A MULTIVARIATE EVALUATION METHOD FOR REPRESENTATIVE HUMAN MODEL GENERATION METHODS: APPLICATION TO GRID METHOD

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A small number of representative human models (RHMs) are used for efficient product design and evaluation in digital environments; however, the multivariate performance evaluation on existing RHM generation methods has not been made. The present study developed a multivariate accommodation evaluation method, and then applied the proposed method to evaluation of the grid method which generates RHMs at scattered grids over the population distribution. The measure multivariate accommodation performance quantifies the proportion of the population within representative grids formed to accommodate a designated percentage of the target population. Twelve RHMs were generated by the grid method to accommodate 95% of the 1988 US Army anthropometric database and it was found that the accommodation performance of the RHMs decreased dramatically as the number of anthropometric dimensions increased (accommodation percentage = 99% for a one dimension and 10% for 10 dimensions). Multiple regression analysis identified that three factors (overlap area of representative grids, adjusted R^2 between key dimensions and other body dimensions, and sum of body size ranges) significantly affect the accommodation percentage of the grid method. The proposed evaluation method is applicable for evaluation of other RHM generation methods.

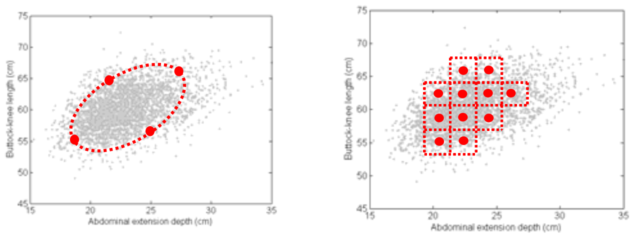
INTRODUCTION

Representative human models (RHMs) of the target population are used in anthropometric product design and evaluation in digital environments. RHMs are a small group of digital human models which statistically represent a designated percentage (e.g., 90%) of the population. These human models provide designers an efficient way in applying the anthropometric database of the population to product design and evaluation. For example, You et al. (1997) evaluated an interior layout design of bus operator's workstation in terms of posture, visibility, and reach using three RHMs (5th, 50th, and 95th %iles).

Depending on the characteristic of a product of interest RHMs can be generated at the boundary accommodating a designated percentage of the population (Figure 1.a) or the scattered grids formed over the population distribution (Figure 1.b). Boundary RHMs can be applied to a one-size product design (one design fits all in the designated percentage of the population) such as workplace and automotive interior layouts. For example, Bittner (2000) generated 9 RHMs at the boundary encompassing 90% of the population using factor analysis for a workspace design. On the other hand, scattered RHMs can be applied to a multiple size product design (*n* sizes fit *n* groups) such as garments. For example, Robinette and Annis (1986) and Kwon et al. (2004) identified grids accommodating a designated percentage of the population and then generated RHMs at the centroid of the grids.

The grid method, a scattered RHM generation approach, uses a 3-step procedure (selection of key dimensions, formation of representative grids, and generation of RHMs) to generate RHMs. First, as key dimensions, a small number (e.g., 1 - 5 dimensions) of anthropometric dimensions, are selected by considering the statistical relationships between anthropometric dimensions (Gordon and Freill, 1994; Hidson, 1991; Resonblad-Wallin, 1987). Second, representative grids are formed to accommodate the designated percentage of the population using the selected key dimensions and a design tolerance (typically determined by a product designer). Lastly, as for the sizes of the RHMs, the sizes of key dimensions are determined at the centroids of the representative grids and then the rest of anthropometric dimensions are estimated by regression equations having the key dimensions as regressors.

Although the grid method has been used for design and evaluation of a multiple-size product, the multivariate accommodation performance of RHMs generated by the grid method has not been quantitatively evaluated. Since the grid method mainly considers key dimensions in the generation of RHMs, other dimensions, which are still important to design and evaluation, are ignored in evaluating its accommodation performance. Therefore, the multivariate performance evaluation is necessary to understand the representativeness of generated RHMs for the population. However, research regarding the evaluation of multivariate performance for the grid method is lacking.



