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A comparison between Chinese and Caucasian head shapes☆

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ABSTRACT

Univariate anthropometric data have long documented a difference in head shape proportion between Chinese and Caucasian populations. This difference has made it impossible to create eyewear, helmets and facemasks that fit both groups well. However, it has been unknown to what extend and precisely how the two populations differ from each other in form. In this study, we applied geometric morphometrics to dense surface data to quantify and characterize the shape differences using a large data set from two recent 3D anthropometric surveys, one in North America and Europe, and one in China. The comparison showed the significant variations between head shapes of the two groups and results demonstrated that Chinese heads were rounder than Caucasian counterparts, with a flatter back and forehead. The quantitative measurements and analyses of these shape differences may be applied in many fields, including anthropometrics, product design, cranial surgery and cranial therapy.

1. Introduction

Knowledge of the form of the human head is essential information for a variety of fields, including design, medicine and anthropometrics (Coblentz et al., 1991; Farkas, 1994; Kouchi and Mochimaru, 2004; Meunier et al., 2000). The differences in head dimensions among various populations have been studied (Lee and Park, 2008; Yokota, 2005). It has also been suggested by both popular anecdote and traditional univariate anthropometric dimensions (Farkas, 1994) that Chinese and Western heads are different. This cultural difference has made it impossible to create eyewear, protective helmets and hygienic facemasks that fit both groups well, as shown by the recent marketing trend advertising "Asian fit" versions of high-end fashion eyeglasses. However, it has remained unknown to what extent and in precisely what way the Chinese and Western heads differ from each other in 3D shape.

Traditionally, univariate anthropometrical measurements of human body using tape and caliper were commonly taken to compare the cultural difference due to its simplicity (Farkas, 1994). Later on, digitizer (Liu et al., 1999; Wang et al., 2005) and other methods were used to collect 3D landmark coordinates which can be used for statistical shape analysis (Bookstein, 1991; Badawi-Fayad and Cabanis, 2007; Mutsvangwa and Douglas, 2007). However, the information of 1D dimension and sparse 3D landmarks could not satisfy the fitting requirements of products (Goonetilleke and Luximon, 2001; Meunier et al., 2000). In order to capture more detailed 3D geometry of human body, researchers started using CT scan (Chen et al., 2002; Niu et al., 2009) and stereophotogrammetry (Coblentz et al., 1991). Even though these 3D geometries have brought new information for anthropometry area, it has been found that the technologies could not be applied to a large number of subjects due to the procedure and difficulty of data processing. Recently, 3D laser surface imaging technology has allowed digitization to record the entire surface of the subjects as a 3D point cloud with high density (Ball and Molenbroek, 2008; Goonetilleke and Luximon, 2001; Krauss et al., 2008; Meunier et al., 2000; Robinette et al., 2002; Witana et al., 2009). The method for processing the huge amount of laser scanning data has become a new challenge for analyses.

Several surface modelling and shape description methods have been applied to 3D anthropometric data processing. In theoretical applications, geometric morphometrics have been widely used to study shape variations in biological forms in evolution (Collard and O'Higgins, 2000), paleoanthropology (Ponce de Leon and Zollikofer, 2001), and medical research (Hammond et al., 2004; Hennessy et al., 2007). Kouchi and Tsutsumi (1996) studied morphological characteristics of cross-section of 3D foot shape model to find out the relation between foot outline medial axis and 3D shape. A 3D face form using the free form deformation method was analyzed for spectacle frames design (Kouchi and Mochimaru, 2004).

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In addition, the non-uniform rational Bsplines (NURBS) method was applied to reconstruct 3D human heads (Zhang and Molenbroek, 2004). Recently, surface parameterization method has been used on 3D human body frequently (Allen et al., 2003; Xi et al., 2007; Xi and Shu, 2009). When the data is manipulated with the surface parameterization technique, a statistical shape analysis comparison can be performed on whole surfaces with dense sample of coordinates. Consistent parameterization (Xi et al., 2007; Xi and Shu, 2009) deformed a generic mesh model and fit it onto each human head scan. This method has ensured that all the parameterized models are well corresponded in 3D positions where anthropometric landmarks locate, and the other parts on the parameterized models are corresponded accordingly. As a result, the same vertices denote the same semantic position on each parameterized head model. The 3D consistent parameterization thus creates a solid basis for latter comparisons, because it represents the individual head shape in all directions and local positions consistently. This approach has been shown previously to be effective in studying the relationship between human facial dysmorphogenesis and cognitive function (Hennessy et al., 2007), 3D human shape variations within a population (Xi and Shu, 2009). Based on the theory of the method development, it will be appropriate method on statistical comparison of different populations.

Therefore, the main objective of this study is to compare the 3D shape differences between Chinese and Western heads using 3D anthropometrical data through various methods including parameterization technique, contour and landmarks. The quantitative measurements and analyses of these shape differences will help to answer practical questions in many fields, including anthropometrics, product design, cranial surgery and cranial therapy.

2. Methods

In order to compare the head shape differences between Chinese and Western population, 3D head shape data was obtained from two recent digital anthropometric databases, one representing North American and European Caucasians (CAESAR) and the other representing the Chinese (SizeChina). The parameterized models, the characteristic contour and the selected landmarks of these two data sets were processed and compared statistically.

