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# DEFINING EXTREME SIZES AND SHAPES FOR BODY ARMOR AND LOAD-BEARING SYSTEMS DESIGN:

## Multivariate Analysis of U.S. Army Torso Dimensions

by

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Percentile models commonly cited in materiel fitting requirements, such as "fits the 5th through 95th percentile soldier", are inadequate definitions of the extremes in body sizes and shapes that must be fit to ensure the intended 90% accommodation of the Army user population. This report reviews shortcomings of the percentile methods in common use since the 1970s and applies multivariate statistical methods to the definition of extreme torso forms for load-bearing and body armor design limit definitions. Principal Component Analysis (PCA) is applied to 12 torso dimensions from the U.S. Army Anthropometric Survey (ANSUR) database, and equal frequency ellipses (EFE) defining 90% accommodation are fit to plots of ANSUR subjects in the PCA space. Central and extreme forms for male-only, female only, and male/female requirements are derived from the EFE equations and presented in tables for use by clothing designers and engineers whose torso clothing and equipment must meet "5th to 95th percentile" criteria. The study raises methodological issues and alternatives for follow-up in future applied research.

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# PREFACE

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# DEFINING EXTREME SIZES AND SHAPES FOR BODY ARMOR AND LOAD-BEARING SYSTEMS DESIGN

## MULTIVARIATE ANALYSIS OF U.S. ARMY TORSO DIMENSIONS

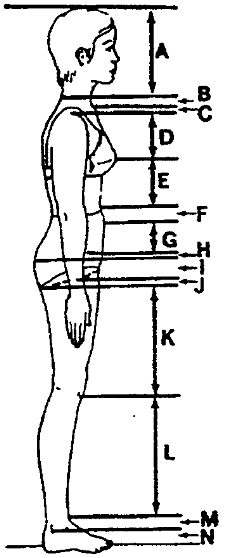
## BACKGROUND

To ensure that materiel systems actually fit the soldiers that will use them, anthropometric requirements for the design of Clothing and Individual Equipment (CIE) are usually included in requirements documents using a common phrase such as ..."must fit the 5th percentile to 95th percentile soldier". The intent of this requirement is to ensure that materiel systems are sized to fit the central 90% of the Army population without special order or customized fitting.

The requirement to accommodate 90% of the population is historical and somewhat arbitrary. It reflects logistical trade-offs regarding the relatively high additional costs of designing, manufacturing, and stocking for those few soldiers with "extreme" body sizes (McConville and Churchill, 1976) compared to the cost and feasibility of special orders or customization. The impact of suboptimal fit on safety and performance and the need for rapid deployment in combat situations also impact trade-off decisions regarding anthropometric requirements. In the case of life-support equipment, for example, anthropometric requirements are often extended to include the "1st to 99th percentile soldier", and the intent is to provide life support equipment that fits 98% of the Army population without customized procurement.

### Shortcomings of Percentile Models

While the intent to fit 90% or more of the Army population may be clear, specification of these design and sizing requirements in terms of percentiles is not actually very helpful to the engineer or designer, and is often misleading. Firstly, just as there is no "average man" (Daniels, 1952), there are no mythical people with all 5th or all 95th percentile body dimensions (McConville and Churchill, 1976).



| | STATURE SEGMENTS (in cm) | 5%ile | Mean | 95%ile |
|---|---|---|---|---|
| A | Cervicale to Vertex | 20.8 | 22.91 | 25.1 |
| B | Suprasternale to Cervicale | 5.1 | 7.19 | 9.4 |
| C | Acromiale to Suprasternale | -2.1 | 0.14 | 2.4 |
| D | Bustpoint to Acromiale | 10.4 | 13.54 | 16.8 |
| E | Waist to Bustpoint | 14.3 | 18.04 | 21.9 |
| F | Abdominal Extension to Waist | 4.9 | 7.13 | 9.7 |
| G | Trochanterion to Abdominal Ext | 7.1 | 10.48 | 13.6 |
| H | Buttock to Trochanterion | -2.8 | 0.46 | 3.9 |
| I | Crotch to Buttock | 4.7 | 7.71 | 10.5 |
| J | Gluteal Furrow to Crotch | -1.3 | 1.80 | 5.1 |
| K | Tibiale to Gluteal Furrow | 26.7 | 30.72 | 34.8 |
| L | Ankle to Tibiale | 27.4 | 30.8 | 34.4 |
| M | Lateral Malleolus to Ankle | 2.4 | 4.41 | 6.8 |
| N | Floor to Lateral Malleolus | 5.8 | 6.77 | 7.8 |
| | **TOTAL OF STATURE SEGMENTS** | 123.4 | 162.1 | 202.2 |
| | **ACTUAL STATURE** | **152.4** | **162.1** | **172.2** |

**Figure 1. Stature segments: nonadditivity of percentiles (from Churchill, 1978)**

As can be seen in Figure 1, because percentiles are not additive, a model composed entirely of 95th percentile segments has a stature that substantially exceeds the 95th percentile stature of the population, whereas a model composed entirely of 5th percentile segments substantially underestimates the actual 5th percentile stature (McConville and Churchill, 1976; Churchill, 1978; Robinette and Churchill, 1979). In short, uniform percentile models suggested by the phrase "5th to 95th percentile soldier" are neither realistic nor proportioned properly for good-fitting designs.

A second issue that limits the utility of percentiles arises because percentiles apply to only one body dimension at a time, whereas most military clothing and equipment must adequately fit several different body dimensions *simultaneously* to function properly. Because body dimensions are not perfectly correlated with one another, when 5th and 95th percentile extremes are used to define the "worst cases" for multidimensional engineering problems, they include less than the intended 90% of the population (Moroney and Smith, 1972; Bittner, 1974;

Churchill, 1978). In the landmark demonstration by Moroney and Smith (1972), 5th to 95th percentile specifications for a six-dimensional cockpit design problem resulted in accommodation of only 64% of the Naval aviator population when 90% was the intended design target. Figure 2 illustrates the same phenomenon for a hypothetical "5th to 95th percentile soldier" requirement for body armor and load-bearing equipment using data from the ANSUR survey (Gordon et al., 1989).