(a) RHMs at the boundary of a designated percentage (b) RHMs at the scattered grids over the population distribution

Figure 1. Illustration of representative human model (RHM) generation (small dots: target population, large dots: RHMs, dotted line: accommodation zone)

The present study evaluated the multivariate accommodation of the grid method, and examined the effects of factors which may affect its accommodation performance. The accommodation performance of the grid method was quantified by analyzing the proportion of the population who were within representative grids and multiple regression analysis was conducted to identify the effects of the factors on the accommodation performance.

METHODS

Anthropometric dimensions and database

Referring to a computer workstation guideline by BSR/HFES (2002), the present study selected 10 anthropometric dimensions (Table 1). The 1988 US Army anthropometric database (Gordon et al., 1988), which complied measurements on 3,987 soldiers (female: 2,213, male: 1,774), was used for the generation of RHMs. The present study separated randomly the anthropometric database into a leaning set (2,982) for generation of RHMs and a testing set (1,000) for accommodation performance evaluation of the generated RHMs.

Key dimensions

The present study analyzed the trend of the average adjusted coefficient of determination (R^2) by increasing the number of key dimension candidates to determine key dimensions. To determine the proper number of key dimensions based on the statistical relationships among anthropometric dimensions, the averages of adjusted R^2 in regression analysis were calculated for different numbers (1 to 9) and combinations of anthropometric dimensions.
Three anthropometric dimensions were selected for key dimensions in this study considering the number of key dimensions (a less number of key dimensions is preferred) and average adjusted R^2 (a set of key dimensions having a larger statistical relationship with other dimensions is preferred). The average adjusted R^2 gradually increased until the number of key dimensions reached at 3, and then eventually leveled off around 0.6 when the number of key dimensions was greater than 3. Therefore, as key dimensions, three dimensions (popliteal height, buttock-popliteal length, and thigh clearance) were selected, having a high average adjusted R^2 with a relatively small number of key dimensions.

Table 1. Anthropometric dimensions considered for computer workstation design

Design dimensions			Code	Anthropometric dimensions
Seat	Seatpan	Height	AD1	Popliteal height
		Depth	AD2	Buttock-popliteal length
		Width	AD3	Hip breadth
	Armrest	Height	AD4	Elbow rest height
		Clearance	AD3	Hip breadth
Desk	Table	Height	AD1	Popliteal height
			AD5	Thigh clearance
			AD6	Buttock-knee length
			AD7	Abdominal extension depth
		Width	AD8	Forearm-to-forearm breadth
	Legroom	Width	AD3	Hip breadth
		Depth at knee	AD6	Buttock-knee length
			AD7	Abdominal extension depth
		Depth at foot	AD1	Popliteal height
			AD9	Foot length
		Clearance at thigh	AD1	Popliteal height
			AD5	Thigh clearance
			AD6	Buttock-knee length
			AD7	Abdominal extension depth
		Clearance at knee	AD10	Knee height

Accommodation performance

The population accommodation percentage by the generated RHMs was quantified by the proportion of the population within a design tolerance. The population accommodation percentage was the proportion of the population within the grids formed by using a design tolerance. For example, when the number of anthropometric dimensions are 2 (say, AD1 and AD2) and the design tolerance is $\pm$ 2.5 cm, the accommodated population by a RHM having 40 cm in AD1 and 50 cm in AD2 were those within 37.5 - 42.5 cm in AD1 and 47.5 - 52.5 cm in AD2.

The population accommodation percentage is subject to the number of anthropometric dimensions considered in accommodation analysis. The accommodation percentage can be quantified for univariate or multivariate dimensions. The present study identified accommodation percentages by increasing the number of dimensions. For efficient generation and evaluation of RHMs, a software program was developed using Matlab version 7.0.

RESULTS

The present study generated 12 RHMs (see Table 2) by the grid method to accommodate 95% of the target population. The RHMs were generated to satisfy the 95% accommodation of the population in terms of the selected three key dimensions. The sizes of RHMs for the key dimensions were determined using the centroids of the grids, and then the sizes of the other body dimensions were estimated by regression equations having the key dimensions as regressors.

Figure 2 shows that the population accommodation percentages of the generated RHMs decreased as the number of anthropometric dimensions increased. The univariate accommodation percentage for each individual anthropometric dimension was relatively higher (99%) than the target accommodation percentage (95%). On the other hand, the multivariate accommodation percentages decreased as the number of anthropometric dimensions increased and finally reached at 10% when all the dimensions were considered. This decreasing trend was caused from estimation inaccuracies of anthropometric dimensions by the key dimensions.