2.1. Data acquisition

2.1.1. SizeChina database

SizeChina was the first high resolution 3D digital anthropometric survey using laser scan technology to study the size and shape of the adult Chinese head (Ball and Molenbroek, 2008). The project was inspired by the widespread perception that headgear designed using Caucasian data was unsuitable for Asian users. Using Cyberware 3030 Color 3D scanner (www.cyberware.com), SizeChina documented head data from both men and women between the ages of 18 and 70+. The scanner captured a cylinder space about 30 cm in height and 40–50 cm in diameter. The sampling pitch or scanning resolution of scanner used in SizeChina survey was 1° on theta, 0.7 mm on y (vertical) and minimum 0.1 mm on z (diameter). Scanning was conducted at six different mainland sites (Shenyang, Beijing, Lanzhou, Chongqing, Hangzhou, Guangzhou), chosen to represent a broad geographical range between north, south, east and west recording a total of more than 2000 subjects. No restrictions were placed on the height, weight or socio-economic status of volunteer subjects. Data collected from each subject included standard univariate measurements including weight, height and head dimensions; high resolution digital photographs of front and side profiles; demographic data; and the 3D digital scans.

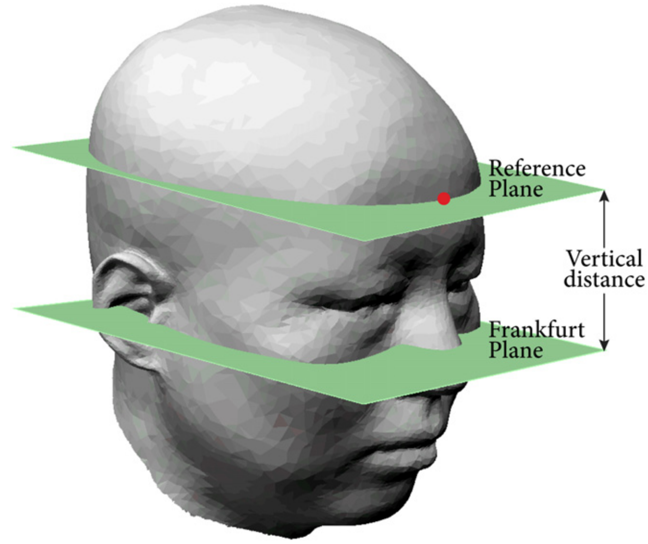

Fig. 1. Location of Reference Plane for characteristic contour.

2.1.2. CAESAR database

The Civilian American and European Surface Anthropometry Resource (CAESAR) (Robinette et al., 2002) offered an extensive 3D digital database recording scan measurements of male and female adult civilian subjects aged 18–65. CAESAR was the first large-scale anthropometric study to record 3D digital scans of body shape in addition to traditional univariate measurements and demographic data. Digital scan data recorded the geometry of body shape in full 3D space, providing a detailed and accurate description of body shape, as well as automatic consistency in data collection. The 4000

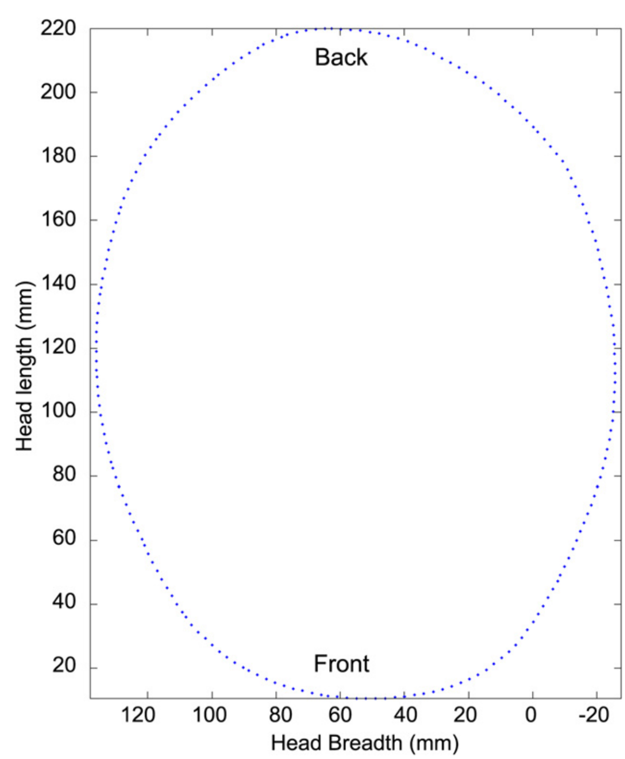

Fig. 2. An example of characteristic contour.

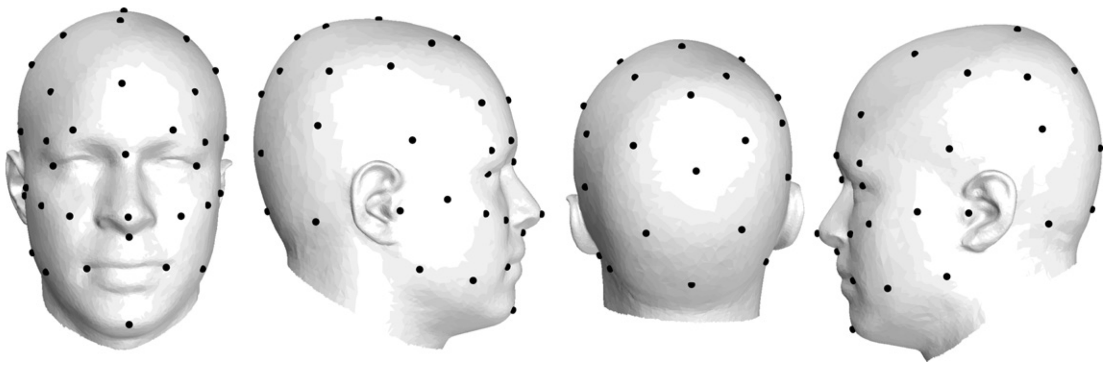

Fig. 3. The 3D landmarks for shape analysis.

individuals surveyed came from three representative NATO (North Atlantic Treaty Organization) countries: the United States of America, the Netherlands, and Italy; and were selected to cover a representative range of weight, ethnic origin, and socio-economic status. Cyberware WB4 scanner (www.cyberware.com) was used in CAESAR survey. The sampling pitch was 1.2 mm on *x* (horizontal), 2 mm on *y* (vertical) and 0.5 mm on *z* (depth).

