

CHAPTER VIII ANTHROPOMETRY IN SIZING AND DESIGN

by
John T. McConville
Anthropology Research Project
Webb Associates

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"

<u>Variable</u>	<u>Range Defining Average (cm)</u>	<u>No. Included</u>	<u>Percent of Sample</u>
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 range 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.

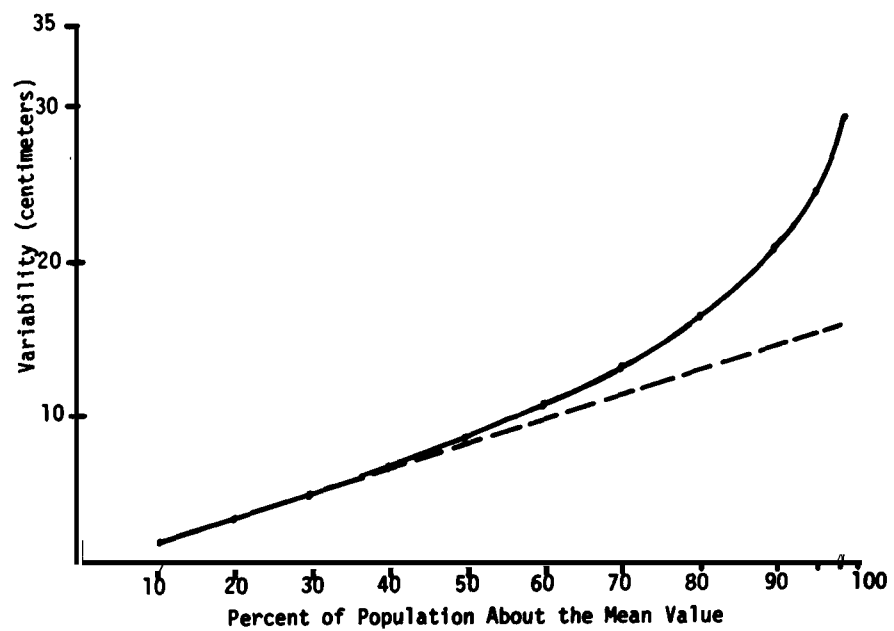


Figure 1. Stature variability by percentile groups.

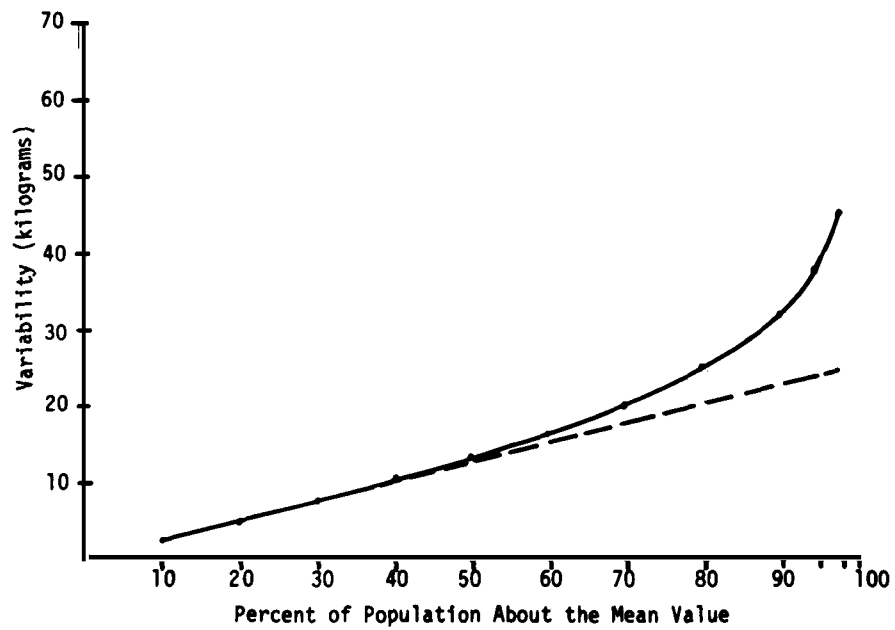


Figure 2. Weight variability by percentile groups.

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 accommodate 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

<u>Size</u>	<u>Weight Range (lbs.)</u>	<u>Height Range (in.)</u>
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)																								Totals																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
	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																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
227 - 232										1	1		1	2	1	2	1	1																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									

Weight (Pounds)

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 ± 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 dimensional 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 Data

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 aircrewmembers. The data show that the mean sitting eye height for aircrewmembers 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.

