Manikin Families Representing Obese Airline Passengers in the US

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ABSTRACT

Aircraft passenger spaces designed without proper anthropometric analyses can create serious problems for obese passengers, including: possible denial of boarding, excessive body pressures and contact stresses, postural fixity and related health hazards, and increased risks of emergency evacuation failure. In order to help address the obese passenger's accommodation issues, this study developed male and female manikin families that represent obese US airline passengers. Anthropometric data of obese individuals obtained from the CAESAR anthropometric database were analyzed through PCA-based factor analyses. For each gender, a 99% enclosure cuboid was constructed, and a small set of manikins was defined on the basis of each enclosure cuboid. Digital human models (articulated human figures) representing the manikins were created using a human CAD software program. The manikin families were utilized to develop design recommendations for selected aircraft seat dimensions. The manikin families presented in this study would greatly facilitate anthropometrically accommodating large airline passengers.

Keywords: Obesity, aircraft passenger space, anthropometry, manikin family

1. INTRODUCTION

Obesity, a physical condition defined as body mass index (BMI)$\geq 30\text{kg/m}^2$, is prevalent worldwide. The World Health Organization reported that 11% of the global adult population were obese as of 2008 [1]. According to an OECD (Organization for Economic Co-operation and Development) report, several countries, including the US, the UK, Canada, Ireland, Australia and Mexico, had obesity rates greater than 20% in 2010 [2]. In the US, more than one third of the adult population are known to be obese [2-3]. It is believed that the current obesity epidemic will continue in the near future.

Despite the prevalence, however, obesity has received relatively little attention in the ergonomics research community [2, 4]. It was only in the recent years that ergonomists started recognizing obesity as an engineering design issue and began to investigate its design implications [5-18]. While the number of ergonomics studies on obesity seems

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to be increasing, knowledge, methods and tools for addressing obese persons design issues still seem lacking. Currently, very few ergonomics design tools/guidelines appear to exist that assist in considering and reflecting the needs of obese individuals.

When determining physical dimensions of artefacts intended for use by general public, ergonomics designers typically aim to provide anthropometric accommodation to the majority (90~99%) of the general population [19] – a user is considered to be accommodated by an artefact if he/she can use it in an efficient, comfortable and safe manner. However, this approach targeting the general population may not guarantee accommodation of the majority of the obese population. This is because, for some design problems, a substantial number of obese persons could be at or near the tails of the population distributions of the design-related anthropometric variables. In such cases, even if a design accommodates the majority of the general population, it can result in excessive disaccommodation for the obese population in a discriminatory manner. For certain design problems, such systematic discrimination can seriously compromise the safety and wellbeing of obese individuals. One example is the aircraft passenger space design, which involves determining various interior dimensions, such as seat dimensions and legroom.

Passenger spaces designed without full, independent consideration of the physical characteristics of obese individuals can cause a number of serious problems for obese passengers. First, some obese individuals may not fit into the designed spaces or could be perceived as not adequately fitting. Multiple airlines adopt the controversial "customer of size" policy, which requires such passengers to purchase two seats. In some occasions, obese individuals are denied boarding [20, 21]. Second, even those who manage to fit themselves into the spaces could experience excessive pressures and contact stresses at body parts from the cramped environment, which could lead to discomfort and pain. Sufficiency of passenger space has been repeatedly identified as one of the most critical factors affecting passenger comfort/discomfort [22-26]. Third, immobility, also referred to as postural fixity [26], may likely occur to obese passengers. Prolonged immobility in a seated position in long-haul flights exposes a person to long-term static loading, which is a risk factor for musculoskeletal discomforts and pains [27, 28]. Also, it is hypothesized that immobility during prolonged flights increases risks of venous thromboembolic diseases [24, 29-34]. A notable aspect of thromboembolism is that obesity by itself is known as one of its risk factors [34, 35]. Thus, immobility resulting from design could be particularly detrimental to obese passengers [36]. Finally, under emergency situations, efficient egress from seats may not be possible for many obese passengers and this may jeopardize the evacuation process. The consequences, of course, can be fatal to both obese and fellow non-obese passengers [24].

In ergonomics and related fields, various design tools and guidelines have been developed to facilitate designing and evaluating ground and air vehicle operator/passenger spaces. Some of such tools/guidelines include functional anthropometric models developed by automotive ergonomics researchers [37-39] and recommendations on seat space dimensions from the aircraft ergonomics studies [24, 40, 41]. Also, collections of anthropomorphic human models, known as manikin families, have been developed as space design tools [17, 19, 42-50]. The manikins are based on multivariate statistical analyses of static anthropometric measurement data and represent central and/or extreme cases (persons) in the distribution of anthropometric variables. They facilitate efficiently evaluating space designs in terms of multivariate accommodation levels. Also, when implemented as digital human models in computer-aided design software programs, they enable visualizing man-artifact interactions and help conduct virtual anthropometry/ergonomics analyses early in the design process [51].

The existing ergonomics space design tools/guidelines mentioned above, however, are not applicable to addressing obese person's accommodation issues as they target the general populations. Recently, Park and Park [17] investigated body shapes of obese and overweight persons in South Korea and determined representative body types. However, the key anthropometric dimensions considered in that study may not be directly relevant to the aircraft passenger space design. Also, that study intended to characterize representative body types (body shapes) rather than define central and/or extreme cases for design evaluation.

The long-term objective of our research is to develop a set of design tools/guidelines that facilitate design of ground and air vehicle operator/passenger spaces for special populations. As an effort towards this goal, this study developed manikin families that represent obese US airline passengers based on multivariate statistical analyses of available anthropometric data. The manikin families were utilized to develop design recommendations for selected aircraft seat dimensions.

The airline industry in the US has seen a consistent growth for the past decades, especially, in the low cost carrier sector [52], and obese passenger accommodation has been identified as one of the pressing passenger space design issues. The manikin families developed in this study are expected to help passenger space designers make informed design decisions.

2. METHOD

This study used anthropometric data from the Civilian American and European Surface Anthropometry Resource (CAESAR) 3-D Anthropometric Database, North American Edition [53]. The CAESAR database intended to support product design activities in various industrial sectors, including automobile, apparel, aerospace and furniture, by providing civilian anthropometric data. In all, the database contains anthropometric data of 2400 subjects aged between 18 and 65 years. The items measured from each participant included 40 traditionally measured static body dimensions.

Two anthropometric datasets for males and females, respectively, were prepared by identifying obese individuals in the CAESAR database and collecting their body dimensions data. A total of 245 males and 213 females with BMI ≥ 30 kg/m^2 were found from the CAESAR database. Only part of the 40 static body dimensions were considered in preparing the anthropometric datasets. The following criteria were utilized to select body dimensions:(1) the body dimensions reflect physical changes associated with obesity, or (2) the body dimensions are relevant to airline passengers' comfort, safety or health issues. Regarding the second criterion, related previous studies [24, 25, 48, 54-57] were reviewed to identify important design issues/considerations. Overall, the studies indicated that passenger seat space design affects passenger comfort and wellbeing the most, and especially, two seat-related dimensions, i.e., seat pitch (the distance between a point on the back of one seat to the same point on the back of the seat in front) and seat width (the distance from armrest to armrest), are critical. Seat pitch is known as an indication of leg room and has been shown to be highly correlated with aircraft interior comfort [22, 57]. Insufficient seat width is known to hinder passengers' side movements and lead to collision of shoulders or arms between passengers sitting next to each other [57]. In addition to these seat dimensions, other design variables related to armrests, foot envelopes, space for ingress/egress, and touch screen located at the back of seat were also found to be related to passenger comfort and wellbeing. These design variables were considered to determine relevant body dimensions. As a result, a set of 18 anthropometric dimensions were selected and the anthropometric datasets were prepared accordingly. The body dimensions selected are shown in Table 1.

As an intermediate step for developing manikin families, this study conducted a principal component analysis (PCA)-based factor analysis on each dataset. This was to reduce the set of 18 anthropometric dimensions (Table 1) to a smaller set of variables (factors). Such dimension reduction allows re-expressing anthropometric data in a lower-dimensional space, and thereby, facilitates visualizing and understanding the data and also defining manikins. The PCA-based factor analysis has been utilized in multiple previous studies on the development of representative human models and body shape analyses [42-44, 46, 48-50]. In performing PCA-based factor analyses, the orthogonal varimax rotation method was employed; Bittner et al. [42, 43] reported that the application of varimax rotation tends to increase the accommodation level represented

Table 1. Selected anthropometric dimensions

Variable type	Anthropometric Dimension
Lengths (9)	Stature
	Thumb tip reach
	Sitting height
	Eye height, sitting
	Shoulder height, sitting
	Elbow height, sitting
	Buttock-knee length
	Foot length
	Knee height
Circumferences (6)	Chest circumference
	Waist circumference
	Hip circumference
	Thigh circumference
	Vertical trunk circumference
	Thigh circumference, sitting
Widths (2)	Hip breadth, sitting
	Shoulder breadth
Weight (1)	Weight

by a manikin family. During the factor analysis process, the body dimensions with communalities less than 0.4 were removed. Also, the body dimensions with multiple loadings on all factors were either removed if the interpretation of meaning was difficult or were placed with the factors that are conceptually most closely related [17].