2.1.3. Data set selection

Original individual scans were selected from both studies: 600 scans from CAESAR and 600 scans from SizeChina. Only male subjects were selected due to the large noise of head scans caused by female's hair. Since SizeChina survey was conducted at 6 locations, 100 high-quality scans from each location were randomly chosen for this study. High-quality scan meant that the data did not include a lot of error such as noise, missing data and big gap caused by the movement of the head during scanning. Selection of CAESAR scans was made by first eliminating all of the subjects who had self-identified themselves as belonging to non-Caucasian groups. Of the remaining scans, 600 high-quality scans were randomly chosen from different regions to match SizeChina sample numerically. The CAESAR 3D head data was extracted from the full body scans to general new head-only files to serve as the basis for comparison with SizeChina data set.

2.2. Data parameterization

Original head scan data from both studies required parameterization to make their results directly comparable. The 3D head data from SizeChina and CAESAR did not correspond to each other in terms of the number of data points since two different resolutions were used when collecting data. The CAESAR scans offered a lower level of data density than did the SizeChina survey. In both cases, this study made use of initial "raw" data scans. The individual "raw" data results from both studies were incomplete due to occlusions and lighting conditions that affect laser scanners. Data gaps in both sets of scans were typically found around the ears, under the nose, and at the top of the head, where "shadowing" had affected the penetration of the laser.

To eliminate the effect of the data density and scan gaps a consistent method was used to parameterize both sets of scans to the same standard, starting with the raw scan data. Using the method of Xi et al. (2007), which improved upon the method originally proposed by Allen et al. (2003) the individual raw scans were fitted onto a generic "head mesh" model obtained from the computer animation industry. The model had 11 213 vertices in total. Homologous correspondence among the models was achieved by using the anthropometric landmarks to guide the surface fitting. The fitting process was an iterative optimization, which minimized the distances between the anthropometric landmarks on the generic model and those on each scan, minimized the distances between the rest vertices and their nearest neighbors on each scan, and ensured smoothness on the deformed mesh. Taking on the dimensions of each scan, the head mesh model created "watertight" parameterized models for use in analysis.

2.3. Alignment

A Procrustes Alignment was conducted on the 3D head models from both SizeChina and CAESAR databases. Due to the computation complexity, it was unrealistic to select all 11 213 vertices for alignment. A test was completed to select the best number of vertices for doing the alignment without sacrificing much accuracy. It was found that the alignment did not generate a big difference after selecting 50 vertices. Therefore, the alignment started with randomly selecting 51 vertices on the generic head model, and applied their indices onto each parameterized 3D head model in comparison. This calculated the coordinates of a set of 51 vertices for each parameterized head model, and the sets of vertices were in a good correspondence. Then the alignment minimized the distances to the corresponding vertices on instant meshes, so as to remove the variance in head pose and position.

Table 1
The demographic information of the data from SizeChina and CAESAR.

	Number of subjects		Age (years)	Head breadth (mm)	Head circumference (mm)	Head length (mm)	Weight (kg)	Height (mm)
SizeChina	600	Mean	40	158	565	188	63.9	1668
		Std	16	7	16	7	10.2	71
		Minimum	17	133	513	163	38.0	1412
		Maximum	77	179	617	235	125.9	1933
CAESAR	600	Mean	38	154	577	199	84.8	1784
		Std	11	6	17	7	16.5	81
		Minimum	18	140	529	176	48.2	1497
		Maximum	65	184	638	219	159.9	2019

Table 2
The correlation coefficients among the demographic variables for SizeChina.

	Age	Head breadth	Head circumference	Head length	Weight	Height
Age	1					
P-value						
Head breadth	−0.268	1				
P-value	0					
Head circumference	−0.026	0.595	1			
P-value	0.520	0				
Head length	0.292	0.046	0.669	1		
P-value	0	0.263	0			
Weight	0.056	0.433	0.575	0.310	1	
P-value	0.171	0	0	0		
Height	−0.332	0.350	0.410	0.161	0.522	1
P-value	0	0	0	0.000	0	

Table 3
The correlation coefficients among the demographic variables for CAESAR.

	Age	Head breadth	Head circumference	Head length	Weight	Height
Age	1					
P-value						
Head breadth	0.234	1				
P-value	0					
Head circumference	0.050	0.569	1			
P-value	0.219	0				
Head length	−0.097	0.207	0.813	1		
P-value	0.018	0	0			
Weight	0.261	0.366	0.552	0.408	1	
P-value	0	0	0	0		
Height	−0.017	0.095	0.385	0.363	0.501	1
P-value	0.674	0.020	0	0	0	

