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Sequestering Size: The Role of Allometry and Gender in Digital Human Modeling

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ABSTRACT

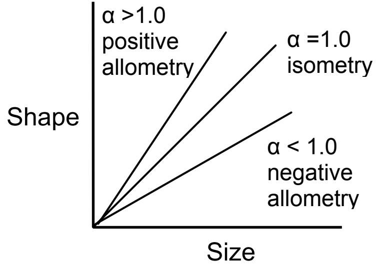
Biologists are aware that sexual dimorphism can result from size differences, shape differences, and differences in the relationship between the two (allometry), but the digital human modeling community has not fully incorporated this knowledge into their design procedures. Using landmark-based geometric morphometric methods and data from the CAESAR survey, we demonstrate that sexual dimorphism between adult males and females is the result of size, shape, and allometry differences between the sexes. Human sexual dimorphism is therefore far more complicated than is represented by standard design procedures, implying that using extreme percentile humans in design confounds male and female allometric differences, and will likely not accommodate all individuals.

INTRODUCTION

Biologists and anthropologists have long recognized that organisms differ in their body dimensions, and as both fields moved from descriptive to quantitative sciences, the analysis of morphology became more rigorous. Some researchers measured anatomical parts of organisms and quantitatively compared them within and among groups (e.g., Bumpus, 1898). Others developed mathematical models to describe changes in body dimensions during the growth of individuals (Huxley, 1932), or the evolutionary changes between species (e.g., Thompson, 1917). Size was regarded as a fundamental characteristic of an organism's morphology, but it was also known that different body dimensions changed disproportionately with size. For instance, two humans may differ in stature by 1 cm, but other body dimensions, such as hip breadth or chest circumference, may differ by smaller or larger amounts. Such differential proportions of particular body dimensions relative to size captures an aspect of morphology other than size, and thus describes the *shape* of an organism. To fully appreciate differences in morphology among groups of individuals, one must examine variation in size, variation in shape, and the relationship between the two.

Allometry, or relative growth, is defined as a change of shape relative to a change in size (Huxley, 1932; Jolicoeur, 1963). Allometry therefore describes the relationship between size and shape (Klingenberg, 1996), and how one body dimension changes as a function of another (for a mathematical description of allometry see Box 1). Biologists have observed that the allometry of body proportions differs among species, and anthropologists have noted that sexual dimorphism in humans and other primates is the result of size differences, of differences in proportional measurements (shape), and of allometric differences in various body measurements (see e.g., Wood, 1976; Jungers, 1984; Jungers et al., 1995; Rosas and Bastir, 2002). Typically, digital human modeling researchers design with human sexual dimorphism in mind.

Box 1: Huxley (1932) found that the growth of a trait y relative to body size x could be described as: $y = bx^{\alpha}$. When log-transformed, the standard linear regression equation results: $\log(y) = \log(b) + \alpha\log(x)$. The slope of the regression, α, describes the allometric relationship between the two traits. When $\alpha = 1$, there is a one-to-one proportional change of x and y, called isometry. If $\alpha > 1$, there is positive allometry (y increases proportionally faster than x). The case of $\alpha < 1$ indicates negative allometry (x increases proportionally faster than y). Huxley's bivariate approach has also been generalized to accommodate multivariate data (Joliceour, 1963).



Allometry showing the relationship of size and shape.

The fields of human factors and digital human modeling (DHM) recognize sexual dimorphism in adults. Numerous interpopulational and intercontinental studies have verified sexual dimorphism in linear body dimensions through the comparison of height, sitting height, shoulder width, hip width, and other anthropometric measurements (Tanner, 1962; Tanner et al., 1976; Hiernaux, 1985; Hauspie et al., 1985). These results have important consequences for design, and separate design standards are generally provided for men and women. Unfortunately, while DHM designs attempt to account for human sexual dimorphism, the manner in which this is done is incomplete because the sexual dimorphism is not decomposed into its relative components of body size dimorphism, body shape dimorphism, and allometric dimorphism. Perhaps most common are the use of manikins to represent the physical and body pivot dimension limits for a specific percentage of the population (e.g. the 5th percentile female and the 95th percentile male). These manikins, like those recommended by the Society of Automotive Engineers (SAE J833, 1989) and the International Organization for Standards (ISO 3411:1995, 1995), are chosen to represent the extremes of body dimension variability, but their use fails to capture the allometric changes in body dimensions of both males and females.