For each dataset, the manikin family was determined by identifying a set of individuals in the lower dimensional factor space. In doing so, a method developed by Kim and Whang [48] was employed: first, for each dataset, a cuboid was constructed in the factor space such that it encloses 99% of the obese population. Then, in order to select representative individuals (manikins) that are evenly distributed around the accommodation boundary, each vertices of the cuboid and the center of the cuboid are selected as the representative manikins. Conceptually, the center of the cuboid corresponds to an average obese person and the eight vertices manikins, anthropometrically extreme individuals within the obese population. The initial set of manikins may be used "as is" to define a manikin family [42-46, 48-49]; however, they are not real but hypothetical humans developed on the basis of the statistical distribution of given sample. Some of these hypothetical humans may have BMI less than 30 kg/m^2 and therefore be ineligible - the enclosure cuboid statistically constructed does not guarantee that all points on and within it have BMI greater than 30 kg/m^2. In this study, each manikin family was constructed primarily with the hypothetical manikins defined at the center and vertices of the enclosure cuboid; however, if some manikins have BMI less than 30 kg/m^2, they were replaced with the closest real persons in the dataset in terms of the Mahalanobis distance.

For each gender, the corresponding manikin family can be used to check if an aircraft passenger space design accommodates 99% of the obese population. If a design accommodates all the manikins in the manikin family, then it can be considered as accommodating approximately 99% or higher of the population. The target accommodation level of 99% was chosen because airplane interior design was considered to be safety-critical. Zehner et al. [48] developed 99.5% manikin families for crew station design considering the safety-critical nature of the application.

The two manikin families were compared in terms of each of the eighteen body dimensions (Table 1) so as to elucidate sex differences in anthropometric characteristics between the male and female obese groups.

To illustrate the utility of the manikin families, they were utilized to develop practical design recommendations for selected aircraft seat dimensions. The recommendations were to represent design requirements for accommodating at least 99% of each obese population. Aircraft seat dimensions closely related to the anthropometric accommodation of obese passengers were selected, including the minimum distance between the back support cushion of a seat and the back of the seat or other fixed structure in front (Airworthiness Notice 64 dimension A [AN64 dimension A]), the minimum vertically projected distance between seat rows or between a seat and any fixed structure forward of the seat (AN64 dimension C), seat cushion length, seat width, and backrest width. According to Quigley et al. [24], AN64 dimensions A and C substantially influence passenger's sitting comfort and ingress/egress. Seat cushion length, seat width and seat backrest width affect accommodation of obese passengers.

The procedure employed to develop the design recommendations is as follows:

1) Prepare a digital mock-up that represents a typical aircraft seat/interior design using an ergonomics CAD software program.
2) Create human figures that represent the eighteen manikins (both males and females) developed in this study using the ergonomics CAD software program.
3) Use the human figures representing all of the eighteen manikins to conduct virtual fitting trials (Figure 1)—the sitting and standing postures utilized by

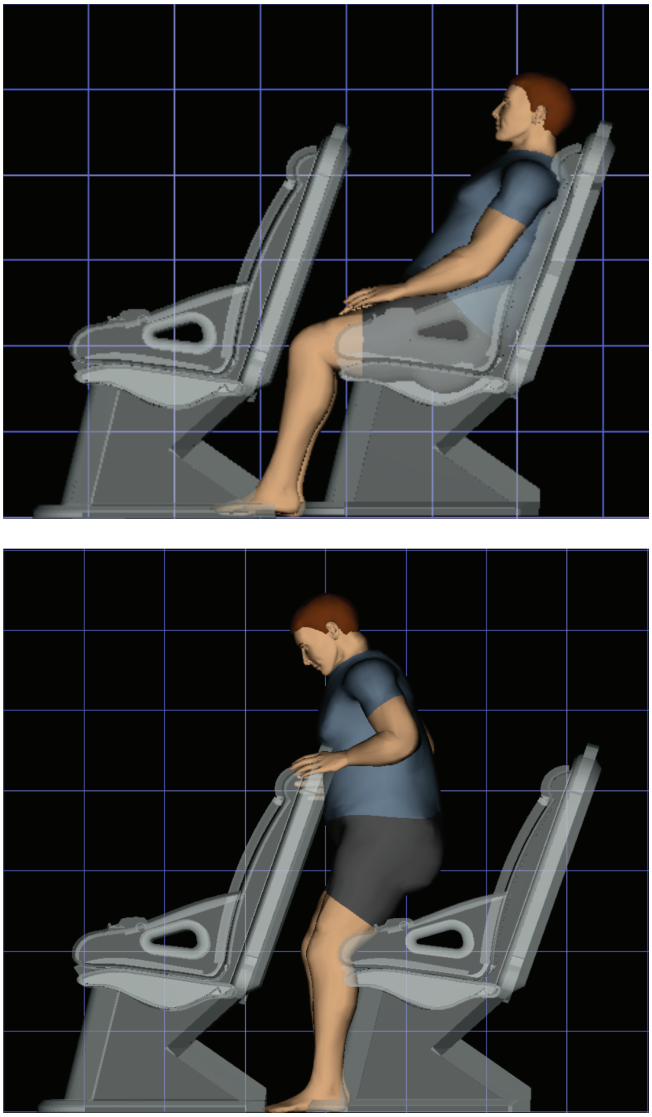


Figure 1. Graphical illustration of virtual fitting trial using a manikin.

Quigley et al. [24] are employed. If the design adequately fits all of the eighteen manikins, it is considered to accommodate 99% of each obese population. By trial and error, determine the optimal design that accomplishes the target accommodation level (99%) with minimum use of space.

4) Develop the selected seat dimensions on the basis of the optimal design found in Step 4.

3. RESULTS

Table 2 presents the PCA-based factor analysis result for the male dataset. Three factors (Factors 1~3) were identified, which collectively accounted for 83.9% of the total variance. Factor 1 showed positive loading with weight, and various breadth and circumference dimensions; it was labeled the "circumferences" factor. Factor 2 exhibited positive loading with stature and length dimensions; it was named as the "lengths" factor. Lastly, Factor 3 was characterized as positive loading with four height dimensions measured in a standard seated posture; these dimensions were measured as vertical distances from the seat pan surface. Factor 3 was labelled the "sitting heights" factor.

Table 2. The factor analysis result for the male dataset

	Factors and factor loadings			
Anthropometric dimensions	**Factor 1: Circumferences**	**Factor 2: Lengths**	**Factor 3: Sitting heights**	**Communality**
Stature (cm)	0.19	0.83	0.48	0.95
Weight (kg)	0.82	0.39	0.33	0.94
Chest circumference (cm)	0.85	0.13	0.23	0.79
Waist circumference (cm)	0.86	0.08	0.20	0.79
Hip circumference (cm)	0.93	0.18	0.15	0.91
Thigh circumference (cm)	0.80	0.29	0.15	0.75
Vertical trunk circumference (cm)	0.73	0.32	0.47	0.86
Knee height (cm)	0.24	0.90	0.20	0.91
Sitting height (cm)	0.16	0.43	0.84	0.92
Eye height, sitting (cm)	0.17	0.38	0.85	0.90
Shoulder height, sitting (cm)	0.32	0.29	0.85	0.91
Elbow height, sitting (cm)	0.34	-0.27	0.83	0.89
Buttock-knee length (cm)	0.54	0.73	-0.01	0.82
Thigh circumference, sitting (cm)	0.82	0.29	0.12	0.77
Shoulder breadth (cm)	0.67	0.25	0.26	0.58
Hip breadth, sitting (cm)	0.88	0.25	0.13	0.85
Thumb tip reach (cm)	0.23	0.85	0.12	0.79
Foot length (cm)	0.27	0.77	0.16	0.69
% total variance explained (cumulative)	58.8%	13.9%	11.2%	83.9%

Note: The underlined data in Table 2 indicate the anthropometric dimensions with significant factor loadings for each factor.

