon the locations of the various foot rest surfaces, and the "stature" of the individual in the neutral body position, to which must be added perhaps one to one and one half inches for the shoe restraint suction-cup system.

Conversion Techniques for Different Populations

The functional arm reach measurements presented in Tables 2-19 were taken on healthy, young, adult, U.S. males and females selected to be anthropometrically representative of U.S. Air Force populations. As such they may be assumed to have certain similarities, and some differences, with the intended Space Shuttle-Spacelab populations. Air Force flying personnel and spaceflight groups may be assumed, physically and in terms of body size, to have much in common. First of all they must both be healthy and in good physical condition. Here the requirements for spaceflight crews will, if anything, be more rigid than those for the military generally. In terms of age, the space crews may be more mature, but are not likely to be elderly. They will both be somewhat above average socio-economically and educationally, with the space crews probably markedly higher in the latter category.

All these characteristics tend to be associated positively with larger body size. Spaceflight crews therefore, would be expected on this basis to be at least as large, or possibly larger, than U.S. Air Force flying personnel. Sex differences in body size are also important since both men and women will be represented in the project, but reach data are available separately on both sexes.

The major population differences that will need to be taken into account are those related to nationality and secular change. Ethnic or national differences in body size will be important since not only U.S. personnel will be manning the Spacelab, but probably some Europeans, and perhaps Asiatics, as well. Secondly, since Space Shuttle-Spacelab operations are planned through 1980-1990, and since we know that there is some apparently continuing increase in body size over time, we can anticipate, all other things being equal, a slightly larger spacecraft population in the future.

TABLE 20

APPROXIMATE CHANGES IN ARM REACHES IN TABLES 2-19 AS A FUNCTION OF VARIATION IN SEAT BACKREST ANGLE*

Direction of arm reach (from 0° or "straight ahead," to 90° to the right)	Approximate changes in reach for each single degree of change in backrest angle (reach increases as backrest angle moves to vertical, and vice versa)
0°	± 1.02 cm. (± 0.40 in.)
15°	± 1.27 cm. (± 0.50 in.)
30°	± 1.14 cm. (± 0.45 in.)
45°	± 0.94 cm. (± 0.37 in.)
60°	± 0.66 cm. (± 0.26 in.)
75°	± 0.36 cm. (± 0.14 in.)
90°	± 0.25 cm. (± 0.10 in.)

*Derived from Ely et al. (1963) and Bullock (1974).

With regard to the latter consideration, it should be pointed out that both the male and female populations for which the arm reach data are presented are above average in body size. They are, in fact, very close to the projected 1980 statures for males and females, and functional reach tends to be highly correlated with stature. Specifically, mean stature of present arm reach males is 69.6 inches (176.8 cm.); projected 1980 mean male stature is 69.5 inches (176.5 cm.). Mean stature of arm reach females is 64.1 inches (162.8 cm.); projected 1980 mean female stature is 64.2 inches (163.1 cm.). In other words, the secular increase in body size need not be taken into account in planning for functional arm reaches of Space Shuttle-Spacelab populations through 1980. For projections for 1990, a further stature increase for males of 0.5 inches (1.3 cm.), and 0.4 inches (1.0 cm.) for females might be postulated, though this is an upper, outside, estimate. Due to the apparent slowing of secular "growth" recently noted for the population from which U.S. astronauts come, any such increase over that 10 year period, would likely be less than those values with rather minimal effects on functional arm reach.

Ethnic, or national, differences in body size, and therefore in functional arm reach, on the other hand, can be of considerable importance. In general, Northwest Europeans will be fairly similar in body size to our United States populations, Southern or Eastern Europeans somewhat smaller, and Asiatics, especially Southeastern Asiatics, the smallest of all. Since the major area of concern relative to functional arm reach is almost always that of the smallest person with the shortest reaches, attention should be directed to the smallest persons likely to be utilizing Spacelab work areas. The 5th percentile Asiatic female would appear to be the most likely candidate, although it should be remembered that personnel selection on the basis of body size, could be employed to establish any desired lower limits of body size.

The present female arm reach data in Tables 12-19 are based on a U.S. population, and the 5th percentile values will therefore be somewhat larger than the corresponding 5th percentile reaches of Asiatic females. Unfortunately, anthropometric data on Southeast Asiatic females comparable to that on U.S. females are not available. Such data on males are available, however, and comparisons between South Vietnamese military groups (one of the very smallest world populations in terms of body size) show that in terms of stature and related body measurements, 5th percentile Vietnamese military personnel have values about 90% of those of 5th percentile U.S. Air Force flying personnel. Comparable percentages for anatomic arm lengths is about 93-94%. Presumably, the corresponding relationships between 5th percentile female Vietnamese and 5th percentile U.S. females would not be too different.

While it is true that functional reach dimensions are not determined solely by static body dimensions, there is nevertheless a strong positive correlation between the two types of measurements (Stoudt, 1973), and it is not unreasonable therefore to assume the same kind of percentage relationship relative to 5th percentile functional reaches. If this is done, the use of a 90% factor applied to the 5th percentile female data in Tables 12-19 should provide a conservative estimate of the 5th percentile functional reach of a very small Asiatic female population. This would be the lower limit of functional reaches to be accommodated.

Leg Reach Data and Its Applications

As compared to the relatively voluminous data available on functional arm reaches from a variety of studies, leg reach data may be said to be minimal. There is, in fact, not one study dealing with leg reaches that has been carried out in the detailed manner of any of the more comprehensive arm reach studies. The single best available study is that of Laubach and Alexander (n.d.), as yet unpublished. Measurements were taken of knee heights and heel point positions in both favored or "comfortable", and maximally extended leg positions.

However, neither these nor any other leg reach data would seem to have any special applicability to Spacelab conditions. Neither the zero-g condition, nor the neutral body position, unrestrained or partially restrained, would appear to be particularly appropriate for the use of foot controls, especially if some type of foot or shoe restraint system is employed. It is true that the Space Shuttle pilot and co-pilot locations might require foot controls similar to those in present day aircraft, but here existing design specifications should be adequate since (presumably) the personnel would be similar in body size and leg reach to U.S. Air Force flying personnel. It is only in Spacelab, with its potentially wide range of body size variability, e.g., 95th percentile U.S. male to 5th percentile Asiatic female, that design problem of leg reach accommodation might have been expected to occur.

It is not, therefore, considered advisable to make recommendations relative to functional leg reaches in Skylab for the following reasons: (1) first and most importantly, the lack of any adequate body of anthropometric data defining functional leg reaches for male and female populations; (2) the difficulties of using foot controls in a zero-g environment, especially with a foot restraint, shoe suction-cup system; and (3) finally, the lack of any apparent clear-cut need for foot controls in the Spacelab working environment.

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CHAPTER VI

RANGE OF JOINT MOTION

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The range of motion of body joints is obviously an important factor in the assessment of body mobility or in the determination of arm and leg reach capabilities. In Chapter V, Stoudt discussed many of the problems faced by the design engineer who must determine the capability of the operator to reach, grasp, and actuate various controls. The information presented in this chapter, integrated with Stoudt's work, should enable the designer to better lay out work stations.

In this chapter we will discuss (1) selected reviews of the range of joint motion literature; (2) techniques for measuring range of joint motion; (3) range of joint motion terminology; (4) recommended range of joint motion data for the design engineer; (5) differences in the range of joint motion due to the effects of age; (6) differences in range of joint motion between men and women; (7) the assessment of differences in range of joint motion caused by protective clothing; and (8) the range of joint motion of selected two-joint muscles.

Selected Review of the Literature

The best of the several reviews of the literature pertaining to the range of joint motion measurement are those by Holland (1968) and Clarke (1975). These two papers cite 136 and 55 references, respectively, pertaining to different aspects of the range of joint motion. Although they are geared toward the physical educator and the physical therapist, these two excellent reviews point out many of the kinds of problems the design engineer will encounter when dealing with range of motion data. For example, the following generalizations, drawn from Holland's paper are pertinent to the concerns of design engineers:

(1) There appears to be little agreement with regard to the definition and limits of so-called normal flexibility, and with regard to what constitutes hypo- or hyper-flexible joint range of motion.

(2) There appears to be general agreement that range of joint motion is a highly specific factor and that measurement of one or several body joints cannot be used to validly predict range of motion in other body parts.

(3) The use of linear techniques to measure rotational joint motion involves rather gross mathematical error; they should not be used for the collection of objective clinical or experimental data. Although there is

conflicting evidence, it appears also that individual limb and trunk length variability may significantly affect the validity of linear range of motion measurements.

Techniques for Measuring Range of Joint Motion

The problem of accurately evaluating the range of motion of body joints has been, and continues to be, a perplexing one. A number of techniques and devices have been proposed for measuring range of joint motion but none has received widespread acceptance. Adrian (1968), the American Academy of Orthopedic Surgeons (1965), Ayoub (1972), Clarke (1975), Dempster (1955), Garrett, Widule, and Garrett (1968), Holland (1968), Leighton (1955), Miller and Nelson (1973), Plagenhoff (1971) and Roebuck, Kroemer, and Thomson (1975) have discussed in some detail the advantages and disadvantages of past and current techniques and equipment. It is beyond the scope of this chapter to discuss each of these techniques and procedures. The reader who is interested in knowing more about range of joint motion measuring techniques and equipment is referred to the above mentioned sources. However, because the majority of the data we will present later in this chapter have been developed from goniometry, the Leighton flexometer, and photography, we will briefly discuss these techniques.

The goniometer consists of a 180-degree protractor, usually made of plexiglass, with extended arms approximately 40 centimeters long. One of the arms is fixed to the zero line of the protractor while the other is movable. Although the goniometer is a very simple device and is subject to inherent errors in measurement due to the complexity of human body joint movements, it provides an extremely valuable tool for range of joint motion analysis.

The flexometer was developed by Leighton (1955) for measuring joint angles without regard to shifting joint centers. This instrument has a rotating, weighted 360-degree dial and a weighted, movable pointer mounted in a glass-enclosed metal case. The dial and the pointer operate independently and are balanced so they always point upward. The movements of the dial and the pointer are controlled by gravity. The flexometer is strapped to the segment being tested. The dial is locked at one extreme position (e.g., full flexion of the knee) and the pointer is locked at the other after complete movement of the joint has been effected (e.g., full extension of the knee). A direct reading of the pointer on the dial gives the range of joint movement in angular degrees. Leighton has developed 19 range of joint motion tests: neck flexion-extension, lateral flexion, and rotation; shoulder flexion-extension, adduction-abduction, and rotation; elbow flexion-extension; radial-ulnar supination-pronation; wrist flexion-extension and ulnar-radial flexion; hip extension-flexion, adduction-abduction, and rotation; knee flexion-extension; ankle flexion-extension and inversion-eversion; trunk flexion-extension, lateral flexion, and rotation. Roebuck (1968) and Roebuck, Kroemer, and Thomson (1975) have discussed the utilization of the flexometer in measuring mobility of men clothed in pressurized and unpressurized space suits.

A photographic method, often employing double exposures, was developed by Dempster (1955) and was used for recording the range of movement of the limb joints. Photographs were made on 35-mm film with an Argus camera by the flash of a speed lamp. The room was darkened and black backgrounds were provided. For double exposures an initial flash exposure recorded one extreme of a joint range; the lens was then kept open following exposure until the subject assumed an opposing position at which point a second flash exposure was made. Parts of the body which would otherwise present a conflicting background for the test joints were covered with black velveteen cloth.

A special work table, painted black, was employed as a support for the subject or his limb segments. Horizontal lines were marked on the table edge with light-reflecting tape to serve as references. Frames of the strip of negatives were projected as enlarged images and the best estimates of link lines connecting joint centers were ruled on paper; horizontal or vertical reference lines were also traced. Angles were then measured with a protractor to the nearest degree.

These techniques have been extensively used and further developed by various researchers working in the area of range of joint motion assessment.

Range of Joint Motion Terminology

The range of joint motion is measured at the angle formed by the long axes of two adjoining body segments, or, in some cases, at the angle formed by one body segment and a vertical or horizontal plane. The total range of movement is measured between the two extreme positions of the joint.

Joint movements in the classical kinesiological terminology are considered to begin from the so-called anatomical position. This position is defined as that of a man standing upright, head facing forward, arms hanging down with palms facing forward. The ten types of joint movement that primarily concern the design engineer are:

(1) Flexion - bending or decreasing the angle between the parts of the body. Supplementing the more commonly measured arm and leg flexions, Kelly (1971) has identified several kinds of flexion to meet special descriptive needs. These are: trunk lateral flexion in which the trunk segments move so as to decrease the angle between them and the right thigh; radial flexion which refers to the movement of the thumb side of the hand toward the radial side of the forearm segments; and ulnar flexion which refers to the opposite side of the hand's movement toward the ulnar side of the forearm segment.

(2) Extension - straightening or increasing the angle between the parts of the body. It is generally defined as the return from flexion. When a joint is extended beyond the normal range of its movement, the movement becomes known as hyperextension.

(3) Abduction - movement of a body segment away from the midline of the body or body part to which it is attached.

(4) Adduction - movement of a body segment or segment combination toward the midline of the body or body part to which it is attached.

(5) Medial rotation - turning toward the midline of the body.

(6) Lateral rotation - turning away from the midline of the body.

(7) Pronation - rotating the forearm so that the palm faces downward.

(8) Supination - rotating the forearm so that the palm faces upward.

(9) Eversion - rotation of the foot which lifts its lateral border to turn the sole or plantar surface outward.

(10) Inversion - lifting the medial border of the foot to turn the sole inward.

Roebuck (1975) firmly believes that the above described classical movement terminology can be misleading and inappropriate. In an effort to provide a more precise terminology for the engineering anthropometrist, Roebuck has developed a very elaborate and comprehensive new system of notation for mobility evaluation. While it is beyond the scope of this chapter to discuss the details of Roebuck's new system, the interested reader is referred to Chapter III, "Measurement of Dynamic Characteristics and Movement," pages 79-92, and Appendix A, Part 3, "Engineering Anthropometry Terminology," pages 423-425 in Roebuck, Kroemer, and Thomson's book entitled Engineering Anthropometry Methods.

Recommended Range of Joint Motion Data for the Design Engineer

In spite of the many techniques and test procedures that have been developed for the measurement of range of joint motion, there is a paucity of descriptive data that can be used by the design engineer. Much of the research has been undertaken by investigators working in the areas of physical education, physical therapy, sports medicine and rehabilitation medicine. Obviously, the research purposes and objectives of these investigators differ greatly from those of the design engineer. Nevertheless, the data which are available do characterize the range of human joint motion for many NASA design applications although the effects of prolonged weightlessness on joint motion have not yet been systematically investigated.

TABLE 1
RANGE OF JOINT MOTION VALUES*
(Barter, Emanuel and Truett, 1957)
MALES

Movement	$\bar{X}$	SD	5%ile	95%ile
Shoulder flexion	188	12	168	208
Shoulder extension	61	14	38	84
Shoulder abduction	134	17	106	162
Shoulder adduction	48	9	33	63
Shoulder medial rotation	97	22	61	133
Shoulder lateral rotation	34	13	13	55
Elbow flexion	142	10	126	159
Forearm supination	113	22	77	149
Forearm pronation	77	24	37	117
Wrist flexion	90	12	70	110
Wrist extension	99	13	78	120
Wrist abduction	27	9	12	42
Wrist adduction	47	7	35	59
Hip flexion	113	13	92	134
Hip abduction	53	12	33	73
Hip adduction	31	12	11	51
Hip medial rotation (prone)	39	10	23	56
Hip lateral rotation (prone)	34	10	18	51
Hip medial rotation (sitting)	31	9	16	46
Hip lateral rotation (sitting)	30	9	15	45
Knee flexion, voluntary (prone)	125	10	109	142
Knee flexion, forearm (prone)	144	9	129	159
Knee flexion, voluntary (standing)	113	13	92	134
Knee flexion forced (kneeling)	159	9	144	174
Knee medial rotation (sitting)	35	12	15	55
Knee lateral rotation (sitting)	43	12	23	63
Ankle flexion	35	7	23	47
Ankle extension	38	12	18	58
Foot inversion	24	9	9	39
Foot eversion	23	7	11	35

*Measurement technique was photography. Subjects were college-age males. Data are in angular degrees.

TABLE 2
RANGE OF JOINT MOTION VALUES*
(Harris and Harris, 1968)
FEMALES

Movement	Mean	SD	5%ile	95%ile
Neck flexion	58.7	10.3	41.7	75.7
Neck extension	89.3	9.9	73.0	105.6
Neck-lateral flexion, right	50.5	7.6	38.0	63.0
Neck-lateral flexion, left	47.2	8.0	34.0	60.4
Neck rotation, right	83.1	10.2	66.3	99.9
Neck rotation, left	78.5	11.2	60.0	97.0
Spine flexion	61.9	11.3	43.3	80.5
Spine extension	29.3	12.5	8.7	49.9
Spine lateral flexion, right	57.8	8.9	43.1	72.5
Spine lateral flexion, left	58.0	8.7	43.6	72.4
Spine rotation, right	65.4	10.6	47.9	82.9
Spine rotation, left	62.8	10.5	45.5	80.1
Shoulder flexion	167.9	10.0	151.4	184.4
Shoulder extension	41.5	10.0	25.0	58.0
Shoulder abduction-adduction	169.5	11.2	151.0	188.0
Shoulder medial rotation	160.0	12.5	139.4	180.6
Shoulder lateral rotation	33.6	11.1	15.3	51.9
Shoulder horizontal abduction	126.6	15.4	101.2	152.0
Shoulder horizontal adduction	38.9	6.6	28.0	49.8
Elbow flexion-extension	151.4	7.1	139.7	163.1
Elbow hyperextension	7.6	6.4	3.0	18.2
Radioulnar supination	88.9	17.1	60.7	117.1
Radioulnar pronation	101.9	15.2	76.8	127.0
Wrist flexion	79.7	15.1	54.8	104.6
Wrist extension	60.6	10.5	43.3	77.9
Wrist abduction	29.7	9.1	14.7	44.7
Wrist adduction	50.4	10.8	32.6	68.2
Hip flexion, center	79.6	14.5	55.7	103.5
Hip flexion, right	94.6	11.3	76.0	113.2
Hip extension, center	15.4	6.6	4.5	26.3
Hip extension, right	18.1	6.2	7.9	28.3
Hip abduction-adduction	71.8	11.6	52.7	90.9
Hip horizontal abduction	49.5	7.9	36.5	62.5
Hip horizontal adduction	25.3	5.6	16.1	34.5
Hip lateral rotation	55.8	9.5	40.1	71.5
Hip medial rotation	43.8	11.6	24.7	62.9
Knee flexion-extension	133.8	7.8	120.9	146.7
Knee hyperextension	11.3	4.9	3.2	19.4
Ankle flexion	18.8	6.2	8.6	29.0
Ankle extension	49.7	8.6	35.5	63.9
Ankle inversion	37.6	10.8	19.8	55.4
Ankle eversion	30.0	9.5	14.3	45.7

*Measurement technique was flexometer. Subjects were college-age females. Data are in angular degrees.

The descriptive range of joint motion data presented in the following tables were selected for their usefulness to design engineers.* Table 1 gives values for males; Table 2 tabulates women's values. The differences which are readily apparent in comparing like measurements can be attributed to two major causes. The first, of course, is the difference in sexes; it can be noted that in many cases where measurements are comparable, one sex or the other appears to be considerably more flexible. (Table 3, in the next section, details percentile differences between selected male and female joint motion measurements). A second source of possible discrepancy between the male and female data is the difference in measurement techniques employed in the two studies.

Variations in Range of Joint Motion Measurements

Differences Between Men and Women

The most carefully controlled study that we know of pertaining to the measured differences in range of joint motion between adult men and women was conducted by Sinelkinoff and Grigorowitsch (1931). Their study of 100 men and 100 women ranging in age from 20 to 50 years, indicated that, in general, women exceed men in range of joint motion measurements at all joints except the knee. Table 3 summarizes the data reported by Sinelkinoff and Grigorowitsch and reveals percentage differences between men and women in range of joint mobility ranging from zero percent for knee flexion-extension, to 17% for wrist adduction-abduction.

TABLE 3
DIFFERENCE IN RANGE OF JOINT MOTION BETWEEN MEN AND WOMEN
(Based on Sinelkinoff and Grigorowitsch, 1931)*

	Men's $\bar{X}$	Women's $\bar{X}$	Difference
Shoulder abduction (rearward)	59.8 **	61.4	103%
Elbow flexion-extension	142.1	149.9	105%
Wrist flexion-extension	141.4	154.0	109%
Wrist adduction-abduction	62.2	72.7	117%
Hip flexion (with extended knee)	83.5	86.8	104%
Hip flexion (with bent knee)	117.9	121.0	103%
Knee flexion-extension	140.5	140.1	100%
Ankle flexion-extension	62.6	66.9	107%

*Percentage differences obtained by dividing the women's reported mean value by the men's reported mean value; e.g., 61.4 divided by 59.8 = 103%.

**Mean values reported in angular degrees.

*Additional sources of specific range of joint motion data include: the American Academy of Orthopaedic Surgeons (1965), Dickinson (1963), Gilliland (1921), Glanville and Kreezer (1937), Kendall and Kendall (1948), Laubach (1970), and Sinelkinoff and Grigorowitsch (1931).

Assessing Differences Caused by Protective Clothing

Like all other dynamic measurements, range of joint motion is significantly affected by bulky protective clothing. Little data has been developed on the modifications in joint motion which occur as a result of heavy clothing assemblies and what data have been generated are of limited value since measurements taken in a given protective garment are not likely to match those taken in another. Since each protective garment is dimensionally unique, the most useful information we can offer NASA design engineers is the description of a method by which joint motion changes can best be evaluated in any suit. A technique which has considerable merit was devised by the Navy to analyze two diving suits and was reported on by Bachrach et al. in 1975. Though not directly relevant to NASA design engineering problems, this study has been chosen for presentation here because of the feasibility of the research design for the practicing engineer and its applicability to the evaluation of joint motion in newly developed NASA pressure suits.

Six male U.S. Navy divers served as subjects. Each subject served as his own control with his baseline measurements taken in a swim suit before donning either of the two diving systems under study. Fourteen range of joint motion measurements were obtained from each subject, both on dry land and in the water. Data was summarized in the following fashion:

		Dry		Wet	
Movement	Swim Suit	Suit I	Suit II	Suit I	Suit II
Trunk Flexion					
Mean	116.4°	103.3°	103.4°	83.1°	84.9°
S.D.	7.5°	7.7°	10.3°	9.9°	15.3°

The summary data were further analyzed to arrive at the mean percentage loss of diver flexibility caused by the two diving suits. These data, shown in Table 4, make it clear that Suit II affords the diver considerable more flexibility than does Suit I.

It is recommended that NASA designers use a comparable method--in which subjects serve as their own controls and the garment is tested under the conditions in which it will be worn--to assess the degree to which newly developed pressure suits hamper movement in their wearers. Joint motions to be measured would, of course, be selected for their relevance to operation in a zero g environment.

The Effects of Age

Under normal circumstances the range of joint motion decreases only slightly during the adult years between age 20 and age 60. West (1945) has reported that between the first and seventh decades of life range of joint motion declines about 10 percent, but no significant changes occur after puberty (Salter and Darcus, 1953). So for all practical purposes the designer can ignore the effects of age on the range of joint motion for the adult population.

TABLE 4
MEAN PERCENTAGE LOSS OF DIVER FLEXIBILITY CAUSED BY TWO DIVING SUITS (Based on Bachrach et al. 1975)

Movement	Dry Suit I	Dry Suit II	Wet Suit I	Wet Suit II
Trunk flexion	11.1%	11.2%	28.5%	26.9%
Trunk extension	26.9	12.5	38.1	26.8
Trunk lateral flexion	27.2	12.3	29.9	31.0
Trunk transverse rotation	42.2	37.8	29.5	31.3
Shoulder joint abduction	40.4	22.1	35.9	17.6
Shoulder joint flexion	47.5	24.1	39.3	16.1
Shoulder joint extension	29.8	20.2	12.9	13.0
Shoulder joint hor. flexion	37.0	23.7	39.0	22.0
Shoulder joint hor. extension	34.6	29.6	23.2	24.9
Elbow flexion	7.9	8.7	6.4	5.4
Knee flexion	24.8	11.1	17.7	8.0
Hip flexion	35.6	32.9	25.1	24.8
Hip extension	46.7	30.0	43.8	31.0
Hip abduction	56.8	42.4	40.8	21.1
Overall mean loss	33.3	22.7	29.3	21.4

Range of Motion of Two-Joint Muscles

Up to this point we have discussed joint motion as though each joint existed in isolation from all others. Most investigations of range of joint motion have been confined to the study of simple planar movement of a single joint and these data are of singular importance in our understanding of human motion as well as of practical value to designers dealing with many problems of workspace layout. The placement of a sidearm controller when the forearm is restrained, for example, is dictated by the range of motion of the wrist alone. However, more often than not, human motion involves the interaction of two or more joints and muscles. Little is known about the effect of one upon the other although we know, for example, that hand pronation is considerably increased if shoulder motion also comes into play.

One common type of dynamic interaction involves two-joint muscles in which the action of one joint may either increase or decrease the effective functioning of the other. The problem of evaluating the range of motion of two-joint muscles has received little attention in the research literature. Brunnstrom (1972), Markee et al. (1955), Steindler (1970), and Rasch and Burke (1971) discuss the biomechanical advantages and disadvantages of two-joint muscles which have potential excursions far beyond the range achieved by one-joint muscles. While this may be an advantage under certain conditions, such interaction may also expose the muscle to the hazards of stretching beyond safe limits (Brunnstrom 1972). The efficiency of the two-joint muscles is substantially influenced by the position of the two joints in accordance with principles governing length-tension relationships of muscles. (The subject has received attention by Basmajian (1957), McLachlin (1969), Olson and Waterland (1967) and Paul (1969) among others.)

There is, however, an almost complete lack of descriptive information in the research literature on specific range of joint motion to show what happens to shoulder flexion, for example, when the elbow is flexed to two-thirds of its total joint range. In a heretofore unpublished piece of research prepared for the Aerospace Medical Research Laboratories, Wright Patterson Air Force Base, Ohio, in 1971, Laubach and McConville reported on an experimental technique for the evaluation of range of motion of selected two-joint muscles. While emphasis in the study was on the development of a usable technique, some of the summary data are presented below.

Using 18 male subjects and a mock-up of a standard USAF aircraft seat (see Figure 1), investigators selected the following two-joint muscle actions for evaluation:

(1) elbow flexion with shoulder extension
(2) shoulder extension with elbow flexion
(3) elbow flexion with shoulder flexion
(4) shoulder flexion with elbow flexion
(5) hip flexion with knee flexion
(6) knee flexion with hip flexion
(7) knee flexion with ankle plantar flexion
(8) ankle plantar flexion with knee flexion
(9) knee flexion with ankle dorsiflexion
(10) ankle dorsiflexion with knee flexion

The experimental protocol for the determination of range of motion for two-joint muscles involved several steps. The range of motion for single joint muscle actions was established by photogoniometry. In our tests, a rapid-sequence camera was used to record the orientation of the segments at the beginning and end of a joint movement. Oversize prints were then made on which the range of motion could be measured. Range of motion for the two-joint muscles was evaluated using a combination of electrogoniometry and photogoniometry. The electrogoniometer was used to assure a positive fix for the distal joint at a point in its range of motion while the adjacent joint was being exercised.

The restrictions in joint motion caused by blockage with another body segment were ignored. For example, elbow flexion is greatly reduced when the shoulder is extended and rotated inward, a decrement caused by the forearm in flexion striking the posterior torso. Every attempt was made to isolate the joint motion to a pure motion in a single plane from a single joint.

Zero Positions for Measurement

A significant problem in studying two-joint muscles is defining the division of the range of movement between flexion and extension, adduction and abduction, etc. If we define the movement of the shoulder in the sagittal plane as extension and flexion, then we must define the origin of the two motions from a common point. In a general sense we might state that the point of origin of the two motions is with the upper arm hanging loosely at the side, or in the mid-axillary line or assuming some other specified orientation. Unless this origin is firmly established--while the total range of joint motion may remain the same--the values for flexion and extension may change radically and show a negative relationship with one another. It has been suggested that the proper measure of flexibility is the total range of motion without attempting to break it down into two discrete movements. Dickinson (1963), however, believes that the two movements which constitute the range of motion to be so poorly related that "adding these two measures of flexibility would be like adding apples and oranges" and suggests that a stable origin point is possible to achieve. We are of a similar opinion and in each instance have divided the total range of motion at a joint into a series of discrete movements. Figures 2-6 define the terminology which applies to the various movements studied and indicate their points of origin.

Test Procedures

The range of joint motion was obtained by measuring the angular change from sequential photos taken when a joint was rotated from its zero position to its maximum.

The generalized test procedure used in the study was as follows: A joint range base line was established for each of the joints to be tested. The base line was measured with the adjacent joints held in the zero position. Each joint was tested twice for agreement and the greater values were used as the joint range of motion. After the base line value was established the adjacent joint was moved to one of two or three intermediate positions (1/2 and total, or 1/3, 2/3 and total range) and the test joint was again exercised throughout its range. The procedure was then reversed with the joint first tested being held at an intermediate point of its range of motion and the adjacent joint being exercised.

The changes in range of motion of a given joint when supplemented by the movement of an adjacent joint are summarized in Table 5. Shown in this table are the base line values of given joint motions with the adjacent joint in neutral position; the increment or decrement which takes place when an adjacent joint is flexed or extended in varying amounts (1/3, 1/2, 2/3 and/or full); and the resulting value as a percentage of the baseline value. For example, the first entry on Table 5 is read as follows: the shoulder can be extended as far as 59.3° (the mean of the subjects tested) with the elbow in a neutral position (locked in hyper-extension). When shoulder extension was measured with the elbow flexed to 1/3 of its full joint range, the mean

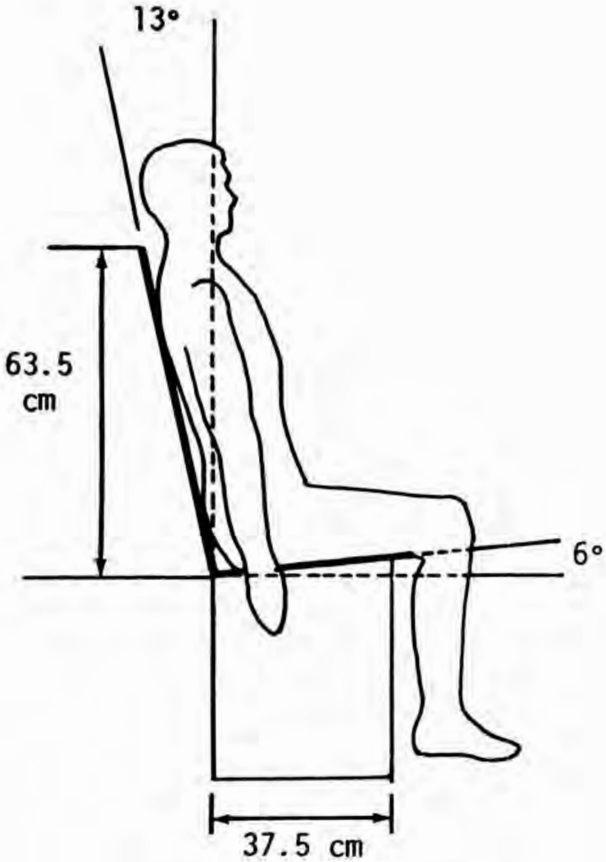

Figure 1. Two-joint muscle test apparatus.

Figure 2. Shoulder extension-flexion.

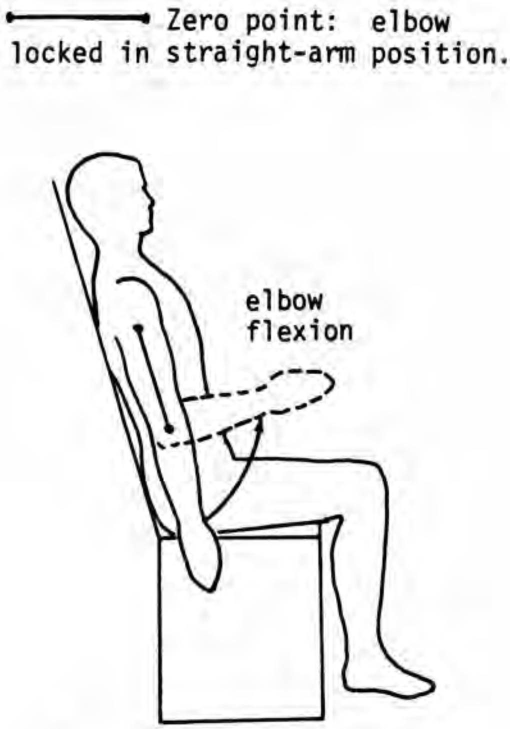

Figure 3. Elbow flexion.

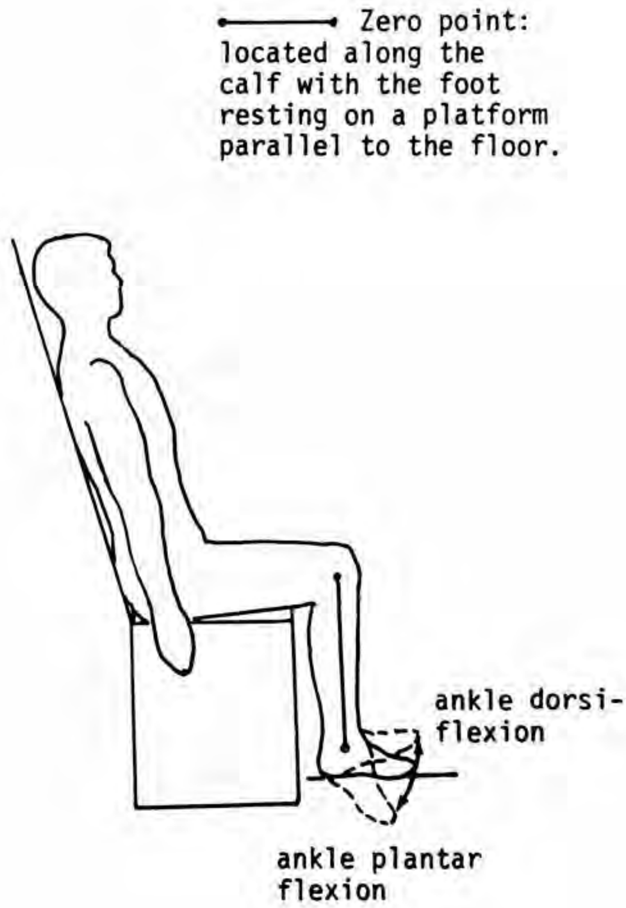

Figure 4. Ankle flexion.

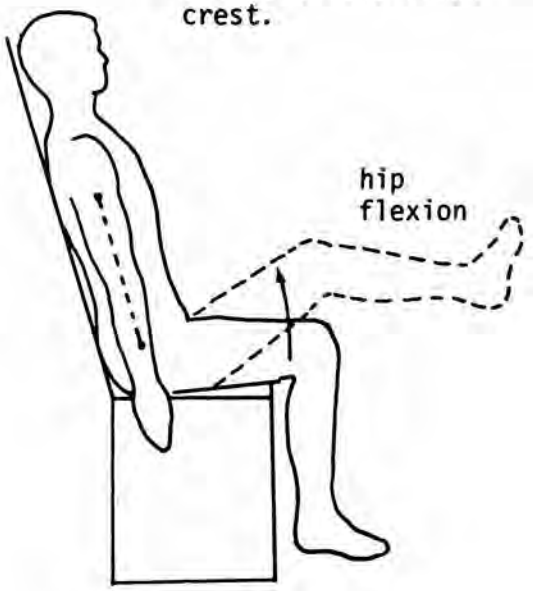

Figure 5. Hip flexion.

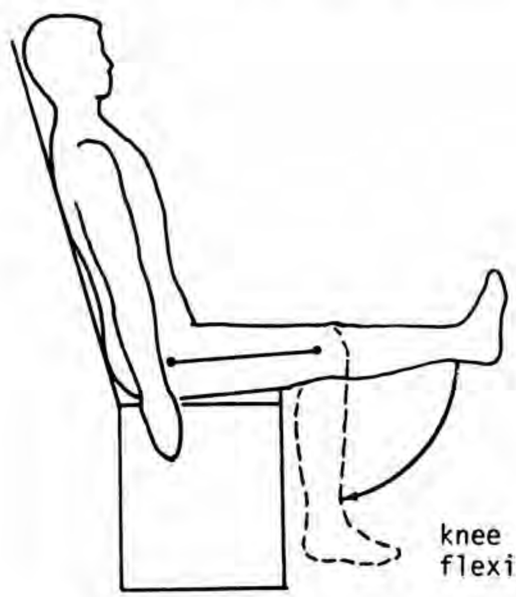

Figure 6. Knee flexion.

TABLE 5
RANGE OF MOTION OF TWO-JOINT MUSCLES

	Baseline	Zero	1/3	1/2	2/3	Full
Shoulder extension with elbow flexion	59.3°		+1.6° (102.7%)		+0.9° (101.5%)	+5.3° (108.9%)
Shoulder flexion with elbow flexion	190.7°		-24.9° (86.9%)		-36.1° (81.0%)	-47.4° (75.0%)
Elbow flexion with shoulder extension	152.2°			-3.78 (97.5%)		-1.22° (99.2%)
Elbow flexion with shoulder flexion	152.2°		-0.6° (99.6%)		-0.8° (99.5%)	-69.0° (54.7%)
Hip flexion with knee flexion	53.3°	-35.6°* (33.2%)	-24.0° (55.0%)		-6.2° (88.4%)	-12.3° (76.9%)
Ankle plantar flexion with knee flexion	48.0°		-3.4° (92.9%)		+0.2° (100.4%)	+1.6° (103.3%)
Ankle dorsiflexion with knee flexion	26.1°		-7.3° (72.0%)		-2.7° (89.7%)	-3.2° (87.7%)
Knee flexion with ankle plantar flexion	127.0°			-9.9° (92.2%)		-4.7° (96.3%)
Knee flexion with ankle dorsiflexion	127.0°					-8.7° (93.0%)
Knee flexion with hip flexion	127.0°			-19.6° (84.6%)		-33.6° (73.5%)

*The knee joint is locked and the unsupported leg extends out in front of the subject.

value of shoulder extension was found to increase by 1.6^{o} or 102.7% of the base value. The results for the other movements and adjacent joint positions are presented in similar manner.

In a very general way these results suggest that:

(1) Shoulder extension is slightly enhanced with full flexion of the elbow.

(2) There is a marked decrement in shoulder flexion as the degree of elbow flexion increases.

(3) Elbow flexion is little reduced with varying degrees of shoulder flexion-extension except for the marked reduction when the shoulder is fully flexed. This test produced the largest variance in subject response, with some subjects showing little or no elbow flexion possible at full shoulder flexion while others showed only minor decrements.

(4) Hip flexion decrements occur with any variation from baseline position. It is believed that we are dealing with two factors here. In the zero (straight leg) and 1/3 knee flexion position the center of mass of the leg has moved distally and the weight of the unsupported leg out in front of the subject reduced significantly the subject's ability to flex his hip. In the 2/3 and full knee flexion positions we believe the data reflect more directly the effects of the two-joint muscle placement.

(5) Ankle plantar flexion is slightly enhanced by increased knee flexion.

(6) Ankle dorsiflexion is substantially reduced with knee flexion from the base position.

(7) Knee flexion is slightly reduced with ankle plantar and dorsiflexion and is markedly reduced with increased hip flexion.

There is an obvious need for more carefully controlled range of joint motion research. For NASA design engineers we recommend that the following list of standard movements, suggested by Roebuck et al. (1975), be assessed for space suit range of motion measurements.

Neck Flexion-Extension
Neck Lateral Flexion, Left and Right
Forearm Supination-Pronation
Wrist Palmar Flexion-Dorsiflexion
Hip Abduction-Adduction
Hip Flexion-Extension
Shoulder Flexion-Extension
Shoulder Abduction-Adduction
Neck Rotation, Left and Right
Shoulder Rotation, Inward and Outward
Elbow Flexion-Extension

Wrist Radial Flexion-Ulnar Flexion
Hip Rotation, Outward and Inward
Ankle Flexion-Extension
Trunk Rotation, Right and Left
Shoulder Horizontal Adduction-Abduction
Knee Flexion-Extension and Hyperextension
Toe Dorsiflexion
Trunk Flexion-Extension
Trunk Lateral Flexion, Left and Right

Summary

A summary of our major findings and recommendations for design engineers are as follows:

(1) The techniques of photography, goniometry, and the flexometer offer practical and realistic means of evaluating the range of joint motion.

(2) The data presented in Table 1 compiled from Barter et al. (1957) can be used for "normative" values of range of joint motion data for adult males. Use the data presented in Table 2 compiled from Harris and Harris (1968) for females.

(3) If it becomes necessary to estimate differences in the range of joint motion between the adult sexes, Table 3 reveals percentage differences for eight different joint range measurements.

(4) Changes in range of joint motion caused by protective clothing can be significant but are usually suit-specific. Test procedures, such as the one recommended in this chapter, should be undertaken for each new NASA assembly.

(5) Few descriptive data have been generated on the effects of interacting joints on motion. A test procedure has been described and a list of joint interactions relevant to space operations has been suggested for investigation.

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CHAPTER VII
HUMAN MUSCULAR STRENGTH

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The purposes of this chapter are to review and summarize selected studies of human muscle strength for the guidance of design engineers in dealing with a large volume of often contradictory strength data, and to present specific data for direct utilization in workspace design for a widely variable population. Included in our discussion will be the following topic areas:

(1) a general review of human muscular strength;
(2) specificity of muscular strength;
(3) relationships between static and dynamic muscular strength;
(4) strength within the arm reach envelope of the seated subject;
(5) comparative muscular strength of men and women.

Many of the theoretical aspects of muscular strength capabilities have been discussed in some detail by Roebuck, Kroemer, and Thompson (1975) in their book entitled Engineering Anthropometry Methods. For the reader who is interested in pursuing a discussion of the measurement of muscular strength capabilities, we recommend Chapter IV, pp. 108-128 in that publication. Other recommended reviews assessing human muscular strength capabilities have been published by Caldwell (1964), Caldwell et al. (1974), Chaffin (1975), Clarke (1973), Clarke (1966 and 1971), Hettinger (1961), Hunsicker and Greey (1957), Ikai and Steinhaus (1961), Kroemer (1970), Kroemer and Howard (1974), and Pipes and Wilmore (1975).

Handbooks that contain data pertinent to muscle strength design problems include those written or edited by Damon, Stoudt, and McFarland (1966), Van Cott and Kinkade (1972), and Webb (1964). These handbooks are extremely useful sources of information to the designer engineer.

Specificity of Muscular Strength

The specificity* of human muscular strength is of major importance for the engineering application of strength data. The concept of strength specificity deals with the fact that strength scores, even when exerted

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*Specificity is the percentage of variance accounted for by other variables than x and is determined by $1 - r^2$. Generality is defined as the percentage of variance of y accounted for by x and is determined by r^2. A correlation coefficient of at least .71 is required to show more generality than specificity: $r^2 \times 100 = 50$ percent or more.

by the same subjects, do not correlate well with each other. Pursuing this topic in some detail, Whitley and Allan (1971) have extensively reviewed the strength related literature. On the basis of their review, of 23 studies representing a variety of strength tests and measurement techniques, the authors point out "...that individual differences in static strength ability demonstrate more specificity than generality."

This concept was further elucidated by Thordsen, Kroemer, and Laubach (1972) and Laubach, Kroemer, and Thordsen (1972). They asked their subjects to exert maximum static force in 44 different exertions. Less than 2% of the 946 intercorrelations among the force exertions exceeded .71, indicating that such correlations may not be very useful in predicting force capabilities. The authors concluded that "...if data are desired on forces exertable in other locations or directions, i.e., under other conditions, than those previously investigated, the information generally has to be gathered experimentally rather than computed from other force data."

The implications from the above quoted research clearly indicate that there is no single quantitative function that can be called general static strength.

Static vs. Dynamic Muscular Strength

The relationship between static and dynamic muscular strength in man is of great concern to design engineers. The ability to predict an operator's success in performing a dynamic strength task from a measurement of static muscular strength would be a tremendous asset for the design engineer who must be concerned with dynamic performance. A large body of literature has been devoted to the question of whether the amount of force that can be exerted in a static muscular contraction is a good or a poor indicator of the amount of force that can be exerted dynamically. Unfortunately, very few unequivocal answers have resulted. A thorough review of the literature, however, does yield provisional answers to the following questions pertaining to the relationships between static and dynamic musuclar strength:

(1) Has there been a definite relationship established between static and dynamic muscular strength?
(2) Do static muscular force measurements yield larger values than dynamic force measurements.
(3) During a dynamic muscular contraction, does a concentric or an eccentric contraction yield the larger value?
(4) What is the relationship between static and dynamic muscular force during different phases of the contractions?
(5) Can dynamic muscular force be more accurately predicted from static force if the motion is linear or angular?

Comparisons that have been made between static and dynamic muscular strength have resulted in conflicting opinions about these relationships. In studies reported by Asmussen, Hansen and Lammert (1965), Berger and

Higginbotham (1970), Carlson (1970), Rasch (1957), Rasch and Pierson (1960, 1963) and Salter (1955), a high degree of correlation was found between measures of static and dynamic strength.

Doss and Karpovich (1965), Lagasse (1970), Singh and Karpovich (1966) and Start (1966), on the other hand, have reported erratic results between measures of static and dynamic strength. In a discussion pertaining to the differing results between static and dynamic strength obtained by various investigators Bender and Kaplan (1966) state:

> Such conclusions, however, are partly derived from reports in which force was evaluated by the amount of weight that the individual could lift through a range of motion and then hold terminally, whereas the isometric measurement was taken at another point, usually midway, in the joint range of motion. This raises the question of whether these testing procedures are comparing the same activity. It is likely that different muscles or muscle groups are being evaluated when the testing occurs at distinctly different points within the range of motion.

Other reasons for these conflicting opinions have been that researchers have (1) inadequately defined the testing terminology, (2) utilized varying intensities of effort, and (3) used different testing positions.

From a thorough review of the muscle strength testing literature, Hunsicker and Greey (1957) concluded that there is a difference between static strength (as defined by a single maximum effort with the subject in a fixed position) and dynamic strength (as defined by repetitious efforts) and that the mathematical relationship between the two is not high.

Doss and Karpovich (1965) compared concentric,* eccentric,** and isometric strength of the elbow flexor muscles. Each subject was given three tests, repeated three times to measure the maximum force during concentric and eccentric movements between 75^{o} and 165^{o} of the elbow angle. The execution of the concentric and eccentric movements took 18 seconds each. The isometric measures were taken between 87^{o} and 150^{o} of the elbow angle and the contractions were maintained at least one second at each angle. When the three force exertions (concentric, eccentric, and isometric) were compared at corresponding elbow joint angles, it was found that the mean maximum concentric (pushing) force was 23% smaller and the eccentric (pulling) force was 13.5% greater than the isometric force.

In a study similar to that of Doss and Karpovich, Singh and Karpovich (1966) studied the relationships among maximum concentric, eccentric, and isometric forces of the forearm flexors and extensors. The mean eccentric

*Concentric indicates that the muscle shortens actively against a resistance.

**Eccentric indicates that the muscle is lengthened passively by an external force.

forces of the flexors and the extensors were 32.7% and 14.2% greater than the concentric forces, respectively. The isometric forces of the flexors were 41.6% greater than the isometric forces of the extensors. Singh and Karpovich conclude that it is possible to predict the concentric, eccentric, and isometric forces of the flexor muscles from one another. The same conclusion holds true for predicting the three forces of the extensors from one another. However, the chances of predicting the different forces of the flexors from the extensors, or vice versa, are quite limited.

Using the factor analysis approach, Start and others (1966) studied the relationships between static strength and power of the lower limb. Total leg strength was measured using a back and leg dynamometer. The bilateral strength of the ankle plantar flexors, the knee extensors, and the hip extensors were determined using cable tensiometer techniques. Power was determined via the power jump, the Sargent jump, the squat jump, and the standing broad jump. The authors concluded that power bore little relationship to static strength and that the two seemed to be separate entities.

Asmussen, Hansen, and Lammert (1965) designed a special dynamometer to measure isometric, concentric, and eccentric muscle forces of the arm-shoulder complex. The distances of travel and velocities were expressed relative to arm length. The subjects were 18 men whose ages ranged from 18 to 30 years. For fairly rapid movements (corresponding to 60% of the arm length per second) the maximal concentric force is 75 to 80% of maximal isometric strength. In resisting a movement of the same velocity, 125 to 130% of the maximal isometric strength can be produced. The concentric and eccentric strength curves at all movement velocities studied were practically parallel to the isometric strength curves with the exception of the first part of the movement in concentric contraction. The authors reported a correlation of 0.80 between dynamic strength (at a velocity of 15% arm length per second) and isometric strength.