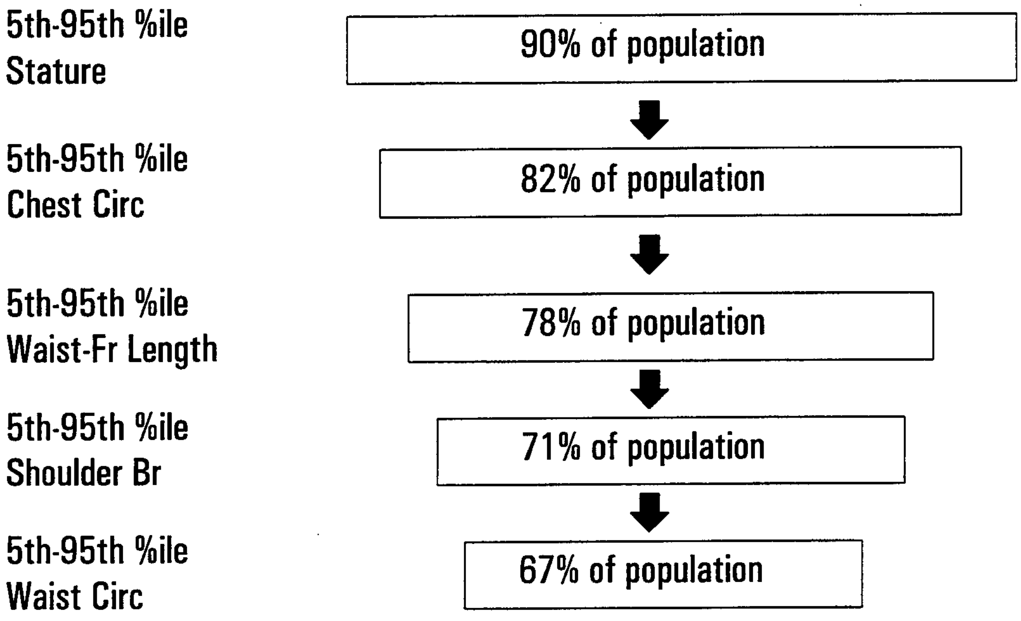


**Figure 2. Reduced population accommodation in percentile-based specifications**

In general, the rate of accommodation degradation in percentile models varies as a function of the number of critical dimensions and the correlations among them (Churchill, 1978). However, percentile models *always* include less than the intended population proportion when the design problem has more than one body dimension critical to fit and function. And since this criterion applies to virtually all military engineering problems, both the US Navy (USN) and the US Air Force (USAF) have explicitly barred the use of percentiles in specifications (Arnoff, 1987, Zehner et al., 1993). Even the current version of MIL-STD-1472D (rev2) contains strong cautions against the use of percentile models in both requirements documents and design aids, such as manikins and CAD models.

## Subgroup and Regression Alternatives to Percentiles

McConville and Churchill (1976) suggested two alternatives to the percentile approach for defining anthropometric design limits: subgroup means and regression estimates. In the subgroup method extreme values, such as the 5th and 95th percentiles for height and weight, are used to select subsets of the population to represent small and large people. The anthropometric means of each subgroup, which are additive, are then used to establish design limits for critical body dimensions. In the regression method, design limits for critical body dimensions are predicted from multiple regression equations, which use the 5th or 95th percentile values for height and weight as predictors. Unlike percentile approaches, both the subgroup and regression methods yield design limits that are additive and characteristic of the body proportions of real people (McConville and Churchill, 1976; Robinette and Churchill, 1979).

However, the subgroup and regression methods also have limitations. In the case of regression estimates, when the correlation between independent (predictor) and dependent (predictee) dimensions is even moderately low, the predicted values of critical design dimensions are much too close to the population mean to be useful as descriptors of extremes in body size (Meindl et al., 1993). Unfortunately, since moderate to low correlation coefficients between body dimensions are common (Cheverud et al., 1990), this limits the usefulness of regression in specifying extreme body size models. As McConville and Churchill (1976) demonstrated, the subgroup mean method yields somewhat more extreme critical design values than does the regression method. However, the subgroup means may be biased by unusual individuals (outliers) whenever the subgroup sample sizes are small, and both subgroup and regression methods assume normal distributions of data (McConville and Churchill, 1976; Robinette and Churchill, 1979). Haselgrave (1986) addressed some of these concerns by using the medians of extreme subgroups rather than the means. However, since neither the subgroup nor regression method can be mathematically related to a desired population accommodation rate (e.g., 90%), designing to fit extreme values specified by these models is no guarantee that established accommodation requirements will be met.

Still another shortcoming of *all* the approaches mentioned above is that they assume that by designing to fit the uniformly largest and/or smallest people, they will automatically capture everyone in between. In fact, the "worst case" engineering design scenarios may not be presented by those people uniformly largest or smallest for all their body dimensions, but rather by individuals with combinations of body dimensions that include both large and small extremes (Roebuck et al., 1975). In cockpit design problems, for example, the pilot with long limbs and a short torso presents an extreme that is not accommodated in seat adjustments designed for uniformly small and large people (Zehner et al., 1993).

### Factor Analytic and Principal Component Models

An approach to defining design limits that addresses the need for multivariate accommodation specification, realistic and proportional models, and inclusion of worst case body proportions was first proposed by Bittner (1976). Bittner applied principal factor analysis to 19 body dimensions critical to workstation and cockpit design, extracting and varimax rotating four principal factors accounting for 75% of the original variation (Bittner et al., 1987). Standardized factor score descriptions for 16 manikins distributed on the surface of a four-dimensional ellipsoid were created by multiplying the factor loadings matrix (4 by 19) by each of the possible 4 by 1 vectors with elements either +1.3517 or -1.3517 (Bittner et al., 1987). These 16 models represent the multivariate "worst case" scenarios for the accommodation envelope defined by the ellipsoid. A 17th model at the centroid of the principal factor ellipsoid was used by Bittner to represent the multivariate mean.

Bittner's approach to defining a family of extreme forms for workstation design (CADRE) was validated by comparing accommodation extremes based on CADRE dimensions to those observed in a random sample of 400 subjects from the USN 1964 survey, and by using CADRE dimensions to set cockpit geometry in the CAR IV computer aided design program. When seat and control locations in the CAR IV program were adjusted to fit CADRE manikin extremes, it was determined that 98-99% of the 400-member USN sample could reach all controls, 98% could achieve design eye position, and between 96% and 98% could reach all controls from the design eye position (Bittner et al., 1987). Bittner interpreted the fact that validated accommodation rates exceeded the 90% target as evidence that not all the body dimensions included in the factor analysis were actually "limiting" variables in the cockpit geometry.

Meindl and colleagues (1993) simplified Bittner's multivariate approach for application to US Air Force cockpit geometry (see also Zehner et al., 1992). Utilizing Principal Components Analysis (PCA) of the correlation matrix, Meindl demonstrated the method by defining extreme forms for a 6-dimensional cockpit geometry problem and an 11-dimensional man-model (COMBIMAN). For cockpit geometry, Meindl retained two principal components (PC's), accounting for 85% of the original 6-dimensional population variation, and rendering 8 "worst-case" models. In the man-model problem, Meindl initially retained six PC's accounting for 90% of the variation, but then employed varimax rotation to distribute the variation more evenly across the axes, and retained only three PC's accounting for 61% of the original variation. Meindl's three PCA solution rendered a minimum of 8 and maximum of 14 extreme models for COMBIMAN.