2.4. Characteristic contour

To study the head shape variation, the upper part of the head at the level of the forehead was examined. The well-known Frankfurt Plane or Basic Plane run through roughly the center of the head, as defined by the lower points of the bony orbit of the left eye socket (infraorbitale), and the upper margin of the auditory meatus or ear canal (tragion). A horizontal section of the head taken through the Frankfurt Plane would include the upper portion of the face, showing an irregular contour. A Reference Plane, which corresponded to the standard Reference Plane of the ASTM F2220-02 Standard Specification for Headforms (American Society for Testing and Materials), was taken through the corresponding vertex just above the eyebrows and parallel to the Frankfurt Plane (Fig. 1). The same vertex on the parameterized head model gave the same meaning of the Reference Plane on the forehead for every subject. The vertical distances from this Reference Plane to Frankfurt Plane are 61.95 ± 3.05 mm (mean ± std) with minimum 52.72 mm and maximum 71.51 mm. The horizontal section of the head taken through this Reference Plane showed a highly regular contour that was characteristic of the head overall, without including the face. Software Polyworks was used to cut the section and create a simulated smooth curve for each 3D head using IMEdit module. A sampling based on the length of the curve was performed to create an equal number of vertices for each curve. This was achieved by choosing the first point to align with the front of the head and evenly sampling 200 points with the same distance on the curve. Therefore 201 points, which could be regarded as landmarks on the curve, were employed to form a characteristic contour (Fig. 2). A Procrustes superimposition on the characteristic contour was conducted for further analysis and comparison.

2.5. 3D landmarks

For further statistical analysis of the shape difference, we selected 50 landmark points across the entire head model, including the facial area (Fig. 3). The principal of landmarks selection was trying to take the anthropometric landmarks on the face and try to have other points more evenly distributed on the head as much as possible. The numbers of points were decided such that the point set provided a representative sample of the points of the model while permitting the statistical tests to remain computationally feasible.

2.6. Analysis

Three general types of analyses were undertaken on the three data sets of the parameterized models, the characteristic contours,

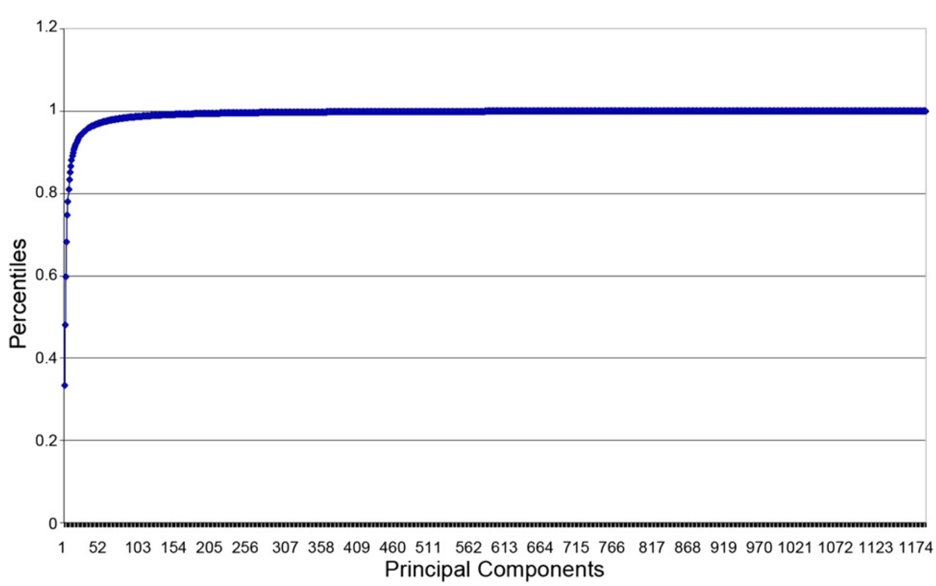

Fig. 4. Percentiles of principal components for parameterized model.

and the selected landmarks. First, three-dimensional Principal Component Analyses were performed on the dense parameterized models, to determine the principal components of the shape changes. Next, the points of the characteristic contours were superimposed by generalized Procrustes analysis to determine whether characteristic shape differences existed between the groups. Here, the probability of the differences being significant was calculated in terms of Goodall's (1991) *F* statistics using the two group subroutine of the Integrated Morphometrics Package (IMP) software (www3.canisius.edu/~sheets/morphsoft.html). Finally, Goodall's *F* statistics were calculated using the selected 3D landmarks.

3. Results

The simple statistics and correlation coefficients of the comparison between 600 scans from SizeChina and 600 scans from CAESAR are shown in Tables 1–3. The ages of all participants were between 17 and 77 years old with 39 years old in average.

3.1. 3D Principal Component Analysis on the parameterized models

Principal Component Analysis (PCA) on the parameterized dense surface data of Chinese and Western heads was performed. The number of variables entered into Principal Component Analysis depended on the number of vertices in each 3D model. In the current comparison, we used a generic model with 11 213 points for both SizeChina and CAESAR. We arranged the *x*, *y*, and *z* coordinates of each vertex into a shape vector; therefore, the dimension of the principal component (PC) was three times the number of vertices. These components were the most significant of the mathematical eigen functions that described the shape of the head. The high density data cloud was reduced into vectors by means of subspace shape analysis. These new vectors were perpendicular to each other and they were sorted in an order of their importance in representing variations within the original data set. The percentiles of all PCs are plotted in Fig. 4 and the eigen values of first 10 PCs are shown in Table 4. The first five PCs explained 74.75% shape variations. By traversing along each PC, the shape variances could be visualized (Fig. 5). Three flat-shading models, representing the shapes by selecting component weights from $-3\sigma_i$, to zero, then to $3\sigma_i$, are displayed for each component. Here the σ_i is squared root of the *i*th eigen value. In non-mathematical terms, the first PC (PC1) could be roughly described as affecting the approximate overall size or volume of the head. PC2 corresponded roughly to the overall height of the head. PC3 affected the relative proportion of the face to head, as well as the height of the cranium alone. PC4 was roughly the depth of the head from front to back. PC5 was related to jaw area and shape of the cranium. In this common PCA space, we mapped the mean Western head and Chinese head onto PCs to calculate their coordinates in the space. By doing an interpolation (and extrapolation) between the two coordinates and doing

Table 4
The eigen values and percentage of variance of first 10 principal components.

