Quantitative assessment of human body shape using Fourier analysis

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ABSTRACT

Fall protection harnesses are commonly used to reduce the number and severity of injuries. Increasing the efficiency of harness design requires the size and shape variation of the user population to be assessed as detailed and as accurately as possible[3]. In light of the unsatisfactory performance of traditional anthropometry with respect to such assessments [7], we propose the use of 3D laser surface scans of whole bodies and the statistical analysis of elliptic Fourier coefficients. Ninety-eight male and female adults were scanned. Key features of each torso were extracted as a 3D curve along front, back and the thighs. A 3D extension of Elliptic Fourier analysis[4] was used to quantify their shape through multivariate statistics. Shape change as a function of size (allometry) was predicted by regressing the coefficients onto stature, weight and hip circumference. Upper and lower limits of torso shape variation were determined and can be used to redefine the design of the harness that will fit most individual body shapes. Observed allometric changes are used for adjustments to the harness shape in each size. Finally, the estimated outline data were used as templates for a free-form deformation of the complete torso surface using NURBS models (non-uniform rational B-splines).

1. INTRODUCTION

Full body fall protection harnesses are a standard equipment serving to reduce the number of severe injuries related to falls from elevation. The successful design of efficient harnesses relies on quantitative data that describe human body shape variation, making anthropometry a crucial element of the design process. Previous studies[2] have shown that traditional anthropometric methods are not satisfactory in establishing good harness design, since linear dimensions provide an incomplete assessment of the spatial variation found in user populations. Therefore, a different approach is required to improve the quantitative analysis of human body size and shape. This paper presents preliminary results of a study of the human torso using a 3D geometric morphometric analysis of outline data[1]. The goal is to quantify size and shape characteristics of the torso so that the current design of fall protection harnesses can be improved. It is common in geometric morphometrics to remove absolute size differences and to refer to the remainder as shape. Given the importance of absolute size differences for the design process of clothing, this study compares outlines that are not standardized for size, i.e. we investigate form variation as assessed by predicted outline data.

2. MATERIAL AND METHODS

The data analyzed are derived from a series of 3D laser surface scans that were made at the National Institute for Occupational Safety and Health in Morgantown (WV). The scanning was done with a Cyberware WB4 whole body scanner on a sample of 98 construction workers (72 male and 26 female subjects). Laser surface scanning is a common method for rapidly obtaining accurate 3D data. It uses a low intensity laser source that is projected onto a surface and

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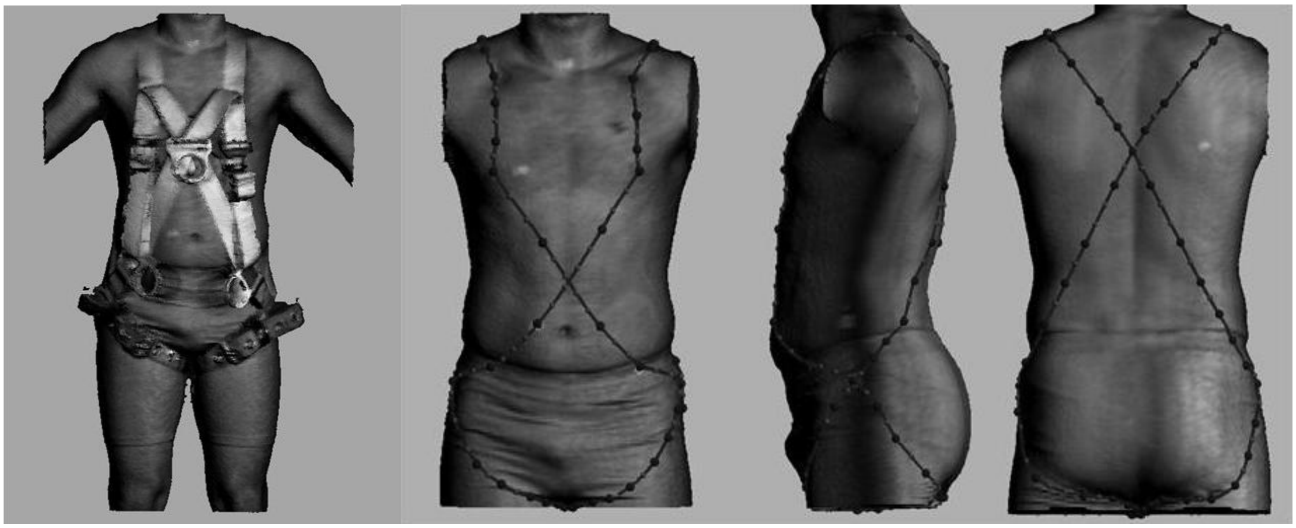
outputs a 3-dimensional high-density polygon mesh. Subjects were scanned in 3 different conditions: standing with tight fitting garments, standing in a harness, and suspended in a harness. The present study reports on observations made in the "nude standing condition" only. Raw scans were edited for missing data points and artifacts. Subsequently, Cartesian coordinates were sampled along a 3D curve that corresponds to how a harness is being donned. The data collection protocol is illustrated in Figure 1.