The Principal Component method introduced by Meindl and Zehner has recently been applied in the procurement process of JPATS (Joint Primary Aircraft Training System), which is destined to replace the USAF T-37 and USN T-38 (Zehner, 1996). The desired accommodation envelope for the JPATS cockpit is the most ambitious ever attempted -- 95% of all males and females eligible to enter USAF flight training. Seven models (referred to as JPATS "cases") were used to define the extreme forms at the surface of the overlapping male and female ellipses (Zehner, 1996).

### Applications of PCA to Body Armor and Load-Bearing System Design

The current work extends development of the PCA methodology by applying it to the definition of central and extreme forms to guide the design and sizing of modular body armor and load-bearing systems. Models for two different accommodation requirements are derived: a "5th to 95th percentile male" requirement, and a "5th to 95th percentile soldier" requirement that includes both genders. Specification of the body dimensions of a multivariate mid-size individual as well as the body dimensions of individuals at the design extremes has a particular advantage in that it gives the engineer a proportionally appropriate starting point and realistic and valid exit criteria that will ensure the design meets the intended fitting requirements. The data can be used as input for computer man-models, as specifications for manikin manufacture, and to guide selection criteria for test subjects who approximate the extremes of the intended design population.

It is important to recognize that PCA methodology does not render the actual number of sizes needed for a body armor or load-bearing system, nor does it specify the optimal dimensions for each size, since in point of fact, these are determined by the adjustability of any particular design and its component materials, which cannot be known until after a prototype is created and actual fitting trials are conducted to determine the range of body sizes the prototype fits. The PCA approach does, however, provide statistically valid anthropometric exit criteria and a logical point of departure for initial engineering designs, which form the basis of anthropometric accommodation requirements in systems developed under military performance specifications.

## MATERIALS AND METHODS

### Selection of Body Dimensions for Analysis

There are more than 130 dimensions in the ANSUR database; however, only a small subset of these are pertinent to this problem. Twenty dimensions relevant to the design, sizing, and functional fit of load-bearing and modular body armor systems were identified with help from NRDEC Survivability Directorate project officers. This "long list" of dimensions was then reduced by eliminating body dimensions so highly correlated with others that they might be considered redundant (e.g., bideltoid breadth), and by dropping variables primarily used for specification of design details rather than the overall design/sizing configuration itself (e.g., strap length). This process resulted in the following short list of body dimensions for analysis:

Biacromial Breadth
Buttock Circumference
Chest Breadth
Chest Circumference
Interscye I
Neck Circumference, Base
Shoulder Circumference
Waist Circumference, Om
Waist-Hip Length
Shoulder Length
Waist-Back Length, Om
Waist-Front Length, Om

Note that exclusion of some torso dimensions from the PCA does not mean that their critical design values cannot be provided later for use in specifying design features and details, only that they are not considered to be "drivers" in the sizing and population accommodation specifications.

## Sampling of the ANSUR Database

Anthropometric data analyzed in this project are from the ANSUR database (Gordon et al., 1989). All nonpilot subjects with complete torso data were utilized (n=3478 females; n=5004 males); however, subjects were weighted to reflect prevailing Army age and race distributions (Defense Manpower Data Center, 1995). Weighted parameter estimation takes advantage of the entire ANSUR database while ensuring that the results of analyses are representative of those expected for the Army as a whole (Gordon, 1996).

## Statistical Approach

The general approach in a PCA analysis for determination of extreme forms can be outlined as follows:

Step 1: use Principal Components Analysis to reduce the anthropometric variation present in all 12 torso dimensions to 2 or 3 orthogonal (independent) dimensions ("components" or "factors"), which are linear combinations of the 12 original body measurements.

Step 2: score each subject on the principal components extracted and plot the design population in "PCA space".

Step 3: fit a 90% equal probability ellipse/ellipsoid to the design population, which represents the multivariate accommodation limit for a 5th-95th percentile requirement.

Step 4: identify critical cases located on the surface of the ellipse that represent "worst case engineering scenarios" of body size and shape, and a centrally located "multivariate average" model where the component axes cross each other at the origin.

Step 5: use Principal Component coordinates for each of the critical cases to estimate all 12 original body dimensions.

Three separate Principal Components Analyses (PCA's) of torso data were conducted: males only, females only, and males and females together. The sex-specific analyses were used to identify the most extreme cases for each gender separately, then a joint analysis was done to examine the location of these cases in a common multivariate space, and to select worst cases for the gender integrated sizing/design application.

## RESULTS

### Male-Only Analyses

Tables 1 and 2 and Figure 3 present the results of the male-only Principal Components Analysis, which was conducted on the covariance matrix of the 12 torso dimensions listed above.

**Table 1. Male-only principal components analysis**

| Principal Component | Eigenvalue | Difference | Proportion of Variance | Cumulative Variance |
|---|---|---|---|---|
| 1 | 19121.07914 | 17137.06319 | 0.7775 | 0.7775 |
| 2 | 1984.01596 | 1106.35198 | 0.0807 | 0.8581 |
| 3 | 877.66397 | 149.83384 | 0.0357 | 0.8938 |
| 4 | 727.83013 | 267.90934 | 0.0296 | 0.9234 |
| 5 | 459.92079 | 22.18495 | 0.0187 | 0.9421 |
| 6 | 437.73584 | 106.60957 | 0.0178 | 0.9599 |

Examination of the cumulative variance column in Table 1 indicates that the first two principal components together explain approximately 86% of the original variation in 12-dimensional space. When the third principal component is added, 89% is explained. As can be seen in Table 1, the more components added, the larger the cumulative explained variance (thus the smaller the unexplained variance). One can think of this in terms of resolution lost: collapsing 12-dimensional space to 6-dimensional space sacrifices less resolution than collapsing 12-dimensional space to 2 dimensions. Determination of how many components to retain in a study is a matter of judgment, and greatly depends upon the intended application of the PCA results. In this case, we have chosen to examine only the first three components, whose mathematical equations in terms of the original body dimensions are derived from the eigenvectors presented in Table 2.

