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A MULTIVARIATE ANTHROPOMETRIC METHOD FOR CREW STATION DESIGN: ABRIDGED (U)

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One of the roots of this problem is the way cockpit accommodation is specified and tested. For many years the percentile pilot has been used. This paper describes the errors inherent in the "percentile man" approach, and presents a multivariate alternative for describing the body size variability existing in a given flying population. A number of body size "representative cases" are calculated which, when used properly in specifying, designing, and testing new aircraft, should ensure the desired level of accommodation.

The approach can be adapted to provide anthropometric descriptions of body size variability for a great many designs or for computer models of the human body by altering the measurements of interest and/or selecting different data sets describing the anthropometry of a user population.

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PREFACE

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Thanks go also to Ilse Tebbetts and Jennifer Schinhofen of ARP for editing this report and producing the final camera-ready copy.

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SUMMARY

Body size accommodation in USAF cockpits is still a significant problem despite all the years of experience and the many aircraft designs that have been developed. Adequate reach to controls, body clearances (particularly during escape), and vision (internal and external), are all functions of pilot body size and position in the cockpit.

One of the roots of this problem is the way cockpit accommodation is specified and tested. For many years the percentile pilot has been used. This paper describes the errors inherent in the "percentile man" approach, and presents a multivariate alternative for describing the body size variability existing in a given flying population. A number of body size "representative cases" are calculated which, when used properly in specifying, designing, and testing new aircraft, should ensure the desired level of accommodation.

The approach can be adapted to provide anthropometric descriptions of body size variablity for a great many designs or for computer models of the human body by altering the measurements of interest and/or selecting different data sets describing the anthropometry of a user population.

A MULTIVARIATE ANTHROPOMETRIC METHOD FOR CREW STATION DESIGN: ABRIDGED

INTRODUCTION

Military personnel of every size and shape must be able to operate complex equipment safely, effectively, and comfortably. Personnel charged with the specification and procurement of complex workstations and personal protective equipment are continually challenged by the need to accommodate and fit very large numbers of an increasingly heterogeneous population. In writing specifications, the goal is to ensure that the body size and proportions of most of the population will be accommodated in each item or system to be procured. Traditionally, this has been done by using percentiles to specify the portion of the population that must be accommodated. Typically, specifications read: "the system shall be designed to allow safe operation by the fifth percentile female pilot through the ninety-fifth percentile male pilot." What is not specified is how the 5th and 95th percentile pilots are defined.

The purpose of this report is to point out the drawbacks inherent in the percentile approach, and to present a more suitable method for describing variability in body size. The proposed method is based on the pioneering work of Bittner et al. (1986). For a detailed statistical description of the technique, see Meindl et al. (in press).

Percentiles

A percentile is a very simple statistic. It shows the relative ranking of a given individual for a single measurement and is expressed in terms of the percentage of people who are smaller than that individual for that measure. For example, the distribution for the body dimension, Stature, in the 1967 anthropometric survey of USAF personnel (Kennedy 1986) is shown in Figure 1. The fifth percentile value indicated on the figure is 65.8 inches. This means simply that 5 percent of this population is shorter than 65.8 inches, and 95 percent of the same population is taller. Two limitations of the percentile approach are immediately apparent. First, percentiles are only relevant for one dimension at a time (univariate), and second, they are specific to the population for which they are calculated.

Secondly, while a 5th percentile Stature value can be accurately located, that value tells us little or nothing about the variability of *other* body dimensions of individuals with 5th percentile Stature. Consider Weight, for example. Individuals of 5th percentile Stature in the 1967 survey ranged from 125 lbs. (less than 1st percentile Weight) to 186 lbs. (74th percentile Weight). A logical next step is to consider the fifth percentile for both measures. It is common for people to assume that the 5th percentile for both Stature and Weight represents a "5th percentile" person. In fact, only 1.3 percent of subjects in the 1967 survey were smaller than the 5th percentile for *both* measures, while 9% were smaller for one *or* the other. The problem is compounded with each additional measurement used to specify the size of a USAF individual. Thus, at worst, use of percentiles can mean that workspaces or equipment are not suitable for anyone. At best, the use of percentiles will mean that the percentage of a given population that can be accommodated is unknown.

