Development of a hierarchical estimation method for anthropometric variables

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Most regression models of anthropometric variables use stature and/or weight as regressors; however, these 'flat' regression models result in large errors for anthropometric variables having low correlations with the regressors. For better accuracy in estimating anthropometric variables, this study proposed a method to estimate anthropometric variables in a hierarchical manner based on the geometric and statistical relationships among the variables. By applying the proposed approach to 60 anthropometric variables selected for the design of an occupant package layout in a passenger car, hierarchical estimation structures were constructed and then based on the estimation structures hierarchical regression models were developed with the 1988 US Army anthropometric survey data. The hierarchical regression models were compared with the corresponding flat regression models in terms of adjusted R^2 and SE, resulting in on average a 55% increase in adjusted R^2 and a 31% decrease in SE when compared to the corresponding flat models.

1. Introduction

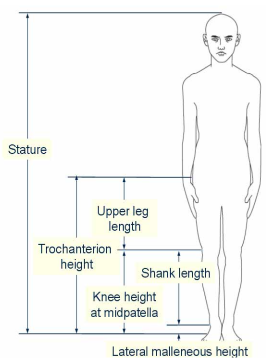
Most anthropometric regression models use only stature and/or weight as regressor(s) to estimate body dimensions (termed 'flat' estimation in the present study), which can result in unsatisfactory estimation for an anthropometric variable whose correlation (r) with the regressor(s) is low. A regression model which relates stature to a body dimension at a low value of r would have a low coefficient of determination (R^2) and produce estimates having a large standard error

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}$$

where y_i = measured value and $\hat{y}_i$ = estimate

For example, a regression model of biacromial breadth by stature whose r = 0.48 in the 1988 US Army anthropometric survey (Gordon et al., 1988) has R^2 = 0.24 and SE = 15.69 cm (similar with SD of biacromial breadth = 17.96 cm). Note that the closer the SE value of a regression model to the SD value of the dependent variable, the lower the utility of the model to estimate the dependent variable.

The present study assumed that the limitation of the flat estimation method for anthropometric variables can be reduced by developing regression models in a hierarchical manner based on the anatomical and statistical relationships between anthropometric variables (termed 'hierarchical' estimation method). While the flat estimation method uses one or two same regressors in building regression models, the hierarchical estimation method employs different regressors by following a systematic procedure (described in Sections 2 and 3). For example, as illustrated in Figure 1, when estimating five anthropometric variables at the leg, the flat estimation method uses only stature as regressor, whereas the hierarchical estimation method employs different anthropometric variables (stature for trochanterion height; trochanterion height for upper-leg length and knee height; knee height for shank length and lateral malleneous height).



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 1. Comparison of flat and hierarchical estimation methods.

The objectives of the present study are to (1) develop a procedure for establishing a hierarchical estimation structure of anthropometric variables for regression and (2) examine the effectiveness of the hierarchical estimation method in comparison with the flat estimation method. The proposed procedure to establish hierarchical estimation structures was applied to 60 anthropometric variables (excluding stature and weight) which were selected in the study for the design of an occupant package layout for a passenger car. Based on the hierarchical estimation structure of the anthropometric variables, regression models were developed by using the 1988 US Army anthropometric data (Gordon et al., 1988). Finally, the hierarchical regression models were compared with the corresponding flat regression models in terms of adjusted R^2 and SE.

2. Hierarchical Estimation Structures of Anthropometric Variables

A four-step procedure shown in Figure 2 was proposed in the present study to establish hierarchical estimation structures of anthropometric variables for regression: (1) classification of anthropometric variables by dimensional type, (2) analysis of geometric relationships between anthropometric variables, (3) construction of hierarchical estimation structures, and (4) selection of anthropometric variables for regression. Based on the hierarchical estimation structures established, regression models of anthropometric variables were constructed (described in Section 3).

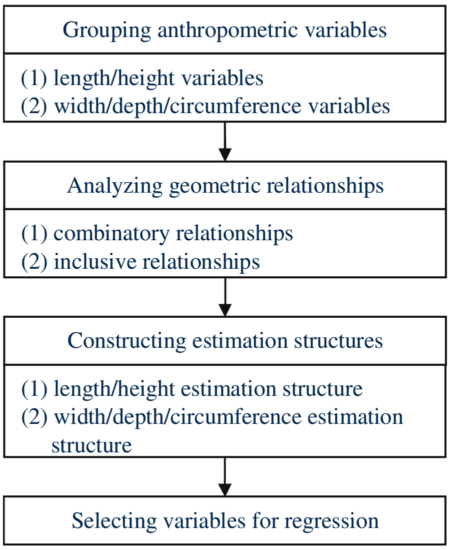


Figure 2. Procedure to establish hierarchical estimation structures of anthropometric variables

