Comparison of Three-Dimensional Korean Male Anthropometric Data with Modeling Data Generated by Digital Human Models

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Abstract

The purpose of this study was first to extract the anthropometric data of typical Korean male adults, based on the three-dimensional anthropometric data measured through the Size Korea project. The data were then analyzed to identify the differences in the anthropometric characteristics between typical Koreans and 3D Korean mannequinmannequins generated by digital human models. Revision equations were then suggested to improve the inaccuracy of digital human models. Typical Korean adults subject to the 3D body scan data were selected by factor analysis with respect to the 5th, 50th, and 95th percentiles. Comparisons of anthropometric differences included the differences of the height and length variables in the vertical direction and the breadth, depth, and circumference variables in the horizontal direction. These comparisons demonstrated the differences in the anthropometric characteristics between typical Koreans and Korean mannequins based on differences in body shape and proportions between Korean and Western populations. Typical Koreans have shorter legs and longer torso than those of such mannequins generated from their own modeling algorithms, and the body shape of Koreans is more of an inverted triangular shape compared to the models. Although 3D digital human models are required to be modified to appropriately reflect the Asian body shape, modification of the modeling algoritms is not available to the public. The revision equations that convert the Korean modeling data of RAMSIS and Human in CATIA into typical Korean anthropometric data were instead suggested by regression analysis. It is expected that the proposed revision equations will help the designer evaluate design alternatives and improve the suitability of ergonomic evaluation for Korean customers. © 2012 Wiley Periodicals, Inc.

Keywords: Korean anthropometry; Digital human models; Revision equations; RAMSIS; Human in CATIA

1. INTRODUCTION

The need for digital human models is increasing in response to the demand for ergonomically sound products and systems. Especially at the early stage of the design process, drawings in CAD systems are required to be ergonomically evaluated for the system to correctly fit humans. Several software packages have been identified that are capable of importing design environments, such as Transom Jack, SAMMIE, Human

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in CATIA, RAMSIS, and ERGOman (Hanson et al., 1999; K. Jung, Kwon, & You, 2009). These tools have the techniques to efficiently visualize the changes in the three-dimensional anthropometric data, helping us understand the variability of the human body shape and size. Two of the most widely and frequently used digital human models among those systems are RAMSIS and Human in CATIA in the automobile industry. These human models generate 3D digital mannequins based on two sets of data: a number of body dimensions measured through anthropometric surveys of specific populations and its own modeling algorithms based on the body shape.

Numerous studies on the human body for design applications have attempted to classify the body shape from anthropometric data. In such studies, the basis of classifying the human body ranges from simple BMI (body mass index) calculated from the stature and weight to the Heath-Carter method, a modified version of Sheldon's method (Ellaway, Anderson, & Macintyre, 1997; Hazir, 2010; Pokrywka, Čabrić, & Krakowiak, 2006; Susanne, Bodzsar, & Castro, 1998). These classification methods involve a series of detailed measurements taken either directly from subjects or indirectly from their photographs (Jones & Rioux, 1997). Several studies obtained objective and detailed facts on the body shape by applying multivariate analysis. Simmons, Istook, and Devarajan (2004) described five body shape categories: the triangle, inverted triangle, rectangle, hourglass, and oval. The side body shapes of the female body were also classified by analyzing photographic data and subjective perceptions of figure drawings (Connell, Ulrich, Brannon, Alexander, & Presley, 2006; M. S. Jung, 2003).

Several recent studies classified the body shapes from 3D body scan data that contain more information about the human body shape than do traditional direct measurement data (Azouz, Shu, Lepage, & Rioux, 2005; Jones & Rioux, 1997). If used in the design process, 3D body scan data can be readily used for 3D human modeling (Feathers, Paquet, & Drury, 2004). Designers will be able to take measurements directly from the models to accurately fit a wide range of subjects as 3D human models that are more accurate become available.

Several groups have successfully collected anthropometric data using 3D body scanning technology in an attempt to gather direct measurement data and 3D body scan data to identify national and racial differences related to body shape and size. National anthropometric surveys were conducted by 3D scanning technology in various countries. The first large-scale 3D anthropometric survey, the CAESAR (Civilian American and European Surface Anthropometry Resource) Project, collected data on 2,400 North American and 2,000 European civilians from 1998 to 2000. The database contains subjects between ages 18 and 65 years in the United States, the Netherlands, and Italy (Azouz et al., 2005; Godil, Grother, & Ressler, 2003; Lu & Wang, 2008). Size UK, a national sizing survey of the UK population (Wells, Treleaven, & Cole, 2007), was completed and Size USA, a collection of 3D body measurement data of more than 10,000 men and women in the United States, was reported in 2004 (Devarajan & Istook, 2004; Kim, Pyun, & Choi, 2010).

In Korea, a national anthropometric survey has been conducted every 5–6 years since 1979. The latest Size Korea project was conducted from 2003 to 2004 to obtain Korean body size and 3D body shape information. One hundred nineteen manually measured dimensions (from direct measurement data) and 205 three-dimensional scan-extracted dimensions (from 3D body scan data) were recorded from 19,700 Koreans ages from 0 to 90 years (Han, Nam, & Choi, 2010; Lee, Istook, Nam, & Park, 2007).

