Modeling, Analysis, and Application of 3D Digital Human Data

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1. Introduction

3D Anthropometry started in Japan in the early 1970s by applying the Moire topography method to the human body. 3D anthropometry data at that time has generally been used to obtain qualitative rather than quantitative information. However, recent technical developments have made it possible to obtain body surface data of sufficient resolution and accuracy for analysis of variation and application of this information to product design, and to conduct statistical analyses of 3D anthropometry data. Modeling of 3D body surface data is the key technology for quantitative analysis of variations, classification of people by body shape, and synthesis of possible virtual body forms. In this article, we describe recently developed technologies for use of 3D anthropometry data.

2. 3D anthropometry

Until recently, dense surface data could not be measured using a body scanner without touching the subject. Many scanners use triangulation to obtain surface data, by projecting light onto the body surface and monitoring the projected light from another direction using a camera. There are 3 problems that must be solved to improve the quality of 3D anthropometry data: 1) alignment and merging of data obtained using different cameras; 2) reduction of self-occluded areas; and 3) reducing effects of body movement. The first 2 problems are general problems, but the third problem is unique to the human body.

When surface data is obtained using many cameras in order to reduce occluded areas, the range images produced by these cameras must be described using the same coordinate system. Data alignment consists of registering data obtained by different cameras, and data merging consists of creation of a continuous surface eliminating overlapping data points. Most merge functions used by commercially available scanners initially approximate the human body as a cylinder, and merge data from different cameras using a cylindrical coordinate system. This method does not always work well when the cross section shape is dissimilar to a circle; e.g., the shoulder area, hands and feet. New merging methods have been developed that correctly captures the topology of an object. For example, Curless and Levoy (1996) distinguished surfaces of the object facing cameras from surfaces facing away from cameras using information about the distance between the camera and the object by a volumetric method. Such techniques are used in several commercially available scanners.

There is a limit to the ability to reduce the occluded area, and the most difficult areas are those such as the armpits, soles of feet, backs of ears, under the chin, and crotch. However, these areas are also important for the fitting of industrial products such as shoes, underwear, spectacle frames, and gas masks. The occluded areas can be reduced by targeting the object to the human body, and finding the optimal arrangement of cameras. For a foot scanner, the sole can be measured with the subject standing on a glass plate (Kouchi and Mochimaru, 2001). Generally, use of more cameras reduces the occluded area. However, use of more cameras entails a longer scanning duration and greater effects of body sway during the scanning. When the scanning duration is greater than 10 sec, there is a high probability that the head will move more than 10 mm during the scanning time. Technologies have been developed to minimize the scanning duration (Mochimaru *et al.*, 2002), and to modify the scanned data using recordings of body movement obtained at the time of scanning (Funatomi *et al.*, 2004). For the former approach, a national project has led to the development of a head scanner that can measure the whole head within 1 sec and a whole body scanner that can measure the whole body within 2 sec (Mochimaru *et al.*, 2002). Using these scanners, a small-scale 3D anthropometric survey was conducted in 2000 and 2001 as a national project (Research Center of Human Engineering for Quality Life, 2001, 2002).

3. Homologous modeling

Locations of anatomical landmarks are usually recorded at the same time as surface data (Fig. 1). These landmarks are located and marked by an anthropometrist. Because this procedure is time-consuming and vulnerable to inter-observer error, techniques have been developed for estimation or precise localization of landmarks using surface data. We are developing a memory-based method for estimation of foot and face landmarks (Mochimaru *et al.*, 2004). However, auto-landmarking is currently not a 100% reliable way to locate landmarks.