Table 3 presents percentile descriptions of the nine hypothetical males defined at the center (Hypothetical Male 9) and boundaries (Hypothetical Males 1-8) of the 99% enclosure cuboid. The percentile descriptions facilitate understanding anthropometric characteristics of the nine individuals. Out of the nine hypothetical males, four (Hypothetical Males 5-8) were found to have BMI < 30 kg/m2. Thus, in creating the male manikin family, these four individuals were replaced with the real persons in the dataset closest to them in terms of the Mahalanobis distance. Table 4 presents descriptions of the nine male manikins.

Table 3. The hypothetical males described in percentile

Anthropometric	Hypothetical males								
dimensions	1	2	3	4	5	6	7	8	9
Stature	99.9	93.3	35.4	0.2	99.8	64.6	6.7	0.003	50.0
Weight	99.9	99.5	98.6	67.5	32.5	1.4	0.5	0.001	50.0
Chest circumference	99.9	98.6	99.7	93.2	6.8	0.3	1.4	0.032	50.0
Waist circumference	99.9	98.5	99.8	95.9	4.1	0.2	1.5	0.060	50.0
Hip circumference	99.9	99.7	99.5	96.4	3.6	0.5	0.3	0.018	50.0
Thigh circumference	99.9	99.7	97.4	87.9	12.1	2.6	0.3	0.024	50.0
Vertical trunk circumference	99.9	96.0	99.4	51.4	48.6	0.6	4.0	0.001	50.0
Knee height	99.9	99.5	12.4	1.4	98.6	87.6	0.5	0.015	50.0
Sitting height	99.9	27.0	94.0	0.2	99.8	6.0	73.0	0.006	50.0
Eye height, sitting	99.9	22.6	95.7	0.3	99.7	4.3	77.4	0.009	50.0
Shoulder height, sitting	99.9	29.7	99.2	1.9	98.1	0.8	70.3	0.004	50.0
Elbow height, sitting	99.3	2.6	99.9	31.4	68.6	0.004	97.4	0.677	50.0
Buttock-knee length	99.9	99.9	34.6	36.5	63.5	65.4	0.02	0.026	50.0
Thigh circumference, sitting	99.9	99.8	97.2	89.7	10.3	2.8	0.2	0.026	50.0
Shoulder breadth	99.9	97.2	97.7	72.7	27.3	2.3	2.8	0.049	50.0
Hip breadth, sitting	99.9	99.8	98.7	94.0	6.0	1.3	0.2	0.020	50.0
Thumb tip reach	99.9	99.5	10.1	2.8	97.2	89.9	0.5	0.062	50.0
Foot length	99.9	99.2	19.6	4.4	95.6	80.4	0.8	0.059	50.0

Table 4. The 99% male manikin family

Anthropometric dimensions	Manikins								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Stature (cm)	208.2	189.5	175.5	156.8	183.1	177.8	173.6	163.1	178.6
Weight (kg)	184.2	154.9	149.8	120.5	108.2	95.2	94.1	85.5	110.1
Chest circumference(cm)	151.4	139.5	144.3	132.4	117.9	109.7	113.6	109.1	118.3
Waist circumference (cm)	149.7	136.6	145.0	131.9	104.1	93.8	102.9	96.1	107.6
Hip circumference (cm)	154.8	146.9	145.4	137.6	112.4	105.9	107.9	107.6	116.9
Thigh circumference (cm)	89.1	84.7	80.0	75.6	65.6	65.7	60.1	63.3	68.4
Vertical trunk circumference (cm)	228.7	202.9	210.5	184.6	187.5	172.9	180.8	161.5	184.4
Knee height(cm)	68.1	64.9	53.7	50.5	59.8	59.0	54.1	52.0	57.2
Sitting height (cm)	107.6	90.4	98.7	81.6	93.7	87.8	90.2	84.1	92.9
Eye height, sitting (cm)	95.0	78.2	87.3	70.6	82.5	75.5	79.6	72.3	81.1
Shoulder height, sitting (cm)	75.1	60.3	70.0	55.1	62.9	58.1	60.1	55.0	62.1
Elbow height, sitting (cm)	32.9	19.5	37.3	23.9	23.5	20.9	25.1	21.2	25.3
Buttock-knee length (cm)	77.6	77.8	62.6	62.7	64.0	66.8	61.8	59.2	64.2
Thigh circumference, sitting (cm)	88.6	84.7	79.5	75.6	68.4	65.1	60.4	63.3	68.6
Shoulder breadth (cm)	64.8	60.1	60.3	55.6	53.5	51.1	51.3	49.3	53.6
Hip breadth, sitting (cm)	56.3	53.9	51.4	49.0	41.6	36.9	39.4	39.4	42.5
Thumb tip reach (cm)	98.0	95.0	77.0	74.0	89.2	82.9	78.4	75.6	83.0
Foot length (cm)	32.3	31.0	26.0	24.8	28.1	27.9	25.8	25.0	27.3

Figure 2 presents scanned images of the real persons in the dataset that are closest to the nine male manikins and also the articulated human figures corresponding to the manikins. The scanned images were obtained from the CAESAR database. The human figures were created using a human CAD software program.

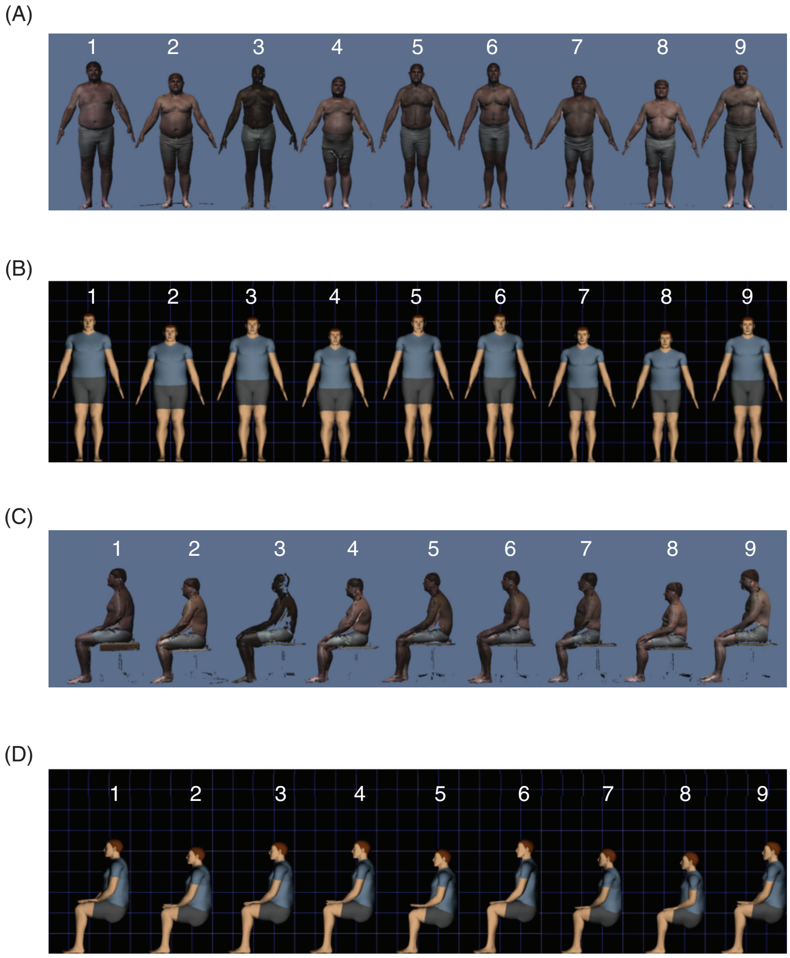


Figure 2. The 99% male manikin family illustrated in (A) standing posture (scanned images of similar real persons); (B) standing posture (digital human models); (C) seated posture (scanned images of similar real persons); and (D) seated posture (digital human models).

The factor analysis result for the female dataset is exhibited in Table 5. Similar to the result for the male dataset, three factors (Factors 1~3) were identified and they accounted for 80.5% of the total variance. The three factors were identical to those identified for the male dataset in meaning and were labelled the “circumferences,” “lengths,” and “sitting heights” factors, respectively. The manikin family generation results are presented in Tables 6 and 7 and Figure 3, similar to those for the male dataset.