RAMSIS, one of the 3D digital human modeling software packages, was developed in the 1980s by Human Solutions GmbH, funded by the German automotive industry. The model contains the most recent databases of China, Germany, the United States, Canada, France, South America, Japan, Mexico, and Korea. RAMSIS updated a new anthropometric database named Korea to generate Korean mannequins that include the Korean modeling data generated by the system (Human Solutions GmbH, 2007). However, these data may not accurately reflect the real Korean body shape and size since the data were based on the modeling algorithm of German subjects to which the Size Korea data have been simply added. A similar inaccuracy is observed when design alternatives are tested in the Korean automobile industry by Human in CATIA (Hong et al., 2006).

Therefore, data on typical Koreans that are more precise are needed for ergonomic evaluation. Comparisons must be made to evaluate the differences between typical Korean adults and the Korean mannequins generated by the digital human models, such as RAMSIS and Human in CATIA. Thus, the objectives of this study are as follows:

1. To extract the anthropometric data of typical Koreans from the 3D body scan data,
2. To determine the typical Korean anthropometric characteristics and understand the Korean body shape and bodily proportions,
3. To identify and discuss the differences between typical Koreans and the Korean mannequins of 3D digital human models such as RAMSIS and Human in CATIA, and
4. To suggest revision equations to replace Korean modeling data generated by the digital human models with actual data of typical Koreans.

2. METHOD

Prior to investigating the differences in the body shape, size, and bodily proportions between actual Koreans and human models, typical Koreans must be properly defined with respect to their percentiles. When referring to a 95th-percentile person, we usually mean a person whose anthropometric variables have 95th-percentile values calculated separately from each anthropometric dimension. In reality, such a person does not exist among subjects surveyed. If only a perfect normality exists on all the body dimensions, the values of all the dimensions of a 50th-percentile person would be very close to the mean values of each dimension. In addition, when there are distinct body shapes for a certain population, the values of some dimensions of 5th- and 95th-percentile persons would differ from the corresponding values of each dimension. If 3D body scan data are to be directly used for design, the task at hand would be to select a person (in fact, his or her 3D data) of a certain percentile with a set of significant dimensions (or factors) that have the least deviations from the corresponding percentile values of those dimensions. In this study, factor analysis was used to extract the factors that significantly affect the body shape.

In this study, the anthropometric database that contains 3D body scan data of Korean adults obtained from the Size Korea project was used. The adult data obtained from 1,896 men ages from 18 to 70 years include 95 3D anthropometric variables, excluding those related to the head, feet, surface lengths, and angles. Table 1 presents these 95 Korean anthropometric

TABLE 1. Ninety-five Korean Three-Dimensional Anthropometric Variables Used in the Study

Variable Type	Anthropometric Variable
Height (34)	Stature, eye height, acromion height, shoulder height, cervical height, front neck point height, axilla height, bust height, underbust height, waist height, waist height (omphalion), abdominal height, iliac spine height, iliocristale height, hip height, gluteal fold height, thigh height, crotch height, leg apart crotch height, calf height, knee height, midpatella height, lateral malleous height, elbow height, finger height, grip height, sitting height, eye height (sitting), cervical height (sitting), shoulder height (sitting), elbow height (sitting), knee height (sitting), popliteal height (sitting), thigh clearance
Length (12)	Thigh vertical length, foot length, bust point-bust point, body rise, vertical trunk length, wall-acromion distance, wall-fingertip distance, shoulder-elbow length, elbow-wrist length, forearm-fingertip length, buttock-popliteal length, buttock-knee length
Circumference (24)	Neck circumference, cervical circumference, neck base circumference, armscye circumference, chest circumference, bust circumference, underbust circumference, waist circumference (natural indentation), waist circumference (omphalion), abdominal circumference, thigh circumference, midthigh circumference, knee circumference, lower knee circumference, calf circumference, minimum leg circumference, foot circumference, ankle circumference, upper arm circumference, elbow circumference, forearm circumference, wrist circumference, trunk circumference, hip circumference
Breadth (14)	Neck breadth, chest breadth, bust breadth, underbust breadth, waist breadth (natural indentation), waist breadth (omphalion), abdominal breadth, foot breadth, hip breadth, hand breadth, biacromial breadth, bideltoid breadth, elbow-to-elbow breadth, hip breadth (sitting)
Depth (11)	Armscye depth, chest depth, bust depth, underbust depth, waist depth (natural indentation), waist depth (omphalion), abdominal depth, hip depth, body depth (standing), abdominal depth (sitting), buttock-abdomen depth (sitting)

variables. In addition, the traditional 5th-, 50th-, and 95th-percentile values of each anthropometric dimension were obtained from the same anthropometric database.

Factor analysis reduced the 95 anthropometric variables down to a set of statistically significant factors that sufficiently explains the original data variability to select typical Koreans from the 3D body scan data. The Mahalanobis distance was used to detect missing values and outliers prior to factor analysis (Maesschalck, Jouan-Rimbaud, & Massart, 2000; Milfont & Duckitt, 2004). The measure of sampling adequacy (MSA) was also computed for each of the 95 variables to test the adequacy of factor analysis (Cogliastro, Gagnon, & Bouchard, 1997; Doremus, Varlinskaya, & Spear, 2006). Variables were excluded after the factor analysis if their extraction communality values were lower than 0.5 (Pedersen & Waye, 2007). The varimax technique was used as a factor rotation method for factor analysis, and principal component analysis was used as a statistical grouping technique (Abdi, 2003; Hair, Anderson, Tatham, & Black, 1995; Johnson & Wichern, 1998).

