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PREDICTING 5TH AND 95TH PERCENTILE ANTHROPOMETRIC SEGMENT LENGTHS FROM POPULATION STATURE

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ABSTRACT

Designing for human variability frequently necessitates an estimation of the spatial requirements of the intended user population. These measures are often obtained from "proportionality constants" which predict the lengths of relevant anthropometry using stature. This approach is attractive because it is readily adapted to new populations—only knowledge of a single input, stature, is necessary to obtain the estimates. The most commonly used ratios are those presented in Drillis and Contini's report from 1966 [1]. Despite the prevalence of their use, these particular values are limited because the size and diversity of the population from which these ratios were derived is not in the literature, and the actual body dimensions that each ratio represents are not clear. Furthermore, they are often misinterpreted and used inappropriately. This paper introduces a new approach, the "boundary ratio" which mitigates many of these issues. Boundary ratios improve on the traditional application of proportionality constants by: 1) explicitly defining the body dimensions, 2) defining constants for the 5^{th}, 50^{th}, and 95^{th} percentile measures, and 3) providing distinct constants for males and females when necessary. This approach is shown to better model the range of variability exhibited in population body dimensions.

INTRODUCTION

The understanding that an individual's arm length is proportional to their stature has been known for thousands of years, and the same can be said for many other segments of the body [2]. These ratios of segment lengths to each other are called "proportionality constants" (PCs). They are typically calculated by taking a large sample of anthropometric data and determining either the mean or 50^{th} percentile ratio of the length of each measure of interest to stature. Drillis and Contini were among the first to publish mathematical relationships of many body dimensions to stature in their 1966 report on body segment parameters [1]. Since then, these values have been extensively used as a design tool for everything from vehicle packaging to manufacturing layouts. They provide a means of estimating the lengths of many body segments while knowing only the stature of an individual. Consequently, proportionality constants allow design engineers to predict the length or range of adjustability of artifact components. The attractiveness of using proportionality constants is due to their ease of use and the ready availability of the single measure, stature, necessary to drive the model. For example the United States conducts an ongoing National Health And Nutrition Examination Survey (NHANES) for which stature data are released every two years [3]. This survey reports summary data for the general population by gender and is broken down by age and ethnicity. Designers can use these data to determine stature distributions for their target user population.

Proportionality constant limitations

A major drawback of Drillis and Contini's proportionality constants is caused by the uncertainty regarding which body dimensions the ratios predict (Figure 1-simplified diagram). In

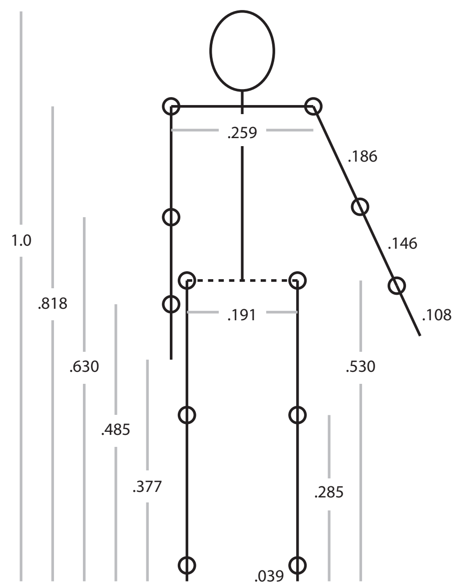

Figure 1. A sample of Drillis and Contini's proportionality constants [1].