Table 5. The factor analysis result for the female dataset

Anthropometric dimensions	Factors and factor loadings			
	Factor 1: Circumferences	Factor 2: Lengths	Factor 3: Sitting heights	Communality
Stature (cm)	0.20	0.80	0.42	0.85
Weight (kg)	0.88	0.35	0.26	0.97
Chest circumference (cm)	0.82	0.04	0.30	0.76
Waist circumference (cm)	0.81	0.04	0.27	0.74
Hip circumference (cm)	0.93	0.21	0.09	0.91
Thigh circumference (cm)	0.76	0.37	-0.04	0.72
Vertical trunk circumference (cm)	0.80	0.20	0.48	0.91
Knee height (cm)	0.22	0.89	0.16	0.87
Sitting height (cm)	0.11	0.49	0.81	0.90
Eye height, sitting (cm)	0.11	0.43	0.84	0.90
Shoulder height, sitting (cm)	0.26	0.29	0.88	0.93
Elbow height, sitting (cm)	0.28	-0.27	0.86	0.89
Buttock-knee length (cm)	0.59	0.71	-0.04	0.85
Thigh circumference, sitting (cm)	0.78	0.34	0.06	0.73
Shoulder breadth (cm)	0.61	0.12	0.27	0.45
Hip breadth, sitting (cm)	0.76	0.39	-0.02	0.74
Thumb tip reach (cm)	0.29	0.77	0.19	0.71
Foot length (cm)	0.19	0.79	0.11	0.67
% total variance explained (cumulative)	54.0%	14.3%	12.3%	80.5%

Note: The underlined data in Table 5 indicate the anthropometric dimensions with significant factor loadings for each factor.

The male and female manikin families were compared in terms of each of the eighteen body dimensions. Among the eighteen body dimensions considered in this study, fourteen were found to show systematic sex differences. Figures 4(A-N) illustrate the notable between-group differences.

Table 8 presents the design recommendations for the selected seat dimensions developed utilizing the manikin families. For each dimension, its definition, the recommendation from Quigley et al. [24] and that from the current study are presented.

4. DISCUSSION

Aircraft passenger spaces designed without proper anthropometric analyses can create serious problems for obese passengers, including possible denial of boarding, excessive body pressures and contact stresses, postural fixity and related health hazards, and increased risks of emergency evacuation failure. This study developed male and female

Table 6. The hypothetical females described in percentile

Anthropometric dimensions	Hypothetical females								
	1	2	3	4	5	6	7	8	9
Stature	99.9	94.6	32.9	0.4	99.6	67.1	5.4	0.007	50.0
Weight	99.9	99.8	98.9	82.4	17.6	1.1	0.2	0.002	50.0
Chest circumference	99.9	95.3	99.9	93.0	7.0	0.1	4.7	0.060	50.0
Waist circumference	99.9	95.9	99.8	93.9	6.1	0.2	4.1	0.083	50.0
Hip circumference	99.9	99.9	99.1	97.0	3.0	0.9	0.1	0.028	50.0
Thigh circumference	99.9	99.9	86.8	90.6	9.4	13.2	0.1	0.102	50.0
Vertical trunk circumference	99.9	94.3	99.9	69.6	30.4	0.1	5.7	0.002	50.0
Knee height	99.9	99.5	9.2	1.6	98.4	90.8	0.5	0.030	50.0
Sitting height	99.9	30.5	87.6	0.1	99.9	12.4	69.5	0.009	50.0
Eye height, sitting	99.9	22.2	91.7	0.1	99.9	8.3	77.8	0.013	50.0
Shoulder height, sitting	99.9	21.7	98.9	0.9	99.1	1.1	78.3	0.006	50.0
Elbow height, sitting	99.0	1.4	99.9	22.7	77.3	0.01	98.6	0.966	50.0
Buttock-knee length	99.9	99.9	38.9	47.3	52.7	61.1	0.01	0.025	50.0
Thigh circumference, sitting	99.9	99.9	93.5	88.4	11.6	6.5	0.1	0.047	50.0
Shoulder breadth	99.7	91.1	98.4	76.6	23.4	1.6	8.9	0.288	50.0
Hip breadth, sitting	99.9	99.9	86.1	88.7	11.3	13.9	0.0	0.072	50.0
Thumb tip reach	99.9	99.1	23.9	4.3	95.7	76.1	0.9	0.037	50.0
Foot length	99.8	99.0	10.2	3.2	96.8	89.8	1.0	0.172	50.0

manikin families of obese US airline passengers in order to help address obese passenger's accommodation issues for the design of aircraft interior spaces. Anthropometric data of obese individuals obtained from the CAESAR anthropometric database were analyzed through PCA-based factor analyses. For each gender, a 99% enclosure cuboid was constructed in the factor space and was used to define a small set of manikins.

Table 7. The 99% female manikin family

Anthropometric dimensions	Manikins								
	1	2	3	4	5	6	7	8	9
Stature (cm)	191.7	175.1	159.5	142.9	179.5	166.3	157.5	156.9	163.1
Weight (kg)	174.8	150.2	141.6	116.9	93.2	84.6	84.1	75.3	97.7
Chest circumference (cm)	152.4	135.0	149.8	132.5	109.0	106.8	110.8	102.0	116.2
Waist circumference (cm)	142.9	124.3	140.5	121.9	91.1	82.5	94.3	80.9	100.9
Hip circumference (cm)	169.2	162.9	156.1	149.7	119.2	115.1	117.4	110.4	125.6
Thigh circumference (cm)	95.7	96.9	81.4	82.5	72.7	70.3	67.1	67.1	72.2
Vertical trunk circumference (cm)	215.1	188.9	203.9	177.7	173.7	165.0	165.9	157.6	172.4
Knee height (cm)	61.2	58.9	47.3	44.9	54.1	53.5	47.6	48.4	51.2
Sitting height (cm)	99.8	84.4	90.5	75.0	91.0	85.8	86.7	84.8	86.3
Eye height, sitting (cm)	88.1	72.7	80.2	64.9	79.8	74.8	76.1	74.2	75.4
Shoulder height, sitting (cm)	69.2	55.4	64.6	50.7	60.1	56.8	56.9	54.4	57.7
Elbow height, sitting (cm)	32.0	18.4	36.3	22.7	25.7	22.5	25.2	22.5	24.9
Buttock-knee length (cm)	76.7	77.7	60.8	61.7	62.5	62.5	57.1	56.7	61.9
Thigh circumference, sitting (cm)	96.8	94.4	83.5	81.0	73.2	69.1	64.5	67.1	71.8
Shoulder breadth (cm)	58.7	53.1	56.1	50.5	50.1	44.9	47.5	42.9	47.6
Hip breadth, sitting (cm)	63.2	63.6	53.2	53.6	47.5	45.9	44.6	44.5	47.6
Thumb tip reach (cm)	89.1	85.0	72.2	68.1	77.9	77.9	72.5	72.6	75.2
Foot length (cm)	28.3	27.6	22.7	22.0	25.6	25.6	22.9	22.8	24.4

For each dataset, the PCA-based factor analysis identified three factors that collectively accounted for more than 80% of the total variance – 83.9% and 80.5% for the male and female datasets, respectively (Tables 2 and 5). The sets of factors found for the two datasets (male and female) were identical in terms of the meanings of the factors – for both genders, the three factors were labelled the "circumferences," "lengths" and "sitting heights" factors. Considering the significant sexual dimorphism