The selection of typical Korean male adults was finally established based on 85 out of 95 three-dimensional anthropometric variables with 0.963 of the overall MSAs for the correlation matrix. Typical Korean male adults of 5th, 50th, and 95th percentiles were extracted by the factor scores weighted by the total variances explained by each factor. Here, factor scores were used to characterize each individual in the data set instead of original anthropometric variables. An individual of a certain percentile with his or her weighted factor scores that least deviated from those of the corresponding percentile was selected as a typical Korean adult (Hong et al., 2006).

In this study, two representative human models, RAMSIS and Human in CATIA, were chosen for the comparison. The Korean mannequins include the modeling data computed from 23 anthropometric variables for RAMSIS. The model predicts the human anthropometry based on three parameters: stature, sitting height, and waist circumference (Bubb, 2004; Meulen & Seidl, 2007; Moss et al., 2000). Users are allowed to limitedly adjust the values of these variables in the system to create a diversity of body shapes. However, this reveals certain limits due to inborn anthropometric characteristics with respect to the race.

Korean mannequins were created with respect to the 5th, 50th, and 95th percentiles by specifying the percentile information required by RAMSIS and Human in CATIA. The values of relevant anthropometric variables were then extracted accordingly to compare differences between actual Koreans and Korean mannequins generated by RAMSIS and Human in CATIA.

3. RESULTS

First, the four major factors that characterize typical Korean male adults were extracted from the 85 anthropometric variables by factor analysis. Table 2 describes the four factors finally chosen for Korean male adults.

Table 2 shows the results of factor analysis, where the four major factors account for 78.81% of total variance. This indicates the high descriptive power of the entire dispersion of Korean male adults. Factor 1 describes the height and length variables of the subject, labeled the "height and length." Factor 2 includes the breadth, depth, and circumference variables related to the torso of the subject, labeled the "torso volume." Factor 3 represents the breadth and circumference variables related to the extremities of the subject, labeled the "extremities volume." Factor 4 describes the sitting height variables of the subject, labeled the "sitting height." Factors 1 to 4 account for 33.44%, 31.05%, 8.30%, and 6.01%, respectively.

Sixteen anthropometric variables that are commonly available from the two human models were used for comparison. The first comparison showed the anthropometric differences between typical Koreans and Korean models generated by RAMSIS and Human in CATIA. The paired t-test for a simple statistic of the mean was conducted to compare the significance of the differences. The test results showed that there are significant differences in the means between the typical Korean anthropometric data and the Korean modeling data. Table 3 shows anthropometric data of typical Korean male adults (extracted from 3D body scan data), the percentile values of each anthropometric variable (calculated from direct measurement data), and two sets of modeling data.

In Table 3, Korean modeling data from RAMSIS show a larger stature, upper arm length, and buttock-knee length than those of typical Koreans for the same percentile. In fact, typical Korean male adults have a smaller stature, longer torso, and shorter arm and leg than the 3D digital mannequins.

There is no significant difference between percentile values for each anthropometric dimension and typical Korean anthropometric data in height and length variables (paired t-test, $P > .05$, $N = 15$). However, there

TABLE 2. Four Factors Selected for Korean Male Adults Ages from 18 to 70 Years

	Height and Length	Torso Volume	Extremities Volume	Sitting Height	Communality
Waist height (omphalion)	0.97	−0.06	0.08	0.07	0.96
Gluteal fold height	0.97	0.00	0.07	−0.04	0.95
Hip height	0.96	0.01	0.06	−0.03	0.94
Iliac spine height	0.96	−0.01	−0.03	0.03	0.94
Axilla height	0.95	0.02	0.07	0.23	0.97
Bust height	0.95	0.01	0.08	0.20	0.96
Front neck point height	0.95	0.08	0.05	0.23	0.98
Underbust height	0.95	−0.02	0.07	0.19	0.96
Cervical height	0.95	0.10	0.09	0.22	0.98
Iliocristale height	0.95	0.05	−0.06	0.06	0.92
Shoulder height	0.95	0.10	0.09	0.24	0.98
Eye height	0.95	0.04	0.08	0.25	0.97
Stature	0.95	0.03	0.11	0.24	0.98
Acromion height	0.95	0.10	0.09	0.24	0.98
Crotch height	0.94	−0.12	0.07	−0.04	0.94
Waist height	0.93	0.05	0.23	0.05	0.94
Thigh height	0.93	−0.03	−0.03	0.00	0.89
Midthigh height	0.93	0.09	0.15	−0.04	0.90
Knee height	0.92	0.12	−0.05	0.03	0.88
Elbow height	0.89	0.12	0.15	0.29	0.96
Abdominal height	0.88	0.12	0.09	0.01	0.80
Popliteal height (sitting)	0.82	0.05	0.16	0.08	0.86
Leg apart crotch height	0.81	−0.13	0.17	0.02	0.92
Knee height (sitting)	0.80	0.13	0.02	0.14	0.89
Grip height	0.77	0.13	0.04	0.44	0.85
Calf height	0.77	−0.02	0.27	−0.12	0.69
Finger height	0.76	0.15	0.01	0.45	0.85
Wall-fingertip distance	0.75	0.19	0.17	−0.05	0.64
Buttock-knee length	0.74	0.31	0.18	0.08	0.87
Shoulder-elbow length	0.72	0.02	−0.02	0.10	0.79
Wall-acromion distance	0.69	0.23	0.32	−0.02	0.77
Forearm-fingertip length	0.68	0.11	0.31	0.11	0.82
Vertical trunk length	0.61	0.35	0.08	0.49	0.85
Thigh vertical length	0.59	−0.31	0.29	−0.07	0.69
Elbow-wrist length	0.57	0.09	0.34	−0.01	0.65
Waist circumference	−0.04	0.97	0.09	0.02	0.96
Waist circumference (omphalion)	0.01	0.96	0.13	0.04	0.96
Abdominal circumference	0.01	0.94	0.14	0.04	0.94
Waist depth (omphalion)	−0.09	0.94	0.09	0.00	0.95
Waist depth (natural indentation)	−0.12	0.93	0.11	0.00	0.94
Underbust circumference	0.06	0.93	0.13	0.05	0.93
Waist breadth (natural indentation)	0.08	0.93	0.06	0.05	0.90
Bust circumference	0.08	0.93	0.09	0.06	0.94
Abdominal depth (sitting)	−0.11	0.93	0.08	−0.01	0.93
Underbust depth	−0.06	0.92	0.12	−0.03	0.88
Abdominal depth	−0.11	0.92	0.09	0.00	0.93
Bust depth	0.00	0.91	0.12	−0.01	0.86
Body depth (standing)	−0.04	0.90	0.10	0.05	0.88
Waist breadth (omphalion)	0.13	0.90	0.17	0.08	0.88