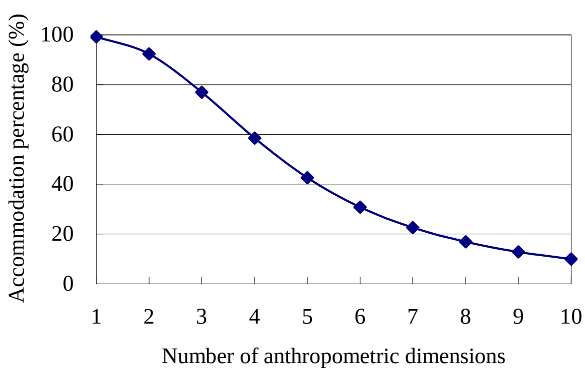
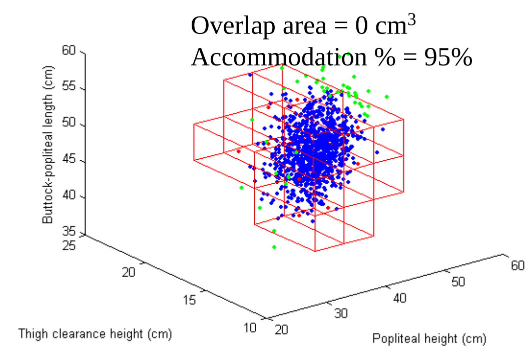
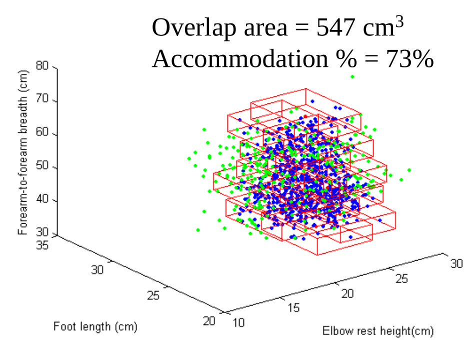


Figure 2.Population accommodation percentages when the number of anthropometric dimensions was increased

A systematic analysis on the generated RHMs identified three factors (overlap area of representative grids, adjusted R^2 between key dimensions and other body dimensions, sum of body size ranges) as those affecting the population accommodation percentage of the grid method. First, the overlap of representative grids affected the population accommodation percentage because the population accommodation area is reduced by the overlap of the grids. For example, the accommodation percentage for popliteal height, buttock-popliteal length, and thigh clearance having no overlap area was 95% (Figure 3a); on the other hand, the accommodation percentage for elbow height, forearm-to-forearm breadth, and foot length having 547 cm^3 decreased to 73% (Figure 3b). Second, the adjusted R^2 between key dimensions and the other body dimensions related to the accommodation percentage because the adjusted R^2 affects the estimation accuracy of the regression equation. For example, the accommodation percentage for buttock-knee length, foot length, and knee height having a high adjusted R^2 (0.89) was 98%; however, the accommodation percentage for hip breadth, elbow height, and abdominal extension depth having a low adjusted R^2 (0.32) decreased to 65%. Lastly, the size ranges of anthropometric dimensions related to accommodation percentage because a large range required a larger area for accommodation. For example, the accommodation percentage for elbow height, thigh clearance, and foot length having small size range (38 cm) was 86%; however, the accommodation percentage for buttock-knee length, forearm-to-forearm breadth, and knee height having a large size range (82 cm) decreased to 48%.