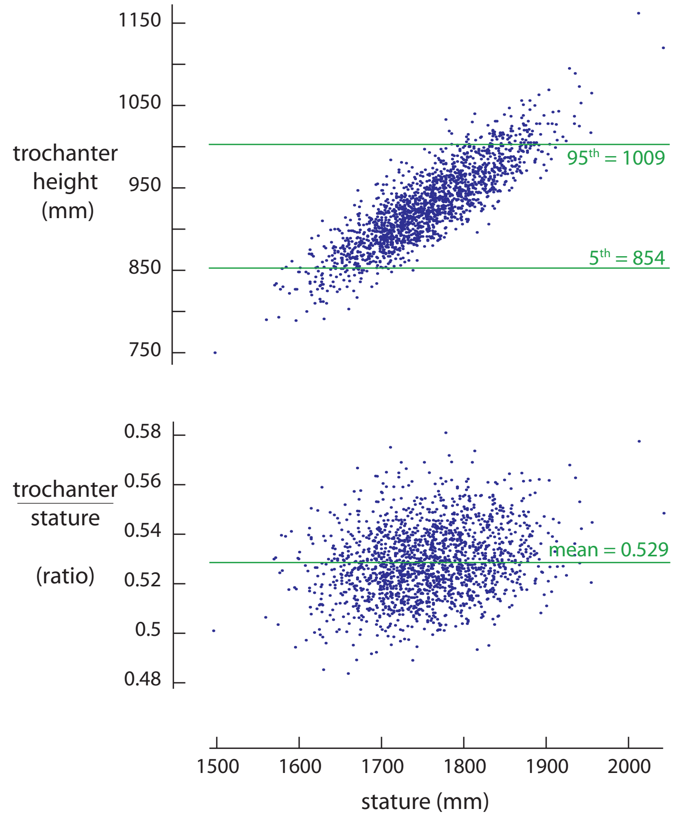

Figure 2. Trochanteric height (leg length) plotted against stature for the male ANSUR population (top) with the 5^{th} and 95^{th} percentile values marked. The ratios of these two measures for each individual within the population are shown, along with the mean value (bottom).

their report no formal definitions of the dimensions are provided [4]. For example, 0.285 is given as the proportionality constant for "knee" height. However, it is not known if this number refers to the midpatella height or the lateral femoral epicondyle height. Although this results in a bias error of only a few cm, this is often quite large relative to the amount of space or adjustability available to the designer. For example, 95% of the range of lateral femoral epicondyle height (a specific "knee height") observed in an extensive survey of male military personnel (ANSUR) is only 10 cm [5, 6]. A design that was shifted by 2-3 cm because of the ambiguity in the definition of the constant could result in unexpectedly large amounts of disaccommodation.

Although proportionality constants have been in the literature for over forty years (e.g., [7, 8]), there has been little validation performed on the accuracy of the ratios themselves [9]. Pheasant released a validation study [10] of the Drillis and Contini values, but used a different population to do the assessment. Likewise, Gannon and Moroney performed a study [4] which focused on analyzing the accuracy of proportionality constants formulated from a different population. Since the ratios in these studies were created from different populations, Drillis and Contini's ratios have not and, due to the ambiguity in their definition, cannot be validated in the traditional sense. Their accuracy as a design tool can be assessed, however, by comparing their predicted segment lengths with actual lengths measured in a target population.

An additional limitation in the application of proportionality constants is the lack of information they provide about variability in segment length ratios across a population [11]. Of particular interest are values in the tails of the distributions, e.g., the 5^{th} and 95^{th} percentile values, which can be used to approximate the requirements for a large percentage of the population. For example, consider one measure of leg length, trochanteric height. Figure 2 shows that measure plotted against stature for the male ANSUR population [5, 6]. Notice that for any given stature the population will exhibit a large range of lengths for a specific body segment. Similarly there is a large range in the ratios of trochanter height to stature. Either the mean or 50^{th} percentile value is traditionally selected for the proportionality constant. As Figure 2 shows, however, there is a range of approximately 20% in these values observed in the data for this measure.

Users of proportionality constants might account for the observed variability by estimating the 5^{th} and 95^{th} percentile segment lengths using the 5^{th} and 95^{th} percentile statures as the model inputs. For example, the 5^{th} percentile trochanteric height might be estimated to be equal to the appropriate proportionality constant (e.g., 0.529) multiplied by the 5^{th} percentile stature in the target population. This is founded in the misconception that an n^{th} percentile person by stature is comprised of n^{th} percentile body segments [2, 12]. This assumption may lead to misallocated adjustability [13], suboptimal designs, and unexpected accommodation levels, particularly when applied to multi-dimensional analyses. For example, the 5^{th}, 50^{th}, and 95^{th} percentile values observed in the ANSUR data in Figure 2 are 854, 926, and 1009 mm, respectively. Using the 0.530 value corresponding to leg length in Figure 1 and 5^{th}, 50^{th}, and 95^{th} percentile statures from the same ANSUR data, values of 874, 930, and 990 mm are obtained. If the 50^{th} percentile values are adjusted to compensate for the ambiguity surrounding the precise measure used for leg length in Drillis and Contini, the calculated 5^{th} and 95^{th} percentile values (870 mm and 986 mm) are actually the 10^{th} and 88^{th} percentile values. A designer using this constant under the best of circumstances (i.e., the values are shifted to match the 50th percentile of a known measure) would be using measures spanning 78% of the population rather than the expected 90%.