Figure 1 provides a simple example. Here seated hip breadth and shoulder breadth are plotted for the 1st, 50th, and 99th percentile male and female manikins (Tilley, 1993). Connecting the small and large individuals of males and females provides a representation of the allometry of shoulder breadth relative to seated hip breadth. These relationships differ between males and females (b_{male} = 0.80; b_{female} = 0.46). When the 1st percentile female and 99th percentile male are used, the allometry between shoulder breadth and seated hip breadth is b_{joint} = 1.09. Similar results were found when percentile values for individual body measurements were used. Clearly, design specifications based upon the 1st percentile female and the 99th percentile male generate an allometric trajectory that is not representative of either that of males or females. Additionally, this design specification fails to accommodate large females and small males, as they fall outside the confidence intervals of this jointly-generated relationship. Clearly, a more rigorous treatment of morphological variability in males and females could improve DHM design.

This simple example shows that there are components of sexual dimorphism that are not captured by percentile designs. An unexamined question however is to what extent this phenomenon is present in more comprehensive data sets, where human body shape is represented by more complex, multivariate data. In this paper, we quantified morphological variation using the North American Civilian American and European Surface Anthropometry Resource (CAESAR) to examine sexual dimorphism in body size, body shape, and allometry. We then discuss the implications of these findings for DHM design specifications.

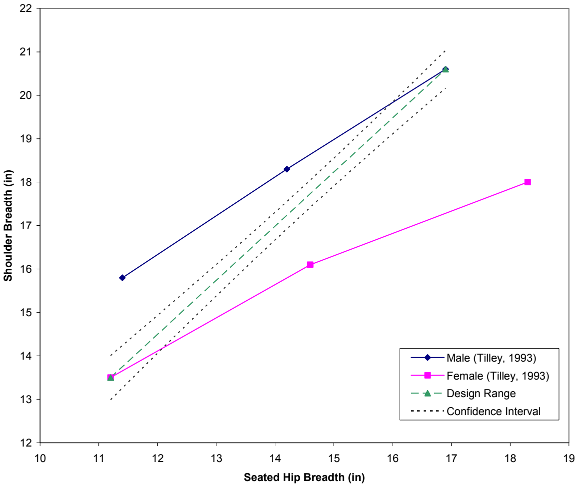


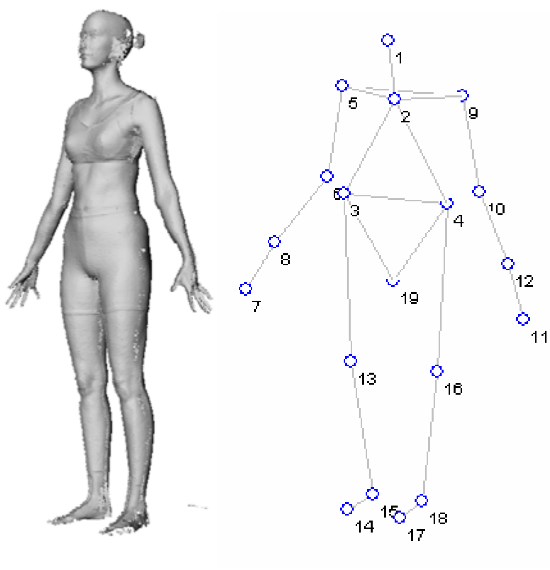
Figure 1: Representative allometric trajectories of shoulder breadth versus seated hip breadth for males and females (data from Tilley, 1993). Trajectories generated using 1st, 50th, and 99th percentile manikins (confidence intervals estimated using summary data of US Army men, 1988).

METHODS

Data were obtained from the North American CAESAR survey, encompassing subjects between the ages of 18 and 65 (Robinette, et al., 2002). Three-dimensional surface scans were acquired for all CAESAR participants in a standing, seated working, and seated coverage position (resolution of a few mm). The locations of 73 anatomical landmark locations were derived from these scans and recorded for each subject (Robinette, 1999). Nineteen landmarks from the standing posture data were selected for this study (Figure 2). These landmarks were chosen for their ability to describe overall body shape and their correspondence to endpoints of commonly-used distance measures. Our data set comprised 2344 adult subjects, including 1103 males and 1241 females.