a) b)

Figure 1: a) A laser surface scan of a subject wearing a fall protection harness. b) 3D curve defining the torso shape across chest, back and around the thighs, following the pattern of the harness and passing by several anatomical landmarks.

Elliptic Fourier analysis provides a means to quantify outline data by expressing it as a weighted sum of a series of ellipses. The following description is based on the work of Kuhl and Giardina[4], and more information as well as examples can also be found in Lestrel[5]:

Any contour can be described by a series of constants and coefficients. The constants are defined as

$$x(t) = A_0 + \sum_{n=1}^{N} a_n \cos nt + \sum_{n=1}^{N} b_n \sin nt \tag{1}$$

and

$$y(t) = C_0 + \sum_{n=1}^{N} c_n \cos nt + \sum_{n=1}^{N} d_n \sin nt \tag{2}$$

and

$$z(t) = E_0 + \sum_{n=1}^{N} e_n \cos nt + \sum_{n=1}^{N} f_n \sin nt \tag{3}$$

where n is the harmonic number, N is the maximum number of harmonics and the variable t is over the range 0 to 2π.

The elliptic Fourier coefficients are defined as

$$a_n = \frac{1}{n^2 \pi} \sum_{p=1}^{q} \frac{\Delta x_p}{\Delta t_p}\left[\cos(nt_p) - \cos(nt_{p-1})\right] \tag{4}$$

and

$$b_n = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta x_p}{\Delta t_p}\left[\sin(nt_p) - \sin(nt_{p-1})\right] \tag{5}$$

for the x projection, and

$$c_n = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta y_p}{\Delta t_p}\left[\cos(nt_p) - \cos(nt_{p-1})\right] \tag{6}$$

and

$$d_n = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta y_p}{\Delta t_p}\left[\sin(nt_p) - \sin(nt_{p-1})\right] \tag{7}$$

for the y projection,

$$e_n = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta z_p}{\Delta t_p}\left[\cos(nt_p) - \cos(nt_{p-1})\right] \tag{8}$$

and

$$f_n = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta z_p}{\Delta t_p}\left[\sin(nt_p) - \sin(nt_{p-1})\right] \tag{9}$$

for the z projection, where q is the number of points in the outline, Δt_p is the distance between point p and p+1 along the outline, and Δx_p, Δy_p, and Δz_p are the x, y, and z components of the line segment from p-1 to p.

In general terms, the input to an EFA is a series of Cartesian coordinates that represent one or several individuals' outlines in 3D. The output is a series of coefficients that mathematically describe the outline and that can be used like any metric variable for statistical purposes. These coefficients can also be used for an inverse Fourier approximation, which uses the coefficient to yield coordinates along the estimated outline. These coordinates can then be used to visually represent individuals, means, or projections in directions of interest such as principal component axes, canonical axes, or regression estimates.