In a well-planned study, Carlson (1970) studied the relationship between isometric and isotonic strength of the right elbow flexor muscles. Carlson found the mean isometric strength value to be 78.1 lbs. and the mean isotonic strength value to be 68.3 lbs., resulting in a difference of 13%. The correlation coefficient between isotonic and isometric strength was found to be 0.83. The author concluded.

> ...that the difference between the two tests is highly significant. The validity of the substitution of a test of isometric strength, therefore, is contingent upon the use of test results. If the purpose of the test is to discriminate between strong and weak persons, the substitution is a valid one. If the purpose of the test is to determine the level of muscular strength, however, the substitution is not valid because of the differences between results of the two tests.

Berger and Higginbotham (1970) studied the relationship between static and dynamic strength of the knee flexors at the joint angles of 35°, 61°, 89°, 135°, and 167°. The following table summarizes the results of the strength testing as reported by Berger and Higginbotham:

TABLE 1
STATIC AND DYNAMIC STRENGTH OF KNEE FLEXORS

Knee Angle	Static Strength X	Dynamic Strength X	r
35°	415 lbs.	275 lbs.	.79
61°	339 lbs.	329 lbs.	.96
89°	490 lbs.	489 lbs.	.99
135°	974 lbs.	966 lbs.	.99
167°	1050 lbs.	1045 lbs.	.99

The correlations between static and dynamic strength of the knee flexors as reported by Berger and Higginbotham are the highest reported relationships found in the literature.

Using a two-hand crank ergometer, Kogi, Mueller and Rohmert (1965) related the isometric moments of rotation at 12 different crank positions to dynamic force measurements performed for 30 minutes at 60 revolutions per minute at differing outputs. The results are depicted in Figure 1. The dashed line --- illustrates the maximum static strength that the subjects were able to exert at 30 degree intervals from 0° through 330° (0°, 30°, ...330°) on the crank ergometer. The solid line —— illustrates the dynamic moment of rotation (at 2, 7, ...37 kpm/sec) at the same hand positions as the static measurements. It is interesting to note that although the dynamic measurements do not reach the same magnitude as the static measurements, the force measurement curves demonstrate remarkably similar profiles.

In summary, the authors found that (1) the nature of the dynamic curve remains essentially unchanged with an increase in output, (2) the curves possess two maximum points, i.e., at positions 90° and 270°, (3) the exertion of strength was always greater with pulling than it was with pushing, and (4) strength curves at high dynamic outputs approach (but never attain) the maximum isometric strength.

Stothart (1970) examined the relationship between specific characteristics of static elbow flexion performance and biomechanical aspects of dynamic elbow flexion performance under each of three different loads. For the three dynamic test conditions, A (minimum load), B (twice the minimum load), and C (three times the minimum load), the maximum dynamic torque means were 51.4%, 60.9%, and 66.8% of the maximum static torque means, respectively. Stothart reported the following correlations between maximum static torque and selected dynamic variables:

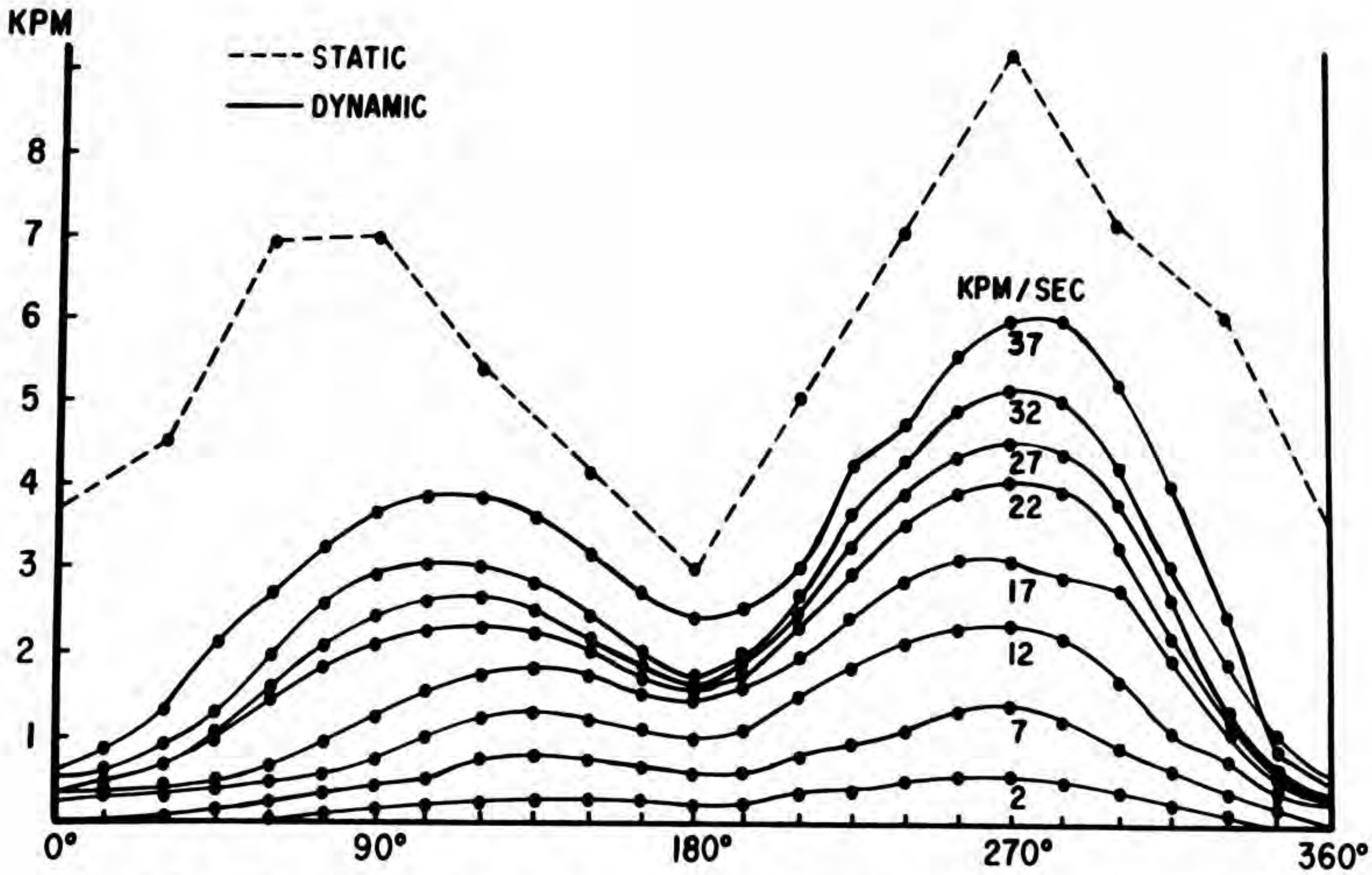

Figure 1. Results of static and dynamic strength testing as reported by Berger and Higginbotham (1970).

TABLE 2
CORRELATIONS BETWEEN STATIC AND DYNAMIC ELBOW FLEXION PERFORMANCE

	Condition A	Condition B	Condition C
Maximum Dynamic Torque	.73	.71	.76
Dynamic Torque at 15°	.70	.75	.73
Dynamic Torque at 30°	.60	.66	.70
Dynamic Torque at 45°	.47	.59	.58
Dynamic Torque at 60°	.25	.45	.37
Dynamic Torque at 75°	-.02	.19	.08
Dynamic Torque at 90°	-.16	-.13	-.12
Dynamic Torque at 105°	-.05	-.20	-.25

The above correlations between dynamic and static torque variables show that the relationship pattern was moderate ($r \cong .70$) during early phases of the movement and dropped exponentially to negative values at the end of the movement. Stothart concludes that static and dynamic force are moderately related in early phases of movement where very little excursion (movement) has occurred.

Summary of Major Findings

1. An intensive review of the literature indicates that the relationship between static and dynamic muscular forces has not been definitely established. Various evaluations of static and dynamic muscular force have resulted in conflicting opinions about these relationships. The following correlation table is a selected summary of those investigations that have particular relevance to our problem. The correlation coefficients shown are the reported relationships between static and dynamic strength.

TABLE 3
A SELECTED SUMMARY TABLE OF REPORTED RELATIONSHIPS
BETWEEN STATIC AND DYNAMIC STRENGTH

Reference	Correlation
Asmussen, Hansen, and Lammert (1965)	.80
Berger and Henderson (1966)	.60
Berger and Higginbotham (1970) (range)	.79 to .99
Carlson (1970)	.83
Lagasse (1970)	.47
Martens and Sharkey (1966)	.77
McClements (1966) (flexion strength and power)	.52
(extension strength and power)	.65
Rasch and Pierson (1963)	.69
Stothart (1970) (range)	.76 to -.25

The basic question to be answered in the application of these relationships is with what degree of accuracy do we want to be able to predict dynamic force from static force? Although the correlation between the two measures may be relatively high (i.e., r=.83) the standard error of estimate for predicting dynamic force from static force may be too large for the regression equation to be of practical value; e.g., if the standard error of estimate equals plus or minus 10 kiloponds from a regression mean of 70 kiloponds the error percentage is of a magnitude of 14%.

2. Static muscular force (whether it is measured in linear or angular motion) is usually larger than dynamic force. Dynamic force, depending on the velocity of the shortening muscles, amounts to about 50% to 90% of the maximal static force.

3. When dynamic force is expressed as a concentric contraction (muscles shortening during the action) or as an eccentric contraction (muscles lengthening during the action), the eccentric contraction yields the larger value.

4. Static and dynamic muscular forces are moderately related ($r \cong .70$) in early phases of the movement where little excursion has occurred; however, this relationship drops exponentially to negative values at the end of the movement.

5. It appears that dynamic force may be more accurately predicted from static force measurements when the motion to be evaluated is angular rather than linear.

Human Force Exertions Within the Arm Reach Envelope of the Seated Subject

This portion of this chapter describes experiments designed to measure the maximum static push forces that seated subjects can exert throughout selected positions of the arm reach envelope. A total of 76 arm force exertions were measured on a sample of 55 young male subjects whose mean age was 21.3 years with a standard deviation of 3.2 years; mean weight was 75.1 kg (165.6 lbs) with a standard deviation of 14.0 kg (30.9 lbs); mean stature was 176.9 cm (69.6 in) with a standard deviation of 5.6 cm (2.2 in). Because this material has not been previously published, we will discuss the equipment used and the experimental protocol in more detail than was done in other previously reported studies. The equipment used for this experiment consisted mainly of a seat, a three-dimensional strain gauge force transducer, and two pieces of recording equipment (See Figure 2).

The seat, complete with belts, simulated a standard aircraft seat with hard surfaces replacing the usual seat cushions. It was constructed in such a way that the seat back angle could be changed to any given angle currently used or considered for use in USAF aircraft. Built on a track, the movable seat could be brought forward and backward and left and right in relation to the handle assembly. The handle assembly was constructed in such a way that it could be raised or lowered, making it possible to

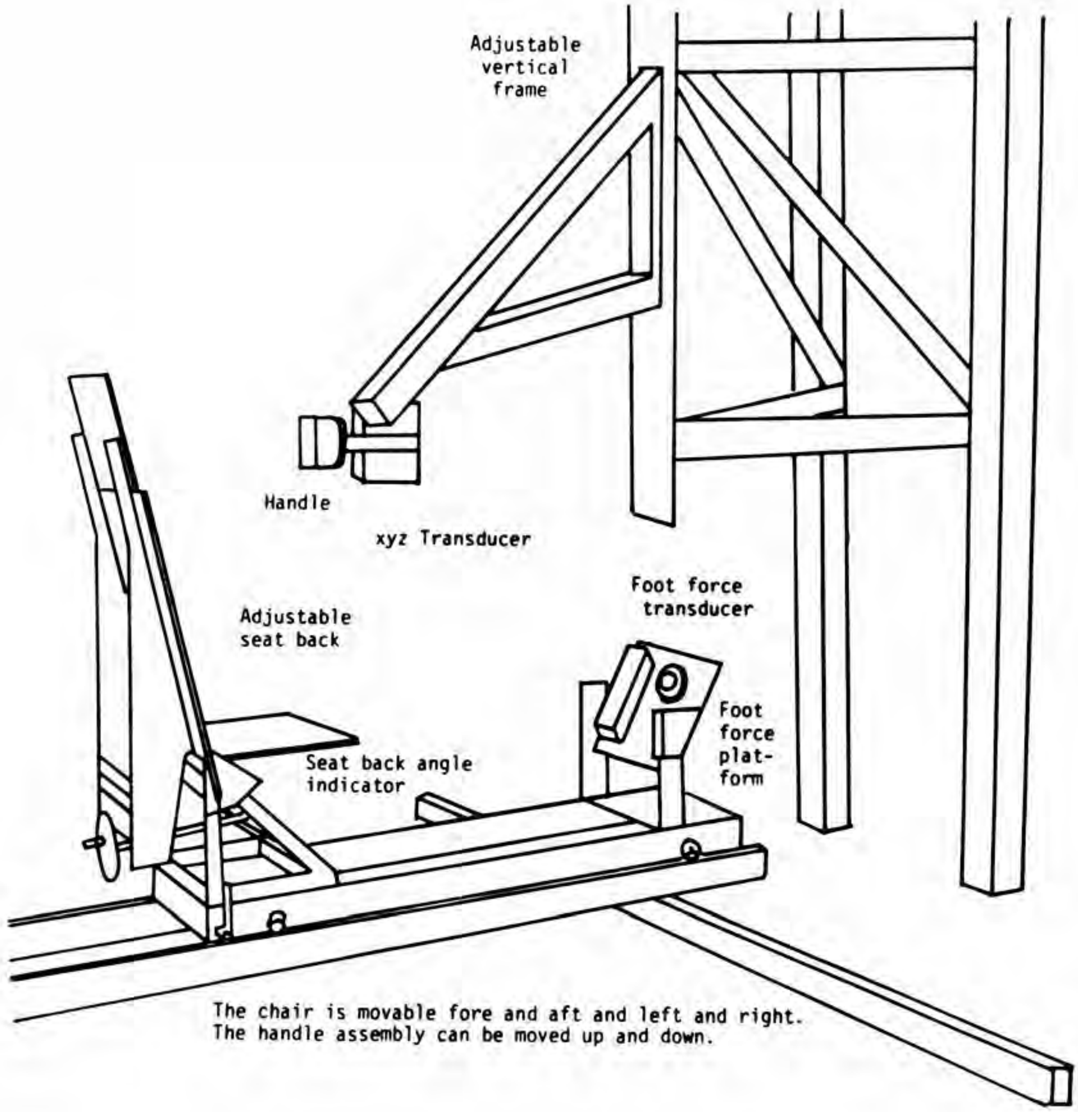

Figure 2. Equipment for measurement of maximum static push forces of seated subject.

locate the handle at any desired spatial location with respect to seat reference point (SRP).*

The handle used in measuring arm forces consisted of an aluminum cylinder with a diameter of 3.8 cm (1.5 in) and a length of 12 cm (4.7 in). Knurled to minimize slippage when grasped, the handle was attached to a Lebow three-dimensional strain gauge force transducer. Inside the transducer were three pairs of strain gauges arranged perpendicularly to each other, operating on the Wheatstone bridge arrangement. When a force was exerted on the handle, the balance between the three pairs of strain gauges was altered accordingly. The range of the transducer in any of the three coordinates was 135 kiloponds. However, to simplify data-reporting in this chapter, we have chosen to present <u>only</u> the push force in a horizontal plane in the forward direction.

Location of the Handle Assembly in Relation to Seat Reference Point

The spatial locations of the handle assembly (See Figure 2) for the arm force exertions were selected from an analysis of unpublished arm reach data gathered by Kenneth W. Kennedy, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. These test positions were established using the fifth percentile arm reach envelopes of the USAF population for each of the three different seat back angles (13°, 25°, and 65°) established for this research.

The final test positions for the arm exertions numbered 76 and included 34 exertions with a seat back angle of 13°, 27 exertions with a seat back angle of 25°, and 15 exertions with a seat back angle of 65°. The exact locations of the 76 final test positions with respect to seat reference point and seat centerline are listed in Tables 4, 5 and 6.

Procedure

The subject sat in the seat, restrained by a regular lap belt, grasping the handle assembly during the arm force exertions. His feet were required to rest "on the deck" during the arm exertions. The subject was not allowed to grasp the chair with his free hand during the exertion.

The general testing instructions for the static muscular strength evaluation of each subject followed, in general, the procedures and techniques reported by Caldwell et al., 1974. From the record of each arm force exertion, the largest amplitude ("peak") value was read; these are the values reported here.

*Seat reference point (SRP) is the point of intersection of the midline of the seat pan with the midline of the seat back.

Data Presentation

We have chosen to present the descriptive statistical data generated from this study in a series of 20 illustrations (Figures 3 through 22). Eight of these illustrations represent arm strength data within the reach envelope of the seated subject at a seat back angle of 13°; seven illustrations present data at the 25° seat back angle; and the remaining five illustrations give data for the 65° seat back angle. These illustrations show the summary statistics, including the mean, standard deviation, and fifth and ninety-fifth percentiles, for a specific seat back angle and handle assembly location in relation to seat reference point and seat centerline. Tables 4, 5 and 6 give the exact location of the handle assembly in relation to seat reference point and seat centerline, as well as listing statistical data for the arm force exertions in tabular form.

Effects of Seat Back Angle Upon the Magnitude of Arm Forces

When the position of the seat back angle of the simulated aircraft seat was positioned at 13°, maximal strength scores seemed to be obtained when the handle assembly was located 76 to 89 centimeters above seat reference point from 13 to 26 centimeters left or right of seat reference point, and from 55 to 65 centimeters forward of seat reference point. The lowest strength values obtained in this position occurred when the handle assembly was located from 38 to 51 centimeters above seat reference point.

In general, the largest arm strength values obtained when the seat back angle was positioned at 25° occurred when the handle assembly was located 76 to 89 centimeters above seat reference point, from 13 to 25 centimeters left or right of seat reference point, and 40 to 50 centimeters forward of seat reference point.

When arm force exertions were measured at the 65° seat back angle, the greatest strength scores occurred when the handle assembly was located from 64 to 76 centimeters above seat reference point, and from 15 to 25 centimeters forward of seat reference point.

These strength data used in conjunction with existing data pertaining to human force exertions for the seated operator (Laubach, Kroemer, and Thordsen, 1972; Thordsen, Kroemer, and Laubach, 1972; and Kroemer, 1975) and the standing operator (Rohmert, 1966; and Rohmert and Jenik, 1971) should aid the design engineer in the selection and arrangement of controls that must be located within the arm reach of the seated and standing operator.

Comparative Muscular Strength of Men and Women

This section will draw heavily upon two recently published articles by Laubach (1976, a and b). The latter report presents detailed, statistical information on comparative muscular strength parameters of men and women

TABLE 4

13° SEAT BACK ANGLE

LOCATION OF THE HANDLE ASSEMBLY IN RELATION TO SEAT REFERENCE POINT AND SEAT CENTERLINE*

Above SRP	Forward of SRP	Left of SRP	Right of SRP	Centerline of Seat	Arm Force Exertions (Kp) Mean	S.D.	5%ile	95%ile
38 cm	46 cm	25 cm			33.7	8.3	19.6	46.9
38 cm	48 cm			X	31.4	8.7	18.9	47.5
38 cm	48 cm		13 cm		35.5	10.5	21.6	56.2
38 cm	41 cm		38 cm		30.7	7.8	18.2	44.2
38 cm	30 cm		51 cm		25.3	6.8	15.0	37.3
51 cm	41 cm		51 cm		32.1	8.4	20.1	48.3
51 cm	51 cm		25 cm		43.1	11.0	27.3	63.6
51 cm	51 cm		13 cm		42.6	11.5	25.5	63.4
51 cm	53 cm			X	36.5	10.2	22.3	56.8
51 cm	51 cm	13 cm			44.3	11.3	24.9	61.8
64 cm	58 cm	25 cm			60.2	15.1	34.3	83.4
64 cm	69 cm			X	48.5	11.2	28.3	62.2
64 cm	58 cm		38 cm		54.5	16.2	31.4	86.4
64 cm	38 cm		64 cm		29.5	8.8	18.3	46.9
76 cm	53 cm		51 cm		46.3	14.9	23.2	73.8
76 cm	64 cm		25 cm		68.2	18.2	37.4	99.5
76 cm	64 cm			X	60.0	14.2	34.2	81.7
76 cm	58 cm	13 cm			65.5	16.4	39.7	95.0
76 cm	25 cm	38 cm			37.1	9.4	23.4	53.9
89 cm	46 cm	25 cm			52.2	15.1	28.9	77.9
89 cm	61 cm			X	67.6	16.7	40.8	95.6
89 cm	61 cm		13 cm		73.9	18.2	48.4	106.0
89 cm	56 cm		38 cm		66.5	19.6	33.2	100.5
89 cm	8 cm		76 cm		17.0	4.7	10.4	26.2
102 cm	25 cm		64 cm		26.2	7.2	15.5	39.6
102 cm	53 cm		25 cm		72.2	19.3	43.9	106.1
102 cm	51 cm			X	51.6	15.3	31.4	79.7
102 cm	48 cm	13 cm			52.5	17.5	29.6	85.1
114 cm	30 cm	13 cm			30.1	9.2	16.2	46.4
114 cm	38 cm			X	32.1	9.4	19.0	50.7
114 cm	20 cm		51 cm		28.4	6.5	19.7	40.4
127 cm	36 cm		13 cm		38.6	9.4	19.5	51.3
127 cm	33 cm			X	31.3	9.7	18.7	50.1
127 cm	25 cm	25 cm			32.5	8.4	20.6	48.0

*The orientation of the handle was always vertical and the requested direction of the exertion was in a horizontal plane in the forward direction.

TABLE 5

25° SEAT BACK ANGLE

LOCATION OF THE HANDLE ASSEMBLY IN RELATION TO SEAT REFERENCE POINT AND SEAT CENTERLINE*

Above SRP	Forward of SRP	Left of SRP	Right of SRP	Centerline of Seat	Arm Force Exertions (Kp) Mean	S.D.	5%ile	95%ile
38 cm	38 cm	25 cm			35.6	10.3	19.2	53.4
38 cm	43 cm			X	31.4	9.6	17.6	48.8
38 cm	41 cm		25 cm		36.1	10.9	21.7	59.5
51 cm	20 cm		64 cm		23.4	7.0	13.0	36.4
51 cm	38 cm		38 cm		41.7	12.7	24.9	66.1
51 cm	43 cm		13 cm		47.4	13.6	27.5	70.6
51 cm	46 cm	25 cm			48.3	13.6	28.8	71.9
64 cm	25 cm	38 cm			39.8	10.9	24.7	61.1
64 cm	56 cm	13 cm			54.8	14.0	33.1	81.6
64 cm	56 cm			X	49.4	11.1	32.6	66.3
64 cm	51 cm		25 cm		61.3	16.1	34.9	86.8
64 cm	38 cm		51 cm		40.8	11.9	23.6	60.3
76 cm	25 cm		64 cm		29.4	8.2	16.9	43.8
76 cm	46 cm		38 cm		59.6	17.9	37.2	90.2
76 cm	48 cm			X	64.1	15.1	36.9	87.7
76 cm	43 cm	25 cm			71.0	18.6	42.5	102.1
89 cm	46 cm	13 cm			71.3	21.8	34.6	110.4
89 cm	48 cm			X	69.6	18.0	39.7	100.5
89 cm	51 cm		25 cm		75.0	19.1	44.4	107.6
89 cm	41 cm		51 cm		50.2	17.6	25.9	83.3
102 cm	5 cm		64 cm		23.0	5.8	15.0	33.7
102 cm	41 cm		13 cm		66.2	20.9	36.1	97.8
102 cm	38 cm			X	52.9	16.5	31.1	85.4
102 cm	23 cm	25 cm			40.9	10.8	25.2	61.1
114 cm	13 cm	13 cm			30.5	10.4	16.2	49.0
114 cm	25 cm		25 cm		46.2	13.5	24.6	69.0
114 cm	20 cm		38 cm		40.3	11.3	23.2	60.0

*The orientation of the handle was always vertical and the requested direction of the exertion was in a horizontal plane in the forward direction.

TABLE 6

65° SEAT BACK ANGLE

LOCATION OF THE HANDLE ASSEMBLY IN RELATION TO SEAT REFERENCE POINT AND SEAT CENTERLINE*

Above SRP	Forward of SRP	Left of SRP	Right of SRP	Centerline of Seat	Arm Force Exertions (Kp) Mean	S.D.	5%ile	95%ile
38 cm	15 cm		51 cm		27.8	9.3	15.7	43.5
38 cm	15 cm		38 cm		37.0	11.3	19.5	54.6
51 cm	15 cm	25 cm			49.7	15.2	20.9	72.3
51 cm	30 cm			X	35.9	10.0	20.8	53.8
51 cm	13 cm		64 cm		23.3	8.3	11.8	39.3
64 cm	5 cm		64 cm		24.6	7.6	14.2	49.3
64 cm	28 cm		25 cm		54.5	15.2	32.9	82.1
64 cm	28 cm			X	49.3	12.6	30.4	66.5
64 cm	20 cm	13 cm			61.7	16.4	35.3	88.8
76 cm	3 cm	25 cm			49.8	18.1	24.1	84.2
76 cm	18 cm			X	57.1	16.0	30.4	81.5
76 cm	20 cm		13 cm		63.8	16.4	38.1	87.8
76 cm	8 cm		51 cm		32.7	9.9	18.4	49.8
89 cm	3 cm			X	40.2	15.9	17.9	69.7
89 cm	3 cm		25 cm		50.6	18.3	25.9	81.0

*The orientation of the handles was always vertical and the requested direction of the exertion was in a horizontal plane in the forward direction.

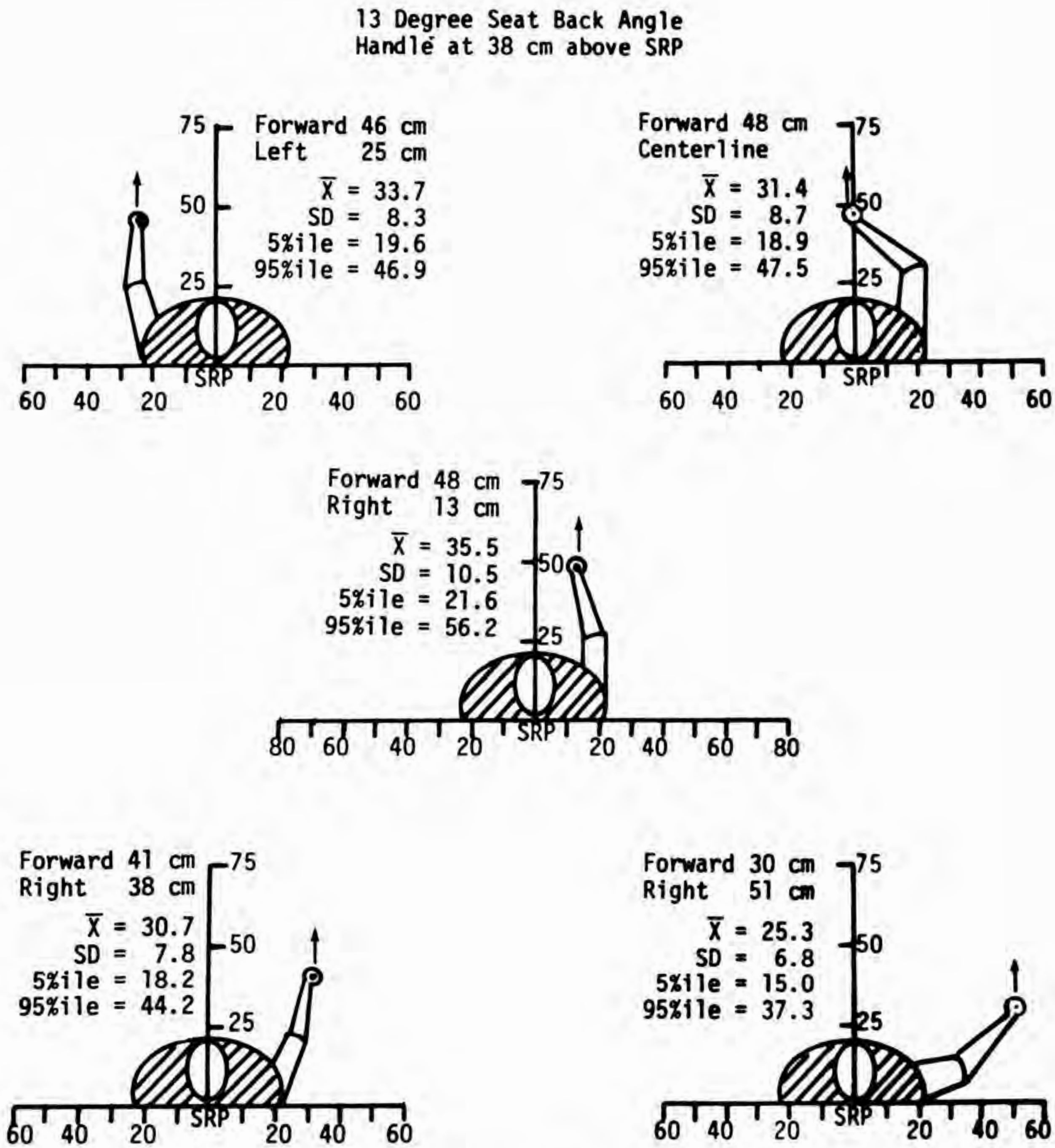

Figure 3. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

13 Degree Seat Back Angle
Handle at 51 cm above SRP

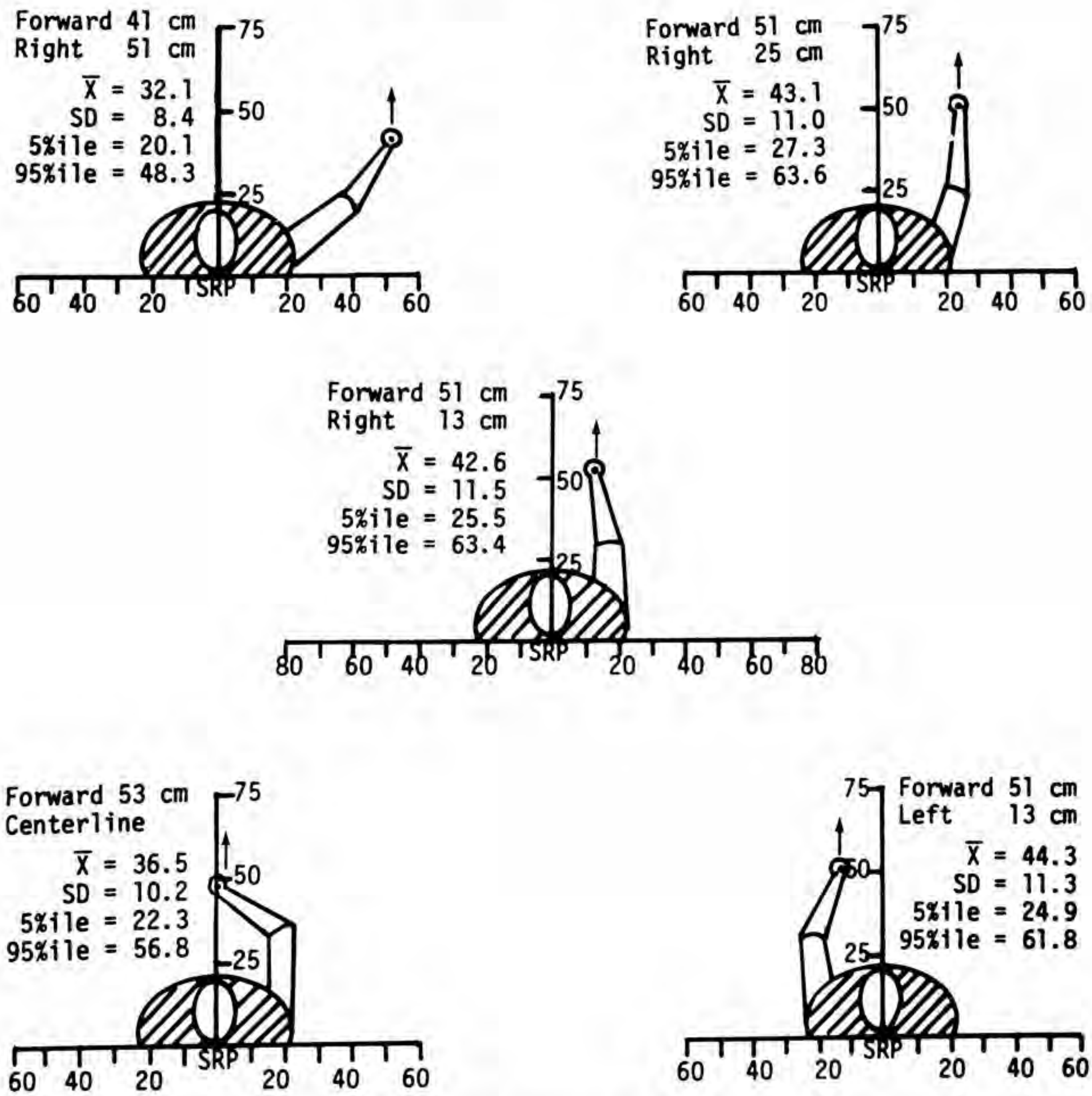

Figure 4. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

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13 Degree Seat Back Angle
Handle at 64 cm above SRP