**Table 2. Variable loadings on PC's: males only**
(shaded areas highlight important loadings)

| | Eigenvectors | | |
|---|---|---|---|
| Variables* | PC 1 | PC 2 | PC 3 |
| bcrmbdth | 0.06085 | 0.18598 | 0.22673 |
| buttcirc | 0.41832 | -0.11277 | 0.56602 |
| chstbdth | 0.16947 | 0.04698 | -0.16409 |
| chstcirc | 0.47907 | 0.26410 | -0.49365 |
| inscye1 | 0.14703 | 0.29937 | -0.13360 |
| neckcrcb | 0.10137 | 0.09602 | 0.07586 |
| shoucirc | 0.38278 | 0.60363 | 0.21880 |
| wscircom | 0.60202 | -0.58563 | -0.20929 |
| wshiplth | 0.00343 | 0.13150 | 0.17371 |
| shoulgth | 0.01357 | 0.09492 | 0.12494 |
| wstblom | 0.10774 | -0.15530 | 0.34389 |
| wstfrlom | 0.10217 | -0.15539 | 0.27978 |

*see appendix for abbreviations

The equation of each principal component is the sum of the products of the standardized variable values and their associated eigenvector coefficients. For example:

**PC1 = (std(bcrmbdth)*0.06085) + (std(buttcirc)*0.41832)+ ... + (std(wstfrlom)*0.10217)**

Often, examination of the magnitudes of these eigenvector coefficients helps to understand what kind of variation is captured by each principal component. The value of PC1, for example, is almost entirely determined by the major torso circumferences - other variables contribute little because their coefficients are so small. We thus might think of PC1 as capturing overall "size". Large males have large PC1 values, whereas small males have small PC1 values. Having the first PC represent overall size variation is a common result in PC analysis of body dimensions, regardless of the species studied (Reyment et al., 1984).

PC2, on the other hand, captures shape variation that is independent of size, and this is where the multivariate approach to the identification of extreme forms begins to radically outperform univariate percentile approaches. The two highest loading variables (see shading, Table 2), shoulder circumference and waist circumference, have coefficients of relatively large magnitude but of opposite sign; other variables with moderate loadings include chest circumference and interscye. The pattern of variable loadings on PC2 quantifies variation in the relationship between upper and central torso circumferences -- a ratio called "drop" that is important in dress shirt/jacket tailoring. Males with large shoulders and chests, broad backs, and relatively small waists have larger PC2 values (because the waist coefficient is negative) than do males with shoulders and waists of similar size (small drop). Similarly, PC3 captures a contrast of upper and lower torso size (chest and buttock circumferences), and includes moderate contributions from skeletal length and frame size variables, such as biacromial breadth, waist front length and waist back length.

It is a matter of judgment whether or not to retain PC3 in the determination of extreme forms for torso design. The component contributes only an additional 4% over and above the variation explained by PC1 and PC2, and its inclusion expands the number of potential "worst cases" from 8 to between 10 and 16 for males alone, which makes practical application of the results more difficult due to increased costs of modeling and/or testing more "cases". In addition, PC3 seems to represent a combination of shape details, and the relative contribution of body lengths and frame size (which load only moderately on PC3) to overall torso variation seems to be small after circumference variation is considered. For this reason, we chose to retain only the first two PCs in our multivariate definition of extreme forms.

Figure 3 is a plot of ANSUR males in two-dimensional PC space. The 90% equal probability ellipse overlay in this figure represents the multivariate limits of a 90% accommodation envelope of Army males for torso design/sizing purposes. The multivariate "average" male is located at the origin, where PC1 and PC2 intersect; the most extreme size and shape cases are located where the PC axes intersect the ellipse, and the

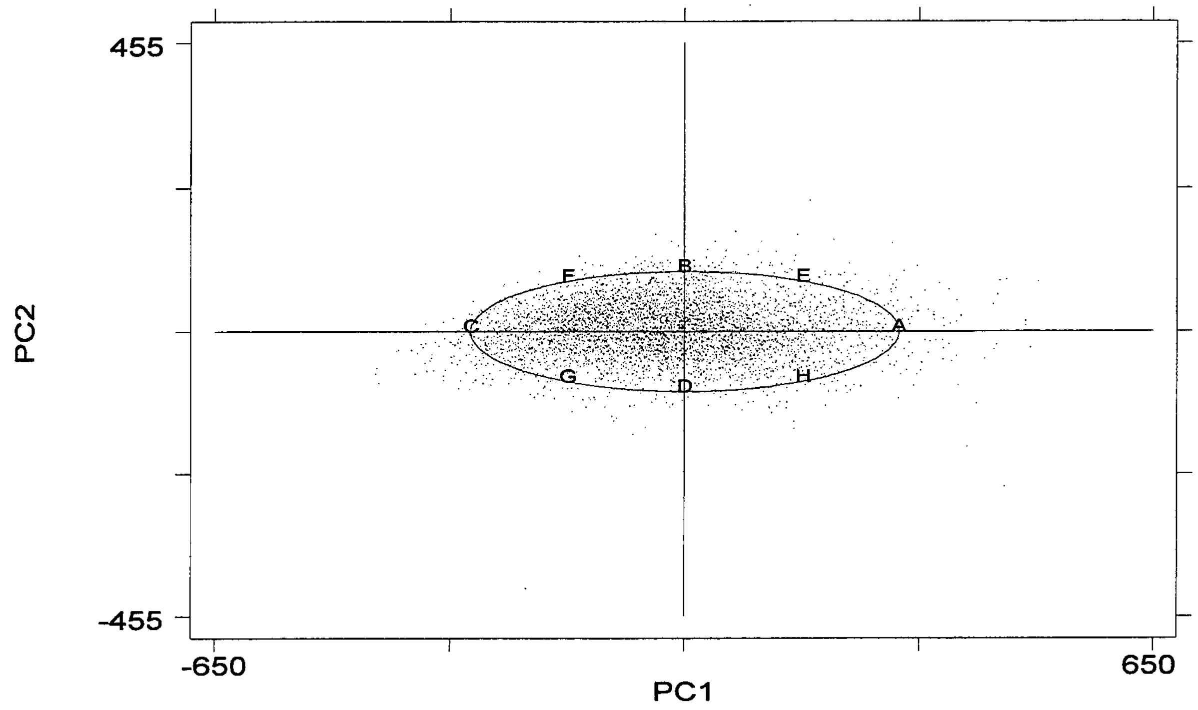


Figure 3. Plot of ANSUR males on PC1 and PC2 axes

most extreme combinations of size and shape taken together are located on the ellipse "midway" between the axes. In practice, if the designer of a load-bearing system (for example) is able to provide adjustments that accommodate the extremes of size and shape specified by the limits of the ellipse, then the system should achieve 90% or better accommodation of Army males in subsequent testing and fielding of the system. Figure 4 depicts the geometric relationship among the worst case forms in terms of their PC scores and the sizes/shapes they describe.