Fourier analysis can be used for any series of coordinate points along a curve in 2 or 3 dimensions. However, with the statistical analysis of variation as a main goal in mind, the data must be standardized in order to remove the effects of non-shape variation such as the location and orientation of the subject. In addition, one must standardize the starting point along the curve as well as the direction (i.e. clockwise or counterclockwise) in which the curve is traced. Various procedures have been proposed to normalize outlines prior to Fourier analysis. These include major axes orientation[4], or registration with two[6] or multiple homologous landmarks[2]. We used right trochanterion as starting and end points, and aligned the scans with left trochanterion and the shoulder blade point in the midsagittal as the third point in the plane. Any other two- or three-point alignment could have been chosen with no apparent technical advantage or disadvantage, but this particular alignment was closest to the anatomical orientation.

Using EFA coefficients as input variables for standard uni- and multivariate statistics, the within-sample variation of torso form was analyzed by a principal components analysis (PCA). Allometric shape changes were assessed by plotting principal component (PC) scores against commonly used size measures, such as stature and weight, as well as by multivariate regression. Observed differences are visually represented by inverse Fourier analysis, which estimates outlines of contrasting groups, means or along axes of interest.

3. RESULTS

The principal components analysis summarizes the major axes of variation within the sample. As is shown in Figure 2, PCs 1 and 2 (59.7%) are mostly driven by sexual dimorphism, as well as variation within the sexes, especially within males, while PC 2 appears to be driven in part by variation within females. Figures 3 and 4 illustrate the form changes along the first 2 components. Note that the rotation of either axis is not optimal with respect to sex, a result that can be imputed onto the unbalanced sex ratio of the sample (72 males, 26 females).

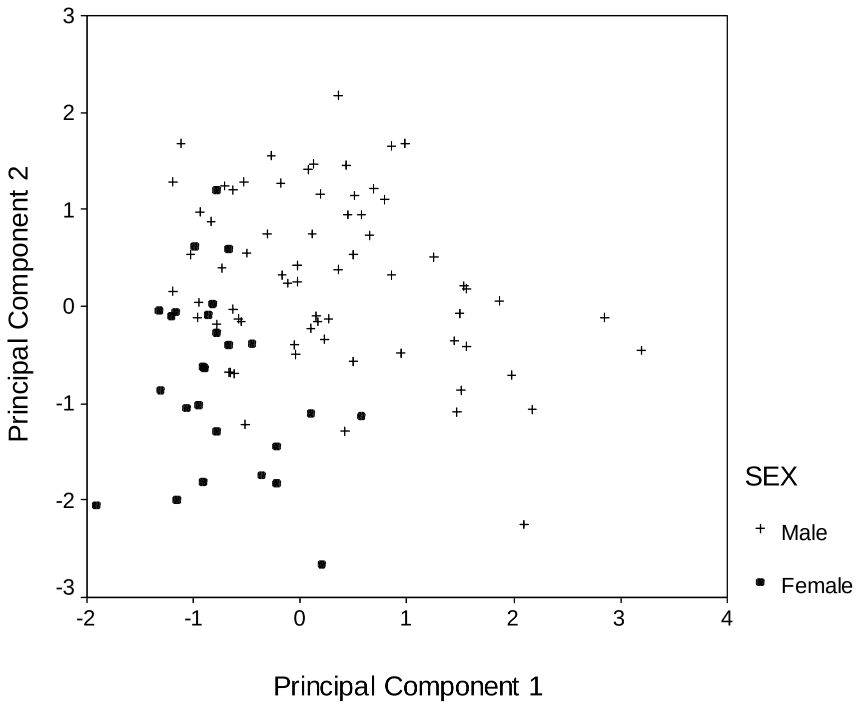


Figure 2: Scatter plot of individual scores for principal components 1 and 2, showing that these 2 axes mostly reflect sex-related variation.