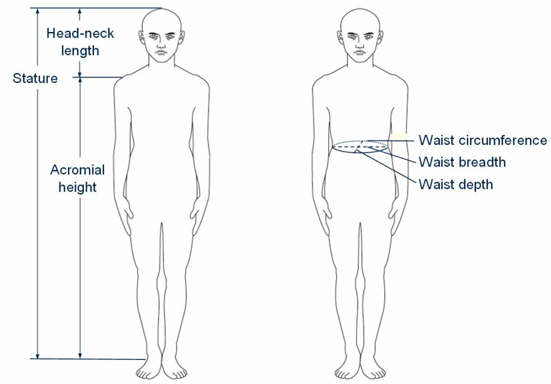
First, anthropometric variables under consideration are grouped into two dimensional categories (length/height and width/depth/circumference) since length/height anthropometric variables are related more closely to each other than width/depth/circumference variables and vice versa. Length and height anthropometric variables measure the lengths of body segments and the vertical distances of anatomical landmarks on the body from the floor/seat, respectively. In contrast, width, depth, and circumference variables measure the cross-sectional sizes of body segments. In general, length/height variables are related to each other with higher correlations than to width/depth/circumference variables and vice versa (Sperling et al., cited in Rosenblad-Wallin, 1987). The 60 variables selected in the present study were classified into 29 length/height and 31 width/depth/circumference variables and correlation analysis on the 58 variables with the US Army data identified that all the length/height and width/depth/ circumference variables have highest correlations with variables of the same dimensional type.

Second, the anthropometric variables categorized by dimensional type are further divided into two geometric relationships:

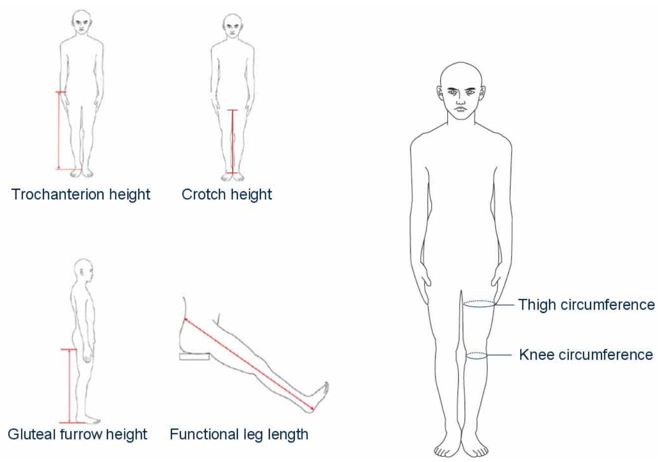
(1) Combinatory relationship: A set of variables in which one variable can be represented by a linear combination of the other variables. (e.g.) {stature, head-neck length, acromial height} where stature = *f*{head-neck length, acromial height}; {waist circumference, waist breadth, waist depth} where waist circumference = *f*{waist breadth, waist depth} (see Figure 3a)

(2) Inclusive relationship: A pair of variables in which both variables measure the same body segment(s) but one variable measures a part of the other variable by using different landmarks and/or in different postures. (e.g.) {trochanterion height, crotch height}, {trochanterion height, gluteal furrow height}, and {trochanterion height, functional leg length} which measure the length/height of the leg at different landmarks and/or postures; {thigh circumference, knee circumference} which measure the circumference of the upper leg at different locations (see Figure 3b)

An analysis on the geometric relationships of the 60 variables is illustrated in Table 1.



(a) combinatory relationships



(b) inclusive relationships

Figure 3. Types of geometric relationships between anthropometric variables (illustrated)

Table 1. Classification of anthropometric variables(illustrated)

Dimensional type	Geometric relationship	No.	Group
Length/height	Combinatory	1	Stature, head-neck length, acromial height
		2	Acromial height, chest-back length, waist height at omphalion
		3	Waist height at omphalion, abdomen-hip length, trochanterion height
		4	Trochanterion height, upper leg length, knee height at midpatella
		5	Knee height at midpatella, shank length, lateral malleneous height
		6	Forearm length, elbow-wrist length, hand length
	Inclusive	1	Acromial height, cervical height
		2	Acromial height, axilla height
		3	Trochanterion height, functional leg length
		4	Trochanterion height, crotch height
		5	Trochanterion height, gluteal furrow height
		6	Upper leg length, buttock-knee length

Third, based on the combinatory and inclusive relationships of the anthropometric variables, hierarchical estimation structures are constructed for length/height and width/depth/ circumference variables (see Figure 4). Two hierarchical structures were developed for the 29 length/height and 31 width/depth/circumference variables, beginning with stature and weight. The estimation structures were first framed by using the variables in combinatory relationship and then completed by adding those in inclusive relationship. In Figure 4, the variables in combinatory relationship are connected by thick lines and those in inclusive relationship by thin lines.