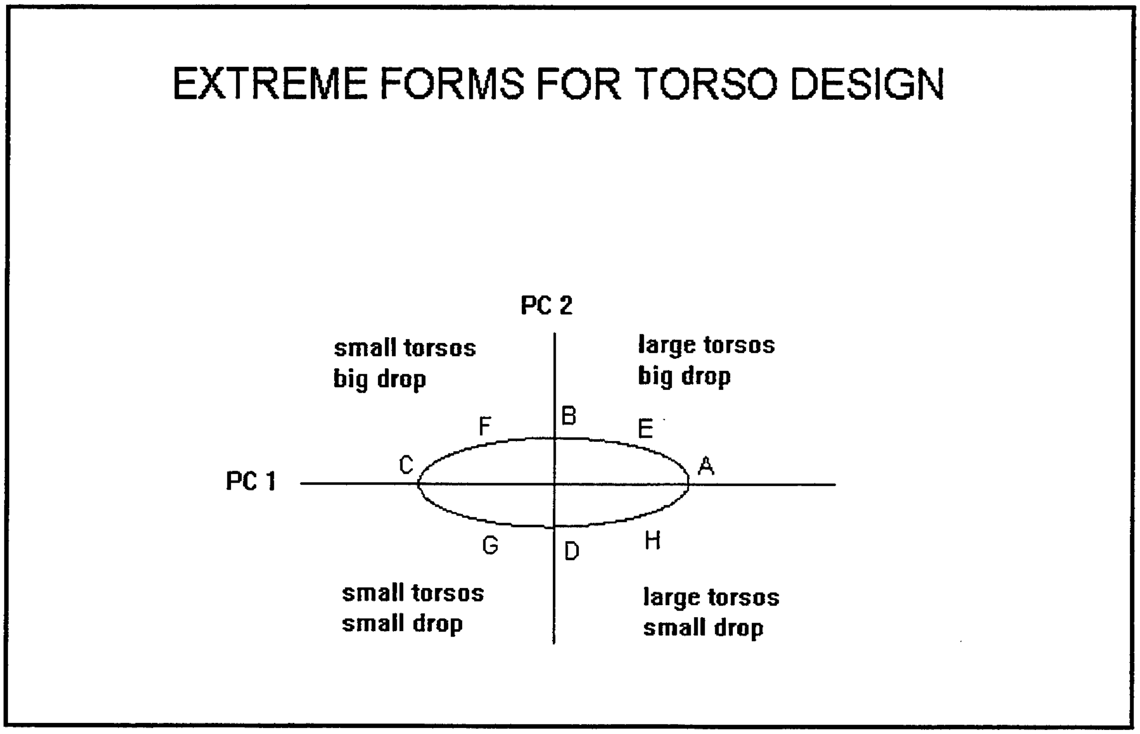


**Figure 4. Locations in PC space of extreme forms (A to H) for 90% accommodation of males only**

In the final step, the PC coordinates of worst case forms on the accommodation ellipse are translated back into 12-dimensional data for implementation. This can be done in one of two ways -- either by computing the body dimensions of "theoretical" forms from the PC coordinates at the appropriate ellipse locations (as was done by Bittner et al. in 1987 and Meindl et al. 1993), or by identifying actual ANSUR subjects at or near the ideal locations. In the case of theoretical forms, the translation from 2-dimensional PC space back to 12-dimensional anthropometric space is accomplished by using the product of PC scores and eigenvector coefficients that determines how far, and in what direction, the cases are located relative to the population means (Harris, 1975). The results of these calculations for a 90% male-only torso requirement are presented in their entirety below. Note that no single extreme form captures all the largest or all the smallest values for each dimension.

**Table 3. Torso dimensions, in mm, for male-only 90% accommodation**

| | Extreme Forms | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Dimensions** | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **Mid** |
| bcrmbdth | 415 | 415 | 379 | 379 | 422 | 402 | 372 | 392 | 397 |
| buttcirc | 1111 | 976 | 863 | 998 | 1047 | 910 | 928 | 1065 | 987 |
| chstbdth | 374 | 328 | 273 | 319 | 355 | 299 | 292 | 347 | 323 |
| chstcirc | 1139 | 1022 | 855 | 972 | 1097 | 940 | 898 | 1054 | 997 |
| inscye1 | 446 | 431 | 359 | 374 | 450 | 402 | 354 | 402 | 402 |
| neckcrcb | 439 | 418 | 379 | 400 | 433 | 400 | 385 | 418 | 409 |
| shoucirc | 1292 | 1236 | 1064 | 1120 | 1289 | 1164 | 1067 | 1192 | 1178 |
| wscircom | 1049 | 814 | 692 | 926 | 922 | 725 | 819 | 1015 | 870 |
| wshiplth | 177 | 188 | 175 | 163 | 187 | 186 | 165 | 166 | 176 |
| shoulgth | 154 | 159 | 146 | 141 | 160 | 156 | 140 | 145 | 150 |
| wstblom | 512 | 465 | 448 | 495 | 485 | 450 | 475 | 510 | 480 |
| wstfrlom | 446 | 401 | 386 | 431 | 420 | 387 | 412 | 445 | 416 |

A question commonly asked by engineers and designers encountering PCA as a method to replace percentile-based specifications is whether the range of anthropometric values observed in the group of extreme forms captures the univariate 5th and 95th percentile values of the population. Table 4 presents the largest and smallest values from the group of eight extreme forms in Table 3 and compares them to male univariate percentiles from the ANSUR database. The multivariate ranges capture the univariate 5th and 95th percentiles for the first six dimensions in Table 4, but do not include them for the last six dimensions listed, although the multivariate models do not miss these 5th to 95th percentile ranges by much (in all but one case <1 cm). It is noteworthy that the last six dimensions in Table 4 also did not load heavily on either of the Principal Components.

**Table 4. Univariate ranges of extreme forms for males only, in cm**

| Dimension | Multivariate Extreme Forms (min, max) | Univariate ANSUR Sample (5th %ile, 95 %ile) |
|---|---|---|
| buttcirc | 86,111 | 89,109 |
| chstbdth | 27,37 | 28,37 |
| chstcirc | 86,114 | 89,111 |
| neckcrcb | 38,44 | 38,44 |
| shoucirc | 106,129 | 108,128 |
| wscircom | 69,105 | 73,104 |
| bcrmbdth | 37,42 | 37,43 |
| inscye1 | 35,45 | 35,46 |
| shoulgth | 14,16 | 13,17 |
| wshiplth | 16,19 | 14,21 |
| wstblom | 45,51 | 44,52 |
| wstfrlom | 39,45 | 38,46 |

Because the length variables loaded moderately on PC3 (see Table 3), we revisited the possibility of retaining PC3 and selecting extreme forms from the surface of a three-dimensional (3D) ellipsoid, hoping that the third axis would capture more of the variation in torso lengths. However, inclusion of the third PC in selection of extreme forms did not substantially change our results. This situation undoubtedly occurred because the loadings of length variables on PC3 are not high.