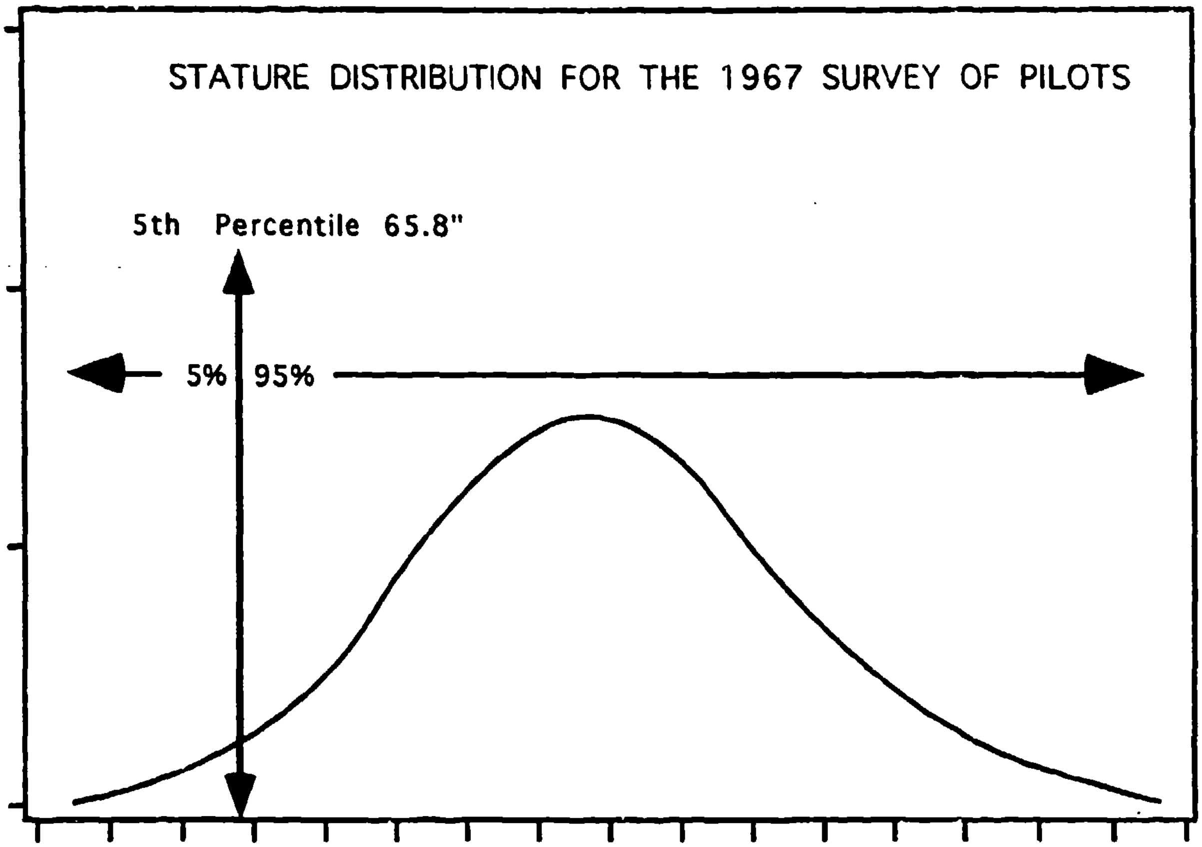


FIGURE 1

Normal Distribution For Stature: 1967 USAF Survey

The pitfalls attendant upon the use of multiple percentiles can be illustrated by considering the body dimensions critical to cockpit design. Dimensions traditionally used to describe body size variability for cockpit layout include Sitting Height, Shoulder Breadth, Buttock-Knee Length, Knee Height Sitting, and Functional Reach. Generally a group of measures such as this is listed in a specification or standard along with 5th and 95th percentile values for each. This gives the impression that if these values are used as design criteria, 90% of the population will be accommodated. This is not the case as can be clearly seen in Figure 2. Since disaccommodation on any one of these measures is a potential source of difficulty in operating or escaping the aircraft, the group of measurements must be considered simultaneously to determine the percentage of the population which will be described by the measurement values. There is no difficulty in identifying the individuals who constitute 90% of the population in Sitting Height. However, as shown in Figure 2, when those same individuals are screened for 5th-95th percentile Buttock-Knee Length values, their numbers drop. With application of each additional cockpit dimension, the group diminishes until, finally, it represents only 67% of the population. In other words, as many as 33% of a given population could experience difficulty operating in a workspace or fitting into an item of equipment that fully met specifications.

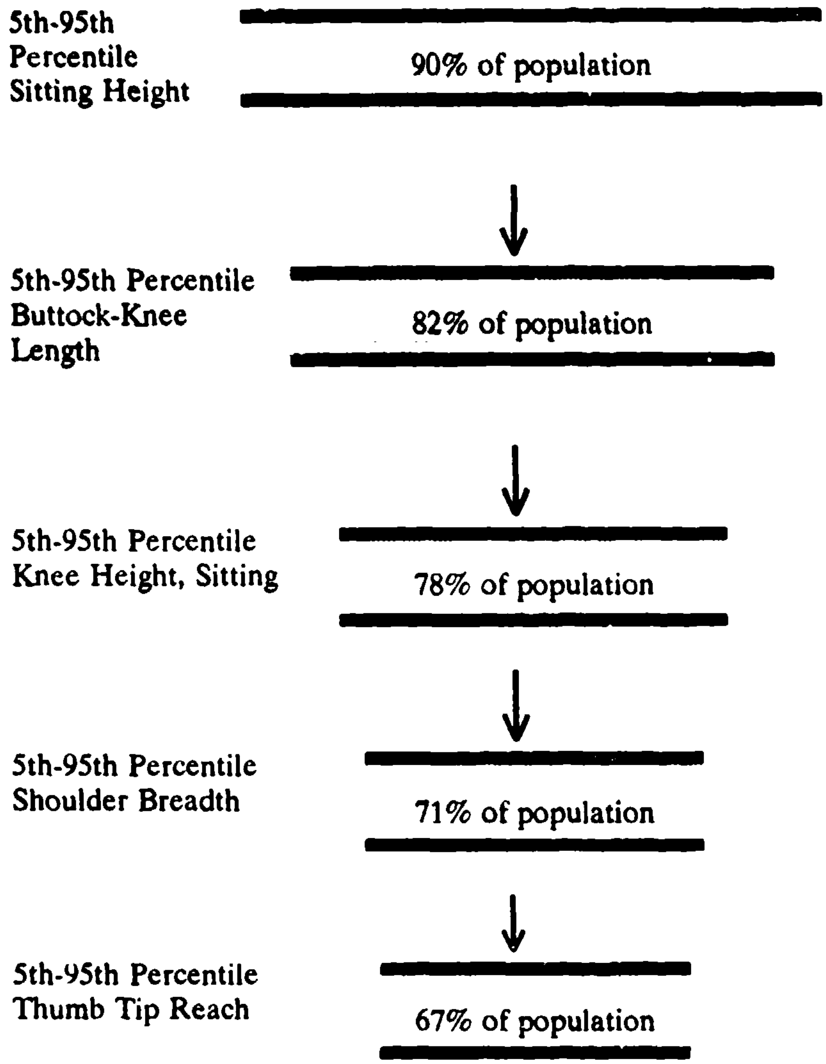
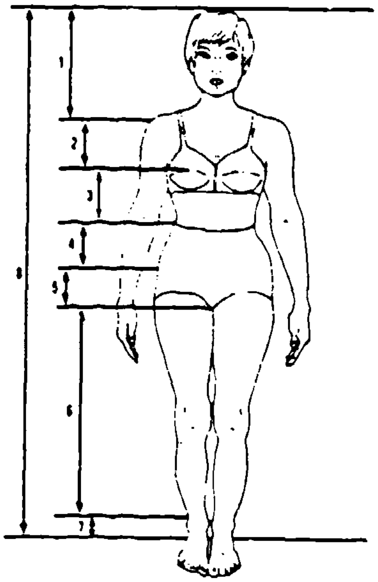


FIGURE 2

Diminution of Population Coverage with Successive Screening for 5th-95th Percentile Values of Selected Dimensions: 1967 USAF Survey Data

The use of a single percentile to represent multiple body measurements presents still another problem: the values are not additive. That is, they could not be assembled into a real person. The problem is illustrated in Figure 3. In a study by Robinette and McConville (1981), Stature was divided into seven component measurements, and the 5th percentile value for each measurement calculated. When summed, the result was not only smaller than the 5th percentile Stature value for that sample, but smaller than the smallest person in the sample of 3235 individuals. A similar result occurred when 95th percentile values were tried. In that case the sum of the parts was 5 cm larger than the tallest woman measured in the sample. In sum, using data of this type can result in a design which is much smaller (or larger) than necessary to accommodate the desired percentage of the population. This problem is particularly apparent when trying to use anthropometric data to develop human body models.