Drillis and Contini's proportionality constants have some unique limitations, but many are inherent in them all regardless of their source (e.g., [10, 14]). Any use of proportionality constants requires that the designer determine the appropriate "posture" of the user. This is as much art as science and the selections are often not repeatable within or across designers. Additionally, they fail to consider behavior that does not correlate with anthropometry. In other words, their use typically assumes that two people of the same size will interact with a designed artifact in the same way. Finally, they are often used inappropriately to do univariate assessments of designs that are inherently multivariate.

They remain, however, widely taught and used. This is primarily because of the ease with which they are explained and implemented and the comparative ease with which the necessary model input (stature) is obtained. While the results of the present work do not resolve all their many issues, they do address some of them by 1) explicitly defining the body dimensions, 2) defining constants for the 5^{th}, 50^{th}, and 95^{th} percentile measures, and 3) providing distinct constants for males and females as well as a combined population.

METHODOLOGY

The current work is neither a replacement nor an update of proportionality constants. Instead, it provides ratios, designated throughout this paper as *boundary ratios* (BRs), which are as simple to use as proportionality constants yet provide results that are more accurate and better suited for use in design analyses. Thirteen measures commonly used in design were selected for development. These are depicted graphically and with their specific names in Figure 5. A detailed explanation of each segment is available in [5]. No ratio provided is a measure of breadth, which is more strongly correlated with body mass index (BMI—a measure of weight-for-stature) than measures of length. Early proportionality constant models included estimates of breadth, but the recent increases in the prevalence of obesity have dramatically increased the amount of residual variance, rendering the use of constants impractical.

Accommodation targets often involve the 5^{th} and 95^{th} percentile body segment lengths. Consider, for a single gender, a design limited by stature that performs in a satisfactory way for everyone shorter than the 95^{th} percentile value. Such a design would theoretically accommodate 95% of that target population. Similarly, a design intended for a target population comprised of 50% males and 50% females might have both minimum and maximum height restrictions. Designing to the 5^{th} percentile female and 95^{th} percentile male is also assumed to accommodate 95% of the population (95% of men and 95% of women). Because of their frequency of use, only the 5^{th} and 95^{th} percentile boundary ratios of each dimension will be analyzed and provided in this paper.

Anthropometric database and formulation of ratios

ANSUR will be used as the database from which the boundary ratios will be calculated. It is the most comprehensive anthropometric survey representing a specific population available, and contains more than 240 measures for 1774 males and 2208 females. Unfortunately the ANSUR database is not representative of the civilian populations most often targeted in product design. Consequently, the ratios derived from ANSUR will be used to predict selected dimensions of a civilian population which has known dimensions so as to validate their accuracy; this is explained in the Validation subsection.

The ANSUR population is first separated into male and female sub-populations. For each dimension within these two populations, the corresponding proportionality constant is calculated by taking the mean of each segment's ratios:

$$p_a = \frac{\sum_{i=1}^{N} l_i/s_i}{N} \tag{1}$$

where p_a is the proportionality constant for segment a, there are N values in the database, and l_i and s_i are the length of the segment of interest and stature for the i^{th} person in the database. The boundary constants are calculated in a slightly different manner. The 5^{th}, 50^{th}, and 95^{th} percentile lengths are extracted, as well as the 5^{th}, 50^{th}, and 95^{th} percentile statures. Each n^{th} percentile dimension is divided by the n^{th} percentile stature:

$$b_{a,n} = \frac{l_{a,n}}{s_n} \tag{2}$$

where b is the boundary constant, n is the percentile of interest, and the other variables are defined as previously. For the present

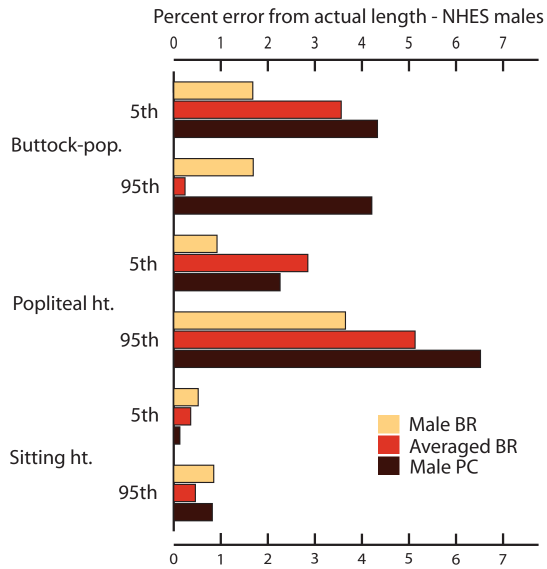

Figure 3. Percent error between predicted lengths and actual lengths of male 1960-62 U.S. NHES population. BR = boundary ratio, PC = proportionality constant.