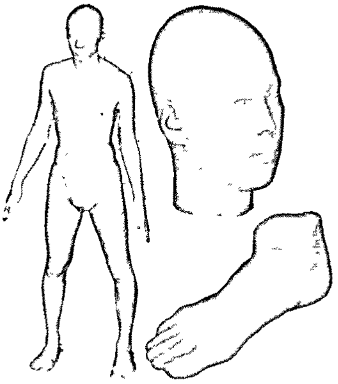

Fig. 1. Examples of scanned body surface data with landmarks

Every subject has the same number of landmarks, which have the same meaning in every subject. This is not true for surface data points. However, the number of landmarks is less than 100, which is not enough to describe the surface form. Landmarks are used to increase the number of surface data points with inter-individual correspondence. All humans have basically the same anatomical structure, and this structure is useful for defining points on the body surface. All body shape data can be represented as polygon data with the same number of data points, the same topology, and the same anatomical meaning. We call this a "homologous shape model", and the term "homologous modeling" indicates the procedure used to generate homologous shape models in this article. Fig. 2 shows examples of homologous models. They are constructed by calculating main cross sections defined by landmarks, and quasi-landmarks are defined on these cross sections, which can be uniquely defined. When landmarks and quasi-landmarks are not enough, dividing points of the surface distance between these landmarks are also calculated. Using this method, we have constructed homologous models of the torso, foot and face (Mochimaru and Kouchi, 2003). In defining a homologous model, we first identify the application target, and then, depending on the purpose of the model, we define new landmarks such as points of contact between the product and the human body, or we use a specific cross section that is closely related to the dimensions of the product, such as the ball

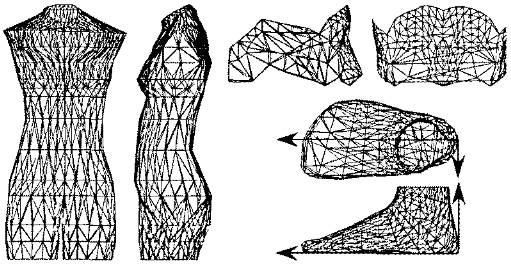

Fig 2 Examples of the homologous model

cross section of the foot.

The shape of the human body is represented in 2 ways: using polygons, and using mathematical surfaces (Kurokawa *et al.*, 1984). Each method has advantages and disadvantages. With the decreasing cost of memory and the availability of graphic processor units specialized in displaying polygon data, more and more studies using polygons are being conducted.

The number of data points that can be defined using the above method is limited (up to several hundreds), and this method is not cost effective because special software must be developed for each specific body part. A homologous modeling using the subdivision surface method has been proposed (Allen *et al.*, 2003; Seo *et al.*, 2003). The subdivision surface method was developed in the 1970s. It has been demonstrated that when a broken curve is subdivided infinitely, the broken curve will converge into a B-spline curve. The same method can be applied to 3-dimensional polygons, and by obtaining vertices of subdivided polygons approximately corresponding to the measured data points, a dense polygon mesh fitted to the measured point cloud can be created. The original polygon mesh is created as a generic human shape model consisting of several hundred data points, and the anatomical landmarks are described by their relationship with the vertices. The generic model is deformed to minimize distances between landmarks of the generic model and landmarks of measured body, to minimize distances between vertices generated by subdividing the generic model and the measured point cloud, and to achieve uniform distribution of the generated subdivided vertices. A single generic model is subdivided to fit different measured bodies, and all measured bodies are described by a homologous dense polygon mesh consisting of a uniform number of vertices and uniform topology, with anatomical correspondence. Fig. 3 demonstrates application of this method to data for the foot (Inagaki *et al.*, 2004).

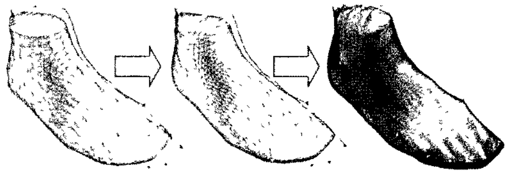

Fig. 3. Homologous modeling of the foot based on the subdivision surface method

4. Average form

When homologous models are constructed for all measurement data, the average form can easily be calculated. The average form is useful if the target population is limited to a specific group. Fig. 4 shows dress-making dummies used to make standard-size (Japanese industrial standard) clothing for young adult Japanese females and males (Kouchi *et al.*, 2001). The shapes of these dummies are based on the average 3D forms of young adults calculated using homologous models as shown in Fig. 2. The data used to make these dummies was obtained from measurements of the bodies of young adults with beautiful bodies, based on the concept of creating cloths that look beautiful when worn by actual people. Thus, young adults with minimal asymmetry and minimal torsion of the torso were selected, and young adults with extreme curvature of the spine at the side view were excluded.

