Developing and Implementing Parametric Human Body Shape Models in Ergonomics Software

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Abstract

Human figure models included with today's high-end simulation systems are widely used for ergonomic analysis. Male and female figures can be scaled by inputting standard anthropometric dimensions, such as stature, body weight, and limb lengths to represent a large range of body sizes. However, the shapes of these scaled figures are often unrealistic, particularly for extreme body types, because only a relatively few dimensions of the figures are adjusted. Several software packages have the capability of adjusting the figure to match a body surface scan of an individual, but this capability is insufficient when individuals with a wide range of attributes must be simulated. We present a new figure generation capability in the Jack human modeling software based on a statistical analysis of laser scans of hundreds of men and women. A template mesh based on the Jack figure model was fitted to each scan, and a statistical shape model was created using principal component analysis and regression. The model was integrated within the Jack software to create Jack figures with highly realistic body shapes, usable natively with all simulation and analysis features.

Keywords: Body Shape, Parametric Modeling, Ergonomics Software

1. Introduction

Scaling of human figure models is one of the most basic functions of digital human modeling software systems. From the time of their introduction, software systems such as Safework (Fortin et al. 1990), RAMSIS (Seidl et al. 1995), and Jack (Badler et al. 1989) have included the capability for the user to adjust the size of the manikin to represent humans with widely varying body size. Yet, accurate representation of the range of human body sizes and shapes is challenging, due to the diversity of the human population.

The widespread use of laser scanning for human body surface measurement in the late 1990s provided for the first time the opportunity to gather the large amounts of data needed to create statistical models of human body shape. A large amount of scan data was first available in the U.S. from the CAESAR study beginning in 1999 (Robinette et al. 2002). Reed et al. (2001) described a segmentation method for fitting a standardized mesh to CAESAR data, but this method was never used with a commercial human model.

For ergonomics applications, a *parametric* body shape model that predicts body size and shape as a function of a few standard anthropometric dimensions is needed. Allen et al. (2003) presented the first such model, based on an analysis of data from the U.S. portion of the CAESAR study. Parametric human models with varying levels of fidelity have been presented by a number of research groups since, yet no widely used commercial human modeling tool currently has a parametric human body model based on laser scan data. During the past decade, academic research in computer graphics has produced a wide range of advancements in human representation, and visually realistic simulated humans have become common in entertainment media. However, most these accomplishments have focused either on (1) representing a generic character with no particular requirements on size and shape, or (2) representing a particular individual, for example to create a digital stand-in for a particular actor. For

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engineering applications, the ability to represent a wide range of individuals within a particular population (or range of populations) with quantitatively documented accuracy is required.

The visual appearance of manikins used for ergonomics applications has improved in recent years. Figure 1 shows a visual history of the Jack human model from 1998 to 2013 as one example. Yet, the scaling of ergonomic manikins to represent different body sizes is accomplished using largely ad hoc methods, with widely varying results. That is, while the dimensions and shapes of midsize-male manikins are similar across ergonomic tools, the dimensions and shape of a manikin with a body mass index (BMI, calculated as body mass in kg divided by stature in meters squared) of 40 kg/m^2 vary more widely.

Figure 1. A visual history of the Jack manikin from 1998 (outside) to present (middle).

Although many factors have delayed the introduction of high-fidelity body shape models in ergonomics software, the experience with the current effort suggest several key issues. The structure of the manikins used in ergonomics software is deeply embedded. In particular, each software manikin has a particular kinematic linkage. Moreover, the definition of the surface of the manikin and the underlying skeleton has been optimized to perform well across a large range of postures and anthropometric scaling. To be readily applied, a statistical body shape model based on scan data needs to be expressed using the linkage and surface representation of the target manikin.

This paper presents a research and development effort at the University of Michigan and Siemens PLM that has led to the introduction of a new, more realistic body shape model in the Jack human modeling software system. The underlying data were gathered in two U-M studies. The development of the data processing and analysis methods was guided by a consideration of the implementation needs of commercial human body model developers.

2. Methods – Body Shape Modeling

2.1 *Data Sources*

Laser scan data for U.S. adults were gathered in two research programs. The Seated Soldier Study, conducted by the University of Michigan Transportation Research Institute (UMTRI) with Anthrotech, Inc., collected whole-body surface scans for 257 male and 53 female soldiers at three Army posts (Reed and Ebert 2013). All data were gathered using a VITUS XXL body scanner (Human Solutions GmbH). Using similar techniques, 100 men and 100 women were scanned at UMTRI in an unpublished study that included a preponderance of men and women over age 60. Scans from a single posture shown in Figure 2 were used for the current analysis. Subjects wore close-fitting shorts (men) and shorts and a sports bra (women).

