Development and Application of a Generation Method of Human Models for Ergonomic Product Design in Virtual Environment

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A group of digital human models with various sizes which properly represents a population under consideration is needed in the design process of an ergonomic product in virtual environment. The present study proposes a two-step method which produces a representative group of human models in terms of stature and weight. The proposed method first generates a designated number of pairs of stature and weight within an accommodation range from the bivariate normal distribution of stature and weight of the target population. Then, from each pair of stature and weight, the method determines the sizes of body segments by using 'hierarchical' regression models and corresponding prediction distributions of individual values. The suggested method was applied to the 1988 US Army anthropometric survey data and implemented to a web-based system which generates a representative group of human models for the following parameters: nationality, gender, accommodation percentage, and number of human models.

Introduction

Computer-aided ergonomic design systems improve the efficiency of product design process by using digital human models. These systems visualize workstation designs such as passenger car interiors, fighter cockpits and factory workplaces in computer environment, diagnose and revise the designs through the evaluation of ergonomic criteria such as reach, visibility and comfort by utilizing human models. Workstation design methods with digital human models make the iterative design process of evaluation, diagnosis and revision more rapid and economical.

Although a group of human models with various body sizes is required in designing a workstation accommodating a designated range of the population properly, existing ergonomic design systems provide only a small number of human models which can't represent the population statistically. To investigate whether a product design accommodate the population properly, product evaluation by using human models with various size, which represent the characteristics of body sizes of the population, is needed. But, the previous system such as JACK®, RAMSIS® and SAFEWORK® generate human models corresponding 5, 50, and 95th percentiles of stature (Case et al., 1990; Fortin et al., 1990; McDanlel, 1990; Sengupta & Das, 1997).

Also, previous methods to generate a group of human models representing various body sizes of the population show limitations in representing various body sizes and proportions of the population. Bittner et al. (1987) and Bittner (2000) proposed methods to generate human models located on the boundary of body size distribution of the population by using factor analysis. The factor method presents the multivariate distribution of anthropometric variables with a few factors and generates several human models corresponding to the boundary defining a designated accommodation range of the distribution. Thus, the factor method doesn't consider the size variety which can exist in the accommodation range. Also, the boundary of a designate accommodation range can be established accurately in the body size distribution presented by less than 3 factors, because it can be presented visually in less than 3 dimensions. Moreover, Eynard et al. (2000) classified a population into 5 body types with stature, weight, trunk length and leg length by using cluster analysis and proposed a method to generate human models having the average body sizes in each body type. But, the cluster method generates only one human model for each body type and can not represent various body sizes of the population.

The present study proposes a method to generate a group of human models with various sizes which represent the target population statistically and reflect the characteristics of body sizes of the population. The proposed generation method of a group of human models forms pairs of stature and weight representing the population of a designated accommodation range based on bivariate normal distribution of stature and weight. And, from each of the pair of stature and weight it determines sizes of body segments by applying hierarchical regression models (see Section 2.2 for details). The developed generation method of a group of human models was applied in developing a web-based system to generate a group of human models automatically based on a designated accommodation range of the population and number of human models to be generated.

Human model generation method

The present developed a two-step method (see Figure 1) forms a group of human models by generating a designated number of pairs of stature and weight within an accommodation range and predicting the body sizes of human models from the pairs. First, the method generates a designated number of pairs of stature and weight within an accommodation range of a population from the bivariate normal distribution of stature and weight. Then, the sizes of the body segments of each human model with certain stature and weight were predicted from the sampling distribution of prediction values of hierarchical regression models (see Section 2.2 for details).

