A new method for classification and averaging of 3D human body shape based on the FFD technique

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ABSTRACT

The classification of body form is important in order to design an industrial product that fits to the human body shape. The conventional methods using principal component analysis or cluster analysis based on body dimensions do not provide enough information for designing product shape. In the present study, a new method is proposed to analyze human body shape using the FFD (Free Form Deformation) technique. The FFD technique is a 3D morphing technique in Computer Graphics; with this technique, a 3D shape is deformed freely by moving control points around the shape. With this new method, a human body shape, modeled so that each data point of an individual anatomically corresponds to that of another individual, is automatically deformed to coincide with the other body shape. The inter-individual distance (dissimilarity) is defined by using the FFD deformation function, which consists of the vectors of the movement of the control points. The distance does not depend on the direction of deformation that is, the distance obtained from the FFD function that deforms object A into object B is practically the same as the distance obtained from the FFD function that deforms object B into object A. We analyzed the 3D foot shapes of 63 adult females with the new method. The distance matrix was analyzed using the multi-dimensional scaling method. The variation of foot shape was well described by the two principal axes contrasting the narrow-wide difference and the flat foot-high arched foot variation, and flat feet produced a cluster distinct from other feet.

1. INTRODUCTION

The Type classification of human body has been conducted to improve the match between the human body and industrial products. For industrial products that must conform to the human body shape such as shoes, the classification of the human body should be based on the 3D body shape, but human body dimensions have been used instead for this because of the lack of appropriate and practical methods. In some reports, morphological factors of the human body have been evaluated by geometrical properties of silhouette outlines (Hawes and Soval, 1994; Kouchi, 1995), and by properties of body cross-sections (Ratnaparkhi,et al., 1992; Kouchi & Tsutsumi, 1996). These methods, however, do not fully utilize 3D information. In this study, a new method for classification of the 3D human body using the Free Form Deformation technique (Sederberg, 1986) has been developed. We analyzed the 3D foot shapes of 63 adult females with the new method. Even when the body form has been classified into appropriate groups, we still need a way to design industrial products which maximize morphological fit. There are no conventional methods for obtaining the average 3D form. Several methods have been proposed to obtain the average 2D form (Hawes et al., 1994), but these methods have not been extended into 3D forms and had no possibility of matching the forms of industrial products with the body. We have also developed a method of obtaining the average form of 3D body forms using the FFD thchnique, and a new method to use the shape transformation function to design a shoe last.

2. METHOD

2.1.Modeling of the 3D form

Modeling means the rearrangement of the data points so that each is anatomically homologous between subjects. The methods for the foot and the human skull (mandible not included) are described here to illustrate. The foot is modeled according to the way proposed by