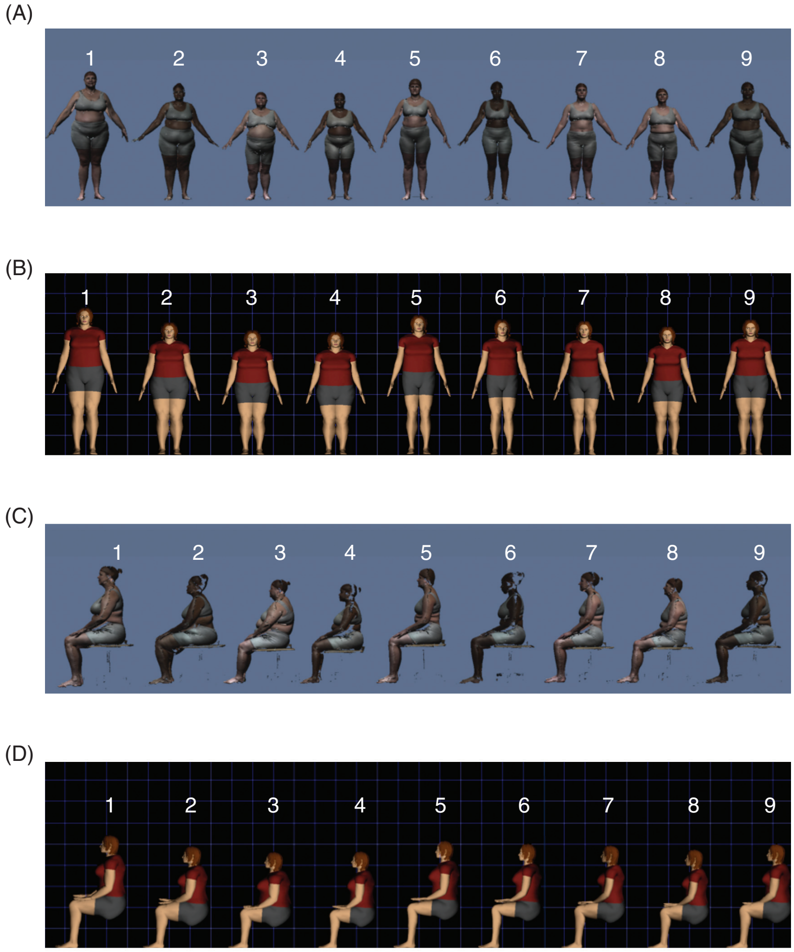
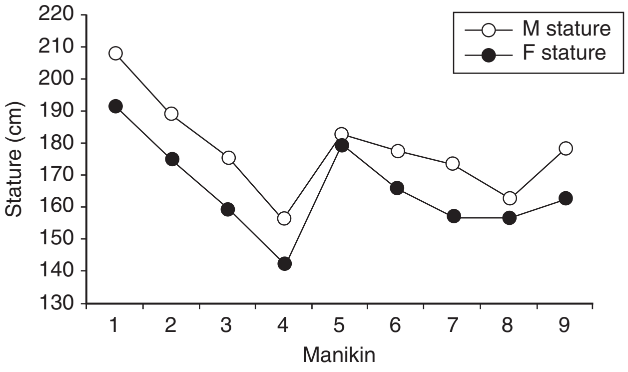
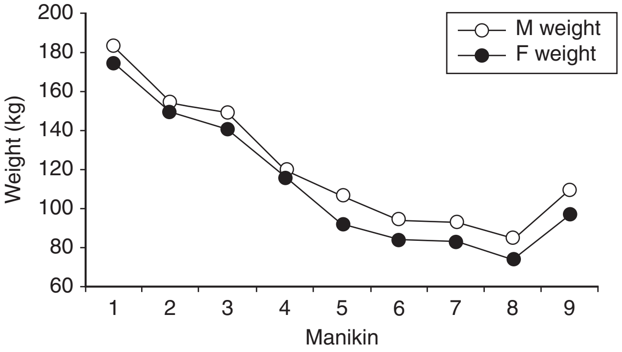


Figure 3. The 99% female manikin family illustrated in (A) standing posture (scanned images of similar real persons); (B) standing posture (digital human models); (C) seated posture (scanned images of similar real persons); and (D) seated posture (digital human models).

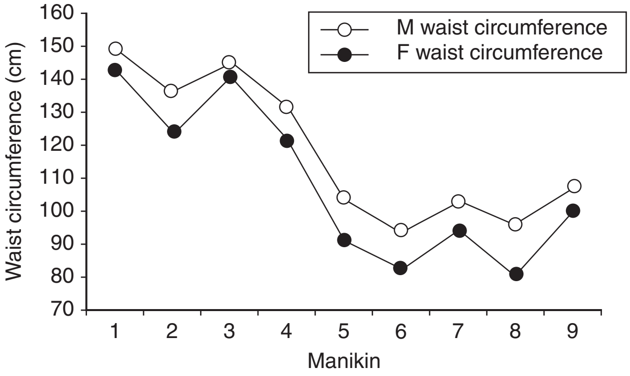
in humans, it is interesting that the same sets of factors were identified for both genders. Related to this, a recent study on the body shapes of obese and overweight persons [17] found different sets of factors for males and females indicating fundamental sex differences in the structure of the body shape space, with five factors ("waist and abdomen," "leg," "upper arm," "torso surface," and "biacromial breadth") identified for males while three factors ("torso," "lower body," and "biacromial breadth") identified for females.



(a) Stature

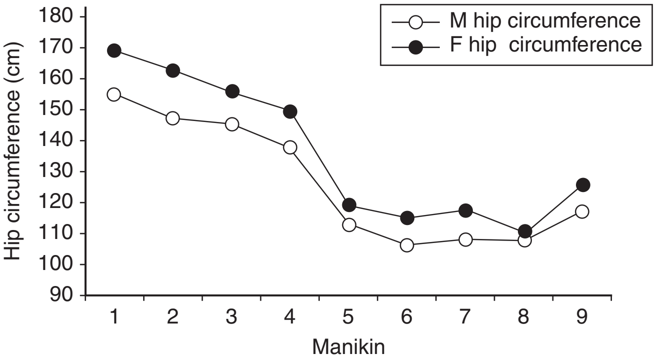


(b) Weight

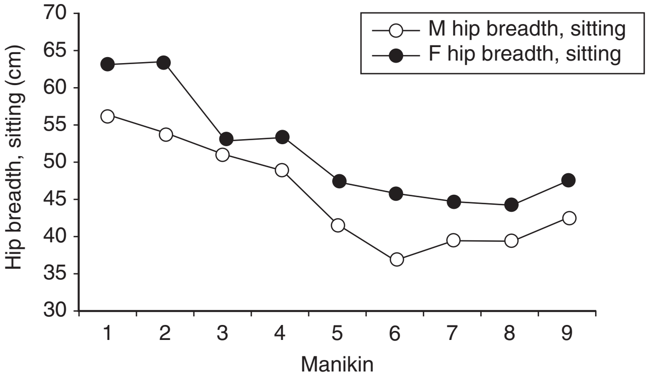


(c) Waist circumference

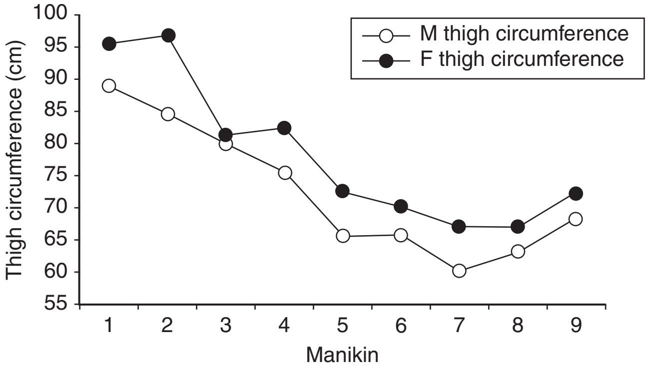
Figure 4. (Continued)



(d) Hip circumference

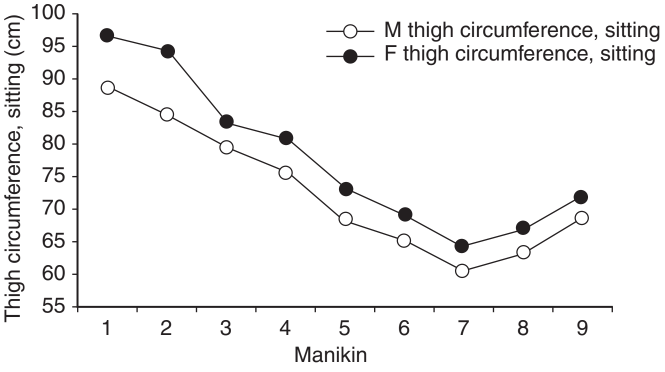


(e) Hip breadth, sitting

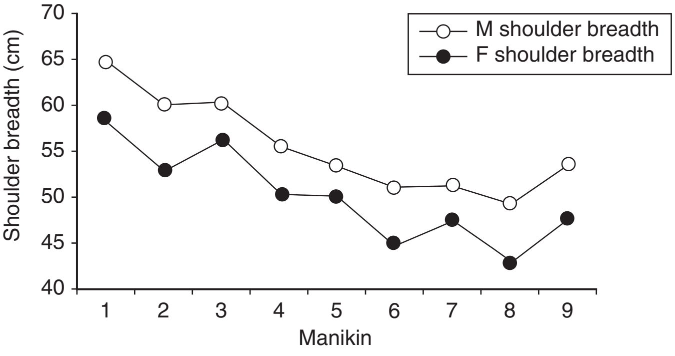


(f) Thigh circumference

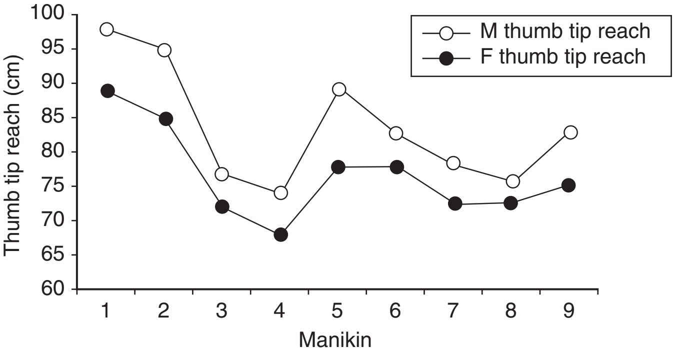
Figure 4. (Continued)