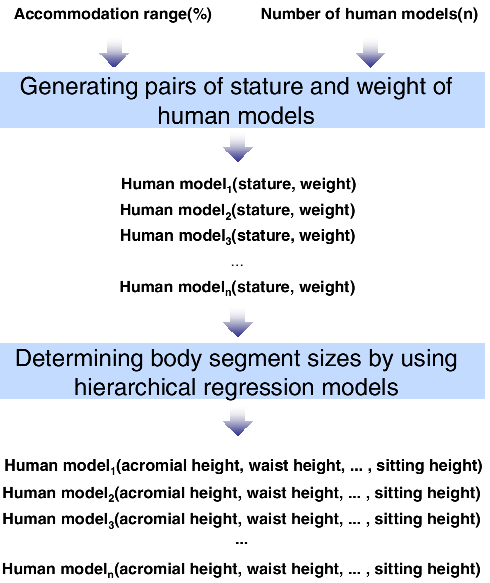


Figure 1. Generation process of representative human models

Generating pairs of stature and weight of representative human models

Pairs of stature and weight are composed by 1) generating a pair from the bivariate normal distribution of stature and weight randomly, 2) testing whether the pair is within a designated accommodation range of the population like Figure 2. First, a pair of stature and weight is generated randomly from the corresponding bivariate normal distribution. Stature and weight are generally known to be normally distributed (Roebuck, 1975), and this study assumed stature and weight have a bivariate normal distribution. By using the 1988 US Army data, stature and weight were identified to follow a bivariate normal distribution with 175.6 cm and 78.5 kg of average, 44.7 and 123.5 of variance, and 0.5 of correlation coefficient ($\chi^2_9 = 9.66$, $p = 0.379$).

Then, the generated pair of stature (S) and weight (W) is tested if it belongs to the accommodation range ($100p$%, $p = 0 \sim 1$) specified. The normalized squared distance (D) of the generated pair from the center of the bivariate normal distribution is calculated.

$$D(S,W) = (S-\mu_s \quad W-\mu_w)\begin{pmatrix}\sigma_s^2 & \sigma_{sw} \\ \sigma_{sw} & \sigma_w^2\end{pmatrix}^{-1}\begin{pmatrix}S-\mu_s \\ W-\mu_w\end{pmatrix} \quad \text{(Equation 1)}$$

If D is less than $\chi_2^2(1 - p)$, accept the pair of stature and weight as one within the accommodation range (Jonson & Wichern, 1988). For example, the values of D of two pairs of stature and weight, (182 cm, 60 kg) and (171 cm, 90 kg), from the center of the corresponding distribution of the 1988 US Army data (175.6 cm, 78.5 kg) are 6.28 and 3.31; for $\chi_2^2(1 - p) = 4.61$ at $p = 0.9$, only the latter pair is selected as one within 90% of accommodation range. The two-step stature and weight generation process is iterated until the required number of pairs is obtained. Figure 3 illustrates one thousand pairs of stature and weight generated by using the proposed method within 90% of accommodation range in the corresponding bivariate normal distribution of the 1988 US Army data.

