Mathematical Methods for Shape Analysis and form Comparison in 3D Anthropometry: A Literature Review

Jianwei Niu[1], Zhizhong Li[1], and Gavriel Salvendy[1,2]

[1] Department of Industrial Engineering, Tsinghua University, Beijing, 100084, China
[2] School of Industrial Engineering, Purdue University, West Lafayette, IN., 47907, USA
zzli@tsinghua.edu.cn

Abstract. Form comparison is a fundamental part of many anthropometric, biological, anthropological, archaeological and botanical researches, etc. In traditional anthropometric form comparison methods, geometry characteristics and internal structure of surface points are not adequately considered. Form comparison of 3D anthropometric data can make up the deficiency of traditional methods. In this paper, methods for analyzing 3D other than 2D objects are highlighted. We summarize the advance of form comparison techniques in the last decades. According to whether they are based upon anatomical landmarks, we partition them into two main categories, landmark-based methods and landmark-free methods. The former methods are further sub-divided into deformation methods, superimposition methods, and methods based on linear distances, while the latter methods are sub-divided into shape statistics-based methods, methods based on function analysis, view-based methods, topology-based methods, and hybrid methods. Examples for each method are presented. The discussion about their advantages and disadvantages are also introduced.

Keywords: 3D anthropometry, form comparison.

1 Introduction

There were controversy and suspicion towards quantitative form compassion at one time [1]. As stated by Adams et al. [2], the reasons to adopt quantitative methods are as follows. First of all, although the difference among forms may appear obvious, the significance of the difference cannot be detected accurately by the naked eye. Moreover, quantitative form comparison also has important meaning for the analysis in ontogenetic and phylogenetic sequence. With the emergence and development of several large three-dimensional (3D) anthropometric surveys [3, 4], the past decades have witnessed rapid progress of mathematical methods for form comparison, which leads Rohlf and Marcus [5] to proclaim a “revolution in morphometrics”. Whereas controversy also has arisen over which method is the optimal one for quantifying the morphological difference between forms and statistical analyzing properly [6]. In addition, a generalization framework for 3D modeling has not emerged yet, and it's sometimes difficult or even impossible to interconvert between those existing modeling

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methods [7]. This brings more challenges for form comparison. The purpose of this paper is to briefly summarize the recent development in the field of 3D form comparison, and bring forward discussion several possible future directions as well.

This paper is organized as follows. Section 1 introduces traditional form comparison methods. Section 2 presents an introduction of various landmarks-based form comparison methods. In section 3, we put our emphasis on landmarks-free form comparison methods. Discussions and speculations for future directions are given in section 4.

2 Traditional Methods

As illustrated by Adams et al. [2], in the 1960's and 1970's, quantitative description of shape, combined with statistical analyses, was adopted by biometricians to describe patterns of shape variations. Such methods, now called traditional morphometrics [8], are usually regarded as the application of multivariate statistical analyses to set of quantitative variables.

Several difficulties remained for methods in this category. For example, a set of linear distances is usually insufficient to capture the geometry of the shape, because the geometric relationships among the variables were not preserved. In the area of population grouping and human accommodation, geometric characteristics and internal structure of human surface points are not adequately considered in traditional methods, leading to design deficiency on fitting comfort [9].

3 Landmark-Based Methods

A summary of the current methods for form comparison using anatomical landmarks were put forward by Richtsmeier et al. [6]. Readers can also refer to other summaries given by Richtsmeier et al. [1], Marcus et al. [10] and Adams et al. [2]. Adapted from the classifying methods for form comparison used by Richtsmeier et al. [6], three main categories of form comparison methods are reviewed in the following section, i.e., deformation methods, superimposition methods, and methods based on linear distances. Piccus et al. [11] provided some simple examples using these methods. All of these methods rely on the identification of anatomical landmarks. The most outstanding disadvantage is that curvature and other geometric characteristic of the surfaces between the landmarks are not preserved in the analysis. Another limitation is that landmarking requires a great deal of physical effort, especially when landmarks not clearly identifiable without palpation of the skin.

3.1 Deformation Methods

Deformation methods deform a form to correspond with the reference form [1, 6]. Three steps should be followed: choose the reference object, employ elastic deformation of templates to deform the target object so that it matches the reference object exactly, and study the deformation to quantify the form difference. Deformation methods include energy matrix [11], Finite Element Scaling Analysis (FESA) [12], Free Form Deformation (FFD) [13] and Thin Plate Splines (TPS) [14], etc.