Var. No.	Variable Name	5th%ile	95th%ile
1	Shoulder to Vertex	27.05	32.79
2	Bust to Shoulder	10.79	17.77
3	Waist to Bust	13.42	21.78
4	Buttock to Waist	13.78	21.67
5	Crotch to Buttock	4.78	10.42
6	Ankle to Crotch	57.84	71.09
7	Ankle Height	9.23	13.29
	TOTAL	136.89	188.81
8	Stature	152.50	173.06

Total sample size=3235
All values are in centimeters

FIGURE 3

Assembling 5th and 95th Percentile Values
(Robinette and McConville, 1981)

Regression Equations

One method which has been used to approximate a percentile person while avoiding some of the pitfalls noted above, is regression analysis. This approach has been particularly useful in constructing crash test dummies. It begins with one or two "key dimensions" such as Stature and Weight, and predicts values for a number of other measurements statistically. In practice, this approach provides the average value for those other measurements for an individual of the entered Stature and Weight. The chief advantage of the regression approach is that the predicted numbers are additive. That is, if one were to use Stature and Weight in a regression equation to predict the seven derived variables shown in Figure 3, the resulting values would add up to exactly the value of Stature. The drawback to the regression approach is that it provides average values for the predicted measurements. In any population there are people who are much larger or smaller than the predicted body size for a number of measurements *other* than Stature and Weight. The difficulty is illustrated in the following exercise based on data from the 1967 USAF survey:

Ninety-fifth percentile Stature (74.3 in) and Weight (215.9 lbs) were used to predict two other dimensions: Sitting Height and Head Length. The regression method resulted in a predicted Sitting Height of 38.6 in. This value ranks at the 93rd percentile for that population -- fairly close to the desired 95th percentile. However, the predicted value for Head Length of a person of this Stature and Weight ranks at the 66th percentile. The discrepancy here is a function of the correlation between the key dimensions and the predicted dimensions. Between them, Stature and Weight account for a large amount of the variability in the population for Sitting Height. In other words, a tall and heavy subject in the 1967 survey, was very likely to have a large Sitting Height value. On the other hand, Stature and Weight have little to do with the length of the head, and the resulting prediction for that measurement ranks closer to the average for the population. Obviously, if a very large head is required, regression from Stature and Weight will not suffice.

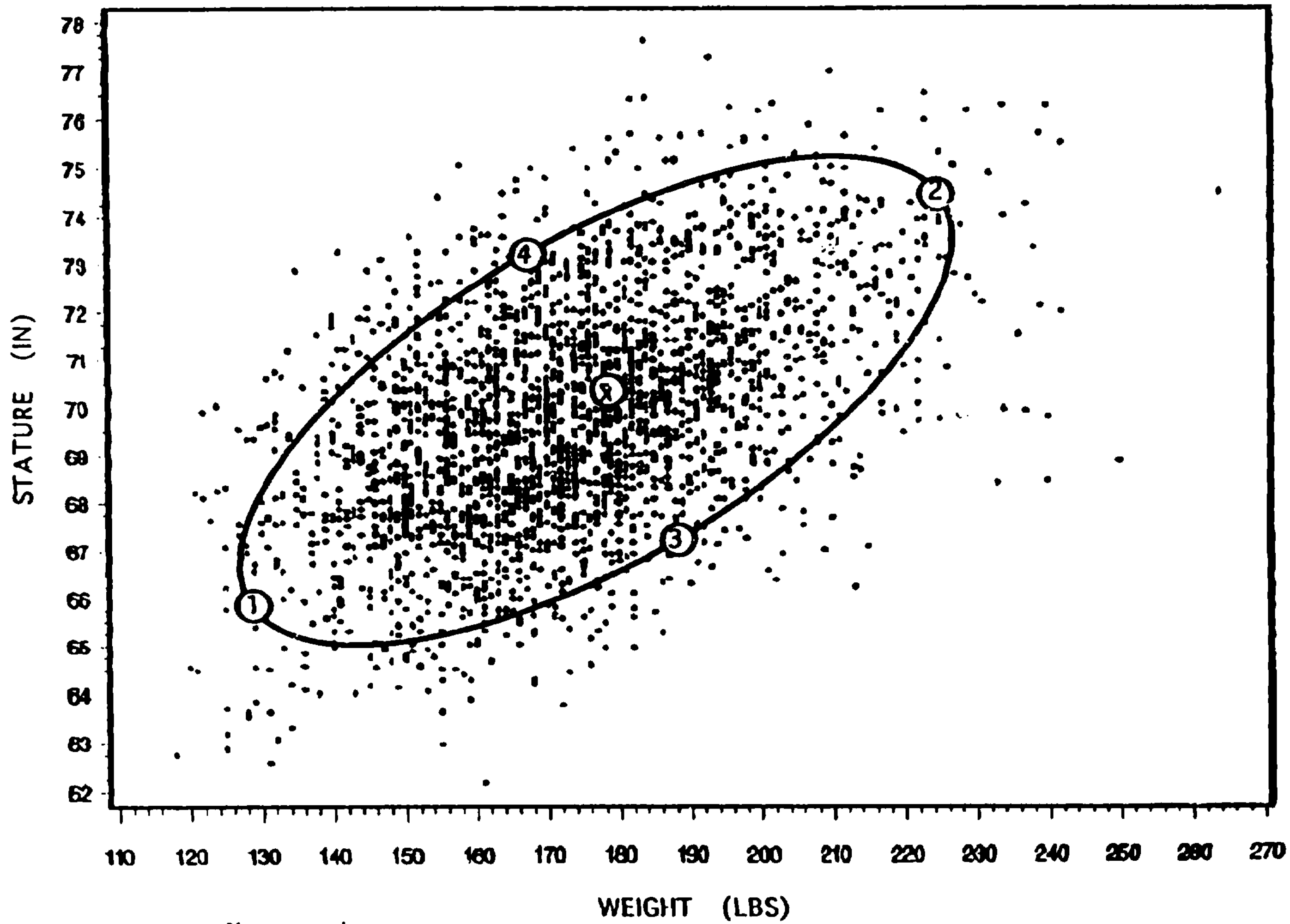
Thus, while the use of regression predictions provides additive values which can be assembled, the results may not be as uniformly extreme as are usually desired when the intention is to look at the ends of the body size distribution. Furthermore, in practical application, neither the percentile method nor the regression approach takes into account the fact that humans manifest considerable variation in their *combinations* of dimensions -- that is, that there are numbers of individuals who combine short torsos with long limbs or tall heavy bodies with small heads. In the case of three-dimensional crash dummies the regression method of arriving at appropriate body part sizes may be the only feasible approach, but its limitations are apparent. Because of prohibitive costs, only two such dummies are typically used -- a "large" one and a "small" one. However, the reaction of a dummy required for testing an ejection system may be quite different depending on the size of various body segments. In assessing potential neck injury due to rapid acceleration with torso restraints, for example, the response of a small dummy with a large head and a small dummy with a small head may be dramatically different. Center of mass and inertial properties of a body in an ejection seat may also vary widely with variations in torso and limb combinations.