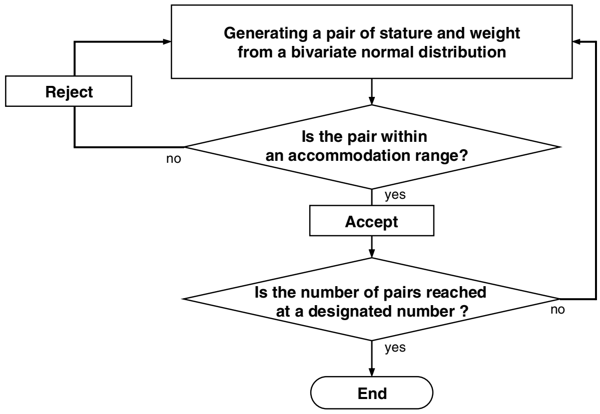


Figure 2. Generating process of stature and weight pairs of human models

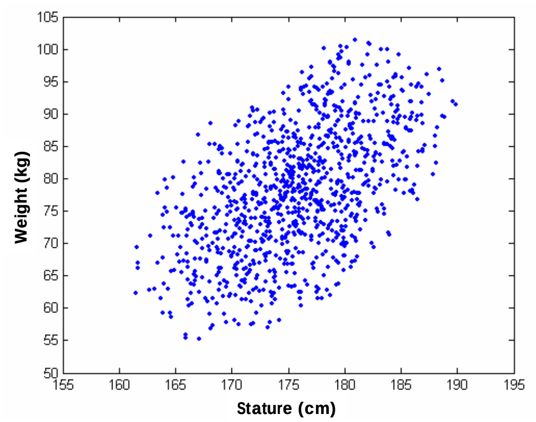
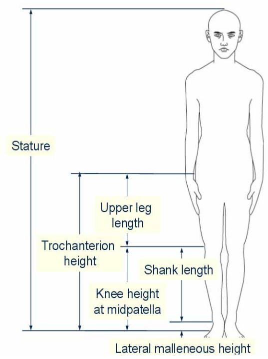


Figure 3. 1000 pairs of stature and weight generated within 90% of accommodation range in the 1988 US Army male data

Generating body segment sizes of human models

Hierarchical regression models for anthropometric variables are used in the present study to predict the body segment sizes of each human model. While in general regression models for anthropometric variables are established by using only stature and/or weight as regressors (termed 'flat' estimation), hierarchical models by using different variables selectively based on the anatomical and statistical relationships between anthropometric variables (Ryu & You, in press). For example, as illustrated in Figure 4, when building regression models for five anthropometric variables at the leg, the flat estimation method uses only stature as regressor, whereas the hierarchical estimation method includes different anthropometric variables as regressors (stature for trochanterion height; trochanterion height for upper leg length and knee height; knee height for shank length and lateral malleneous height). Ryu & You (in press) showed most of hierarchical models were superior to flat models in terms of estimation accuracy and adequacy of fit: of 45 pairs of hierarchical and flat models, 39 hierarchical models showed an average decrease of 31% (0 ~ 72%) in MSE and an average increase of 55% (0 ~ 343%) in adjusted R^2 when compared to the corresponding flat models.



trochanterion height = f_1(stature)
upper leg length = f_2(stature)
knee height at midpatella = f_3(stature)
shank length = f_4(stature)
lateral malleneous height = f_5(stature)

(a) flat estimation

trochanterion height = g_1(stature)
upper leg length = g_2(trochanterion height)
knee height = g_3(trochanterion height)
shank length = g_4(knee height)
lateral malleneous height = g_5(knee height)

(b) hierarchical estimation

Figure 4. Comparison of flat and hierarchical estimation methods.

From the sampling distribution of prediction values of hierarchical regression models, the body segment sizes of each human model are randomly determined. For a human model with certain values of stature and weight, the size of each body segment is determined by selecting a value at random in the prediction sampling distribution of corresponding regression model.

$$N\left(\hat{\boldsymbol{\beta}}'\mathbf{x}_{new},\quad MSE(1+\mathbf{x}'_{new}(\mathbf{X}'\mathbf{X})^{-1}\mathbf{x}_{new})\right) \qquad \text{(Equation 2)}$$

where: $\hat{\boldsymbol{\beta}}$ = vector of regression coefficients,
MSE = mean squared error,
$\mathbf{x}_{new}$ = vector of new values of regressors, and
$\mathbf{X}$ = matrix of measured values of regressors

By determining the sizes of body segments with values randomly selected from corresponding sampling distribution of prediction, it is possible to define human models of the same stature and weight in various sizes. For example, the regression model of acromial height built from the 1988 US Army male data is

Acromial height = -101.311 + 0.863 × stature + 0.036 × weight

and the corresponding sampling distribution of prediction is

N(-101.311 + 0.863 × stature + 0.036 × weight, 256.08(1 + 0.43 - 0.0004 × stature))

From the sampling distribution of acromial height prediction, 100 values of acromial height are generated in Figure 5 for human models with stature = 175.6 cm and weight = 78.5 kg.