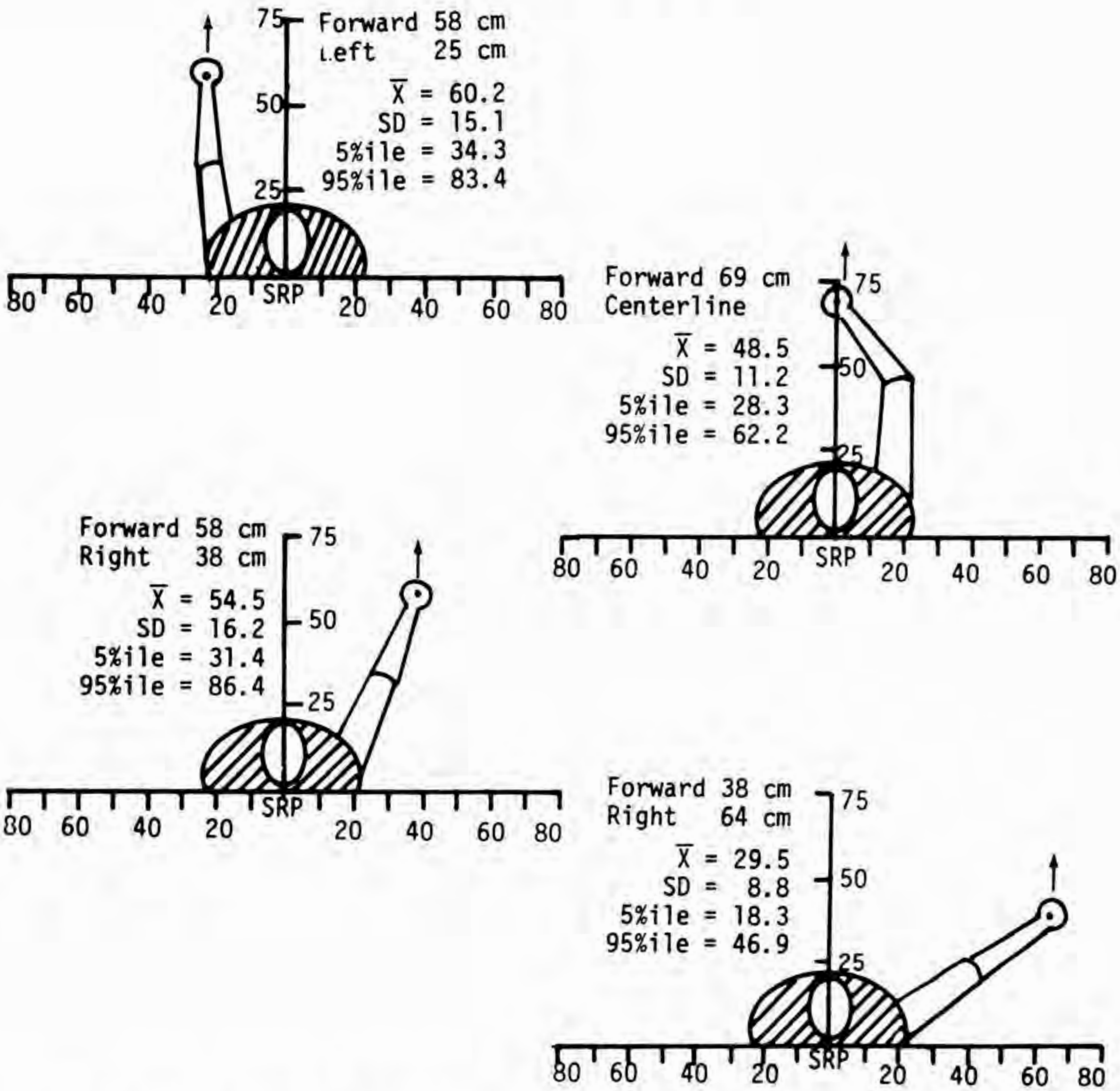


Figure 5. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

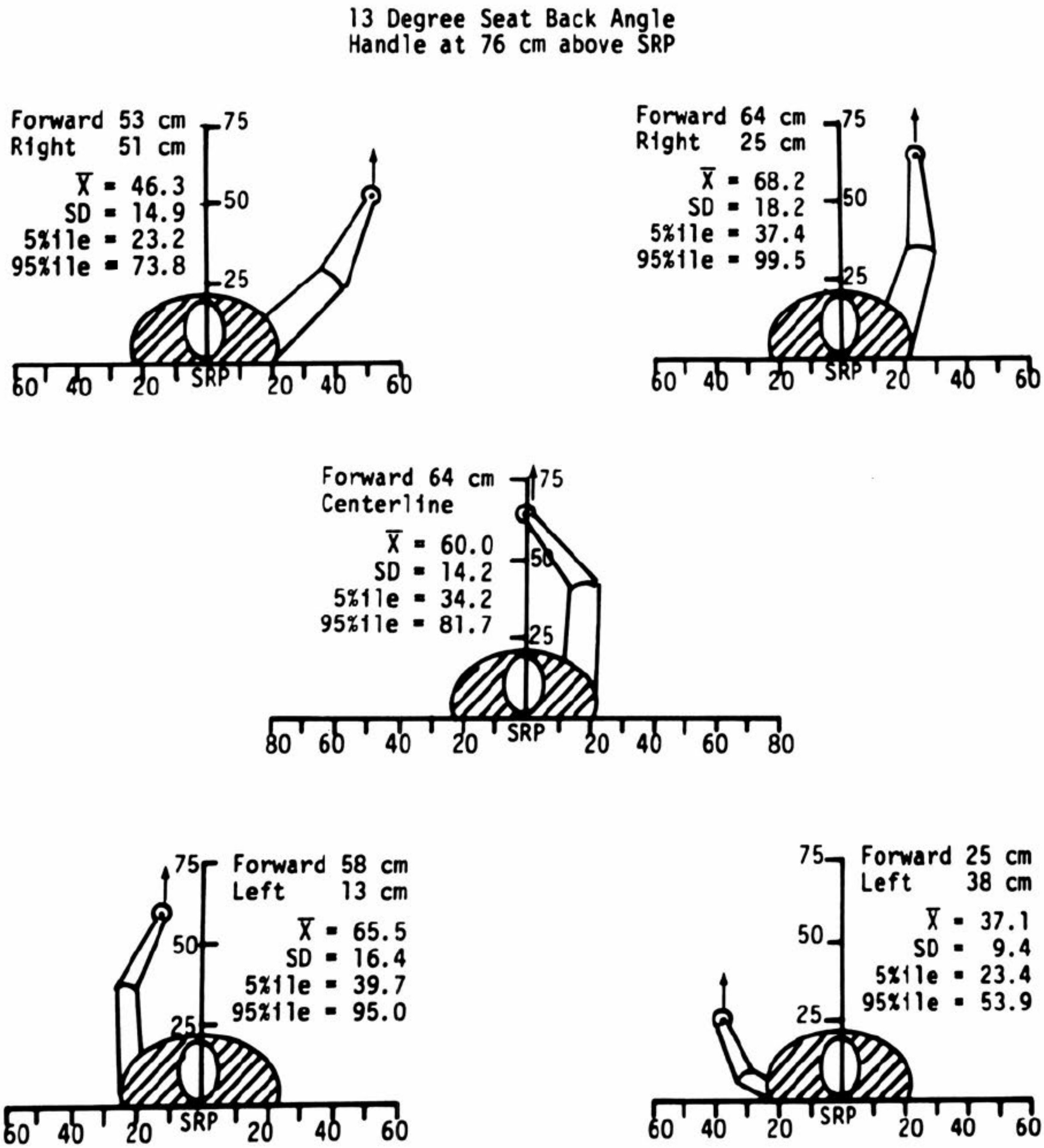


Figure 6. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

13 Degree Seat Back Angle
Handle at 89 cm above SRP

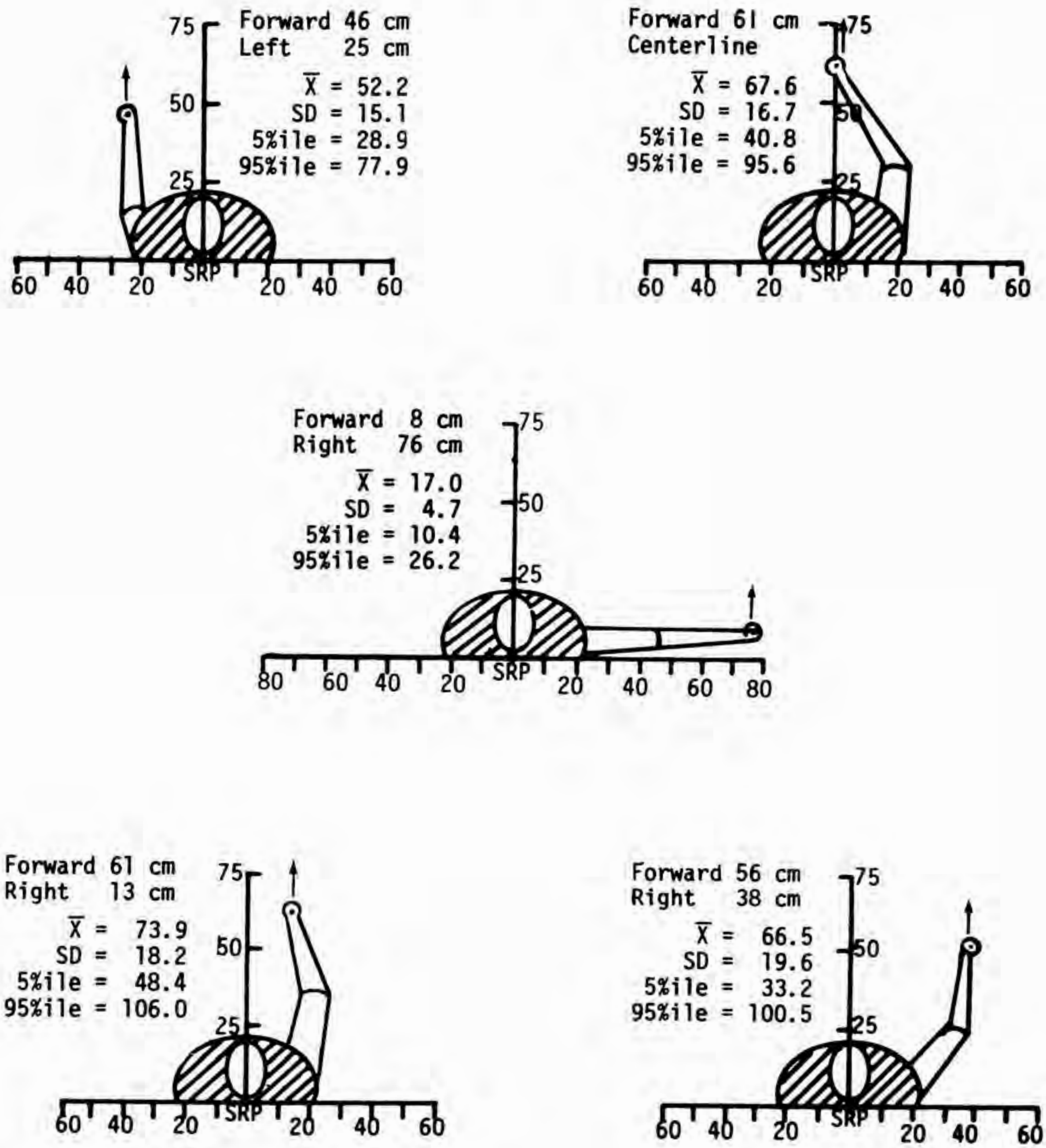


Figure 7. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

13 Degree Seat Back Angle
Handle at 102 cm above SRP

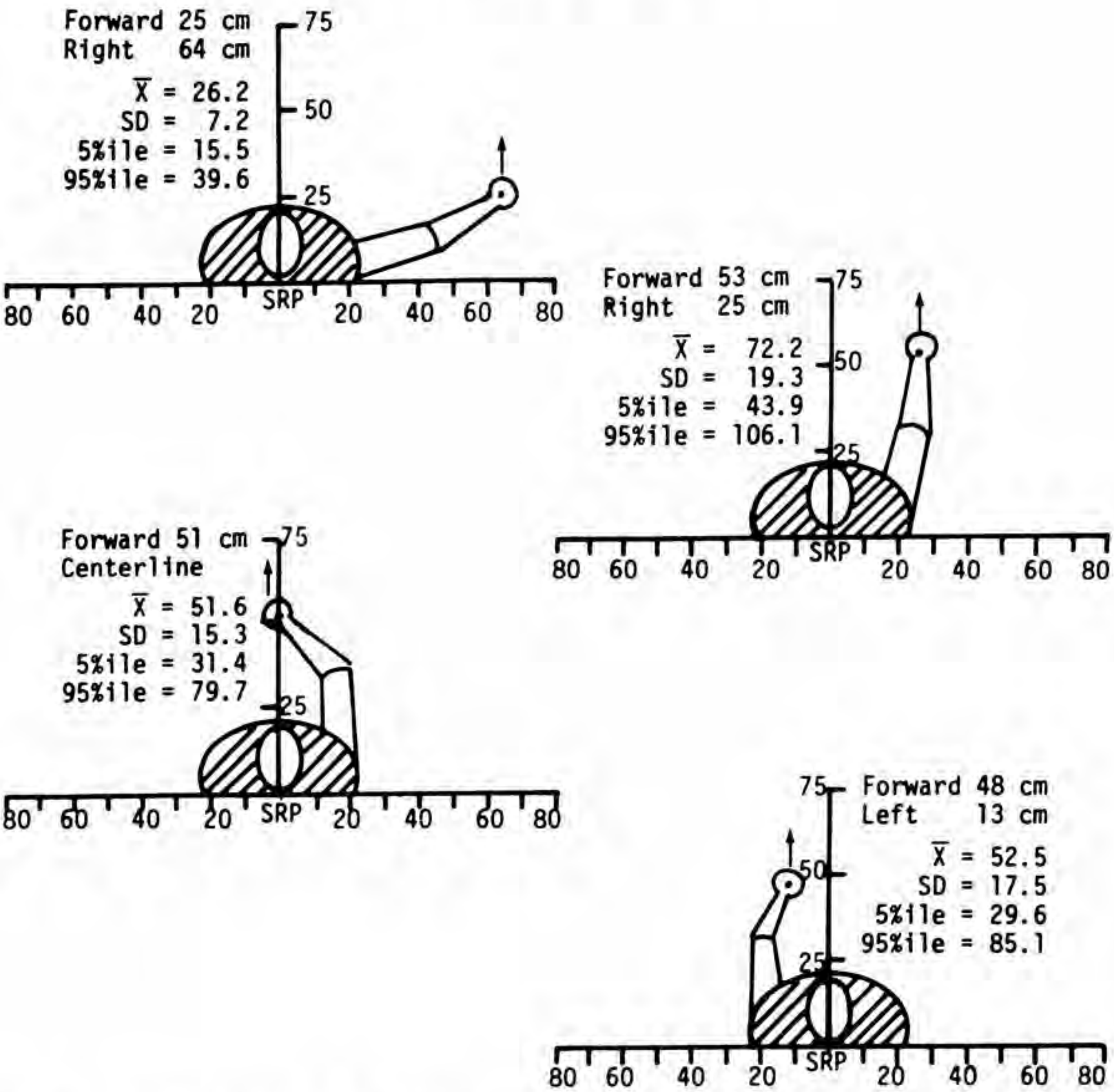


Figure 8. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

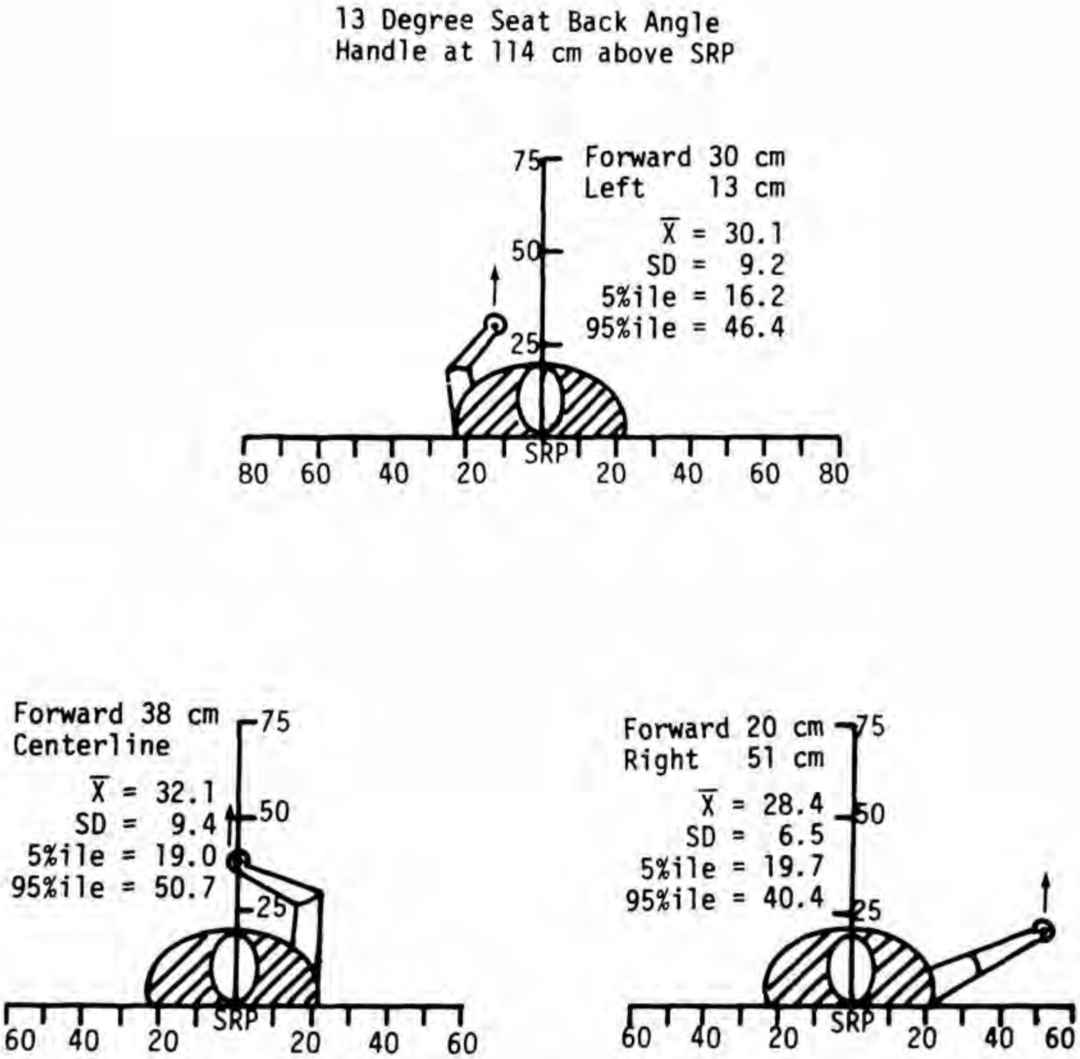


Figure 9. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

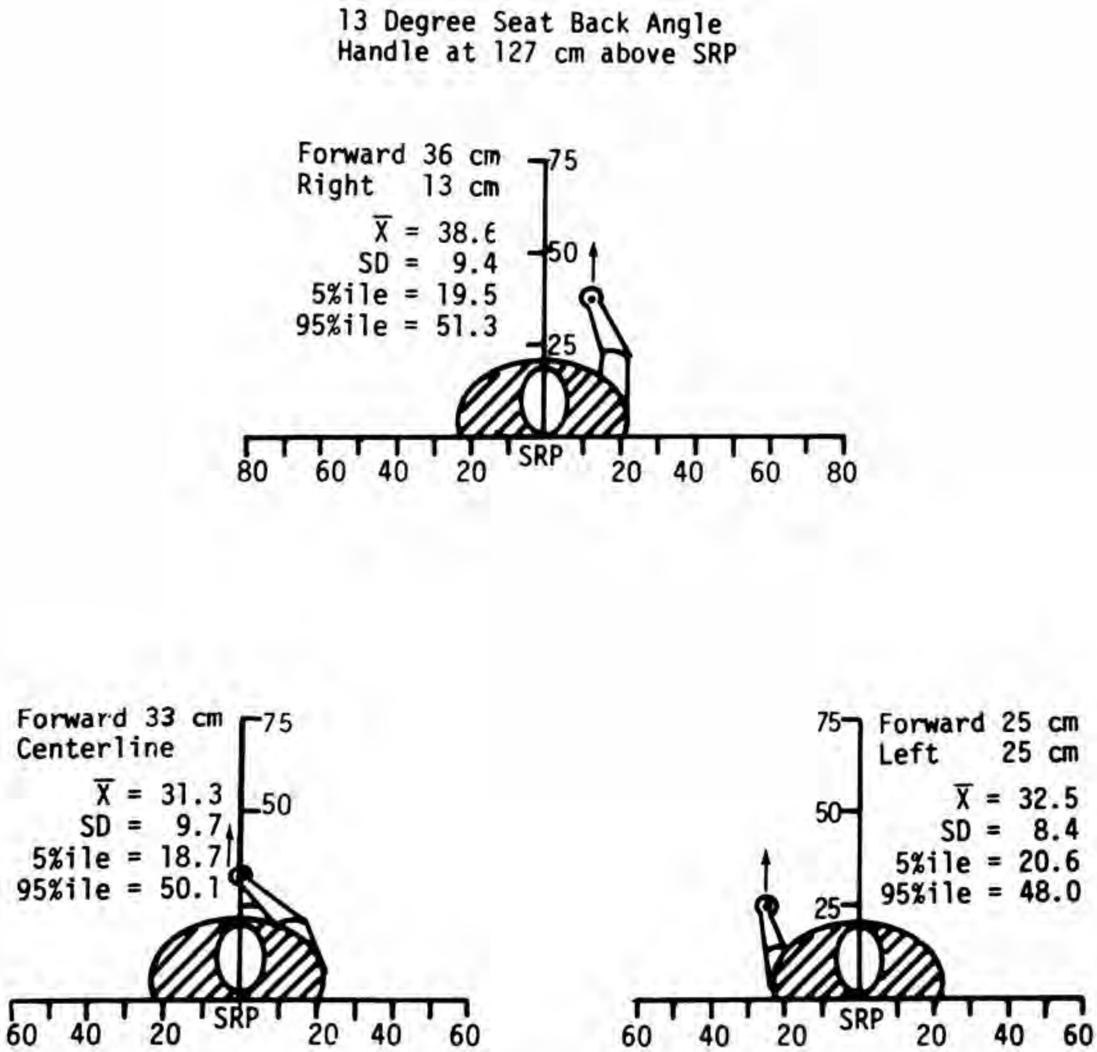


Figure 10. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

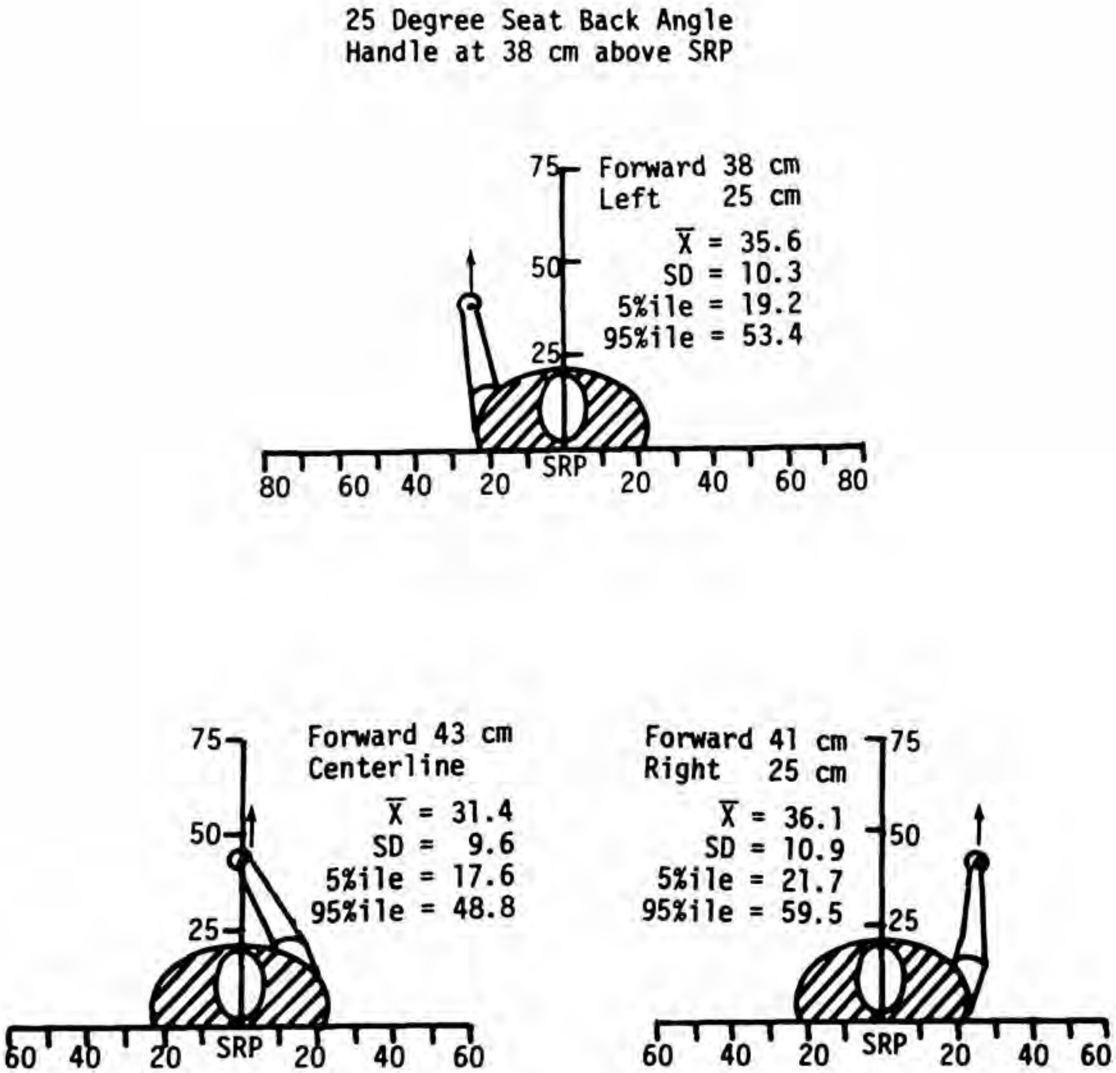


Figure 11. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

25 Degree Seat Back Angle
Handle at 51 cm above SRP

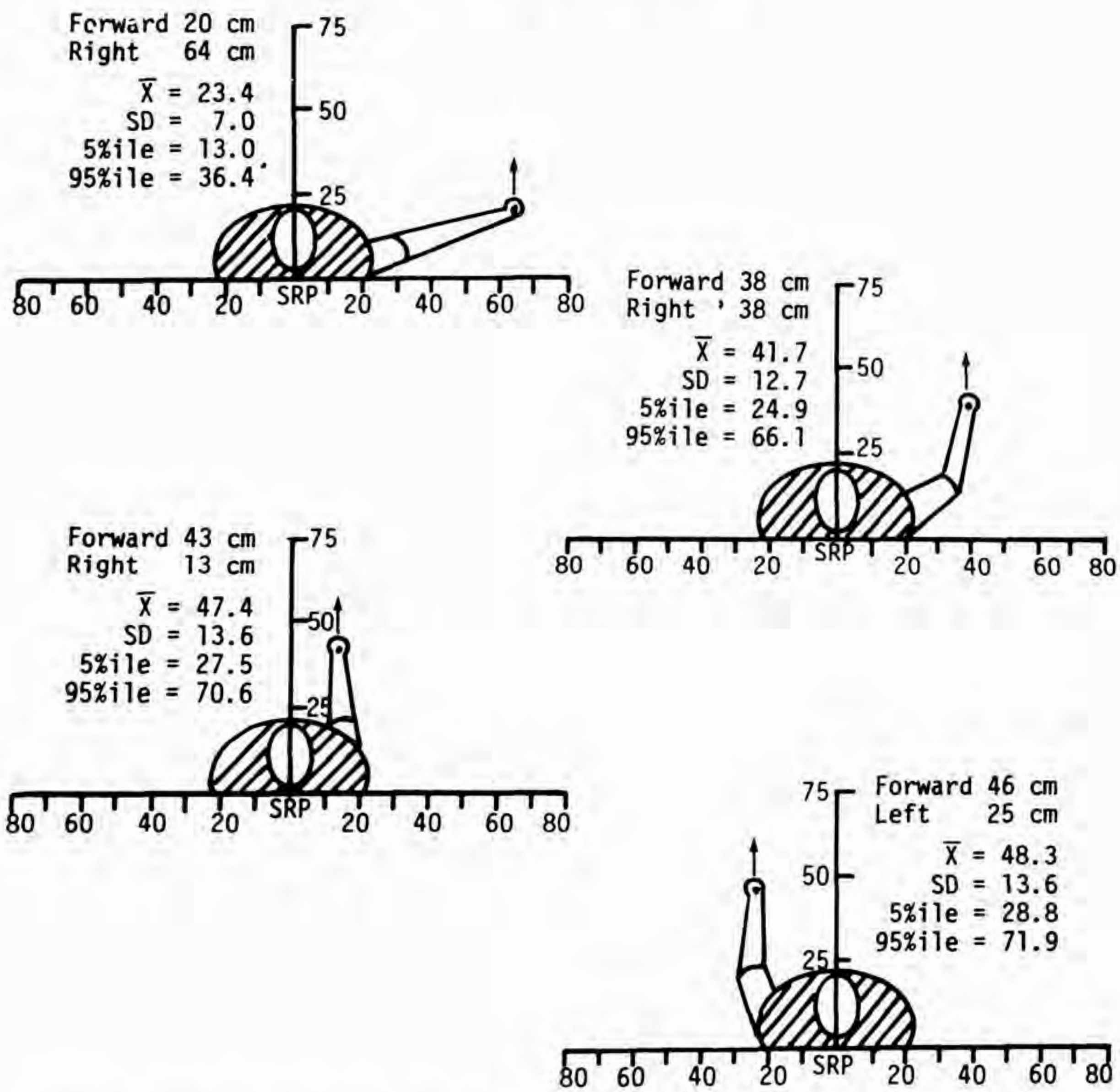


Figure 12. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

25 Degree Seat Back Angle
Handle at 64 cm above SRP

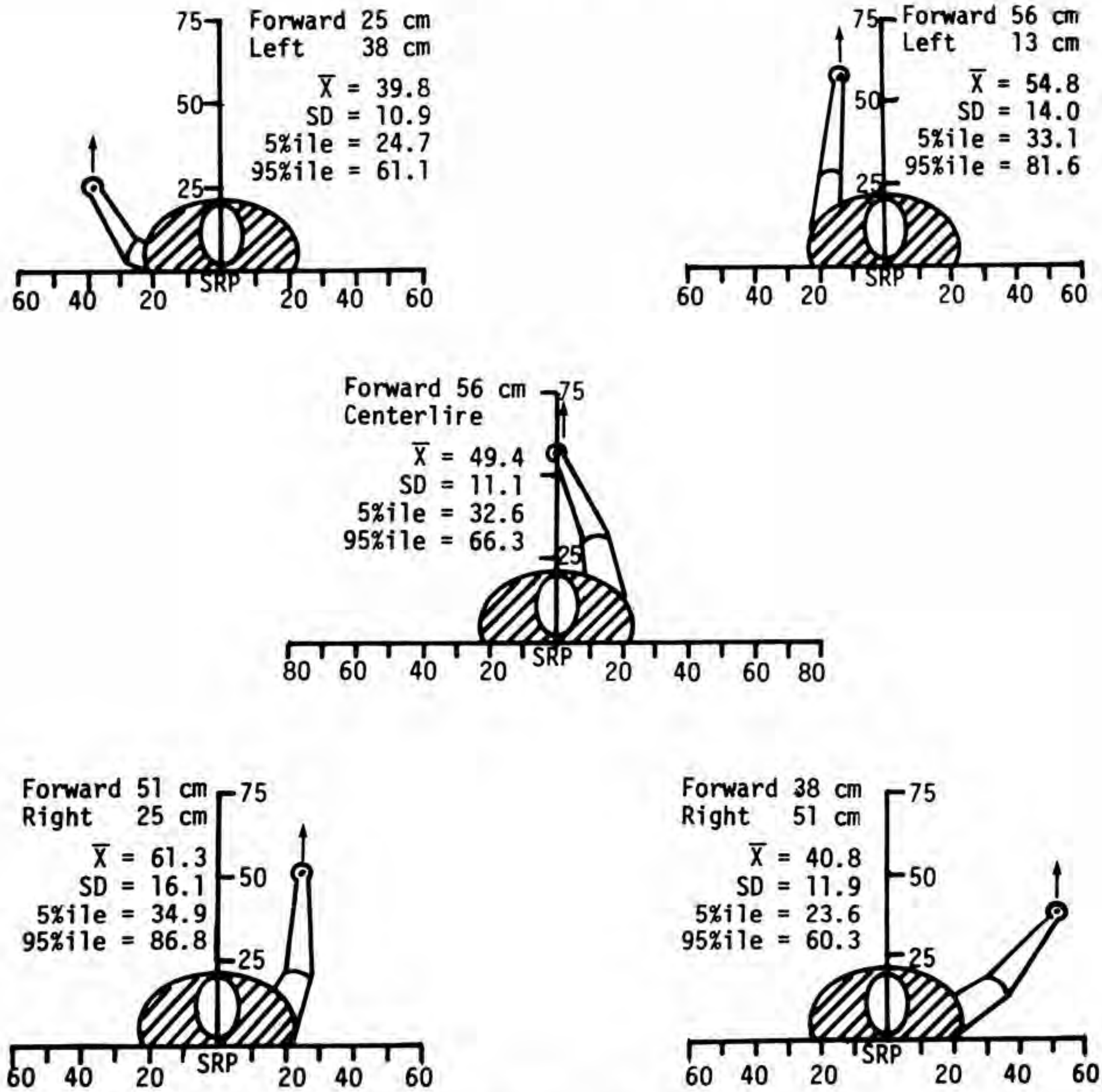


Figure 13. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

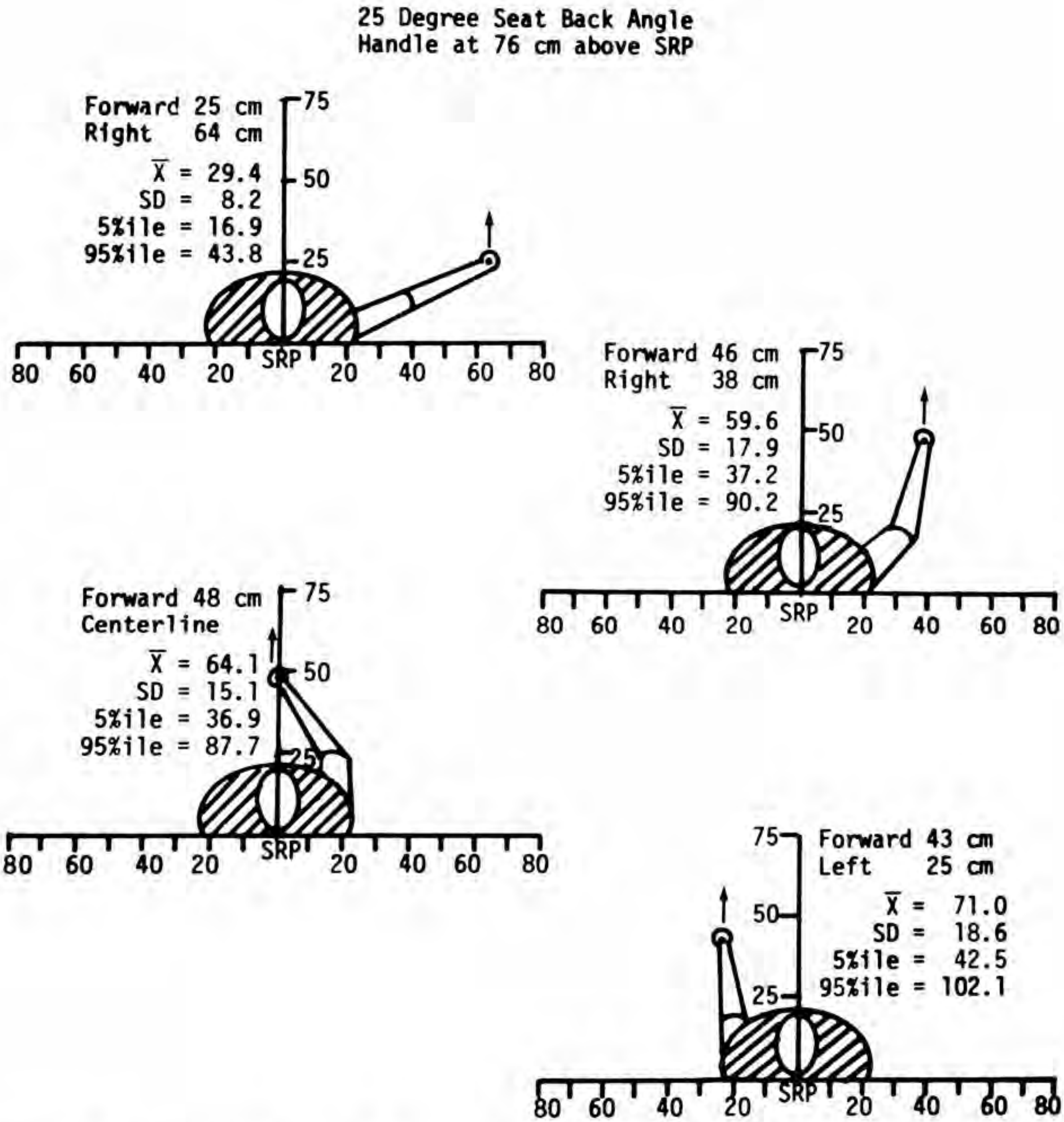


Figure 14. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

25 Degree Seat Back Angle
Handle at 89 cm above SRP

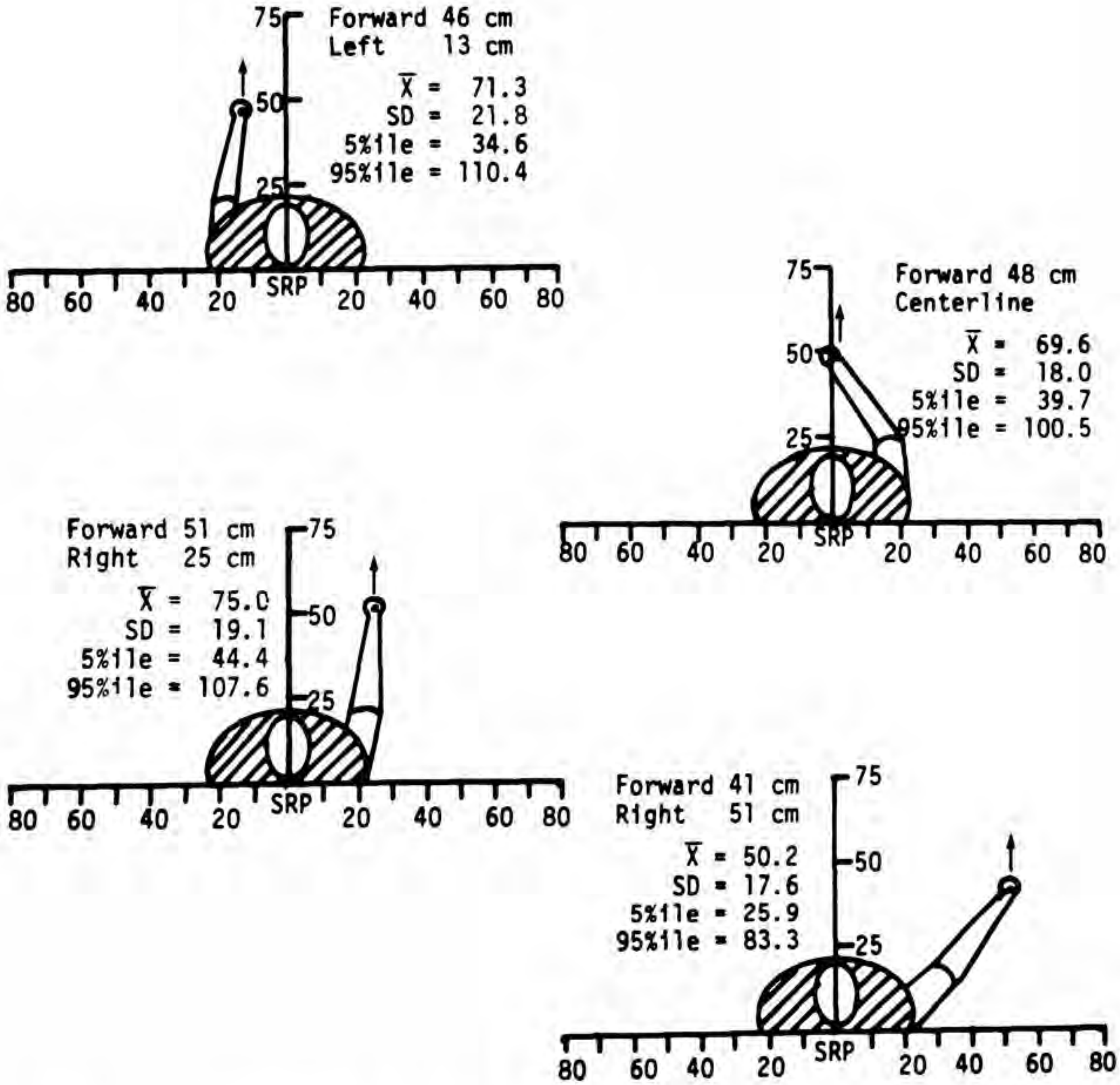


Figure 15. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

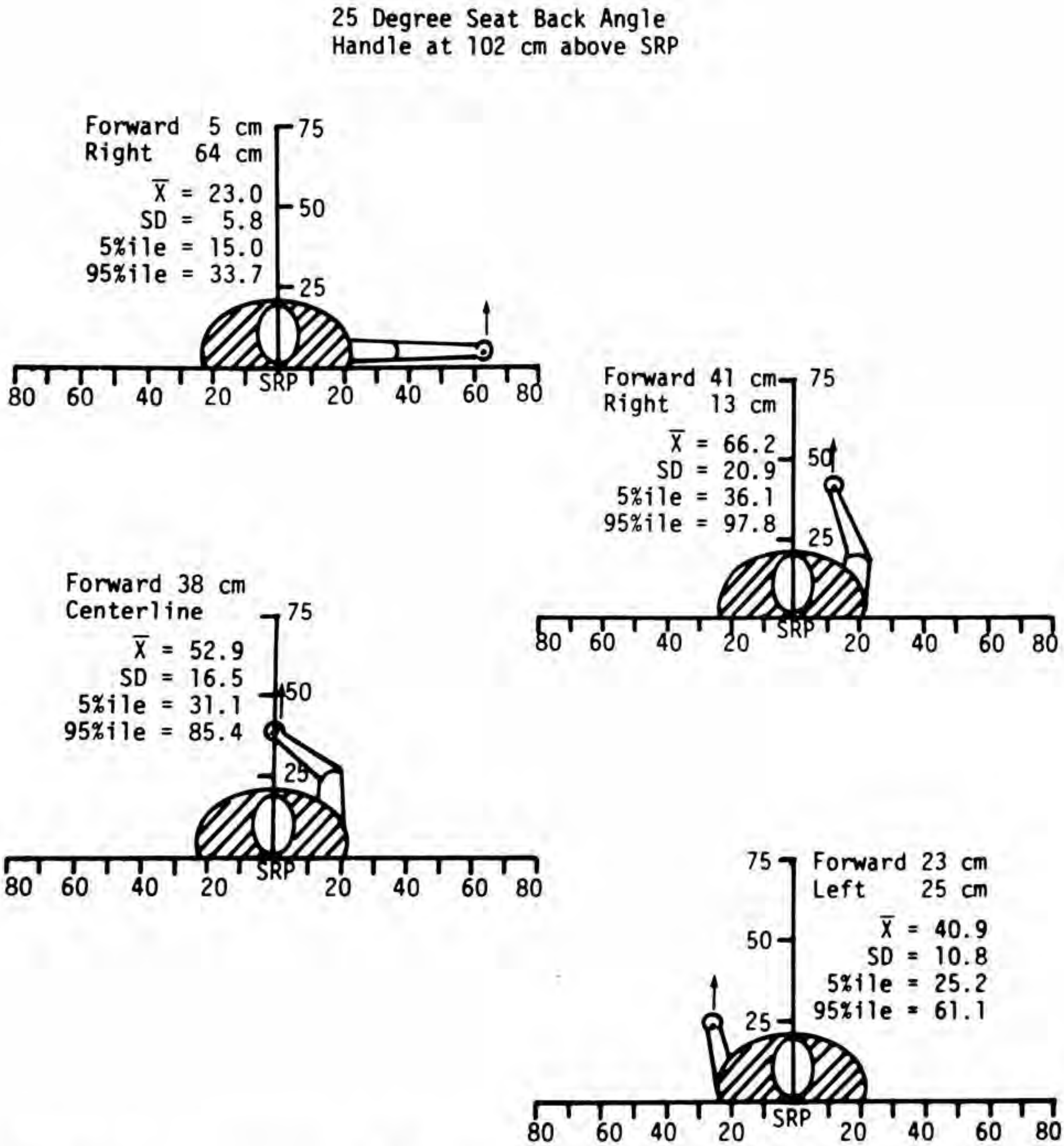


Figure 16. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

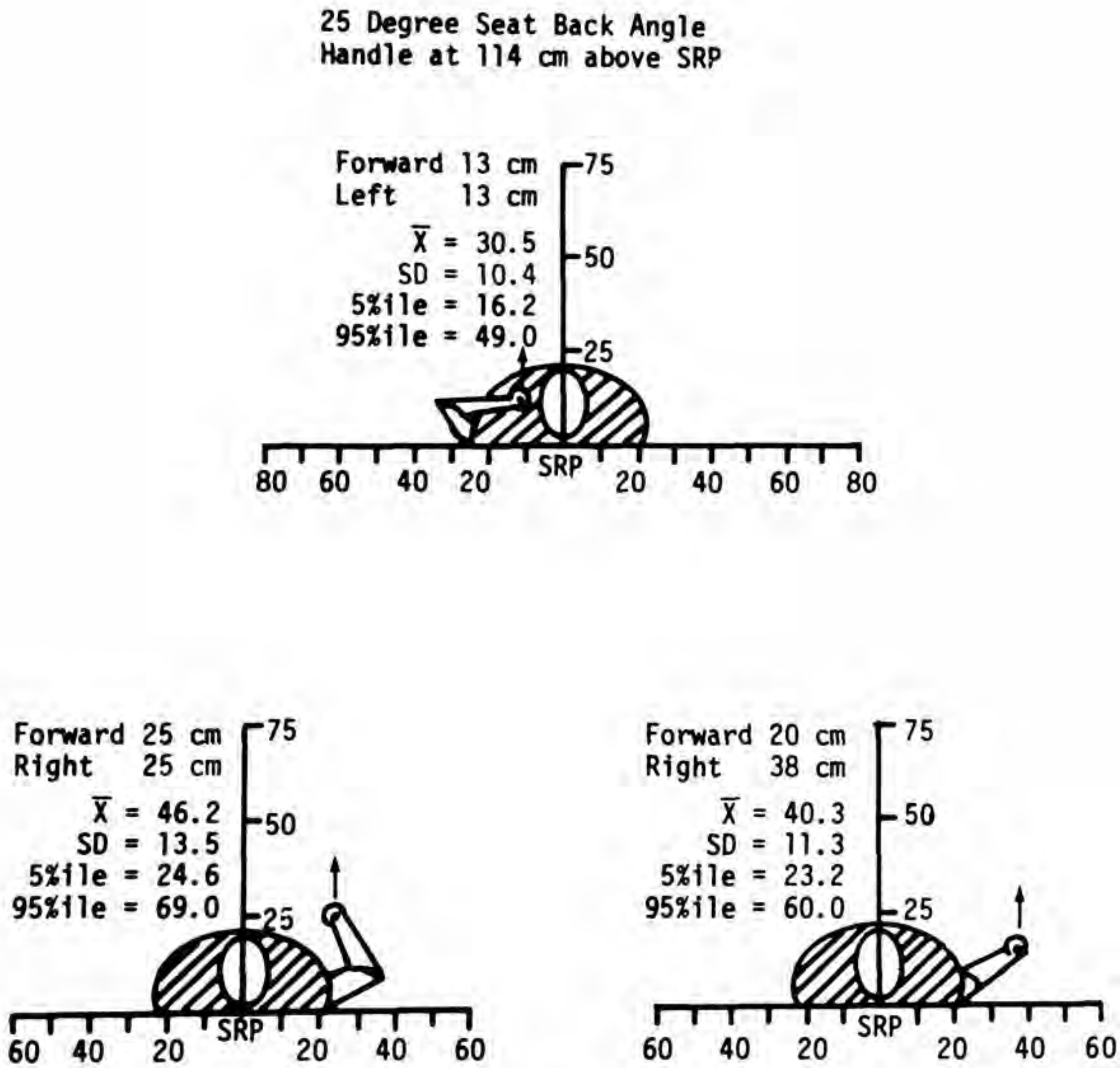
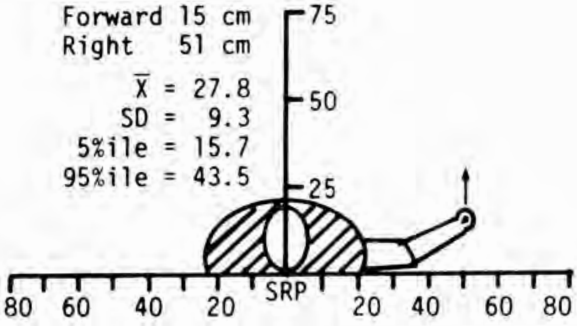


Figure 17. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

65 Degree Seat Back Angle
Handle at 38 cm above SRP



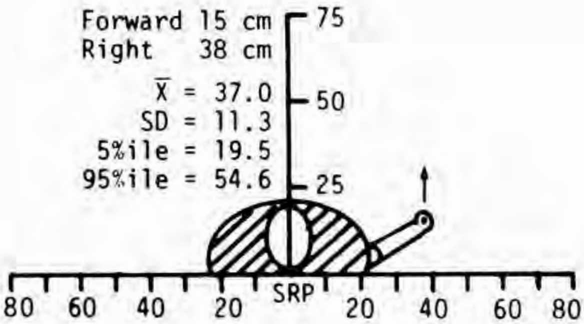


Figure 18. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

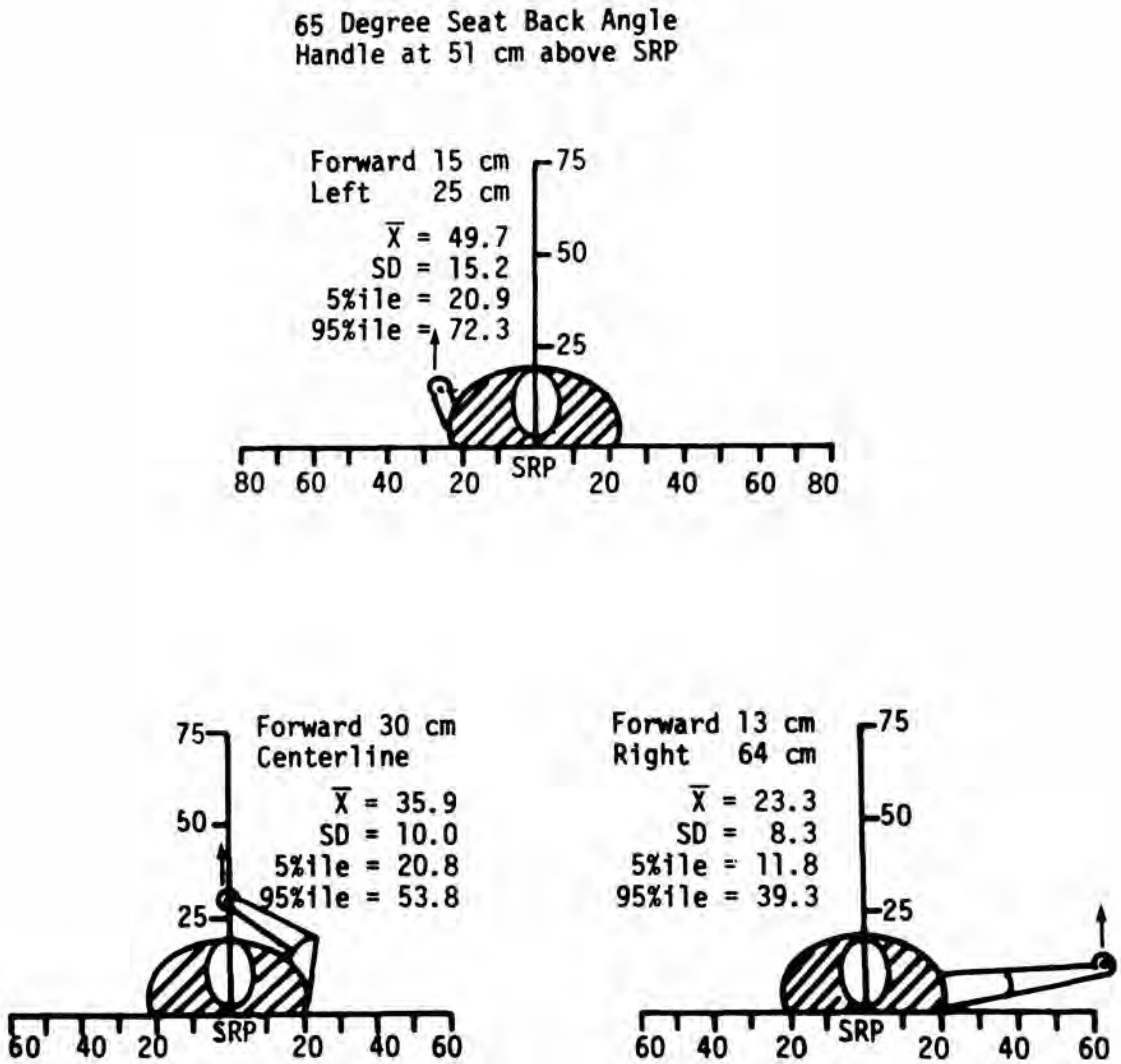


Figure 19. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

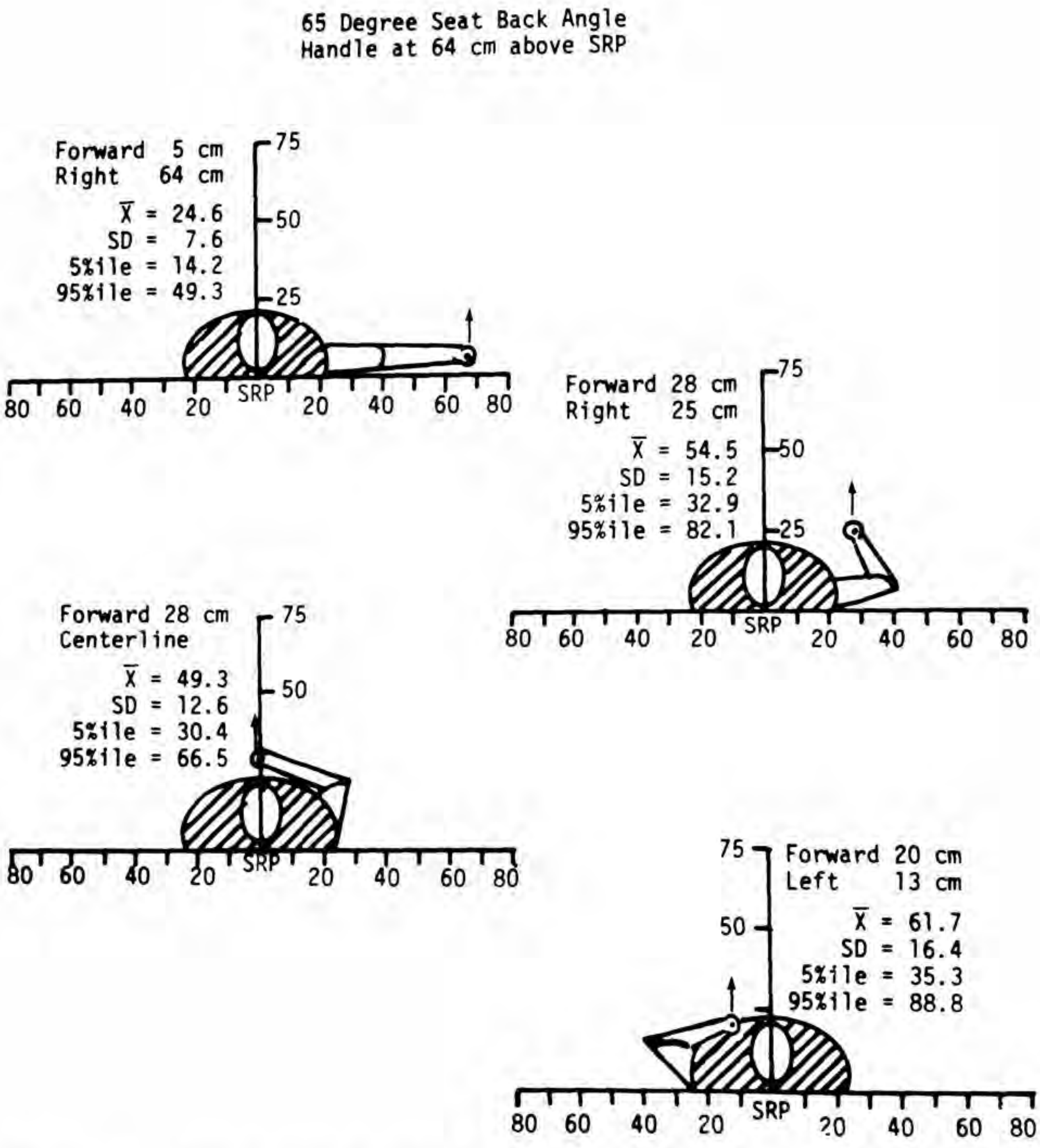


Figure 20. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

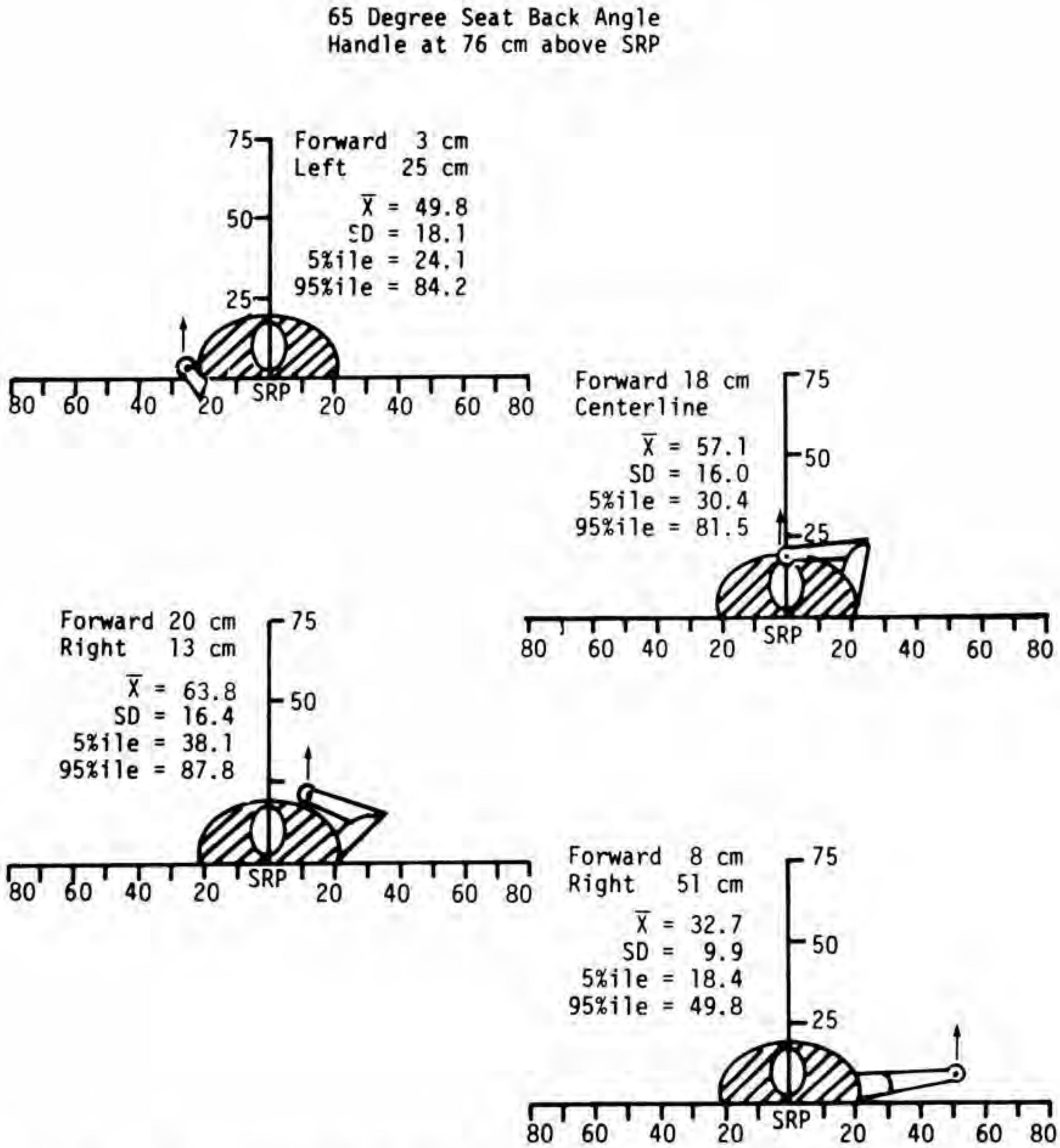
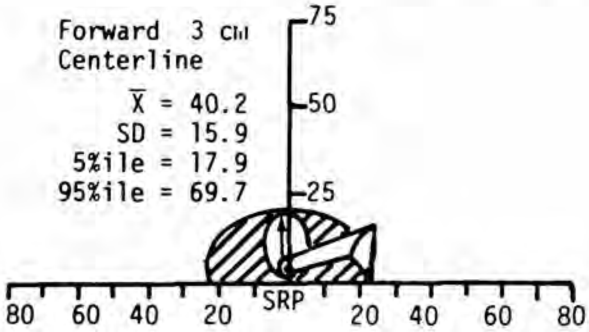


Figure 21. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

65 Degrees Seat Back Angle
Handle at 89 cm above SRP



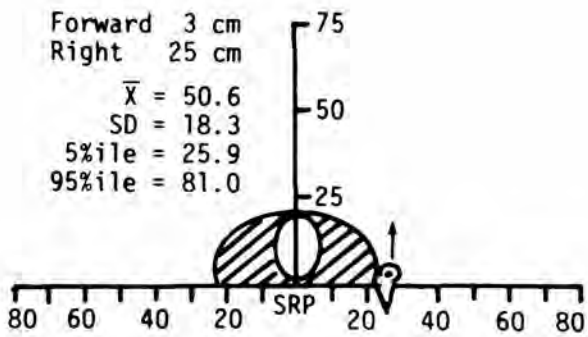


Figure 22. Force exerted on handle assembly at various locations relative to the seat reference point and seat centerline (values in kiloponds).

from approximately 70 static and dynamic strength measurements in both tabular and graphic form. Portions of this material selected for optimum usefulness to design engineers are presented here.

The relationship between muscle strength capacities of men and women is a research topic that has been under investigation since the early 1900's (Hettinger, 1961). Interest in this subject has been spurred recently in the United States by actions of the federal Occupational Health and Safety Administration in expanding opportunities for women under the impetus of the Equal Employment Opportunities Act. The National Aeronautics and Space Administration is obviously well aware of these developments with the proposed advent of female astronauts and mission payload specialists in the Space Shuttle Program.

Designers of equipment that require muscular strength capabilities for possible usage for both the male and female segment of the population tend to design around the oft-mentioned contention that "general muscle strength in women is about two-thirds that of men" (Hettinger, 1961). We will show in this section the fallacy of designing equipment capabilities around this classical two-thirds figure. Figures 23 through 46 illustrate in graphical form, the mean, ± 1 S.D., and the mean percentage of women's strength compared to men's for each measurement. As previously mentioned, readers desiring more detailed information are referred to the original sources, in this case, Laubach (1976, a and b).

