3D MODELING OF FALL PROTECTION HARNESSES

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This paper presents an analysis of human torso shape in 3 dimensions with the goal of improving the design and accommodation efficiency of fall harnesses. For this purpose, a sample of 98 male and female adults of mixed ethnic background were scanned using a Cyberware 3D whole body scanner. The initial scan data, representing the body as a high density polygon mesh, were post-processed in order for key features to be extracted and registered as Cartesian coordinates. The data analysis was limited to the individuals' torso as the principal body portion the harness has to fit and support. The coordinates form landmark data that were used to describe the spatial relationship of body shape and harness design under 'normal' and suspended conditions. The shape analysis of the landmarks was performed using Generalized Procrustes Analysis (Rohlf, 2000). This approach, also known as geometric morphometrics, has several advantages over traditional morphometrics, such as aligning spatial data in a least-squares type approach, which makes shape variation independent of predefined body planes and orientations. It also provides a better control of size and size effects that are relevant for the design of the harness. Finally, the derived parameters of size and shape variation can then be used as input to a computer analogue of the human torso, which can serve in the design process as well as in virtual reality animations.

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 (e.g. Gross et al., 2001) 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 shape. This paper presents preliminary results of a study of human torso shape using a 3D geometric morphometric analysis of landmark data (Bookstein, 1991). The goal is to quantify shape characteristics of the torso that can be used to improve the current design of protection clothing. Shape differences between mean landmark configurations of male and female torsos serve as an example.

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 outputs a 3 dimensional high density polygon mesh. Subjects were scanned in 3 different conditions: nude standing, standing in a harness, and suspended in a harness. Here we present results using the nude standing scans only. Raw scans were edited for missing data points and artifacts. Subsequently, Cartesian coordinates of specific locations were collected using Cyslice (© headus), which is illustrated in Figure 1.

In order to make individual sets of landmarks statistically comparable, each data set has to be registered in the same orientation. It is common in anthropometry to take an anatomical reference plane (i.e. 3 predefined points) for standard orientation. However, the use of multiple point registration