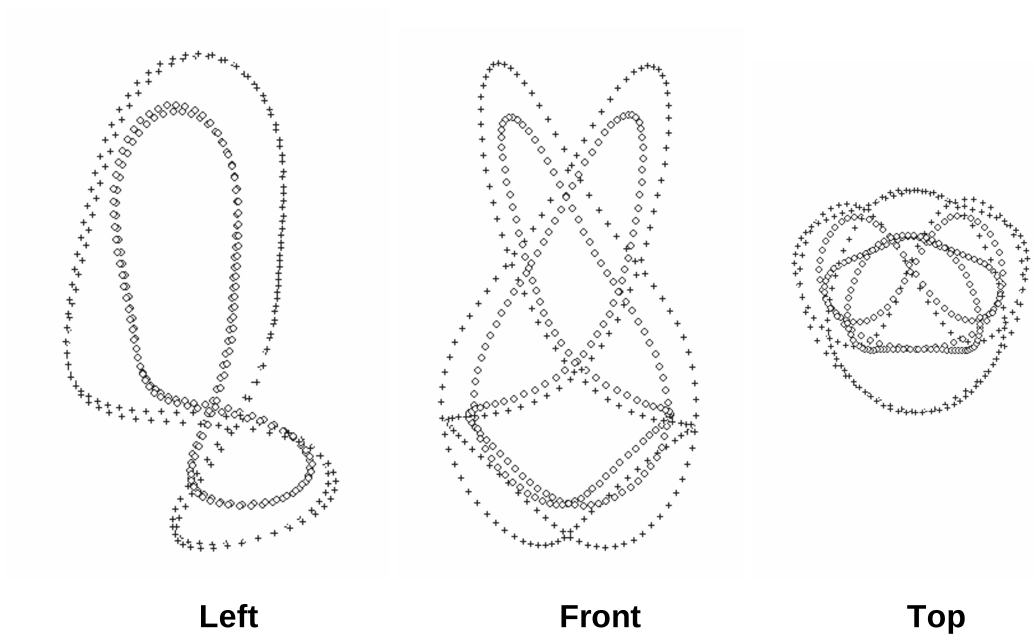


Figure 3: Visualization of form variation in the 3D Curve Along PC 1. The circled outline (o) corresponds to negative scores, the (+) outline to positive scores along the axis.