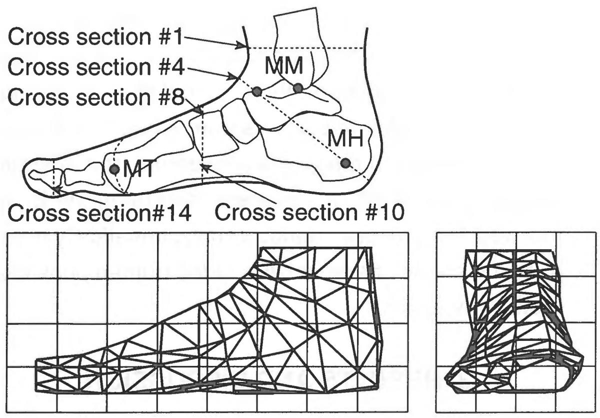

Figure1 Modeling of the foot shape

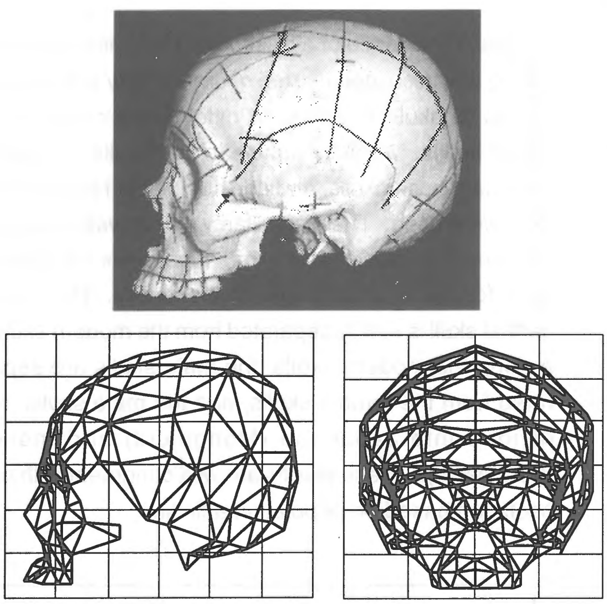

Figure 2 Modeling of the skull shape

Tsutsumi and Kouchi (1992) where a plaster model is taken from a standing subject with markings for the anatomical landmarks. The shape of each foot is represented by 174 data points (324 polygons) consisting of 12 data points on 14 cross sections and six points on the navicular region as shown in Figure 1. Each cross section is defined as passing through a specific anatomical landmark or as an interior division of a cross section. A skull is represented by 179 data points (280 polygons) as shown in Figure 2. The modeled data points are digitized using a 3D digitizer (3SPACE FASTRACK, Polhemus Inc.).

2.2.Form deformation and dissimilarity

The Free Form Deformation (FFD) technique (Sederberg, 1986) is used to evaluate the dissimilarity between two 3D forms. With FFD, reference form is modified by moving defined lattice points. ér In the present method, cubic B-splines are used instead of Bezi curves used in the original FFD technique to minimize theoretical errors (Mochimaru,et al., 1995). When there are two forms, form A is transformed into form B by moving the control lattice points defined around form A. The control points are defined to satisfy the following conditions: (1) the control points cover the size of the reference form approximately 1.1 times; (2) the control points are distributed equidistant for each of the three axes, and the inter control point distance is about the same in all three directions; (3) the total number of control points is about 1.5 times the number of data points. Figure 1 shows the 225 (9x5x5) control points for the foot, and Figure 2 shows 175 (7x5x5) control points for the skull. The movement of the control points is calculated automatically. Since the number of data points is smaller than the number of control points, the control points are calculated to minimize the following evaluation function using the quasi-Newton method.

$$
\begin{aligned}
E = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\Big\{ & \big((C_{(i,j,k)} - C_{(i-1,j,k)}) - (D_{(i,j,k)} - D_{(i-1,j,k)})\big)^2 \\
& + \big((C_{(i,j,k)} - C_{(i+1,j,k)}) - (D_{(i,j,k)} - D_{(i+1,j,k)})\big)^2 \\
& + \big((C_{(i,j,k)} - C_{(i,j-1,k)}) - (D_{(i,j,k)} - D_{(i,j-1,k)})\big)^2 \\
& + \big((C_{(i,j,k)} - C_{(i,j+1,k)}) - (D_{(i,j,k)} - D_{(i,j+1,k)})\big)^2 \\
& + \big((C_{(i,j,k)} - C_{(i,j,k-1)}) - (D_{(i,j,k)} - D_{(i,j,k-1)})\big)^2 \\
& + \big((C_{(i,j,k)} - C_{(i,j,k+1)}) - (D_{(i,j,k)} - D_{(i,j,k+1)})\big)^2 \Big\} \\
& + w\sum_{n=1}^{N}\left(Po_{(n)} - Pt_{(n)}\right)^2
\end{aligned}
$$

where, the first member of the equation indicates the sumation of difference between the initial lattice points and the modified lattice points. The second member of the equation indicates the summation of difference between the original data points and the deforomed data points, and w indicates a weight factor. The evaluation function is defined as the weighted linear summation of the magnitude of distortion for the control lattice and the residual error between the deformed form and the target form.

Figure 3 shows that the movement is small when the two forms are similar to each other (Figure. 3(b)) and the movement of control points is large when the difference between the two forms is large (Figure. 3(c)). The dissimilarity between two forms is defined as the total movement of the control points that are calculated as the sum of the norms for the moving vectors. The dissimilarity is calculated for each pair of n forms, and by analyzing the dissimilarity matrix using multidimensional scaling, a scatter gram of the n forms is obtained.