(Continued)

TABLE 2. Continued.

	Height and Length	Torso Volume	Extremities Volume	Sitting Height	Communality
Chest circumference	0.15	0.87	0.12	0.15	0.95
Chest depth	0.01	0.86	0.18	−0.03	0.81
Buttock-abdomen depth (sitting)	−0.09	0.85	−0.07	0.12	0.84
Abdominal breadth	0.13	0.85	0.16	0.08	0.81
Hip depth	0.11	0.83	0.26	0.13	0.82
Bust breadth	0.14	0.83	0.05	0.12	0.87
Underbust breadth	0.13	0.82	0.12	0.11	0.84
Thigh circumference	0.12	0.76	0.29	0.09	0.79
Neck breadth	0.00	0.75	0.36	0.05	0.78
Armscye circumference	0.17	0.74	0.32	0.15	0.81
Armscye depth	0.07	0.74	0.19	0.11	0.81
Hip circumference	0.42	0.74	0.21	0.13	0.91
Chest breadth	0.20	0.72	0.04	0.23	0.82
Trunk circumference	0.36	0.69	0.20	0.54	0.94
Midthigh circumference	0.16	0.68	0.37	0.12	0.89
Upper arm circumference	0.05	0.67	0.21	0.09	0.70
Elbow-to-elbow breadth	0.10	0.67	0.34	0.01	0.70
Forearm circumference	0.05	0.64	0.63	0.06	0.89
Bideltoid breadth	0.37	0.61	0.22	0.21	0.85
Neck base circumference	0.09	0.61	0.54	0.05	0.77
Hip width	0.54	0.60	0.19	0.12	0.81
Calf circumference	0.16	0.58	0.51	0.08	0.78
Hip breadth (sitting)	0.24	0.55	0.16	0.22	0.55
Minimum leg circumference	0.15	0.42	0.80	0.06	0.86
Ankle circumference	0.19	0.35	0.80	−0.02	0.80
Lower knee circumference	0.25	0.56	0.67	0.06	0.86
Foot breadth	0.21	0.20	0.67	0.10	0.59
Elbow circumference	0.10	0.61	0.67	0.05	0.89
Wrist circumference	−0.02	0.33	0.64	−0.02	0.65
Foot circumference	0.19	0.25	0.63	0.07	0.54
Knee circumference	0.26	0.59	0.63	0.09	0.87
Elbow height (sitting)	0.01	0.22	0.08	0.86	0.86
Shoulder height (sitting)	0.45	0.21	0.06	0.82	0.93
Eye height (sitting)	0.52	0.05	0.04	0.78	0.93
Cervical height (sitting)	0.52	0.19	0.06	0.77	0.93
Sitting height	0.55	0.04	0.13	0.75	0.94
Total variance (%)	33.44	31.05	8.30	6.01	78.81

is a statistically significant difference between typical Koreans and Korean models from RAMSIS in height and length variables (paired t-test, $P < .05$, $N = 15$). In addition, there is also a significant difference between typical Koreans and Korean models from Human in CATIA in circumference and breadth variables (paired t-test, $P < .10$, $N = 9$). This indicates these 3D digital human models do not accurately represent Korean adults in almost all the variables.

The second comparison was made to see the anthropometric differences in the chest and hip breadths that represent the torso shape. This comparison computed the ratio of chest breadth to hip breadth that can be used to classify the upper body shape of the subjects (Y.-L. Lin & Wang, 2010; Simmons et al., 2004). Although bust and hip circumferences are often used for the classification of female subjects, the ratio is used to categorize the human body shape into several types, such as A, H, N, and V types, where A describes the triangular shape of subjects with a larger hip breadth than their chest breadth, H type has both large chest and hip, N is the average type, and V indicates the inverted

TABLE 3. Anthropometric Data and Modeling Data for Height, Length, Circumference, and Breadth Variables