	Eigen values	% Variance
PC1	0.149522	33.36
PC2	0.065827	14.69
PC3	0.052578	11.73
PC4	0.037723	8.42
PC5	0.029341	6.55
PC6	0.01493	3.33
PC7	0.013287	2.96
PC8	0.010123	2.26
PC9	0.008045	1.80
PC10	0.007123	1.59

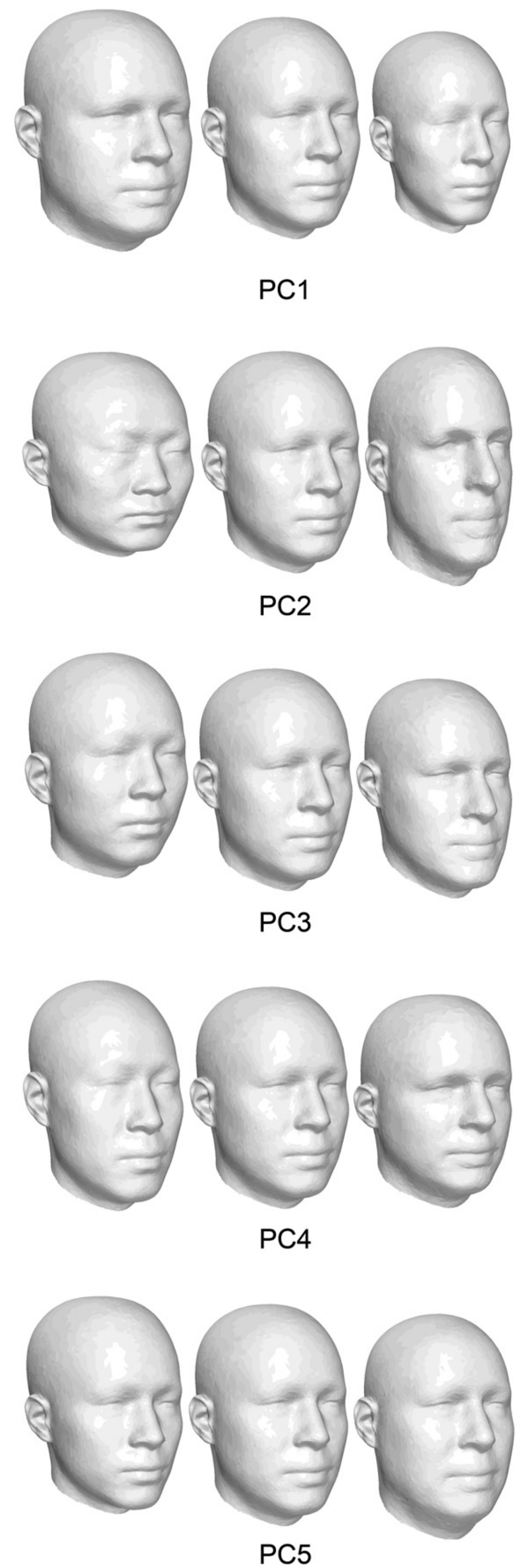

Fig. 5. Shape variations along the first five principal components.

reconstructions on 3D head mesh, a series of 3D head shapes were created for visualizing the shape differences. Fig. 6 demonstrates that the head shape changes from Chinese (round shape) to Caucasian (oval shape).

3.2. Procrustes analysis on the characteristic contours

A Procrustes superimposition of the 201 points on the characteristic contours from each of Chinese and Caucasian was performed to align all the points (Fig. 7), demonstrating the existence of a difference. In general, the Caucasian head is more oval than the Chinese head. To establish the probability of the difference being chance, Goodall's F test was performed with results of F value (264.24) and $P < 0.0001$, which showed that the chance that the two populations were the same was extremely low. The high level of difference was further confirmed by the results of the Canonical Variate Analysis (CVA) shown in Fig. 8. The CVA could simplify the difference descriptions among groups (Zelditch et al., 2004). It started with a PCA of within-group variances and created a new coordinate system in which the groups of variables were redefined. A rescaling on the coordinate system was done in proportion to within-group variances in the original space. A new direction was calculated in which groups of data tended to be farthest by performing a PCA on the group centroids. The axis produced by this computation was called Canonical Variates (CVs).

Procrustes superimposition calculated the mean contours of Chinese and Caucasian heads. Since the two mean contours were corresponded, a vector representing the distance between two corresponding vertex could be calculated and labeled. The vector plot in Fig. 9 illustrates the shape differences between two groups at each of the 201 points. The mean contour of Chinese is drawn as the basic contour, and the vectors labeled on the points represent distance vectors which correspond to the points on the mean contour of Caucasian. We found that the contours can be represented with a simple model that consisted of an ellipse at the back of the head and a circle in the front. Fig. 10 shows this model fitted to the mean shapes of the two populations. In this fitting, each contour could be represented by three coefficients: radius of the circle, long (A) and short (B) radius of the ellipse. By plotting each contour into a new coordinate space, Fig. 11 displays the difference between the two groups and the variation inside each group with the radius of front circle against the ratio of the long and short radius of the ellipse (A/B). This confirmed the anecdotal observations and traditional univariate anthropometric dimensions (NASA, 1978) of the head shape differences.