It is possible that torso lengths and breadths may not be loading highly on these PC's because their magnitudes and associated variances are not as large as torso circumferences, thus do not contribute much to PC models estimated from the covariance matrix. When means and variances are positively correlated in such an analysis, two alternatives are possible: undertake a natural log transformation of the data to "unhook" the means and variances (Jolicoeur, 1963;

Sokal and Rohlf, 1981), or undertake PCA on the correlation matrix (Reyment et al., 1984; Johnson and Wichern, 1988), where all variables are standardized (mean 0 and variance 1).

Unfortunately, there is no consensus among experts in morphometric analysis as to which approach is preferred. Robinette (1997) advocates the correlation matrix approach used by Meindl and colleagues (1993) on the basis that accommodation problems are naturally related to distances from the population mean regardless of magnitude. Corruccini (1997), Jensen (1997), and others advocate the covariance matrix approach, with natural log transform of the data, so that scale is not lost in the data when the PCA is undertaken. In the absence of a consensus, we simply chose to replicate our analysis using both the correlation and natural log transform approaches, to see if the univariate extremes of torso breadths and lengths were captured in the PCA once means and variances of the original anthropometric variables were uncorrelated. In this case, neither the correlation matrix nor natural log transform approaches extended the univariate ranges of our multivariate models in terms of torso lengths and breadths, and so we wondered whether actual subjects near the theoretical extreme models displayed univariate extremes for torso lengths and breadths.

When we move from 2D or 3D PCA space to 12D anthropometric space, our predictions are most precise for those variables that are closely related to the values of the PC's themselves. This fact suggests that whereas hypothetical worst cases may not capture the full range of univariate variation in dimensions of secondary importance to overall torso variation, ANSUR subjects at or near these hypothetical worst cases may display these more extreme values. To test this hypothesis, the regional case selection tool in SYSTAT (Version 6.0) was used to mark ANSUR subjects in close proximity to extreme forms A,B,C, and D of Figure 3. Body dimensions of the 31 ANSUR subjects selected in this way were then summarized. As can be seen in Table 5, the largest and smallest values among the 31 ANSUR subjects in close proximity to the PCA extreme forms *do* encompass the univariate 5th-95th percentiles, even for those body dimensions that do not load heavily on the principal components. The only exception is the 5th percentile value of waist-back length (omphalion), which is 44 cm whereas the observed minimum for the 31 ANSUR subjects in close proximity to the PCA extreme forms is 44.6 cm.

**Table 5. Univariate ranges of ANSUR males, in cm, near PCA extreme forms**

| Dimension | PCA Forms (min, max) | ANSUR Subjects Near PCA Forms (min,max) | Univariate Percentiles (5th, 95th) |
|---|---|---|---|
| bcrmbdth | 37,42 | 36,45 | 37,43 |
| inscye1 | 35,45 | 33,50 | 35,46 |
| shoulgth | 14,16 | 13,18 | 13,17 |
| wshiplth | 16,19 | 13,22 | 14,21 |
| wstblom | 45,51 | 45,55 | 44,52 |
| wstfrlom | 39,45 | 37,47 | 38,46 |

Since actual people have more extreme values for design variables loading moderately to poorly in a PCA, theoretically calculated extreme values may be most extreme for those critical dimensions with relatively high PCA loadings, whereas actual subject data may provide the best guidance for variation in dimensions of secondary importance in the PCA. Examination of actual subjects in close proximity to the theoretical extreme forms also suggests that when PCA results are used to guide the recruitment of human test subjects, the extremes of all the critical variables will be captured in the sample as well.

## Female-Only Analyses

A separate female-only PCA was conducted in order to identify the primary drivers of torso variation in this gender, and to locate their multivariate extremes for use in deriving extreme forms for a joint male and female accommodation requirement.

### Table 6: Female-only principal components analysis

| Principal Component | Eigenvalue | Difference | Proportion of Variance | Cumulative Variance |
|---|---|---|---|---|
| 1 | 16330.20589 | 14510.10792 | 0.7412 | 0.7412 |
| 2 | 1820.09797 | 463.95949 | 0.0826 | 0.8238 |
| 3 | 1356.13848 | 553.50074 | 0.0616 | 0.8854 |
| 4 | 802.63775 | 219.43803 | 0.0364 | 0.9218 |
| 5 | 583.19972 | 241.55553 | 0.0265 | 0.9483 |
| 6 | 341.64419 | 114.15901 | 0.0155 | 0.9638 |

Tables 6 and 7 present the results of female-only principal component analyses. Examination of the cumulative variance column in Table 6 indicates that the first two principal components together explain approximately 82% of the original variation in 12D space. When the third component is added, 88% is explained. As was noted in the previous PCA for males only, the more components added, the larger the cumulative explained variance. However, each PC after the first three adds relatively little to our model of torso variation so again, we have chosen to examine only the first three principal components, whose relationships to original body dimensions are derived from the eigenvectors presented in Table 7.

**Table 7. Variable loadings on PC's: females only**
(shaded areas highlight important loadings)

| | Eigenvectors | | |
|---|---|---|---|
| Variables | PC 1 | PC 2 | PC 3 |
| bcrmbdth | 0.04931 | 0.18190 | 0.00369 |
| buttcirc | 0.42064 | 0.16619 | 0.82699 |
| chstbdth | 0.13610 | 0.08112 | -0.10051 |
| chstcirc | 0.47278 | 0.29987 | -0.42611 |
| inscye1 | 0.13524 | 0.22106 | -0.14948 |
| neckcrcb | 0.08371 | 0.09394 | -0.02335 |
| shoucirc | 0.36711 | 0.48653 | -0.16138 |
| wscircom | 0.63062 | -0.66201 | -0.08647 |
| wshiplth | -0.02878 | 0.27180 | 0.24842 |
| shoulgth | 0.01035 | 0.08438 | -0.00024 |
| wstblom | 0.10139 | -0.14327 | 0.07459 |
| wstfrlom | 0.09811 | -0.09280 | 0.02676 |

As can be seen in Table 7, the PCA results for females are very similar to those obtained on the male sample. PC1 captures overall torso size which accounts for most of the variation in the sample (74%), PC2 captures shape -- a contrast between shoulders and waist that accounts for approximately 8% of the variation in the sample, and PC3 captures a contrast between chest and buttock circumferences, which accounts for 6% of female torso variation. Once again, length and frame size variables such as waist-back and waist-front lengths and biacromial breadth fail to figure prominently in the principal axes.

As in the previous males-only analysis, the first two principal components were retained, and an equal probability ellipse capturing 90% of the female population was fit to the PC scores of ANSUR females (Figure 5). Table 8 presents the anthropometric values for female forms located on this ellipse, which represent worst case extreme torso sizes and shapes for Army females.