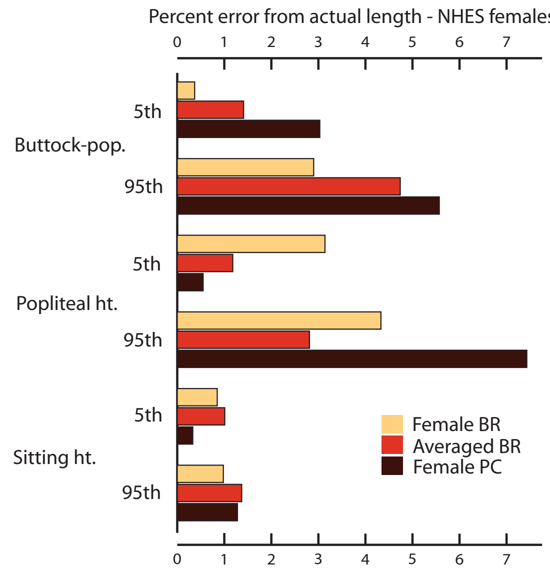

Figure 4. Percent error between predicted lengths and actual lengths of female 1960-62 U.S. NHES population. BR = boundary ratio, PC = proportionality constant.

work, these calculations provide 13 proportionality constants and 39 (3 levels $\times$ 13 measures) boundary constants for each of the male and female populations. A third set of boundary constants is determined by averaging those obtained for the males and females. All are reported in the table shown in Figure 5. Using the 5^{th} and 95^{th} percentile statures in these ratios allows information about the range of statures in a target population to be captured. This improves the accuracy of the predictions and the extensibility of the model to new populations where the standard deviations in the stature data are different than those observed in the data from which the model was made.

Validation

To demonstrate the accuracy of these boundary ratios compared to traditional proportionality constants, two validation analyses are performed. Segment lengths were predicted at several percentile levels for each of two populations. The calculations were made using the both the boundary constant approach and the traditional proportionality constants. In order to make more useful comparisons, proportionality constants were calculated from the same population as the boundary constants (i.e., ANSUR). These removes the effects of differences across populations that might be evident were the PCs calculated for one population and the BRs for another. The percentage of absolute error was used as an indication of the relative effectiveness of the models. Using absolute error should not impact the significance of the validations because overestimation and underestimation of body dimensions both cause significant problems. Underestimation results in products with less accommodation than expected. Overestimation might provide better-than-expected accommodation, but often at additional cost.

The first validation example uses anthropometric data from the 1960-62 U.S. National Health Examination Survey (NHES) (contained within [9]). The data within the NHES survey are limited in some respects. They contain a limited number of anthropometric measurements so only three measurements (buttock-popliteal length, popliteal height, and sitting height) are examined. Additionally, they contain some error due to variation in measurement technique. These data are a good candidate for validation, however, since the NHES population is so different than that from from which the model was built (ANSUR). Among the differences are those in ethnicity, fitness, age distribution, and secular increases in stature and BMI that occurred in the 35 years between the NHES and ANSUR studies. Predicted 5^{th} and 95^{th} percentile values for the NHES population were calculated and compared against known values for the measures. The predictions were made using proportionality constants and both gender-specific and averaged boundary ratios.

A more comprehensive validation was performed for all of the measures using two sub-populations of ANSUR. These data are generally not useful for designing for civilian populations because they are more "fit" than the general population. To provide some indication of the applicability of the boundary ratios to a general population, only individuals with BMI ≥ 26 (those over 25 are generally considered to be overweight) are used for the analysis. This yielded data for 843 men and 434 women, sample sizes large enough to effectively perform the test. Segment lengths were calculated using both the proportionality constant and boundary ratio approaches. For either approach the length is intended to be either the 5^{th} or 95^{th} percentile value. To quantify the error in the estimation, the lengths were predicted then compared to the actual data to determine the actual percentile represented. Although data could have been withheld from the model-building to use for the validation exercise, the value of keeping the full diversity of samples within the data set was more important. Since both the BRs and PCs were calculated from the same full data set, comparisons across the two methodologies when using the reduces set should still be a good indication of their relative accuracy.