THE MULTIVARIATE ACCOMMODATION METHOD

The multivariate accommodation method is an alternative to the percentile and regression methods described above. It corrects the deficiencies of both while retaining the concept of accommodating a specific percentage of the population in the design. Briefly, the multivariate accommodation method is based on principal component analysis, which reduces a list of variables to a small manageable number, and then enables designers to select the desired percentage level of a population to be accommodated. This percentage level is accommodated in a way which takes into account not only size variance but proportional variability as well -- i.e. not only individuals who are uniformly large or small, but those whose measurements combine, for example, small torsos with long limbs, or vice versa. As noted, the method is a simplification of a technique developed by Bittner et al. (1986).

A number of examples of the approach are given below, beginning with a very simple two-measurement example, building to a basic cockpit layout, and concluding with a fairly complex 11-variable computer man-model.

A bivariate distribution (Figure 4) is analogous to the univariate distribution curve shown in Figure 1. The difference is that in a bivariate two measurements are plotted simultaneously. In this example the distribution of Stature in the 1967 USAF flyers survey is plotted on the vertical axis, while Weight is plotted on the horizontal axis. Each individual pilot is plotted at the point where his Stature and Weight intersect. Using the mean value for both Stature and Weight as a starting point (X), an ellipse can be imposed on the plot which includes any desired percentage of the population. The 90% ellipse in Figure 4 passes near points (1 and 2) that are similar to the 5th and 95th percentile pilot concept. That is, they represent pilots who are small or large for both values. However, since selecting only the individuals who are small or large for both Stature and Weight does not describe all the variability in body size that must be considered in a design, the ellipse also intersects those points representing a tall-thin person (4) and a short heavy person (3) who are just as likely to occur in the population as any other individual along the perimeter of the circle. The multivariate accommodation



X = mean value
1 = Small Stature - Small Weight
2 = Large Stature - Large Weight
3 = Small Stature - Large Weight
4 = Large Stature - Small Weight

FIGURE 4

Stature/Weight Bivariate for 1967 USAF Survey:
90% Accommodation Model

approach would select at least four points, subsequently called *representative cases*, along the perimeter of the ellipse and use them to describe size variability. The rationale is that several individuals spread along the edge of an ellipse better represent the variety of extreme body types that must be accommodated than does the use of only two points in the distribution.

In the design of a workstation, of course, more than two variables are needed to ensure the proper accommodation of an individual and his or her equipment. Obviously, the bivariate approach will be inadequate as soon as a third body size variable such as head volume is considered. The two-dimensional problem shown above now becomes a three-dimensional one, the ellipse becomes an ellipsoid, and more than four *representative cases* (points on the surface of the ellipsoid) are necessary to describe the various combinations of these measures. That is, it now becomes necessary to describe tall heavy pilots with large heads, tall heavy pilots with small heads, etc.. As each additional measurement is added to the design, an additional dimension or level of complexity is added to the analysis with the accompanying geometrical expansion of the number of *representative cases* which must be considered in the design. Clearly the problem becomes unworkable very quickly.

Principal component analysis is a statistical approach which helps get around this problem. It is a data reduction procedure which reduces the number of measurements needed to describe body size variability by combining a large number of related measurements into a smaller set of factors or components based on their correlation or co-variance. For the purpose of constructing accommodation ellipses like that shown in Figure 4, each factor can be considered one "measurement." Standardized scores (Z scores) for each individual in the population are calculated for each factor. This procedure turns the ellipses into circles and the ellipsoids into spheres.

For most cockpit and workstation designs the total number of relevant measures can be reduced to two or three factors. This means that a bivariate circle or tri-variate sphere can be used to define population limits and identify the *representative cases*. The results can be graphically demonstrated. The following example uses six cockpit-related variables to demonstrate the approach. A 99.5% accommodation circle is described for the Air Force flying population based on anthropometric data gathered in the 1960's.

Cockpit Accommodation

There is a great deal of historical evidence describing typical body size accommodation problems encountered in the cockpit. Such difficulties include the pilot's inability to reach controls (both arm and leg reaches), inadequate clearance for ejection, inadequate external visibility due to eye position in the cockpit, inability to assume the very erect posture required for ejection due to inadequate overhead clearance, and finally, a generalized lack of mobility.

If these problems are to be avoided, cockpit designers must take into account human variability in a number of dimensions. Six of these so-called cockpit dimensions are critical: Sitting Height, Eye Height Sitting, Shoulder Height Sitting, Thumbtip Reach, Buttock-Knee Length, and Popliteal Height Sitting. While many other measurements could arguably be included, most are simple clearance dimensions which can be dealt with in terms of minimum and maximum values. The six measurements cited above, however, *must* be considered in varying combinations. It is important, for example, to consider the accommodation problems of an individual with a very short Sitting Height who also has very long legs. This individual would adjust the ejection seat to maximum height to attain proper over-the-nose vision, but would also adjust the rudder carriage full forward to accommodate the long legs. This configuration may bring the knee/shin close enough to the bottom edge of the instrument panel to create the potential for an ejection injury. In aircraft with a yoke (steering wheel), this configuration reduces the vertical distance between the seat and the bottom edge of the wheel, thus increasing the likelihood of interference problems, particularly during cross-control maneuvers.

The position of the pilot's shoulder is also important in locating controls. Imagine two individuals with equally short arms but markedly different Shoulder Height Sitting values. Their ability to reach down to a control on a side panel, or to an overhead control, will differ considerably. Considering only one "small" individual would not take this type of variability into account.