Figure 47 is a summary of the data presented in Figures 23-46 and includes a calculation for "total body strength."* These values were derived by simply summing the mean percentage differences for each strength capacity and dividing by the number of measurements observed. The horizontal bar at the top indicates that the range of mean percentage differences in "total body strength" is from 35% to 86%. The average mean percentage difference (vertical line intersecting each horizontal bar) was 63.5% for "total body strength."

The major objective of Figure 47 is to emphasize the broad range of mean percentage differences that were found to exist in selected muscle strength dimensions. Figures 23 through 33, illustrating selected capabilities of the upper extremities, show that women's measurements range from 35 to 79% of men's with an average mean percentage of 55.8%. The strengths in the lower extremities (Figures 34-38) of women compared to men average 71.9% with a range of 57 to 86%. Trunk strength measurements (Figures 39-41) revealed that women averaged 63.8% of men with a range of 37 to 70%. The indicators of dynamic strength (Figures 42-46) showed that women ranged from 59 to 84% of men for an average mean percentage of 68.6%.

Laubach (1976b) has also noted that the <u>fifth percentile</u> value for a particular strength measurement for men often exceeds the <u>ninety-fifth percentile</u> value for women. This, obviously, is not the case in all situations but was found to be true in at least fifty percent of the reported

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*Includes all static and dynamic measurements reported here.

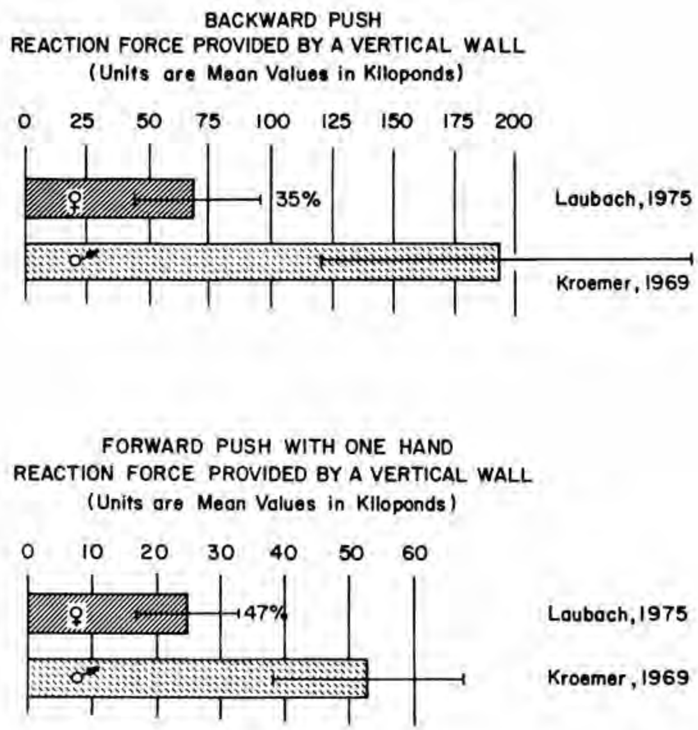

Figure 23. Female/male strength comparison: upper extremities.

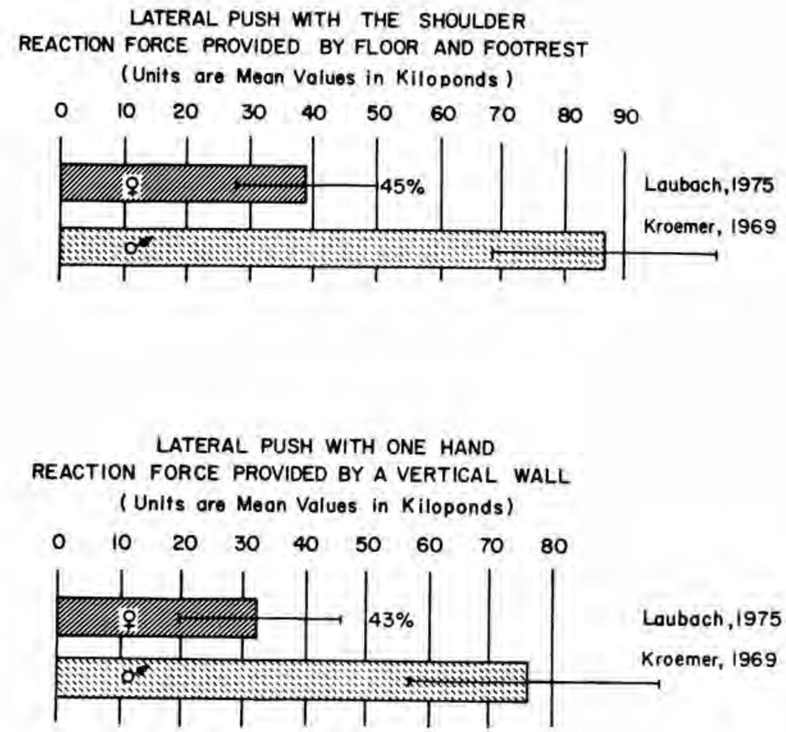

Figure 24. Female/male strength comparison: upper extremities.

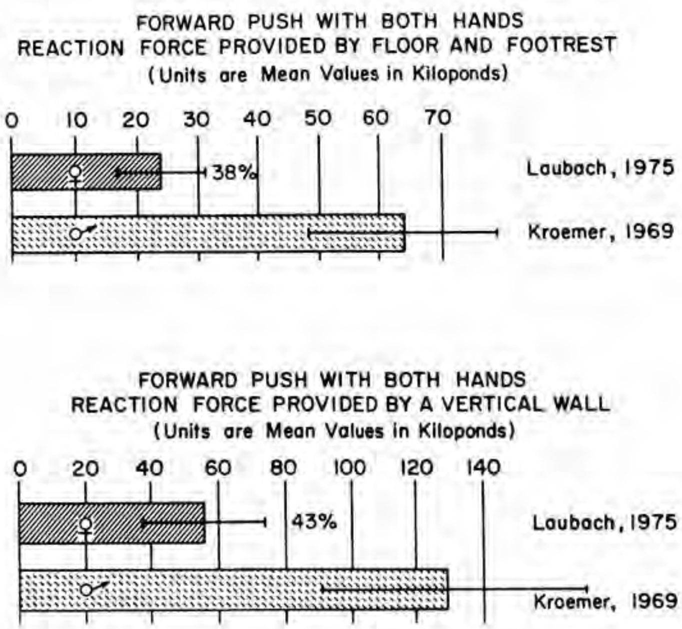

Figure 25. Female/male strength comparison; upper extremities.

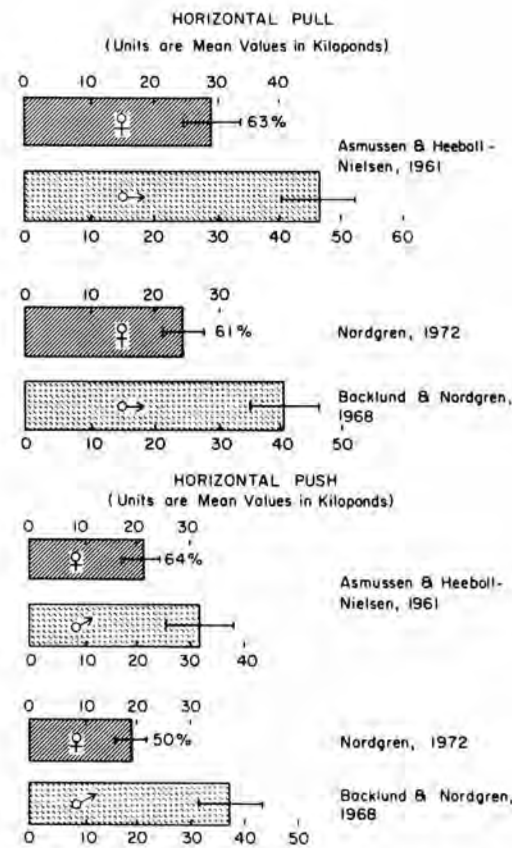

Figure 26. Female/male strength comparison: upper extremities.

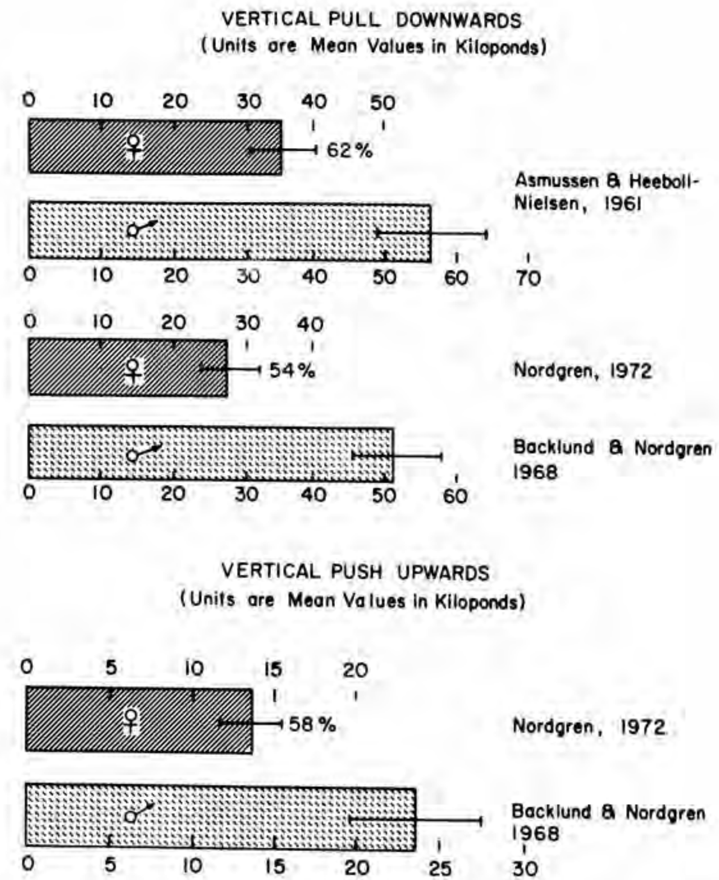

Figure 27. Female/male strength comparison: upper extremities.

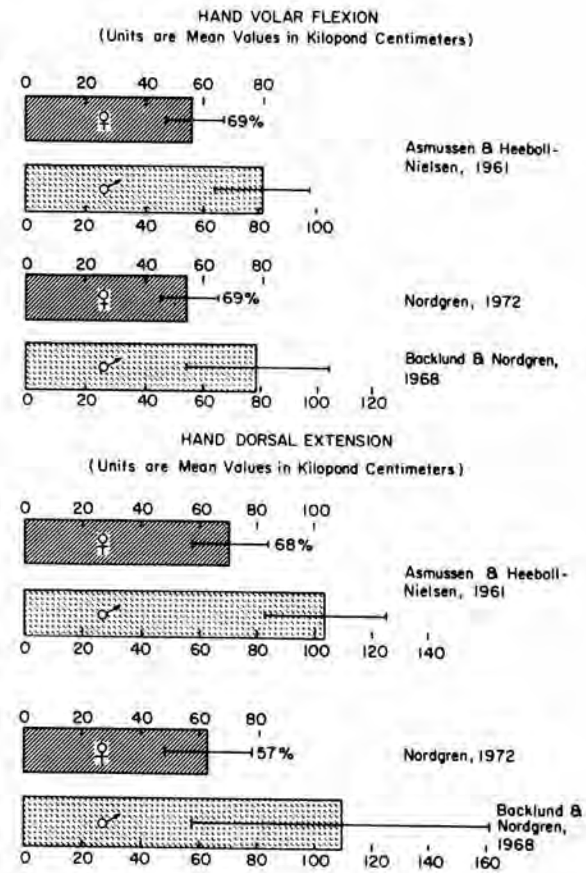

Figure 28. Female/male strength comparison: upper extremities.

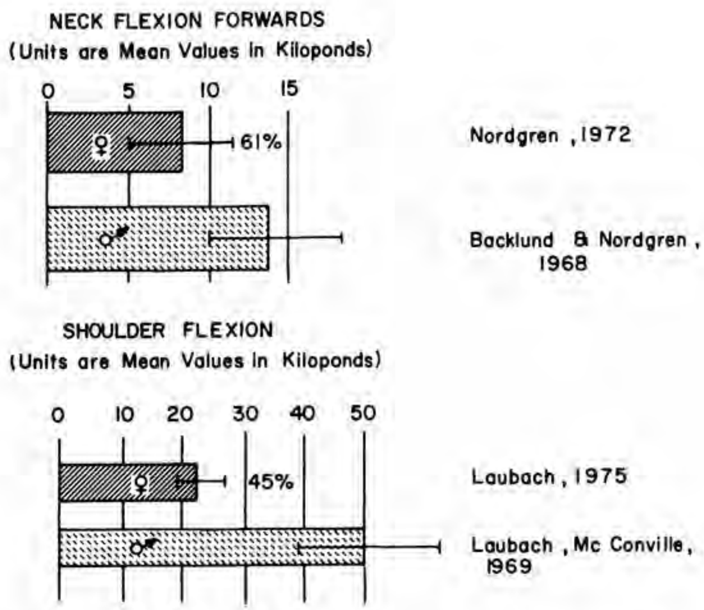

Figure 29. Female/male strength comparison: upper extremities.

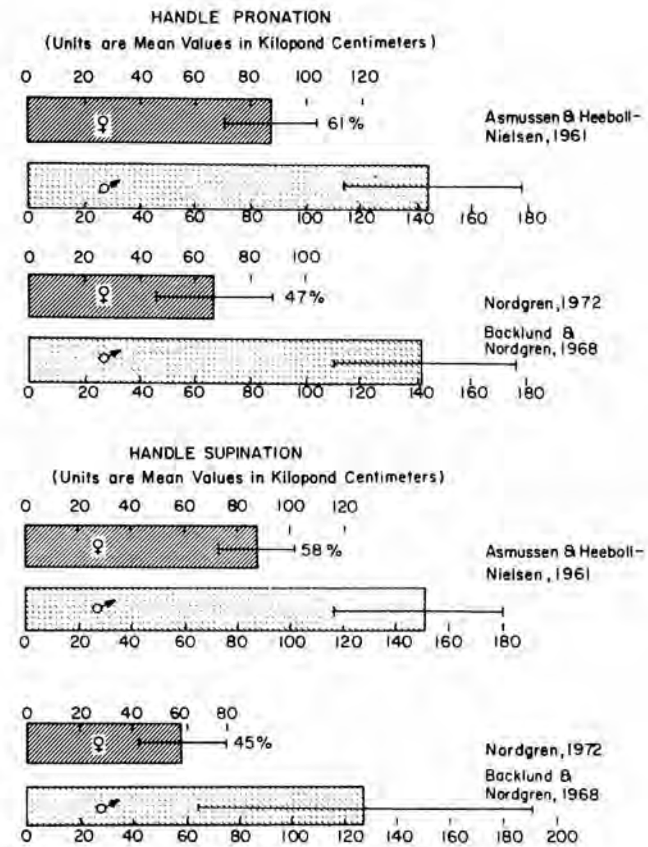

Figure 30. Female/male strength comparison: upper extremities.

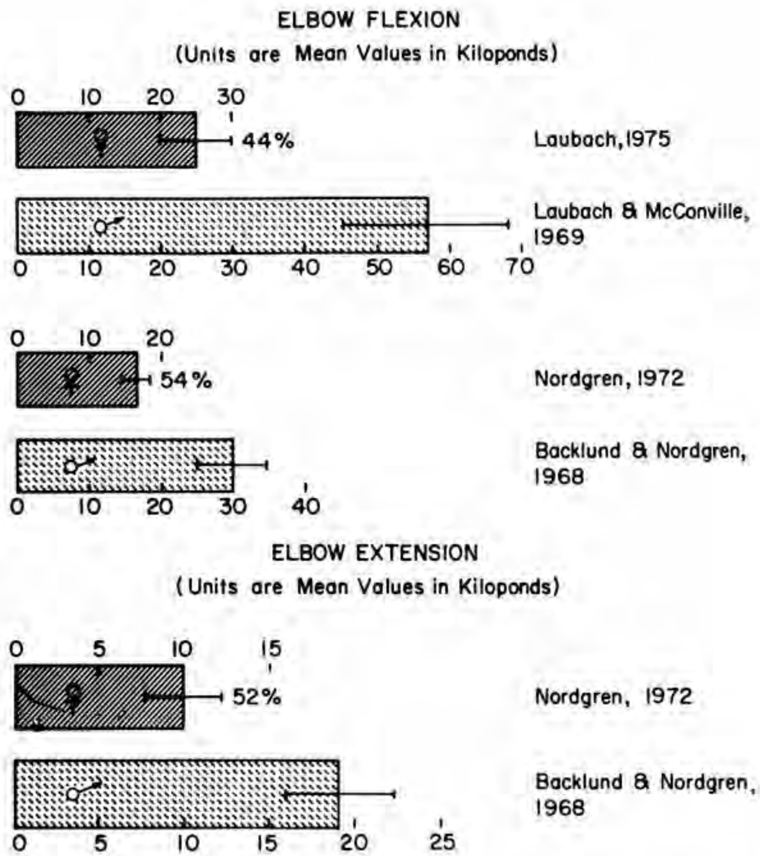

Figure 31. Female/male strength comparison: upper extremities.

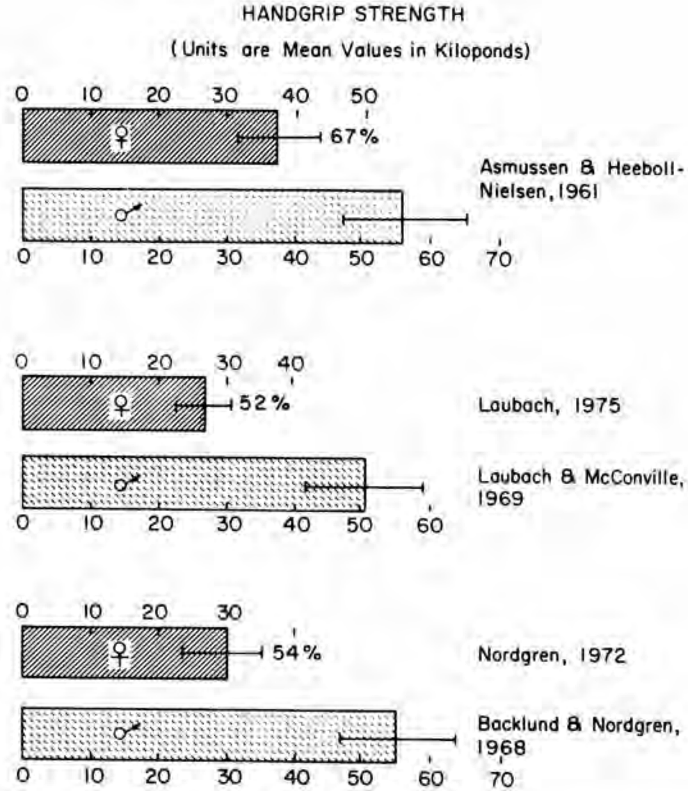

Figure 32. Female/male strength comparison: upper extremities.

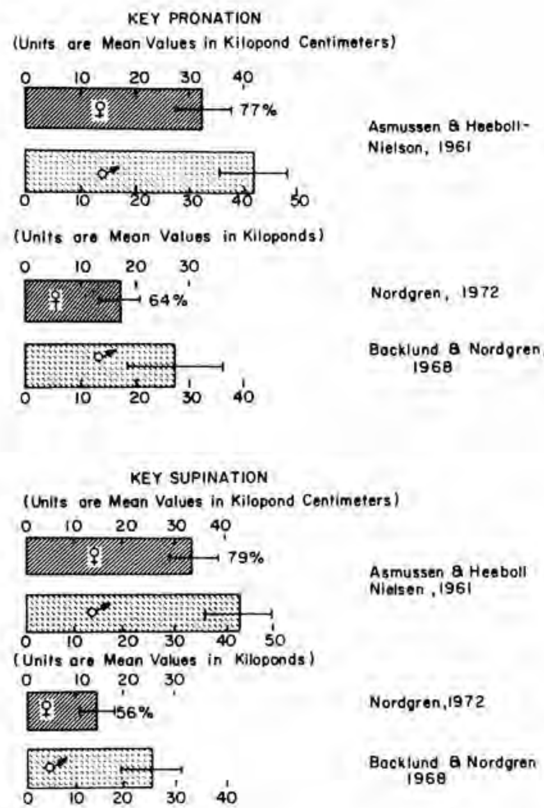

Figure 33. Female/male strength comparison: upper extremities.

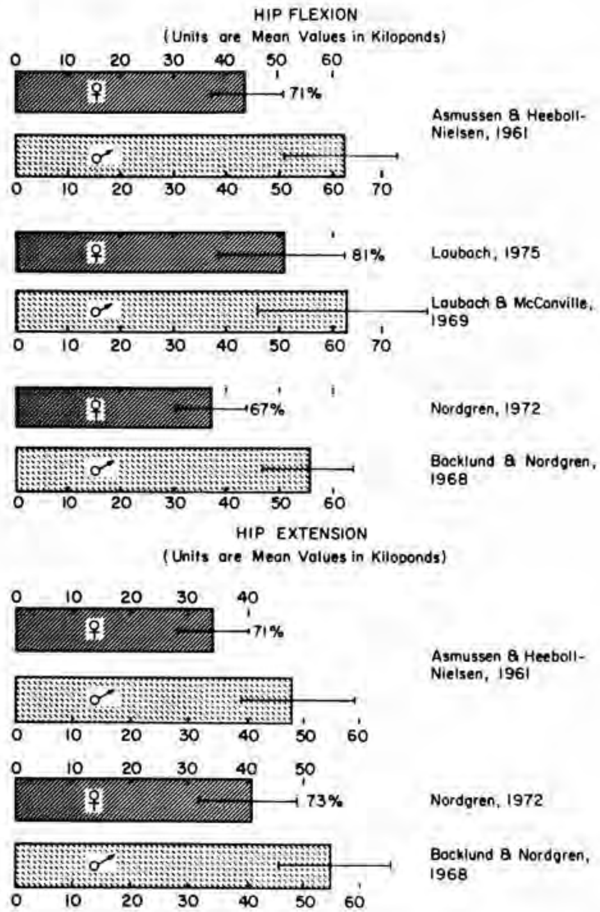

Figure 34. Female/male strength comparison: lower extremities.

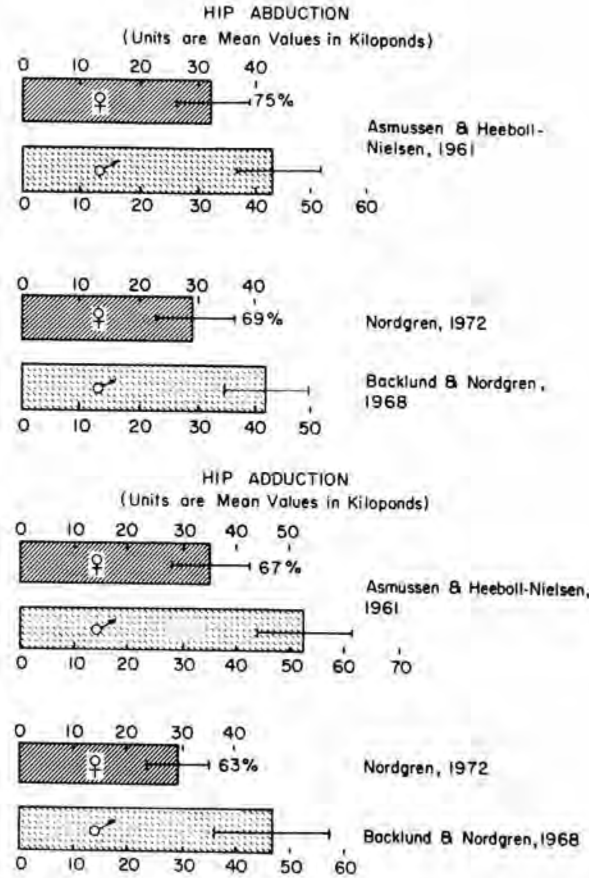

Figure 35. Female/male strength comparison: lower extremities.

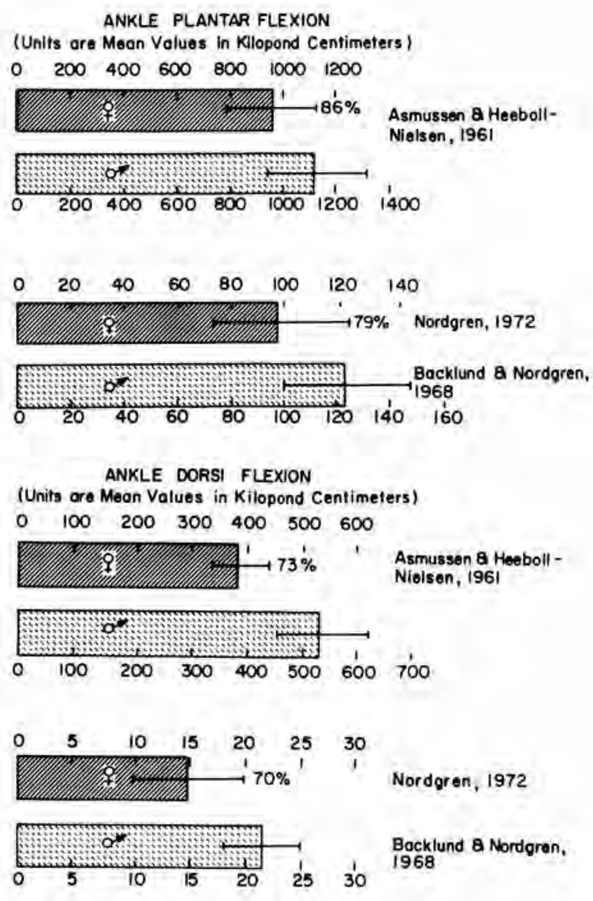

Figure 36. Female/male strength comparison: lower extremities.

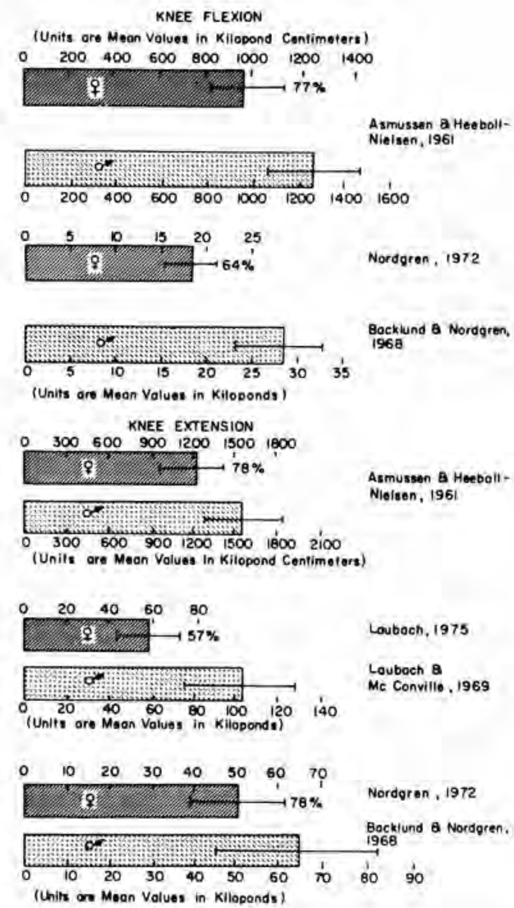

Figure 37. Female/male strength comparison: lower extremities.

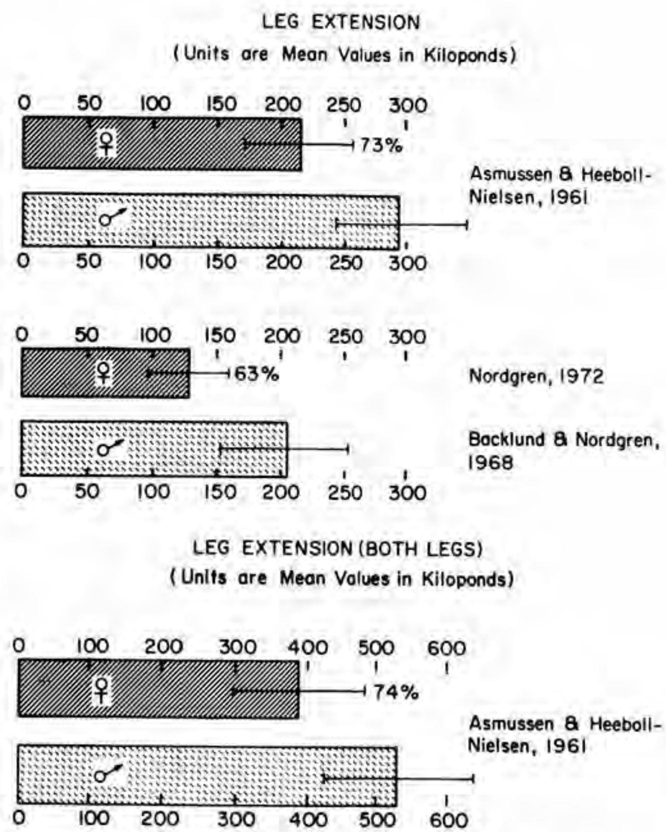

Figure 38. Female/male strength comparison: lower extremities.

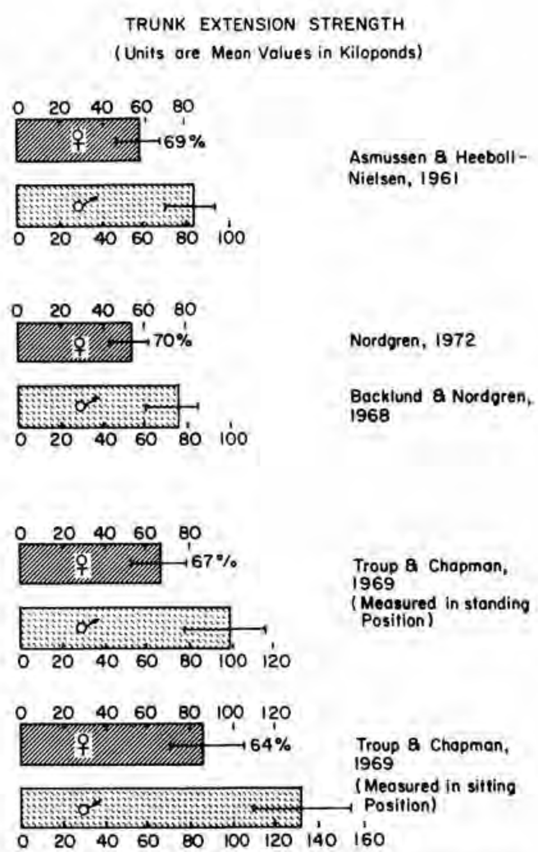

Figure 39. Female/male strength comparison: trunk.

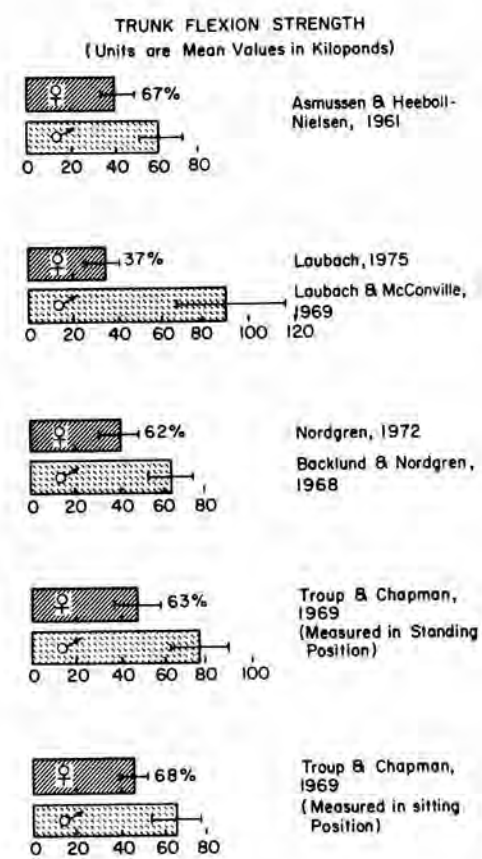

Figure 40. Female/male strength comparison: trunk.

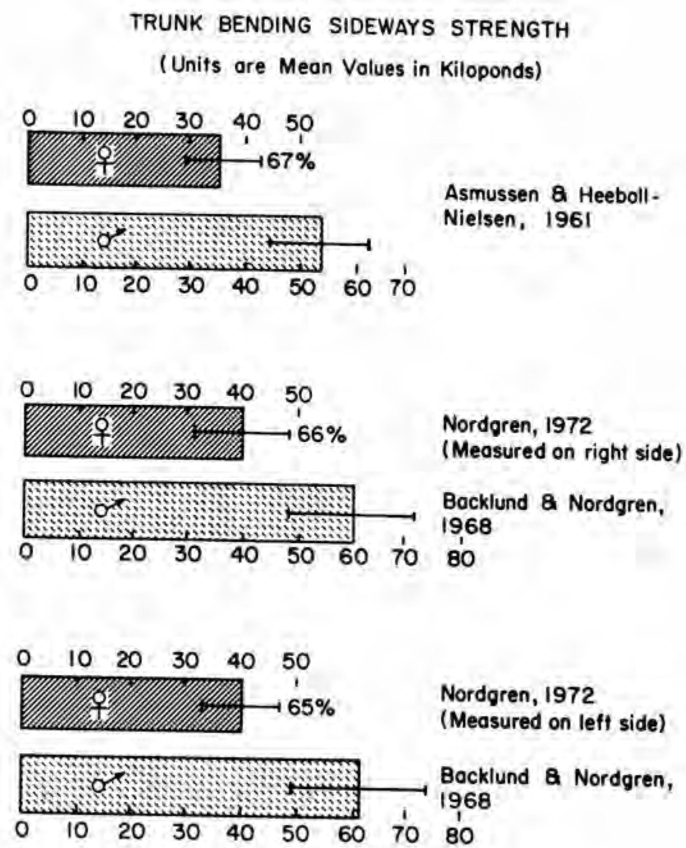

Figure 41. Female/male strength comparison: trunk.

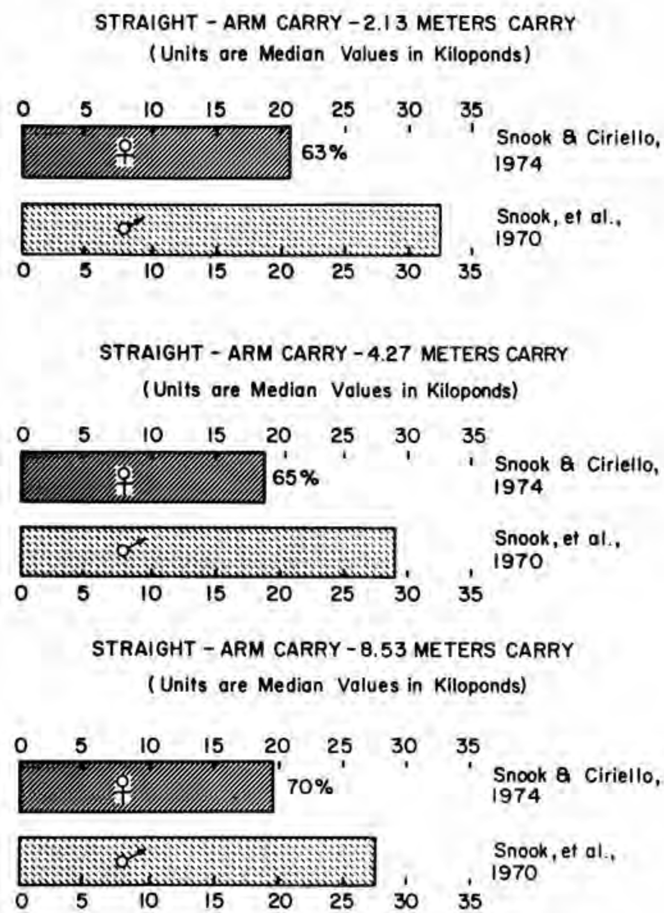

Figure 42. Female/male strength comparison: dynamic.

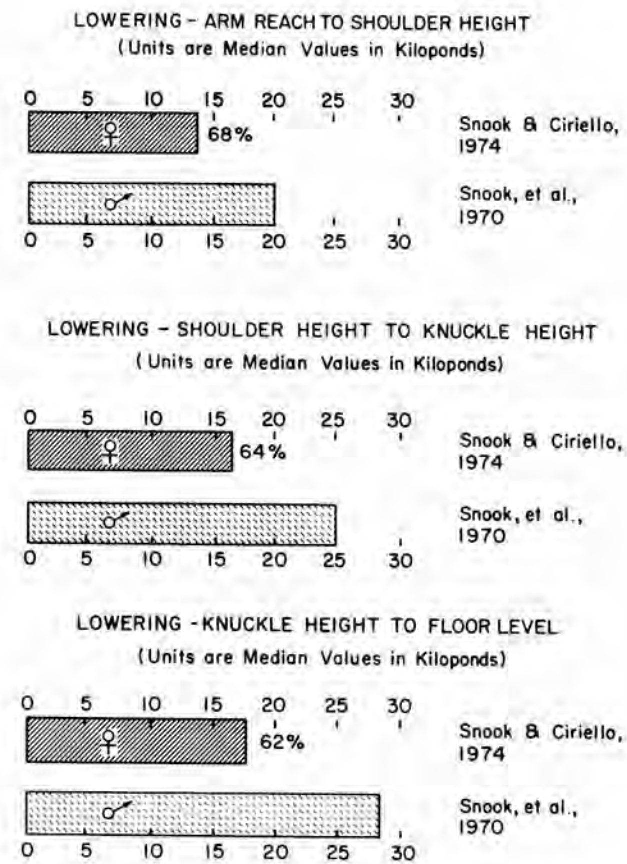

Figure 43. Female/male strength comparison: dynamic.

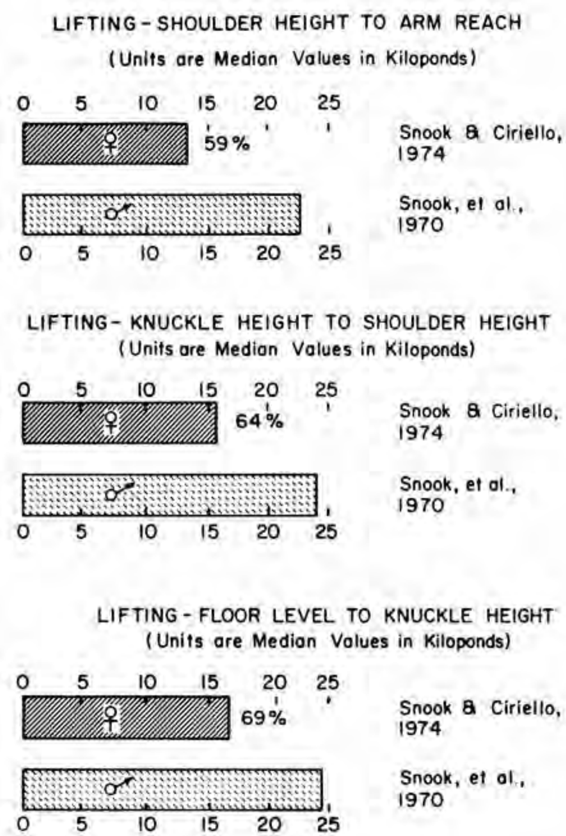

Figure 44. Female/male strength comparison: dynamic.

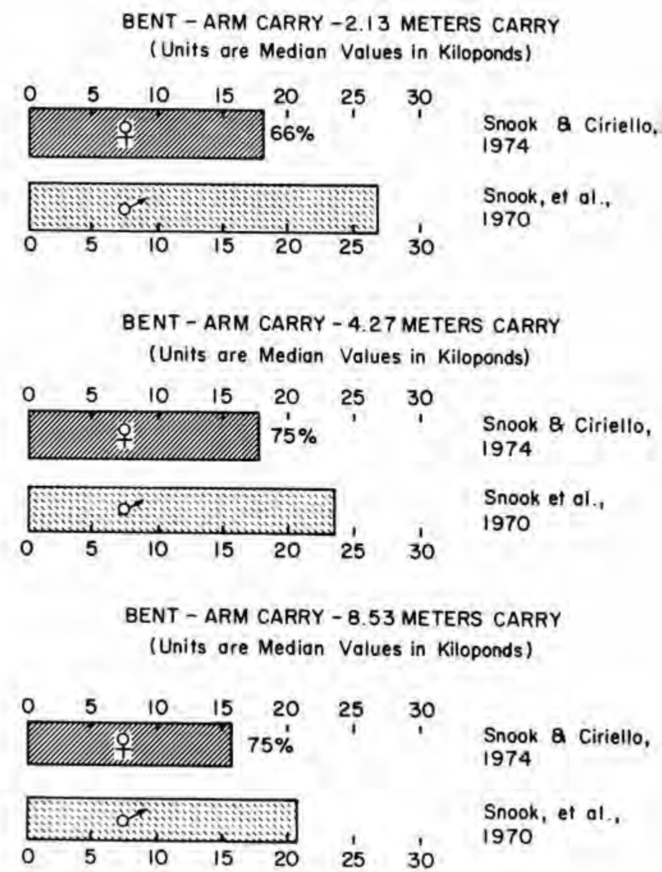

Figure 45. Female/male strength comparison: dynamic.

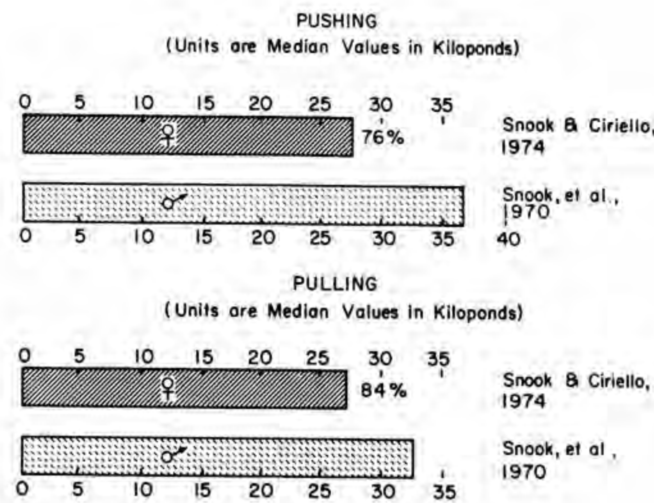

Figure 46. Female/male strength comparison: dynamic.

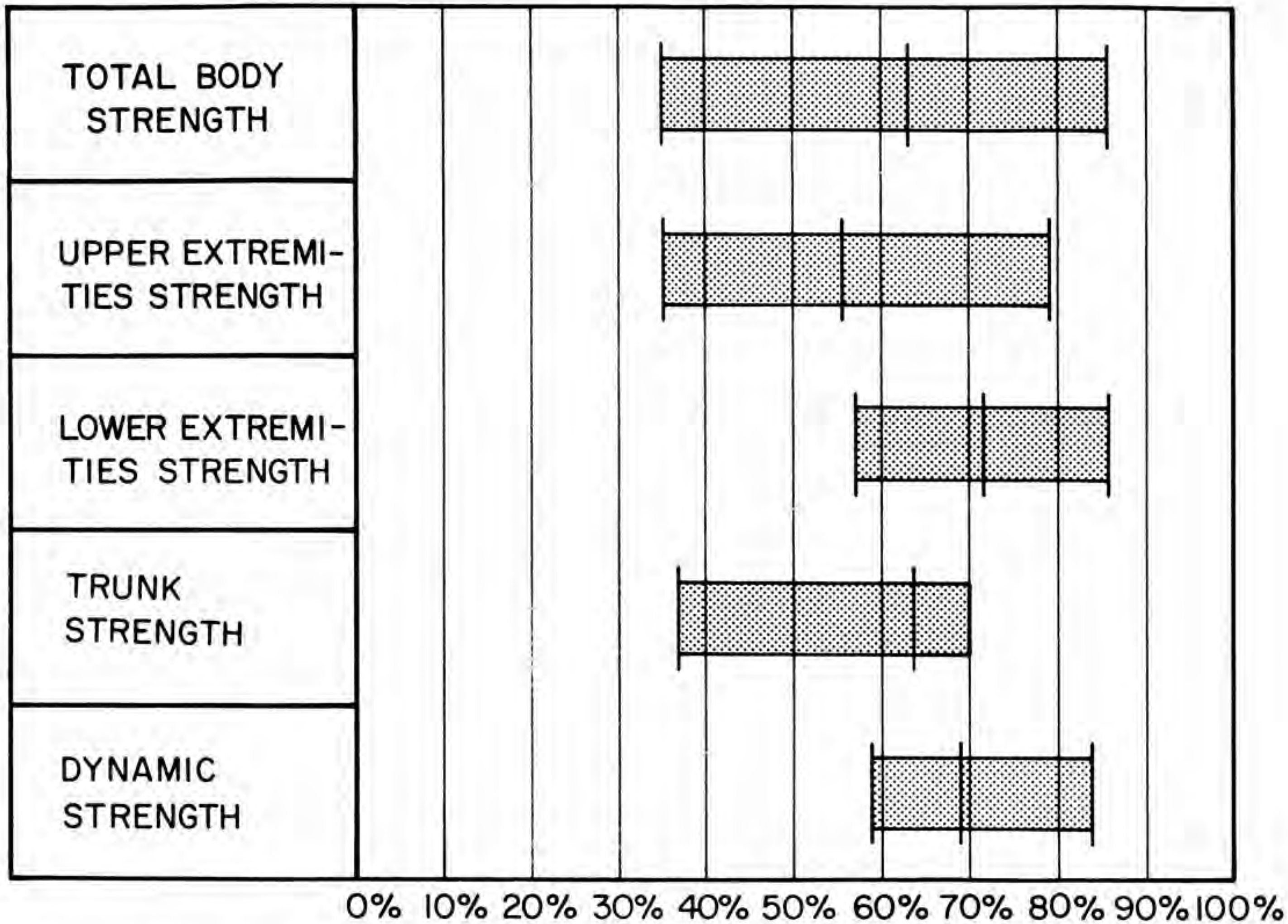

Figure 47. The range and average mean percentage differences in muscle strength characteristics between women and men.

strength data. The finding that the value obtained for a fifth percentile strength score for men in approximately fifty percent of the strength tests investigated in this research often exceeds that of the ninety-fifth percentile value for women is a precautionary reminder for engineers who often use 50th percentile values for design purposes.

In conclusion, our research would seem to substantiate that the mean percentage of women's total body strength is about 63.5% of men's total body strength. However, we believe that the emphasis should be re-focused on the broad range (from 35 to 86%) of mean percentage differences that were found to exist rather than on a single mean figure.

Because of the extreme variability in muscle strength measurements, ergonomists and design engineers should be careful in making extrapolations from muscle strength data. It is, of course, useless to suppose that such precautionary advice will prevent a designer from making estimates of female muscle strength from male data if no relevant information is available for females. To assist the designer in making such an estimate for females, Laubach (1976a) has suggested using the following statistical procedure for computing the often-used criteria of the fifth percentile:

(1) Select a test item from Figures 23-46 that most closely approximates the strength movement for which you have available data, e.g., if the movement approximates a horizontal pull (Figure 26) measurements as described by Asmussen and Heeboll-Neilsen (1961), use the percentage difference of 63 in your calculations.

(2) Assume that the data you have obtained from your sample of male subjects yield a mean value of 50 kiloponds (kp) with a standard deviation of 10 kiloponds.

(3) To calculate the estimated fifth percentile value for men, multiply 1.65 times 10 kp (S.D.) to give 16.5 kp. Subtract 16.5 kp from 50 kp (mean) to give 33.5 kp for the estimated fifth percentile value for men.

(4) Take the fifth percentile value for men, 33.5, and multiply by the percentile difference, 63, to give 21.1 kp for the estimated fifth percentile values for females.

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ADDITIONAL DATA SOURCES

The following documents are not readily available because of limited distribution (unpublished or preliminary data). However, copies/information may be obtained by contacting the author/source.

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CHAPTER VIII
ANTHROPOMETRY IN SIZING AND DESIGN

by
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Knowledge of body size variability within a particular design population is of significant value if an item of clothing, personal protective equipment or work station is to be made to accommodate the users for which it is designed. The mere grasp of the facts and figures relative to variations in sizes is only the beginning, however. It can hardly be stressed enough that the successful resolution of an engineering design problem depends on a thorough understanding of how this knowledge is used within the framework of the particular task at hand. The source of human body size diversity and the quantification of this variability have been covered in Chapters II and III. In this chapter we will discuss the application of this knowledge to engineering design and outline procedures for using anthropometric data in the development of effective sizing programs.