RESULTS

Using the boundary ratios in Figure 5 and the proportionality constants derived from ANSUR, segment lengths were predicted for five populations: NHES, the male and female ANSUR populations, and two sub-population of ANSUR: males with BMI ≥ 26 and females with BMI ≥ 26. The absolute error for the male and female NHES populations are shown in Figures 3 and 4. Gender-specific boundary ratios show a moderate improvement over proportionality constants in eight of twelve cases.

The results from the ANSUR comparisons are much more conclusive and more easily interpreted. Using the procedure outlined in the Methodology section, the actual percentiles which match the predicted values are calculated for the general male ANSUR and the male ANSUR with BMI ≥ 26 sub-populations. The same procedure is followed for the general female ANSUR and female ANSUR with BMI ≥ 26 sub-populations. This is possible because all the measures for each person within the database are reported (rather than just the summary statistics reported in NHES and other surveys).

Using either the proportionality constant or boundary ratio approaches, the designer would be expecting that the calculated range would indicate 90% of the range of values on that measure. The actual ranges are different however (Table 2). For the general male and female ANSUR populations the boundary ratios perform exactly as expected. The range should be exactly 90% since they were calculated from these data directly. The proportionality constants, however, which were also calculated from these data, do not perform very well. The average range using them is 78.6% for males and 77.2% for females. For the sub-populations the boundary ratio approach still performed well, producing an average range across the 13 measures of 89.2% for males and 89.9% for females. The average range for the proportionality constants is 78.0% for males and 77.6% for females. In other words, designers are likely to underestimate univariate accommodation for males by 12% and for females by 12.4% using a best-case proportionality constant approach.

DISCUSSION

Boundary ratios, as described in this paper, make three principal contributions. First the segments for which the ratios are calculated are explicitly defined and are related to a known and publicly available dataset. Second, ratios for extreme percentiles (5^{th} and 95^{th}) where much of the design work is done, are provided. Third, ratios are provided for both the male and female populations in addition to an averaged set of data.

As expected boundary ratios show increased accuracy over equivalent proportionality constants, particularly in the tails of the distributions. The results of the NHES validation analysis show both the gender specific and the combined boundary ratios have less error. While this study only examines three dimensions, there is consistency in the results showing increased prediction accuracy, and as a result it is reasonable to infer the boundary ratios of other dimensions (Figure 5) will produce better estimates than proportionality constants. The second, more in-depth analysis of the male and female ANSUR sub-populations strengthens the conclusions from the NHES analysis regarding gender specific boundary ratios. The male boundary ratio predictions provide an average range across 13 measures of 89.2%, which closely matches the expected range of 90%. Proportionality constants however, produce a range of 78.0%, showing significantly less prediction accuracy. Similarly, female boundary ratio predictions estimate an average range of 89.9%, while proportionality constants provide a considerably smaller range of 77.6%. Based on these results, it is expected that the boundary ratios provided in Figure 5 can be used instead of proportionality constants to more consistently predict the 5^{th} and 95^{th} percentile dimensions of a population. Additionally, the nearest ratio might be used when other percentiles are desired (e.g., use the 95^{th} percentile ratio with the 97^{th} percentile stature to estimate a 97^{th} percentile length).

There are some limitations in the approach, however. As in any proportionality constant approach, the boundary ratios were calculated for a particular population (ANSUR) at a particular moment in time. This population had age, fitness, and ethnicity distributions which are likely different than those in a target design population. Although secular trends such as the increase in stature and weight within a population over time are not likely to affect the boundary ratios (as the HFES example demonstrated) different ethnicities can exhibit different ratios of body dimensions. As such, extending these ratios to vastly different populations (e.g., a target population in China or Scandinavia) might produce poor results. Nevertheless this work assumes that ratios and the relative distributions of segments are somewhat constant across large populations and that is not necessarily the case. Although the approach was shown to work well for a very different population from which it was derived, it is likely that target populations that differ significantly (e.g., in ethnicity distribution, in overall fitness, etc.) from the ANSUR population will experience more error than those that are similar. The approach also does not address measures of breadth such as seated hip breadth or shoulder breadth which are strongly correlated with BMI. This is a critical gap in current approaches that is becoming increasingly important as the prevalence of obesity in the U.S. population rapidly increases.