The Multivariate Accommodation Models program, which provides data to help designers treat critical body size dimensions as an interlocking set, is available to government researchers and contractors through the Center for Anthropometric Research Data (CARD) data base. The data base is described in AL-TR-1992-0036 (Robinson et al. 1992). The program allows users to select data relevant to their design problems from available military anthropometric surveys and measurements, and to choose from among a number of population accommodation percentages for determining the design limits. The statistical output of the program has been limited to data considered essential to the analysis, but a great deal more information can be printed out on request. Listed below is the output from an analysis using the six measurements cited above and the 1967 anthropometric survey data.

The first portion of the printout (Table 1) describes simple summary statistics for those measurements in that sample.

TABLE 1

Summary Statistics for Selected Cockpit Dimensions: 1967 USAF Survey
(values in inches)

Variable	Mean	Standard Deviation
Thumb Tip Reach	31.612	1.567
Buttock-Knee Length	23.776	1.064
Popliteal Height Sitting	17.200	0.885
Sitting Height	36.682	1.251
Eye Height Sitting	31.865	1.188
Shoulder Height Sitting	24.031	1.126

Table 2 displays the factor correlation matrix for the two components which, analysis shows, account for most of the variation among these variables. The data in Table 2 are given in terms of correlation coefficients. (A value of 1.0 indicates a perfect correlation.) Notice that on Table 2, all the values of Factor I are relatively high positive values of about the same magnitude. Thus, Factor I, as is often the case, is a good predictor of general overall body size.

TABLE 2

Two-Component Factor Correlation Matrix

Variable	Factor I	Factor II
Thumb Tip Reach	0.69451	0.51817
Buttock-Knee Length	0.69608	0.51063
Popliteal Height Sitting	0.74656	0.46231
Sitting Height	0.88639	-0.39995
Eye Height Sitting	0.86122	-0.41069
Shoulder Height Sitting	0.80865	-0.43561

The second factor, on the other hand, shows a marked contrast between the first three measures and the second three. The values are positive for the three limb dimensions and negative for the three torso dimensions. This contrast allows individuals to be ranked or classified based upon the relative sizes of these two body components and is the basis for discriminating between individuals with varying body proportions.

The program establishes eight *representative cases* when two factors are selected. Figure 5 is a bivariate distribution showing individuals in the 1967 USAF sample distributed (via Z scores) with regard to the two factors. The superimposed circle represents a 99.5% accommodation model. That is, 99.5% of the subjects in this sample appear within the circle which is defined by the eight *representative cases.*

The horizontal scale on Figure 5 displays overall body size of each subject (Factor I) ranked as Z scores. Thus Case 2 is the smallest overall and Case 5 is the largest. These two cases are near zero on the vertical scale which represents the contrast factor (Factor II) between limb and torso dimensions. Thus, Case 2 represents individuals whose limbs and torsos are both small; Case 5 is large in both limb and torso dimensions. Cases 1 and 7 also represent small individuals but display marked contrast between limb and torso dimensions (Factor 2). Case 1 has smaller torso dimensions than Case 2 but longer limbs. Case 7 has smaller limbs than Case 2 but larger torso dimensions. Together, these three cases (2, 1, and 7) better represent variability in small individuals than does a single case that is small on all dimensions (2). Similarly, on the large end of the body size scale, Cases 6 and 8 are nearly as large as Case 5, but show contrasting torso and limb dimensions. Case 6 exhibits larger limb measures but a smaller torso while Case 8 has the largest torso but smaller limbs. Finally, Cases 3 and 4 are fairly average on overall body size but show extreme contrast in limb and torso dimensions. Case 3 has approximately 96th percentile limb values combined with approximately 9th percentile torso dimensions. By contrast, Case 4 has roughly 4th percentile limb dimensions combined with approximately 91st percentile torso dimensions.