Landmark-based geometric morphometric (GM) techniques were used to quantify body shape (Rohlf and Marcus, 1993; Adams et al., 2004). Recent work in DHM has begun to include the tools of geometric morphometric methods for evaluating body shape differences and visualizing digital human models (Cerney, 2003; Cerney, Adams & Vance, 2003; Friess, Rohlf, & Hsiao, 2003). GM methods are preferable to methods quantifying body shape using sets of linear distances because the geometric relationships among the variables are preserved throughout the analysis. With this approach, morphology was first quantified using a set of homologous landmarks. Unfortunately, direct analysis of the landmark coordinates was not possible, as they contained components of both shape and non-shape variation. Non-shape variation was therefore removed using Generalized Procrustes Analysis, or GPA (Gower, 1975; Rohlf and Slice, 1990).

GPA removed differences in scale, position, and orientation by scaling all subjects to unit size, translating them to a common location, and rotating them so that corresponding landmarks lined up as closely as possible. After GPA superimposition, each subject was represented by a dot in a curved, non-Euclidean shape space. The aligned subjects were then projected orthogonally into a linear tangent space, with the consensus subject describing the point of tangency (Rohlf, 1996). A set of shape variables (Kendall's tangent space coordinates: Rohlf, 1999) were then obtained using principal component analysis (PCA), which eliminated redundant dimensions standardized by GPA. These shape variables are mathematically equivalent to the set of partial warp scores and uniform shape components commonly used in GM analyses (Bookstein, 1991; 1996; Rohlf and Bookstein, 2003), and can be used in statistical comparisons of shape variation within and among groups (see e.g., Caldecutt and Adams, 1998; Adams and Rohlf, 2000; Rüber and Adams, 2001; Kassam et al., 2003). Using GPA, the size of each subject was calculated as centroid size, the square root of the sum of the squared inter-landmark distances (Bookstein, 1991), and was retained for further analysis. GM analyses were performed in Morpheus et al. (Slice, 1998) and NTSYSpc (Rohlf, 2000).



No.	Landmark
1	Sellion
2	Suprasternum
3	R. Iliac Crest
4	L. Iliac Crest
5	R. Acromion
6	R. Olecranon
7	R. Dactylion
8	R. Ulnar Styloid
9	L. Acromion
10	L. Olecranon
11	L. Dactylion
12	L. Ulnar Styloid
13	R. Femoral Epicondyle, Lateral
14	R. Digit II
15	R. Calcaneus Posterior
16	L. Femoral Epicondyle, Lateral
17	L. Digit II
18	L. Calcaneus Posterior
19	Crotch

Figure 2: (Left) Standing posture CAESAR body scan. (Center) Landmarks identified for a representative subject. (Right) Description of three-dimensional landmarks.

Several statistical procedures were used to investigate sexual dimorphism in the data set. First, to determine whether body size varied significantly between genders, a student's *t*-test of centroid size was performed. The degree of correspondence between centroid size and two common DHM measurements—stature and weight—was also assessed using regression analysis. Sexual dimorphism in shape was first examined graphically, using the first two principal components of shape variation. We then determined whether body shape varied significantly between genders using a multivariate analysis of variance (MANOVA). The allometry of body shape was compared between males and females, using a multivariate analysis of covariance (MANCOVA), where body size was the covariate. With this analysis a significant interaction between body size and gender would reveal that allometry differed significantly between the sexes. Finally, the allometric trajectories of body shape for both males and females were visualized graphically by generating representative subjects at comparable body sizes. Statistical analyses were performed in JMP (SAS, 2002).

RESULTS

BODY SIZE DIMORPHISM – Not surprisingly, we found significant differences in body size between genders (t = 4.427; df = 2342; P = 0.00001), with males attaining significantly larger body sizes ($\overline{C}_{size} = 2505.04$) than females ($\overline{C}_{size} = 2338.81$). Significant sexual dimorphism was also revealed using both stature and weight. When these were compared to centroid size, both revealed a significant correlation, though stature was a much better predictor of centroid size than was weight (stature R^2 = 0.92; weight R^2 = 0.46). This too was not surprising, as the stature of each subject was represented by a subset of the landmarks used to estimate centroid size.