It is important when utilizing the boundary ratios provided in this paper to understand what they represent, how they can be used, and the results that they give. Using boundary ratios, either gender-specific or averaged, for design purposes is one way to size artifacts which are solely driven by anthropometry (i.e., don't include preference [13]. However, more accurate estimates can always be obtained using data from a study of the intended participants. In particular, gathering information about variability that is not correlated with anthropometry is vital to the success of designing for human variability [15, 16].

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Table 1. Estimated percentile values for the full ANSUR male population and a sub-population consisting of those participants with BMI≥ 26. Predictions are made using male boundary ratios (BR) and ANSUR proportionality constants (PC). In each case the designer would expect the range to include 90% of the data in the population.

	full ANSUR male population						ANSUR males BMI $\geq$ 26					
	PC %tile		Δ	BR %tile		Δ	PC %tile		Δ	BR %tile		Δ
expected	**5**	**95**	**90**	**5**	**95**	**90**	**5**	**95**	**90**	**5**	**95**	**90**
acromial ht	8	93	85	5	95	90	6	92	86	4	94	90
trochanterion ht	11	88	77	5	95	90	12	89	77	6	96	90
lat femoral epicondyle ht	11	88	77	5	95	90	11	88	77	5	94	89
lat malleolus ht	21	80	59	5	95	90	22	79	57	6	92	86
hand ln	11	89	78	5	95	90	8	85	77	4	92	88
radiale-stylion ln	13	86	73	5	95	90	14	84	70	5	94	89
acromion-radiale ln	11	90	79	5	95	90	11	88	77	4	94	90
popliteal ht	13	87	74	5	95	90	16	90	74	7	96	89
buttock-popliteal ln	12	88	76	5	95	90	11	85	74	5	93	88
acromial ht, sit	11	90	79	5	95	90	8	88	80	3	93	90
eye ht, sit	7	93	86	5	95	90	6	93	87	4	95	91
sitting ht	6	95	89	5	95	90	5	95	90	4	95	91
thumbtip reach	11	90	79	5	95	90	10	86	76	5	93	88
			mean 78.6			mean 90.0*			mean 78.0			mean 89.2

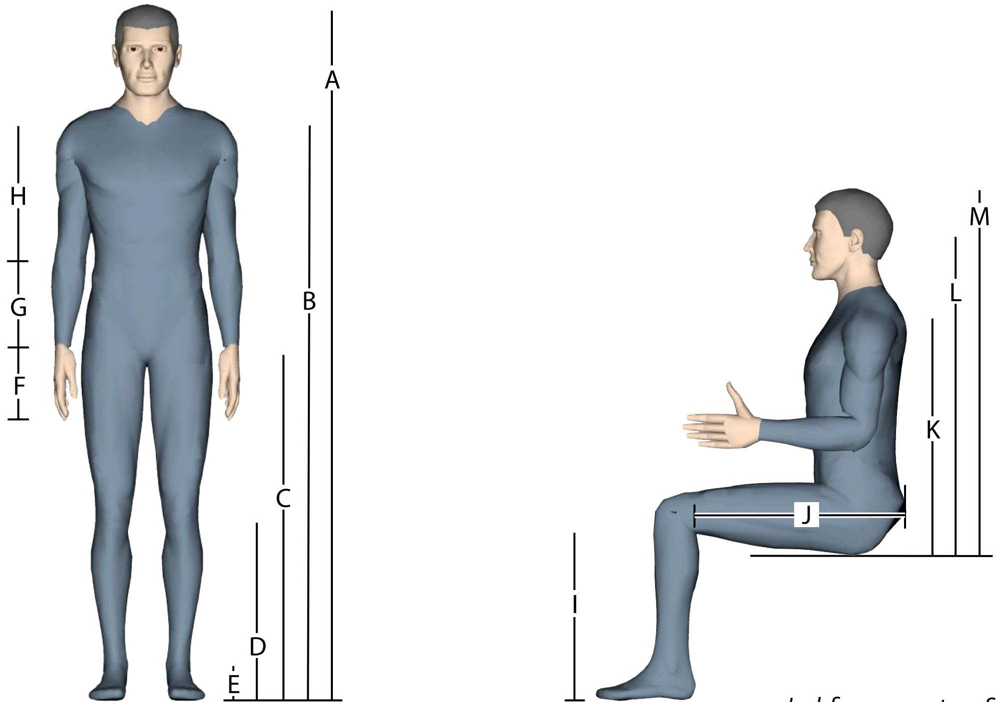
*boundary ratios were calculated directly from this population and are exact by definition