Figure 2. Posture used to generate body shape models.

2.2 *Data Processing and Template Fitting*

The scan data were manually cleaned to remove artifacts and a watertight mesh was obtained using ScanWorX software (Human Solutions, GmbH). Up to 100 landmarks were manually identified on each scan by research assistants using MeshLab software (meshlab.org). Most of these landmarks were marked on the surface of the body prior to scanning and were visible in the grayscale texture obtained with the scans. Internal joint locations were estimated from surface landmarks using methods described in Reed et al. (1999). Figure 3 shows an example scan with the landmarks.

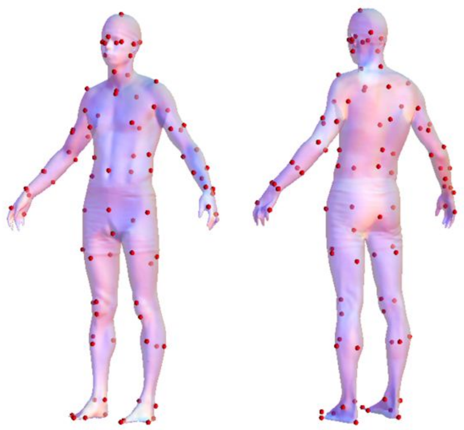

Figure 3. Sample scan with surface landmarks.

To facilitate statistical analysis of the scan data, a standardized template with 12035 vertices (male) or 13489 vertices (female) was fitted to each scan using custom software. Because the target for this application was the Jack software, the Jack version 7 manikin meshes were used as the template.

Fitting was accomplished using a two-step process. First, the template was morphed to approximate the shape of the scan using a landmark-driven process. A radial-basis-function interpolator was generated using a method that morphed the template such that 90 landmarks on the template exactly corresponded with the homologous landmarks on the scan (see Li et al. 2011 for details on this method). Second, an implicit surface representation of the scan data was created using a method derived from Carr et al. (2001). The vertices of the template were adjusted to lie on the implicit surface. Figure 4 shows these steps. At the conclusion of the template-fitting process, each scan was represented by a homologous mesh as well as the locations of 97 surface landmarks and internal joint centers.

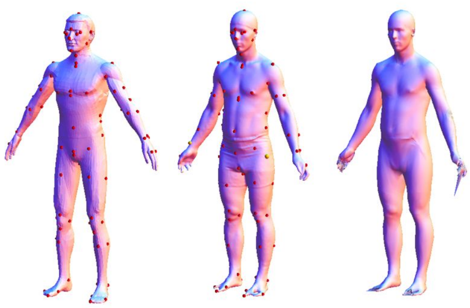

Figure 4. Template (left), sample data (center), and template fit to data (right).

2.3 *Data Analysis*

Separate analyses using identical processes were conducted for the male and female models. The analysis method was based on the techniques presented by Allen et al (2003) and subsequently used by many researchers. The full method is described in Reed and Parkinson (2008). A principal component analysis (PCA) was conducted on a flattened geometry vector consisting of the coordinates of all of the landmarks, joints, and vertices. Following the techniques of Turk and Pentland (1991), the number of principal components (PCs) equal to the number of subjects was computed. The male model was based on 213 subjects and the female on 115. For the current analysis, 60 PCs, representing over 99% of the variance, were used.

A regression analysis was conducted to predict PC scores from 11 standard anthropometric dimensions. These dimensions were chosen as a minimal set that would provide scaling information for all major body segments. Table 1 lists the predictors chosen for this analysis. A secondary regression was conducted to predict the remaining 8 body dimensions from stature, body weight, and the ratio of sitting height to stature. This allows the user to either input all 11 dimensions or to obtain predictions with only stature, body mass, and erect sitting height. The latter can be predicted as a constant fraction of stature if desired.