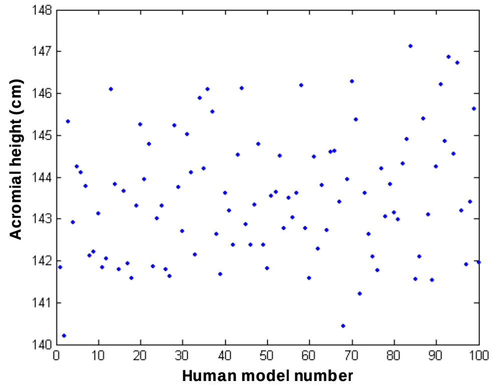


Figure 5. 100 values of acromial height of human models with stature = 175.6 cm and weight = 78.5 kg

Human model generation system

The human model generation method of this study was implemented to a web-based system which automatically generates a group of human models which are used in designing vehicle interiors. As the anthropometric variables of human models, 59 variables related with designing vehicle interiors were selected and the 1988 US Army data were utilized in developing hierarchical regression models. The methods to generate pairs of stature and weight of human models from the bivariate normal distribution of the population and to generate the body sizes of human models from the generated pairs of stature and weight by using the hierarchical regression models was programmed by MatLab® and incorporated to the web-based human model generation system.

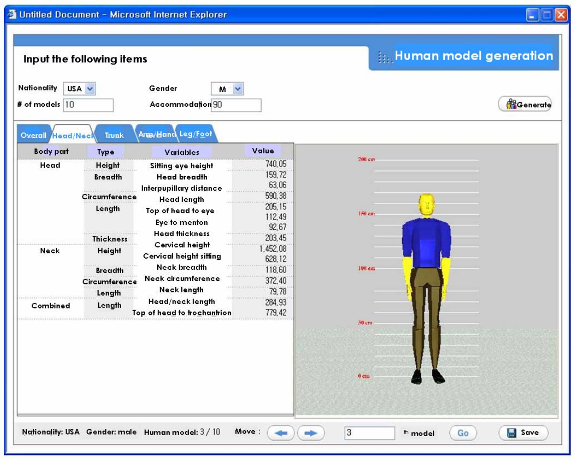


Figure 6. Web-based human model generation system

The human model generation system generates a representative group of human models for the population with simple inputs and presents the generated body sizes of human models. The human model generation system (see Figure 6) generates a group of human models with the simple inputs of nationality, gender, accommodation rage and number of models. Also, the system presents the size of each body segment of human models and visualizes 3-dimensional human models by using VRML (Virtual Reality Modeling Language).

Discussion

This study specified the accommodation range of the population based on stature and weight basically measured in anthropometric surveys and generated human models with various body sizes needed in the evaluation of product designs. The previous human model generation methods generate human models corresponding 5, 50 and 95th percentiles of stature with the identical body proportions, or generate human models located on the boundary of a designated accommodation range by factor analysis and also generate the averaged human models of 5 body types identified by cluster analysis. A small number of human models generated by each of the methods have limitations in being applied to product design and evaluation for variously sized users, because they don't represent various sizes of the population. The present study defined the accommodation range of the population by using the bivariate normal distribution of stature and weight which are basically measured in anthropometric surveys and describe bony linkage and the volume of flesh and muscle in the human body. And, the study generated human models with various body sizes and proportions needed in the product design and evaluation with the pairs of stature and weight within the boundary of an accommodation range.

The random generation method of body segment sizes according to the prediction sampling distribution of regression models made it possible to generate human models with various body proportions. The body sizes of human models are randomly generated from the prediction sampling distributions, thus the human models with same stature and weight have different body proportions. The previous ergonomic design systems don't consider various body proportions which can exist in the population actually, because they let the human models with same stature and weight have the same body sizes by using the identical body proportions.

The human model generation system which is developed by applying the generation method of human models in the study generates a group of human models representing a certain accommodation range of the population with ease of use by inputting simple conditions. With the inputs of nationality, gender, accommodation range and number of models the human model generation system generates body sizes of human models, visualizes human models with VRML and presents the sizes according to body segments. Also, the system which is developed using the 1988 US Army data presently can be extended to generate a group of human models representing each of various populations by adding the anthropometric data of other populations.

Acknowledgments

The present study was funded by an exploratory research grant of NGV for the development of a next generation vehicle.

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