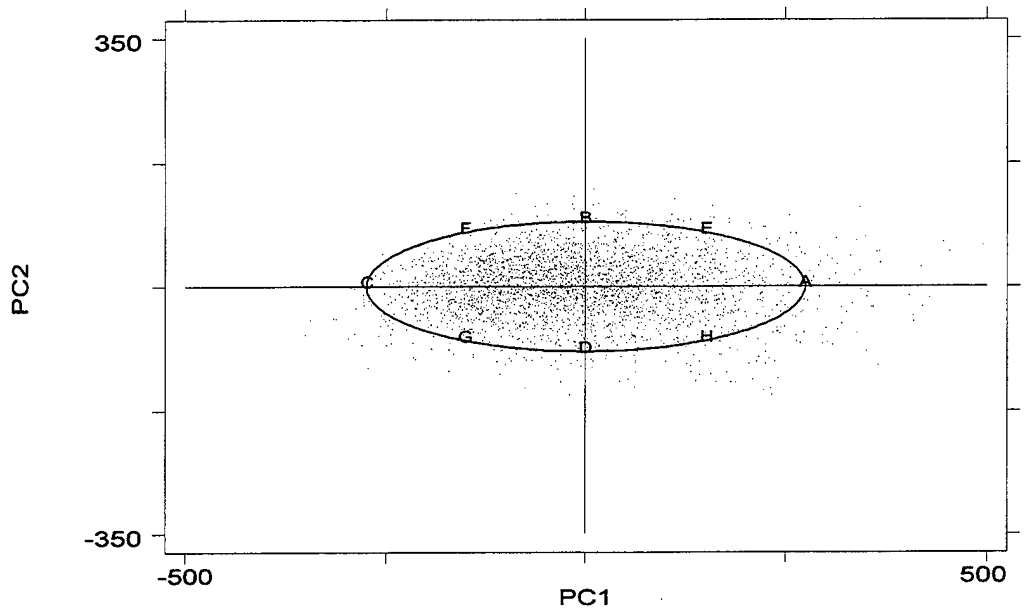


Figure 5. Equal probability ellipse for 90% of ANSUR females

Table 8. Torso dimensions, in mm, for female-only extreme forms (see Figure 5)

| | Extreme Forms | | | | | | | | Mid- |
|---|---|---|---|---|---|---|---|---|---|
| Dimensions | A | B | C | D | E | F | G | H | Size |
| bcrmbdth | 376 | 379 | 349 | 346 | 384 | 369 | 341 | 356 | 363 |
| buttcirc | 1085 | 985 | 854 | 954 | 1046 | 918 | 893 | 1021 | 969 |
| chstbdth | 318 | 288 | 243 | 273 | 308 | 266 | 254 | 295 | 281 |
| chstcirc | 1040 | 938 | 781 | 883 | 1005 | 861 | 816 | 959 | 910 |
| inscye1 | 390 | 373 | 316 | 333 | 390 | 349 | 316 | 357 | 353 |
| neckcrcb | 370 | 355 | 324 | 338 | 367 | 341 | 327 | 352 | 347 |
| shoucirc | 1130 | 1074 | 929 | 985 | 1122 | 1011 | 936 | 1048 | 1029 |
| wscircom | 971 | 737 | 625 | 859 | 843 | 652 | 753 | 944 | 798 |
| wshiplth | 139 | 172 | 155 | 122 | 164 | 172 | 131 | 122 | 147 |
| shoulgth | 147 | 152 | 142 | 137 | 152 | 149 | 136 | 139 | 144 |
| wstblom | 471 | 430 | 415 | 456 | 448 | 417 | 439 | 469 | 443 |
| wstfrlom | 417 | 382 | 363 | 399 | 398 | 368 | 383 | 412 | 390 |

### Extreme Forms for a Joint Male and Female Fitting Requirement

In order to select the appropriate extreme forms for a joint male and female requirement, the male and female forms need to be plotted together against common PC axes. Since the results from gender-specific PCA's were quite similar, a joint male and female PC analysis was undertaken in order to establish common PC axes for scoring and plotting, and to verify that the gender-specific extremes were good estimates of the mixed gender population extremes. Tables 9 and 10 present details of the joint male and female PCA and Figure 6 represents the overall result of this work, with 90% ellipses plotted for males and females individually, as well as for the male and female population as a whole.

**Table 9. Principal components analysis of male and female torso data**

| Principal Component | Eigenvalue | Difference | Proportion of Variance | Cumulative Variance |
|---|---|---|---|---|
| 1 | 26916.0310 | 22970.8618 | 0.7687 | 0.7687 |
| 2 | 3945.1692 | 2772.4747 | 0.1127 | 0.8813 |
| 3 | 1172.6944 | 193.9279 | 0.0335 | 0.9148 |
| 4 | 978.7665 | 431.2302 | 0.0280 | 0.9428 |
| 5 | 547.5364 | 141.1182 | 0.0156 | 0.9584 |
| 6 | 406.4181 | 44.8655 | 0.0116 | 0.9700 |

**Table 10. Variable loadings on PC's: males and females**
(shaded areas highlight important loadings)

| | Eigenvectors | | |
|---|---|---|---|
| **Variables** | **PC 1** | **PC 2** | **PC 3** |
| bcrmbdth | 0.10223 | 0.19379 | 0.02795 |
| buttcirc | 0.30055 | -0.45019 | 0.74837 |
| chstbdth | 0.18063 | 0.06501 | -0.05738 |
| chstcirc | 0.47037 | 0.00642 | 0.08140 |
| inscye1 | 0.18623 | 0.20218 | 0.03207 |
| neckcrcb | 0.17652 | 0.24528 | -0.09042 |
| shoucirc | 0.52374 | 0.55499 | 0.10374 |
| wscircom | 0.52136 | -0.54743 | -0.46812 |
| wshiplth | 0.04796 | 0.20400 | 0.20935 |
| shoulgth | 0.02031 | 0.06022 | 0.03290 |
| wstblom | 0.13526 | 0.03681 | -0.30352 |
| wstfrlom | 0.11127 | -0.01319 | -0.23045 |