FESA is widely used in engineering and a deformation method that can be used to determine the difference between forms [15]. In FESA, it's required to subdivide the landmarks located on an object into groups to form so called "elements". There exists a one-to-one correspondence between landmarks on the initial reference form and the target form. FESA determines the amount of "morphometric strain" required to produce the target model from the reference model [16, 12]. Mochinaru et al. [17, 18] used the FFD method, one computer graphics technology of deforming the shape of objects smoothly by moving control lattice points set around the object [19], to analyze and classify the 3D foot forms of 56 Japanese females and faces for spectacles design. The distortion of the FFD control lattice points that transform the reference form into the target form is defined as the dissimilarity between two forms.

One limitation of deformation methods is that they lack of appropriate statistical procedures and are dependent on landmarks. Richtsmeier et al. [1] pointed out that care must be taken when choose element types in partitioning form for study.

3.2 Superimposition Methods

According to some specified rules, landmark data of the reference form and the target form are arranged into one same coordinate space. Form variation is determined by the displacement of landmarks in the target form from the corresponding landmarks in the reference form. How to choose the specified rule of superimposition has no universal principia, dependent on the particular application [1]. According to Richtsmeier et al. [6], superimposition methods involves three steps: fix one form in a particular orientation and use it as the reference object; translate and rotate the other form so that it matches the reference object according to some criterion; and study the magnitude and direction of difference between forms at each landmark. Based on different criteria for matching, superimposition methods consist of Procrustean approaches [20], Bookstein's edge matching [21], and roentgenographic cephalometry [22], etc.

One advantage to the method is that interpretable graphic of the difference between forms can be easily accessible. Unfortunately, different matching criteria can result in different superimpositions [6]. Lele and Richtsmeier [23], as well Lele and McCulloch [24] have shown in a mathematically precise fashion that no amount of data can ever tell us how to choose between different superimposition methods. Furthermore, sperimposition methods explicitly depend on landmark data and ignore the geometric information about the area between landmarks [25].

3.3 Methods Based on Linear Distances

These category methods compare linear distances that connect landmark pairs in one form with the corresponding linear distances in another one. Compare each linear distance of the form matrices as a ratio, or an absolute difference or some other metric [6]. Study the matrix of linear distance comparisons to determine the difference between the forms. Examples include Euclidean Distance Matrix Analysis (EDMA) [23] and its variations [26]. The statistics of EDMA have been formally developed [27].

Drawbacks of Linear distance-based methods have been argued by researchers from different aspects [6], e.g., the loss of geometric characteristic of the surfaces between landmarks, a great deal of physical effort in landmarking, short of providing the intelligible graphics available from other methods. It has also been argued that the information contained within the form matrix is redundant [6].

4 Landmark-Free Methods

Adapting the classifying methods of Zhang [28] and Cui & Shi [29], we divide landmark-free methods into five categories, namely shape statistics-based methods, methods based on function analysis, view-based methods, topology--based methods and hybrid methods.

4.1 Shape Statistics-Based Methods

Shape statistics-based methods extract the global characteristics of 3D objects, which are applicable to compare 3D shapes on coarse granulations. They mainly describe the feature relationship between randomly selected surface vertices. Such kind of shape descriptors include shape properties such as number of vertices falling into the subdivision grid [30], weighted points set [31], Gaussian curvatures [32], Extend Gaussian Image (EGI) [33], principal axes of the tensor of inertia [34], shape distribution [35], Parameterized Statistics [7], 3D Shape Spectrum Descriptor [36], point signatures [37], etc. Wong et al. [38] introduced EGI for 3D shape comparison of heads. Because normal vectors in EGI methods are sensitive to 3D postures, researchers made improvements on EGI, e.g., Complex Extend Gaussian Image [39, 40], HEGI (Hierarchical Extended Gaussian Image) [41], and MEGI (More Extended Gaussian Image) [42]. EGI based methods need normalization before feature extraction to be rotation invariant. Since the information of the patch's area and normal vector are involved, these methods have a poor robustness correlative with noise, grid sub-division and grid reduction.

Shape statistics-based methods are simple and fast calculative. Their intrinsic randomicity results in the poor calculation stabilizations. Also it's difficult to visualize the shape characteristics. Generally speaking, curvature-based histogram is sensitive noise, histogram made up by using amount of vertices, patch area or voxel volume is sensitive to grid division of 3D object.

4.2 Methods Based on Function Analysis

Function analysis has been adopted in 3D shape comparison, e.g., Fourier analysis, moment invariants, spherical harmonics analysis and wavelet analysis, etc.