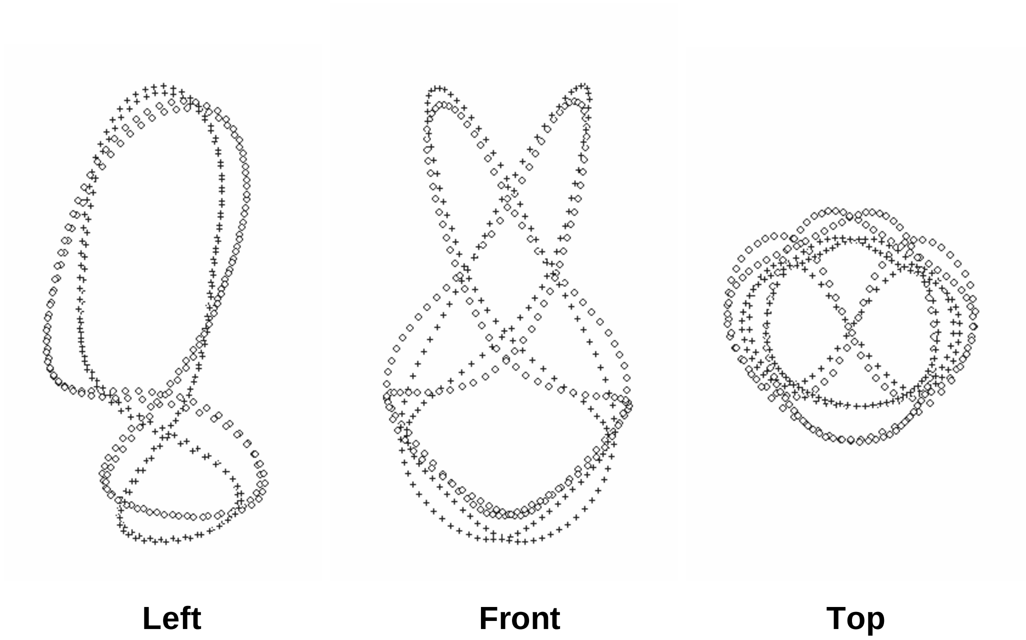
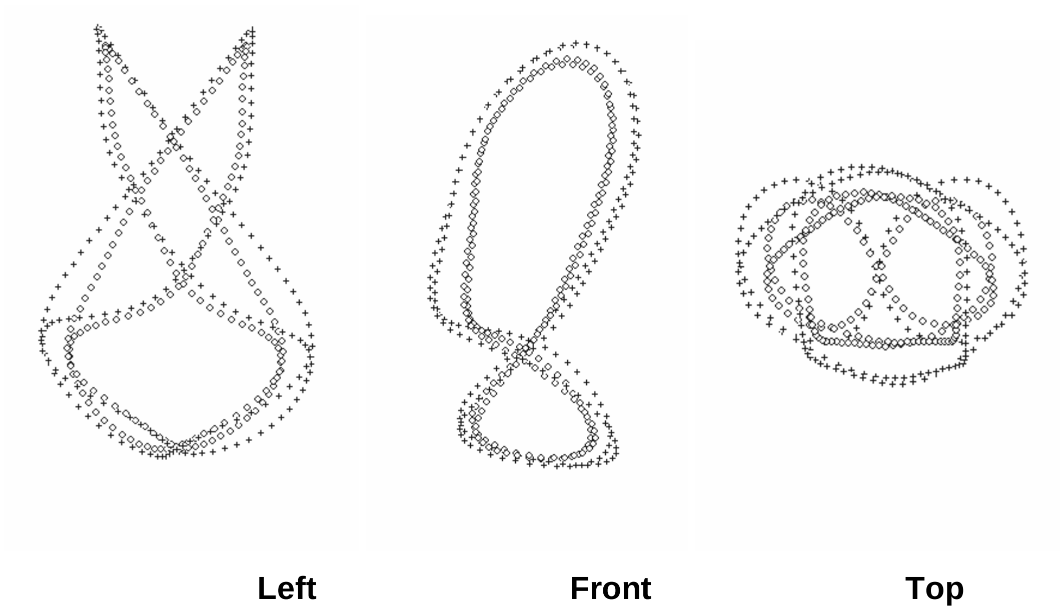
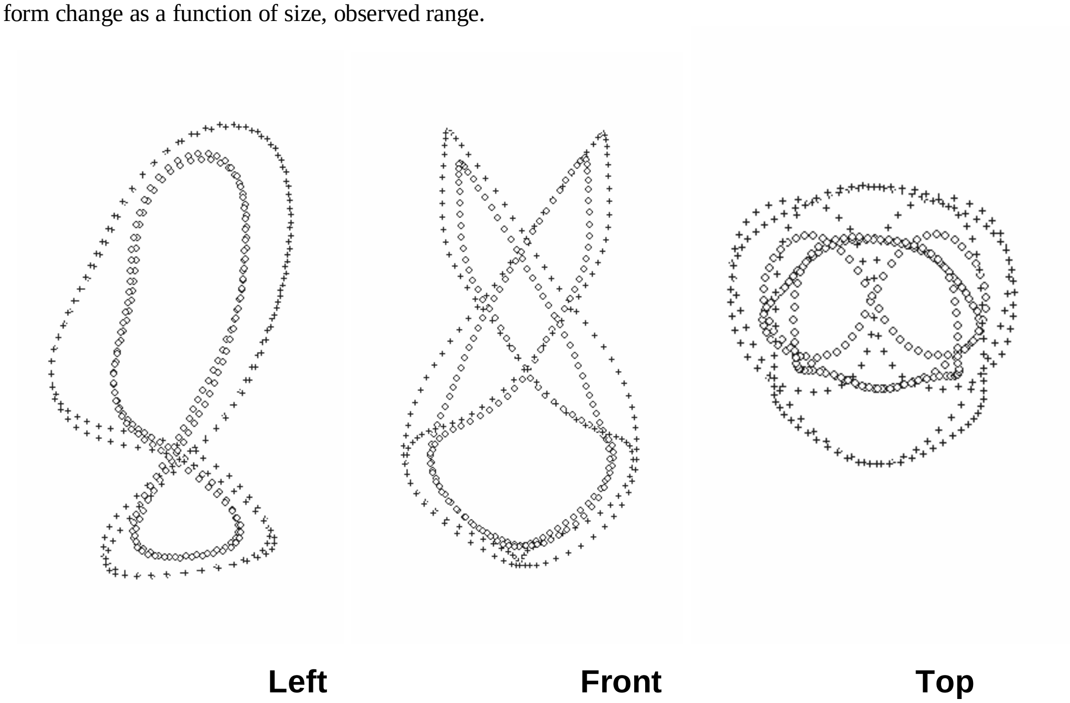