(a) small overlap area



(b) large overlap area

Figure 3. Overlap analysis of representative grids

The statistical significance of the three factors and their relative influence on accommodation performance were examined by multiple regression analysis. All the factors were standardized and stepwise regression analysis (probabilities to enter and to remove = 0.05) was conducted (Equation 1). The three factors were found highly related to the population accommodation percentages (adjusted R^2 = 0.85). The relative influence to the accommodation percentage was evaluated by the coefficients of the regression model in Equation 1: (1) 0.552 for the adjusted R^2 between key dimensions and other body dimensions, (2) 0.398 for the overlap area of representative grids, and (3) 0.201 for the sum of body size ranges.

$$\text{Accommodation } \% = (0.565 - 0.398 \times OA + 0.552 \times AR - 0.201 \times SR) \times 100 \quad (1)$$

where: OA = overlap area
AR = average adjusted R^2,
SR = sum of body size ranges

Table 2. Representative human models accommodating 95% of the population by grid approach (unit: cm)

No.	Key dimensions			Other dimensions (estimated by regression equation)						
	Popliteal height (AD1)	Buttock-popliteal length (AD2)	Thigh clearance(AD5)	Hip breadth (AD3)	Elbow rest height (AD4)	Buttock-knee length (AD6)	Abdominal extension depth (AD7)	Forearm-to-forearm breadth (AD8)	Foot length (AD9)	Knee height (AD10)
1	34.9	42.3	14.6	35.8	23.2	52.4	20.1	43.8	22.5	46.5
2	34.9	47.3	14.6	38.8	21.0	57.2	21.3	42.0	22.5	47.4
3	34.9	47.3	19.6	43.0	24.0	59.3	27.6	54.4	24.2	49.6
4	39.9	42.3	14.6	32.8	24.1	52.9	19.4	47.6	24.6	50.6
5	39.9	47.3	14.6	35.8	22.0	57.7	20.6	45.8	24.6	51.6
6	39.9	52.3	14.6	38.8	19.8	62.4	21.8	44.0	24.6	52.5
7	39.9	47.3	19.6	40.1	24.9	59.8	26.9	58.2	26.2	53.8
8	39.9	52.3	19.6	43.0	22.8	64.6	28.1	56.4	26.2	54.7
9	44.9	47.3	14.6	32.8	22.9	58.2	19.8	49.7	26.7	55.7
10	44.9	52.3	14.6	35.8	20.8	62.9	21.0	47.9	26.7	56.6
11	44.9	47.3	19.6	37.1	25.9	60.3	26.2	62.0	28.3	57.9
12	44.9	52.3	19.6	40.1	23.8	65.1	27.4	60.3	28.3	58.9

DISCUSSION

The present study evaluated the multivariate accommodation performance of the grid method which generates RHMs at the scattered grids over the population distribution. The accommodation performance of the grid method has been evaluated in terms of a small number of key dimensions (McCulloch et al., 1998; Chung et al., 2007) so that the accommodation performance for other design-related anthropometric dimensions has not been evaluated. This study developed a method to evaluate the multivariate accommodation performance of the grid method using a design tolerance. The developed method is also applicable to evaluate the multivariate accommodation percentage of any distributed RHM generation method.

The design tolerance used in the accommodation performance analysis should be determined by considering user fitness and production economy (Moon, 2002). A small tolerance can increase the level of fit to the users; however, but produce a large number of sizes for a product which negatively affects production economy. On the other hand, a large design tolerance can reduce the number of sizes; however, it may decrease the user fitness of the product. This study applied 2.5 cm as design tolerance to all anthropometric dimensions.

To generate RHMs which statistically satisfy the designated accommodation percentage (e.g., 90%) by the grid method, the statistical relationship between key dimensions and other dimensions and overlap of representative grids should be considered. First, key dimensions should be selected among anthropometric dimensions that are highly correlated with other dimensions because the adjusted R^2 between key dimensions and other dimensions was positively correlated with the accommodation percentage of RHMs. Second, representative grids should be determined to minimize the overlap area because the overlap area of representative grids was negatively correlated with the accommodation percentage.

It is necessary to evaluate the multivariate accommodation performances of the existing RHM generation methods. Previous research has developed various methods using statistical and optimization methods (e.g., factor analysis) to generate scattered RHMs over the population distribution. For example, Laing et al. (1999) and Eynard et al. (2000) used cluster analysis to classify the target population according to figure types and then generate RHMs at each figure type; McCulloch and Ashdown (1998) applied an optimization algorithm under given constraints (e.g., the number of RHMs and design tolerance) to generate RHMs. However, the comparison among RHM generation methods has not been made in terms of the multivariate accommodation performance. Therefore, the performance comparison between the methods is needed in the future by using the proposed multivariate accommodation evaluation method.

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