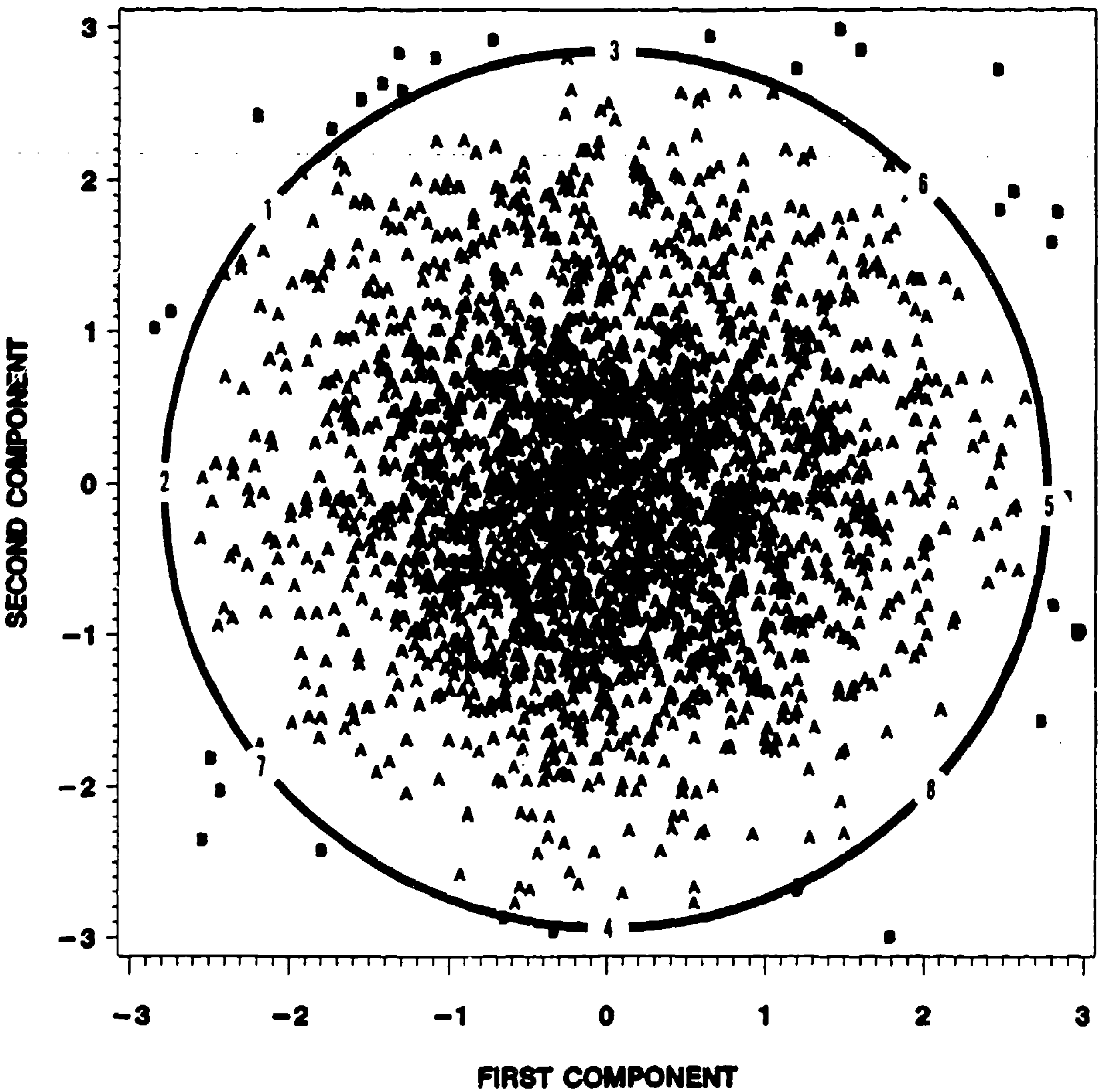


FIGURE 5

Two-dimensional Principal Components Solution: 99.5% Accommodation

Standardized Z scores for each of these *representative cases* come up in the third part of the output and are shown on Table 3. Z scores are calculated in terms of standard deviations from the mean. Thus, on Table 3, the first three variables (the limb lengths) for individual 6 are all approximately 2.8 standard deviations above the mean. The Z scores are converted to percentile values (Table 4) for easier interpretation in the next section of the output. This makes even clearer the differences between the *representative cases*. Table 5 lists the actual values of individuals 1 through 8 based on the 1967 survey.

The traditional approach of using "percentile people" in cockpit layouts for aircraft with ejection seats has led to the assumption that small flyers position the seat full up and the rudder carriage full aft. Large flyers adjust for the opposite configuration. In aircraft which do not have ejection capability, the seats adjust fore and aft as well as up and down. The 5th and 95th percentile pilot designation leads to the assumption that small pilots fly full up and full forward while large pilots fly full aft and full down. Case 5 (generalized large male) and Case 2 (generalized small male) do just that. However, Cases 6 (longer limbs but smaller torso than 5) and 7 (shorter limbs but longer torso than 2) may be slightly more difficult to fit into a cockpit designed on this basis. These cases are roughly .5 inch more extreme in limb length than Cases 5 and 2, but would have their seats adjusted differently. In an ejection equipped aircraft, Case 6 should have the seat 2.14 inches higher than Case 5 to achieve comparable over-the-nose vision. This may move the knee or shin closer to the instrument panel. In non-ejection aircraft the seat may also be moved aft to provide more leg room for Case 6. Case 7 has slightly shorter reach than Case 2 and should adjust the seat 2.3 inches lower to provide head clearance and to obtain similar over-the-nose vision. The effect of this is to originate any reach to controls at different points in the cockpit. In non-ejection aircraft, Case 7 may move the seat further forward.

Additional consideration must be given to the "combination" Case 3 (shortest torso-longest limb) and Case 4 (longest torso-shortest limb). Case 3 has limbs nearly 1 inch shorter than Case 5 (the generalized large male) but would adjust the seat 5 inches higher. The knee or shin could be much closer to the instrument panel, or yoke clearance could be greatly reduced in this configuration. Similarly, Case 4 has limbs 1 inch longer than Case 2 (generalized small male) but should adjust the seat about 5 inches lower. Reach to controls for these two cases will again be quite different. Finally Case 8 (largest torso but closer to average limb length) and Case 1 (smallest limbs but closer to average torso height) represent two additional points of seat and rudder adjustment. Each of these *representative cases* should be considered in a cockpit design since each will fly with the seat and rudder carriage adjusted to different points and will be in a different position relative to controls and cockpit structure. If a workspace is designed to enable all these cases to operate efficiently, then all other less extreme body types and sizes in the target population (within the circle) should also be well accommodated.

Principal component analysis cannot describe all the variability in body size which must often be taken into account and, indeed, is a needlessly complex technique for calculating some necessary dimensions for which only minimum or maximum values need be known. In the case of Shoulder Breadth, for example, it does not matter if the widest shoulders are found on an individual with a tall Sitting Height or a short one. Both sets of shoulders must clear the sides of the cockpit. The Multivariate Accommodation Models program can list univariate minimum and maximum values for a large number of anthropometric measurements at any desired population accommodation percentage. Measurements such as Shoulder Breadth or Foot Length must be considered in a cockpit design, but are problems that can be considered

TABLE 3

Variable Z Scores for Two-Component Representative Cases
(values = standard deviation about the mean)

Variable	6	1	7	8
Thumb Tip Reach	2.855	-0.415	-2.855	0.415
Buttock-Knee Length	2.841	-0.437	-2.841	0.437
Popliteal Height Sitting	2.846	-0.669	-2.846	0.669
Sitting Height	1.145	-3.029	-1.145	3.029
Eye Height Sitting	1.061	-2.995	-1.061	2.995
Shoulder Height Sitting	0.878	-2.930	-0.878	2.930

Variable	5	3	2	4
Thumb Tip Reach	2.313	1.726	-2.313	-1.726
Buttock-Knee Length	2.318	1.700	-2.318	-1.700
Popliteal Height Sitting	2.846	1.539	-2.846	-1.539
Sitting Height	2.952	-1.332	-2.952	1.332
Eye Height Sitting	2.868	-1.368	-2.868	1.368
Shoulder Height Sitting	2.693	-1.451	-2.693	1.451

TABLE 4

Percentile Values for Two-Component Representative Cases

Variable	6	1	7	8
Thumb Tip Reach	100	34	0	66
Buttock-Knee Length	100	33	0	67
Popliteal Height Sitting	100	25	0	75
Sitting Height	87	0	13	100
Eye Height Sitting	86	0	14	100
Shoulder Height Sitting	81	0	19	100

Variable	5	3	2	4
Thumb Tip Reach	99	96	1	4
Buttock-Knee Length	99	96	1	4
Popliteal Height Sitting	99	94	1	6
Sitting Height	100	9	0	91
Eye Height Sitting	100	9	0	91
Shoulder Height Sitting	100	7	0	93