5. Statistics and synthesis

When homologous models are made for various people, the quantitative inter-individual comparison is easy. A morphological distance can be defined as the sum of all distances between correspondent ver-

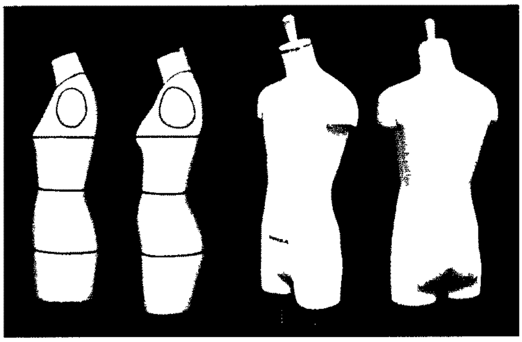

Fig. 4. Conventional dress-making dummy for females (left); dress making dummies for females (middle) and males (right), made using the present methods

tices of 2 homologous models. A distance matrix can be obtained by calculating the morphological distance for all possible pairs of subjects. By analyzing the distance matrix using Multi-Dimensional Scaling (MDS), new variables representing shape variations among subjects are obtained. These variables are independent of each other: the first variable represents the largest variance, and the second variable represents the second largest variance, and so on. Using these new variables, a distribution map of 3D shapes is obtained. Fig. 5 shows a distribution map of 3D shapes for the right feet of 56 adult Japanese females. In this case, 4 variables represented about 80% of the information carried by the distance matrix.

Using the results of MDS, a virtual form at an arbitrary point on the distribution map can be calculated. When the coordinates for the virtual form are small (smaller than ± 1 standard deviation), the homologous model for them can be interpolated as the weighted average of actual subjects with the condition that the weight is not less than 0. If the deformation of a virtual form along a line passing through the origin is represented using the movement of control points for the Free Form Deformation technique, any virtual form on this line can be calculated by extrapolating the movement of control points (Mochimaru and Kouchi, 2000).

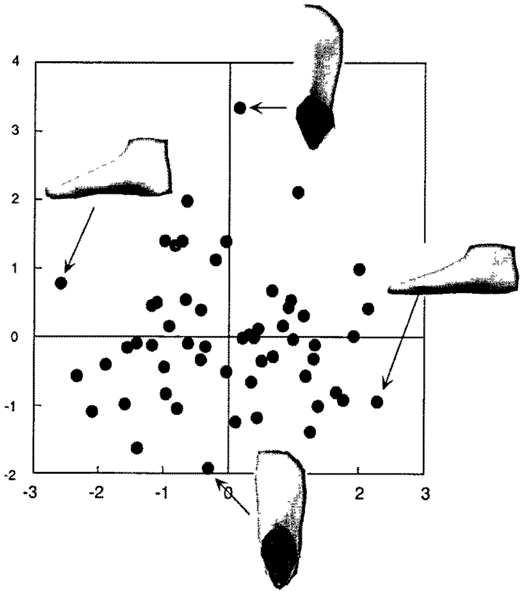

Fig. 5. A distribution map of the right feet of 63 adult Japanese females

There is another method for calculating a virtual form at an arbitrary point on the distribution map. In this method, coordinates of homologous models are analyzed using principal component analysis, and eigenvectors for each principal component (eigenshape) are used to calculate a virtual shape (Allen *et al.*, 2004). This method requires less computation than the above-described method that uses MDS. However, because the number of variables is extremely large (the number of vertices × 3), many new variables (principal components) are necessary to explain the variance carried by the original data. When the number of vertices (data points) is 300, the number of variables used for principal component analysis is 900 (300 × 3). When a homologous model represents the surface form accurately, as in the case of modeling based on the subdivision surface, the number of variables is extremely large. Thus, dozens of principal components are necessary to explain 80% of the total variance. Therefore, analysis of the distance matrix using MDS is more practical for classification of subjects.