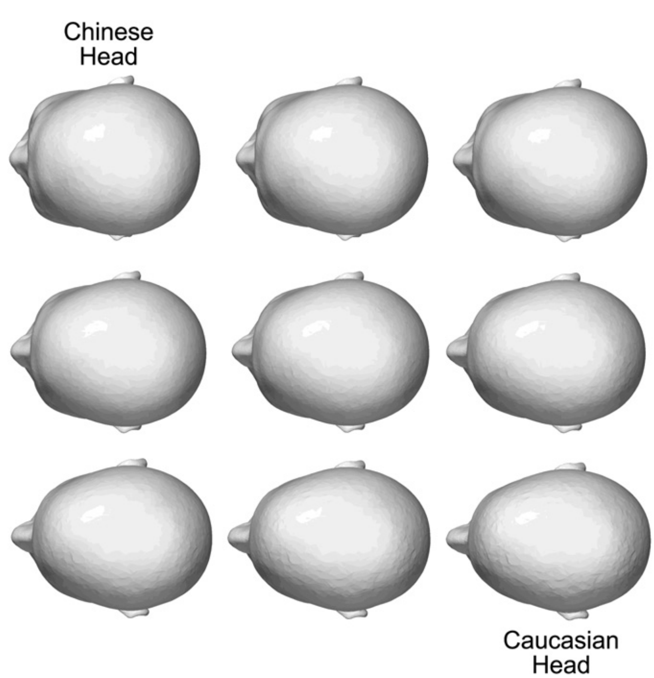

Fig. 6. The demonstration of differences between Chinese head and Caucasian head.

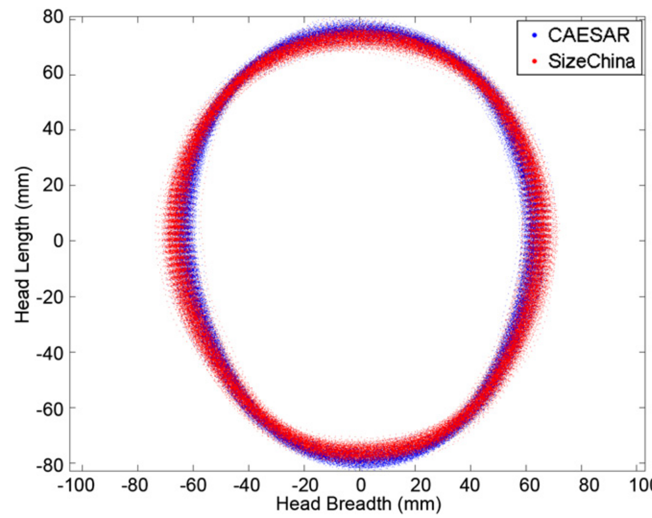

Fig. 7. Scatter plot of characteristic contour after general Procrustes analysis.

3.3. Geometric morphometric analysis on 3D landmarks

In a final comparison of the differences between the two populations, we performed geometric morphometric analysis using the 50 selected 3D landmarks. Analysis of three-dimensional configurations of landmarks was performed within the same theoretical framework as analysis of two-dimensional configurations (Zelditch et al., 2004). The software "Simple3D" in the IMP package was used to take raw data of landmarks, perform Procrustes superimposition, compute centroid size, and perform Goodall's F test for significant differences between two groups. Goodall's F test ($F = 186.24$, $P < 0.0001$) indicates that the two populations are different. The permutation version (with 1600 permutations) of Goodall's F test resulted in the same F value.

4. Discussion

Formal research into univariate anthropometric differences between different ethnic populations is long overdue. New

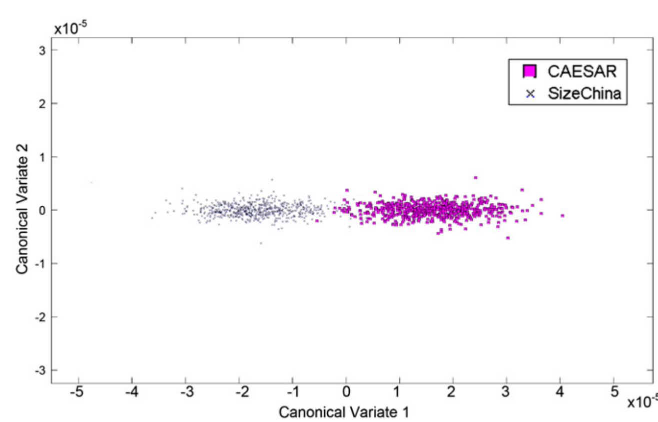

Fig. 8. Canonical Variate Analysis (CVA) for characteristic contour.

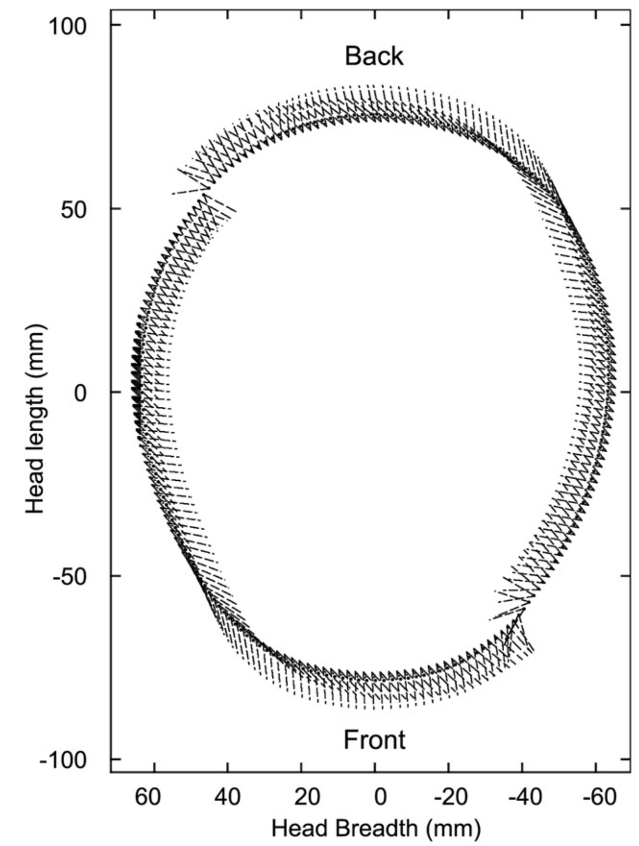

Fig. 9. Vector plot of the contour differences between Chinese and Caucasians.