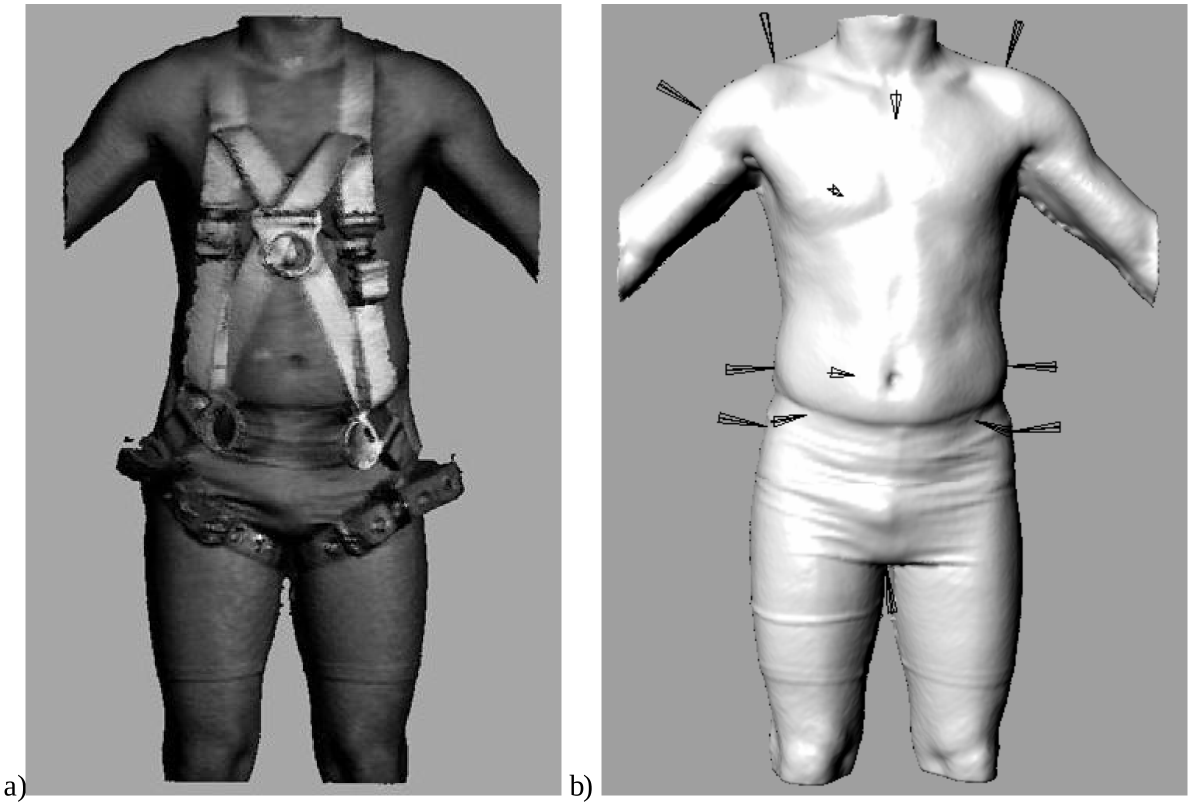


Figure 1: a) A laser surface scan of a subject wearing a fall protection harness. b) Cartesian coordinates are selected from the polygon mesh interactively using cyslice (© headus).

methods has been shown to provide better quantification of shape differences than 2 or 3 point registrations, as differences tend to change significantly when the reference plane is changed (Rohlf & Marcus, 1993). We use Generalized Procrustes Analysis (GPA, Rohlf, 2000) for the alignment of landmark data and subsequent analyses. GPA performs a least-squares type of alignment of 3D coordinates by minimizing the distance of corresponding landmarks relative to the mean or consensus configuration. In order to control for size and size related shape differences (allometry), GPA sets each landmark configuration to a common centroid size.

The differences between the landmarks of each individual and the consensus configuration are used as input variables for standard uni- and multivariate statistics. The within-sample variation of torso shape was analyzed by a principal components analysis (pca) of the Procrustes aligned coordinates. Allometric shape changes are assessed by plotting principal component (pc) scores against commonly used size measures, such as stature and weight. Observed shaped differences are visually represented as landmark displacements between group means, as well as between individuals and the consensus.

RESULTS

The individual scores for the first 2 principal components (34%) are displayed in Figure 2. Despite the relatively low percentage of explained variance, these 2 components clearly separate male from female torsos, which means that a large portion of the variation in the sample is driven by sexual dimorphism. Subsequent components do not appear to be related to either sex differences or any other factor pertinent to harness design, such as harness size or fit rating, thus fore indicating a high degree of overall individual variation.

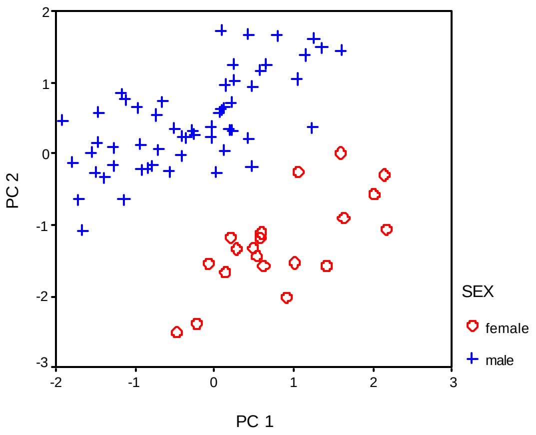


Figure 2: Result of a PCA using residuals of a Procrustes alignment.