Table 2. Estimated percentile values for the full ANSUR female population and a sub-population consisting of those participants with BMI≥ 26. Predictions are made using female boundary ratios (BR) and ANSUR proportionality constants (PC). In each case the designer would expect the range to include 90% of the data in the population.

	full ANSUR female population						ANSUR females BMI $\geq$ 26					
	PC %tile		Δ	BR %tile		Δ	PC %tile		Δ	BR %tile		Δ
expected	**5**	**95**	**90**	**5**	**95**	**90**	**5**	**95**	**90**	**5**	**95**	**90**
acromial ht	7	93	86	5	95	90	6	93	87	5	95	90
trochanterion ht	11	89	78	5	95	90	11	90	79	5	96	91
lat femoral epicondyle ht	12	89	77	5	95	90	13	90	77	6	96	90
lat malleolus ht	24	78	54	5	95	90	22	78	56	4	96	92
hand ln	12	89	77	5	95	90	7	85	78	3	93	90
radiale-stylion ln	16	84	68	5	95	90	18	84	66	7	95	88
acromion-radiale ln	12	88	76	5	95	90	10	88	78	5	95	90
popliteal ht	16	86	70	5	95	90	27	93	66	10	97	87
buttock-popliteal ln	13	88	75	5	95	90	9	83	74	3	93	90
acromial ht, sit	12	90	78	5	95	90	8	87	79	3	93	90
eye ht, sit	8	93	85	5	95	90	7	93	86	5	95	90
sitting ht	7	94	87	5	95	90	6	95	89	4	95	91
thumbtip reach	11	91	80	5	95	90	7	89	82	4	94	90
			mean 77.2			mean 90.0*			mean 77.6			mean 89.9

*boundary ratios were calculated directly from this population and are exact by definition

Figure 5. Some anthropometric segments common in designing for human variability. The boundary ratios for estimating the 5^{th}, 50^{th}, and 95^{th} percentile lengths for a general population are provided in the table.



Jack figure courtesy Siemens PLM Software

Boundary Ratios (fraction of appropriate stature value) for 5th, 50th, and 95th percentile segment lengths

		females			males			averaged		
		5	50	95	5	50	95	5	50	95
A	stature	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
B	acromial ht	0.814	0.818	0.823	0.814	0.821	0.827	0.814	0.820	0.825
C	trochanterion ht	0.517	0.528	0.539	0.518	0.527	0.540	0.518	0.528	0.540
D	lat femoral epicondyle ht	0.276	0.283	0.290	0.280	0.285	0.292	0.278	0.284	0.291
E	lat malleolus ht	0.034	0.037	0.040	0.036	0.038	0.041	0.035	0.038	0.041
F	hand ln	0.108	0.111	0.113	0.109	0.110	0.112	0.109	0.111	0.113
G	radiale-stylion ln	0.144	0.149	0.155	0.149	0.153	0.159	0.147	0.151	0.157
H	acromion-radiale ln	0.186	0.191	0.196	0.190	0.194	0.198	0.188	0.193	0.197
I	popliteal ht	0.230	0.239	0.247	0.240	0.247	0.255	0.235	0.243	0.251
J	buttock-popliteal ln	0.288	0.295	0.304	0.278	0.285	0.292	0.283	0.290	0.298
K	acromial ht, sit	0.334	0.341	0.348	0.333	0.341	0.346	0.334	0.341	0.347
L	eye ht, sit	0.448	0.453	0.458	0.447	0.451	0.454	0.448	0.452	0.456
M	sitting ht	0.520	0.523	0.524	0.518	0.521	0.520	0.519	0.522	0.522
*	thumbtip reach	0.443	0.450	0.458	0.449	0.456	0.463	0.446	0.453	0.461

* Thumbtip reach is the horizontal distance from a back wall to the tip of the thumb

additional information at *http://www.dfhv.org*