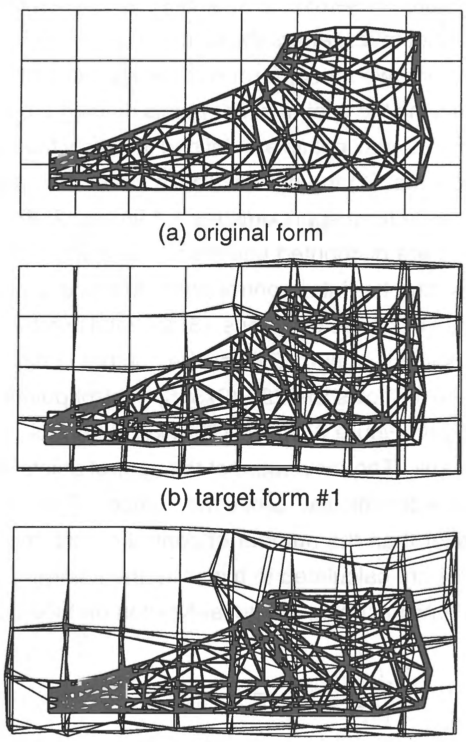

Figure 3 Movements of control lattice points

2.3.Averaging 3D forms

The 'average 3D form' for N subjects is calculated as follows: (1) Inter individual dissimilarity is calculated for (N(N-1)) pairs by the method detailed in Mochimaru and Kouchi (1997); (2) Standard deviation of dissimilarity is calculated for each subject using (N-1) distances between the subject and other (N-1) subjects, and the subject with the smallest standard deviation is selected as the 'median shape', (3) Using the median shape as the reference form, FFD functions that transform the reference form into other N subjects (including itself) are calculated, and from these functions the 'mean FFD function' is calculated; (4) The reference form is deformed using the 'mean FFD function' to obtain the average form.

2.4.Application to modeling product shape

If subjects are divided into two groups A and B; A with 'standard' shape, and B with distinctive shape, then the average form can be calculated for both groups according to the above method. Though these averages would be only theoretical, a transformation function that deforms the average form of group A into the average form of group B could be calculated. Since the obtained transformation function could deform the whole 3D space within the control lattice points, if another object were inserted into the space, it would be deformed as well. If the inserted object were a product model that matched to subjects from group A, the obtained deformed product model would fit to subjects from group B, because the transformation function would deform the average form for group A into the average form for group B. In this way, the present method can systematically introduce the shape characteristics of the human body into product design.

3. RESULTS AND DISCUSSION

3.1.Significance of a dissimilarity

The significance of a dissimilarity is verified by comparing the calculated degree of dissimilarity with expectations for skulls known to be different. Six adult male Indian skulls, two adult female Indian skulls, two adult male Japanese skulls, and one adult male Neanderthal skull were used. The dissimilarity matrix was analyzed using multidimensional scaling. Figure 4 is the scatter gram for the 11 skulls based on the results. The Neanderthal skull is widely separated from the modern skulls. Among the modern skulls, the male skulls are separated from the female skulls, and the male skulls are divided into Japanese (Mongoloid) and Indian (Caucasoid). These results are well congruent with expectation based on population affinities.

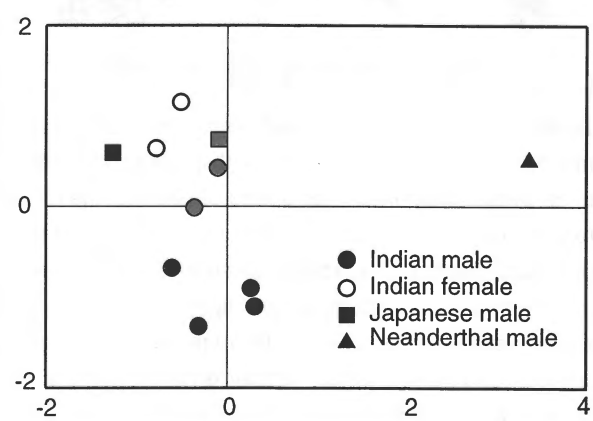

Figure 4 Distribution of the skull

3.2.Classification of the 3D foot forms

The right foot of 63 adult females with foot length 235 ± 7 mm was used. Foot length was standardized, the dissimilarity calculated, and the dissimilarity matrix was then analyzed using multidimensional scaling. The results are shown in Figure 5. The first ditribution scale