There are a few basic concepts that reoccur continually in anthropometric design problems. One is the use of the average value which may manifest itself in the form of an "average man." The average (arithmetic mean, median or mode) can be computed for any measured dimension and, if the sampling is adequate, is an estimate of central tendency for that variable in the population. When the average is used in conjunction with some measure of variability, such as the standard deviation, it becomes a useful descriptive tool to specify population parameters. Because the average is a measure of the location of central tendency, it appears logical to assume that it must serve some important role in design, which indeed it does but only when handled with care.

The indiscriminate and uninformed use of average values can lead to grave consequences. If, for example, the average value of stature is used as the design criterion for clearance of a doorway, it would soon be apparent that approximately half the potential users would not be able to walk through it without stooping. In similar fashion, if the average anthropometric values for a population were used to design or fashion a full body garment, the degree of fit for individuals would be based on how closely the body dimensions of those individuals approximate average values. Individuals below the mean could possibly be accommodated but the garment would fit loosely and, if they were considerably below the mean, they would be definitely hampered by the excess material. Individuals whose physical size falls above the mean would have a tight-fitting suit to contend with and those far above the mean would probably not even be able to get the garment on.

It appears to be commonly assumed that an average-sized individual will be essentially average in all dimensions. This is a rather common extension of the idea that body proportions are more or less constant and that a small individual is a miniature version of an average sized individual while the larger sized person is an expanded version of an average sized individual. Nothing could be farther from the truth.

In a study of the concept of the average man, Churchill and Daniels (Daniels, 1952) tested the assumption that certain measurement values constitute the average man using ten dimensions useful in clothing design. The average was defined for purposes of the study as any value which fell within the limits of the mean ±0.3 of a standard deviation rounded to the nearest whole centimeter. This means that approximately 23 to 30 percent of the population would be included as average for any one dimension. Churchill and Daniels found that of the 4,063 subjects in the study sample* 1,055 were classified, within the limits of their definition, as being of average stature. In the next step, the average range of each of the nine additional selected measures were added with the following results (Table 1):

TABLE 1
"THE AVERAGE MAN"

Variable	Range Defining Average (cm)	No. Included	Percent of Sample
Stature	173.95 - 177.95	1055	25.97
Chest Circ	96.95 - 100.95	302	7.43
Sleeve Length	83.95 - 86.95	143	3.52
Crotch Height	81.95 - 84.95	73	1.80
Vert. Torso Circ	162.95 - 166.95	28	0.69
Hip Circ	103.95 - 108.95	12	0.30
Neck Circ	36.95 - 38.95	6	0.15
Waist Circ	78.95 - 83.95	3	0.07
Thigh Circ	54.95 - 57.95	2	0.05
Crotch Length	69.95 72.95	0	--

Thus, of the 1,055 men of "average" stature, only 302 were also of average chest circumference, of these, only 143 had average sleeve lengths and so forth. The investigators concluded that the "average man" can be "a misleading and illusory concept as a basis for design criteria" and suggested that the <u>range</u> of variability in body dimensions is more valid than an "average" value in design solutions (Daniels, 1952).

*Data from Hertzberg et al. 1954.

The more sophisticated designer will look beyond the "average" and think in terms of a design concept which incorporates the tails of the distribution of values as well. Ideally, a designer should cover the entire range of variation in a population but in practice this can seldom be achieved successfully. A few individuals on either end of the normal curve often require so many additional sizes and/or range of adjustability in a given item that their inclusion is impractical or uneconomical. In general terms, it is almost impossible to design for more than the middle 90-95 percent of the population without compromising the effectiveness of an item of clothing, personal protective equipment, or work place layout.

To illustrate the problem, one might, for example, examine the range of variability for a single dimension to demonstrate the variability associated with various segments of the population distribution. Using the dimension of stature (USAF 1967 anthropometric data), we find that the variability in the central half of the distribution (between the 25th and 75th percentiles) is approximately 8.4 cm. (3.3 in.); the range for the central 90 percent is 20.4 cm. (8 in.); and the total range, shortest to tallest, is 35.5 cm. (14 in.). Furthermore, the increase in variability is not linear with the distribution of subjects as is demonstrated in the following graphs (see Figures 1 and 2) for dimensions of stature and weight.

The X axis in these figures denotes the percentage of the population about the mean value or 50th percentile. For example, the 10 percent designation represents all those individuals who fall in the distribution between the 45th and 55th percentiles, 20 percent designates all the individuals between the 40th and 60th percentiles, etc. The Y axis denotes the variability in centimeters or kilograms of measured stature or weight, respectively, for the specified groups. It is apparent from this line graph that the 10% and 20% groups -- that portion of the population closest to average -- demonstrate relatively little variability of measurement among themselves. It is also clear that while the increase in variability is relatively constant in the middle of the distribution, it increases very rapidly toward the tails. The dotted line in the graph represents the variability that would be anticipated if one extrapolated the tendency observed in the central third of the distribution values. The solid line is characteristic of the ever-steepening rate of variability which is associated not only with stature and weight but with other body measurements as they move toward the tails of the distribution.

Because of this non-linearity, it is general practice to seek a design solution for that part of the population which constitutes the central 90 to 95 percent of the total and largely to disregard the extreme values in the distribution. In fact, it is often found that when a design is successful for the design population, it will also accommodate a portion of the individuals who lie beyond the design limits although seldom, if ever, will such a solution accommodate all potential users without some custom fabrication or modification.

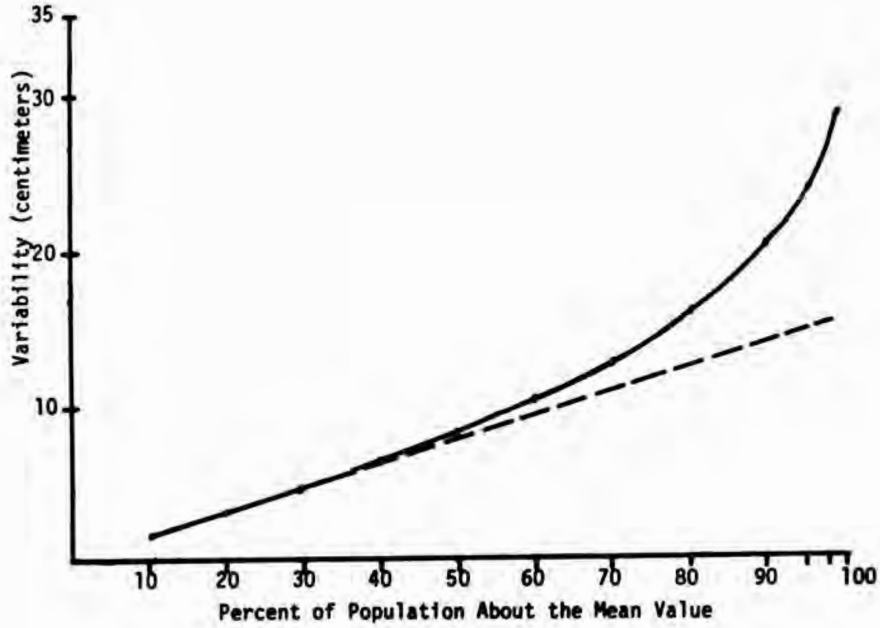

Figure 1. Stature variability by percentile groups.

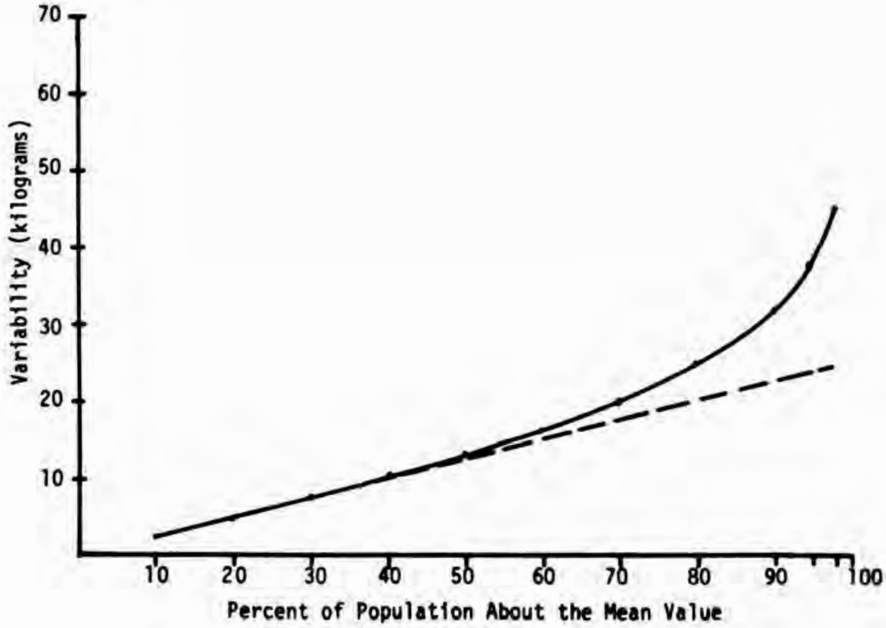

Figure 2. Weight variability by percentile groups.

While this concept of design limits is widely held and is in some ways extremely useful, it has acquired some unfortunate interpretations. We find, for example, that the 5th and 95th percentile values from the design population have become accepted as the only operating design values for accommodation of those portions of the population and the dimensional values have become formulated as the 5th and 95th percentile body form, head form, etc. Designers have then worked to design to the size or shape variance in these forms with the idea that by so doing they would accommodate in their design all the possible combinations of body size and shape that fall within these limits.

The reservations which apply to the "average man" are, if anything, intensified in dealing with the 5th and 95th percentile form. Not only are the percentile forms unrealized in nature, but they are statistically impossible. The problem is illustrated in Table 2. To create this table, based on data from Clauser et al. (1972), we divided the human body into fourteen vertical segments and obtained the 95th percentile value for each vertical distance. Adding these values together, we get a stature of 202.2 cm. (79.6 in.), almost a full foot (30 cm.) greater than the 95th percentile for stature and some 19.2 cm. larger than the tallest subject measured in the survey sample of 1,905 women.

TABLE 2
95TH PERCENTILES--AFW HEIGHT SEGMENTS

Floor to lateral malleolus level	7.8
Lateral malleolus level to ankle level	6.8
Ankle level to tibiale level	34.4
Tibiale level to gluteal furrow level	34.8
Gluteal furrow level to crotch level	5.1
Crotch level to buttock level	10.5
Buttock level to trochanteric level	3.9
Trochanteric level to abdominal extension level	13.6
Abdominal extension level to waist level	9.7
Waist level to bustpoint level	21.9
Bustpoint level to acromial level	16.8
Acromial level to suprasternale level	2.4
Suprasternale level to cervicale level	9.4
Cervicale level to vertex	25.1
Total	202.2

While Table 2 demonstrates only what occurs with linear measurements of the body, it is possible to speculate what the use of all 95th percentile breadths, depths and circumferences would mean in terms of body volume and the resulting weight.

One may well ask, then, how 5th and 95th design forms were ever constructed. The answer is that they are inevitably a mixture of percentile values, some specified and others left to fall as they must to permit assembly into a two- or three-dimensional form. For example, if the stature and sitting height (or torso length) are both held to the 95th percentile values, the leg length must of necessity be disproportionately short. The resulting forms are so strikingly unrealistic as to cause serious doubt about their usefulness (Searle and Haslegrave, 1969, 1970). Nevertheless, such forms often become established as the 5th or 95th percentile "standard" and are widely used for design applications whether or not they are particularly appropriate for a specific solution.

The foregoing is not meant to imply that the concept of 5th and 95th percentile values are worthless as designers' tools but to point out some of their obvious limitations. In a recent paper, McConville and Churchill (1976) focused on the 5th and 95th percentile body forms and recommended an improved approach to the portrayal of body size of these segments of the population for use by designers. In this report, a statistical analysis was made of the tails of the height-weight distribution to demonstrate the usefulness of subgroup or regression values for body design dimensions. The authors suggest that, for many design purposes, regression values be used since these values would maintain the statistical integrity of the data while at the same time portraying the ends of the distribution more accurately than is presently done with the 5th and 95th percentile data.

The mean, the standard deviation and the various percentiles are important and usable statistics both for descriptive and design purposes but they must be used with care and they decidedly cannot be used as the sole basis for solutions to large-scale design problems.

What then is a more useful approach in designing to accommodate the body sizes of various potential users? There are essentially four general methods which have been used.

The simplest but least satisfactory approach is that of limiting the body size range to fit the design product. Prior to World War II, for example, it was recommended that Army Air Force fighter pilots be limited to 70 inches in stature and 180 pounds in weight in order to gain maximum performance from fighter aircraft. For a period prior to World War II, stature of pilots was actually restricted to 68 inches (Randall et al. 1946). With the heavy demands for aircrews after the entry of the United States in World War II, the size limits for pilot selection were drastically expanded in complete disregard for the limited body size criteria which had been used in the design of the cockpits and work stations of the aircraft then in service. The staggering problems that resulted from this mismatch and the work carried out in their solution by the newly formed Army Air Force Anthropology Group has been documented by Randall et al. (1946). This type of design solution, sometimes still used as an expedient, often proves to be no solution at all where extensive redesign and retro-fit are later required.

A second method is simply to design the clothing and workspace around the individuals who will occupy them. This was done in the NASA Mercury program in which the actual body sizes of crew members dictated the design limits. Much of the clothing, personal life support items and workspace were custom tailored to the individual crew members. This approach should, of course, provide the ultimate in good fit but it is also the most expensive procedure and the least flexible.

While both of the above-mentioned design concepts result in a high degree of fit, they are both also inflexible and impractical for all but very special applications, in the first instance highly wasteful of potential human resources and in the second, profligate in the use of material resources. What is needed is a practical approach to designs which must potentially accommodate a population both numerous and various. Two such approaches are described below; one is used to accomodate the variation in body size of a diverse user population in the design of clothing and personal protective equipment while the other is most often used in the development of workstations.

Clothing and Personal Protective Equipment

The method probably most familiar to everyone is the development of sizing systems in which a user population is analyzed and subsequently divided into subgroups of users similar in certain body size dimensions. The more alike the subgroup of persons are in body size, the more satisfactorily they will be fitted by a single-size article, and the less the adjustability or tolerance the designer must provide. Differences in average values, from size to size, while they must be known and taken into account, are of minor importance; it is the variation in a frequently large number of dimensions within the men who make up a single size group which is important. Control of this range of variations is the major goal in the development of a sizing program.

The major steps in developing an effective anthropometric sizing program are as follows:

1. Selection of the appropriate data for analysis.
2. Selection of the key or basic sizing dimensions.
3. Selection of intervals for the key dimension which will establish the sizing categories.
4. Developing for each sizing category all other dimensional data which would be of use in the design or sizing of the item.
5. Conversion of the summary data to an appropriate design value for the end item in terms of fit and function.
6. Establishment of estimates of the sizing tariff (i.e., the proportion of the population that fall within the limits of each size category) for manufacture of the end item.

STEP ONE: Selection of the Appropriate Data

This first step is critical but often difficult. It may be, in many instances, that the desired target population has not been described anthropometrically or that the data are not available or that they are inadequate for design purposes. It is then incumbent upon the designer either to collect the necessary data or to utilize from existing data that which most closely matches the design population under consideration. In Chapter III the sources of human variation are discussed. With this background, it is often possible to select knowledgeably from existing anthropometric surveys those data which best reflect the body size variability of the design populations.

For example, a new state law might require the use of respirators by vocational education students learning automotive body repair and painting. Such an item may not be commercially available and it is likely that anthropometric data for this group is totally nonexistent. This does not mean that a full-scale anthropometric survey of vocational education students must be launched before designing and fabricating appropriate protective masks. The knowledge that this design group is predominantly male, of mixed ethnic origins, and ranges in age from 16 to 19 years gives us enough information to initially characterize the facial size of the design group. A sample for study from one of the military surveys of the anthropometry of young basic trainees would serve as a good starting point.

STEP TWO: Selection of the Key Sizing Dimensions

This step is also of critical importance yet the choice of key sizing dimensions is seldom, if ever, clear cut. The basic dimensions should (1) be those which can be conveniently measured, (2) be an integral part of the fabrication of the end item, and (3) have a high degree of correlation with the other dimensions which are important to the design of the item.

If a series of variables all have the necessary attributes, the selection of a key dimension may depend on which of the variables exercises the maximum control over the other measures of size. Here we are referring to the degree of relationship among variables which is quantified by a statistic known as the correlation coefficient. The higher the correlation coefficient of the key variable with the other design parameters, the more efficient is our sizing program.

Key or sizing dimensions for common items of ordinary clothing are often intuitively rather than statistically selected. The key dimensions for a dress shirt are normally neck circumference and sleeve length (spine to wrist length) or, for men's slacks, waist circumference and leg inseam length. Clothing is thus designed to "fit" these body dimensions but will otherwise "fit" only to the degree that the individual conforms to the standards used for the other dimensions that go into the garment. In recent years many manufacturers of clothing have added additional garments in each size and termed these as tapered, regular, full cut, robust, etc. to allow individuals to select a garment size which conforms more closely to their actual overall body size.

In practice, this system works reasonably well for the loosely-fitting garments which make up the bulk of an individual's wardrobe. In the development of flight clothing, however, especially personal protective clothing and equipment, this approach may prove to be inadequate and extensive modification of the garments might be required to prevent compromising the functions for which the garments were designed.

One solution to the problem of poor fit would be the sizing of a garment on the basis of all its most critical dimensions. A dress shirt, for example, sized on the basis of neck circumference and sleeve length, may require five sleeve lengths for each neck size. If five neck sizes are also required, then a total of 25 shirt sizes are required in order to adequately fit the variability in body size of the using population. If there were some need for the shirt to fit the chest and waist girth as well, the number of sizes would increase radically. Even if only four chest sizes and four waist sizes were required, the total number of sizes would be five times five times four times four, or a total of 400 sizes to clothe a given population. Needless to say, such a solution is economically unfeasible. It is interesting to note, however, that 69 sizes of a single dress shirt are offered in a recent mail order catalogue and this garment is sized solely on neck circumference and sleeve length.

The sizing of protective clothing and equipment is considerably more complex than the sizing of dress shirts. Instead of two critical dimensions, there are often many critical dimensions: instead of 25 or 50 sizes, economics and logistics limit the number of sizes to a dozen or fewer. Thus, the selection of the key dimensions becomes a problem requiring subtle and skillful handling.

It is instructive to look at this process as outlined by Emanuel et al. (1959) who developed an anthropometric sizing program for high altitude protective clothing (full and partial pressure suits). They made an analysis of U.S. Air Force anthropometric data to determine the combinations of key dimensions which would minimize to the greatest degree the variability of the other dimensions needed in the design of the garment. Some fifteen pairs of dimensions were tested. These included height and weight, stature and vertical trunk circumference, sleeve length and chest circumference, among others. The paired body dimensions were deliberately chosen to combine a body length and a body girth because of the high relationship among the various body length measurements and the correspondingly high relationship among the body girths and weight. This is not to say that lengths and girths correlate well with each other. In fact, the level of relationship between the two key dimensions in any pair need not be strong as long as one or another of these variables has a high relationship with all the other anthropometric design variables.

Emanuel et al. (1959) tested the level of relationship by computing the multiple correlation coefficient (R) of each pair with all other anthropometric dimensions of interest in clothing design and comparing the results. They found that some 58% of the dimensions had 'R's as high or higher with the pair, height and weight, as with any other combination of key dimensions tested. In addition, height and weight were found to have the highest level of relationship overall with the circumferences which are of particular importance in clothing design. They therefore concluded that the key dimensions of height and weight were optimal for their particular purpose.

STEP THREE: Selection of Intervals for the Key Dimensions

A series of considerations may be involved in selecting intervals of the key dimensions to determine the width of the sizing category. The number of sizes for a particular end item may already be specified, the maximum permissible width of a sizing category in terms of the key dimensions may be specified, or the possible range of adjustability within the end item may be a consideration. The material that the garment will be made of, the cut of the garment, whether the end item must fit snugly or loosely, whether it must be a single-piece coverall or a combination blouse and trouser suit all enter into the picture in establishing the sizing intervals.

At some point, a decision will be made about the trade-offs among the various design considerations and the sizing category intervals will be established. The primary consideration in any such decision will be to offer a good "fit" for the maximum number of users with the fewest number of sizes in the system. We specify the maximum number of users because it is often impossible to fit all potential users with a specific item. There will usually be some individuals who cannot be accommodated by any item designed to the normal population variance because of physical deformities or because they fall at the extremes of the distribution with regard to size and shape. An effective sizing and design scheme, however, will keep the size of this disaccommodated group to the absolute minimum.

In the height-weight sizing system discussed by Emanuel et al. (1959), a total of five sizing programs were described--a six-, an eight-, a nine- and two twelve-size schemes. The authors pointed out that selection of a particular sizing program required a thorough evaluation of the design problem at hand. The six-size program had, in general, the largest within-a-size standard deviations and the twelve-size program the smallest. In general, they found, as might be expected, that the larger the number of sizes, the larger the percent of the population that is covered in the sizing scheme. In addition, the increase in the number of sizes has the effect of increasing the overlap between sizes for most dimensions. This has a very practical appeal as it theoretically provides the assurance of obtaining a good fit when it becomes necessary to upgrade or downgrade from an individual's indicated size. There are, however, some very real limits which are reached which cannot be overcome by the addition of sizes.

The overall homogeneity of the individuals within a sizing category selected from one or two key dimensions cannot be infinitely improved by the addition of sizes. At some point the minimum level of within-group variance will be approached for all the body dimensions and even by doubling or tripling the number of sizes this level of within-group or within-size variance remains essentially constant. This is a function of the less than perfect relationship that the body dimensions have with the key dimensions by which the individuals in the sizing group are selected. If all the body dimensions used in a sizing analysis correlated perfectly then the break down of sizing groups could theoretically continue indefinitely until one would arrive at a size category which contained individuals of 175 cm. in height and 80 kg. in weight all of whose body dimensions such as sleeve length, waist circumference, etc. would be identical.

Table 3, taken from Emanuel et al. illustrates an eight-size height-weight program. Each bivariate cell contains a tabulation of all the individuals in the survey who fall within a specific six-pound increment of weight and 0.8 inch increment of stature. The eight-size program categories, bounded by the heavy dark lines, are comprised of four weight categories each with two categories of height. The fitting table (Table 4) for this eight-size program is as follows:

TABLE 4
EIGHT-SIZE HEIGHT-WEIGHT PROGRAM

Size	Weight Range (lbs.)	Height Range (in.)
Small Regular	125-149	63.0-67.5
Small Long	125-149	67.5-72.0
Medium Regular	150-174	64.5-69.0
Medium Long	150-174	69.0-73.5
Large Regular	175-199	66.0-70.5
Large Long	175-199	70.5-75.0
X-Large Regular	200-224	67.5-72.0
X-Large Long	200-224	72.0-76.5

Each weight category (Small, Medium, Large and X-Large) contains a 25 pound increment of body weight and each length category a 4.5 inch increment of height. The systematic placement of the sizing intervals on the bivariate distribution was designed to include the maximum number of individuals in the sizing categories: in this instance some 94 percent of the sample fell into one or the other of the eight sizing categories.

When the interval of the size categories was reduced from 4.5 inches to 3.0 inches, and the number of categories increased from eight to 12, the coverage of the population remained the same (94%) and the average standard deviation for the body dimension useful to the designer was not appreciably reduced. This indicates that the subjects who fell within any single sizing category were almost as variable in body size in the eight-size system as in the twelve-size system and whatever gain was achieved must be weighed against a 50 percent increase in sizes that would have to be produced in the 12-size system.

TABLE 3
EIGHT-SIZE HEIGHT-WEIGHT BIVARIATE FROM EMANUEL ET AL. 1959

Height (Inches)

Weight (Pounds)	61.4-62.2	62.2-63.0	63.0-63.8	63.8-64.5	64.5-65.3	65.3-66.1	66.1-66.9	66.9-67.7	67.7-68.4	68.4-69.3	69.3-70.1	70.1-70.8	70.8-71.6	71.6-72.4	72.4-73.2	73.2-74.0	74.0-74.8	74.8-75.6	75.6-76.4	76.4-77.1	Totals
227 - 232										1	1		1	2	1	2	1	1			10
221 - 226									1		1	2	1	2	3	1	1	1	1		14
215 - 220									2	2	4	3	2	6	1	2	2	1	1		26
209 - 214						1			3	2		10	9	6	5	5	3	2	3		49
203 - 208						1		3	5	4	11	7	7	9	8	5	1	4		1	66
197 - 202				1			1	3	7	12	14	19	23	10	10	7	6	2		2	117
191 - 196						2	3	9	8	22	23	22	23	17	15	8	1	4	3		160
185 - 190					1		6	9	18	38	21	37	20	26	7	6	7	1	2	1	200
179 - 184				1	1	2	11	14	29	36	35	40	22	29	15	6	6	1	1	1	250
173 - 178				1	3	4	16	26	38	44	54	48	38	26	16	21	7	2	1		345
167 - 172	1		2	2	5	14	16	30	45	51	61	56	43	26	13	11	7	2	1		386
161 - 166			3	4	10	20	25	41	51	85	64	53	42	26	16	12	3		1		456
155 - 160		2	3	5	10	20	32	45	63	76	71	50	48	25	14	9	3	1	2		479
149 - 154	2		4	8	17	33	36	54	57	52	61	53	39	14	8	3		1	1		443
143 - 148		3	2	6	25	28	43	45	51	53	42	34	13	8	7		2		1		363
137 - 142	2	3	6	13	14	33	49	46	43	32	32	23	12	6	3	2					319
131 - 136	2	1	1	9	12	24	27	27	30	13	14	11	3	2	1						177
125 - 130	2	4	3	10	11	22	12	13	16	10	6		1								110
119 - 124		1	3	5	8	8	4	7	5					1							42
113 - 118		1	1	3	2	2	1	2	1												13
Totals	9	15	28	68	119	214	282	374	473	533	515	468	347	241	143	100	50	23	18	5	4025

Once again, the decision that must be made can only be made with the fit and function of the end item in mind and its relationship matched to the user population.

STEP FOUR: Development of Dimensional Data for Each Sizing Category

After the sizing categories are specified as to interval and number, we move to the fourth step of our sequence. Here all subjects within each of the sizing categories are treated as a sub-population and summary statistics are prepared for each variable to be included in the analysis.

Referring again to the bivariate table (Table 3), the sizing category at the lower left is the size designated as Small-Regular and consists of all individuals in the sample who are between 125-149 pounds in weight and are also between 63.0 and 67.5 inches in height. Of the 4025 individuals in the survey, some 426 (10.58 percent) fell within this sizing interval. This group is then treated statistically as a sizing subsample. It next becomes necessary to select a group of relevant body dimensions for analysis in order to zero in more accurately on the sizing requirements of each sizing subsample. The body dimensions of interest are those which will conceivably be of use to the designer in developing the items of clothing or personal protective equipment. If the item is a full-face respirator, the relevant variables are measurements of the head and face; elaborate sizing analysis of torso girths and appendage lengths are neither warranted nor of any particular value. In Emanuel's study of high altitude protective clothing, some 53 variables, predominantly circumferences and body surface measurements, were selected for analysis.

The mean and standard deviation is computed for each body dimension of interest for each sizing subgroup. For reasons relating to sampling stability, the sizing category standard deviations are, in effect, averaged to provide, for each dimension, a single within-a-size standard deviation.

With these statistics at hand, we can move to the fifth step of the analysis.

STEP FIVE: Conversion of Summary Data to Appropriate Design Values

The design value is a single numerical value for each variable that is meaningful in the design of a given item. The waist girth design value may be the upper limit of the waist in each size category as it must be large enough to fit around the largest waist in that group while the design value for an elasticized wrist closure may be the category mean minus two standard deviations so it will be small enough to seal the sleeve of the person having the smallest wrist circumference. The proper design value thus relates to a functional property of the design rather than to a statistical function.

The design value can be any combination of the mean $\pm$ some increment of the within-a-size standard deviation. In the Emanuel et al. study, the design range was established to be the category mean $\pm$1.5 standard deviations. These design values would thus accommodate the central 87 percent of the individuals that fell within any one height-weight size. They concluded that an additional 8% of the subjects would be fitted by upgrading and downgrading from the indicated size so that a total of 95 percent of the population would be expected to be accommodated. Their primary concern was, however, for the circumferences and breadths, depths and surface dimensions of the body. The placement of the joints, such as in a pressure suit, should not be based upon the design ranges but on the size category mean value. In other design problems the design values may be a combination of upper and lower design values again depending upon fit and function of the end item.

In a recent study by McConville and Alexander (1975), the design values of a new oral-nasal sizing program and face forms were established. The length of the face, for example, was established as a mid-point of a sizing category range and the proportion of the upper and lower face developed from regression equations based upon the value of the face length used. The projection of the nose, nose breadth, lip length, and lip protrusion were established as the size mean plus 1.65 or 2.0 standard deviations (95th or 97.7th percentile value respectively) since these are facial dimensions that must be cleared by the main part or internal sealing edge of the facepiece. The design values for facial breadths were established as the sizing category mean minus 1.0 within-a-size standard deviations (a value equivalent to approximately the 16th percentile) based on the logic that the external sealing edge of the facepiece must not be so wide as to extend beyond the limits of the narrower faces.

The design values are, of course, based on the purpose of the end item and how best to accommodate the variance within the sizing subgroup. It again requires a knowledge of how the end item must function to be effective.

STEP SIX: Preparation of a Tariff

In essence a tariff is a schedule showing the number of each size of an item that is necessary to outfit the user population. If, for example, we found as Emanuel et al. did, that the Small-Regular category contained 12.7% of the total number of subjects included in all eight sizing categories, then the best estimate for production of that size item would be some 12.7% of the total production run.

Fit-Testing

This completes the anthropometric design analysis but does not in any way signal the end of participation in the developmental program. The final validation or proof of the success of the design lies in establishing that the end item fits and performs up to design standards. This is normally established by a fit-test in which the prototype items are tested on a sample of subjects drawn from the user population.

A number of such fit-tests have been described (Barter and Alexander, 1956; Emanuel, Alexander and Churchill, 1959; McConville and Alexander, 1975). A fit-test of an oral-nasal oxygen mask is described in McConville and Alexander, 1975. Sixty-six subjects, crew members from the 17th Bombardment Wing, SAC, were measured for six facial dimensions and fitted in their indicated mask sizes; a quantitative leak rate was established at five pressure settings and a subjective evaluation was made of the fit, comfort, wearability and compatibility with the helmet/visor, eyeglasses, etc. The fit-test sample was found to be representative of the USAF flying population in terms of the six facial dimensions measured and adequate in the range of facial sizes for the purposes of the test. A quantitative leak rate was established for each subject in his indicated size mask. Eight subjects were also tested in alternate sizes as they fell at the extreme end of a sizing interval in their key or fitting facial dimension. Comments were solicited from each test subject at the end of the test regarding the fit, comfort and suitability of the mask for flight operators. The results of the fit-test and subject comments appeared to validate the dimensionsal sizing of the oral-nasal facepiece.

A comparable fit-test should always be conducted as soon as it is feasible. In addition, when possible, a limited production run of the item should be placed in service by users in the actual work condition and evaluated for a reasonable period of time. It is often only at this point that deficiencies in the design become apparent.

Work Station Design

The fourth of the anthropometric design approaches mentioned at the beginning of this chapter is the one most often used in the development of work stations, a generalized category that includes desks, consoles, cockpits, driver compartments, etc. The goal of this design approach is the same as in the previous example--the optimum accommodation of the body size variance of the potential user population--but the method differs. Rather than developing a sizing program and a range of sizes, the technique here is to build a range of adjustability into the item or work station that will successfully accommodate the body size variance.

The method used in developing the anthropometric design data will depend in a very large part on the particular equipment or work station involved. Of utmost importance is a comprehensive understanding of the function of the equipment and the relationship of the operator to the equipment. As in the previous example, the approach can be outlined in a series of steps as follows:

1. Determine the characteristics of the potential user population and select the appropriate anthropometric data base for analysis.
2. Establish what the equipment must do for the user (form, function and interaction).

3. Select the principal interface of the user with the equipment.
4. Establish the anthropometric design values to be used in fabrication.
5. Design and evaluate a mock-up and revise design as necessary.

STEP ONE: Selection of the Appropriate Date

See Step One in the previous section.

STEP TWO: Establish What the Equipment Must Do for the Operator

Consider the requirements in the design of a fighter aircraft cockpit. The cockpit encloses and supports the pilot. It must, therefore, include a seat which is large enough to accommodate the pilot with all his clothing and necessary personal protective equipment. The arm rests must be sufficiently separated and high enough to enclose and support the arms during ejection so that they will not be caught in the cockpit or injured by windblast. All controls manipulated by the arms and legs should be placed within reach of the pilot, or the seat should adjust so that all controls are brought within reach, but the ejection envelope must be free of impingement. Any obstructions to vision must be minimal. The canopy clearance fore and aft and side-to-side must be large enough to allow the pilot to enter and leave the cockpit. Furthermore, the canopy must allow the taller pilot to sit in a proper position without fear of bumping his head. In order that each of these requirements be met, the relationships between the cockpit and the user population should be analyzed in such a way that specific anthropometric dimensions can be applied to specific requirements.

For most engineering purposes, body dimensions which are maximum straightline distances between extremes of body segments are needed (the so-called workplace dimensions). Such dimensions include body lengths, breadths (side-to-side diameters), and depths (fore and aft diameters).

A number of anthropometric measurements may be used in the design of the seat. The seat pan dimensions can be derived from the seated hip breadth and the buttock-popliteal length. The seat arm rest position can be determined from the dimensions elbow-rest height and seat back dimensions from shoulder breadth and perhaps shoulder height/sitting. The clearance envelope is related to elbow-to-elbow breadth and buttock-knee length. If the canopy is to clear all potential pilots, the dimension of sitting height becomes relevant.

It should be relatively obvious to any design engineer that an adequate sitting height clearance for the user population must be an integral part of any cockpit design. Yet in a recent study Cressman (1972) found that certain deficiencies in the KIOWA helicopter limited the size of the aircrew who could use it. Cressman found, for instance, that men who were more than 96 cm. (37.8 in.) in sitting height (approximately 15% of the user population) lacked adequate head room and that an estimated additional 20% would have inadequate clearances for leg length and body breadths--enough to affect their safety and efficiency in flight.

Numerous dimensions can be shown to be of aid in specifying cockpit design values. These dimensions are, however, for the nude or lightly clothed individual and adjustments for increase in body size due to clothing and equipment must be made (Alexander, Laubach, McConville (1976)). At the conclusion of this step, a good working knowledge of the relevant body dimensions involved in the design will be achieved.

STEP THREE: Select Principal User/Equipment Interface

The next step is to apply the dimensional data in some systematic fashion to establish the overall anthropometric design. This can be done by determination of the principal interface between the user and the equipment and use of this as a reference or design point for the initial layout of a workplace. A rather obvious interface for a typewriter console would be the keyboard and the design reference point the geometric center of the keyboard. In other design problems, the interface and reference point may be far from clear.

In cockpit design, a theoretical point designated as the design eye point, or eye reference point, is generally accepted as the design datum. The reasoning here is that vision requirements are critical for a pilot and the interface of the crewmen with the work station must take cognizance of this essential requirement first and foremost. This eye point is a theoretically optimum crewman's eye position and, as it lies in three-dimensional space removed from an actual physical surface of the aircraft, poses some practical difficulties in actual use. It is often the practice, therefore, to relate this design datum to a second "hard" point which lies at the middle of the intersection of the seat back and seat pan called the seat reference point. This design point can be further specified as the neutral seat reference point (NSRP) which would be the midpoint in vertical seat height adjustability in a vertical plane design to accommodate the range of sitting eye height in the design population. In aircraft with ejection seats, there may be no fore and aft adjustment possible but in other design situations, the supporting seat may include a range of adjustability to permit the user to select the correct placement of the seat relative to the control surfaces. Automobile seats, in general, lack vertical adjustability but provide horizontal adjustability. Aircraft passenger seats lack both but do generally have seat back tilt adjustability.

STEP FOUR: Establish the Anthropometric Design Values

Once the interface has been established, workspace layout can proceed on the basis of the body size variability of the design population and other relevant factors such as arm reach and leg reach capabilities, permissible head and eye movement, strength capabilities, range of joint motion, and so forth. As noted in the previous discussion, the proper design values to be used relate to function and the anticipated interaction between the user and the work station environment.

In establishing the vertical seat adjustment, for example, the users' seated eye height is of relevance. The range of adjustment must be sufficient to allow the eyes of persons having a range of sitting heights to reach the eye reference point. Let us assume that the USAF flying population is the target population and the design requirement is to accommodate the body size variance from the 5th to the 95th percentile. The most current data for the target population would be those found in the 1967 USAF survey of rated aircrewmen. The data show that the mean sitting eye height for aircrewmen was 80.95 cm. with the 5th and 95th percentile values at 76.1 cm. and 86.1 cm. respectively. The vertical range of adjustability would thus be 10 cm. and the neutral seat reference point would be located approximately 81 cm. below the level of the eye reference point. This example is rather simplified as we have disregarded in our discussion factors such as torso slump, seat back angle, etc., which must also be taken into account by the designer.

For other design values either the upper (95th percentile) or lower (5th percentile) value might be needed. The fore and aft length of the seat pan must be short enough so as not to interfere with the calf of users having shorter thigh lengths. This dimension is then governed by the lower anthropometric limit. The seat pan breadth however must accommodate the upper limit of sitting hip breadths to assure that larger potential users can physically get into the seating space. The development of the anthropometric design values is thus an application of the anthropometry of the user population to an excellent working knowledge of how the user functions and interfaces with the work station.

At this point in the design, attention must be directed primarily to the development of the body envelope that is, the clearance needed to accommodate the actual physical size of the potential users in the design population. After this, the functional body size envelope is established. A designer must take care to see that an individual at a work station has adequate room to move around without being constrained by the work station itself. The need to shift body position from the upright posture in which it was originally measured to a more comfortable resting posture must not be overlooked. The body size variability now interacts with joint range data to provide guidance in establishing the functional envelope. If, for example, an operator removes his hands from the control surface and places them on his chest to adjust a harness, the elbows are rotated out and behind the elbow rest and seat back. This area is then part of the functional body envelope and can be infringed upon only at the risk of losing comfort and efficiency for the operator.

Various graphic design aids are often used to establish the body size and functional operations envelope of the design population and to develop and evaluate the workspace layout on the drawing board. Two-dimensional drawing board manikins are routinely used in the preliminary drawing of a workspace layout. These manikins range from rather simple cardboard cutouts, often with fixed limb orientation, to extremely sophisticated scale 2-D models with simulated human movement characteristics. Kennedy (1975, 1976) developed a family of drafting board manikins for crew station design in USAF systems. These are described and patterns actually provided in Chapter III of this handbook.

Designers have also developed three-dimensional scale models either as anthropomorphic dummies (Hertzberg, 1969) or three-dimensional plastic templates (Carlyle, 1960). Such models require the construction of scale and actual size physical mock-ups which are expensive and time consuming. More recently computer simulations have been developed and are being refined to simulate, in three-dimensional space, an anthropometric variable man model in a realistic cockpit or work station geometry. Kroemer (1972) has described the evolution of these models, initially little more than stick men, to the sophisticated and functional analogues such as BOEMAN and COMBIMAN. The latter, an acronym for computerized biomechanical man-model, is a computer interactive graphic simulation developed for work station design (McDaniel, 1976). COMBIMAN is a three-dimensional variable geometric model that can be viewed from any angle. The man-model is constructed initially of 33 links which correspond functionally to the human skeletal system. The link dimensions are variables used as inputs to the model and thus can duplicate size and proportion as desired to depict a specific population. Each link has a local coordinate system attached to its distal end to provide a realistic range of joint mobility. The link system is fleshed out by a series of ellipsoids each having a height and breadth consistent with the surface dimensions of the joint. The ellipses are then joined with tangential lines which are drawn separately for each viewing angle to reduce the clutter around the man model.

Using either the keyboard or light pen, a designer can define a series of control/display panels around the man model and by connecting them create the geometry of the workspace. This can then be evaluated by calling up a variety of man models with variable dimensions to determine the interaction with the created workspace in terms of arm, leg reach, ejection clearance, vision interface, etc. In the future, widespread use of the computer analogue can be expected in the design of control/display panels and layout of work stations.

STEP FIVE: Design and Evaluate a Mock-Up

The final but crucial step is to mock up the work station and begin the final evaluation of the adequacy of the design for the ultimate users.

The true test of any design is how well it meets the need of the user population and whether it accommodates the body size variance of the design group for whom it was intended. Some modification can be made at this point in the design. If the design process has been conducted from the beginning with the functioning needs and the size variability of the operator in mind, such modification will be minimal and the workspace will be well-matched in all its aspects to the capabilities of its ultimate users.

This brief introduction to the use of anthropometry in sizing and design is in no sense meant as a blueprint. It is, rather, a framework which outlines the principles and processes to be followed in the application of anthropometric data to sizing and design problems. The reader has been alerted to common pitfalls and misconceptions surrounding the uses and misuses of anthropometric data and, it is hoped, will have gained some understanding of how to approach sizing and design problems practically, knowledgeably and efficiently. For a fuller treatment of the subject, the reader is referred to the excellent work by Roebuck et al. (1975), Engineering Anthropometry Methods, a comprehensive 459-page manual which details methods for measuring and applying data on human body dimensions and strength to the engineering design of workspaces, clothing and equipment.

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CHAPTER IX
STATISTICAL CONSIDERATIONS IN MAN-MACHINE DESIGNS

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Large portions of this handbook are statistical in nature--numbers pure and simple, or the results of analyses of statistical materials, or discussions about and suggestions for solving problems which call for the use and interpretation of statistics. A full use of this book--or any similar collection of anthropometric information--will require some acquaintance with the language of statistics and some skill in extracting from the wealth of material presented here--both explicitly and implicitly--that which is most relevant to a given problem.

Most users of this handbook already have such an acquaintance and, in varying degrees, such a skill. Nonetheless, it seems appropriate to review the statistical concepts which occur over and over again in this book and to touch on some of the statistical problems which typically confront the individuals for whom this book was prepared. This we shall do in this chapter.

The statistical concepts discussed here will be few in number and, in the main, these few will be discussed within the context of the material included in this book and the use of this material in design problems.

Initially, we shall define the basic univariate statistical measures: averages, measures of variability, and percentiles. The relationship between percentiles and mean-standard deviation combinations will be explored and tables detailing this relationship will be presented.

A brief section on the interrelationships among anthropometric variables will deal with the simple bivariate and multivariate statistics. These statistics will include the correlation coefficient as a measure of the intensity of the relationship between two variables, the regression equation as a technique for predicting or estimating the value of one dimension on the basis of one or more other anthropometric variables, and the standard error of estimate as a measure of the accuracy of such estimates. Our discussion will center on these statistics as they relate to pairs of variables, but brief comments will be included about the statistics as they apply to combinations of three, four, or more variables. An analysis of the distribution of almost 8,000 correlation coefficients from the Air Force Women's Survey of 1968 is included to provide some insight into whether--and to what extent--such coefficients tend to be large or small.

The "normal" distribution will be discussed as a mathematical model for most anthropometric data. The use of this model in the univariate case will have been anticipated in our discussion of the relationship between the mean, the standard deviation, and the percentiles. Use of the model in dealing with pairs of variables will be illustrated with artificial bivariate frequency tables, constant-probability ellipses, and problems related to the proportions of potential users disaccommodated in bivariate designs.

This chapter will conclude with brief discussions of sampling errors, "percentile men", and an example of the use of Monte Carlo methods with body size data.

The Basic Statistical Measures: One Variable at a Time

We begin with those statistics which--in vast numbers--constitute Volume II of this handbook and which appear as well throughout this volume: averages, measures of variability, and percentiles.

Averages: the mean and the median

Most common of all the statistical concepts is the notion of an average, a statistic, which is in some sense representative of an entire set of data. Of the many types of averages that have been defined, only two need concern us--the arithmetic mean and the median.

The arithmetic mean is probably the oldest and certainly the most widely used of the averages. So widespread is this use that the arithmetic mean is often not specified as such, but is referred to simply as the "mean" or the "average." Unless an average is otherwise specified, it is usually safe--particularly in the field of anthropometry--to assume it is the arithmetic mean. Similarly, the term "to average" usually signifies, to layman and professional alike, the act of computing the arithmetic mean. The unmodified term "mean" is used in the tables of this handbook, as Table 1 illustrates.

The arithmetic mean of a set of data is defined as the sum of these values divided by the number of values. Thus, for example, to determine the mean of nine values:

5,2,8,-4,4,1,5,1,5

we add them:

$$\Sigma X = 5+2+8+(-4)+4+1+5+1+5 = 27$$

We then divide the sum (27) by the number of values:

$$\text{Mean} = \bar{X} = \Sigma X/N = 27/9 = 3.0$$

TABLE 1
AN EXCERPT FROM VOLUME II: THE MAJOR UNIVARIATE STATISTICS

English Values	Mean	STD DEV	COEF OF V	-N-	1st	5th	10th	Percentiles 25th	50th	75th	90th	95th	99th
805. Stature..........													
1. Stewardesses 1971	65.45	1.91	2.92%	422		62.5	63.0	64.1	65.4	66.8	68.1	68.8	
2. US Women-D/A 1940	63.16	2.48	3.93	****		(59.1)		(61.5)		(64.8)		(67.2)	
3. WASP Pilots 1942	64.90	2.10	3.24	447		61.7	62.2	63.4	64.9	66.1	67.7	68.3	
4. AAF Nurses 1942	63.50	2.10	3.31	152		60.1	60.8	62.0	63.5	64.9	66.1	67.5	
5. WAC Separatee 1946	63.87	2.37	3.71	7563	58.5	60.0	60.8	62.2	63.8	65.5	66.9	67.8	69.5
6. WAF Basic Tr 1952	64.07	2.34	3.65	851	59.3	60.3	61.0	62.3	64.0	65.7	67.2	68.2	69.9
7. Air Force Women 1968	63.82	2.36	3.70	1905	58.9	60.0	60.7	62.1	63.8	65.4	66.9	67.8	69.5
8. WAF-Nurse Ofcrs	64.08	2.44	3.81	548	58.7	60.0	60.8	62.4	64.1	65.8	67.2	68.1	69.9
9. Enlisted WAFS/W	63.75	2.32	3.64	1216	58.9	60.1	60.8	62.1	63.7	65.3	66.8	67.7	69.4
10. Enlisted WAFS/B	63.50	2.28	3.59	131		60.0	60.5	61.7	63.4	65.2	66.7	67.5	
11. Health Exam/F 1962	63.10	2.59	4.10	3581	56.9	58.9	59.8	61.4	63.2	64.9	66.5	67.4	69.0
12. Health Ex/F 25-40	63.65	2.47	3.88	1165	58.1	59.6	60.5	62.0	63.8	65.4	66.8	67.7	69.3
13. Air Traffic Cntrl	69.56	2.50	3.59	678		65.5	66.5	67.7	69.5	71.2	72.6	73.6	
14. Army Separatee 1946	68.43	2.49	3.64	****		(64.3)		(66.8)		(70.1)		(72.5)	
15. A.A.F. Cadets 1942	69.40	2.40	3.46	2959		65.4	66.1	67.5	69.2	70.8	72.4	73.1	
16. A.A.F. Gunners 1942	67.90	2.50	3.68	583		63.4	64.5	66.2	67.9	69.5	70.9	71.7	
17. USAF Basic Tr 1952	68.54	2.61	3.81	3331	62.5	64.2	65.1	66.8	68.6	70.3	71.9	72.7	74.7
18. USAF Fly Persnl 1950	69.12	2.43	3.52	4000	63.5	65.1	66.0	67.5	69.1	70.7	72.2	73.1	75.0
19. USAF Survey 1965	69.01	2.58	3.74	3869	63.1	64.8	65.7	67.3	69.0	70.7	72.3	73.3	75.1
20. Officers 1965	69.72	2.50	3.59	549	64.4	65.5	66.3	67.9	69.8	71.5	73.0	73.8	75.1
21. Enlisted Men 1965	68.79	2.65	3.85	792	62.6	64.5	65.5	67.1	68.7	70.4	72.1	73.3	75.8
23. Basic Trainees 1965	68.93	2.55	3.70	2527	63.0	64.7	65.7	67.2	68.9	70.7	72.2	73.2	74.9
24. Navy Flyers 1964	69.94	2.33	3.33	1529	65.1	66.2	66.9	68.3	69.9	71.6	73.1	73.9	75.3
25. USAF Fly Personnel 1967	69.82	2.44	3.49	2420	64.3	65.9	66.7	68.1	69.8	71.5	73.0	73.9	75.5
26. Student Pilot 1967	69.89	2.30	3.29	505	64.8	66.2	67.0	68.3	69.8	71.5	72.9	73.8	75.3
27. Rated Pilots 1967	69.84	2.43	3.48	1187	64.1	65.9	66.8	68.2	69.8	71.5	73.0	73.9	75.5
28. SDT Navigat 1967	70.06	2.42	3.45	188		66.0	67.0	68.5	70.0	71.7	73.2	74.2	
29. RTD Navigat 1967	69.68	2.56	3.67	505	64.2	65.6	66.4	67.9	69.6	71.4	73.1	74.1	75.9
30. Army Enlisted 1965	68.71	2.60	3.78	6682	62.6	64.5	65.4	67.0	68.7	70.4	72.1	73.1	74.9
31. Navy Enlisted 1965	69.03	2.57	3.72	4095	63.2	65.0	65.8	67.3	69.0	70.7	72.4	73.4	75.2
32. Navy Divers 1972	69.38	2.36	3.40	100		65.5	66.4	67.8	69.4	71.0	72.4	73.3	

We have used X here to represent the set of individual data values and N to represent the number of data or sample size. We will use these notations often. Note also the use of Σ, the upper case Greek letter sigma, to represent the idea of "the sum of" whatever follows.