Anthropometric Variable		Stature	Sitting Height	Knee Height (sitting)	Upper Arm Length	Buttock-Knee Length	Thigh Circumference	Lower Arm Circumference	Chest Breadth
Percentile values for each anthropometric dimension	5th	1,591	864	458	286	520	496	224	324
	50th	1,699	925	498	312	562	582	262	362
	95th	1,802	978	539	339	605	682	297	403
Typical Korean anthropometric data	5th	1,591	875	456	296	515	489	228	329
	50th	1,698	926	504	317	563	589	260	362
	95th	1,799	967	533	331	608	678	291	393
Korean modeling data from RAMSIS	5th	1,622	881	487	322	548	541	254	305
	50th	1,713	925	512	337	574	555	263	315
	95th	1,804	967	536	351	599	562	268	323
Korean modeling data from Human in CATIA	5th	1,608	873	467	—	509	477	248	266
	50th	1,702	921	505	—	552	543	276	306
	95th	1,796	969	543	—	595	610	304	346

Note: All dimensions are in millimeters.

TABLE 4. Ratio of Chest Breadth to Hip Breadth from Four Types of Korean Data

Type of Data		Chest Breadth/ Hip Breadth
Percentile values for each anthropometric dimension	5th	1.049
	50th	1.077
	95th	1.107
Typical Korean anthropometric data	5th	1.075
	50th	1.071
	95th	1.068
Korean modeling data from RAMSIS	5th	0.950
	50th	0.949
	95th	0.939
Korean modeling data from Human in CATIA	5th	0.890
	50th	0.944
	95th	0.991

triangular shape (Lee et al., 2007). Table 4 presents the ratios of chest breadth to hip breadth of Korean male adults and their mannequins.

Table 4 demonstrates that the chest breadth of typical Koreans is larger than the hip breadth. In fact, typical Korean male adults have a narrow hip, representing an inverted triangular shape. In contrast, the hip breadth in 3D digital human models is larger than the chest breadth, rather showing a triangular shape. This coincides with the previous research result that Koreans were close to the inverted triangular shape and Americans were close to the triangular shape (Moss et al., 2000).

Although there is no significant difference in the ratio between percentile values for each anthropometric dimension and typical Korean anthropometric data (paired t-test, $P > .05$), there are statistically significant differences in the ratio between typical Koreans and Korean models from RAMSIS (paired t-test, $P < .05$) and between typical Koreans and Korean models from Human in CATIA (paired t-test, $P < .10$). No difference was found between the modeling data from RAMSIS and the modeling data from Human in CATIA (paired t-test, $P > .05$).

The third comparison shows a critical difference in the bodily proportion for circumference, breadth, and depth variables. When the values of these variables were normalized by the stature, it was found that both human models underestimated these bodily proportions for male adult. Table 5 shows several bodily proportions for the 5th, 50th, and 95th percentile males.

Table 5 shows that there are considerable differences between typical Koreans and the models from RAMSIS for the higher percentile subjects. In most circumference, breadth and depth variables, bodily proportions of typical Koreans are larger than those of the models from RAMSIS (paired t-test, $P < .05$, $N = 24$), and those from Human in CATIA (paired t-test, $P < .05$, $N = 18$). As expected, there is no significant difference between percentile values for each anthropometric dimension and typical Korean anthropometric data

TABLE 5. Bodily Proportions of Circumference, Breadth, and Depth Variables Normalized by Stature for Adult Males

Bodily Proportion		Percentile Values for Each Anthropometric Dimension			Typical Korean Anthropometric Data			Korean Modeling Data from RAMSIS			Korean Modeling Data from Human in CATIA		
		5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
Circumference	Waist	0.433	0.486	0.547	0.446	0.493	0.546	0.507	0.480	0.449	—	—	—
	Thigh	0.312	0.343	0.378	0.307	0.347	0.377	0.334	0.324	0.312	0.297	0.319	0.340
	Calf	0.204	0.218	0.234	0.201	0.222	0.228	0.229	0.217	0.207	0.201	0.213	0.224
	Upper arm	0.186	0.204	0.226	0.193	0.209	0.218	0.182	0.177	0.168	—	—	—
Width	Chest	0.204	0.213	0.224	0.207	0.213	0.219	0.188	0.184	0.179	0.165	0.180	0.193
	Hip	0.194	0.198	0.202	0.192	0.199	0.205	0.198	0.194	0.191	0.186	0.190	0.194
	Bideltoid	0.270	0.275	0.283	0.270	0.275	0.280	0.271	0.267	0.262	0.271	0.280	0.288
Depth	Chest	0.124	0.135	0.148	0.128	0.132	0.146	0.129	0.124	0.118	0.118	0.129	0.140

Paired t-test	P-value
Percentile values for each anthropometric dimension and typical Korean anthropometric data	$P = .591$ ($n = 24$)
Typical Korean anthropometric data and Korean modeling data from RAMSIS	$P = .026$ ($n = 24$)
Typical Korean anthropometric data and Korean modeling data from Human in CATIA	$P = .002$ ($n = 18$)

(paired t-test, $P > .05$, $N = 24$). From the second and third comparisons, both human models revealed a significant gap in representing the real Koreans in terms of the circumference, breadth, and depth variables as well as the height and length variables.