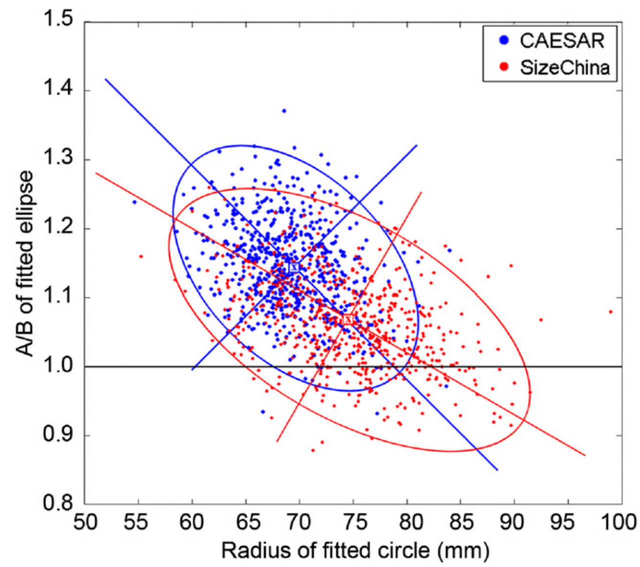

Fig. 11. The plot of the A/B of ellipse and radius of circle from the fitting models for all contours.

technology has brought a complete new area for 3D anthropometry studies. High resolution laser scanning system provides massive and accurate 3D surface information which enables more detailed 3D comparisons than univariate measures typically including only head length, width and circumference. Through data parameterization from 3D head scans obtained from the two recent anthropometric surveys CAESAR and SizeChina, we were able to compare the two populations using 3D parameterized head model, characteristic contour and 3D landmarks in this study. Statistical comparisons of the 3D scan data confirmed that there was a significant morphological difference between the shape of the Caucasian head and the shape of the Chinese head. This difference was revealed through Procrustean and Goodall's *F* analysis of data from the two surveys, as illustrated with visual schematics and scatter graphs. The results were consistent with univariate measures in the literature (Farkas, 1994). However, the measures from this study were slightly larger than traditional univariate measures. The differences might be caused by non-contact measure (the laser scanning technology) and contact measure (traditional caliper). More attention will need to be paid in product design process when using the measures from different techniques.

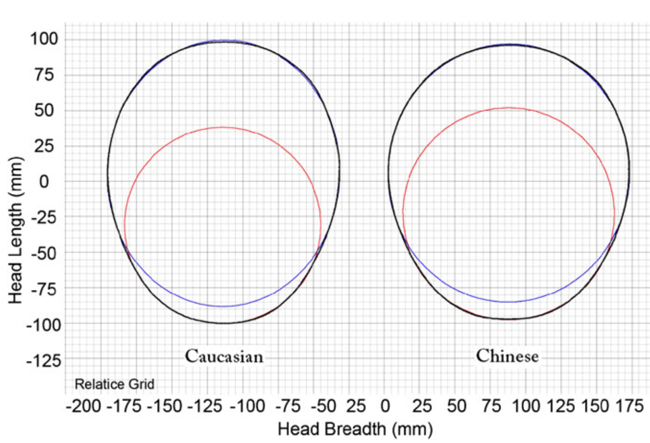

Fig. 10. A model with an ellipse and a circle fitted to the mean contours of Chinese and Caucasians.

The findings of this study explain why headgear designed using Caucasian anthropological head shape data has never been able to enjoy success in Asian markets. With access to SizeChina data, Western designers can now begin to meet the needs of Asian clients in head related products for the first time. The 3D standard head form for Chinese should be used in order to achieve better performance and satisfaction especially for the products such as helmets which requires small tolerance and high performance.

Further understanding of head shape differences between populations will require a concerted multi-disciplinary effort, offering insight into both practical and theoretical areas. In combination with genetics, evidence of physical differences may help to trace the origin of different ethnic groups. Combined with anthropology, shape data can offer insight into whether head differences relate to social customs or environmental factors.

5. Conclusion

Head shape is an important anthropometric variable, relevant to the fields of biology, medicine and design. Using a large digital data set taken from two recent 3D anthropometric surveys (SizeChina and CAESAR), we show significant statistical variations between head shapes of Chinese and Caucasians. We applied geometric morphometrics to the dense surface data to quantify and characterize the shape differences. The comparison shows that Chinese heads can be generally characterized as rounder than their Western counterparts, with a flatter back and forehead. The findings of this study show that head related products such as headgear designed using Western anthropological head shape are not appropriate for the Chinese head. Designers and manufactures have to understand more the disparity and build new standards for different populations in order to achieve better fitting and performance.

