

Extrapolation of Anthropometric Measures to New Populations

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ABSTRACT

This paper advances a method of extrapolating, to target populations, inter-relationships in the anthropometry of an existing population database. Previous methods, including those that are based on using proportionality constants and those that involve developing regression relations, make use of stature as the primary predictor. This new approach distinguishes itself by accounting for the variability, across all the measures, that is not correlated with stature or other anthropometry. It builds on previous efforts by incorporating both stature and body mass index (BMI) as basic predictors in a single-step regression analysis of existing anthropometric data. The method is validated and shown to produce anthropometric measures for a population that are equivalent to the true measures. Additionally, this paper examines the effectiveness of multi-step regression in predicting anthropometry. This technique is compared with the single-step regression approach and is shown to not always result in improved accuracy. While the methodology proposed in this paper is not a replacement for gathering true anthropometric data from populations of interest, it is a useful tool for estimating larger sets of anthropometry when only a few measures (such as stature and BMI) are available. This will facilitate the use of digital human models in designing, with increased efficacy, for human variability.

INTRODUCTION

Digital human modeling is being increasingly used in virtual simulations of human-machine interfaces. The applications of these models are diverse, ranging from designing workstations for industrial workers to planning vehicle cabin layouts (Lockett et al., 2005; Ziolek and Kruithof, 2000; Archer and Kolich, 2005). The keystone of all these designs is maximizing the *accommodation*, i.e. making a

product suitable for use by as high a percentage of the target population as is feasible.

Designing for maximum accommodation of a target population requires the determination of the relevant anthropometric variability of potential users. For example, in seat design, it might be necessary to ascertain the minimum seat height and adjustability required to accommodate the desired percentage of the target population. Adjustability, however, has a drawback: in general, the manufacturing costs associated with a product increase with the amount of built-in adjustability. Minimizing adjustability while maximizing accommodation is, therefore, one of the principal challenges in designing for human variability.

Numerous techniques have been used over the years to achieve this goal. Fundamental to them all is the idea of determining the limiting values of those body segment lengths that are pertinent to the design (HFES 300 Committee, 2004). For example, in order to achieve 90% accommodation of a target population, a product may be designed for users between the 5th and 95th percentiles. The values of the pertinent body measures at these two percentile limits are used to determine, respectively, the minimum and maximum values of the design parameters. Accurate information about the variation of these body measures is, therefore, of prime importance to the designer. However, this information is not always available.

It is hence necessary to accurately estimate the variation of the anthropometry that is relevant to a design. Stature and body mass index (BMI) are among the most readily available body measures. Furthermore, since the correlation between the two measures is minimal, they can be used simultaneously in statistical analysis without compromising on its accuracy. It is, therefore, convenient to be able to develop a model based on these two measures to predict the required body segment lengths.

Anthropometry required in accommodation analyses may be computed by making use of proportionality constants—a fixed set of ratios of various body segment lengths to stature (Drillis and Contini, 1966). For instance, the 5th and 95th percentile body segment lengths of a population can be obtained by multiplying the proportionality constants with the 5th and 95th percentile statures, respectively. In this way the upper and lower limits of the design variables for the required accommodation (90% in the example) are determined. A-CADRE (Bittner, 2000) is a more rigorous boundary manikin approach in which much of the anthropometric variability relevant to workstation design is considered. Commonly used digital human modeling software such as Jack (UGS, 2007) and RAMSIS (Human Solutions, 2007) are other methods which base manikin anthropometry on statistical analyses of population data.

Approaches that rely on proportionality constants are often based on certain assumptions. Among them: a) that all humans are similarly proportioned, b) that if, for example, an individual is 5th percentile by stature, all the individual's body segment lengths are 5th percentile, and c) that the required accommodation can be achieved by independently accommodating for each of the relevant body measures. However, body proportions are known to vary both within and across populations (Ruff, 2002). Additionally, people are not generally composed of body segments that are all of the same percentile (Roebuck, 1995). In other words, it is possible, for example, for a subject who is 90th percentile by stature to be 50th percentile by body mass index, 70th percentile by buttock-knee length, etc. Furthermore, techniques that are based on proportionality constants are prone to inaccuracies when used in designing for multiple dimensions, causing undesirably and unexpectedly high disaccommodation (Friess, 2005; Moroney and Smith, 1972; Gannon and Moroney, 1998). This has been proven to be caused by correlations between anthropometric variables (Moroney and Smith, 1972). For instance, the set of disaccommodated subjects in a population differs depending on whether a 5th to 95th percentile stature criterion or a 5th to 95th percentile BMI criterion is applied. Applying both these criteria while using a technique based on proportionality constants causes the percentage of disaccommodated subjects to exceed the targeted value of 10%.

An alternative to the aforementioned techniques may be used when data about the relevant anthropometric measures are readily available. This alternative involves developing regression relations with basic anthropometry (stature, BMI, etc.) as predictors of those body measures that most directly influence the design parameters. The limiting values of the design parameters may thus be calculated (Robinette and McConville, 1981; Flannagan et al., 1998; Reed et al., 1999). An extension of this method is a hybrid approach, wherein regression models based on data collected in experiments are extended to existing population databases. The drawback of this

approach is its inability to represent the variability of anthropometric measures, since only their mean values may be calculated from the regression equations. The method fails to account for the possibility, for example, that two people with the same stature may have different knee lengths.

Recent data modeling methods make it possible to account for this variability in body segment lengths about their mean values. Anthropometric variables from a population database are subjected to regression analyses to formulate relations between the pertinent body measures and the chosen predictors. Next, these relations are extrapolated to the target population to generate the required body segment lengths using the new values of the same predictors. Variability in the design parameters is then simulated by retaining the residual variance from the regression and reintroducing it into the predictive model as a stochastic component (Reed et al., 2002; Parkinson and Reed, 2006; Garneau and Parkinson, 2007). This method has been proven capable of generating anthropometric measures that are statistically equivalent to the actual measures.