(g) Thigh circumference, sitting

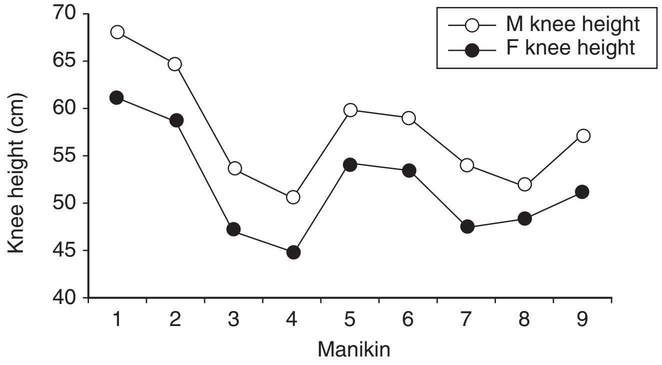


(h) Shoulder breadth

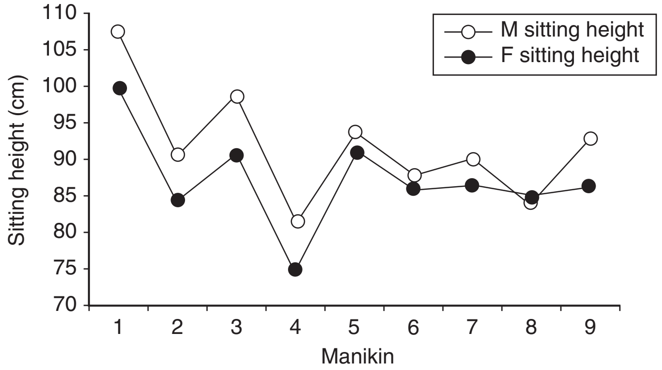


(i) Thumb tip reach

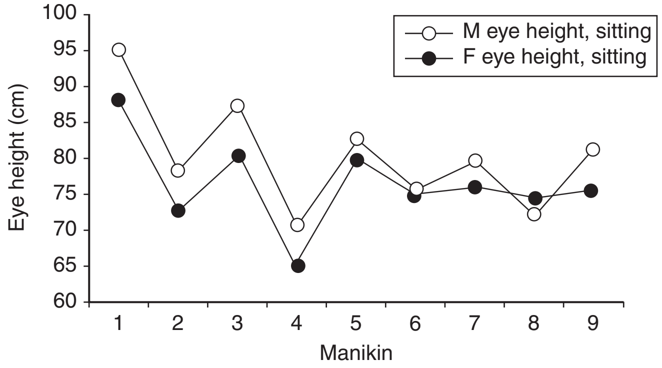
Figure 4. (Continued)



(j) Knee height

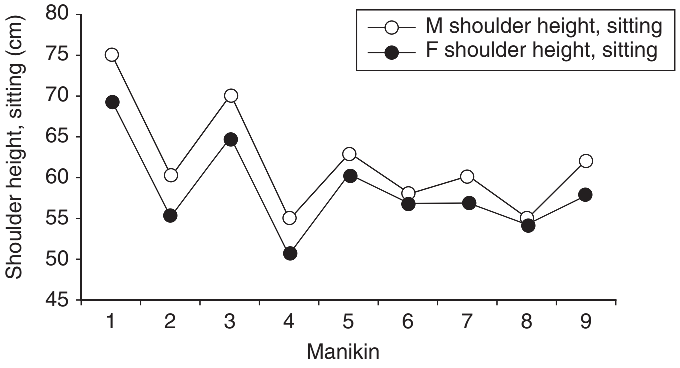


(k) Sitting height

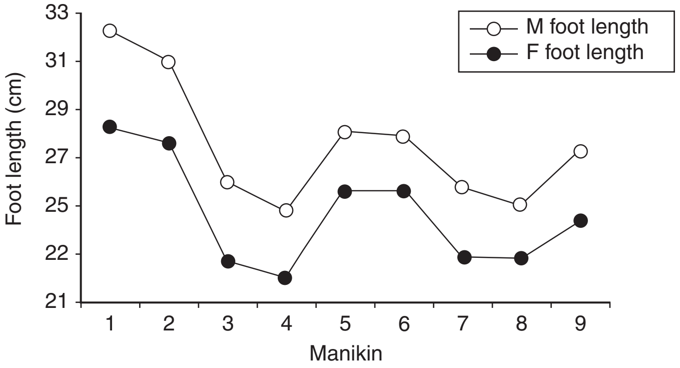


(l) Eye height, sitting

Figure 4. (Continued)



(m) Shoulder height, sitting (cm)



(n) Foot length

Figure 4. Anthropometric differences between the male (M) and female (F) manikin families.

It should be pointed out that the body shape study [17] and the current study differed in the research objective, and consequently, in the treatment of anthropometric data. The body shape study [17] investigated body shapes, and therefore, utilized stature-normalized anthropometric data so as to consider body shapes in a manner independent of body size. On the other hand, this study used body dimensions data "as is" without such normalization because both size and shape were considered to be relevant to the passenger-space interaction. It is thought that in general, the two sexes' body shape spaces structurally differ but their body dimensions spaces, in which both size and shape are represented, do not. This conjecture is currently under investigation using multiple anthropometric datasets. One thing that seems certain is that body shape space and body dimensions space are two very different concepts and should be clearly distinguished in considering anthropometric design problems or creating ergonomics design tools. For example, a manikin family defined in a body shape space of a population would be completely different from that in the corresponding body dimensions space, and the manikin families would have different applications.

Table 8. Design recommendations for selected seat dimensions

Dimension	*Quigley et al. (2001) [24]*	*Obese US Airline Passengers (current study)*
The minimum distance between the back support cushion of a seat and the back of the seat or other fixed structure in front (AN64 dimension A)	747mm (29.41”)	803mm (31.61”)
The minimum vertically projected distance between seat rows or between a seat and any fixed structure forward of the seat (AN64 dimension C)	438mm (17.24”)	470mm (18.50”)
Seat cushion length (distance from the front to the back of a seat cushion)	379mm (14.90”)	391mm (15.39”)
Seat width (distance between the two armrests)	584mm (22.99”)	616mm (24.25”)
Backrest width (distance between the right to the left side of a seat back)	608mm (23.94”)	640mm (25.20”)

The male and female manikin families developed in this study facilitated identifying sex differences in the anthropometric characteristics of obese individuals (Figures 4A-4N). Some observations are as follows:

- The male manikins in general were larger than the corresponding female manikins in stature, weight, waist circumference, shoulder breadth, thumb tip reach distance, knee height, sitting height, eye height, shoulder height (sitting) and foot length.
- The female manikins were generally larger than the corresponding male manikins in hip circumference, hip breadth, thigh circumference and thigh circumference (sitting).

The observed sex differences in waist circumference, hip circumference, hip breadth and thigh circumference are consistent with the previously documented sex-specific body fat deposit patterns. In general, females tend to accumulate body fat primarily in the hip and buttock areas, whereas males, in the waist and abdominal areas [58, 59].

The manikin families developed in this study are expected to serve as a useful aircraft interior design tool for accommodating the obese passenger population. To illustrate their utilities, they were used to derive design recommendations for some important seat dimensions (Table 8). The ingress/egress and seated postures used to estimate the AN64 dimensions A and C are illustrated in Figure 1. These postures were obtained from photo images of actual passengers taken inside aircrafts during ingress/egress and in the seated position. It is also noted that seat length, seat width and backrest width were determined without any estimations of whole body postures because each of them could be determined from a single body dimension. As can be seen from Table 8, accommodating the majority of the obese passenger population requires increased multiple seat dimensions. Table 8 provides quantitative recommendation in terms of how much larger the seat dimensions should be to accommodate obese passengers. Such information along with an estimated percentage of obese passengers among all passengers, commercial airlines may consider installing in each aircraft a certain number of larger seats particularly for obese passengers, perhaps at an optional higher ticket price. Increased seat dimensions will improve comfort and reduce postural fixity for not only obese but also non-obese passengers; also, they are expected to benefit both obese and non-obese passengers in terms of evacuation safety—during emergency evacuation, large clearances provided by increased seat dimensions would help both groups evacuate efficiently.

The manikin families might also be utilized as basic design references for design of aircraft seat safety belts for obese passengers. In the automotive domain, some recent studies [60-62] reported problems with the safety belt fit and function for obese occupants. Similar problems may exist for obese airline passengers. Future research studies on this topic seem to be warranted.

While increased seat dimensions (Table 8) would improve comfort and evacuation safety for all passengers, it is possible that they adversely affect the safety of some non-obese passengers during crash landing. An excessively large seat and long seat belt would create extra spaces on both sides around the body for a small passenger. While it is not clear how such extra space/slack affects the body kinematics and impacts during crash landing, it may hamper properly securing small passengers, and therefore, hinder optimally reducing the crash impacts.