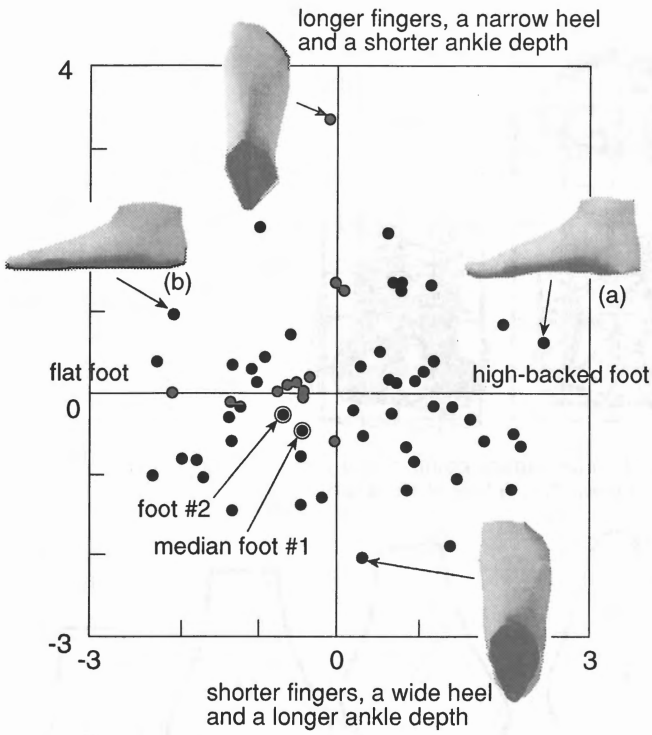

Figure 5 Distribution of the 63 female feet

has correlation with "boundary height between the instep and the ankle / foot length", and a coefficient of correlation is r=0.082. It also has correlation with "height of medial malleolus / foot length", and a coefficient of correlation is r=0.061. Thus, a foot which has larger value for the first distribution scale indicates "high-backed foot", as shown in Figure 5(a). A foot which has smaller value for this scale has a lower instep, such as "flat foot" (Figure 5(b)). Hence, it is found that the first scale indicates a characteristic of "high-back and flat". A correlation between the scond scale and "sagittal position of the instep and the ankle / foot length" was observed, and a coefficient of correlation is r=0.076. It also has correlation with "toe length / foot length", and a coefficient of correlation is r=0.055. A foot, therefore, which has larger value of the scale has longer fingers,

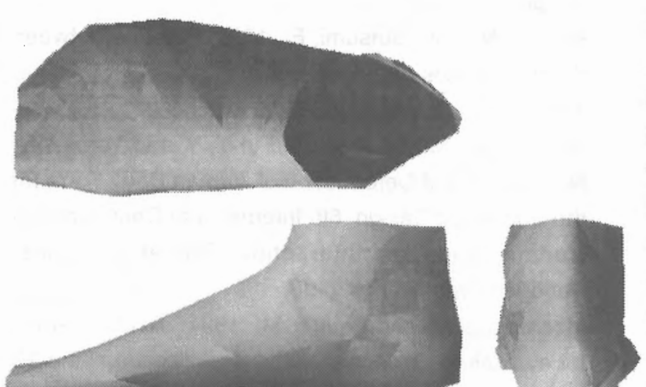
Figure 6 The average foot shape of the 63 feet

a narrower heel and a longer ankle depth. A foot, whereas, which has smaller value of the scale has shorter fingers, a wide heel and a shorter ankle depth. Thus, this scale indicates horizontal proportion of the foot.

3.3.Average forms for the standard foot

The average form of 63 female foot forms was calculated using the median form, foot #1, as shown in Figure 5. Figure 6 shows the average foot obtained by applying average transformation function to foot #1. The foot circumference of the average form was very close to the mean foot circumference for the 63 feet after normalization. In order to verify the robustness of the averaging method, another average normal foot was calculated using another foot (#2 in Figure 5) as the reference form. The obtained average normal foot based on foot #1 and that based on foot #2 are very similar to each other. This fact indicates the robustness of the present method.

3.4.Application to shoe last grading

A foot with the average ball girth for the same foot length is standarized for a foot of E width in Japanese Industrial Standards; this is based on the measurement of Japanses feet. The standard ball girth for the measuremd foot length (235 $\pm$ 7 mm) is 231 mm in Japanese females. With a conventional grading method, a wide last was created from a last of E width by similarity conversion to increase in its ball girth. In the present study, a typical foot was selected from feet of E width, and the typical foot has medium value in the first scale and the second scale on the foot distribution. It is shown in Figure 5. The foot shape standing is on a sole stage was measured to make even condition in the foot shape and the last shape. The sole Figure 7 shows the transformation function from average standard width foot (solid line) into average very wide foot (gray line). The movement of the control points was larger at the forefoot and smaller at the heel. Such movements reflect the allometry of the foot. The foot changes its proportion with the increase of width, but the conventional method of shoe last grading does not reflect all aspects of foot allometry. Figure 8 compares the 4E lasts obtained by the conventional method (thin gray line) and the present method (thick line). The 4E last obtained by the present method is wider at the toe without changing the thickness and narrower at the heel, and reflects the