BODY SHAPE DIMORPHISM – To determine whether body shape varied significantly between males and females, we first visually examined the distribution of male and female subjects with respect to the first two principal components of body shape (Figure 3). We found clear separation of males and females along the first principal component axis, indicating that the major trend in body shape variation was due to gender, rather than some other factor. There was still much overlap within the gender data however, indicating that some males and females have similar body shapes. To determine whether body shape varied significantly between genders, a MANOVA was performed. We found significant differences between the body shapes of males and females with this analysis ($F = 2.849$; $df = 49$; $P < 0.00001$), indicating that sexual dimorphism was present in body shape, as well as body size.

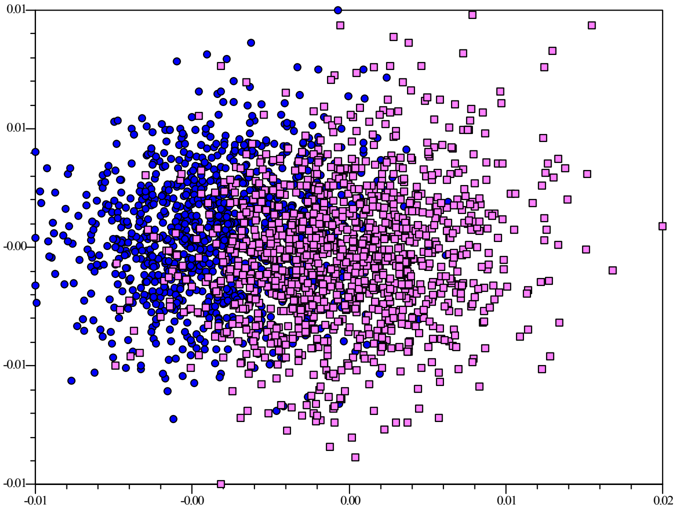


Figure 3: First two principal axes, labeled by gender. The first two factors represent 49.8% of the total variation in the data set.

ALLOMETRIC DIMORPHISM – Using MANCOVA, we examined whether the relationship between body size and body shape was the same for males and females. First we found a significant size effect (Table 1). This demonstrated that allometry was present in the data set, and that body shape changed as a function of size. We also found a significant interaction between size and gender (Table 1). This indicated that the manner in which body shape changed as a function of size was not consistent between males and females. Therefore, while there was significant allometry in both males and females, this allometry was not the same in the two sexes. This demonstrated significant sexual dimorphism in allometry, denoting separate allometric trends for each gender.

Table 1: MANCOVA results for the relationship between body size, body shape, and gender.

	F value	NumDF	DenDF	Prob>F
Centroid Size	44.3761	49	2292	< 0.0001
Gender	86.0635	49	2292	< 0.0001
Centroid Size*Gender	2.0688	49	2292	< 0.0001

To visualize the allometric differences between genders, we generated depictions of the body shapes of males and females over a range of comparable body sizes (Figure 4, Figure 5). We selected the 2.5th percentile male centroid size, the 97.5th percentile female, and three values evenly spaced between these as our representative body sizes in order to obtain body shape estimates that existed within the body size range of both genders. The landmark coordinates representing the body shapes of each of these were then determined from the gender-specific allometric trajectories.

Overall, the sexual dimorphism in shape was described by a lengthening of the torso and a shortening of the upper body in males relative to females, as well as distal motion of the upper extremity landmarks (see Figure 5). When male allometry was examined (Figure 4), we found that as males increased in size, their torso became relatively squat, with a proximal and anterior motion of the crotch and iliac crest landmarks. For female allometry (Figure 4) we found a similar trend in the relative motion of the hip landmarks, but minimal motion of the crotch landmark. A proximal and distal shift in the location of the sellion was also clearly visible, particularly in the male subjects. Finally, allometric differences between males and females were also evident, visualized as a lengthening of the torso, an increase in the proximal positioning of the sellion, motion of the elbow, wrist and hand landmarks away from the body, and a shortening of the feet. Clearly, there are overall differences in body shape between males and females, as well as differences in the manner in which body shape changes with respect to body size (i.e. allometry).