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References

Allen, B., Curless, B., Popovic, Z., 2003. The space of human body shapes: reconstruction and parameterization from range scans. ACM Transactions on Graphics (ACM SIGGRAPH 2003) 22 (3), 587–594.
Badawi-Fayad, J., Cabanis, E., 2007. Three-dimensional Procrustes analysis of modern human craniofacial form. The Anatomical Record 290, 268–276.
Ball, R.M., Molenbroek, J.F.M., 2008. Measuring Chinese heads and faces. In: Proceedings of the Ninth International Congress of Physiological Anthropology, Human Diversity: Design for Life. Delft, The Netherlands, pp. 150–155.
Bookstein, F.L., 1991. Morphometric Tools for Landmark Data. Cambridge University Press, Cambridge.
Chen, X., Shi, M., Zhou, H., Wang, X., Zhou, G., 2002. The "standard head" for sizing military helmet based on computerized tomography and the headform sizing algorithm. Acta Armamentarii 23 (4), 476–480 (in Chinese).
Coblentz, A., Mollard, R., Ignazi, G., 1991. Three-dimensional face shape analysis of French adults, and its application to the design of protective equipment. Ergonomics 34 (4), 497–517.
Collard, M., O'Higgins, P., 2000. Ontogeny and homoplasy in the papionin monkey face. Evolution and Development 3, 322–331.
Farkas, L.G., 1994. Anthropometry of the Head and Face. Raven Press, New York, NY, USA.
Goodall, C., 1991. Procrustes methods in the statistical analysis of shape. Journal of the Royal Statistical Society 53 (2), 285–339.
Goonetilleke, R.S., Luximon, A., 2001. Designing for comfort: a footwear application. In: Das, B., Karwowski, W., Mondelo, P., Mattila, M. (Eds.), Proceedings of the Computer-Aided Ergonomics and Safety Conference (Plenary Session, CD-ROM), 28 July–2 August 2001, Maui, Hawaii.
Hammond, P., Hutton, T., Allanson, J., Campbell, I., Hennekam, R., Holden, S., Patton, M., Shaw, A., Temple, I.K., Trotter, M., Murphy, K., Winter, R., 2004. 3D analysis of facial morphology. American Journal of Medical Genetics 126A (4), 339–348.
Hennessy, R., Baldwin, P., Browne, D., Kinsella, A., Waddington, J., 2007. Three-dimensional laser surface imaging and geometric morphometrics resolve frontonasal dysmorphology in schizophrenia. Biological Psychiatry 61, 1187–1194.
Kouchi, M., Mochimaru, M., 2004. Analysis of 3D face forms for proper sizing and CAD of spectacle frames. Ergonomics 47 (14), 1499–1516.
Kouchi, M., Tsutsumi, E., 1996. Relation between the medial axis of the foot outline and 3-D foot shape. Ergonomics 39 (6), 853–861.
Krauss, I., Grau, S., Mauch, M., Maiwald, C., Horstmann, T., 2008. Sex-related differences in foot shape. Ergonomics 51 (11), 1693–1709.
Lee, H.J., Park, S.J., 2008. Comparison of Korean and Japanese head and face anthropometric characteristics. Human Biology 80 (3), 313–330.
Liu, W., Miller, J., Stefanyshyn, D., Nigg, B.M., 1999. Accuracy and reliability of a technique for quantifying foot shape, dimensions and structural characteristics. Ergonomics 42 (2), 346–358.
Meunier, P., Tack, D., Ricci, A., Bossi, L., Angel, H., 2000. Helmet accommodation analysis using 3D laser scanning. Applied Ergonomics 31 (4), 361–369.
Mutsvangwa, T., Douglas, T.S., 2007. Morphometric analysis of facial landmark data to characterize the facial phenotype associated with fetal alcohol syndrome. Journal of Anatomy 210 (2), 209–220.
NASA reference publication 1024, 1978. Anthropometric Source Book. In: Anthropometry for Designers, vol. 1.
Niu, J., Li, Z., Salvendy, G., 2009. Multi-resolution description of three-dimensional anthropometric data for design simplification. Applied Ergonomics 40 (4), 807–810.
Ponce de Leon, M., Zollikofer, C., 2001. Neanderthal cranial ontogeny and its implications for late hominid diversity. Nature 412, 534–538.
Robinette, K., Blackwell, S., Daanen, H., Fleming, S., Boehmer, M., Brill, T., Hoeferlin, D., Burnsides, D., 2002. Civilian American and European Surface Anthropometry Resource (CAESAR). Final Report. In: Summary, AFRL-HE-WP-TR-2002-0169, vol. I. Air Force Research Laboratory, Human Effectiveness Directorate, Bioscience and Protection Division, 2800 Q Street, Wright-Patterson, AFB OH 45433-7947.
Wang, X., Zheng, W., Liu, B., Wang, R., Xiao, H., Ma, X., 2005. Study on 3-dimentional digital measurement of face form in fighter pilots. Chinese Journal of Aerospace Medicine 16 (4), 258–261 (in Chinese).
Witana, C.P., Goonetilleke, R.S., Xiong, S., Au, E.Y.L., 2009. Effects of surface characteristics on the plantar shape of feet and subjects' perceived sensations. Applied Ergonomics 40 (2), 267–279.
Xi, P., Shu, C., 2009. Consistent parameterization and statistical analysis of human head scans. The Visual Computer 25 (9), 863–871.
Xi, P., WonSook, L., Shu, C., 2007. Analysis of segmented human body scans. Proceedings – Graphics Interface, 19–27.
Yokota, M., 2005. Head and facial anthropometryof mixed-race US Armymale soldiers for militarydesign and sizing: a pilot study. Applied Ergonomics 36, 379–383.
Zelditch, M., Swiderski, D., Sheets, D.H., Fink, W., 2004. Geometric Morphometrics for Biologists. Academic Press, New York and London.
Zhang, B., Molenbroek, J.F.M., 2004. Representation of a human head with bi-cubic B-splines technique based on the laser scanning technique in 3D surface anthropometry. Applied Ergonomics 35 (5), 459–465.