Table 1
Anthropometric Predictors

Stature	Hip Breadth, Sitting
Body Mass	Head Circumference
Erect Sitting Height	Chest Circumference
Biacromial Breadth	Waist Circumference
Knee Height, Sitting	Hip Circumfererence
Forearm-Hand Length	

3. Methods – Jack Implementation

3.1 *Integrating Body Shape Model*

For the practitioner, the value of statistical shape models is increased dramatically if the generated figure shapes can be animated for use in human task assessment. Thus, a method to associate the predicted shape model to the underlying Jack figure construct was implemented in the software. The pieces of this method consisted of fitting the Jack skeleton to the predicted mesh form, enhancing areas where the scanning, and thus the predicted model, provided insufficient information, and finally adding the ability to utilize the body shape models with the clothed Jack figure meshes.

3.1.1 *Skeletal fit*

Recent evolution of the Jack human figure model is characterized by the switch from rigid body segment geometry to deformable mesh. As part of this development, a rigging that defines how the skeletal motion deforms the surface mesh of the figure was defined. Since the Body Shape Model (BSM) predicts the node locations of the same mesh, the rigging information could be reused. However, unlike artistically sculpted figure meshes, the BSM predictions produce figure shapes that are non-symmetrical both in posture and segment-length dimensions, and thus require skeletal fit algorithms that support these realities. BSM predicted joint locations were used to calculate mean segment lengths for the skeletal limbs. Further, the predicted joint locations on the limbs were refined via analysis of the surrounding mesh nodes such that the skeleton could be more accurately positioned within the mesh at these locations and avoid surface penetrations. Subsequently, an existing analytical approach that finds the best fit of the skeleton to the predicted joint centers was enhanced to support hyper-extension at the knees and elbows, which can occur with the BSM. That is, the model accurately reflects the fact that many individuals, particularly women, are able to extend their knee and elbow angles beyond "straight".

3.1.2 *Mesh Hands, Feet and Head*

Due to the limitations of the laser scanning system, the hands and feet remain only crudely represented in the BSM (Figure 4) and thus need to be addressed separately. The hand and foot data were removed from the predicted mesh and substituted with separately scaled native Jack hand and foot geometry. A blending method was used to smoothly transition from the BSM predicted mesh nodes to the hand and foot nodes. Scaling of the hands and feet was accomplished via Mean Value Coordinate method (Ju et al. 2005). A similar approach was used for the head, which additionally serves to maintain a recognizable face for the Jack and Jill manikins. As the head can scale asymmetrically, the hair mesh was deformed and positioned base on the movement of nearest neighbor head mesh nodes.

3.1.3 *Clothed Figures*

The latest Jack figures are available in both *Base* and *Casual* clothing variants (Figure 1). The base mesh was used to build the BSM, as the tight exercise clothing configuration matches the clothing worn by the subjects while being scanned. The clothed figures have artistically rendered looser pants and shirt. These are typically preferred for task assessment as they more realistically match worker attire. Promoting mesh scaling changes from the base mesh to the clothed mesh was accomplished via a linear transformation that maintains the relative offset of the clothed nodes from the base mesh nodes

4. Results

4.1 *Body Shape Modeling*

The body shape models developed from laser scan data are capable of representing a wide range of body sizes and shapes. Figure 5 shows three male body forms generated by inputting median male stature and body weight (175 cm and 77 kg) with three waist circumferences. The model captures the differences in patterns of adiposity associated with waist circumference while holding stature and body weight constant.

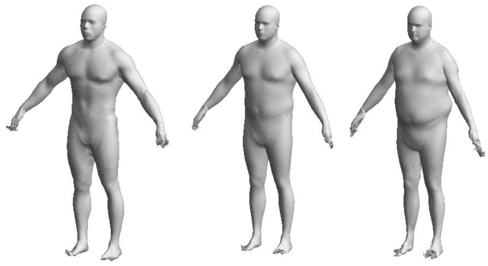

Figure 5. Illustration of male body shape model output showing predictions for 50th-percentile stature and body weight with 3 levels of waist circumference.

4.2 *Jack Implementation*

The body shape model implementation produces Jack figures that match the fidelity of the statistical models, and can be postured freely for use in analysis. Figure 6 shows two male and two female figures in several postures. Figure 7 shows a range of statures for the male and female figures. Figure 8 shows the figures being used for task analyses.