4. DISCUSSION

The main objective of this study was to compare anthropometric characteristics between typical Koreans and the corresponding Korean mannequins provided by digital human models. For instance, when a set of typical Korean anthropometric data was inserted into Human in CATIA, we can visualize the differences in anthropometric characteristics between typical Koreans and their modeling data from Human in CATIA. Figure 1 illustrates a typical 95th-percentile male Korean and the corresponding mannequin generated from Human in CATIA. Figure 1a shows a CAD representation of the 95th percentile male Korean while Figure 1b shows the mannequin often used in the habitability evaluation for the rear seat of a passenger car. The typical Korean male shows relatively narrow headroom with wider legroom reflecting typical Korean

(a) 95th-percentile typical male Korean

(b) 95th-percentile male, mannequin generated from Human in CATIA

Figure 1 Two CAD representations of the 95th-percentile Korean male.

TABLE 6. Comparison of Height and Length Variables for the 50th-Percentile Male among Korean, Taiwanese, Japanese, and German Populations

Anthropometric Variable	Korean	Taiwanese (Lin et al., 2004)	Japanese (Lin et al., 2004)	German (Wilke et al., 2001)
Stature	1,698	1,699	1,690	1,717
Sitting height	926	907	909	899
Knee height (sitting)	504	523	—	536
Upper arm length	317	302	315	—
Buttock-knee length	563	558	559	606
Shoulder height	1,370	1,391	1,374	1,416
Knee height	444	449	449	466

Note: All dimensions are in millimeters.

Paired t-test	Percentile	P-value
Korean and Taiwanese	50th ($n = 7$, height/length)	$P = .870$
Korean and Japanese	50th ($n = 6$, height/length)	$P = .321$
Korean and German	50th ($n = 6$, height/length)	$P = .093$

anthropometric data. However, the mannequin shows wider headroom with narrower legroom. This indicates that, even with the use of Korean anthropometric data, the modeling data did not accurately reflect the real Korean anthropometric characteristics. This implies that a simple insertion of Korean data into the digital human model based on a Western modeling algorithm would not provide an accurate representation of typical Korean body shape.

An additional comparison was made between Asian and Western anthropometric data, specifically data related to height and length, to see why such a gap exists in the representation of human body shape between real and modeling data. Table 6 presents some of the 50th-percentile male anthropometric data of Korean, Taiwanese, Japanese, and German populations (Y.-C. Lin, Wang, & Wang, 2004; Wilke, Neef, Hinz, Seidel, & Claes, 2001).

As listed in Table 6, Germans have a larger stature, knee height, and buttock-knee length than Far Eastern Asians, such as Koreans, Taiwanese, and Japanese. Although this comparison was made based on samples too small to lead to a definite conclusion, there were differences at the level of αg .10 among different populations. There were differences between German and Korean anthropometric data in height and length variables (paired t-test, $P < .10$) between German and Taiwanese data (paired t-test, $P < .10$) and between German and Japanese data (paired t-test, $P < .10$). However, there were no significant differences among Korean, Taiwanese, and Japanese (all three paired t-tests, $P > .10$). Thus, Far Eastern Asians have a relatively smaller stature, a longer torso, and shorter arm and leg lengths than Germans.

Other studies also reported that there were considerable differences between Korean and American anthropometric characteristics. Dewangan, Prasanna Kumar, Suja, and Choudhury (2005) reported that Koreans generally have a smaller stature than Americans or the British, but Koreans have a larger sitting height. Moss et al. (2000) indicated that the major anthropometric difference between Asians and Westerners is the leg length, and S. G. Jung, Kim, and Roh (2000) showed that Koreans have a longer upper body but shorter arms and legs than Americans.

Another comparison was made to show anthropometric distinctions between Korean modeling data from both RAMSIS and Human in CATIA and Western data. Table 4 shows the ratios of chest breadth to hip breadth from both sets of modeling data range from 0.89 to 0.99 for all three percentiles, indicating the triangular shape, whereas all three ratios from typical Korean anthropometric data exceed 1, indicating the inverse triangular shape. According to American