The cascading prediction model (Reed et al., 2002) and the hierarchical regression technique (You and Ryu, 2004, 2005) have been found to increase the accuracy of body posture and anthropometry calculations, respectively, through a series of regressions. The basic idea behind these approaches is to estimate the required measures using the variables they are most closely correlated to. A sequence of regressions is developed in which a variable that is predicted in one step becomes the predictor in the next. With variables such as stature or BMI as the predictors in the first step, the required design parameters can be calculated using this multi-step regression method.

The current work does the following: a) demonstrates the use of error variance to improve the realism of predicted body segment variation, b) explores the use of BMI as a predictor to increase accuracy of predictions of certain anthropometric measures, and c) examines the impact of the multi-step regression technique on body segment length prediction. The body segments selected for this demonstration are popliteal height and standing and sitting hip breadths.

METHODS

Existing anthropometry-prediction models could be improved in three ways: a) by increasing the accuracy of predictions for the higher and lower percentiles of the population, b) by introducing, into the predictions, the variability that is characteristic of any body segment measure, and c) by making the model reconfigurable (i.e., fit for use across populations). These were explored and are described in the following sections.

Taking into consideration their relevance in human modeling and the availability of accurate data, three body measures—popliteal height and standing and sitting hip breadth—were chosen for the study. Their relations to their respective predictors were studied through linear regression analyses. The error variances determined in these analyses were incorporated into the predictions and the results compared with actual anthropometric values from the population database. Multivariate regression was used to study the dependence of hip breadth on BMI. Finally, for the multi-step regression analyses, the predictors were classified as being primary or secondary, with the latter being more closely related to the required anthropometry. A two-step procedure was used to relate the secondary predictors to the primary predictors, and then the required anthropometry to the secondary predictors.

All the anthropometric measures used in the analyses—stature, weight, popliteal height, standing and sitting hip breadth, and trochanteric height—were drawn from the ANSUR database (Gordon et al., 1989). The sample population consisted of the entire male population of 1774 individuals.

RESIDUAL VARIANCE IN THE PREDICTION Linear, univariate regression was performed to formulate a relation between all the popliteal height (P) and stature (S) measures in the ANSUR database

$$P_{det} = 0.3176S - 123.6. \quad (1)$$

Using Eq. 1, popliteal heights were calculated using the same stature predictors S . The resulting predicted popliteal heights are P_{det} since the values are deterministic—for any given S a specific P will result. The error variance resulting from the regression analysis is termed the *residual variance*. The standard deviation of error s in popliteal height prediction was calculated as the square root of its residual variance. The residual variance was added to the regression Eq. 1 as a stochastic term randomly drawn from a normal distribution with mean 0 and variance s^2 :

$$P_{var} = 0.3176S - 123.6 + N(0, 13.0^2). \quad (2)$$

A new set of popliteal heights, P_{var} , was calculated using Eq. 2 with the same stature predictors S as used previously.

BODY MASS INDEX AS A PREDICTOR Anthropometric variables that correlate well with stature can be predicted to an acceptably accurate degree with stature as the sole predictor. Similarly generated predictions of body measures that are more strongly correlated to BMI are not sufficiently accurate. This was demonstrated when regression was performed on standing hip breadth using stature (H_{stat}) and BMI (H_{BMI}) separately as predictors:

$$H_{stat} = 0.1374S + 100.5 + N(0, 18.1^2) \quad (3)$$

and

$$H_{BMI} = 4.675B + 220.7 + N(0, 14.9^2). \quad (4)$$

The stochastic term, which includes the error variance, is included in both Eqns. 3 and 4.

In the third step, standing hip breadth H_{sB} was calculated by a linear, multivariate regression with both stature and BMI as predictors,

$$H_{sB} = 0.1345S + 4.635B - 14.4 + N(0, 11.2^2). \quad (5)$$

MULTI-STEP REGRESSION The final part of the analysis was used to study the impact of multi-step regression on anthropometry prediction. This method is a sequence of regression analyses with each step involving the prediction of a variable of interest using, as the predictor, the variable that was predicted in the previous step. For the present work two variables of interest—popliteal height and standing hip breadth—were explored. For the first example, stature was used to determine trochanteric heights for the population, then both stature and trochanteric height were used to predict popliteal height. Similarly stature and BMI were used to predict standing hip breadth, which was then included in the prediction of seated hip breadth.

Popliteal Height First, regression determined the relationship between trochanteric height and stature

$$T_{var} = 0.6174S - 155.7 + N(0, 24.0^2). \quad (6)$$

The stochastic component was included as described above.

Next, regression analysis of the ANSUR data was used to relate stature and trochanteric height to popliteal height

$$P_{multi-step} = 0.3082S + 0.0151T - 121.1 + N(0, 13.0^2). \quad (7)$$

In practice $T = T_{var}$ since the trochanteric heights used in Eq. 7 were obtained using Eq. 6. This procedure was followed, again driven by the stature (S) of the ANSUR population.

Seated Hip Breadth Since Eq. 5 gives standing hip breadth (H_{sB}) as a function of stature and BMI, only the second step in determining the multi-step regression equations needed to be performed

$$H_{sit} = 0.1578S + 6.3177B + 0.0048H_{std} - 72.4 + N(0, 12.2^2) \quad (8)$$

where H_{sit} is the ultimate variable of interest. A set of these seated hip breadth values was determined using the ANSUR stature and BMI as predictors.

RESULTS

The results of the analyses described in the previous section are presented in the following paragraphs.