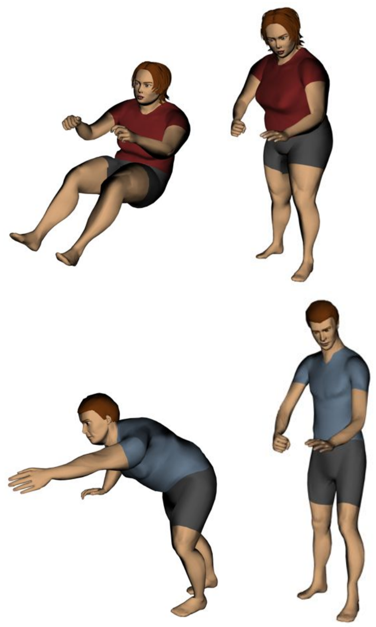

Figure 6. Illustration of Jack base figures scaled with the body shape model and postured in a variety of configurations. BMI range from 22 for the slighter figures to 38 for the larger ones.

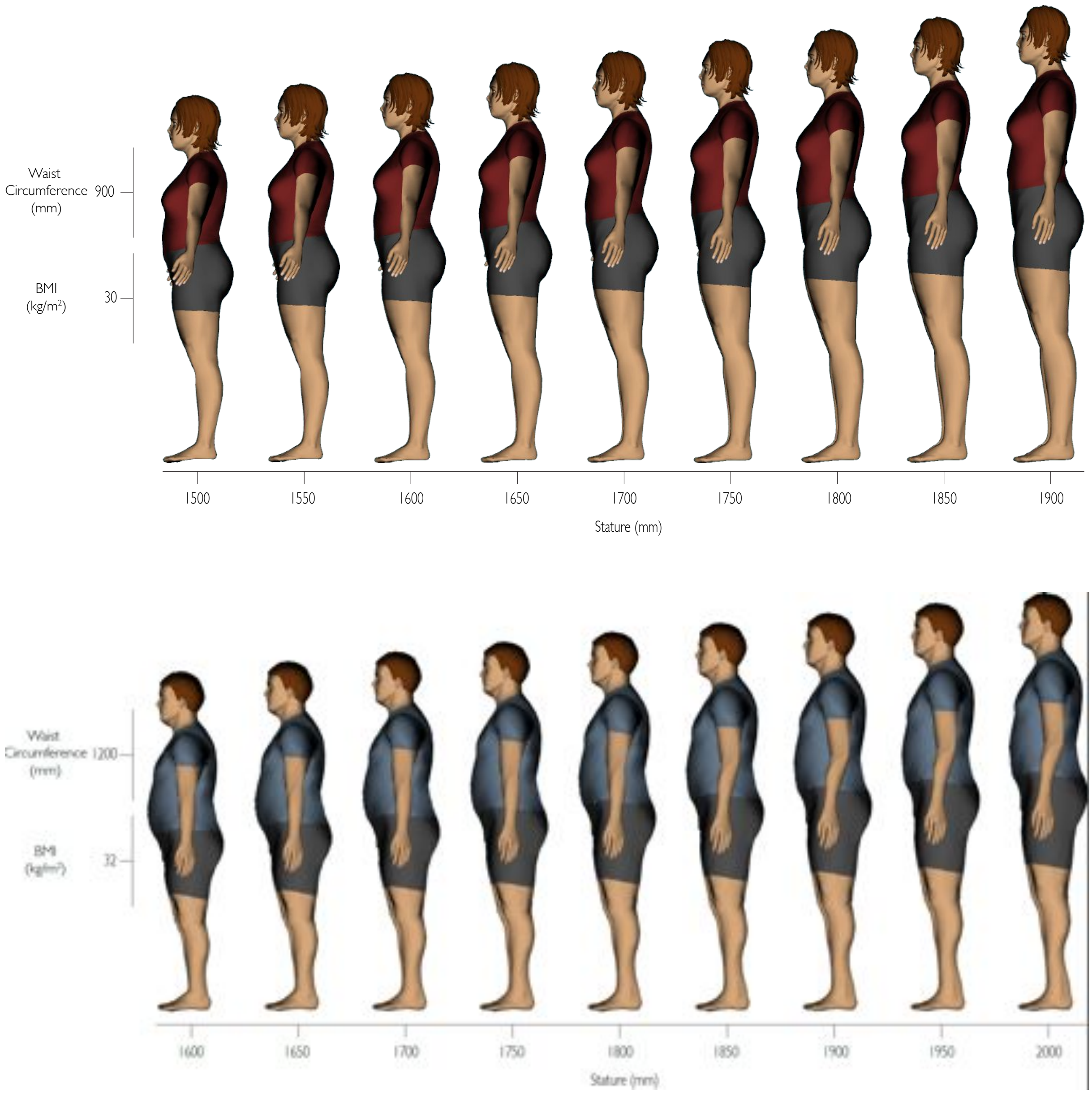

Figure 7. Images of the male and female Jack base figures created using the new model. In each panel, stature is varied while BMI and waist circumference are held constant.