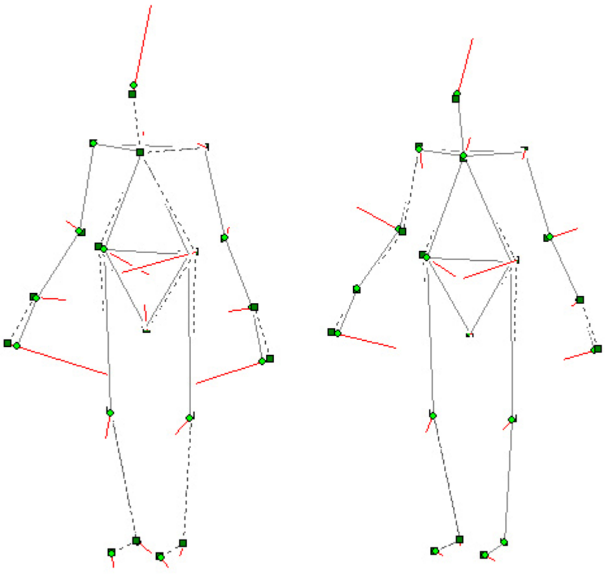


Figure 4: Allometric trajectories for males and females. (Left) Shape changes from small to large males. (Right) Shape changes from small to large females. The small subject is represented by the squares and the large subject is represented by circles. The vector direction of deviation from the small subject to the large subject is shown at each landmark point by a solid line. The length of these lines indicates the strength of this deviation. (The lines have been lengthened tenfold for ease of interpretation.)