TABLE 5

Variable Values for Two-Component Representative Cases
(values in inches)

Variable	6	1	7	8
Thumb Tip Reach	36.09	30.96	27.14	32.26
Buttock-Knee Length	26.80	23.31	20.75	24.24
Popliteal Height Sitting	19.72	16.61	14.68	17.79
Sitting Height	38.11	32.89	35.25	40.47
Eye Height Sitting	33.13	28.31	30.60	35.42
Shoulder Height Sitting	25.02	20.73	23.04	27.33

Variable	5	3	2	4
Thumb Tip Reach	35.24	34.32	27.99	28.91
Buttock-Knee Length	26.24	25.59	21.31	21.97
Popliteal Height Sitting	19.40	18.56	15.00	15.84
Sitting Height	40.37	35.02	32.99	38.35
Eye Height Sitting	35.27	30.24	28.46	33.49
Shoulder Height Sitting	27.06	22.40	21.00	25.66

separately from the combinations of torso and limb size discussed above. The list of additional dimensions used in the minimum and maximum values option can be selected through the CARD data base. A representative list is shown in Table 6.

TABLE 6

Minimum and Maximum Values for Additional Cockpit Design Measures: 99.5% Accommodation Model (values in inches)

Variable	Minimum	[illegible]
Buttock to Popliteal Fossa Length (Leg Flexed)	16.5	[illegible]
Chest Depth	6.6	[illegible]
Elbow to Fingertip Length (Arm Flexed)	16.2	[illegible]
Foot Length	8.7	12.4
Forearm to Forearm Breadth (Seated)	14.5	25.5
Hip Breadth (Seated)	11.7	18.1
Popliteal Height Sitting	15.0	21.2
Shoulder Breadth	14.1	21.6
Shoulder to Elbow Length (Arm Flexed)	12.5	16.6
Thigh Clearance	3.8	8.0
Weight	103.0	245.0

The cockpit accommodation example described above is relatively simple since only a small list of measurements and a restricted set of factors were selected. Computer programs such as COMBIMAN (Krauskopf et al., 1989) or the Articulated Total Body (ATB) model (Fleck and Butler, 1975) require larger lists of measurements to define the body size of the individual models. COMBIMAN, for example, uses a list of 11 anthropometric measurements to establish model parameters. The Multivariate Accommodation Models program was run on this set of measurements and, as expected, three factors were required to fully describe body size for this application. Not only were torso and limb lengths required but body mass measurements (widths and depths) made a third factor necessary. The result of this third factor on the models was that the *representative cases* encompassed many more combinations of body proportions (14) including, for example, a long limb-long torso-large widths/depths case as well as a long limb-long torso-small widths/depths case. With the addition of a third factor, *representative cases* are located on a three-dimensional spheroid. Tables 7 through 11 describe the results of this analysis. The interpretations are similar to those previously discussed.

TABLE 7

Three-Component Representative Cases: Summary Statistics
(values in inches)

Variable	Mean	Standard Deviation
Sitting Height	36.681	1.250
Acromion Height Sitting	24.032	1.124
Knee Height Sitting	21.949	0.982
Buttock-Knee Length	23.776	1.064
Shoulder Elbow Length	14.148	0.674
Elbow Wrist Length	11.804	0.556
Biacromial Breadth	16.030	0.765
Hip Breadth Sitting	14.875	0.906
Chest Depth	9.649	0.760
Foot Length	10.638	0.468
Hand Length	7.518	0.323

TABLE 8

Three-Component Factor Correlation Matrix

Variable	Factor I	Factor II	Factor III
Sitting Height	0.68644	-0.14768	0.63708
Acromion Height Sitting	0.61756	-0.04367	0.73092
Knee Height Sitting	0.89294	-0.13282	-0.16367
Buttock-Knee Length	0.82138	0.12771	-0.24231
Shoulder Elbow Length	0.79339	-0.20613	-0.12995
Elbow Wrist Length	0.80584	-0.22631	-0.22328
Biacromial Breadth	0.49074	0.19242	-0.08891
Hip Breadth Sitting	0.58134	0.68078	0.10944
Chest Depth	0.43275	0.78190	-0.08761
Foot Length	0.79984	-0.17233	-0.14090
Hand Length	0.76740	-0.26423	-0.16925

TABLE 9

Variable Z Scores for Three-Component Representative Cases
(values = standard deviation about the mean)

Variable	6	1	7	8
Sitting Height	2.267	-0.190	2.837	-0.380
Acromion Height Sitting	2.516	-0.303	2.685	0.134
Knee Height Sitting	1.150	1.781	1.662	-2.294
Buttock-Knee Length	1.363	2.297	0.870	-1.805
Shoulder Elbow Length	0.882	1.383	1.677	-2.178
Elbow Wrist Length	0.687	1.548	1.560	-2.421
Biacromial Breadth	1.146	1.489	0.404	-0.747
Hip Breadth Sitting	2.645	2.223	0.019	0.403
Chest Depth	2.173	2.511	-0.842	0.504
Foot Length	0.938	1.482	1.603	-2.146
Hand Length	0.644	1.297	1.663	-2.316

Variable	11	12	13	14
Sitting Height	0.380	-2.837	0.190	-2.267
Acromion Height Sitting	-0.134	-2.685	0.303	-2.516
Knee Height Sitting	2.294	-1.662	-1.781	-1.150
Buttock-Knee Length	1.805	-0.870	-2.297	-1.363
Shoulder Elbow Length	2.178	-1.677	-1.383	-0.882
Elbow Wrist Length	2.421	-1.560	-1.548	-0.687
Biacromial Breadth	0.747	-0.404	-1.489	-1.146
Hip Breadth Sitting	-0.403	-0.019	-2.223	-2.645
Chest Depth	-0.504	0.842	-2.511	-2.173
Foot Length	2.146	-1.603	-1.482	-0.938
Hand Length	2.316	-1.663	-1.297	-0.644

TABLE 9 (cont'd)

Variable	9	10	5
Sitting Height	2.293	-0.493	2.128
Acromion Height Sitting	2.063	-0.146	2.441
Knee Height Sitting	2.982	-0.444	-0.547
Buttock-Knee Length	2.743	0.427	-0.809
Shoulder Elbow Length	2.650	-0.688	-0.434
Elbow Wrist Length	2.692	-0.756	-0.746
Biacromial Breadth	1.639	0.643	-0.297
Hip Breadth Sitting	1.942	2.274	0.366
Chest Depth	1.445	2.612	-0.293
Foot Length	2.671	-0.576	-0.471
Hand Length	2.563	-0.883	-0.565