Figure 8. New Jack figures used for task analysis.

5. Discussion

5.1 Accomplishments

Statistical body shape models for adult men and women were developed based on body scans from more than 300 subjects with a wide range of body sizes. The models include surface landmarks and internal joints and each subject was characterized by standard anthropometric measurements. The models were implemented in the Jack human modeling software, a widely used tool for human simulation ergonomic analysis.

5.2 Limitations

The size and diversity of the subject pool is the primarily limitation of the current models. The male model is based predominantly on enlisted U.S. Army soldiers, whereas the female model is based primarily on civilians. Both models are based on a wide range of age, but the male model has more young subjects. Approximately 80% of the subjects for both models self-identify as White, while the majority of the remainder self-identify as Black or African-American. The subject pool includes relatively few individuals who identify as Asian-American or Hispanic. Consequently, the body shapes produced by the model are not necessarily representative of populations with different distributions of race/ethnicity or national origin.

The fidelity and resolution of the scans and the decisions made during modeling affect the utility of the model. The scans do not capture the shapes of the hands and feet well. The modeling approach does not capture the face with sufficient fidelity for some face analysis applications, because only 10 face landmarks were aligned during fitting of the template mesh.

The PCA+regression modeling approach is linear in all components. The regression models that predict PC scores could incorporate interactions and transformations of the predictor variables (for example, squared terms) but these were not found to be important for the current model. In practice, this linear modeling approach has been found to produce excellent predictions across a wide range of body sizes, but a nonlinear model might produce better results. The PCA methodology, in particular, identifies linear combinations of correlated variables. It is conceptually possible that nonlinear combinations of the original variables, or nonlinear transformations of those variables, could yield a better model. Alternative modeling approaches are also available, at the cost of model compactness. For example, interpolation models could be created "on the fly" by creating a model based on N nearest neighbors to a desired manikin. Such an approach would be of minimal utility with the current relatively small dataset, but incorporating larger datasets would make the method more appealing. Such an approach would make the results more dependent on the idiosyncrasies of the particular subject pool, whereas an advantage of the current approach is that all subjects affect the results, minimizing the influence of outliers and gaps in the data.

The question as to what constitutes an acceptably accurate modeling approach for creating manikins for ergonomics analysis remains open, because the answer is dependent on the particular analysis for which the software is used. For example, the modeling accuracy needed for assessing close-fitting protective clothing is probably different from the accuracy needed for vehicle occupant packaging. Model accuracy can be evaluated on an essentially infinite number of dependent measures, but the problem is further complicated by the fact that the modeled posture is rarely the application posture. That is, the modifications in body shape that occur with posture change have a strong effect on the body shape for applications, but the current statistical BSM does not address these changes. Above all, the accuracy can only be assessed within a population for which extensive data are available; the population for which the body shape model was generated will almost never be the target population. Notwithstanding these challenges, considerably more quantitative work on the accuracy and precision of the body shape predictions generated by this methodology is needed.

5.3 Future Work

Many of the limitations of the current models will be addressed in future work. The data processing and modeling methodology is readily scalable to larger datasets; work is currently underway to add hundreds of scans to both the male and female models, which will make them more robust, particularly for extreme body shapes. Importantly, the architecture of the model will enable more robust models to be generated and implemented in Jack with much less work than this first implementation required.

Modeling alternative postures and the effects of posture change is also underway. This topic has received considerable research interest (Allen et al. 2002). The dataset from which the current scans were drawn includes up to 20 postures per subject, providing a foundation for modeling the effects of posture change. An important factor to be considered is that the effects of posture change on surface shape depend on individual attributes, such as the level of adiposity.

The biggest challenge is obtaining scan data from populations of interest. For example, publicly available data for large markets, such as China, India, and Brazil, are not yet available. Note that it is not necessary or even desirable for scanning subjects to be randomly sampled from the target populations. Instead, scanning studies should focus on anthropometrically unusual individuals (short, tall, heavy, lean, etc.) to provide greater statistical power for modeling. The target dimensions for generating manikins for ergonomic research should come from broadly sampled studies using conventional anthropometric measures to maximize subject participation. Lower-cost scanning technologies now becoming available, including those based on depth cameras, may lead to greater availability of data.

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