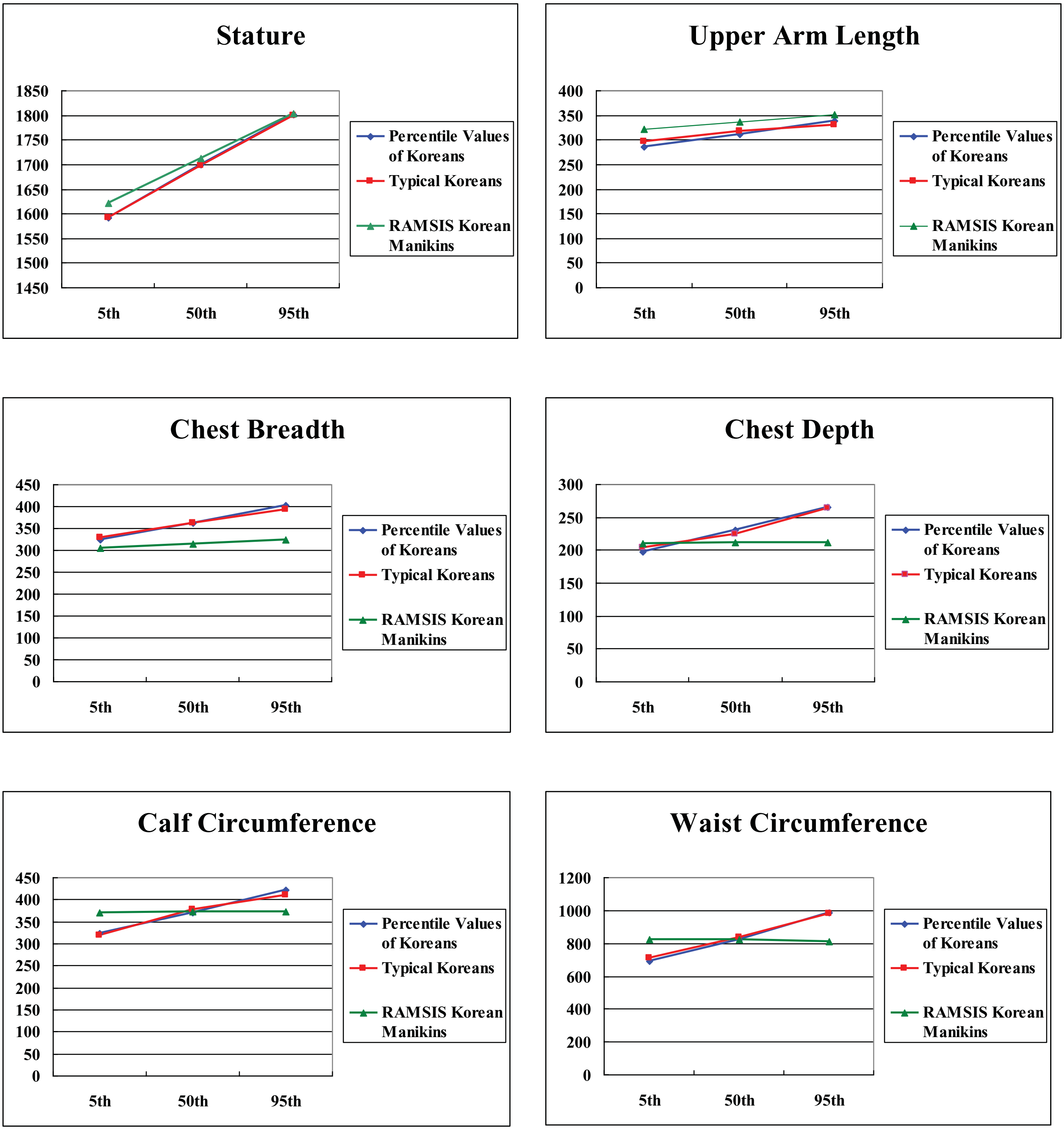

Figure 2 Anthropometric data of Korean male adults and corresponding modeling data plotted with respect to the 5th, 50th, and 95th percentiles.

anthropometric data reported by Reilly, Kozey, and Brooks (2005), the three ratios calculated from 5th-, 50th-, and 95th-percentile data were 0.80, 0.87, and 0.83, respectively. This discrepancy was also observed in Swedish anthropometric data by Hanson, Sperling, Gard, Ispen, and Vergara (2009) with three ratios being 0.90, 0.89, and 0.93, respectively. This implies that, although Korean data were used in both models, the ratios computed from the models are still closer to Western ratios, corresponding to the triangular shape. Therefore, this comparison reveals a limit to the use of 3D digital human models based on Western modeling

TABLE 7. Revision Equations of the Modeling Data for Height and Length Variables

Body Dimension		Korean Modeling Data from RAMSIS	R^2	Korean Modeling Data from Human in CATIA	R^2
Height/length	Upper limbs	$Y = 1.003X_1 + 0.138X_2 - 23.065$	.999	$Y = 0.993X_1 + 0.001\ X_2 + 6.680$	.999
	Lower limbs	$Y = 1.039X_1 + 0.367X_2 - 52.573$	.992	$Y = 1.371X_1 - 0.289X_2 - 180.038$	.995
Circumference	Upper limbs	$Y = 1.002X_1 + 1.511X_2 - 51.727$	.967	$Y = 1.023X_1 + 0.337X_2 - 27.575$	.997
	Lower limbs	$Y = 1.207X_1 + 1.396X_2 - 150.690$	.983	$Y = 1.211X_1 + 0.131X_2 - 78.139$	.996
Breadth	Upper limbs	$Y = 0.742X_1 + 0.556X_2 + 100.211$	.999	$Y = 0.622X_1 + 0.207X_2 + 160.736$	.999
	Lower limbs	$Y = 1.053X_1 + 0.247X_2 - 24.865$	.997	$Y = 1.097X_1 - 0.01X_2 - 17.503$	.999
Depth	Upper limbs	$Y = -9.5X_1 + 0.867X_2 + 2{,}194.667$	.999	$Y = 0.544X_1 + 0.441X_2 + 88.911$	.951

Note: X_1 = input anthropometric variable, X_2 = percentile value.

algorithms, when applied to Asian populations. This is also confirmed by Moss et al. (2000), in which the chest widths of Koreans and Americans were found to be 300 mm and 296 mm, respectively, and the pelvis widths of Koreans and Americans were 287 mm and 299 mm, respectively.

The final comparison was made to see whether the differences between typical Koreans and models have a systematic pattern with respect to the percentile. Representative anthropometric data obtained from typical Koreans and RAMSIS mannequins were plotted with respect to three percentiles in Figure 2. Stature and upper arm length represent the height and length variables, while chest breadth and depth and calf and waist circumferences represent the breadth, depth, and circumference variables.

Figure 2 shows an interesting pattern in the differences between typical Koreans and models. RAMSIS tends to overestimate the values at lower percentiles for the height and length variables. However, it underestimates at higher percentiles for the breadth and depth variables. For circumferences, both overestimation and underestimation occur at lower and upper percentiles, respectively. A modification in the form of a regression equation can be made to correct these differences, since a systematic bias occurs in representing the human body shape.