Variable	3	2	4
Sitting Height	-2.293	0.493	-2.128
Acromion Height Sitting	-2.063	0.146	-2.441
Knee Height Sitting	-2.982	0.444	0.547
Buttock-Knee Length	-2.743	-0.427	0.809
Shoulder Elbow Length	-2.650	0.688	0.434
Elbow Wrist Length	-2.692	0.756	0.746
Biacromial Breadth	-1.639	-0.643	0.297
Hip Breadth Sitting	-1.942	-2.274	-0.366
Chest Depth	-1.445	-2.612	0.293
Foot Length	-2.671	0.576	0.471
Hand Length	-2.563	0.883	0.565

TABLE 10

Percentile Values for Three-Component Representative Cases

Variable	6	1	7	8
Sitting Height	99	42	100	35
Acromion Height Sitting	99	38	100	55
Knee Height Sitting	87	96	95	1
Buttock-Knee Length	91	99	81	4
Shoulder Elbow Length	81	92	95	1
Elbow Wrist Length	75	94	94	1
Biacromial Breadth	87	93	66	23
Hip Breadth Sitting	100	99	51	66
Chest Depth	99	99	20	69
Foot Length	83	93	95	2
Hand Length	74	90	95	1

Variable	11	12	13	14
Sitting Height	65	0	58	1
Acromion Height Sitting	45	0	62	1
Knee Height Sitting	99	5	4	13
Buttock-Knee Length	96	19	1	9
Shoulder Elbow Length	99	5	8	19
Elbow Wrist Length	99	6	6	25
Biacromial Breadth	77	34	7	13
Hip Breadth Sitting	34	49	1	0
Chest Depth	31	80	1	1
Foot Length	98	5	7	17
Hand Length	99	5	10	26

TABLE 10 (cont'd)

Variable	9	10	5
Sitting Height	99	31	98
Acromion Height Sitting	98	44	99
Knee Height Sitting	100	33	29
Buttock-Knee Length	100	67	21
Shoulder Elbow Length	100	25	33
Elbow Wrist Length	100	22	23
Biacromial Breadth	95	74	38
Hip Breadth Sitting	97	99	64
Chest Depth	93	100	38
Foot Length	100	28	32
Hand Length	99	19	29

Variable	3	2	4
Sitting Height	1	69	2
Acromion Height Sitting	2	56	1
Knee Height Sitting	0	67	71
Buttock-Knee Length	0	33	79
Shoulder Elbow Length	0	75	67
Elbow Wrist Length	0	78	77
Biacromial Breadth	5	26	62
Hip Breadth Sitting	3	1	36
Chest Depth	7	0	62
Foot Length	0	72	68
Hand Length	1	81	71

TABLE 11

Variable Values for Three-Component Representative Cases
(values in inches)

Variable	6	1	7	8
Sitting Height	39.52	36.44	40.23	36.21
Acromion Height Sitting	26.86	23.69	27.05	24.18
Knee Height Sitting	23.08	23.70	23.58	19.70
Buttock-Knee Length	25.23	26.22	24.70	21.86
Shoulder Elbow Length	14.74	15.08	15.28	12.68
Elbow Wrist Length	12.19	12.66	12.67	10.46
Biacromial Breadth	16.91	17.17	16.34	15.46
Hip Breadth Sitting	17.27	16.89	14.89	15.24
Chest Depth	11.30	11.56	9.01	10.03
Foot Length	11.08	11.33	11.39	9.63
Hand Length	7.73	7.94	8.06	6.77

Variable	11	12	13	14
Sitting Height	37.16	33.13	36.92	33.85
Acromion Height Sitting	23.88	21.01	24.37	21.20
Knee Height Sitting	24.20	20.32	20.20	20.82
Buttock-Knee Length	25.70	22.85	21.33	22.33
Shoulder Elbow Length	15.62	13.02	13.22	13.55
Elbow Wrist Length	13.15	10.94	10.94	11.42
Biacromial Breadth	16.60	15.72	14.89	15.15
Hip Breadth Sitting	14.51	14.86	12.86	12.48
Chest Depth	9.27	10.29	7.74	8.00
Foot Length	11.64	9.89	9.94	10.20
Hand Length	8.27	6.98	7.10	7.31

TABLE 11 (cont'd)

Variable	9	10	5
Sitting Height	39.55	36.06	39.34
Acromion Height Sitting	26.35	23.87	26.78
Knee Height Sitting	24.88	21.51	21.41
Buttock-Knee Length	26.69	24.23	22.91
Shoulder Elbow Length	15.93	13.68	13.86
Elbow Wrist Length	13.30	11.38	11.39
Biacromial Breadth	17.28	16.52	15.80
Hip Breadth Sitting	16.63	16.94	15.21
Chest Depth	10.75	11.63	9.43
Foot Length	11.89	10.37	10.42
Hand Length	8.35	7.23	7.34

Variable	3	2	4
Sitting Height	33.82	37.30	34.02
Acromion Height Sitting	21.71	24.20	21.29
Knee Height Sitting	19.02	22.38	22.49
Buttock-Knee Length	20.86	23.32	24.64
Shoulder Elbow Length	12.36	14.61	14.44
Elbow Wrist Length	10.31	12.22	12.22
Biacromial Breadth	14.78	15.54	16.26
Hip Breadth Sitting	13.12	12.81	14.54
Chest Depth	8.55	7.66	9.87
Foot Length	9.39	10.91	10.86
Hand Length	6.69	7.80	7.70

DISCUSSION

There are a number of multivariate statistical techniques which could be utilized to determine similar combinations of body size test cases. The technique described here, however, when combined with lists of minimum and maximum values, gives a much more accurate description of the body size and proportional variability existing in the population and, if used in designing workspaces, will greatly reduce the accommodation problems experienced by users. This assumes, of course, that the seat, rudder, and other adjustable components can be adjusted in sufficiently small increments. Without such adjustability, it may be necessary, as Hendy (1990) suggests, to pick many more *representative cases* than the numbers suggested here to ensure the desired level of accommodation. However, for the purposes of writing anthropometric specifications, large numbers of *representative cases* may overwhelm the designer and thus, be counterproductive.

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