To find the mean weight of the 2,420 subjects in the 1967 USAF survey of flying personnel, we might add up all of these weights, obtaining a total of 420,088 pounds, and divide this total by the number of subjects.

$$\text{Mean Weight} = \frac{\text{Sum of Weights}}{\text{Number of Subjects}} = \frac{420,088}{2420} = 173.6 \text{ pounds}$$

The mean value is usually designated in tables and formulas by $\overline{X}$, M, or μ. When several sets of data are considered together, their mean values may be denoted by $\overline{X}$, $\overline{Y}$, $\overline{Z}$, or $\overline{X}_1$, $\overline{X}_2$, $\overline{X}_3$, or M_x, M_y, M_z, or some similar variation of the usual symbols. In computer printouts, notations such as M(X), M(Y) or M(1), M(2) are often used because of the limited set of symbols available on most printers.

The median is, after the arithmetic mean, the most important average. The median of a set of values is formally defined as the value in the middle when the values are arranged in numerical order, or, equivalently, the value located at a point where as many values fall below it as fall above it. Arranging the nine values we have just considered in order by size, we get:

-4,1,1,2,4,5,5,5,8.

Since the middle value is the fifth one from either end, the median of the group is 4.

The median is also the 50th percentile--a concept we shall soon define --and is listed among the percentiles in Volume II and throughout this handbook. From Table 1, we note that the median stature of the stewardesses was 65.4 inches. The comments we shall make about the computation of percentiles apply equally to the computation of the median.

For most anthropometric data--and for all types of data for which the normal distribution is a reasonable model--the mean and the median tend to be almost equal. The median of the USAF '67 flying personnel weights is 172.4 pounds, a trifle lower than the 173.6 pound value we obtained for the mean. This difference of scarcely more than a pound probably represents the most significant difference to be found among our mean/median data for these men. The mean and the median for the total height (stature) of these fliers--statistically a much more typical set of data--were 69.82 inches and 69.78 inches respectively. Here the mean is a mere twenty-fifth of an inch larger than the median. Other mean/median comparisons can be made using the values in Table 1. There are, it is true, a few anthropometric variables for which this level of close agreement between the mean and the median does not exist. This lack of agreement will be most substantial for age and skinfold measures, variables not directly related to basic design problems. For most sets of data, we have reported the mean and, as the 50th percentile, the median.

In addition to the mean and the median, there are two averages which, it can be argued, are more logically related to design problems: the mode and the mid-range value. The mode is defined as the most frequently occurring value in a set of data and the mid-range as the average of the maximum and minimum values. We have included neither of these averages here for two reasons. Both statistics, when computed on large sets of continuous data; are highly dependent on the precise method of computation and editing and are highly sensitive to minor variations in measurement techniques and sample selection. In addition, whenever the normal probability model is appropriate, the mode, the mid-range, the mean and the median are all theoretically equal. If, then, all four of these averages are, in theory, equal, our choice among them is logically the one we can determine most accurately from a sample of a given size. On this basis, the arithmetic mean is clearly the preferred statistic.

None of these averages--considered by itself--has great usefulness in design problems. It is true, of course, that there are more men of average height than of any other particular height, but it is equally true that most men are shorter than average or taller than average, some of them by small amounts and others by considerable ones. Along with our averages, we need statistical measures which measure and describe the variations, large and small, up and down from the average value. These are discussed next.

Measures of Variability: the Standard Deviation and the Coefficient of Variation

A pioneer in the field of statistics, Sir Francis Galton, wrote years ago that "it is difficult to understand why statisticians commonly limit their interests to averages. Their souls seem as dull to the charm of variety as that of a native of one of our flat English counties whose retrospect of Switzerland was that, if its mountains could be thrown into its lakes, two nuisances could be got rid of at once." Basic to virtually all design problems is the fact that mankind is far more like Switzerland than a flat English county, and that, whatever the charms of variety may be, we need statistics to quantify this variety.

The standard deviation is virtually the sole measure of variability of concern to us. The coefficient of variation is also of considerable importance, but this statistic, as we shall see, is simply a restatement of the standard deviation as a percent of the mean.

The standard deviation for a set of data can be obtained by the following sequence of steps:

a. compute the mean value: $(\bar{X})$;
b. compute the deviation of each value from the mean: $(X-\bar{X})$;

c. square these deviations: $(X-\bar{X})^2$;
d. obtain the mean of these squares: $\Sigma(X-\bar{X})^2/N$;
e. compute the square root of this quantity.

The value at this last step is the standard deviation. Stated as a formula*:

$$\text{Standard deviation} = \sqrt{\Sigma(X-\bar{X})^2/N}$$

To compute the standard deviation of the nine values we have just averaged (5,2,8,-4,4,1,5,1,5), we follow this sequence of steps:

a. we already have $\bar{X} = 3$
b. the deviations are 2,-1,5,-7,1,-2,2,-2,2
c. the squared deviations are 4,1,25,49,1,4,4,4,4
d. their mean value is (4+1+•••+4)/9 = 96/9 = 10.7
e. and the square root of 10.7 = 3.26

The sequence of steps usually used to compute the standard deviation differs from that just described, but is mathematically equivalent and gives identical results.

The standard deviation is commonly denoted either by the initials SD or by σ, the lower case Greek letter sigma, with, if necessary, suitable subscripts. The use of σ is sufficiently general so that the word "sigma" itself is sometimes used to denote the standard deviation. In Table 1, the standard deviation is the second of the statistics, listed in the columns headed "STD DEV".

The way the standard deviation relates to the distribution of a set of data is illustrated by the four graphs in Figure 1. The first of these graphs represents the statures (total heights) of all the women measured in the Air Force Women's survey of 1968. The mean of these heights is 63.82 inches and the standard deviation is 2.36 inches.

The three other graphs also represent the statures of women measured in this survey, but correspond to subgroups chosen on the basis of each woman being of average value in a second measurement: weight, sitting height, or cervicale height. Because of the relationships between stature and the other measurements, the women in these subgroups are less variable in their heights and the standard deviations decrease progressively as we go from curve (a) to curve (d). The standard deviation for the total series was 2.36 inches as we have already noted; the other standard deviations are, in order, 2.00 inches, 1.42 inches, and 0.50 inches. The mean value in each case remains 63.82 inches.

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*Sometimes N-1 or N-1.5 is used in place of N in this formula. When the standard deviation is considered as a descriptive statistic, the proper divisor is N. When the value of N is large, it makes little difference which divisor is used. The formula given here was used in computing the standard deviation for most major sets of data in Volume II.

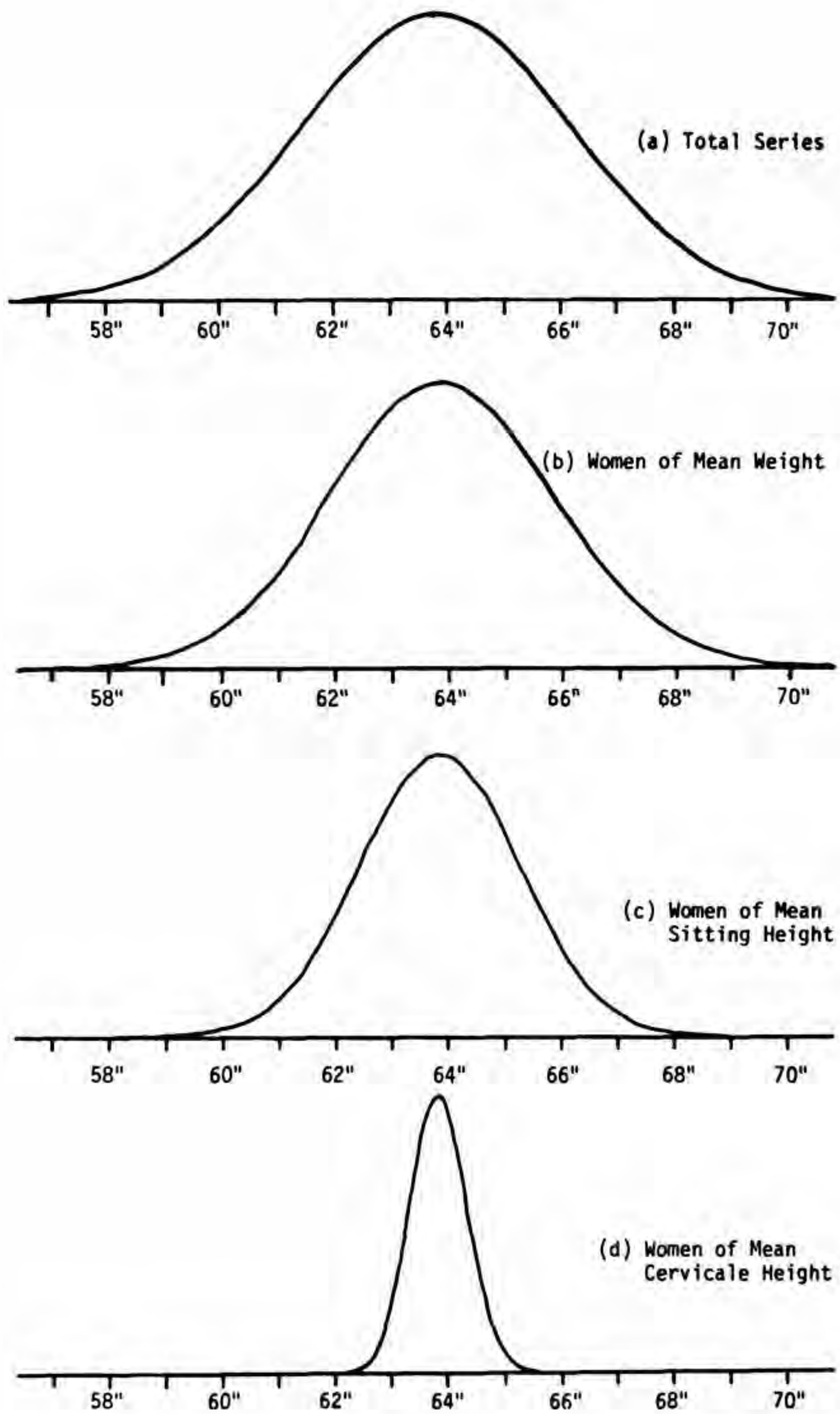


Figure 1. Distribution of stature measurements (AFW'68 data).

The range in statures in graph (a) would appear to be from about 7 inches below the mean (56.8 inches) to about 7 inches above it (70.8 inches). Graph (b) is a little narrower than graph (a). Here the range would seem to be about 6 inches up and down from the mean value (57.8 inches to 69.8 inches). Graph (c) is in turn still narrower--only slightly more than half as wide as the first graph. Here the range seems roughly about $X \pm 4.2$ inches or from 59.6 inches to 68.0 inches. Finally, the last graph, little more than 20% as wide as the first one, shows a range of statures from about 62.3 inches to 65.3 inches.

The ranges suggested by these graphs are, in each case, from approximately three standard deviations below the mean ($\bar{X}$ - 3 SD) to three standard deviations above it ($\bar{X}$ + 3 SD). Other important points on the distribution of a set of anthropometric data can be located, at least approximately, by adding or subtracting a multiple of the standard deviation to the mean value. In particular, it is worth noting (see also Figure 2) that:

about 2/5 of a set of data fall between $\bar{X}$-0.5 SD and $\bar{X}$+0.5 SD
about 2/3 of a set of data fall between $\bar{X}$-1.0 SD and $\bar{X}$+1.0 SD
about 87% of a set of data fall between $\bar{X}$-1.5 SD and $\bar{X}$+1.5 SD
about 95% of a set of data fall between $\bar{X}$-2.0 SD and $\bar{X}$+2.0 SD
almost all of a set of data fall between $\bar{X}$-3.0 SD and $\bar{X}$+3.0 SD.

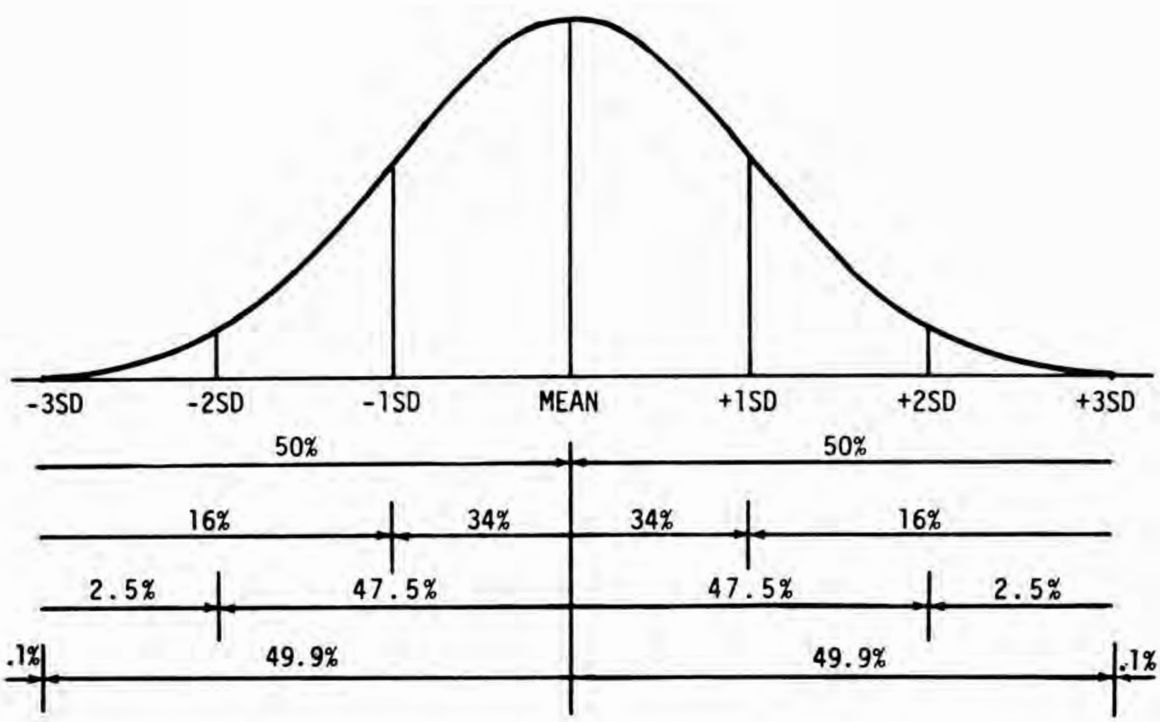


Figure 2. Areas under the normal curve.

These figures can be restated in several ways. One could say, for example, that about one-third of the data will fall in the range from the mean to the mean plus a standard deviation and that about one-sixth of the data will exceed the mean plus a standard deviation.

In Table 2, we have listed for more or less normally distributed data the approximate percentages which will fall into ranges which are based on the mean ($\overline{X}$) and various multiples of the standard deviations (K•SD).* Here we may note, for example, that if K = 0.5, then:

about 31% of a set of such data fall below $\overline{X}$ - K•SD (Column A)
about 31% fall above $\overline{X}$ + K•SD (Column A)
about 38% fall between $\overline{X}$ - K•SD and $\overline{X}$ + K•SD (Column B)
about 69% fall below $\overline{X}$ + K•SD (Column C)

To illustrate one typical use of a table such as Table 2, we can estimate the proportion of USAF flying personnel who are taller than 6'1". Our best data for these men are those from the USAF '67 flying personnel survey. From Table 1 (or Volume II) we find that the appropriate statistics are these:

Mean stature: 69.82"; standard deviation: 2.44".

Using these figures, we next determine how far 6'1" is above the mean in standard deviation units:

$$K = \frac{6'1''-\overline{X}}{SD} = \frac{73.00-69.82}{2.44} = \frac{3.18}{2.44} = 1.30$$

Column A in Table 2 gives a value of 9.7% for K=1.30, from which we may conclude that about 10% of the Air Force's male fliers are 6'1" tall or taller.

We can similarly estimate the proportion of Air Force women shorter than 5' 1". From Table 1, we obtain the relevant statistics from the survey of such women made in 1968:

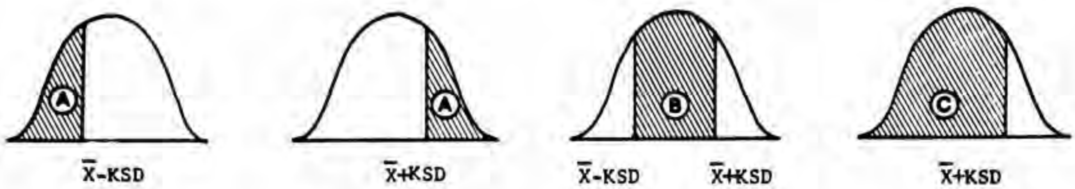
mean stature: 63.82"; standard deviation: 2.36".

On the basis of these statistics, 5' 1" is 2.82" or 1.19 standard deviations below the mean. Entering Table 2 with the value K = 1.2, we get 11.5% as the approximate number of these women shorter than 5 feet. Since there are virtually no Air Force women taller than 6'1" and virtually no flying personnel shorter than 5 feet, we are in a position to conclude that a design range for statures from 61" to 73" would include roughly 90% of both the USAF flying personnel and USAF women.

*More detailed versions of Table 2 (and Table 5) are available in Abramowitz and Stegun (1964).

TABLE 2

APPROXIMATE PROPORTIONS OF DATA FALLING INTO INTERVALS BASED ON MEAN ±K STANDARD DEVIATIONS



K	A	B	C
0.0	50.0%	0.0%	50.0%
0.1	46.0%	8.0%	54.0%
0.2	42.1%	15.8%	57.9%
0.3	38.2%	23.6%	61.8%
0.4	34.5%	31.1%	65.5%
0.5	30.9%	38.3%	69.1%
0.6	27.4%	45.1%	72.6%
0.7	24.2%	51.6%	75.8%
0.8	21.2%	57.6%	78.8%
0.9	18.4%	63.2%	81.6%
1.0	15.9%	68.3%	84.1%
1.1	13.6%	72.9%	86.4%
1.2	11.5%	77.0%	88.5%
1.3	9.7%	80.6%	90.3%
1.4	8.1%	83.8%	91.9%
1.5	6.7%	86.6%	93.3%
1.6	5.5%	89.0%	94.5%
1.7	4.5%	91.1%	95.5%
1.8	3.6%	92.8%	96.4%
1.9	2.9%	94.3%	97.1%
2.0	2.3%	95.4%	97.7%
2.1	1.8%	96.4%	98.2%
2.2	1.4%	97.2%	98.6%
2.3	1.1%	97.8%	98.9%
2.4	0.8%	98.4%	99.2%
2.5	0.6%	98.8%	99.4%
2.6	0.5%	99.1%	99.5%
2.7	0.3%	99.3%	99.7%
2.8	0.3%	99.5%	99.7%
2.9	0.2%	99.6%	99.8%
3.0	0.1%	99.7%	99.9%

An important restatement of the standard deviation is known as the coefficient of variation. This statistic, often designated by the letter V, is the standard deviation expressed as a percentage of the mean value:

$$V = \frac{SD}{\overline{X}} \cdot 100\% \quad \text{or} \quad (SD/\overline{X}) \cdot 100\%$$

Thus, the coefficient of variation of the statures measured in the USAF '67 flying personnel survey, based on the statistics just used, is

$$V = \frac{2.44''}{69.82''} \cdot 100\% = 3.49\%$$

The coefficients of variation are presented for all sets of data in Volume II*. They are designated there, as can be seen from Table 1, by "COEF OF V."

The importance of the coefficient of variation for body size data is that this statistic tends to have roughly the same value for anatomically similar measurements. A few values, based on the 1968 Air Force Women's survey and the USAF '67 and USAF '50 flying personnel surveys, are shown in Table 3. Weight usually has a coefficient of variation of 10%-15% for military samples, skinfold measures have values in the 30% to 50% range, but most measurements have considerably smaller values. The major head measurements have among the lowest values of V, usually in the 2.5% to 3.5% range. Heights and long bone measurements have coefficients of variation in the 3.5% to 5.0% range. Major circumferences, breadths, and depths have values usually falling between 5% and 10%. Within these broad categories, the smaller the measurement, the larger the coefficient of variation is likely to be, in part because the smaller the measurement, the relatively greater the measurement error. The more closely a measurement is related to the bony structure of the body, the smaller the value of V. Thus, for example, the values of V in Table 3 for shoulder circumference (5.0-5.2%) are only about 60% as great as those for waist circumference (8.2-9.3%). Small measurements not based on bony landmarks are particularly prone to large coefficients of variation.

There are a few standard anthropometric measures which do not correspond to a single anatomic entity as much as they represent the difference between two such entities. For such measurements, the coefficient of variation is likely to be quite high. A major example of such a measurement is elbow-rest height--the distance from the underside of the elbow to the

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*The coefficient of variation is clearly independent of the units in which a measurement is expressed. However, there are occasional minor differences in Volume II between the values of V given with the metric data and those given with the English values. This is because V was computed in each case from the values of $\overline{X}$ and SD exactly as they are listed.

TABLE 3
COEFFICIENTS OF VARIATION BY MEASUREMENT TYPE

a) Major Head Measurements (2.5%-4.0%)

	1967 Flying Personnel	Air Force Women	1950 Flying Personnel
Head circumference	2.5%	3.0%	2.7%
Head length	3.4%	3.7%	3.3%
Head breadth	3.5%	4.1%	3.4%
b) Major Heights and Long Bone Lengths (3.5%-5.5%)			
Stature	3.5%	3.8%	3.6%
Acromial height	4.0%	4.2%	4.0%
Cervicale height	3.9%	4.0%	3.9%
Chest height	4.1%	4.5%	4.1%
Waist height	4.5%	4.5%	4.3%
Crotch height	4.9%	5.5%	5.2%
Sitting height	3.5%	3.8%	3.6%
Knee height sitting	4.5%	-	4.6%
Sleeve length	3.9%	4.2%	4.5%
c) "Bony" Circumferences (5.0%-6.5%)			
Shoulder circumference	5.0%	5.2%	5.2%
Ball of foot circumference	5.0%	-	5.0%
Knee circumference	5.4%	6.3%	5.8%
Wrist circumference	5.2%	4.8%	5.3%
Buttock circumference	5.6%	6.0%/6.4%	6.0%
Chest circumference	6.5%	6.4%	6.2%
d) "Fleshy" Circumferences, Breadths, Depths (6.5%-10.0%)			
Waist circumference	8.5%	8.2%	9.3%
Biceps circumference (relaxed)	7.6%	9.0%	7.9%
Thigh circumference	7.6%	7.7%	7.6%
Calf circumference	6.2%	6.6%	6.5%
Buttock depth	8.6%	8.5%	9.2%
Chest breadth	6.5%	6.9%	6.6%
Chest depth	7.9%	8.2%	8.2%
e) Weight (10%-15%)			
Weight	12.4%	13.1%	12.8%
f) Skinfolds (30%-50%)			
Triceps	40.2%	28.5%	-
Subscapular	38.7%	37.3%	-
Juxtanipple	49.3%	-	-

sitting surface. This measurement is basically the difference between sitting shoulder height and shoulder-elbow length and, not surprisingly, usually has a coefficient of variation in excess of 10% even though it is classified as a "length."

In addition there are a few measurements for which the coefficient of variation is not an appropriate statistic. Primarily, these are measurements for which the zero value is arbitrary. An example, illustrated in Figure 3, relates to the inclination of a line joining the center of the earhole and the outer corner of the eye. We could measure the angle this line makes with a horizontal axis (θ) or its angle with a vertical axis (ϕ). Both (θ) and (ϕ) will contain the same information, be equally valid and useful, and have the same standard deviation. However, since the mean value of the first will be about 10° and of the second about 80°, the coefficient of the first will be about eight times as large as the first.

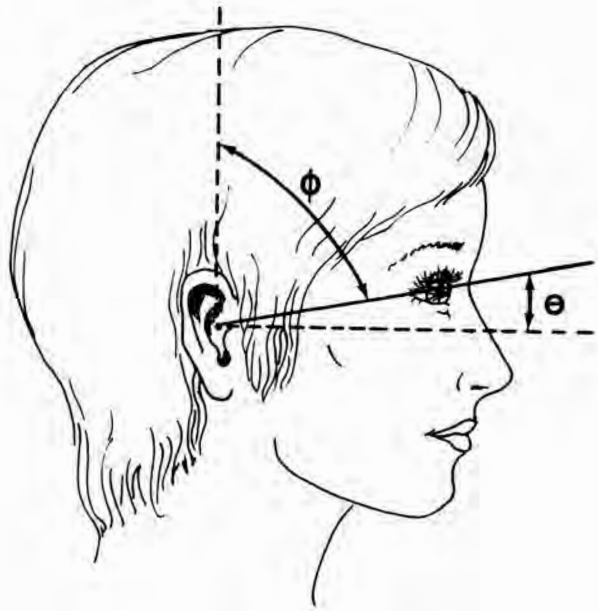

Figure 3. Measurement with an arbitrary zero value.

Other measures of variability are occasionally used: the range, the mean deviation, the probable deviation, the semi-interquartile range, and so forth. The range is simply the difference between the largest and smallest values in a set of data. The mean deviation is the average of the absolute values of the deviations from the mean (sometimes from the median). The probable deviation is about two-thirds as large as the standard deviation; it was defined so that 50% of a set of data would fall within a probable deviation of the mean. The semi-interquartile range is half the distance from the 25th percentile (soon to be defined) and the 75th percentile.

Of these, only the range is likely to be encountered in compilations of anthropometric data. The range is obviously an easily computed and easily understood statistic. Unfortunately, except as a purely descriptive statistic, it is a notoriously poor one because it is dependent on sample size, because its sampling error decreases at no more than a snail's pace as the sample size increases, because it is completely dependent on the two most atypical and most probably erroneous individual values in a set of data, and because, when computed from edited data, it is highly dependent on the subjective judgment of the editor. Range values have not been included in Volume II.

The Percentiles

The class of statistics which are most closely related to design problems are the percentiles and other so-called measures of position.

The definition of the percentiles is fairly simple. For any set of data--the weights of a group of pilots, for example--the first percentile is a value which is, on the one hand, greater than the weights of each of the lightest 1% of the pilots and is, on the other hand, less than the weights of each of the heaviest 99% of these men. Similarly, the second %ile is greater than each of the lightest 2% and less than each of the heaviest 98%. Whatever the value of K--from 1 to 99--the K-th percentile is a value greater than each of the smallest K% of the weights and less than the largest (100-K)%. The 50th percentile, which we encountered among the averages as the median, is a value dividing a set of data into two groups containing the smallest and largest 50% of the values.

The role of percentiles in many types of design problems is to provide a basis for judging the proportion of a group of individuals who exceed --or fall below--some possible design limit. There are, naturally, 99 percentiles, from the 1st to the 99th, although even the most complete computations of body size data are usually limited to the 1st, 2nd, 3rd, 5th, 10th, ..., 90th, 95th, 97th, 98th, and 99th. Space constraints have limited those listed in Volume II to the 9 most important of these as they appear in Table 1. Those omitted--mostly percentiles between the 25th and the 75th--are rarely, if ever, used in design problems and can, as we shall see, be easily approximated if they are needed. A few of the percentiles in addition to the median have other names. In particular, the 25th and 75th percentiles are the 1st and 3rd quartiles (the median is the 2nd quartile); and the 10th, 20th, etc. percentiles are also known as the 1st, 2nd, etc. deciles.

The computation of the percentiles is not quite as simple as our definition would suggest. The basic problem is that, in general, there are no values which satisfy the definition. A strict reading of the definition says that the 1st percentile is a weight such that 1% of the 2,420 flyers (or 24.2) are lighter and 99% (or 2,395.8) are heavier. One problem is that we are limited to integer numbers of men; we can count off 24 or 25 men, but not 24.2. A second problem is that we can't really arrange all 2,420 men in order of their weights; all these men undoutedly have different weights, but they don't all have different recorded weights. In practice, we rely on computational methods based on the spirit, rather than the precise letter, of the definition.

One useful method of computing percentiles is based on the special graph paper shown in Figure 4. This graph paper has been designed so that we get points which fall on a straight line if we plot the cumulative frequencies of a perfect normal distribution. Plots of real data for body size dimensions on this type of graph paper usually consist of points which can be fitted by a smooth curve which, at least in the mid-range, is almost linear.

To illustrate the process, we have provided in Table 4 the frequency table for U.S. Navy pilots' statures. In Figure 4, the cumulative frequencies are plotted against the upper limits of the intervals in this table. We have drawn on this figure a smooth curve passing close to, but not always through, the plotted points. The percentiles are ultimately read from this curve. Thus, for example, we note that the 5th percentile here is 168.3 cm, the 10th percentile is 170.0 cm, etc. The computational procedure not only circumvents the problems we have discussed, but also tends to minimize the irregularities from which data from finite samples always suffer. In Figure 5 we have plotted the same points on conventional graph paper to illustrate the differences in the graphs which the two types of paper provide.

Percentiles for the major series of data included in this handbook were computed using a method similar to this graphic one but one designed for use on a computer in order to reduce the labor involved and to provide more objective results. Full details of this method, including the computer program, are given in Anthropometry of Air Force Women by Clauser and his associates. Every set of percentiles appearing in Volume II which includes the 1st and 99th percentiles were computed using this computer program. Percentiles for a few small series of data included in Volume II were also computed by this method, but the extreme percentiles are not listed because of sample size. Details of the calculation of most of the other percentiles listed in Volume II, unfortunately, have never been published.

Our earlier discussion of the mean and the standard deviation came close to establishing--for more or less normally distributed data--a relationship between the standard deviation and the percentiles. Table 5 makes this relationship more explicit by indicating for each percentile its distance in standard deviations above or below the mean. The table indicates, for example, that the 5th and 95th percentiles are, approximately, 1.645 standard deviations below and above the mean; these percentiles for USAF '67 flying personnel statures can thus be approximated as 69.82-1.645•2.44= 65.8" and 69.82+1.645•2.44=73.8", values not very different from those shown in Table 1 (65.9" and 73.8").

Table 5 points up an important fact about percentiles: the difference between consecutive percentiles increases substantially as one goes from

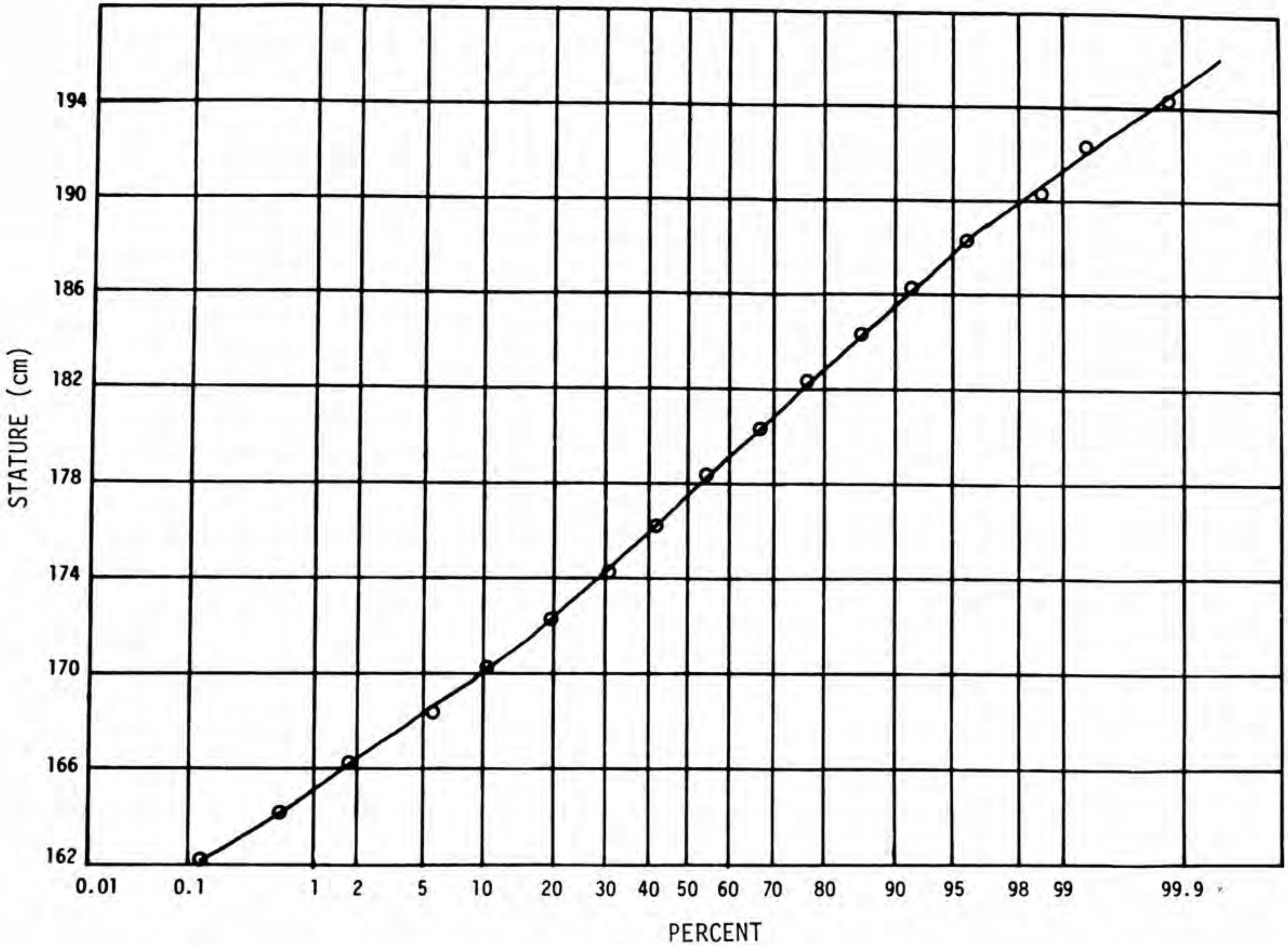

Figure 4. Computation of percentiles using normal probability graph paper.

TABLE 4
FREQUENCY TABLE FOR U.S. NAVY PILOTS' STATURES

Value	F	Cum F	Cum F %
194.25-196.25	2	1529	100.00
192.25-194.25	8	1527	99.87
190.25-192.25	11	1519	99.35
188.25-190.25	40	1508	98.63
186.25-188.25	62	1468	96.01
184.25-186.25	93	1406	91.96
182.25-184.25	129	1313	85.87
180.25-182.25	157	1184	77.44
178.25-180.25	192	1027	67.17
176.25-178.25	191	835	54.61
174.25-176.25	180	644	42.12
172.25-174.25	173	464	30.35
170.25-172.25	133	291	19.03
168.25-170.25	74	158	10.33
166.25-168.25	58	84	5.49
164.25-166.25	18	26	1.70
162.25-164.25	6	8	0.52
160.25-162.25	2	2	0.13

TABLE 5
PERCENTILE-STANDARD DEVIATION RELATIONSHIPS

Percentile		Percentile	Percentile		Percentile
1st	M* ± 2.326 SD**	99th	26th	M ± 0.643 SD	74th
2nd	M ± 2.054 SD	98th	27th	M ± 0.613 SD	73rd
3rd	M ± 1.881 SD	97th	28th	M ± 0.583 SD	72nd
4th	M ± 1.751 SD	96th	29th	M ± 0.553 SD	71st
5th	M ± 1.645 SD	95th	30th	M ± 0.524 SD	70th
6th	M ± 1.555 SD	94th	31st	M ± 0.496 SD	69th
7th	M ± 1.476 SD	93rd	32nd	M ± 0.468 SD	68th
8th	M ± 1.405 SD	92nd	33rd	M ± 0.440 SD	67th
9th	M ± 1.341 SD	91st	34th	M ± 0.412 SD	66th
10th	M ± 1.282 SD	90th	35th	M ± 0.385 SD	65th
11th	M ± 1.227 SD	89th	36th	M ± 0.358 SD	64th
12th	M ± 1.175 SD	88th	37th	M ± 0.332 SD	63rd
13th	M ± 1.126 SD	87th	38th	M ± 0.305 SD	62nd
14th	M ± 1.080 SD	86th	39th	M ± 0.279 SD	61st
15th	M ± 1.036 SD	85th	40th	M ± 0.253 SD	60th
16th	M ± 0.994 SD	84th	41st	M ± 0.228 SD	59th
17th	M ± 0.954 SD	83rd	42nd	M ± 0.202 SD	58th
18th	M ± 0.915 SD	82nd	43rd	M ± 0.176 SD	57th
19th	M ± 0.878 SD	81st	44th	M ± 0.151 SD	56th
20th	M ± 0.842 SD	80th	45th	M ± 0.126 SD	55th
21st	M ± 0.806 SD	79th	46th	M ± 0.100 SD	54th
22nd	M ± 0.772 SD	78th	47th	M ± 0.075 SD	53rd
23rd	M ± 0.739 SD	77th	48th	M ± 0.050 SD	52nd
24th	M ± 0.706 SD	76th	49th	M ± 0.025 SD	51st
25th	M ± 0.674 SD	75th	50th =	M	

* Mean
** Standard Deviation

the center out to either end of the range. To emphasize this point, in Table 6 we have taken the difference between the 50th and the 51st percentiles as a "mid-range design unit" and have tabulated, in terms of this unit, the increases in the width of a design which would be required in order that it cover an additional one percent of the population. This cost rises slowly over the middle of the range; to go from 75th to 76th percentile requires an increase only about 1.3 times as large as was required to go from the 50th to the 51st. Not until we are almost at the 90th percentile does an increase of one percentile value cost twice the mid-range unit but from there on the cost increases rapidly. To include the one percent of the population between the 98th and 99th percentiles will require an increase of almost 11 mid-range design units. We can be confident that the top one percent of the values will be spread over an exceedingly wide range, but it is unrealistic to expect accurate estimates of just how wide.

Measures of Symmetry and Kurtosis

Measures of symmetry (β_1) and kurtosis (β_2) are sometimes given in reports of anthropometric surveys. Since these statistics are usually close to the normal distribution values of 0.0 and 3.0 for body measurements of interest to the design engineer, we have not included them in this handbook. The value of β_1 (sometimes spelled out as veta, corresponding to the Greek pronunciation, other times as beta) is based on the cubes of the differences between the data and their mean. Positive values of β are suggestive of a pattern in which data are distributed at greater distances above the mean than they are below it. The value of β_2 is based on the fourth power of these differences and normally relates to the degree of peakedness of the distribution of the data.

The Interrelationship Among Anthropometric Measures

Tall men tend to have long arms, short men tend to be below average in hip breadth. Men with long faces, on the other hand, are almost as likely to have narrow faces as they are to have wide ones. All anthropometric measures are to one degree or another statistically related to each other; the nature and degree of these relationships are often matters of substantial importance in the design of equipment, workspace, and clothing.

In Figure 6 we have illustrated examples of four rather different degrees of relationship:

a. the almost perfect relationship between stature and stature maximum;
b. the less close but still quite substantial relationship between weight and shoulder circumference;
c. the modest relationship between stature and weight;
d. the almost negligible relationship between lip length and face length (menton-sellion length).

TABLE 6
COST OF ACCOMMODATING ADDITIONAL PERCENTAGES OF A USER-POPULATION IN MID-RANGE UNITS

Population Percentage	Cost in Mid-Range Units*
50th to 51st	1.00 unit
60th to 61st	1.04 units
70th to 71st	1.16 units
75th to 76th	1.27 units
80th to 81st	1.45 units
85th to 86th	1.75 units
90th to 91st	2.36 units
91st to 92nd	2.56 units
92nd to 93rd	2.82 units
93rd to 94th	3.15 units
94th to 95th	3.59 units
95th to 96th	4.22 units
96th to 97th	5.18 units
97th to 98th	6.88 units
98th to 99th	10.86 units
(99th to 99.5th)	19.88 units/percent
(99.5th to 99.9th)	51.24 units/percent

*i.e., the width of the interval required for a particular percent expressed as multiples of the width of a similar interval near the center of the distribution.

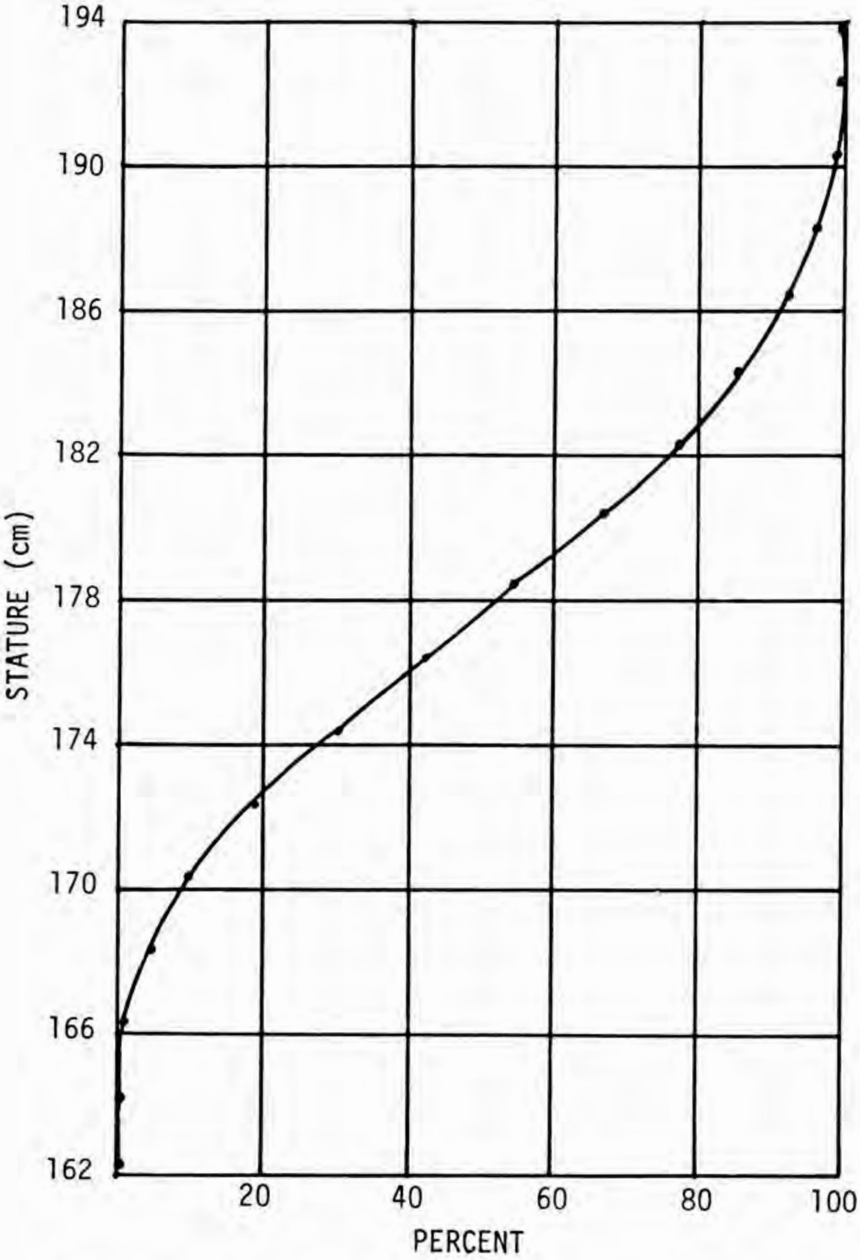

Figure 5. Cumulative frequencies--U.S. Navy Flyers'64 statures--on rectangular graph paper.

STATURE AND STATURE, MAXIMUM

STATURE, MAXIMUM

STATURE	145 .25	147 .25	149 .25	151 .25	153 .25	155 .25	157 .25	159 .25	161 .25	163 .25	165 .25	167 .25	169 .25	171 .25	173 .25	175 .25	177 .25	179 .25	181 .25	183 .25	TOTALS
183.25																				1	1
181.25																			1		1
179.25																		8	1		9
177.25																	9	5			14
175.25																10	3				13
173.25														1	41	11					53
171.25														61	21						82
169.25												1	83	41							125
167.25												113	74								187
165.25										1	125	57									183
163.25										164	77										241
161.25								2	183	75											260
159.25								146	65												211
157.25							132	58													190
155.25						101	59														160
153.25					58	29	1														88
151.25				42	18																60
149.25			13	4																	17
147.25		5	3																		8
145.25	2																				2
Totals	2	5	16	46	76	130	192	206	248	240	202	171	157	103	62	21	12	13	2	1	1905

Summary Statistics

	Mean	Std Dev	Regression Equations	SE-Est
Y-Stature	162.10	6.00	0.995X + 0.169	0.38
X-Stature, Maximum	162.75	6.02	1.001Y + 0.482	0.38

A. An exceedingly close relationship: correlation coefficient = 0.998

WEIGHT AND SHOULDER CIRCUMFERENCE

SHOULDER CIRCUMFERENCE

WEIGHT	87 .25	89 .25	91 .25	93 .25	95 .25	97 .25	99 .25	101 .25	103 .25	105 .25	107 .25	109 .25	111 .25	113 .25	115 .25	117 .25	119 .25	121 .25	TOTALS
200.00														1				1	2
195.00																1	1		2
190.00													1			1			2
185.00												1		1	3		2		7
180.00											1			1	1				3
175.00									1			1	1	1	2	1			7
170.00									1		2	5	1	2	2	1			14
165.00									2	2	4	6	1		2				17
160.00								1	1	3	2	15	1	2	1	3	1		30
155.00							1	1	5	10	10	13	6	3					49
150.00					1			3	19	13	17	12	5	2					72
145.00						2	4	19	28	23	29	12	4	1					122
140.00					3	5	14	24	28	34	22	8	3	1					142
135.00				2	6	5	22	56	44	28	16	1	1						181
130.00				1	9	28	52	58	48	27	7	1							231
125.00			1	1	24	44	72	56	28	12	3								241
120.00				14	29	53	74	32	16	3									221
115.00			5	21	48	60	54	15	5	1									209
110.00		2	7	25	49	47	14	8											152
105.00		4	11	37	29	25	6	1											113
100.00		6	15	21	17	2													61
95.00	1	2	10	6	3														22
90.00			2	2															4
85.00	1																		1
Totals	2	14	51	130	218	271	313	274	226	156	113	75	24	15	11	7	4	1	1905

Summary Statistics

	Mean	Std Dev	Regression Equations	SE-Est
Y-Weight	127.28	16.59	2.695X - 143.330	9.13
X-Shoulder Circ	100.41	5.14	0.259Y + 67.447	2.83

B. A close relationship: correlation coefficient = 0.835

Figure 6. Bivariate frequency tables illustrating interrelationships of anthropometric data (from Clauser et al. 1972).