Inaccuracy of the 3D human models in representing a human form or mannequin raises a need for a new modeling algorithm that reflects Asian body shape and size. This study attempted to suggest revision equations that allow Korean modeling data from RAMSIS and Human in CATIA to be converted into typical Korean anthropometric data using regression analysis, since the modeling algorithms of two human models are not available to the public.

Table 7 presents two types of regression equations for both RAMSIS and Human in CATIA with respect to the anthropometric variable to be revised and the percentile. These equations were generated separately for upper and lower limbs, depending on the type of anthropometric variables: height/length, circumference, breadth and depth. The R^2 values of all the equations exceed .9. Revision equations for the lower limb depth variables were not included because these anthropometric variables were not chosen as significant factors during factor analysis. These equations allow the user to properly modify the values of the anthropometric variables that need to be revised.

Table 8 depicts the modified values of anthropometric variables that are needed as an input to the model, using the revision equations with typical Korean anthropometric data. There was no significant difference between typical Korean data and corresponding modifications of RAMSIS data (paired t-test, $P > .05$). No difference was found as well for the modifications of Human in CATIA (paired t-test, $P > .05$). These modifications are believed to be helpful to a certain degree to the designer of products and systems targeted to Asian customers as well as Korean customers and help improve the accuracy of 3D digital human models.

5. CONCLUSIONS

This study first showed the anthropometric data of typical Korean male adults from 3D body scan data. These data will provide more accurate and real representation of Korean body shapes. Next, the study compared typical Korean data with those of Korean mannequins provided by RAMSIS and Human in CATIA. The results demonstrated the Korean mannequins provided by the human models based on a Western modeling

TABLE 8. Original Modeling Data Provided by Three-Dimensional Digital Human Models, Modified Data, and Typical Korean Male Anthropometric Data for Height and Length Variables

Revision Formula		Typical Korean Anthropometric Data			Modified data from RAMSIS		
Anthropometric Variables		5th	50th	95th	5th	50th	95th
Height/length	Stature	1,591	1,698	1,799	1,604	1,702	1,799
	Sitting height	875	926	967	861	912	960
	Knee height (sitting)	456	504	533	455	498	539
	Upper arm length	296	317	331	301	322	342
	Buttock-knee length	515	563	608	519	562	605
Circumference	Waist circumference	710	836	982	779	848	903
	Thigh circumference	489	589	678	509	589	660
	Calf circumference	320	376	410	304	368	432
	Upper arm circumference	308	356	391	251	327	395
	Forearm circumference	228	260	291	210	287	360
Width	Chest breadth	329	362	393	329	362	393
	Foot breadth	86	94	99	79	93	107
	Hip breadth	306	338	368	314	337	361
	Bideltoid breadth	430	467	504	429	467	504
Depth	Chest depth	204	224	263	204	224	263
				Paired *t*-test	.961	.801	.959

Revision Formula		Typical Korean Anthropometric Data			Modified data from Human in CATIA		
Anthropometric Variables		5th	50th	95th	5th	50th	95th
Height/Length	Stature	1,591	1,698	1,799	1,603	1,697	1,790
	Sitting height	875	926	967	874	921	969
	Knee height (sitting)	456	504	533	459	498	537
	Shoulder-elbow length	320	337	354	312	337	363
	Buttock-knee length	515	563	608	516	562	608
Circumference	Waist circumference, omphalion	717	850	1,002	738	858	977
	Thigh circumference	489	589	678	500	586	673
	Calf circumference	320	376	410	315	368	421
	Elbow circumference	228	259	288	204	245	286
	Lower arm circumference	228	260	291	228	272	315
Width	Chest breadth	329	362	393	327	361	396
	Foot breadth	86	94	99	82	93	103
	Hip breadth	306	338	368	303	329	356
	Bideltoid breadth	430	467	504	432	467	502
Depth	Chest depth	204	224	263	194	231	267
	Waist depth	187	223	282	191	230	269
	Abdominal depth (sitting)	202	233	290	197	242	287
				Paired *t*-test	.846	.840	.826

Note: All dimensions are in millimeters except for P-values of paired t-test.

algorithm do not accurately reflect typical Koreans, since the algorithm was developed based on Western body shapes. In fact, the Korean modeling data are still closer to the data of Westerners, such as Americans and Germans, than Koreans in terms of their upper body shape.

The study also showed that the modeling data from two human models reveal a systematic bias: overestimation of the height and length variables at lower percentiles, underestimation of the breadth and depth variables at higher percentiles, and both overestimation of circumference variables at lower percentiles and underestimation at higher percentiles. In addition to replacing anthropometric data with Asian data, there is clearly a need for those human models to improve their modeling algorithms to better accommodate Asian populations. Revision equations were also suggested in this study to correct such systematic inaccuracy.

Theoretically, the designer should be able to use all of the population data for ergonomic evaluation instead of relying on limited data taken from selected percentiles. However, in practice, most industries still rely on commercial human models with key percentile data. For example, most automobile manufacturers worldwide use RAMSIS to evaluate vehicle interior designs. Therefore, the comparisons made in this study will allow the designer to understand anthropometric characteristics of Koreans and to correct the systematic gap between actual and modeling data found in digital human models.

In conclusion, it is recommended that the anthropometric data of typical Koreans extracted from 3D data be used directly or the Korean anthropometric data be appropriately modified when digital human models are used for ergonomic evaluation.

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