REFERENCES

- Alexander, Milton, L. L. Laubach, and J. T. McConville 1976. Effect of Encumbering Clothing, Personal Protective Equipment and Restraints on Body Size and Arm Reach Capability of USAF Aircrewmembers. Preprint of the 1976 Aerospace/Medical Assoc. Annual Meeting, Bal Harbor, Fla.
- Barter, J. T., and Milton Alexander 1956. A Sizing System for High Altitude Gloves. WADC-TR-56-599, Aero Medical Laboratory, Wright-Patterson Air Force Base, Ohio.
- Clauser, Charles E., Pearl E. Tucker, Joan A. Reardon, John T. McConville, et al. 1972. Anthropometry of Air Force Women. AMRL-TR-70-5, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.
- Cressman, P. W. 1972. Anthropometric Survey of COH58A 'Kiowa' Helicopter. Technical Memo No. 879, Defense and Civil Institute of Environmental Medicine, Dept. of Defense, Downsview, Canada.
- Daniels, Gilbert S., and Edmund Churchill 1952. The "Average Man"? Technical Note WCRD TN 53-7, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.
- Emanuel, Irvin, Milton Alexander, Edmund Churchill, and Bruce Truett 1959. A Height-Weight Sizing System for Flight Clothing. WADC-TR-56365, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.
- Hertzberg, H. T. E., G. S. Daniels, and Edmund Churchill 1954. Anthropometry of Flying Personnel - 1950. WADC-TR-52-321, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.
- Hertzberg, H. T. E. 1969. "The Anthropology of Anthropomorphic Dummies (Anthropology of Anthropomorphic Crash Dummies for Use in Vehicle Crash Tests)," Proceedings of the Thirteenth Stapp Car Conference, Boston; also published as AMRL-TR-69-61, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.
- Kennedy, K. W. 1976. Estimating Relaxed Tolerance to +G's Acceleration Through the Use of Drawing Board Manikins. Preprints of the 1976 Aerospace Medical Assoc. Meeting, Bal Harbor, Fla.
- Kroemer, K. H. Eberhard 1972. COMBIMAN - Computerized Biomechanical Man Model. AMRL-TR-72-16, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.
- McConville, John T., and Milton Alexander 1975. "Anthropometric Sizing Program for Oral-Nasal Oxygen Masks Based on 1967 U.S. Air Force Survey Data," Aviation, Space, and Environmental Medicine, 46(11):1383-1389.

- McConville, John T., and Edmund Churchill 1976. Statistical Concepts in Design. AMRL-TR-76-29, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.
- McDaniel, J. W. 1976. "Computerized Biomechanical Man-Model," Proceedings of the 6th Congress of the Int. Ergonomics Assn., College Park, Md., pp. 384-389.
- Randall, Francis E., Albert Damon, Robert S. Benton, and Donald I. Patt 1946. Human Body Size in Military Aircraft and Personal Equipment. AAF-TR-5501, Army Air Force, Wright Field, Dayton Ohio.
- Roebuck, J. A., Jr., K. H. E. Kroemer, and W. G. Thomson 1975. Engineering Anthropometry Methods, John Wiley and Sons (New York, N.Y.).
- Searle, J. A., and C. M. Haslegrave 1969. "Anthropometric Dummies for Crash Research," MIRA Bulletin (Motor Industry Research Assoc., England), 5:25-30.
- Searle, J. A., and C. M. Haslegrave 1970. "Reply by the Authors of the Original Article," MIRA Bulletin (Motor Industry Research Assoc., England), 4:20-21.

BIBLIOGRAPHY

- Alexander, Milton, R. S. Zeigen, and Irvin Emanuel 1961. "Anthropometric Data Presented in Three-Dimensional Forms," Amer. J. Phys. Anthrop., 19(2):147-157.
- McConville, John T., Milton Alexander, and Seth M. Velsey 1963. Anthropometric Data in Three-Dimensional Form: USAF Height-Weight Sizing Manikins. AMRL-TDR-63-55, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.
- Zeigen, Robert S., Milton Alexander, and Edmund Churchill 1960. A Head Circumference Sizing System for Helmet Design: Including Three-Dimensional Presentation of Anthropometric Data. WADD-TR-60-631, Wright Air Development Division, Wright-Patterson Air Force Base, Ohio.

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.

- Carlyle, L. 1960. Man and Space. Engineering Paper No. 899, Douglas Aircraft Co., Los Angeles, Calif.

Kennedy, K. W. 1975. New USAF Drawing Board Manikins for Crew Station Design. Preprint of the 1975 Aerospace Medical Assn. Meeting, San Francisco, Calif.