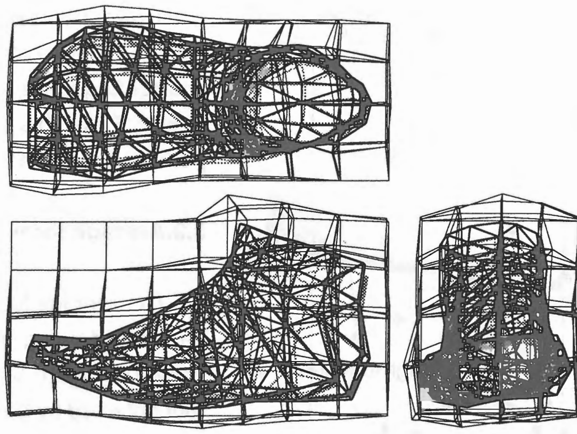

Figure 7 Movements of control lattice points to convert from a foot of E width to a foot of 4E width

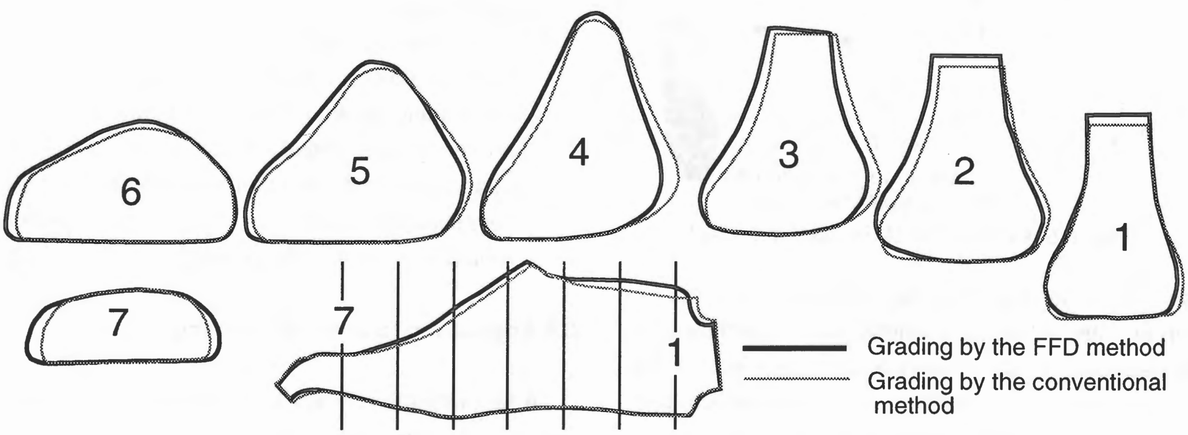

Figure 8 Application for shoe last grading

differences in proportion between narrow and wide feet of the same foot length better than the existing wide last. The actual advantage of the new last remains to be tested.

4. CONCLUSION

A new method has been developed to clasify human 3D forms and to calculate an average form for them using the FFD technique. The dissimilarity pattern of 11 skulls is congruent with expectation about the relationship between them. The data for 63 feet were analyzed for dissimilarity, and the results suggested that the variation between a flat foot and a 'normal foot' with a well-developed plantar arch is the most important factor. A method for averaging the clasified human 3D forms has also developed. The average foot shape of 63 feets was calculated using this method, and the foot circumference for the obtained average form was very close to the mean foot circumference of the 63 feet. Using foot and shoe last forms as examples; it was verified that the transformation function from average form for the standard group into the average form for the distinctive group can be used to design product shape.

REFERENCES

Hawes, M. R. and Soval, D., 1994. Quantitative morphology of the human foot in a North American population, Ergonomics, 37, pp.1213-1226.

Kouchi, M., 1995. An analysis of foot shape variation based on the medial axis of foot outline, Ergonomics, 38, pp.1911-1920.

Kouchi, M. and Tsutsumi, E., 1996. Relation between the medial axis of the foot outline and 3D foot shape, Ergonomics, 39, pp.853-861.

Mochimaru, M., Kouchi, M., Fukui, Y. and Yamazaki, N., 1995. Local Deformation of Human Body Form for the Shoe Last Design, 6th International Conference of Human-Computer Interaction, Poster Sessions: Abridged Proceedings, p.96.

Mochimaru, M. and Kouchi, M., 1997. A new method for evaluating similarity and the classification of the 3D human body shape based on the FFD technique, IEA'97, pp.382-384.

Ratnaparkhi, M. V., Ratnaparkhi, M. M. and Robinette, K. M., 1992. Size and shape analysis techniques for design, Applied Ergonomics, 23, pp.181-185.
Sederberg, T. W., 1986. Free-From Deformation of Solid Geometric Models, Proceedings of ACM SIGGRAPH'86 in Computers & Graphics, 20, pp.151-160.
Tsutsumi, E. and Kouchi, M., 1992. Geometrical modeling of the foot, 5th ASEE International Conference ECGDG 1992, pp.171-174.