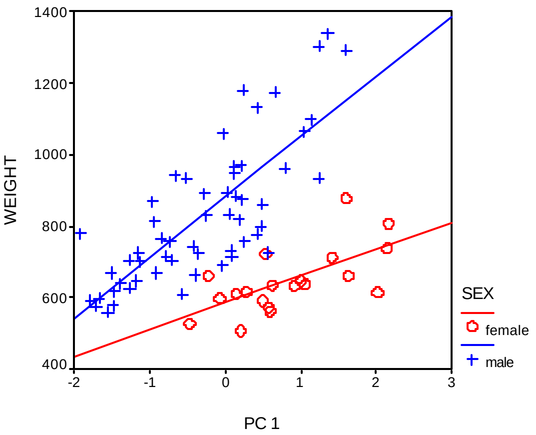
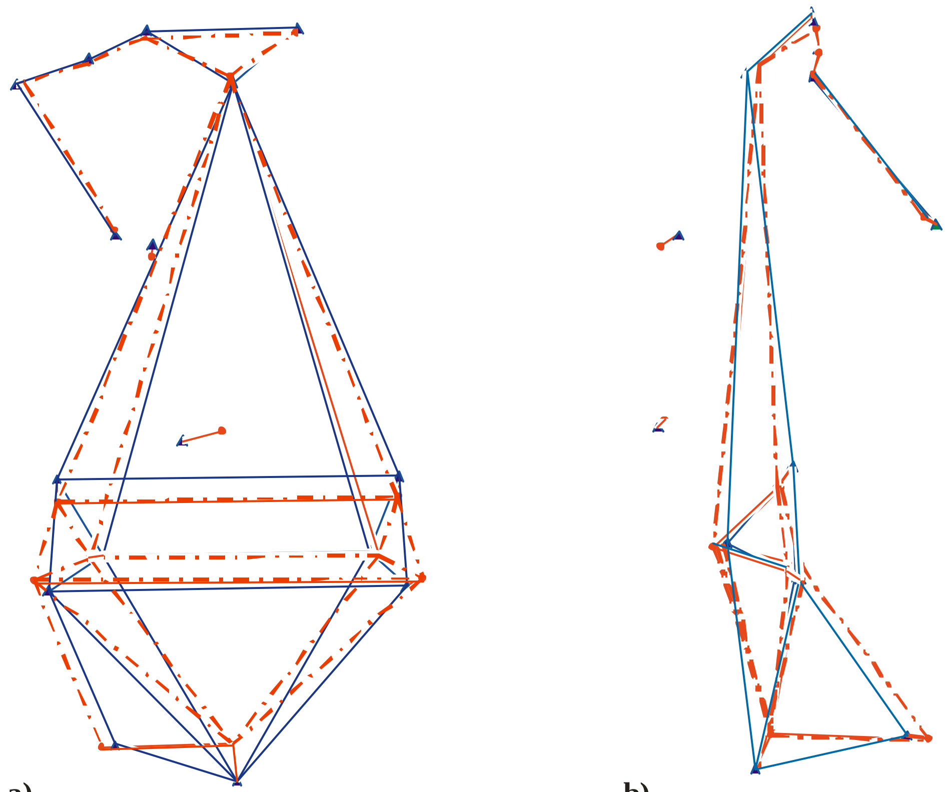


Figure 3: plot of pc 1 against weight, illustrating different allometric relationships in male and females torsos.

In order to better assess the sex-related shape differences, mean landmark configurations were computed for males and females and Procrustes superimposed (Figures 4a, 4b). Besides more or less expected differences in the projection of the landmarks at the chest and the crotch (Figure 4b), male and female torsos also exhibit very distinct shape characteristics in their hips: Males have vertically longer hip bones, especially from the suprailliac crest to the hip joint, while the width is clearly reduced at the level of the hip joint. The difference in hip height results in a relatively (not absolutely) shorter trunk height for males. Furthermore, the relative depth of the buttock area is clearly increased in the female torso, while shoulder proportions are remarkably similar between males and females. This observation may reflect the fact that the subjects for this study were all recruited among construction workers. From a more general perspective, it should be noted that, given that absolute size differences have been removed from the landmark data, all of these characteristics reflect different shapes or proportions. Removal of size does not remove allometry from the data. Therefore, the relation between size and shape has to be assessed. Both pc 1 and 2 show relatively low, yet highly significant correlations with body weight (pc 1: r=0.38 p<0.001, pc 2: r=0.68, p=0.000) and stature (pc 1: r=-0.29, p=0.01, pc 2: r=0.36, p=0.001). A bivariate plot of weight against pc 1 (Figure 3) clearly indicates that the shape differences driving pc 1 are size-dependant. Moreover, the degree to which these shape differences are correlated with size is very distinct between males and females, allometric shape changes in males being much more pronounced than they are in females. These observations indicate that males and females not only require different sizes and shapes of protective clothing, but that male and female torsos do not ‘grow bigger’ in the same way: Within each sex, the body shape changes allometrically, but not identically. Therefore, sex-specific size differences should be integrated into the design so that these allometric differences are accommodated by the harnesses.



a)

b)

Figure 4: Visual depiction of mean torso shapes of males (solid lines) and females (dotted lines) using Procrustes registered landmarks. a) frontal view b) left lateral view) Landmark configurations are scaled to a common size.

CONCLUSION

The safety requirements involved in the use and design of fall protection harnesses necessitate a high degree of constraints, while allowing enough flexibility in order to fully accommodate all the different sizes and shapes of human bodies. The quantitative assessment of these accommodation requirements can be improved by a 3D geometric morphometric approach, because it captures the spatial covariation of relevant landmarks 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 shape characteristics of both sexes, as well as shape change as a function of size. The results lead to the conclusion that in order to improve the fit and performance of protective clothing, it not only needs to reflect shape differences between males and females, but also the fact that within each sex, the shape changes differently from small to large bodies and therefore requires a different type of adjustability.

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