Aside from seat dimensions, seat structure may also require some modifications in consideration of the obesity-associated increase in body mass. An obese passenger's body mass impose large mechanical stresses on an aircraft seat. The current US government regulations on aircraft seat design, such as Parts 23, 25, 27 and 29 of Title 14 of the Code of Federal Regulations (CFRs), do not seem to be based on consideration of obese passengers' large body masses. For example, Part 25.562 requires the use of a 77 kg (170 lb) anthropomorphic dummy for dynamic seat tests [63]. Therefore, current aircraft seats designed to pass the regulation may not be able to support an obese passenger's large body mass during take-off or landing; the seat may deform and even collapse inflicting direct injuries to passengers. It is thought that seat structure needs to be strengthened to adequately protect obese passengers. In line with this, perhaps, one possible application of the manikin families developed in this study is the design of a new test dummy or dummies for aircraft seat tests. The manikin families may serve as references for such new development.

The manikins developed in this study were utilized to derive design recommendations for some important seat dimensions (Table 8). In doing so, this study utilized photo images of real human passengers' postures taken inside aircrafts. This ensured that the ingress/egress and seated postures used in this study were realistic.

It should be noted that an alternative to using photo images or motion capture data of real persons is to utilize human posture and motion simulation algorithms. These algorithms can predict realistic human postures and motions corresponding to given scenarios in a time- and cost-effective manner. Multiple studies [64-66] employed posture prediction models to systematically predict human postures/motions in various situations. Recently, Howard and Yang [67] introduced a new stability criterion to predict human motions in the seated position. It would be important to consider standing stabilityand all interaction forces in simulating posture and motion behaviors of obese airline passengers.

The manikin families developed in this study represent one of the few existing design tools for considering large persons' accommodation issues in aircraft passenger space design, and are expected to help designers make informed design decisions. In addition to airplane passenger space design, the manikins may also be useful for other design activities, including occupant packing for ground vehicles and general furniture design, as the 18 body dimensions used in this study seem relevant to these design applications.

This study presented 99% manikin families, since aircraft passenger space design was considered to be safety-critical; however, manikin families for other accommodation levels, for example, 90% and 95%, may be useful for certain design applications that are less safety-critical. These manikin families are currently under development.

Some limitations of the current study exist. The current study considered only the US population. Obese individuals in other regions need to be investigated in future studies. Also, this study examined only the obese (BMI ≥ 30 kg/m^2) segment of the population. Future studies may consider developing manikin families for other segments of the population, including the overweight (25 kg/m^2 $\leq$ BMI $<$ 30 kg/m^2) and severely obese (BMI $\geq$ 35 kg/m^2) segments. Such manikin families may further inform design decisions. Finally, the manikin families developed in this study may not correspond to the current US obese populations. The CAESAR database was established about 15 years ago; therefore, the obese individuals in the CAESAR database represent the US obese populations 15 years ago. While the definition of obesity (BMI $>$ 30 kg/m^2) has not changed, it is possible that the US "obese" population today is different from that of 1999/2000 in terms of anthropometric characteristics, especially the obese male population. While no studies, to the authors' knowledge, seem to have specifically investigated possible anthropometric changes of the US obese populations over the past decades considering various anthropometric dimensions, Flegal et al. [3] examined the BMI changes of the US "general" population from 1999 to 2010. The study showed a significant increase in BMI in men ($p = .001$) and no significant increase in women ($p = .06$). Thus, at least for males, the current and 1999/2000 "obese" populations may differ in the distribution of BMI.

The best way to develop manikin families for today's obese populations is certainly to use a CAESAR-like anthropometric database describing today's obese individuals; however, such a CAESAR-like database does not seem to be available, to the best of the authors' knowledge. A possible alternative to using a CAESAR-like anthropometric database describing today's obese individuals is to synthesize today's obese people based on mathematical models. Related to this, de Vries [68] developed an approach to synthesizing a virtual population. Adopting the approach of de Vries [68], a virtual obese population representing today's obese population may be generated following the steps below:

1) A set of regression models are developed that predict the anthropometric dimensions related to aircraft interior design (Table 1) based on height and BMI for obese individuals. The CAESAR data may be utilized in developing such regression models. The regression models should include the stochastic components, that is, normal random variables representing the residuals.
2) The regression equations (stochastic models) are used along with the latest NHANES (National Health and Nutrition Examination Survey) height and BMI datasets (for example, 2009-2010) of obese individuals to generate body dimensions of many virtual obese individuals (say, 3000 males and 3000 females).

Based on the virtual obese individuals and their body dimensions synthesized using the method described above, manikin families representing today's obese populations may be developed. The multivariate statistical method described in the current paper can be used to do so. Until a newer CAESAR-like database becomes available, the model-based manikin families may be used along with the 1999/2000 obese manikin families provided in this study. We are currently developing such model-based manikin families.

5. CONCLUSION

This study developed male and female manikin families that represent obese US airplane passengers. Multivariate statistical analyses were conducted on anthropometric data of obese individuals obtained from the CAESAR database. Each manikin family consists of nine individuals and they collectively cover 99% of the target population. The manikin families will facilitate accommodation of large persons in the design of aircraft passenger spaces. They may also be useful for other applications, including occupant packaging for ground vehicles and furniture design.

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CONFLICT OF INTEREST

The authors indicated no potential conflicts of interest.

REFERENCES

[1] World Health Organization. Obesity and overweight. 2013. http://www.who.int/mediacentre/factsheets/fs311/. Accessed August 5, 2013.

[2] Sassi F. Obesity and the economics of prevention: fit not fat. *OECD Publishing*, Paris, 2010.

[3] Flegal KM, Carroll MD, Kit BK, Ogden CL. Prevalence of obesity and trends in the distribution of body mass index among U.S. adults, 1999-2010. *Jama*, 2012, 307:491–497

[4] Allender S, Rayner M. The burden of overweight and obesity-related ill health in the UK. *Obesity reviews*, 2007, 8:467–473.

[5] Williams N, Forde M. Ergonomics and obesity. *Applied Ergonomics*, 2009, 40:148–149.

[6] Buckle P, Buckle J. Obesity, ergonomics and public health. *Perspectives in Public Health*, 2011, 131:170–176.

[7] Fontaine KR, Gadbury G, Heymsfield SB, Kral J, Albu JB, Allison D. Quantitative prediction of body diameter in severely obese individuals. *Ergonomics*, 2002, 45:49–60.

[8] Matrangola SL, Madigan ML, Nussbaum MA, Ross R, Davy KP. Changes in body segment inertial parameters of obese individuals with weight loss. *Journal of Biomechanics*, 2008, 41:3278–281.

[9] Xu X, Mirka GA, Hsiang SM. The effects of obesity on lifting performance. *Applied Ergonomics*, 2008, 39:93–98.

[10] Park W, Singh DP, Levy MS, Jung ES. Obesity effect on perceived postural stress during static posture maintenance tasks. *Ergonomics*, 2009, 52:1169–1182.

[11] Singh D, Park W, Levy MS. Obesity does not reduce maximum acceptable weights of lift. *Applied Ergonomics*, 2009, 40:1–7.

[12] Singh D, Park W, Levy M, Jung ES. The effects of obesity and standing time on postural sway during prolonged quiet standing. *Ergonomics*, 2009, 52:977–986.

[13] Park W, Ramachandran J, Weisman P, Jung ES. Obesity effect on male active joint range of motion. *Ergonomics*, 2010, 53:102–108.

[14] Chambers AJ, Sukits AL, McCrory JL, Cham R. The effect of obesity and gender on body segment parameters in older adults. *Clinical Biomechanics*, 2010, 25:131–136.

[15] Matrangola SL, Madigan ML. The effects of obesity on balance recovery using an ankle strategy. *Human movement science*, 2011, 30:584–595.

[16] Miller EM, Matrangola SL, Madigan ML. Effects of obesity on balance recovery from small postural perturbations. *Ergonomics*, 2011, 54:547–554.

[17] Park W, Park S. Body shape analyses of large persons in South Korea. *Ergonomics*, 2013, 56:692–706.

[18] Gragg J, Yang JJ. Effect of obesity on seated posture inside a vehicle based on digital human models, *SAE International Journal of Materials and Manufacturing*, 2011, 4(1):516–526.

[19] HFES 300 Committee. Guidelines for Using Anthropometric Data in Product Design. Human Factors and Ergonomics Society, Santa Monica, CA, 2004.