Figure 4: Visualization of form variation in the 3D Curve Along PC 2. The circled outline (o) corresponds to negative scores, the (+) outline to positive scores along the axis.

One of the key goals of this study was to understand the changes in body form that occur under the influence of easy to measure anthropometric size measures, such as body weight and stature. In order to determine the influence of these variables, a multivariate multiple regression model was calculated. A total of 21 anthropometric standard variables were subjected to preliminary testing and 3 were identified as yielding the best prediction model: Stature, weight and hip circumference. These dimensions were used as independent variables to predict elliptic Fourier coefficients, which were then used to estimate the 3D curves.



a) Female form change as a function of size, observed range.



b) Male form change as a function of size, observed range.

Figure 5: Visual depiction of form change in the human torso, based on a multivariate multiple regression of EFA coefficients onto stature, weight and hip circumference. Variation is illustrated in the front, left and top view from smallest subjects (circles) to largest (+). See also Fig. 6 for a complete surface model in the same view.

As is shown in Figure 5, the increase in all three anthropometric variables leads to an increase in the corresponding portions of the torso, i.e. its length and its width in the pelvic girdle. Weight has no corresponding dimension than can be localized on the torso a priori, however, the result of this regression is a striking illustration of how weight effects the abdominal development especially in males, and to a lesser extent in females.

Several observations on male and female allometry can be reported: First, the area between shoulders and hip increases in length as well as in anteroposterior diameter, more so in males than in females. This corresponds in large scale males to a heavy abdominal protrusion, as well as a bulkier shoulder girdle. Male allometry is also characterized by a clear increase in shoulder width, while in females shoulder width increase is less. Note that the visualization in Figure 5 is limited to the actually observed size range of the sample, which seems to be not as large in females (consistent with the variation shown in Figure 2). One can also notice that, while the area around the hip articulation is predicted to increase strongly in both sexes, the area around the waist and above is clearly following this increase in males, while females exhibit relatively wider hips and a marked reduction in width toward the waist and the rib cage. Finally, there is a noticeable difference between males and females in the position of the crease between the *gluteus maximus* and the thigh. This furrow is in a much lower position in women than it is in men, and this difference is not size related.

In order for these statistical observations to become of practical use in a CAD/CAM process, a 3D surface model of a human torso, representing the exact range of geometric properties found in this study, can be generated. Using commercially available software, a generic surface was derived from the scan data base and a free-deformation algorithm was used to achieve an exact match with the largest predicted 3D curve.
These types of surface models (Figure 6) can be used by manufacturers and designers for further development of protective equipment, such as fall protection harnesses, apparel products, or for the design of work places, where complete human analogues are required.