Fourier transform produces orthogonal coefficients which allows for comparatively straightforward statistical analysis. The similarity between shapes is the normalized difference between the Fourier descriptors of the shapes. Ratnaparkhi et al. [43] used the Fourier transform to model 2-D horizontal cross-sections of the human head. Dietmar and Dejan [44], Dekubgette et al [45] implemented spherical parameterization and then regularly sampling both along with longitude and woof directions. Finally they got the spherical Fourier coefficients as the feature. This spherical representation can be implemented in multi-resolution style, and not sensitive with little disturbance of the 3D object's surface. Fourier descriptor based methods ground on the well-established FFT theory and easy to implement. One disadvantage is its un-unique representation of some surface vertices. As stated by Paquet et al [46], Vranic and Saupe [47], and Elad et al. [48], Fourier descriptor is sensitive to the change of the object's edge.

Moment invariants are usually thought as one method based on function analysis as well. Several forms of invariant moments have appeared in the literatures, e.g., Zernike moments [49, 50], and Geometrical moments [48]. Moment invariants give a compact mathematical representation for shapes. One deficiency is that high order moment invariants are too sensitive with little disturbance of the 3D object's surface. Another deficiency is it's difficult to build the relationship between high order moment invariants and shape features. Finally, as shown in the works of Paquet et al [51] and Elad et al. [48], moments are sensitive to the mass distribution of object. Spherical harmonics is often deemed as 2D FFT on unit sphere [47] and introduced for form comparison [52]. The spherical harmonic coefficients can be used to reconstruct an approximation of the underlying object at different levels.

Researchers also presented some other methods based upon function analysis, e.g., wavelet transform [34, 53], Angular Radial Transform [54], 3D Radon transform [55], and Optimal 3D Hough Transform [36].

In order to get invariability to geometry transforms, PCA, e.g., Karhunen-Loeve transform, is usually adopted in most cases. However, the principal axes may not be the ideal representatives for shape differences; normalization will make the object sensitive to local distortion; and much information will be lost due to the substitution of volume features with surface features, etc.

4.3 View-Based Methods

View-based methods are based on the common sense that if two 3D objects look similar to each other from any different projection view, then they are regarded as similar. It’s believed 2D images comprise abundant information for 3D shape. Furthermore, 2D image retrieval methods have been successfully applied in many fields. This invokes some researchers to borrow such methods to 3D shape comparison. Ohbuchi et al. [56] calculated the orthogonal depth projections of a 3D object from 42 different views, and then compare the Generic Fourier Descriptors (GFD) of each projection image one by one. Chen et al [57] presented the idea of Light Fields, using side images other than margin silhouettes. They took 100 photos in 10 light fields for each 3D object from the vertices of one dodecahedron.

View-based methods are sensitive to coordinates' rotation. The robustness is related with the number and distribution of projections.

4.4 Topology-Based Methods

Topology-based methods are usually used in CAD database retrieval, e.g., Reeb graphs [58] or augmented Reeb graphs [59], shock scaffold [60] and 3D sketch [61]. Some intrinsic shortcomings of these methods include difficult to describe the genuine topology of 3D, high calculation cost, huge storage requirements, low differentiating ability between miniature shape variance, low level stabilization [62], and incompatibility for large size database [63]. What is more, 3D object must satisfy some strict conditions, e.g., connectivity. Consequently topology-based methods are scare in real application [28].

4.5 Hybrid Methods

Hybrid feature representation will combine several shape features from different aspects. For example, 3D Hough transform methods [36] convert the surface points from the Euclidean coordinate system to polar coordinates system and qualify the polar coordinates values by using histogram. Morphing-based feature methods [64] build radials starting from the origin to intersect with the surface and calculate the statistic attributes of the intersections. In order to eliminate the influence of posture, the researchers implemented FFT on the extracted features and used the Fourier coefficients as the final shape feature. Hybrid methods must be used carefully since on one hand they may materialize the advantages of one type method, on the other hand they may also enlarge the disadvantages of another type method. One important problem is how to assign the weights of different features. Bustos et al. [65] introduced Entropy Imputity in decision tree to solving the weights' assignment problem.

5 Conclusions and Future Directions

In the last decades, much progress has been made for form comparison. More than ten years ago, there were few logical criteria for choosing the optimal method. As stated by Adams et al. [2], several basic properties, including consistency, systematic bias or veracity of estimation, and statistical power, should be taken into consideration. Now a standard protocol based on Procrustes methods with various extensions has been widely accepted for most applications [2]. The development of special extensions to the selected methods has allowed addressing particular explanatory hypotheses [1], and found applications such as developmental or evolutionary trajectories, hypothetical geometries, and reconstruction of forms when landmarks are missing, etc. It is clear that techniques for form comparison deserve further attention and investigation, and they have the potential to significantly impact researches in a multitude of various fields as well. We anticipate that new exciting improvements of the aforementioned methods will continue.

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