[20] Smith K. “I’m never going on Southwest again.” CNN, 2010. http://edition.cnn.com/2010/SHOWBIZ/Movies/02/15/kevin.smith.southwest/index.html. Accessed Feb 6, 2013.

[21] Pawlowski A. “Obese flier turned away by airlines dies overseas.” CNN, 2012. http://cnntopstory.blogspot.kr/2012/11/obese-flier-turned-away-by-airlines.html. Accessed Mar 15, 2013.

[22] Vink P. Aircraft interior comfort and design, 5, CRC Press, 2011.

[23] Hinninghofen H, Enck P. Passenger well-being in airplanes. *Autonomic Neuroscience*, 2006, 129:80–85.

[24] Quigley C, Southall D, Freer M, Moody A, Porter JM. Anthropometric study to update minimum aircraft seating standards. Report prepared for the Joint Aviation Authorities, ICE Ergonomics Ltd, 2001.

[25] Richards LG, Jacobson ID. Ride quality evaluation 1. Questionnaire studies of airline passenger comfort. *Ergonomics,* 1975, 18:129–150.

[26] Grieco A. Sitting posture: an old problem and a new one. *Ergonomics*, 1986, 29:345–362.

[27] Fazlollahtabar H. A subjective framework for seat comfort based on a heuristic multi criteria decision making technique and anthropometry. *Applied Ergonomics*, 2010, 42:16–28.

[28] Luttmann A, Schmidt K-H, Jäger M. Working conditions, muscular activity and complaints of office workers. *International Journal of Industrial Ergonomics*, 2010, 40:549–559.

[29] Symington IS, Stack BH. Pulmonary thromboembolism after travel. *British journal of diseases of the chest*, 1977, 71:138–140.

[30] Cruickshank J, Gorlin R, Jennett B. Air travel and thrombotic episodes: the economy class syndrome. *The Lancet*, 1988, 332:497–498.

[31] Ball K. Deep vein thrombosis and airline travel—the deadly duo. *AORN Journal*, 2003, 77(2): 346–358.

[32] Paganin F, Bourde A, Yvin J-L, Genin R, Guijarro J-L, Bourdin A, Lassalle C. Venous thromboembolism in passengers following a 12-h flight: a case-control study. *Aviation, space, and environmental medicine*, 2003, 74:1277–1280.

[33] Philbrick JT, Shumate R, Siadaty MS, Becker DM. Air travel and venous thromboembolism: a systematic review. *Journal of general internal medicine*, 2007, 22:107–14.

[34] Stein PD, Beemath A, Olson RE. Obesity as a risk factor in venous thromboembolism. *The American journal of medicine*, 2005, 118:978–980.

[35] Eichinger S, Hron G, Bialonczyk C, Hirschl M, Minar E, Wagner O, Heinze G, Kyrle PA. Overweight, obesity, and the risk of recurrent venous thromboembolism. *Archives of internal medicine*, 2008, 168(15):1678–1683.

[36] Brundrett G. Comfort and health in commercial aircraft: a literature review. *The Journal of the Royal Society for the Promotion of Health*, 2001, 121:29–37.

[37] Philippart NL, Roe RW, Arnold AJ, Kuechenmeister TJ. Driver selected seat position model, *SAE Technical Paper*, 1984.

[38] Flannagan CA, Schneider LW, Manary M. Development of a new seating accommodation model. *SAE transactions*, 1996.

[39] Flannagan CA, Manary MA, Schneider LW, Reed MP. An improved seating accommodation model with application to different user populations. *SAE transactions*, 1998.

[40] UK Civil Aviation Authority Airworthiness Notice, Minimum Space for Seated Passengers, 2001, vol. 64(2) 1–3.

[41] Kremser F, Guenzkofer F, Sedlmeier C, Sabbah O, Bengler K. Aircraft seating comfort: the influence of seat pitch on passengers' well-being. *Work*, 2012, 41:4936–42.

[42] Bittner AC, Glenn F, Harris RM, Iavecchia HP, Wherry RJ. CADRE: A family of manikins for workstation design. *Trends in ergonomics/human factors IV*, 1987, 733–740.

[43] Bittner AC. A-Cadre: Advanced Family of Manikins for Workstation Design. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting,* 2000, 44:774–777.

[44] Kim JH, Whang MC. Development of a set of Korean manikins. *Applied Ergonomics*, 1997, 28:407–410.

[45] Geuß, Hartwich. Entwicklung eines anthropometrischen Meßverfahrens für das CAD-Menschmodell RAMSIS. Dissertation am Institut für Ergonomie der Technischen Universität München, 1994.

[46] Hsiao H, Whitestone J, Bradtmiller B, Whisler R, Zwiener J, Lafferty C, Kau TY, Gross M. Anthropometric criteria for the design of tractor cabs and protection frames. *Ergonomics*, 2005, 48:323–353.

[47] Jung K, Kwon O, You H. Development of the boundary zone method for generation of representative human models. *Proceedings of the Human Factors and Ergonomics Society Annual Meetings*, 2009, 1472–6.

[48] Zehner GF, Meindl RS, Hudson JA. A multivariate anthropometric method for crew station design, Technical Report AL-TR-93–0054, Wright-Patterson Air Force Base, Ohio, 1993.

[49] Bertilsson E, Högberg D, Hanson L. Using experimental design to define boundary manikins. *Work*, 2012, 41:4598–4605.

[50] Young K, Margerum S, Barr A, Ferrer M, Rajulu S. Generation of Boundary Manikins Anthropometry. *SAE Technical paper*, 2008.

[51] Ozsoy B, Yang J, Simulation-Based Sit-to-Stand Motion Prediction, ASME DETC, August 17-20, 2014, Buffalo, NY, USA.

[52] Dunn G. "Low-cost carriers: growth expectations", Flight global, 2011. http://www.flightglobal.com/news/articles/low-cost-carriers-growth-expectations-355702. Accessed Aug 20, 2013.

[53] Harrison C, Robinette K. CAESAR: summary statistics for the adult population (ages 18–65) of the United States of America, Technical report AFRL-HE-WP-TR-2002-0170, Human Effectiveness Directorate Crew System Interface Division, Wright-Patterson Air Force Base, Ohio, 2002.

[54] Greghi MF, Rossi TN, de Souza JBG, Menegon NL. Brazilian passengers' perceptions of air travel: Evidences from a survey. *Journal of Air Transport Management*, 2013, 31:27–31.

[55] Vink P, Bazley C, Kamp I, Blok M. Possibilities to improve the aircraft interior comfort experience. *Applied Ergonomics*, 2012, 43:354–359.

[56] Richards LG, Jacobson ID. Ride quality assessment III: questionnaire results of a second flight programme. *Ergonomics*, 1977;20:499–519.

[57] Röggla G, Moser B, Röggla M. Seat space on airlines. The Lancet, 1999, 353(9163):1532.

[58] Wilson S, Loesch D. Principal component analysis of shape variables in adult individuals. *Annals of human biology*, 1989, 16:361–368.

[59] Cootes TF, Taylor CJ. Combining point distribution models with shape models based on finite element analysis. *Image and Vision Computing*, 1995, 13(5): 403–409.

[60] Reed MP, Ebert-Hamilton SM, Rupp JD. Effects of obesity on seat belt fit. *Traffic Injury Prevention*, 2012, 13(4):364–372.

[61] Shi X, Cao L, Reed MP, Rupp JD, Hu J. Effects of obesity on occupant responses in frontal crashes: a simulation analysis using human body models. *Computer methods in biomechanics and biomedical engineering*, 2014, 1–13.

[62] Reed MP, Sheila E, and Hallman J. Effects of driver characteristics on seat belt fit. *Stapp car crash journal*, 2013, 57:43–57.

[63] "Emergency landing dynamic conditions." 14 CFR 25.562. 1988.

[64] Yang J, Howard B, Cloutier A, Domire JZ, Vertical ground reaction forces for given human standing posture with uneven terrains: prediction and validation, *IEEE Transaction on Human-Machine Systems*, 2013, 43(2):225–234.

[65] Howard B, Cloutier A, Yang J, Physics-based seated posture prediction for pregnant women and validation considering ground and seat pan contacts, ASME *Journal of Biomechanical Engineering*, 2012, 134(7):071004.

[66] Howard, B, Yang J, Calculating support reaction forces in physics-based seated posture prediction for pregnant women, *International Journal of Robotics and Automation*, 2012, 27(3):308–321.

[67] Howard B, Yang J, A new stability criterion for human seated tasks with given postures, *International Journal of Humanoid Robotics*, 2012, 9(3).

[68] de Vries C, Garneau CJ, Nadadur G, and Parkinson MB. Considering secular and demographic trends in designing long lifetime products for target user populations. *Journal of Mechanical Design*, ASME, 2011.