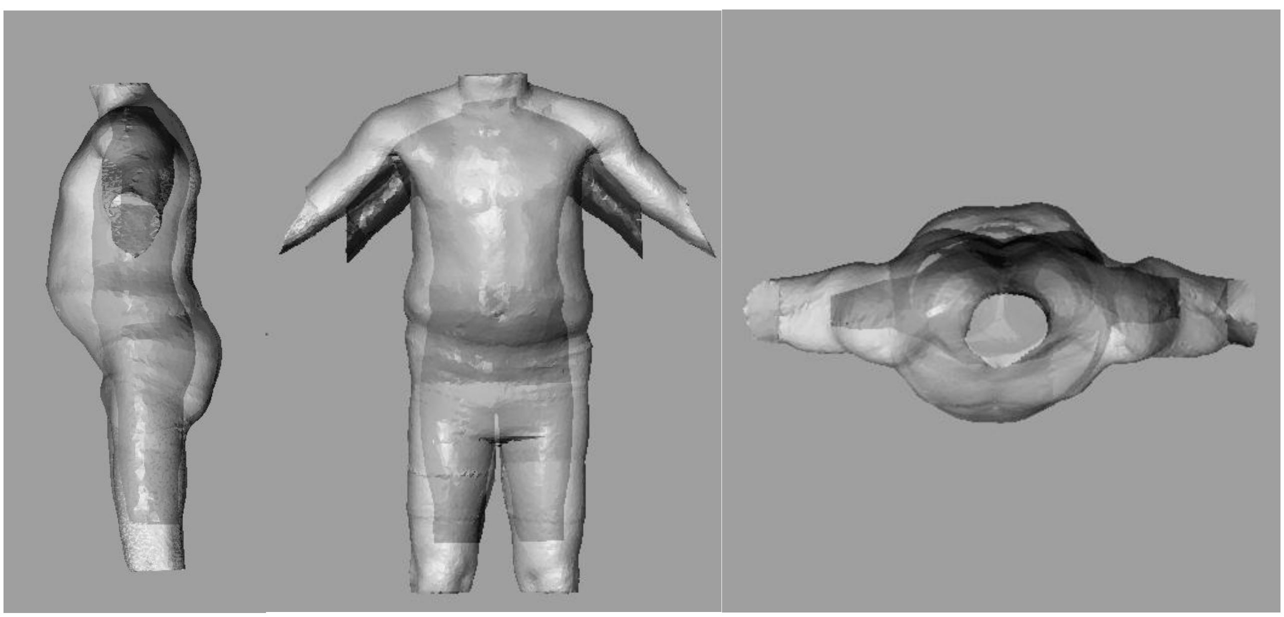


Figure 6: A generic surface that has been warped (using FFD) to match the target, which is a 3D curve estimated using 15 EFA coefficients (predicted by a GLM).

4. DISCUSSION AND CONCLUSION

The present study investigates human body form variation by means of multivariate shape statistics, also referred to as geometric morphometrics. While the chosen example, the design of fall protection harnesses, involves safety requirements that are well beyond the scope of this paper, it does lend itself to exploring advanced methods for analyzing size and shape relationships of different sizes and shapes of the human body. Ultimately, our approach aims at providing tools for designers and manufacturers that yield data necessary to improving the fit and accommodation of all kinds of protective equipments and garments, whether they are used in a work environment or not. The quantitative assessment of these accommodation requirements can be improved by a 3D geometric morphometric approach, because it captures the spatial variation of the body much better than traditional anthropometric measurements, while still utilizing the statistical machinery of traditional anthropometry. The present study shows how this approach can be used for the design of fall harnesses by identifying size and shape characteristics of both sexes, and in particular form change as a function of size or other variables of interest. The results lead to the conclusion that in order to improve the fit and performance of clothing, it not only needs to reflect form differences between males and females, but also the fact that within each sex, a large amount of form variation is different for small to large bodies and therefore requires a different type of adjustability of the harness.

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