STATURE (columns) / WEIGHT (rows)

WEIGHT	145.25	147.25	149.25	151.25	153.25	155.25	157.25	159.25	161.25	163.25	165.25	167.25	169.25	171.25	173.25	175.25	177.25	179.25	181.25	183.25	TOTALS
200.00										1							1				2
195.00									1					1							2
190.00										1		1									2
185.00										2	2			3							7
180.00													2	1							3
175.00										1		3	1		1					1	7
170.00					1		1	1	1	1		2	1	2	1	1	2				14
165.00								2	1	1	1	5	1	3	3						17
160.00						1		3	1	4	1	6	4	5	3		1	1			30
155.00							4	1	4	6	9	6	4	8	3	1	1	2			49
150.00				1		2		3	2	10	9	18	14	7	5		1				72
145.00			1				4	2	10	24	21	15	18	8	10	3	4	2			122
140.00			1		1	7	11	9	15	19	17	23	22	8	3	4	1		1		142
135.00				1	3	9	13	15	22	30	23	26	14	8	13	3		1			181
130.00		1		5	5	14	14	28	35	39	35	26	12	13	3			1			231
125.00			2	5	10	16	28	35	42	32	23	23	11	6	4	1	2	1			241
120.00				6	11	18	27	38	44	22	23	13	12	4	1		1	1			221
115.00		3	4	7	15	24	32	33	40	19	11	11	6	3	1						209
110.00		2	2	8	18	23	26	20	21	17	4	5	2	2	2						152
105.00		1	3	12	11	24	18	13	14	9	4	3	1								113
100.00	2		1	11	10	14	7	7	5	3		1									61
95.00		1	2	4	1	8	3	1	2												22
90.00			1		1		2														4
85.00					1																1
Totals	2	8	17	60	88	160	190	211	260	241	183	187	125	82	53	13	14	9	1	1	1905

Summary Statistics

	Mean	Std Dev	Regression Equations	SE-Est
Y-Weight	127.28	16.59	1.471X - 111.172	14.04
X-Stature	162.10	6.00	0.193Y + 137.536	5.08

C. A modest relationship: correlation coefficient = 0.533

LIP LENGTH AND MENTON-SUBNASALE LENGTH

MENTON-SUBNASALE LENGTH (columns) / LIP LENGTH (rows)

LIP LENGTH	3.95	4.15	4.35	4.55	4.75	4.95	5.15	5.35	5.55	5.75	5.95	6.15	6.35	6.55	6.75	6.95	7.15	7.35	7.55	TOTALS
5.75									2	1			1							4
5.55							1	2	2	3	2		1	1	2					14
5.35				1		1	4	2	4	2	3	5	1	1		1				25
5.15				2	1	1	15	12	9	11	10	8	3	1	1			1		75
4.95	1	1	1	3	10	8	13	17	16	21	19	13	9	1		3	1			137
4.75		1	2	7	9	17	23	35	27	32	29	22	9	7	2					222
4.55	1	2	4	7	16	26	38	53	53	45	44	26	18	6	5				1	345
4.35	2	3	3	8	11	22	41	41	57	30	37	21	7	2	5	4				294
4.15	1		6	8	16	37	47	69	66	48	44	25	6	9	6	2				390
3.95			5	6	10	19	28	30	46	18	26	10	6	4	3	2				213
3.75		1	1	2	2	12	16	19	26	12	19	5	3	2		1				121
3.55				1	2	3	6	6	9	6	11	2	1		1					48
3.35							1	1	4	2	2	1	1							12
3.15					1	1	1				1	1								5
Totals	5	8	22	45	78	147	234	287	321	231	247	139	66	34	25	13	1	1	1	1905

Summary Statistics

	Mean	Std Dev	Regression Equations	SE-Est
Y-Lip Length	4.38	0.42	0.058X + 4.057	0.42
X-Menton-Subnasale L	5.54	0.51	0.085Y + 5.169	0.51

D. A negligible, almost non-existent relationship: correlation coefficient = 0.070

Figure 6. (continued)

In the first of these tables we may note that everybody with a specific value for stature has a common, or almost common, value for stature, maximum. In the fourth table, on the other hand, an individual's value for lip length provides virtually no indication of the size of her face length. In the other two tables, the patterns are intermediate between these two.

Two basic statistical concerns in this area of interrelationships are suggested by these tables. One is that of quantifying the differences in degrees of relationships so obvious here; this is the role played by the statistic known as the correlation coefficient. The second concern is that of establishing the pattern that values of one variable follow in relationship to a second; this is the role of the regression equation and the standard error of estimate. These two statistical concerns and the statistics involved are themselves well interrelated.

The correlation coefficient is the standard measure of the degree or intensity of the relationship between two variables. It ranges in value from 1.00, which indicates a perfect relationship, to 0.00, which indicates, on the other hand, no relationship. The first and fourth of our tables, with correlation coefficients of 0.998 and 0.128 come close to representing these extremes. The correlation coefficient can also fall in the range from 0.00 to -1.00 (this is somewhat rare for body size measurements) indicating that one variable tends to decrease in size as the other increases.

There are a substantial number of correlational measures. Of these, the most common for use with continuous data--such as our measurement data --is the Pearsonian product-moment correlation coefficient. Almost without exception this is referred to simply as the correlation coefficient. There are a variety of other types of correlation coefficients for use with categorized data (blood type, region of birth, etc.) but as these play little role in the solution of design problems we shall not discuss them.

Pearson's correlation coefficient derives from the related concept of the regression line or the regression formula. Given any two variables, we can set up an equation for estimating values for one variable in terms of the other. A typical example is the equation for estimating a man's sitting height from his stature shown in Figure 7. If the variables have a close relationship, the estimates given by the equation will be quite accurate. When, on the other hand, the degree of relationship is low or negligible, the estimates will have little accuracy.

No complete listings of the correlation coefficients for any of the sets of anthropometric data on which Volume II is based are included in this handbook. A few coefficients for USAF fliers and for Air Force Women are included, primarily for illustrative purposes, in Table 7. Correlation matrices for the USAF flying personnel surveys of 1967 and 1950, for Air Force Women (1968) and several other surveys are included in Churchill, Kikta, and Churchill (1977).

A. Calculations from Raw Data

X	Y	$X-\bar{X}$	$Y-\bar{Y}$	$(X-\bar{X})(Y-\bar{Y})$	$(X-\bar{X})^2$	$(Y-\bar{Y})^2$
7	6	0	1	0	0	1
9	7	2	2	4	4	4
5	1	-2	-4	8	4	16
4	3	-3	-2	6	9	4
10	8	3	3	9	9	9
Σ 35	25	0	0	27	26	34

a) The correlation coefficient: $r = \frac{\Sigma(X-\bar{X})(Y-\bar{Y})}{\sqrt{\Sigma(X-\bar{X})^2\Sigma(Y-\bar{Y})^2}} = \frac{27}{\sqrt{26 \cdot 34}} = 0.91$

b) The regression line: $SD_x = \sqrt{\Sigma(X-\bar{X})^2/N} = \sqrt{26/5} = 2.28$; $SD_y = \sqrt{34/5} = 2.61$

i. to estimate y: $\alpha = r\ SD_y/SD_x = 0.91 \cdot 2.61/2.28 = 1.04$

$\beta = \bar{Y} - \alpha\ \bar{X} = 5 - 1.04 \cdot 7 = -2.28$

$SE_y = SD_y\sqrt{1-r^2} = 2.61\sqrt{1-(.91)^2} = 2.61 \cdot .41 = 1.07$

$Y^* = 1.04\ X - 2.28$

ii. to estimate x: $\alpha = r\ SD_x/SD_y = 0.91 \cdot 2.28/2.61 = 0.79$

$\beta = \bar{X} - \alpha\ \bar{X} = 7 - 0.79 \cdot 5 = 3.05$

$SE_x = SD_x\sqrt{1-r^2} = 2.28\ \sqrt{1-(.91)^2} = 2.28 \cdot .41 = 0.93$

$X^* = 0.79Y + 3.05$

B. Calculations Based on Computed Statistics

a) Simple regression equations:

i. to estimate sitting height from stature (USAF'67 data)

from Table VI: $r = 0.786$

from Volume II: sitting height - mean = 36.69", SD = 1.25"
stature - mean = 69.82", SD = 2.44"

$\alpha = r\ SD_y/SD_x = 0.786 \cdot 1.25/2.44 = 0.403$

$\beta = \bar{Y} - \alpha\ \bar{X} = 36.69 - 0.403 \cdot 69.82 = 8.55''$

$SE_y = SD_y\sqrt{1-r^2} = 1.25\ \sqrt{1-(.786)^2} = 1.25 \cdot 0.618 = 0.77''$

$Y^* = 0.403 \cdot X + 8.55$

For men 6 feet tall, we can estimate sitting height as

$Y^* = 0.403 \cdot 72 + 8.55 = 37.57''$

two-thirds in a ±1 SD range: 37.57 - 0.77 = 36.8" to 37.57 + 0.77 = 38.3"

95% in a ±2 SD range: 37.57 - 1.54 = 36.0" to 37.57 + 1.54 = 39.1"

ii. to estimate stature from sitting height (the same data)

$\alpha = r\ SD_y/SD_x = 0.786 \cdot 2.44/1.25 = 1.53$

$\beta = \bar{Y} - \alpha\ \bar{X} = 69.82'' - 1.53 \cdot 36.69 = 13.69$

$SE_y = SD_y\ \sqrt{1-r^2} = 2.44\ \sqrt{1-(.786)^2} = 2.44 \cdot 0.618 = 1.51$

$X^* = 1.53\ Y + 13.69$

Figure 7. Correlation coefficients and regression equations: a few illustrative calculations.

For men with sitting heights of 34",

$Y^* = 1.53 \cdot 34 + 13.69 = 65.71"$

two-thirds in a ±1SD range: 65.71 - 1.51 = 64.2" to 65.71 + 1.51 = 67.2"

95% in a ±2SD range: 65.71 - 3.02 = 62.7" to 65.71 + 3.02 = 68.7"

b) Multiple correlation and regression:

i. correlation of X_3 with the combination of X_1 and X_2:

$$R = \sqrt{\frac{r_{1,3}^2 + r_{1,2}^2 - 2r_{1,2} \cdot r_{1,3} \cdot r_{2,3}}{1 - r_{1,2}^2}}$$

to estimate chest circumference (X_3) in terms of stature (X_1) and weight (X_2): (USAF'67 data)

$r_{1,3}$ = correlation of stature with chest circumference = 0.257

$r_{2,3}$ = correlation of weight with chest circumference = 0.799

$r_{1,2}$ = correlation of stature with weight = 0.533

$$R = \sqrt{\frac{(.257)^2 + (.799)^2 - 2(.533)(.257)(.799)}{1 - (.533)^2}} = \sqrt{\frac{0.486}{0.716}} = 0.824$$

ii. to estimate X_3 from X_1 and X_2

$$\frac{X_3^* - \bar{X}_3}{SD_3} = \beta_1 \frac{X_1 - \bar{X}_1}{SD_1} + \beta_2 \frac{X_2 - \bar{X}_2}{SD_2}$$

where $\beta_1 = \dfrac{r_{1,3} - r_{1,2} \cdot r_{2,3}}{1 - r_{1,2}^2} = \dfrac{.257 - .533 \cdot .799}{1 - (.533)^2} = -0.236$

$$\beta_2 = \frac{r_{2,3} - r_{1,2} \cdot r_{1,3}}{1 - r_{1,2}^2} = \frac{.799 - .533 \cdot .257}{1 - (.533)^2} = 0.925$$

The standard error of estimate = $SD_3 \sqrt{1 - R^2} = 0.567\ SD_3$

$$X_3^* = \beta_1 \frac{SD_3}{SD_1} X_1 + \beta_2 \frac{SD_3}{SD_2} X_2 + \bar{X}_3 - \beta_1 \frac{SD_3}{SD_1} \bar{X}_1 - \beta_2 \frac{SD_3}{SD_2} \bar{X}_2$$

Since, $\bar{X}_1$ = 69.82", SD_1 = 2.44"

$\bar{X}_2$ = 173.6 lb, SD_2 = 21.4 lb

$\bar{X}_3$ = 38.80", SD_3 = 2.50"

$$X_3^* = -.236 \frac{2.50}{2.44} (X_1 - 69.82) + .925 \frac{2.50}{21.4} (X_2 - 173.6) + 38.80$$

$$= -.242\ X_1 + .108\ X_2 + 36.95$$

Thus, our estimate of chest circumference of a man 6' tall who weighs 200 pounds is

$$X_3^* = -.242 \cdot 72 + .108 \cdot 200 + 36.95 = 41.13"$$

Since $SE_y = 2.50 \cdot \sqrt{1-(.824)^2} = 1.42"$, we can expect that about two-thirds of such men will have chest circumferences in the range $X_3^* \pm SE_y$:

41.13 ± 1.42 = 39.7" to 42.6", and 95% in the range $X_3^* \pm 2SE_y$ =

41.13 ± 2.84 = 38.3" to 44.0"

Figure 7. (continued)

TABLE 7
SELECTED CORRELATION COEFFICIENTS FOR USAF FLIERS AND AIR FORCE WOMEN*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. Age		.223	.048	-.023	.039	-.055	.091	-.072	.233	.287	.234	.219	.149	.146	.194	.095	.118	.190	.189	.089
2. Weight	.113		.533	.457	.497	.431	.481	.370	.835	.799	.824	.886	.495	.768	.770	.403	.304	.290	.264	.358
3. Stature	-.028	.515		.927	.914	.849	.801	.728	.334	.257	.279	.360	.456	.329	.348	.331	.318	.136	.267	.199
4. Chest height	-.028	.483	.949		.897	.862	.673	.731	.271	.183	.216	.289	.412	.266	.276	.284	.284	.085	.222	.162
5. Waist height	-.033	.422	.923	.930		.909	.607	.762	.308	.238	.238	.336	.409	.293	.318	.306	.297	.123	.225	.200
6. Crotch height	-.093	.359	.856	.866	.905		.467	.788	.264	.190	.221	.246	.380	.277	.225	.294	.280	.089	.205	.172
7. Sitting height	-.054	.457	.786	.681	.580	.453		.398	.312	.239	.236	.383	.384	.277	.379	.294	.275	.136	.248	.146
8. Popliteal height	-.102	.299	.841	.843	.883	.880	.485		.230	.172	.186	.201	.327	.249	.181	.235	.253	.087	.185	.189
9. Shoulder circumference	.091	.831	.318	.300	.261	.212	.291	.182		.810	.775	.717	.581	.719	.606	.330	.248	.252	.217	.313
10. Chest/bust circumference	.259	.832	.240	.245	.203	.147	.171	.114	.822		.796	.674	.370	.706	.551	.273	.204	.255	.176	.273
11. Waist circumference	.262	.856	.224	.212	.142	.132	.167	.068	.720	.804		.722	.382	.886	.600	.281	.149	.267	.174	.310
12. Buttock circumference**	.105	.922	.362	.334	.278	.217	.347	.149	.744	.766	.852		.396	.668	.893	.310	.214	.238	.180	.269
13. Biacromial breadth	.003	.452	.378	.335	.339	.282	.349	.316	.555	.401	.288	.355		.401	.361	.311	.239	.178	.266	.211
14. Waist breadth	.214	.852	.287	.260	.215	.195	.216	.133	.715	.801	.936	.849	.327		.576	.292	.168	.263	.182	.296
15. Hip breadth	.105	.809	.414	.380	.342	.283	.376	.221	.632	.647	.724	.895	.340	.760		.265	.183	.188	.155	.215
16. Head circumference	.110	.412	.294	.251	.233	.188	.287	.194	.327	.340	.309	.330	.251	.310	.288		.692	.430	.273	.299
17. Head length	.054	.261	.249	.218	.208	.170	.244	.175	.201	.196	.158	.195	.179	.164	.166	.779		.115	.311	.113
18. Head breadth	.122	.305	.133	.097	.089	.066	.132	.075	.245	.271	.265	.252	.188	.268	.227	.521	.058		.174	.497
19. Face length	.119	.228	.275	.220	.226	.199	.253	.193	.162	.172	.129	.186	.187	.151	.161	.315	.289	.148		.144
20. Face breadth	.233	.453	.190	.169	.142	.099	.185	.098	.401	.421	.412	.394	.278	.410	.364	.464	.131	.660	.206	

*Air Force Women '68 above diagonal; USAF Fliers '67 below diagonal.

**Hip circumference 9" below waist for Air Force Women '68.

Logically, there are two correlation coefficients for each pair of variables: the one defined in terms of how well we can estimate Y from X and that defined in terms of how well we can estimate X from Y. Fortunately these two are numerically equal and need not be distinguished. This is not true when regression equations corresponding to curved lines are used or when more than one variable is used in the estimating process. There are, of course, different regression lines for each variable.

The basic definition for the correlation coefficient for X and Y can be written as follows:

$$r = \frac{\Sigma(X-\overline{X})(Y-\overline{Y})}{\sqrt{\Sigma(X-\overline{X})^2 \cdot \Sigma(Y-\overline{Y})^2}}$$

and is illustrated in Figure 7. We can argue that this formula is at least a reasonable one as a measure of relationship. The terms in the denominator are always positive, but the terms in the numerator can be either positive or negative. They will be positive when X and Y are both above average and when both are below average; they will be negative whenever X is above average and Y below average or vice versa. Since terms of one sign cancel those of the other sign, the size of the numerator (and therefore of the correlation coefficient) will reflect the extent to which terms of one sign predominate. We have used the letter r here to designate the correlation coefficient; this is standard practice. When it is necessary to specify the relevant variables, we may write $r_{1,2}$ or $r_{x,y}$ or some similar expression.

There is a bit more to this formula than noting how often individuals are, on the one hand, either below or above the mean on both of a pair of measurements and how often, on the other hand, they are above the mean on one and below the mean on the other. Still, this concept of the correlation coefficient is accurate enough to provide a useful basis for judging the size of a correlation coefficient. By replacing the mean with the median in this concept (which will make little difference for most body size measurements) we can reduce our data for a pair of variables to a simple 2x2 table:

Measurement Y	Measurement X: Below Median	Measurement X: Above Median
Above Median	B	A
Below Median	A	B

and take as an approximation:

$$r(\text{approx}) = \frac{A - B}{A + B}$$

Thus, if in a group of 200 pilots, 75 of the 100 men who are above the median value for weight are also above the median in stature and vice versa, we would have the table:

	-	+
+	25	75
-	75	25

A-B = 75-25 = 50

A+B = 75+25 = 100

r (approx) = 50/100 = 0.5

Restated, this formula suggests that out of every 100 individuals who are above the median on one measurement, the number who will also be above the median on a second measurement is about:

50 whenever r = 0.0
55 whenever r = 0.1
60 whenever r = 0.2
65 whenever r = 0.3
70 whenever r = 0.4
75 whenever r = 0.5
80 whenever r = 0.6
85 whenever r = 0.7
90 whenever r = 0.8
95 whenever r = 0.9

This relationship is an approximate one but is reasonably good for the purpose of evaluating the degree of relationship that a correlation coefficient, based on body size data, represents.

Another quite important interpretation of the correlation coefficient is in terms of the accuracy of the regression equation estimates. It is customary to measure this accuracy by a statistic--the standard error of estimate--which is similar to the standard deviation but is based on the differences between the actual data values and the estimated values, rather than on the differences between the data and the arithmetic mean. The standard error of estimate is defined as

$$SE_y = \sqrt{\Sigma(Y-Y^*)^2/N}$$

where Y* represents the regression estimates and Y the actual values. By algebraically manipulating this formula and the one for the correlation coefficient we arrive at the important relationship between these two statistics:

$$SE_y = SD\sqrt{1-r^2}$$

Note that, as we should expect, SE is zero for perfect correlations (r = +1 or -1) and equals the standard deviation where r = 0. We may further observe that, since the correlation coefficient appears here as a squared value, a negative value of r has the same effect as a positive one of equal magnitude.

Just as, in general, two-thirds of a set of data lie within a standard deviation of the mean, so too about two-thirds of a set of estimates will lie within one standard error of estimate of the actual values. Similarly, about 95% of the data fall within two standard deviations of the mean, and about 95% of the estimates fall within two standard errors of estimate of the actual values. Reversing these last statements, we find that about two-thirds of the actual values lie within a band running from a standard error of estimate above the regression line to a standard error of estimate below it, 95% lie within the ± 2 SE band, and so forth. Thus, referring to Figure 8, our best estimate of the sleeve inseam of a USAF flyer who is 180 centimeters tall is about 49.3 centimeters, the regression value, and the chances are about two out of three that the inseam measurement is somewhere between 47.5 and 51.1 centimeters since SE_y = 1.8 cm.

The standard error of estimate, like the regression value, has a second important identity: the standard error is both a measure of the accuracy of a single estimate and, at the same time, the standard deviation for Y of all individuals with a fixed X-value. The regression value is both our best estimate of Y for an individual with a specified value of X and the mean value of Y for these individuals. Thus, we can say both:

a. for an individual with a stature of 180 centimeters, our best estimate of his sleeve inseam is 49.3 cm and there are two chances in three that this estimate will be in error by no more than 1.8 cm; and
b. for the group of men with statures of 180 centimeters, the mean sleeve inseam is 49.3 cm and the standard deviation is 1.8 cm.

The relationship between the standard error of estimate and the correlation coefficient is further illustrated by the following:

r	SE_y	r	SE_y	r	SE_y
0.00	100% SD	0.40	91.7% SD	0.80	60.0% SD
0.10	99.5% SD	0.50	86.6% SD	0.90	43.6% SD
0.20	98.0% SD	0.60	80.0% SD	0.95	31.2% SD
0.30	95.4% SD	0.70	71.4% SD	0.99	14.1% SD

Regression Equations

The regression equation has already been more or less defined as the equation or formula for estimating one variable's value from that of a related variable. Tacitly we have assumed that this equation was linear in nature; that is, that its graph is a straight line, and that our equation is the "best" possible. These are universal assumptions when working with anthropometric data.

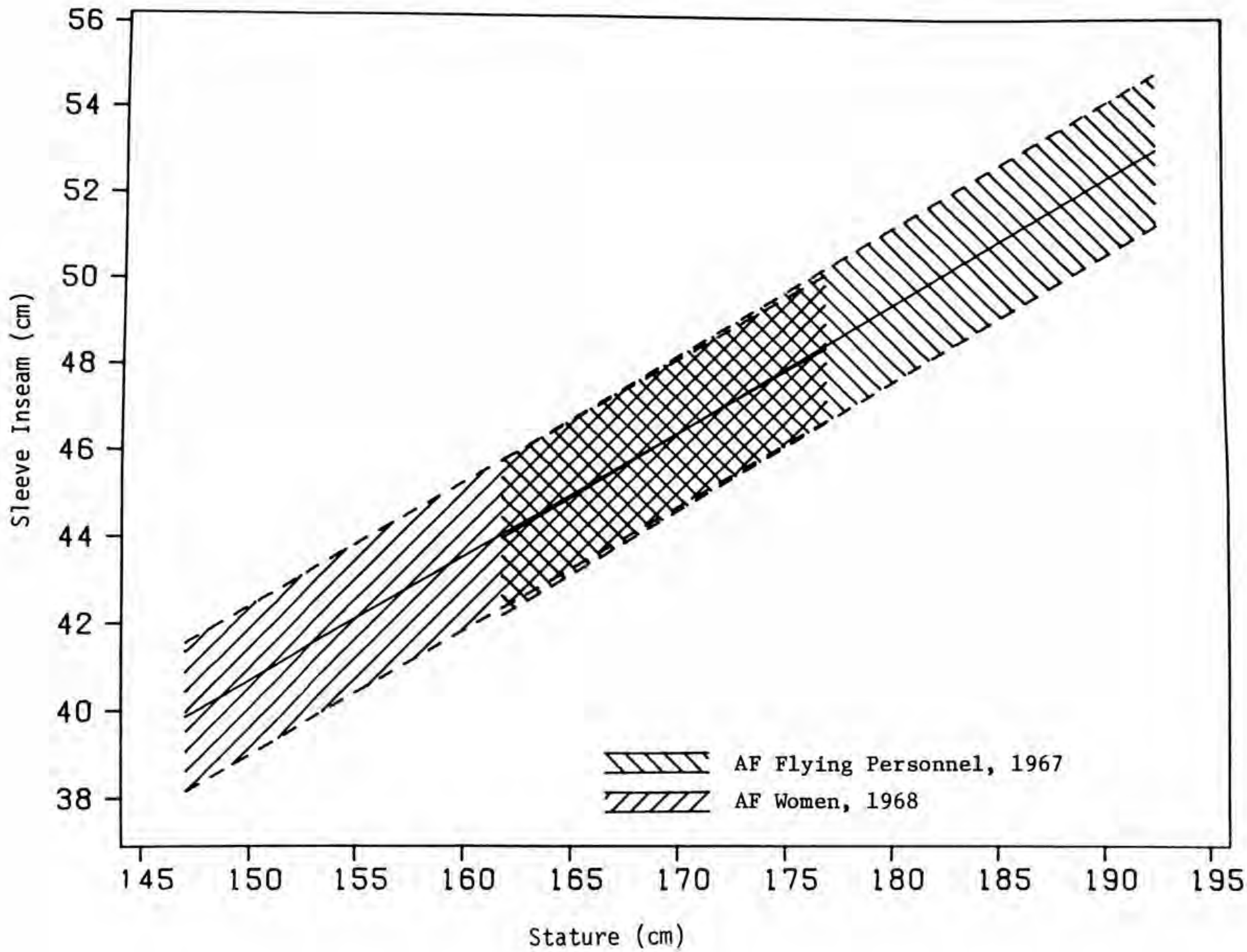

Figure 8. Regression bands: regression values ± 1 SE_y.

A useful way of writing the formula for the regression equation for Y in terms of X is this:

$$\frac{Y^*-\bar{Y}}{SD_y} = r\,\frac{X-\bar{X}}{SD_x}$$

The equation, written in this form, points up the statement about the estimates "regressing" to the means. If X is "K" standard deviations from its mean, the estimate Y* will be K·r standard deviations from its mean. Since r cannot exceed unity, and in any practical situation never equals it, K·r will always be less--in absolute value--than K and in standard deviation units, Y* will be closer to $\bar{Y}$, than X is to $\bar{X}$. In our earlier statement that the regression estimate of the weight of a man who was 2SD above the mean in stature would be about 1SD above mean weight, we used 0.5 as the approximate correlation between stature and weight, a fairly good estimate of the correlation found for many series of data obtained by measuring healthy, youngish adults.

A more conventional form of the regression equation--one absolutely algebraically equivalent to the one just given--is:

$$Y^* = \alpha X + \beta \text{ where } \alpha = rSD_y/SD_x;\ \beta = \bar{Y} - \alpha\,\bar{X}$$

The value of α, the coefficient of X, is the slope of the regression line; β is, in theory, the Y-intercept of the line, that is, the value of Y* for X=0. We have qualified this last phrase with "in theory" because the range of values for which we may reasonably assume the regression line to be valid does not exceed the range of the data on which it is based. USAF flying personnel measured in 1967 ranged in stature from about 62" to 77"; no attempt should be made to use regression equations based on the data from these men with values of stature outside this range. In addition, one should expect regression estimates to be less accurate when based on values near the ends of the range than those based on values close to average.

The computation of regression equations, based on this last formula, is illustrated in Figure 7. Needless to say, the calculations based on a sample of five are intended to illustrate a formula and not to suggest that it is appropriate to use correlational techniques with very small samples.

Intercorrelations of Body Size Data--High or Low?

How big correlation coefficients for anthropometric variables tend to be is a question without a precise answer. While the correlational coefficients obtained from a particular set of data will depend somewhat on the individuals measured, they will depend even more on the measurements included in the data. The "typical" coefficient for a survey in which only a few major dimensions were measured will, almost certainly, be much higher than the "typical" value for a major survey in which a large number of major and minor dimensions were measured.

One of the most comprehensive analyses of a large batch of anthropometric correlations appears in Anthropometry of Air Force Women (Clauser et al. 1972). It may be of interest to consider the results of this analysis since it is reasonable to assume that these results are, in broad terms, about the same as those we would find by studying data from other large surveys.

The distribution of the 7,626 correlation coefficients based on age and the 123 body size measurements made on the entire sample in the Air Force Women's survey is summarized in Table 8 and Figure 9. Several things are clear from Figure 9. The size of the correlation coefficients ranges from rather small, negative values almost to a perfect correlation of 1.00. Most of the values are positive; if we ignore the values which are not significantly different from zero (the shaded area in Figure 9), there are almost no negative values. Despite this wide range, most of the correlation coefficients lie between 0.1 and 0.4, values which may sometimes be of interest but which are of almost no significance in design problems. The most common (model) correlation coefficient is equal to a little more than 0.2, corresponding to a rather trivial level of intercorrelation.

To explore the question of how the correlation coefficients are distributed when the variables involved are of a particular type, the 124 variables involved in this analysis were divided into 9 categories: (1) age, (2) weight; (3) skinfold measurements; (4) heights (excluding lateral malleolus height), reaches, and long bone measurements; (5) torso breadths and depths; (6) torso (including neck) circumferences and horizontal surface measurements; (7) limb breadths and circumferences; (8) hand and foot measurements (including lateral malleolus height); and (9) head and face measurements.

Table 8 shows the distributions obtained when the variables are divided into these categories. Section I of this table presents essentially the same information as is contained in Figure 9: the range of the correlation coefficients is from a minimum of -0.21 to a maximum 1.00* with a median of 0.24. Section II summarizes the patterns, by category, for the correlations of all the variables with the variables in each of the nine categories. Only the correlations with weight show a pattern of values distinctly higher than the pattern for the total distribution. The median value for the correlations with weight is 0.50, but for none of the eight other categories were as many as 25% of the correlations that large.

Section III carries the process of breaking down the distribution one step further and considers, at each step, only those correlations involving variables from a specified pair of categories. Of the 37 sets of coeffi-

*Lest this value be regarded as a refutation of the statement made several times in this chapter that the correlation coefficient is never +1.00 in any realistic situation, we note that this value is really 0.998. As it is the correlation between stature measured two ways, its large size is not surprising.

TABLE 8

DISTRIBUTION OF CORRELATION COEFFICIENTS BY VARIABLES, GROUPS OF VARIABLES, AND ENTIRE GROUP
(from Anthropometry of Air Force Women by Clauser et al., 1972)

I. Total Series Summary

	Percentiles											
	MIN	1	5	10	25	50	75	90	95	99	MAX	N
	-.21	-.02	.05	.08	.15	.24	.39	.62	.73	.88	1.00	7626

II. Major Groups Summaries

Group	MIN	1	5	10	25	50	75	90	95	99	MAX	N
1. Age	-.08		-.02	.00	.05	.12	.19	.28	.29		0.33	123
2. Weight	0.08		.17	.22	.31	.50	.74	.80	.82		0.90	123
3. Skinfolds	-.10	-.07	-.02	.00	.04	.12	.36	.56	.61	.68	0.72	486
4. Heights	-.21	-.05	-.04	.09	.16	.25	.36	.58	.72	.90	1.00	3531
5. Breadths	-.08	.04	.08	.12	.19	.29	.49	.66	.72	.84	0.89	1298
6. Circumferences	-.10	.03	.08	.11	.19	.30	.47	.65	.73	.84	0.94	2166
7. Limb C's & B's	-.06	.03	.08	.12	.19	.31	.45	.64	.72	.81	0.98	2270
8. Hand & Foot	-.07	.00	.06	.10	.18	.26	.35	.46	.57	.68	0.74	723
9. Head & Face	-.14	-.02	.03	.06	.11	.16	.23	.28	.31	.62	0.95	3161

III. Cross Group Summaries

	MIN	1	5	10	25	50	75	90	95	99	MAX	N
1 & 4					.00	.05	.08					33
1 & 5						.23						11
1 & 6						.23						19
1 & 7						.15						20
1 & 9					.07	.09	.14					29
2 & 4					.41	.46	.53					33
2 & 5						.77						11
2 & 6						.79						19
2 & 7						.78						20
2 & 9					.19	.26	.30					29
3 & 4	-.08		-.03	-.01	.02	.05	.10	.18	.22		0.29	132
3 & 5					.36	.47	.57					44
3 & 6				.16	.26	.37	.54	.61				76
3 & 7				.20	.28	.41	.54	.63				80
3 & 8					.04	.05	.08					24
3 & 9	-.10		-.03	-.02	.01	.05	.10	.16	.21		0.27	116
4 & 4	-.21	-.09	.16	.25	.39	.63	.75	.87	.91	.97	1.00	528
4 & 5	-.08		.08	.13	.18	.24	.31	.38	.42		0.59	363
4 & 6	-.10	.06	.11	.15	.20	.27	.35	.44	.53	.70	0.82	627
4 & 7	-.06	.01	.08	.11	.18	.29	.35	.42	.45	.49	0.59	660
4 & 8	0.01		.16	.21	.29	.34	.46	.60	.66		0.70	198
4 & 9	-.13	-.05	.03	.07	.12	.17	.22	.27	.29	.33	0.36	957
5 & 5				.31	.50	.59	.67	.71				55
5 & 6	0.09		.26	.33	.44	.56	.69	.76	.83		0.89	209
5 & 7	0.25		.29	.31	.37	.50	.64	.70	.72		0.84	220
5 & 8				.11	.19	.23	.30	.35				66
5 & 9	-.02		.05	.07	.11	.17	.22	.26	.29		0.35	319
6 & 6	0.07		.21	.29	.44	.54	.66	.79	.83		0.94	171
6 & 7	0.11		.23	.29	.37	.48	.62	.73	.76		0.89	380
6 & 8	0.08		.12	.13	.19	.26	.32	.36	.40		0.49	114
6 & 9	-.03	.00	.04	.07	.10	.16	.22	.27	.30	.33	0.37	531
7 & 7	0.33		.37	.39	.43	.54	.69	.80	.92		0.98	190
7 & 8	0.07		.11	.17	.23	.32	.39	.49	.55		0.71	120
7 & 9	0.00	.03	.06	.08	.12	.17	.23	.26	.29	.32	0.36	580
8 & 8						.47						15
8 & 9	-.04		.05	.08	.13	.19	.23	.28	.31		0.40	174
9 & 9	-.14		.01	.04	.10	.16	.30	.53	.78		0.95	406

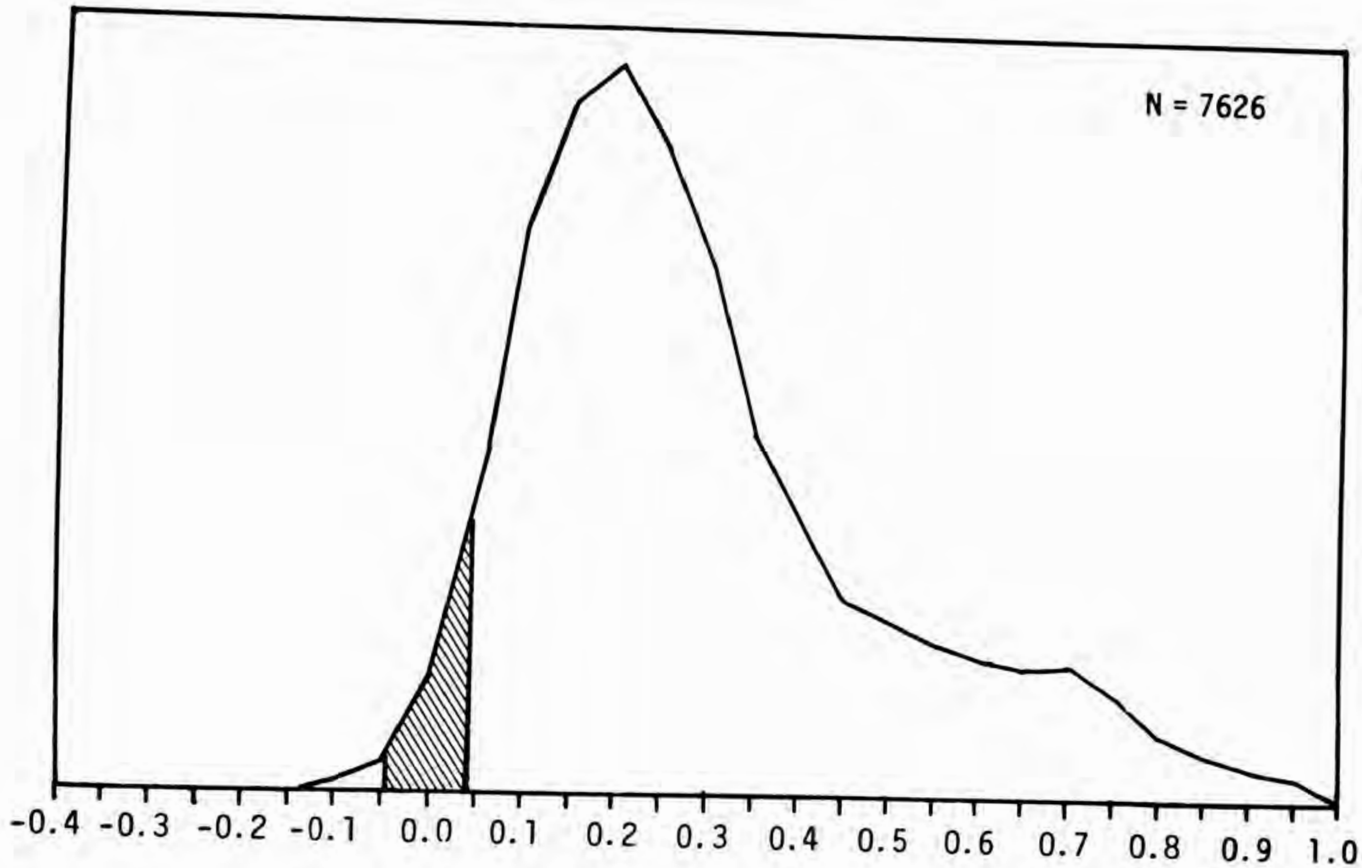

Figure 9. Distribution of correlation coefficients (from Clauser et al. 1968).

cients with more than 10 values, only the following nine had median values of at least 0.50:

weight and breadths-depths	median r = 0.77
weight and circumferences	median r = 0.79
weight and limb circumferences-breadths	median r = 0.78
heights and heights	median r = 0.63
breadths-depths and breadths-depths	median r = 0.59
breadths-depths and circumferences	median r = 0.56
breadths-depths and limb circumferences-breadths	median r = 0.50
circumferences and circumferences	median r = 0.54
limb circumferences-breadths and limb circumferences-breadths	median r = 0.54

Five other groups almost reached the 0.50 level: weight and heights (0.46), skinfolds and breadths-depths (0.47), skinfolds and circumferences (0.47), circumferences and limb circumferences-breadths (0.48), and hand-foot measurements and hand-foot measurements (0.47).

This breakdown has demonstrated that there are a few categories of body size measurements for which the correlation coefficients are, typically, of at least modest size. It also demonstrates that the overall distribution of correlations is weighted heavily towards the low end of the scale by large numbers of correlations which would rarely, if ever, be of any importance. Over a third of the correlation coefficients, for example, are correlations between measurements of the head and face and measurements of other parts of the body. That these 2,755 correlations have a median value of 0.16 is probably of no importance in any real design problem. On the other hand, the fact that the correlation coefficients for one head-face measurement with another also have a median value of 0.16 presents serious problems in the design of helmets and masks.

Interrelationships--More than Two Variables at a Time

The regression equation concept--that of estimating values of one variable from values of a second--is easily extended to the concept of the multiple regression equation. Using such an equation, we can estimate a man's weight from his height and his chest circumference, or from his height and his head, shoulder, chest, waist, and buttock circumferences, or from any other combination of two, three, four, or more variables. The quality of these estimates, as measured by their agreement with actual values, can be expressed in terms of the multiple correlation coefficient and the multiple standard error of estimate, statistics absolutely equivalent* to the simple correlation coefficient and the simple standard error of estimate.

*The multiple correlation coefficient is always considered to be positive.

All these multivariate statistics can be computed directly from the simple correlation coefficients and the means and standard deviations; we shall limit our display of formulas here to the inclusion in Figure 7 of the formula for the correlation between one variable and a pair of other variables. Other formulas are included in Churchill et al. (1977); many examples of multiple regression equations for body size measurements are given in the report of the Air Force Women's survey.

When we use a multiple regression equation based on a pair of variables, our input into the equation contains more information than when we use a simple equation based on either member of the pair. With more information we should get more accurate estimates and, as a matter of fact, we do. The multiple correlation of, say Z with X and Y will always be larger than both the simple correlations of Z with X and Z with Y. Unfortunately, the multiple correlation will often be only trivially larger than the larger of the two simple correlations. This is all too true with body size correlations. It is commonly assumed, for example, that the multiple regression equations based on stature and weight provide good estimates of most anthropometric measurements. While this is, in large measure, true, it is also true that most of the time these estimates are not much better than those obtained from the better of two simple equations. In the 1968 Air Force Women's data, for example, for 121 measurements, the multiple correlation coefficient based on stature and weight provided an improvement over the simple equations (based on either stature or weight) of no more than 0.01 for about half the measurement and an improvement of from 0.01 to 0.02 for 27 measurements. For only 35 of the measurements did the increase exceed 0.02. A typical case was that for thumb-tip reach which correlated 0.433 with weight and 0.646 with stature; the multiple correlation with weight and stature, 0.655, represented only a minor increase.

A relatively new approach to multiple regression is worth mentioning briefly--"stepwise" regression equations. This is a technique which became practical only with the advent of the modern computer. A matrix of correlation coefficients is entered into the computer which then computes for each variable the best equation based on a single other variable, then the best equation based on two variables, and so on for as many equations as are desired. The results obtained by applying this approach to a set of survey data are often interesting. Applied blindly, however, this technique is not likely to satisfy the hope of those who expect it to identify a small group of variables on which to base equations for estimating all the other variables. The resulting equations are, unfortunately, all too likely to use a substantial portion, if not almost all, of the variables. The 121 one-predictor equations for the 1968 Air Force Women's data used well over half that many predictors, the two-predictor equations used about 100 different variables, and the three-predictor ones all but half a dozen of the variables. About a dozen two-variable combinations were "best" for predicting two variables apiece, but none was best for more than two. Nonetheless, this approach would seem to have potential usefulness in the analysis of body size interrelationships, and references to it appear from time to time in anthropometric literature.

A Mathematical Model for Body Size Data

There are at least two fairly common ways of determining the circumference of a bicycle wheel: first, we can measure it directly; secondly, we can measure the distance from the center of the axle to the edge of the wheel and multiply the result by 2π. When we use this second method, we use the circle as a mathematical model for the wheel and make use of the fact that, for this model, $C=2\pi R$.

In working with anthropometric data, we often have a similar choice of procedures. We can measure some statistical value directly or we can estimate it indirectly using a mathematical model appropriate to such data. For most body size data, the most appropriate model is the normal distribution, the "normal curve," (see, for example, Figure 2). Just as there are circles of many sizes, so too there are an infinite number of normal distributions corresponding to all possible values of the mean and the standard deviation.*

No set of data fits this model perfectly, but then, there has never been a perfectly round bicycle wheel. Sometimes neither model may be adequately close to the real thing: subscapular skinfold measurements and wheels with flat tires are, perhaps, somewhat equivalent examples of this. Most body size measurements, on the other hand, fit our mathematical model within usual design tolerances and over the usual range of design values; both these reservations are real--and also realistic. The proportion of USAF pilots between $\bar{X} \pm 1SD$ values in stature is, according to the tables of the normal distribution, 68.268%; in more reasonable and more realistic words, we can expect about two-thirds of the pilots to fall in this range. For most designs, the two-thirds is likely to be adequate and accurate; the use of 68.268%, in contrast, will probably make as much sense as using 3.14159265 for π in determining the circumference of the wheel.

Virtually all men have statures within 3 or 3.5 standard deviations of the mean value; only an occasional individual will fall outside this range and what his stature will be and, relatively speaking, how many such individuals exist in any group of men, are matters too erratic for close

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*The mathematical statement of the normal distribution is that, in a population of values with a mean of M and a standard deviation of SD, the proportion of values less than any value X_0 is given by the integral:

$$P(X \leq X_o) = \frac{1}{SD\sqrt{2\pi}} \int_{-\infty}^{X_0} e^{-\frac{1}{2}\left(\frac{t-M}{SD}\right)^2} dt$$

where $\Pi = 3.14....$ and $e = 2.78....$ have their usual meanings. The value of the integral cannot be expressed as a simple function of X_0 but tables of the integral are legion. This integral is closely related to, but not quite the same as, the error function (ERF) sometimes used in engineering studies.

prediction. The number of men in a group the size of the USAF flying personnel sample (N=2,420) more than 4 standard deviations above the mean in stature (or any other measurement) is, on the basis of the normal distribution, just about one. In practice, we're likely to find one, or two, or three men this tall--or, quite often, none at all. No matter what the actual number is, our mathematical model has indicated, quite accurately, that there are so few men in this "tail" of the distribution that only a most unusual design plan need concern itself with them.

The importance of a mathematical model is not only its usefulness in providing an alternative to direct computation for determining statistical values, but also in the help it provides in generalizing about statistical problems and in developing approaches to their solutions. The mathematical model at times also makes it possible to determine statistical values which cannot be determined directly or to provide such values in a form not possible by direct computation. This is true, of course, not only of the normal distribution model for body size (and many other types of data) but for other models (binomial distribution, Poisson distribution, hypergeometric distribution, etc.) more appropriate to other types of statistical data.

Percentiles and Related Values

One of the most important applications of the normal distribution model has already been mentioned several times in this chapter--the estimation of percentiles and similar values in terms of the mean and standard deviations, and the estimation of the proportions of a set of data which lie within specified ranges. Tables 2, 5 and 6 are based directly on the evaluation of the integral of the normal distribution.

The Bivariate and Multivariate Models

The mathematical model of the normal distribution for a single anthropometric variable can be extended easily--and with reservations similar to those already noted--to the joint distribution of two or more body size measurements. While the model for a single variable is determined by matching model and actuality in terms of a mean and standard deviation, in the two-variable case, the matching is done in terms of five statistics: the two means, the two standard deviations, and the correlation coefficient. The model can be extended to any number of variables, depending in each case on the means and standard deviations of the variables involved plus all their correlation coefficients. The mathematics involved in using this model becomes somewhat complex as the number of variables increases, but computer programs are available for a variety of uses of the two- and three-variable forms and for some uses involving essentially any number of variables.*

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*Formulas for, and related to, these models are included in Churchill et al. (1977). Relevant computer programs will be included in Computer Programs

We shall discuss three uses of the bivariate normal distribution model: the construction of equal probability ellipses, the construction of artificial bivariate tables, and the determination of proportions disaccommodated by two-variable designs.

Equal Probability Ellipses

The concept of the equal probability ellipse can be approached by considering a design range defined by a pair of complementary percentiles, say, the 5th and the 95th. The range of values between these percentiles has two important characteristics:

(1) a specified proportion (i.e., 90%) of the data lies in this range, and
(2) every value within the range has a higher probability than every value outside it.

Combined, these two characteristics add up to the fact that the 5th-95th percentile range is the shortest range containing 90% of the data.

The extension of these concepts to the two-variable case leads to the notion of the equal probability ellipse, as shown in Figure 10. These ellipses have been constructed so that, like the 5th-95th percentile range:

(1) 90% of the pairs of values lie inside the ellipse,
(2) every point inside the ellipse corresponds to a higher probability (or relative frequency) than every point outside the ellipse, and, consequently,
(3) the interior of the ellipse is the smallest region (as measured in SD units) containing 90% of the data.

It is not particularly clear how one would use an ellipse in establishing design limits for a piece of equipment or clothing. Nonetheless, these ellipses are useful in indicating the major distribution of the data for a pair of variables. When data for two or more groups of individuals must be considered in a single design program, the appropriate ellipses for the several groups, drawn on a single graph, may help to indicate the nature of the problems involved; Figures 10 and 11, for example, illustrate well how differently different types of anthropometric measurements for women relate to the same measurements for men.

It may be worth noting in passing how a 90% constant-probability ellipse differs from the rectangle whose sides correspond to the 5th and 95th percentiles for the two variables involved. First, the relative frequency of the individuals who fall in such a rectangle, i.e., the individuals who are within the 5th-95th percentile range on both variables, is

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for Anthropometric and Statistically Similar Data by Churchill, Kikta, and Churchill (in preparation) and can be obtained from Webb Associates, Box 308, Yellow Springs, Ohio 45387.

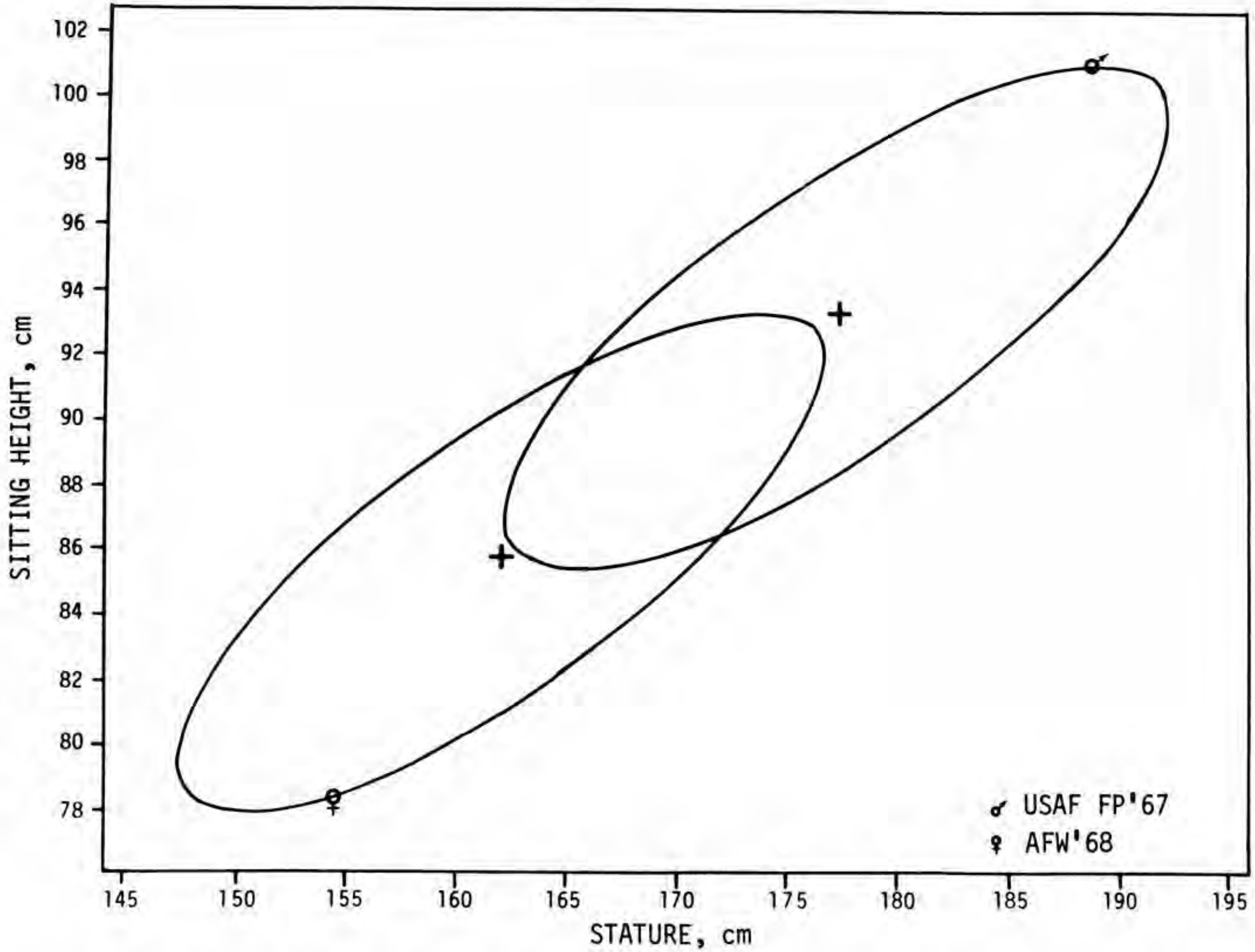

Figure 10. Ninety-five percent probability ellipse for sitting height and stature.