6. Grouping of subjects and designing mass-produced products

The distribution map of 3D shapes described in the previous section is useful for efficient sizing of mass-produced products. In a collaboration study with a spectacle frame manufacturer, we measured the 3D face shape of 56 young adult Japanese males,

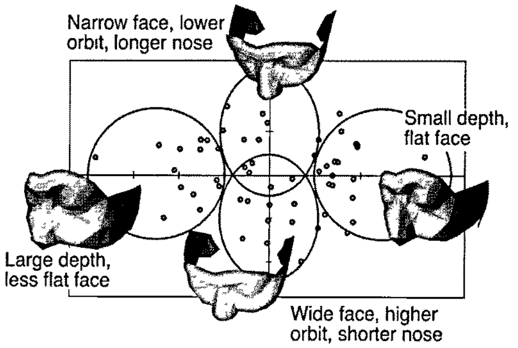

Fig. 6. Distribution map of 3D face data and grouping of subjects

made a homologous model for each face, and obtained the distribution map of 3D face shapes shown in Fig. 6 (Koucni and Mochimaru, in press). The first scale (the X axis) described the size (particularly depth) and flatness of the nasal bridge. The second scale (the Y axis) described the mid-face breadth and the relative location (height) of the ear and nasal bridge. These 2 variables explain 68% of the total variance carried by the morphological distance matrix. Because the third and the fourth variables were not directly related to spectacle frame design, subjects were grouped into 4 face-type groups using the distribution map based on the first 2 variables (Fig. 6). When deciding the number of groups, the cost of production and circulation was also taken into account. An average form was calculated for each face-type group and was imported to CAD software, and a new frame was designed (Fig. 7). The design of the new frame was based on the hypothesis that fit and comfort are best with a small tightening force without slippage. The material and weight of the new frame were the same as those of a conventional frame. The characteristics of the new frames were examined in an experiment comparing the prototypes of new frames and conventional frames. The results indicated that when a new frame was worn on the appropriate type of face, it had better fit and comfort and less tightening force without slippage, compared to conventional frames. The 4 types of new frames have been on the market since 2001.

7. Customized product

Homologous models are also useful for customizing products. We have proposed designing a product shape by analyzing the difference between an individual' s body shape and an ideal (or standard or average) body shape using the Free Form Deformation technique (Mochimaru *et al.*, 2000). Fig. 8 shows an example of the use of this method to design a custom last. The homologous model of the ideal foot shape (Fig. 8, top left) is deformed into the homologous model of an individual (Fig. 8, top right) using the Free Form Deformation. Control lattice points are set around the ideal shape (grid in Fig. 8, top left), and the movements of these points that are required to deform the ideal shape into the individual shape are calculated using a non-linear optimization method (deformed grid in Fig. 8, top right). The deformed lattice (or movements of control points) is a function representing the difference between the 2 shapes. When this function is applied to the original last shape, which is designed for the ideal foot shape, the last shape changes so that it would fit the individual's foot (bottom right).

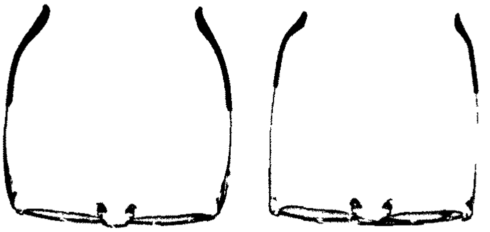

Fig. 7. Conventional frame (right) and frame made using the present methods (left)

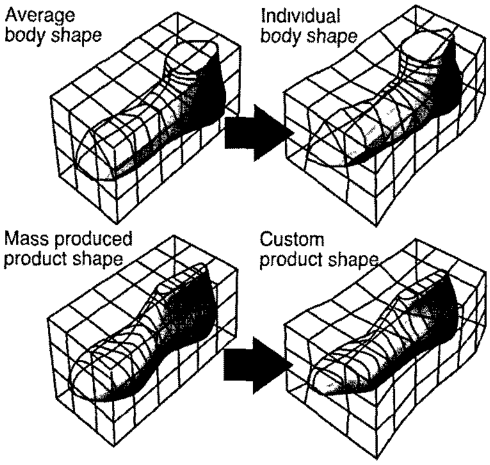

Fig. 8. Deformation of product shape by Free Form Deformation technique

Fig. 9 shows an example of the Free Form Deformation technique. An average foot of normal width (foot length=23.5 cm, foot circumference size=E) was deformed into an average of very wide feet (foot length=23.5 cm, foot circumference size=EEEE). In the Japanese industrial standard for shoe size, the foot circumference size (width) E indicates average foot circumference for the foot length. The difference in foot circumference between 2 adjacent foot circumference sizes is 6 mm; thus, the difference in