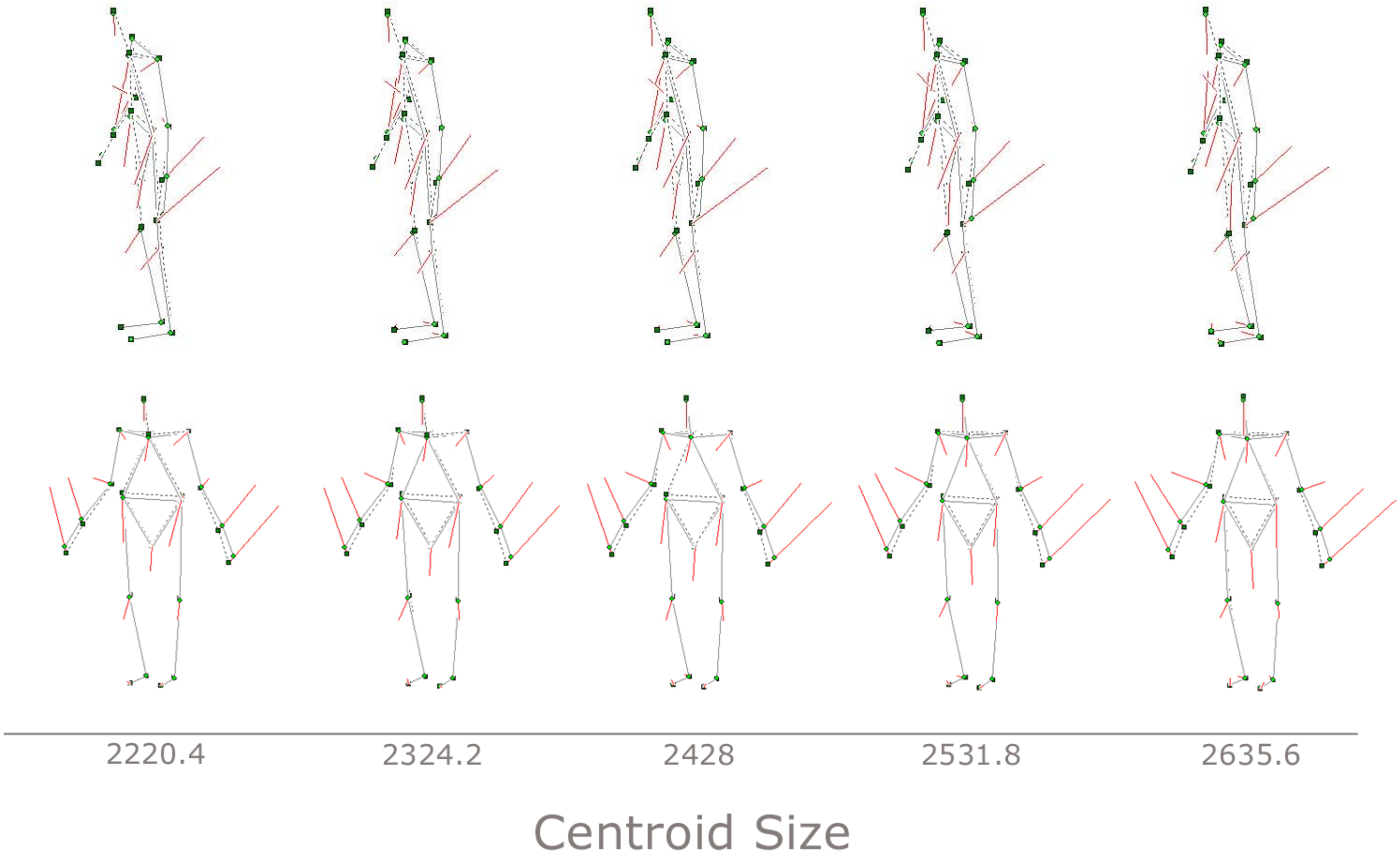


Figure 5: Sexual dimorphism in shape. Front and side views of shape changes from males to females over a range of body sizes. In each image, the male subject is represented by squares connected by dotted lines, and the female subject is shown as circles connected by solid lines. The vector direction of deviation from the male subject to the female subject is shown at each landmark point by a solid line. The length of these lines indicates the strength of this deviation. (The lines have been lengthened tenfold for ease of interpretation.)

DISCUSSION

In this study, we used landmark-based GM techniques to examine patterns of body size, body shape, and allometric variation in adults from the North American CAESAR survey. We found that body size and body shape both varied significantly between genders, and that a change in body shape with a change in size (allometry) was present in the data. Statistical evidence of separate allometric trends for each gender was corroborated by visualization of the allometric differences between males and females. We conclude that sexual dimorphism between adult males and females is the result of body size, body shape, and allometric differences between the sexes. While DHM and human factors fields are aware of sexual dimorphism of both body size and body shape, standard design methods often fail to account for gender differences in allometry. Separate design specifications for a range of male and female sizes exist in the form of manikins which are often used to design for a specific percentage of the population. When used to represent the extremes of body dimension variability however, these methods do not account for gender differences in allometry and may therefore fail to accommodate all individuals within the chosen range. In addition, most DHM procedures treat size as the more important component of human morphology. Our results strongly suggest that body shape represents an equally important component of variation in human form, and therefore must explicitly be taken into account during design procedures.

For a more comprehensive design strategy, sexual dimorphism must be decomposed into its relative components of body size dimorphism, body shape dimorphism, and allometric dimorphism. We propose the following protocol for incorporating allometric effects in the process of digital human modeling and human-centered design:

1. Collect two or three-dimensional homologous landmark data descriptive of body shape relevant to the design.
2. Extract size and shape information from the data.
3. Analyze size and shape information separately to explore sexual dimorphism or demographic effects.

4. Assess the allometric effect and determine whether separate allometric trajectories should be designated for males and females.
5. Design such that any allometric trajectories present in the data are taken into account.

The final step in this procedure is critical, as it ensures that DHM designs more closely match the observed variation in body size and shape data. Further, this step will allow more individuals to be accommodated by a particular design specification. Whether separate designs for males and females, or a combined male-female allometric design procedure is more efficient in these tasks is the subject of future work. We intend to further develop design methods which can incorporate body size, body shape and allometric differences in digital human design.

In conclusion, we found that body size, body shape, and allometry significantly differed between adult males and females. Incorporating these in design strategies should significantly improve DHM procedures. To accomplish this, we advocate methods that design first for shape variation and then subsequently account for size through allometric relationships. Using this approach, these shape-specific designs should better match the human form, thereby accounting for a larger percentage of the population without losing the generality of size-dependent effects.

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