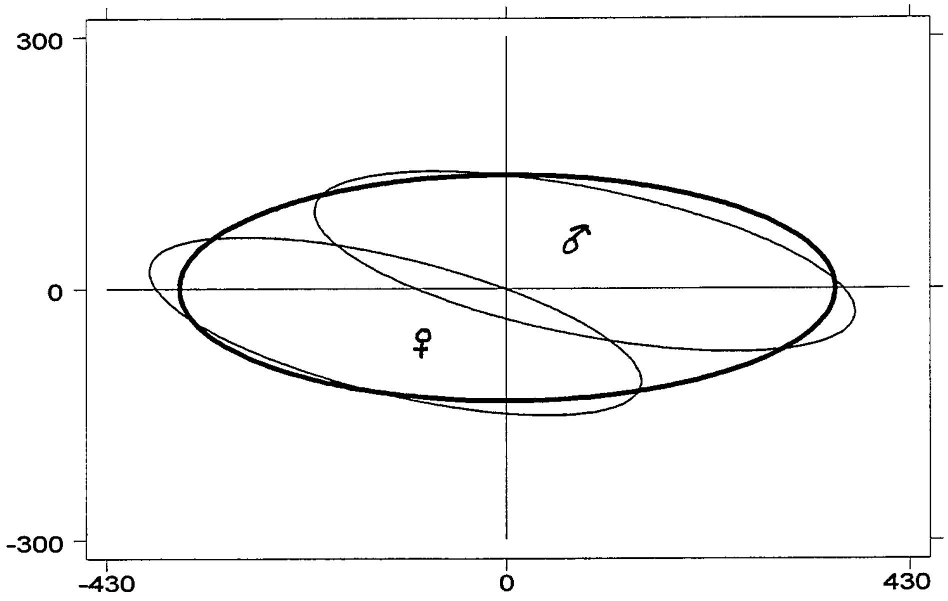


Figure 6. Male, female, and population 90% ellipses in joint PCA space

As can be seen in Figure 6, the 90% male and female ellipses overlap within the 90% joint male and female accommodation ellipse, so that "small" male extreme forms G, D, and H, and "large" female extreme forms E, B, and F (see Figure 4) do not represent extremes in the male and female population as a whole. The other gender-specific extremes are distributed around the population ellipse at approximately the correct intervals for adoption as population extremes. Although theoretical extreme forms could be taken from the joint male and female population ellipse, since the ellipse itself represents a statistical compromise of two underlying subpopulations, we believe the more conservative approach is to adopt the appropriate gender-specific forms once their locations have been verified. Table 11 presents these results, identifying the source for each of the extreme forms as either M (male) or F (female) with the letter of the gender specific form afterward. Extreme form A for the joint male and female requirement, for example, is represented by Male-only form "A". The joint male and female mid-size model is the only form whose values were calculated directly from the jointly estimated PCA.

**Table 11. Torso dimensions, in mm, for male and female 90% accommodation**

|  | A | B | C | D | E | F | G | H | Mid |
|---|---|---|---|---|---|---|---|---|---|
| SOURCE | M-A | M-F | F-C | F-H | M-B | M-C | F-D | F-A | MF |
| bcrmbdth | 415 | 402 | 349 | 356 | 415 | 379 | 346 | 376 | 383 |
| buttcirc | 1111 | 910 | 854 | 1021 | 976 | 863 | 954 | 1085 | 980 |
| chstbdth | 374 | 299 | 243 | 295 | 328 | 273 | 273 | 318 | 306 |
| chstcirc | 1139 | 940 | 781 | 959 | 1022 | 855 | 883 | 1040 | 962 |
| inscye1 | 446 | 402 | 316 | 357 | 431 | 359 | 333 | 390 | 382 |
| neckcrcb | 439 | 400 | 324 | 352 | 418 | 379 | 338 | 370 | 384 |
| shoucirc | 1292 | 1164 | 929 | 1048 | 1236 | 1064 | 985 | 1130 | 1117 |
| wscircom | 1049 | 725 | 625 | 944 | 814 | 692 | 859 | 971 | 841 |
| wshiplth | 177 | 186 | 155 | 122 | 188 | 175 | 122 | 139 | 164 |
| shoulgth | 154 | 156 | 142 | 139 | 159 | 146 | 137 | 147 | 148 |
| wstblom | 512 | 450 | 415 | 469 | 465 | 448 | 456 | 471 | 465 |
| wstfrlom | 446 | 387 | 363 | 412 | 401 | 386 | 399 | 417 | 405 |

# DISCUSSION

Although clearly quite valuable in the identification of extreme torso forms for the Army's 90% accommodation requirements, this application of PCA has raised a number of methodological questions and suggested some enhancements to the methods that are the subject of ongoing work.

First of all, there is the issue of variables we consider important to design and sizing, but these are not as precisely controlled in the PCA model as we would like. Waist-back length is a good example of this phenomenon, as it is a critical design variable for both load-bearing and armored vest systems. Since the PCA analysis was conducted on the covariance matrix (which is not standardized), we wondered whether the larger variances of the chest, shoulder, waist, and buttock circumferences could have "swamped" variation in dimensions half their magnitude. Accordingly, we also conducted PC analyses on the correlation matrix, which is standardized, and after log-transformation of the data, which should decrease the association of means and variances. Neither approach provided substantially different results in terms of the univariate ranges of extreme forms for torso lengths and breadths, and so PCA on the covariance matrix was retained as the primary method in this study. Future work should, however, include a detailed contrast of these methodological alternatives within sizing and design applications, and an examination of alternative estimation methods for dimensions of secondary design importance.

Future work will also examine the ability of this method to reduce excess disaccommodation of racial/ethnic groups that comprise statistical minorities in the Army population. In this study, we have chosen to analyze the genders separately, and thus female accommodation within the 90% soldier accommodation requirement received equal priority even though that gender comprises only 13% of the regular Army. A similar approach might be taken with racial/ethnic subgroups, and it would be useful to know the impact on the design values of extreme forms, and the relative improvement in proportions of the population accommodated by these requirements.

## SUMMARY

Weaknesses in the percentile approach to defining body size and shape extremes for engineering design have been reviewed in this report, including non-additivity of body segments, unrealistic body proportions, and overestimation of population accommodation rates. Alternative methods have been discussed, including Principal Components Analysis (PCA), which has proven useful in USAF and USN cockpit design specifications. Unlike percentile methods, PCA approaches provide extreme models with realistic body proportions, include both size and shape extremes, and yield more accurate and reliable accommodation rates in resulting designs. In this study, PCA has been used to define extreme torso sizes and shapes for the design of integrated body armor and load-bearing systems. The results suggest that PCA is also useful in developing clothing and equipment specifications. Future work is needed, however, to refine and extend the methodology.

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# APPENDIX

## ABBREVIATIONS FOR ANTHROPOMETRIC DIMENSIONS*

| Abbreviation | Dimension | Variable # |
|---|---|---|
| bcrmbdth | Biacromial Breadth | 10 |
| buttcirc | Buttock Circumference | 23 |
| chstbdth | Chest Breadth | 32 |
| chstcirc | Chest Circumference | 33 |
| inscye1 | Interscye I | 69 |
| neckcrcb | Neck Circumference, Base | 81 |
| shoucirc | Shoulder Circumference | 90 |
| wscircom | Waist Circumference, Omphalion | 114 |
| wshiplth | Waist-Hip Length | 122 |
| shoulgth | Shoulder Length | 92 |
| wstblom | Waist-Back Length, Omphalion | 111 |
| wstfrlom | Waist-Front Length, Omphalion | 117 |

*Descriptions and illustrations of anthropometric dimensions appear in Gordon et al., 1989.

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