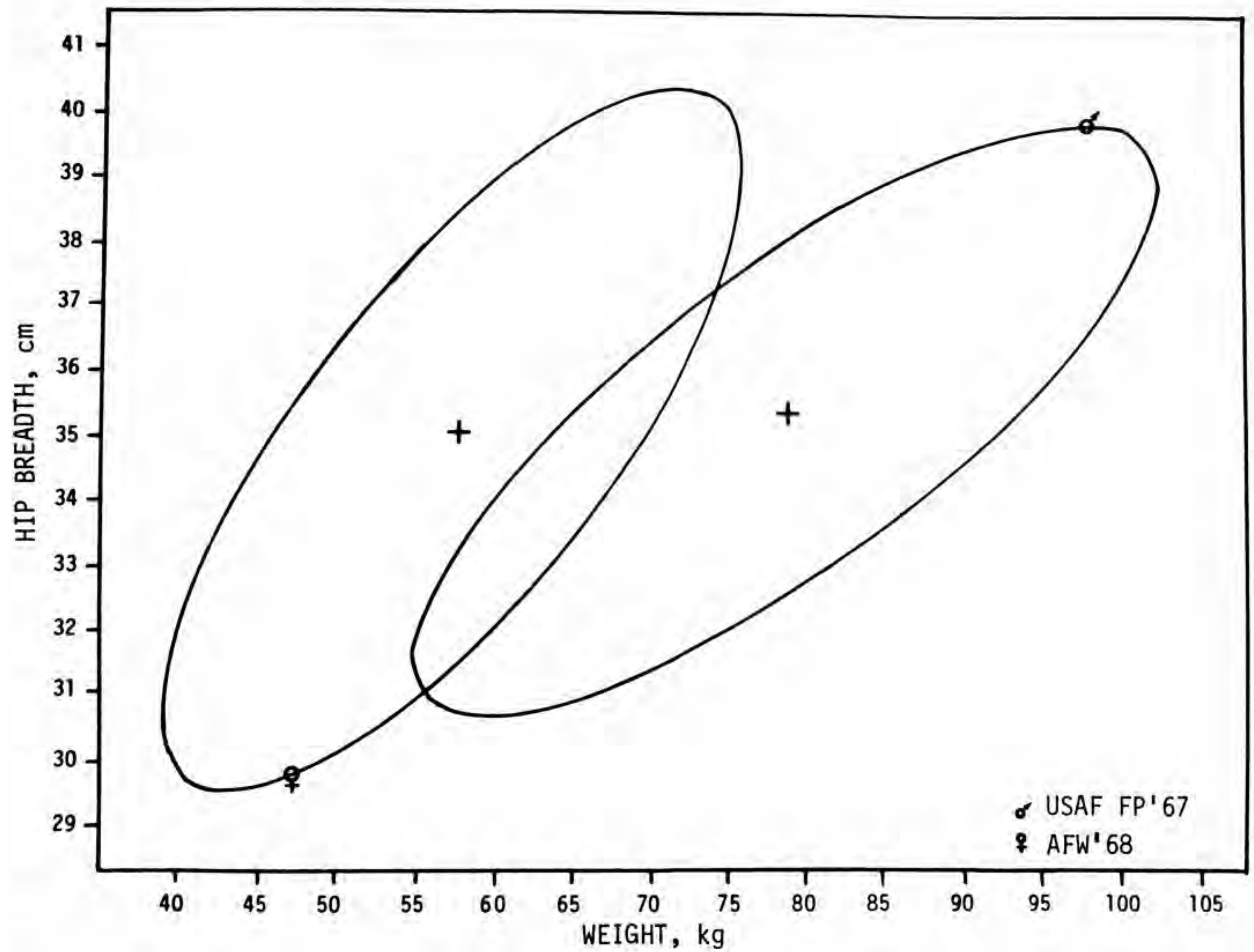

Figure 11. Ninety-five percent probability ellipse for weight and hip breadth.

almost certainly not 90%. For variables with almost zero correlations--face length and face breadth, for example--the rectangle will contain only about 81% of the data. The higher the correlation--its sign is irrelevant --the higher the percentage within the rectangle, with 90% corresponding only to a perfect correlation. Second, the rectangle will include, in its lower right and upper left corners, if the variables are positively correlated, some relatively atypical individuals--the 6'1" pilot who weighs 140 pounds and the 5'6" one who weighs 210 pounds, for example--while excluding much more likely individuals, such as a 6'1" pilot who weighs 215 pounds. This problem probably cannot be avoided if rectangular design limits must be used. The question of how to obtain rectangular design limits which include a specified proportion of the data will be addressed below.

Artificial Bivariate Tables

A bivariate table, like those pictured in Figure 6 is made by recording the number of individuals whose values for a pair of variables fall within specified limits. What we have called artificial bivariate tables (see Figure 12) are made by computing such numbers on the basis of the bivariate normal frequency distribution. The problem is akin to that of determining, in the one-variable case, the proportion of the data between two values, but differs from it in that, because of the number of parameters involved, concise, easily usable tables for constructing artificial bivariate tables do not exist. However, these bivariate tables are easily and quickly computed.*

The artificial bivariate tables have a number of things to recommend them over the conventional tables. The former are much more available than the latter since only the means, standard deviations, and correlation coefficients are required to construct them. The correlation source book of Churchill et al. (1977) contains all the information needed to create artificial bivariate tables for every pair of variables measured in each of the seven surveys covered there--a number of tables well in excess of 50,000. In contrast, few conventional bivariate tables have been published for these data. Some 500 such tables appear in Anthropometry of Air Force Women by Clauser et al. (1972) and about 100 in a report of the 1946 survey of women separating from the U.S. Army (Randall and Munroe, 1949). Conventional tables for all pairs of variables can, of course, be computed from the raw data, but this requires access to these data plus considerably more computer time than do the artificial bivariates.

Since the artificial bivariate tables are based on the summary statistics rather than the raw data, they are independent of the units in which the data were measured. For example, instead of a stature-weight table with stature in centimeters and weight in pounds--a combination of units pleasing to nobody but almost universal for U.S. data--an artificial bivariate table can be in inches and pounds or in centimeters and kilograms or in any mul-

*See previous footnote about the availability of appropriate programs.

BUTTOCK-KNEE LENGTH

BUTTOCK-POPLITEAL LENGTH	20"–21"	21"–22"	22"–23"	23"–24"	24"–25"	25"–26"	26"–27"	27"–28"	Total
22"–23"					1	8	6	1	16
21"–22"				4	42	53	10		109
20"–21"			5	89	170	43	1		308
19"–20"		3	72	205	76	3			359
18"–19"		21	94	53	4				172
17"–18"	3	16	13	1					33
16"–17"	1	2							3
Total	4	42	184	352	293	107	17	1	1000

Figure 12. Artificial bivariate table for buttock-knee and buttock-popliteal lengths (USAF'67 data).

tiple or fraction of these units, with any derived choice of intervals, and with whatever total frequency count is preferred.

A third advantage is that the bivariate normal distribution tends to smooth the data, and the frequencies in adjacent cells form more or less reasonable patterns. Even with survey samples of several thousands or more, rather irregular patterns which make no biological sense often occur, particularly around the perimeter of a conventional table. The regularities of the artificial bivariate tables can, however, also gloss over irregularities which are real and which do make biological sense. In the use of these tables we must take into account the possibility of this occurrence. This often happens when one of the pairs of variables is weight because of the asymmetry of its distribution. More serious problems may arise when using data based on a group which consists of two or more subgroups which have major anthropometric differences. It would be unwise, for example, to compute an artificial bivariate table for weight and stature for a group consisting of equal numbers of basic trainees and of senior officers, or a table of sitting heights and crotch heights for a group consisting of substantially equal numbers of Blacks, Whites, and Orientals. If such tables are needed, it might make considerable sense to create artificial bivariate tables separately for each subgroup and then combine the computed frequencies. The use of our model, and the computer, makes the creation of such tables a simple matter.

Proportions Disaccommodated by Two-Variable Designs

Equipment and workspace units are frequently designed to functionally fit all potential users except for a small number of individuals who are too small (or too large) in one or the other or both of two bodily dimensions. The number of potential users who will be disaccommodated by such a design depends not only on the number who are disaccommodated on each of the design dimensions but also on the correlation between these dimensions. If, for example, 10% of the potential users are disaccommodated on each dimension, the total proportion disaccommodated can be as low as 10% or as high as 20%. By one more use of our bivariate mathematical model, we can estimate the proportion of potential users who will be left out by a specified design. We can equally well determine pairs of design limits which will exclude a specified proportion of the potential users. (See Figure 13)

The shaded areas in Figure 13 illustrate six different types of design patterns in which the disaccomodated potential users will be:

- Type A - individuals who are too small in either dimension.
- Type B - individuals who are too large in either dimension.
- Type C - individuals who are too large in one dimension or too small in the other.
- Type D - individuals who are either too large or too small in either dimension.

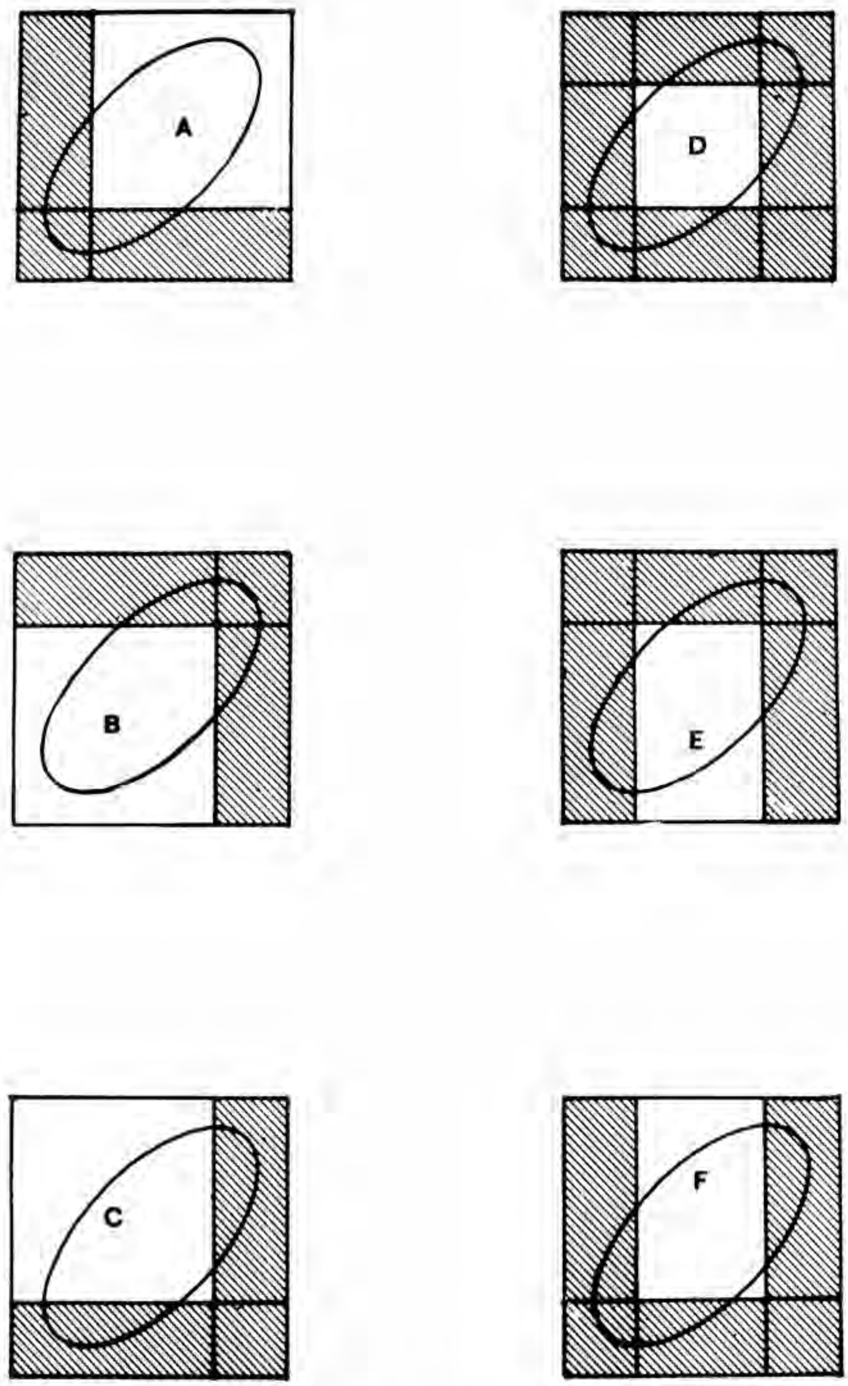

Figure 13. Proportions disaccommodated: six types of two-variable design patterns.

Type E - individuals who are either too large or too small in one dimension or who are too large in the other.

Type F - individuals who are either too large or too small in one dimension or who are too small in the other.

From a statistical point of view, types A and B are equivalent and so are types E and F; we shall, as a consequence, concern ourselves with types A, C, D, and E.

In each case, the problem is the number of persons in the corner box or boxes--those, that is, who are out of range on both dimensions. If the two design dimensions are positively correlated, and we shall assume here that they are, few individuals will be in the lower right-hand corner box or in the upper left-hand one. Type C can, therefore, be easily taken care of. If, for example, a design requires that users not exceed some value in sitting height and that they not fall below some value in arm reach, it will be a rare individual who is out-of-range on both variables. In this case, then, the proportion of potential users disaccommodated will be essentially just the number disaccommodated on sitting height plus the number disaccommodated on arm reach.

For type A designs, the number of individuals in the left-hand column of Figure 12, P_y, and the number in the row at the base of the figure, P_x, are, we presume, either known or can be estimated using Table 2. The number in the corner, P_{xy}, usually must be calculated using a computer program such as the artificial bivariate table or one similar to it. The total number disaccommodated will be given by

$$P_{total} = P_x + P_y - P_{xy} .$$

The eye height, sitting, values for USAF flyers are M = 31.87, SD = 1.19; the design limit of 30.0" is thus (31.87-30.0)/1.19 or 1.57 standard deviations below the mean. From Table 2, we estimate that 5.8% of the flyers fall below the prescribed limit.

Similarly, the thumb-tip reach values are M=31.62, SD=1.57; the design limit of 29.5" is thus (31.62-29.5)/1.57 or 1.35 standard deviations below the mean. Again from Table 2, we obtain 8.9% as an estimate of the proportion of flyers with arms that are too short. The value of P_{xy}, unfortunately, is not so easily obtained since an appropriate table for determining it is not only not available, but would be cumbersome to use if it were. However, by specifying 1.57, 1.35, 0.392 (the correlation between the two dimensions) in the proper computer program, we find that P_{xy} = 1.6%, and,

$$\text{Total disaccommodated} = P_x + P_y - P_{xy} = 5.8\% + 8.9\% - 1.6\% = 13.1\%$$

The type D design can be considered, with reasonable accuracy, as a combined type A and type B design. The number disaccommodated will be essentially the sum of those who exceed one or the other (or both) of the upper limits and of those who fall below one or the other (or both) of the lower limits; the error in this computation will be represented by the rare individuals who are above the upper limit in one dimension and below the lower limit on the other.

Finally, similar reasoning suggests that a type E design be treated as a type B design, plus the strip at the left of the box.

The reverse problem, that of selecting design limits to provide a specified level of accomodation, while more complex mathematically, is easily handled on a computer. Figure 14 shows the output of one computer program which provides for a Type A design, 5%, 10% and 20% disaccomodated design limits for eye height, sitting and thumb tip reach. Any pair of values from the proper curve will serve as appropriate design limits. Thus, for example, a design which will accomodate men who are not over 33.5" in eye height, sitting or over 34.8" in thumb-tip reach is likely to disaccomodate about 10% of the USAF flying personnel. The same will be true of designs based on eye height, sitting and thumb-tip reaches of 34.0" and 33.9", of 35.0" and 33.7", of 35.5" and 33.6", etc.

The problem of selecting rectangular design limits which contain a specified proportion of a set of data can be handled by using the computer program which created Figure 14 twice. An initial run of this program would supply a choice of lower limits which would exclude K_1% of the data, and a second computer run would provide a choice of upper limits designed to exclude K_2 % of the data. The rectangle defined by any pair of lower limits and any pair of upper limits will include at least $(100-K_1-K_2)$% of the data. While the values of K_1 and K_2 may be equal in many problems, nothing in this approach requires that they be equal.

It may be appropriate to end this discussion of the bivariate normal model with the explicit recognition that it is the modern computer which has made this model the useful tool it is. Without a computer, most applications of this model would require the awkward and laborious use of cumbersome tables; what the computer will do well in seconds, it would take hours to do poorly without it.

Sampling Errors

In 1967 the Air Force measured a sample of 2,420 men. Had this survey been carried out a few months earlier or a year later or had a different choice of air bases been made, the sample would have been made up of a somewhat different group of men, a little taller, perhaps, or a bit shorter, somewhat heavier or somewhat lighter. Like the sample that was measured, this hypothetical group would differ in a multitude of ways from the total USAF flying personnel population.

All data collected on samples are subject to sampling error and we cannot, therefore, expect them to represent the population precisely. Parenthetically, we may observe that complete precision is impossible even with 100% sampling; by the time data from a 100% survey of Air Force pilots could be analyzed, and long before such data would be used, the population of

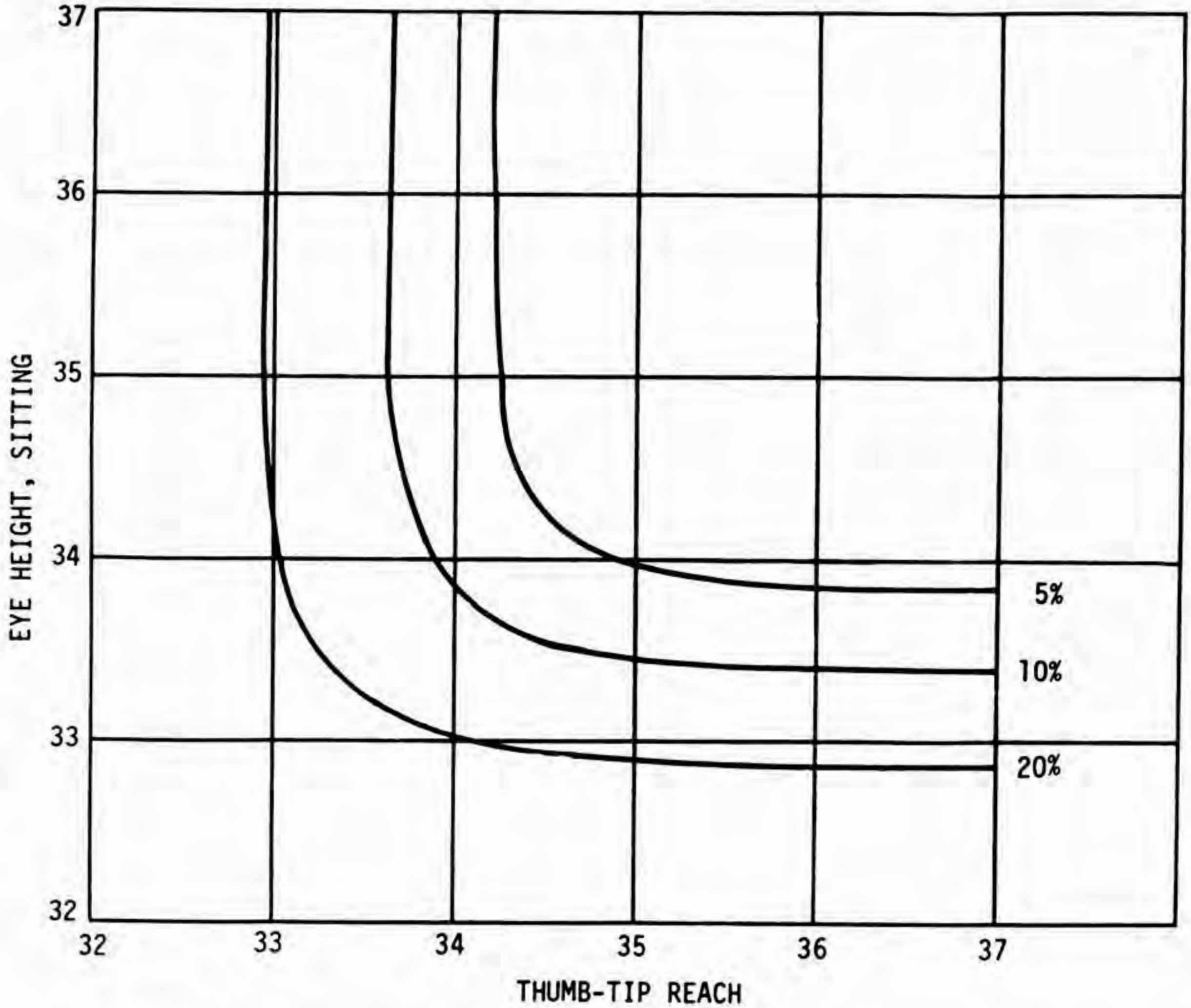

Figure 14. Design limits based on a specified percent disaccommodated: Type A design, Eye Height, Sitting and Thumb-tip Reach.

pilots would already have changed. In addition, the population the design engineer wishes our statistics to describe is usually a population which does not yet exist--pilots or astronauts who will fly or use or wear equipment still years from the production line. Nonetheless, reasonably accurate, useful data can be obtained from samples; this handbook is based on just such data.

Sampling errors arise in the anthropometric surveys from a number of sources; the magnitude of errors from each source is, in the main, all but impossible to evaluate. Military body size surveys are not based on random or "probability" sampling, types of sampling which yield solid estimates of the sampling errors. On the other hand, conscious efforts are usually made to sample a broad spectrum of the population--senior pilots and student navigators, crew members of huge, multi-engine cargo planes and those of much smaller fighters, and so forth. Usually, too, data from various segments of the population can be studied to determine whether significant differences exist among these segments. If important differences are found, separate statistics can be provided for individual subgroups and the statistics for the total group can be adjusted to compensate for sample-population differences in background variables. Various aspects of sample-population matching and of sampling errors are discussed at length in Sampling and Data Gathering Strategies for Future USAF Anthropometry, by Churchill and McConville (1976).

One important component of sampling error is that due to the more-or-less random aspect of the sampling process. This component is directly related to sample size and can be easily evaluated in a probability sense. For most sample statistics, one can compute a statistic known as the standard error which depends on the nature of the statistic, the size of the sample, and, as a rule, the variability of the data, and can be written in the form

$$SE_S = K \cdot SD / \sqrt{N}$$

where the value of K depends on the statistic involved. For the mean, K=1.0; for the standard deviation, K=0.707; for the percentiles, K runs from 1.3 for the 50th percentile, to 2.1 for the 5th and 95th percentiles, and 3.7 for the 1st and 99th ones. For combinations of the mean and standard deviation, such as $M + A \cdot SD$, the value of K is $\sqrt{1 + A^2/2}$.

The standard errors of the basic summary statistics are thus directly proportional to the standard deviation* and inversely proportional to the square root of the sample size. Because of the inverse relationship with the sample size, the standard error for any of these statistics can be made as small as desired by increasing the sample size. However, since the sample size enters this formula as its square root, an increase to four times the original sample size is needed to cut the standard error in half and a nine-fold increase is required to reduce it to one-third.

*Theoretically, the population SD; however, for samples of 50 or more the distribution is trivial.

In Table 9 we have listed for illustrative purposes a few numerical examples: the standard errors of the mean, standard deviation, and a few percentiles for weight, stature, waist circumference, and foot length for samples of 50, 100, 250, 500, 1,000, and 2,000. In preparing this table we have used standard deviations for the USAF '67 flying personnel survey, but the values from most of the other surveys would give about the same results.

The standard error is a standard deviation type statistic. It does not tell us, of course, what the error is in any instance. If it did, we could use this information to convert the computed value into an errorless one. Rather it enables us to establish probability bounds for the random sampling errors: about 2/3 of the time the error will be less than ± 1 SE; about 95% of the time the error will be less then ± 2 SE; almost never will the error be more than ± 3 SE. The term "confidence limit" is given to bands established by adding to and subtracting from a statistic certain multiples of its standard error. The range from 1.96 standard errors below to 1.96 standard errors above a sample statistic constitutes a "95% confidence limit" the range based on 2.58 standard errors, a "99% confidence limit," and so forth.*

From the values in Table 9, it is quite clear that random sampling errors are fairly small for samples of 1,000 or more but can be of considerable size for the small samples--30 or so--which are often used in experimental studies. For example, the 95% confidence limits for the 5th percentile of stature for the USAF '67 flying personnel data are from about 68.8"-0.2" to 68.8"+0.2", while the same confidence limits for a sample of 30 men would extend from about 2" below the sample mean to 2" above it.

Churchill and McConville (1976) have suggested that samples of 350 will usually be large enough to provide design values of adequate accuracy, and that samples of 250 will generally suffice if certain control processes are used. An essential part of their analysis was the selection of criteria for judging what constituted adequate accuracy. Their conclusions about the adequacy of samples of 350 and 250 were based, in part, on the assumption that 5th and 95th percentile values of height measurements need not be known with greater relative precision than the diurnal variations in stature and that circumferential measurements need not be known with greater relative precision than the cyclic variation in chest circumfernece. It is likely that other criteria based on realistic design factors would have led to similar results.

The random sampling errors of two major statistics, the correlation coefficient and the range, do not follow the pattern of the standard errors just discussed. The sampling error for the correlation coefficient, like

*Appropriate multiples for other confidence limits can be obtained from Table 5. Note, however, that the constant for 90% confidence limits, for example, is that for the 95th percentiles, and not that for the 10th and 90th.

TABLE 9
TYPICAL STANDARD ERRORS

	SAMPLE SIZE					
	50	100	250	500	1000	2000
Weight (lbs)						
Mean	3.03	2.14	1.36	0.96	0.68	0.48
Std. Dev.	2.14	1.51	0.96	0.68	0.48	0.34
5th/95th%ile	6.37	4.50	2.85	2.01	1.42	1.01
1st/99th%ile	11.22	7.93	5.02	3.56	2.51	1.78
Stature (cm)						
Mean	0.35	0.24	0.15	0.11	0.08	0.05
Std. Dev.	0.24	0.17	0.11	0.08	0.05	0.04
5th/95th%ile	0.72	0.51	0.32	0.22	0.16	0.11
1st/99th%ile	1.28	0.90	0.57	0.41	0.29	0.20
Waist Circumference (cm)						
Mean	0.41	0.29	0.18	0.13	0.09	0.07
Std. Dev.	0.29	0.21	0.13	0.09	0.07	0.05
5th/95th%ile	0.86	0.61	0.39	0.27	0.19	0.14
1st/99th%ile	1.52	1.08	0.68	0.48	0.34	0.24
Foot Length (cm)						
Mean	0.07	0.05	0.03	0.02	0.01	0.01
Std. Dev.	0.05	0.03	0.02	0.01	0.01	0.01
5th/95th%ile	0.14	0.10	0.06	0.04	0.03	0.02
1st/99th%ile	0.25	0.18	0.11	0.08	0.05	0.04

Based on the USAF '67 standard deviations: for weight, 21.44 lbs; for stature, 2.44 cm; for waist circumference, 2.91 cm; for foot length, 0.47 cm.

that for the mean, varies inversely with the square root of the sample size, but does not depend on the standard deviation. Rather, this error depends on the correlation itself in a somewhat complex fashion. The confidence limits do not as a rule extend equally above and below the sample correlation coefficient. This nonsymmetry is minor for samples of several thousand, but becomes substantial when the sample size is small and the correlation coefficient large. Tables and formulas for determining confidence limits for correlation coefficients are given by Churchill et al. (1977). The following values illustrate the 95% confidence limits for correlation coefficients for the USAF '67 flying personnel and 1968 Air Force Women's surveys:

r	AFW '68	FLY '67	r	AFW '68	FLY '67
0.0	±0.045	±0.040	0.70	-.024,+.022	-.021,+.019
0.2	-.004,+.043	-.030,+.029	0.75	-.020,+.018	-.018,+.016
0.3	-.041,+.040	-.028,+.028	0.80	-.017,+.015	-.017,+.013
0.4	-.038,+.037	-.034,+.033	0.85	-.013,+.011	-.011,+.010
0.5	-.034,+.032	-.030,+.029	0.90	-.009,+.007	-.008,+.006
0.6	-.030,+.027	-.026,+.024	0.95	-.005,+.003	-.004,+.003

Thus, for example, the 95% confidence limits for a correlation coefficient whose sample value was 0.600 would be from 0.570 to 0.627, if based on a sample of 1,905, or from 0.574 to 0.624 if based on a sample of 2,420. Ninety-nine percent limits in these cases would be from 0.561 to 0.636 and from 0.565 to 0.633.

The sample range has a standard error which decreases quite slowly as the sample size increases, much more slowly than, for example, the standard error of the mean. The large standard error which the range has, even for rather large samples, is one of the many reasons that the range is usually judged a poor statistic for all but the smallest of samples ($N<20$).

One final standard error--that of a proportion--does not appear to follow the basic formula although it is in fact equivalent to the standard error of the mean. For a proportion P, the standard error is

$$SE_P = \sqrt{P \cdot (1-P)/N} \quad .$$

For values of P from 30% to 70%, this error is roughly equal to $0.5/\sqrt{N}$.

The non-random sampling errors present in our data cannot, as a rule, be evaluated by any set of mathematical formulas. Extensive compilations of data, such as that given in Volume II, do provide a basis for some evaluation of these errors. Each user of these data will probably wish to make such evaluations in his own way, and we limit ourselves to a pair of illustrations of one approach.

One source of error is the failure of a sample to properly correspond to the population in terms of background variables. One might question, for example, whether the sample in the USAF '67 survey accurately reflects the division between students and rated officers, or between pilots and navigators, and, if the sample is faulty in either of these respects, to what extent are the body size statistics affected. Because Volume II contains detailed statistics in this case not only for the entire sample but for the four relevant subgroups as well, we can estimate the changes in the total group statistics that shifts in the sample composition would make. On checking the values for stature, for example, we find that only one of the subgroup means--that for the rather small (N=188) group of student navigators--differs from the total group mean by much more than 0.15". From this perhaps we can conclude that, for stature at least, errors of this type in the sample composition are not likely to be significant errors. We might also be willing to assume that the same thing is done for comparable surveys, statistics such as the RAF 2,000 man survey, for which subgroup data are not available.

Differences in measuring techniques are, of course, a major source of differences in the statistical summaries. Unfortunately, differences in measuring techniques may be present even when published descriptions of the techniques agree. Again, the wealth of material in Volume II will often provide a basis for judging the comparability of measurement techniques. One might, for example, compare the statistics of major measurements on the basis of the statures and weights, the statistics for head and face measurements on the basis of head breadths and head lengths, and so forth, in two surveys. The following numbers are the result of one such comparison based on the USAF '67 flying personnel survey data and the data given by Bolton (1973) for the Royal Air Force 2,000-man survey:

	Weight	Stature	Crotch Height	Chest Circ.	Waist Circ.
RAF	165	69.9	33.6	38.3	33.7
USAF	174	69.8	33.5	38.8	33.5

If we can assume the weight and stature means to be correct, we would expect that mean values for other heights would be about the same, but that USAF circumferences would be a bit larger than the RAF ones. The crotch height and chest circumference mean values clearly follow this pattern; those for waist circumference do not. This last result is not surprising, however, since according to the RAF survey report (Bolton et al., 1973) the technique that the British used to measure waist circumference was quite different from that used in the USAF survey.

Comparison of all the statistics for a single dimension will also provide some clues as to the likely reliability of the measurements and the consistency of the measurement techniques. The wide range of mean values for interscye, maximum, for example, would suggest--and correctly so--that this measurement is quite sensitive to small differences in measurement technique and subject position. Much more typical than interscye maximum are the many dimensions for which the statistics show, in the main, only small and logical patterns o[illegible] [illegible]r these dimensions are ones in which we can put considerable confidence.

Little, Average, and Big Men and Women: 5th, 50th, and 95th Percentiles

With the growing acceptance of the need to design for small and large individuals as well as for those of average size, the practice has arisen of designating small, average and large men and women as 5th percentile, 50th percentile and 95th percentile men or women. To the extent that these terms imply individuals who are 5th, 50th or 95th percentiles in all dimensions*, there are statistical problems with the concept of the "percentile individual." This is particularly true when the concept is applied to anthropometric dummies, head and body forms, and to other items in which a multiplicity of dimensions must be integrated.

The 50th percentile man and woman differs from other percentile men and women in that they are statistically possible, if rather improbable. Actually, even for this to be true we need to equate the 50th percentile with the mean value. We note in Table 10, for example, that the mean value for waist height (39.5") of Air Force women, plus the mean value for the vertical distance from waist level to vertex (24.3") is equal to the mean value of their statures (63.8").

TABLE 10
SELECTED STATISTICS FOR STATURE AND FLOOR-TO-WAIST AND WAIST-TO-VERTEX HEIGHTS (AFW '68 DATA)

	Mean	5%ile	95%ile	X-1.65SD	X+1.65SD
Stature	63.8"	60.0"	67.8"	59.9"	67.6"
Waist height	39.5"	36.6"	42.5"	36.6"	42.4"
Waist to vertex	24.3"	22.7"	26.1"	22.6"	26.0"
SUMS	(63.8")	(59.3")	(68.6")	(59.2")	(68.4")

Stature could be further segmented: the distance from floor to ankle, from ankle to calf, from calf to knee and so forth. No matter how this segmentation is carried out, the sum of the mean values of the segment lengths of the 50th percentile person will inevitably add to the mean value of stature (see Table 11). Similarly, we can expect that a man who is of average value in height and all of his breadths, depths, and circumferences, will also be of average weight.**

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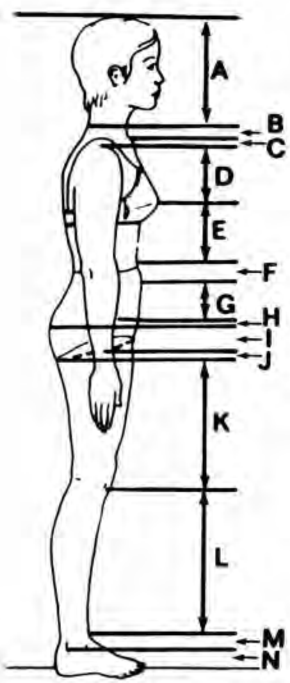
*Hertzberg (1970) defines an anthropometric dummy as one which "...closely approximates a given percentile level of the human body in size, form, segment mobility, total weight, segment weight, (and) weight distribution."

**Even with the mean values there is a minor problem: mean values for indices and shape variables are not as a rule equal to the indices computed from the mean values of the dimensions, but the differences are usually trivial. For example, the mean value for the sitting height/stature ratio (AFW '68 data) is 52.82%; the ratio of mean sitting height (85.60 cm) to mean stature (162.10 cm) is 52.81%.

TABLE 11

FIFTH PERCENTILES, MEANS AND NINETY-FIFTH PERCENTILES FOR STATURE SEGMENTS

(Based on Clauser et al., 1972)



	Stature Segment	5%ile	Mean	95%ile
A	Cervicale Level to Vertex	20.8	22.91	25.1
B	Suprasternale Level to Cervicale Level	5.1	7.19	9.4
C	Acromial Level to Suprasternale Level	- 2.1	0.14	2.4
D	Bustpoint Level to Acromial Level	10.4	13.54	16.8
E	Waist Level to Bustpoint Level	14.3	18.04	21.9
F	Abdominal Extension Level to Waist Level	4.9	7.13	9.7
G	Trochanteric Level to Abdominal Ext. Level	7.1	10.48	13.6
H	Buttock Level to Trochanteric Level	- 2.8	0.46	3.9
I	Crotch Level to Buttock Level	4.7	7.71	10.5
J	Gluteal Furrow Level to Crotch	- 1.3	1.80	5.1
K	Tibiale Level to Gluteal Furrow Level	26.7	30.72	34.8
L	Ankle Level to Tibiale Level	27.4	30.80	34.4
M	Lateral Malleolus Level to Ankle Level	2.4	4.41	6.8
N	Floor to Lateral Malleolus	5.8	6.77	7.8
O	TOTALS	123.4	162.10	202.2
		(48.6")	(63.8")	(79.6")

This, however, is not the case if we consider percentile values other than the 50th. Except for the 50th percentile, no percentile man can possibly exist. The essence of the problem with other "percentile men", the 5th, 95th, and so forth, is that, as illustrated in Table 10, percentiles (other than the 50th) for segments do not add to the corresponding percentile for the sum of the parts. A set of segments, all 5th percentile, will add to less than the 5th percentile for the total; the 95th percentiles of the segments will, in turn, exceed the 95th percentile of the total. The problem is not that a man cannot be 5th percentile in crotch height and sitting height but that if he is, he isn't 5th percentile in stature. In Table 10, we note that the sum of the 5th percentiles for waist height (36.6") and waist level to vertex (22.7") is 59.3". This sum is 0.7" less than the 5th percentile for stature and approximately equal to stature's 2nd percentile. Similarly the two 95th percentiles add to 68.6", a value close to the 98th percentile for stature.

The exact way in which these percentiles have been computed has nothing to do with the heart of the problem nor has our choice of the 5th and the 95th percentiles. We can change our approach slightly and use values of the mean minus 1.65 standard deviations to define our 5th percentile man and values of the mean plus 1.65 standard deviations for the 95th percentile man. But such a change changes little or nothing, as the last two columns of Table 10 show. Just as the percentiles of the parts don't add to the corresponding percentile of the whole, the standard deviations of the parts--here they are 1.77" for waist height, and 1.04" for waist level to vertex--don't add to the standard deviation of the whole--2.36" for stature. The man who is 1.65 standard deviations above average on these two segments of stature simply does not end up 1.65 standard deviations above average in stature.

When we divide stature into more than two segments, the differences are even larger. In Table 11, are the 5th and 95th percentiles and mean values for 14 vertical distances which together constitute stature computed on the same 1968 Air Force Women's data. As was to be expected, the mean values for these segments add exactly to the mean value for stature (162.10 cm or 63.8"); the sums of the percentiles, on the other hand, differ drastically from the corresponding percentiles for stature. The sum of the 5th percentiles is a tiny 48.6"--almost a full foot less than the 5th percentile for stature and about 8" less than the height of the shortest woman measured in the AFW '68 survey. Similarly, the sum of the 95th percentiles, 79.6", is almost a foot above the 95th percentile and about 8" more than the height of the tallest survey subject.

These results are not unique to our choice of illustrative data. Rather they are a direct consequence of the fact that the standard deviation of a sum is given by the formula:*

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*This formula is similar to the one for the length of the 3rd side of a triangle with r being related to the angle between the two known sides; the 3rd side is always less than the sum of the other two except in the abnormal case in which the triangle degenerates into a line segment.

$$SD_{x+y} = \sqrt{(SD_x)^2 + 2r\, SD_x SD_y + (SD_y)^2}$$

where r is the correlation coefficient for X and Y. Only if r = 1.00 will $SD_{x+y} = SD_x + SD_y$, otherwise the standard deviation of the sum is less than the sum of the standard deviations of the parts. Since, in practice, the correlation coefficient is always less than 1.00, the results will be similar to our illustrative case. The formula for the sum of three or more parts is similar to that for two parts; the standard deviation of the total will be equal to the sum of the separate standard deviations only if all the relevant correlation coefficients are equal to 1.00.

Not only don't percentile values for a set of linear segments add to the percentile value of the total, but the percentile values for interrelated dimensions in a cross section of the body do not as a rule mesh together and can lead to distorted shapes. Cross section areas of normal shape based on 95th percentile breadths and depths will as a rule exceed the 95th percentile in area; a man consistently 95th percentile in breadths, depths, and heights will unquestionably be abnormally heavy, a man consistently 5th percentile abnormally light.

An analysis of the problems of achieving percentile values for "form" will be omitted here, in part because most statistical measures of form yield ambiguous definitions of large and small. It is not unusual that an individual could be both 5th percentile and 95th percentile on the basis of logically equivalent definitions of the same shape measure. For example, a USAF woman with a head breadth of 6" and a head length of 7" is about 95th percentile on the head breadth-head length (cephalic) index; she is also about 5th percentile on the head length-head breadth index. Traditionally, it is true, anthropologists have divided head breadth by head length, but this practice is quite arbitrary.

This non-existence of all percentile men except the 50th is a problem relating basically to anthropometric dummies and coordinated body forms. Exceedingly useful "large" test dummies, "small" head forms, and the like can, of course, be constructed. The design of such dummies and forms, however, will have to be based on a perceptive awareness of the way the multiplicity of body dimensions interrelate and the statistical principles which describe these relationships. It is, in addition, highly likely that there will need to be an awareness that there are many "types" of large men, and that, for different uses, body forms will need to be based on different designs. Some of the matters relevant to this problem are discussed by McConville and Churchill (1976).

The design of equipment which must accommodate big men or small men is quite different from attempting to create a body form which corresponds to equivalent percentile values in all dimensions. No theoretical limitations usually exist to rule out designs which will simultaneously accommodate men who are 95th percentile in one dimension, others who are 95th percentile in a second dimension, and still others who are 95th percentile in a third dimension. Such designs require only the proper anthropometric data and, all too often, considerable amounts of insight and ingenuity.

The Monte Carlo Method

Some statistical problems which are awkward to solve directly can be tackled by what has come to be known as the Monte Carlo Method. While it has rarely been used in dealing with anthropometric data, we conclude this chapter with a brief description and illustration of this method in the hope that its potential value in helping with design problems will not be ignored.

The typical Monte Carlo type problem is one which asks the question: If we do something by some random method, what are the probabilities of some particular set of outcomes? The essence of the method is to actually "do" the same thing a great many times, usually with the aid of random numbers and a computer, and observe the outcomes. The relative frequency of each outcome is then considered as an approximation to its probability. Such an approach can be used with problems so complex that few alternative approaches exist; it is also a practical solution to many less complex problems for which feasible, but laborious or time consuming alternatives, are available.

As an illustration of the Monte Carlo method, we consider a problem of picking crews consisting of five members each. The members of each crew are to be selected randomly from a population similar to the USAF 1967 flying personnel group with the restriction that no man over 5'8" tall or weighing more than 165 lbs will be accepted. The questions to be answered are:

(1) What is the distribution of total crew weights? and
(2) What is the distribution of the maximum stature in each crew?

To answer these questions, the statures and weights of the 2,420 subjects in the 1967 survey sample were stored in the computer. By the use of random numbers, subjects were selected until five satisfying the height and weight limitations were obtained. The total weight of these men was then computed and the height of the tallest man noted. The process was continued until samples of 100, 200, 500, and 1,000 "crews" were obtained. The results are summarized in Tables 12 and 13.

In using this method, we presumably select samples until the results show a stable pattern. The entries in Tables 12 and 13 for 1,000 trials are not very different from those for 500 trials. In fact, the general distribution suggested by the results of 100 trials is rather similar to that for 1,000. Median values, for example, for total crew weight and maximum stature, are about 752 pounds and 172.1 cm (67.8") for each number of trials.

The procedure just described was based on using actual survey data, but the availability of these data is not essential. We could have had recourse once again to the bivariate normal distribution as a mathematical model for the statures and weights, constructed an approximation to the stature-weight distribution,* and sampled it just as we sampled the actual

*This could be done in a variety of ways. One method, for example, could be based on the artificial bivariate program. A second method could be based on repeated selection of pairs of uncorrelated, normally distributed, random

TABLE 12
DISTRIBUTION OF WEIGHTS OF FIVE-MAN CREWS*

Weight (lb)	NO. OF TRIALS 100	200	500	1000
800 & up		0.5%	1.2%	1.0%
790 & up	2.0%	2.5%	3.6%	3.4%
780 & up	12.0%	11.5%	12.2%	11.6%
770 & up	22.0%	21.0%	22.0%	20.5%
760 & up	42.0%	39.5%	40.2%	35.9%
750 & up	55.0%	55.0%	55.4%	53.7%
740 & up	67.0%	67.0%	67.4%	68.3%
730 & up	78.0%	78.5%	79.2%	80.3%
720 & up	84.0%	85.5%	87.4%	88.9%
710 & up	87.0%	91.0%	93.6%	94.2%
700 & up	91.0%	94.5%	96.8%	97.3%
690 & up	97.0%	99.0%	99.2%	99.5%
680 & up	98.0%	99.5%	99.6%	99.8%

* See text for method of selection.

TABLE 13
DISTRIBUTION OF MAXIMUM STATURES OF FIVE-MAN CREWS*

Stature (cm)	NO. OF TRIALS 100	200	500	1000
172.6 & up	15.0%	12.5%	10.2%	10.0%
172.4 & up	30.0%	30.0%	28.8%	27.1%
172.2 & up	48.0%	50.0%	46.0%	44.2%
172.0 & up	68.0%	67.5%	63.8%	61.3%
171.8 & up	75.0%	75.5%	73.8%	73.2%
171.6 & up	80.0%	79.5%	79.0%	79.4%
171.4 & up	88.0%	87.5%	85.2%	84.3%
171.2 & up	88.0%	88.5%	86.4%	86.2%
171.0 & up	92.0%	92.0%	90.2%	89.9%
170.8 & up	94.0%	94.0%	92.4%	92.5%
170.6 & up	94.0%	94.5%	93.6%	94.0%
170.4 & up	97.0%	96.5%	95.6%	96.2%
170.2 & up	97.0%	97.0%	96.6%	97.3%

* See text for method of selection.

distribution. To do this, only the means and standard deviations plus the correlation coefficient are needed.

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numbers, X_1 and X_2 and then setting: stature = X_1 and weight = $(X_2 - rX_1)/\sqrt{1-r^2}$, where stature and weight are interpreted as being in standard deviation units, and r is the correlation coefficient.

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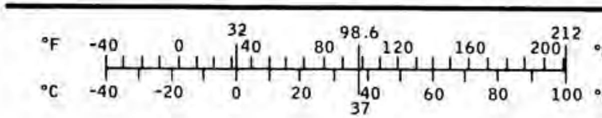
METRIC CONVERSION FACTORS

Approximate conversions to metric measures

Symbol	When you know	Multiply by	To find	Symbol
		LENGTH		
in.	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate conversions from metric measures

Symbol	When you know	Multiply by	To find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in.
cm	centimeters	0.4	inches	in.
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10 000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.036	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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5. Supplementary Notes

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and original units are written parenthetically thereafter. The physiological pressure unit used, mm Hg, has not been supplemented with an SI equivalent because of its universal usage in the biomedical field.

6. Abstract

This three-volume publication brings together a large mass of anthropometric data which define the physical size, mass distribution properties, and dynamic capabilities of U.S. and selected foreign adult populations. Aimed specifically to meet the needs of design engineers engaged in the design and execution of clothing, equipment, and workspaces for the NASA Space Shuttle Program, the book is also designed to be of use to human engineers in a wide variety of fields. It is not only a comprehensive source of specific anthropometric information but also a guide to the effective applications of such data. Subjects covered in Volume I include physical changes in the zero-g environment, variability in body size, mass distribution properties of the human body, arm and leg reach, joint motion, strength, sizing and design of clothing and workspaces, and statistical guidelines. Material presented includes such unpublished anthropometric data measured under one-g and zero-g conditions. Also included are 1985 body size projections and actual cutouts of quarter-scale two-dimensional manikins for use by designers.

Volume II contains data resulting from surveys of 61 military and civilian populations of both sexes from the U.S., Europe, and Asia. Some 295 measured variables are defined and illustrated.

Volume III is an annotated bibliography covering a broad spectrum of topics relevant to applied physical anthropology with emphasis on anthropometry and its applications in sizing and design.

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