Lastly, in the hierarchical estimation structures, anthropometric variables that would be estimated by regression and those by linear combination are identified by considering the geometric relationships and correlations between the variables. All the variables except some length/height variables in combinatory relationship are selected for regression. A linear combination exists for each group of three length/height variables in combinatory relationship in Table 1 (e.g., stature = head-neck length + acromial height), thus, in each group one variable is determined if the other two variables are known. For better accuracy in estimation, for each group of three length/height variables in combinatory relationship, when a regressor is determined, of the other two variables, one with a higher correlation with the regressor is selected for regression and the other for estimation by the corresponding linear combination. For example, of stature, head-neck length, and acromial height in combinatory relationship, when stature is used as regressor, acromial height is selected for regression because of its higher correlation (r = 0.96) with stature than that of head/neck length (r = 0.39) and head-neck length is estimated by the linear combination, head-neck length = stature - acromial height. As shown in Figure 4, 54 (out of 60) variables were identified those for regression and 6 (indicated by dashed rectangles) those for estimation by linear combination.

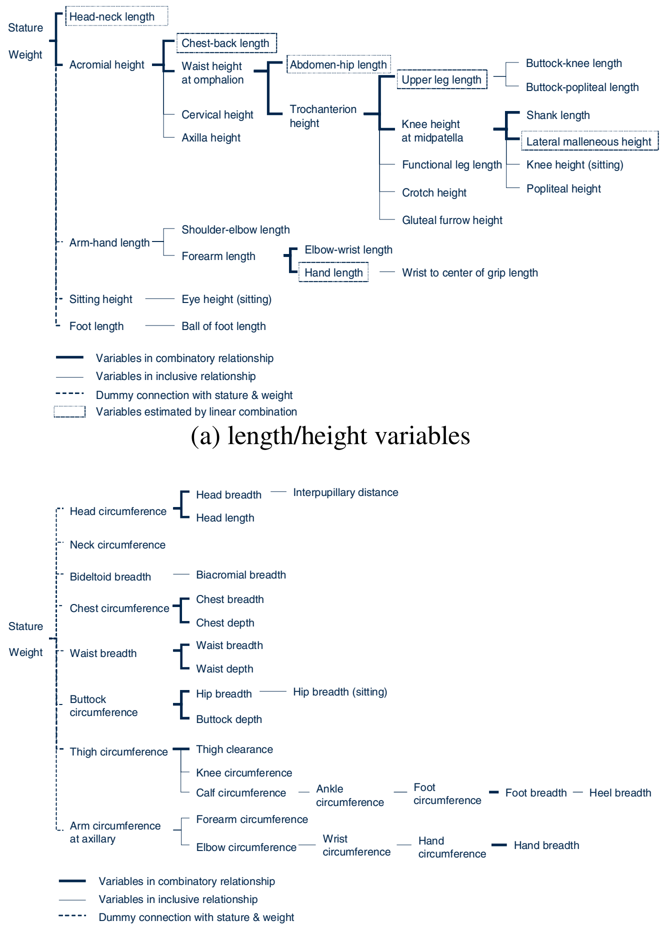


Figure 4. Hierarchical estimation structures for anthropometric variables

3. Hierarchical regression models of anthropometric variables

Hierarchical regression models were developed for the 54 anthropometric variables selected for regression by the following procedure: (1) develop and evaluate regression models based on the hierarchical estimation structures, (2) if the performance of a model is satisfactory, accept the model, (3) if not, develop alternative models and select the best model. Regression models were first developed in a hierarchical manner based on the estimation structures constructed. For example, stature and height were used as regressors for the regression models of head-neck length, acromial height, arm-hand length, sitting height, and foot length, and then acromial height as regressor for those of waist height, cervical height, and axilla height, and so forth. The performance of each model was evaluated in terms of adjusted R^2. If the adjusted R^2 of a model is greater than a cut-off value specified (say, 0.6 in the present study), the model is accepted as satisfactory. Otherwise, alternative models are searched by increasing the order of a regressor in the model and/or introducing a new regressor to the model; then, out of the model candidates, select the best model from both the performance and simplicity aspects. It was identified that, out of the 54 anthropometric variables, 41 variables could be modeled with an adjusted $R^2 > 0.6$ based on the hierarchical estimation structures. For the other 13 variables, the model improvement process was applied, as illustrated in Table 2. The selected hierarchical regression models developed for the 54 anthropometric variables for males and females were presented in Table 3. Of the models, 46 models have an adjusted $R^2 > 0.6$, 4 models an adjusted R^2 between 0.6 and 0.3, and 4 models (head circumference, head breadth, interpupillary distance, and wrist to grip length) an adjusted $R^2 < 0.3$.