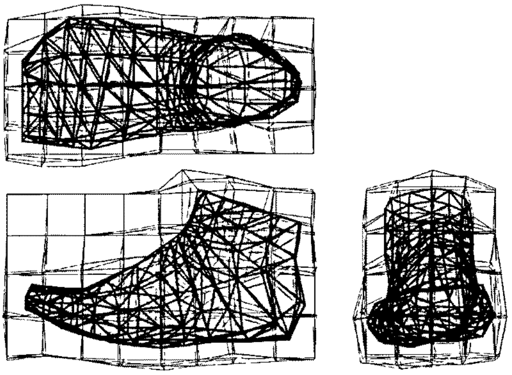

Fig 9. Deformation of the average foot of average width into the average of very wide feet using Free Form Deformation technique

foot circumference between E and EEEE is 18 mm. Fig. 9 (top view) shows that a very wide foot is very much wider than average at the forefoot, but is not particularly wide at the heel. Also, a very wide foot has greater dorsal arch height, but the thickness of the toes is not very great. A last for very wide feet is graded from a last for an average foot with normal width. In the conventional grading method, the original last is expanded uniformly along the longitudinal axis of the last. However, Fig. 9 shows that this is not the case for foot shape. In living organisms, when the overall size changes, its proportion also changes. This phenomenon is called allometry. The proportions of the human foot change when the length or circumference of the foot changes. The deformed grid shown in Fig. 10 carries information about the 3D allometry of the foot shape. Fig. 10 shows a comparison of lasts for very wide feet created by 2 different methods. The thick line indicates the last created by applying the deformed grid shown in Fig. 10. The thin line indicates the last created by the conventional method. The last created using the FFD method is wider and lower at the toes, higher at the instep, and reflects the shape characteristics of very wide feet (Mochimaru *et al.*, 2000).

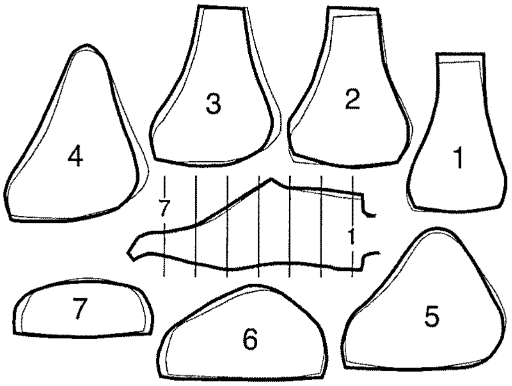

Fig. 10 Comparison of lasts for very wide feet Thick line. last made using the Free Form Deformation technique. Thin line: last made using the conventional grading method

8. Conclusions

Homologous modeling of human body shape and statistical analysis of homologous models are indispensable techniques for use of 3D anthropometry databases in industrial applications. Along with development of such techniques, development of 3D anthropometry databases is also necessary. From 1992 to 1994, the Research Center of Human Engineering for Quality Life (HQL) measured 30,000 people using a whole body scanner. However, the shape data obtained in this scanning were not used extensively, due to the limited technology available for measurement and application. The Ministry of Economy, Trade and Industry (METI) of Japan has continued to support 3D anthropometric research at HQL, where measurements of 200 elderly people were obtained in 2001 and 2002. METI started a new 3D anthropometry survey in 2004. HQL plans to obtain measurements of about 8000 people from 2004 to 2006.

Homologous modeling of human body shape is also used to design customized products. An individual customer is scanned at a retail shop, and the scanned data is modeled and used to produce the custom product. If the scanned data is stored in an internet server as an anonymous data, the customer can use his/her own data for shopping on e-commerce sites. Also, a large-scale, worldwide, and even longitudinal body shape database can be obtained through scanners distributed over many shops. Such practices could make massive 3D anthropometric surveys unnecessary in the future. National surveys should cover minority populations for whom scanning in shops can be difficult: infants, elderly and disabled persons.

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