Table 2. Model improvement process (illustrated)

(a) Models for buttock-knee length (male)

Regressors included	adjusted R^2	Remark	Selection
Upper leg length	0.55	Based on the corresponding hierarchical estimation structure	
Upper leg length, (upper leg length)^2	0.55	Increased the order of the regressor	
Functional leg length	0.83	Introduced a new regressor	O

(b) Models for foot circumference (male)

Regressors included	adjusted R^2	Remark	Selection
Ankle circumference	0.46	Based on the corresponding hierarchical estimation structure	
Ankle circumference, (ankle circumference)^2	0.46	Increased the order of the regressor	
Ankle circumference, hand circumference	0.59	Introduced a new regressor	O
Ankle circumference, hand circumference, (ankle circumference)^2, (hand circumference)^2	0.59	Increased the order of the regressors	

Table 3. Hierarchical regression models by using the 1988 US Army anthropometric survey data (illustrated)

(unit: weight in 10×kg, other variables in mm)

Body part	Type	Dependent variable	Gender*	Regression model	SE	Adj. R^2
Overall	Length/ height	Sitting height	M	144.664 + 0.930×top of head to trochanterion length	14.3	0.839
			F	149.167 + 0.915× top of head to trochanterion length	13.7	0.846
Head/ neck	Length/ height	Cervical height	M	96.350 + 0.987×Acromial height	14.0	0.950
			F	80.217 + 0.996×Acromial height	13.6	0.946
		Eye height (sitting)	M	-67.253 + 0.940×Sitting height	7.2	0.956
			F	-54.228 + 0.931×Sitting height	7.1	0.955
	Width/depth/ circumference	Head circumference	M	480.736 + 0.021×Stature + 0.063×Weight	13.2	0.263
			F	445.926 + 0.039×Stature + 0.059×Weight	13.1	0.203
		Head breadth	M	43.650 + 0.190×Head circumference	4.5	0.293
			F	52.920 + 0.168×Head circumference	4.3	0.247
		Head length	M	-16.592 + 0.376×Head circumference	4.0	0.672
			F	-9.869 + 0.361×Head circumference	3.6	0.679
		Interpupillary distance	M	31.957 + 0.216×Head breadth	3.5	0.098
			F	34.707 + 0.191×Head breadth	3.5	0.068
		Neck circumference	M	336.648 - 0.041×Stature + 0.147×Weight	12.8	0.578
			F	262.746 - 0.020×Stature + 0.138×Weight	10.7	0.507

* M: male; F: female

4. Comparison of hierarchical and flat regression models

The hierarchical regression models developed in the present study were compared with corresponding flat regression models (which use stature and weight as regressors; Annis and McConville, 1996) in terms of adjusted R^2 and SE by using the 1988 US Army anthropometric data. Of the 54 hierarchical regression models, 45 were found different from the corresponding flat models. The measures adjusted R^2 and SE are often employed to assess the adequacy of fit and the estimation accuracy of a model, respectively.

Of the 45 pairs of hierarchical and flat models different from each other, except 6 hierarchical models (for cervical height, waist height, buttock depth, knee circumference, calf circumference, and elbow circumference), 39 hierarchical models showed an average increase of 55% in adjusted R^2 and an average decrease of 31% in SE when compared to the corresponding flat models. The adjusted R^2 and SE values of the 39 hierarchical models were on average 20.9% (0.2 ~ 62.7%) larger and 4.4 mm (0.004 ~ 16.3 mm) smaller than those of the corresponding flat models, respectively. However, the other six hierarchical models showed an average decrease of 5.8% (0.6 ~ 10.3%) in adjusted R^2 and an average increase of 1.7 mm (0.4 ~ 3.4 mm) in SE in comparison with those of the corresponding flat models.

5. Discussion

Establishment of hierarchical estimation structures for anthropometric variables played an effective role to develop hierarchical regression models of anthropometric variables. By analyzing the dimensional characteristics and geometric relationships of anthropometric variables of interest, hierarchical estimation structures could be constructed systematically and then variables that would be estimated by regression or linear combination were identified effectively. In addition, while establishing the hierarchical estimation structures, the analyst could have a better understanding of anthropometric variables so that meaningful regression models from the anatomical and geometric aspects could be developed. The present study identified that hierarchical regression models for anthropometric variables are preferred to flat regression models for better adequacy of fit and estimation accuracy. Of the 54 pairs of hierarchical and flat regression models, 45 pairs had different regressors; of the 45 pairs, 39 hierarchical models showed a 55% increase in adjusted R^2 and a 31% decrease in SE on average when compared to the corresponding flat models. This comparison result indicates that use of hierarchical regression models as available benefits estimation of the body dimensions of a person for accuracy.

Acknowledgments

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