The 3D Chinese head and face modeling
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A R T I C L E   I N F O

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A B S T R A C T

Perfect fit for people has always been a target for product design. Designers commonly use traditional anthropometric dimensions for 3D product design thus creating a lot of fitting problems when dealing with the complexities of human body shapes. The development of recent 3D anthropometric survey has created an opportunity for complex shape analysis on human model by collecting 3D scan data. Using 3D point cloud data from the SizeChina survey, a methodology of creating a homologous 3D head and face model was demonstrated in this study. Anatomical and virtual landmarks, and surface modeling algorithm based on point cloud data were applied in building the model. The head and face models for all scans had the same amount of vertices with consistent features. The average Chinese models showed obvious differences between male and female. The variations of head and face shapes were analyzed using Principal Component Analysis and the results showed that the largest variations among people were general size, especially for width and depth. However face height, forehead, back of the head, chin and jaw area were also important when describing the 3D shape. The results from this study may be useful in the design of head and facial products.

1. Introduction

The human head and face houses many important organs and sensors including brain, eyes, nose, mouth and ears for life support and information processing. A multitude of medical or information display products are designed to wear on the head and face. Studies of the anthropometric variations among people's heads and faces [1,2] are not new. Traditional anthropometry uses numerical dimensions to describe the shape and provide references for product design [1,3,4]. Calipers and tapes are commonly applied directly on human heads and faces, as well as photography is used for taking measurements [1,3,5,6]. A recent survey of the head and face of Chinese workers [7,8] used facial dimensions collected by traditional techniques for respirator design. However manual measurements have many drawbacks such as time consuming procedures and low reliability. More importantly, the numerical dimensions do not satisfy the current product design practice which requires more complex geometry of the human head and face. Health and safety products like motorcycle helmets, head-mounted displays and surgical masks, require a highly accurate fit between the product’s shape and the surface of the human head and face [9]. With the development of computer-aided design software such as Alias and Rhino, product designers are venturing into complex surface and curve development during the design process. These designers need an accurate representation of the human head and face, not only the average shape but also the variations. An accurate and detailed 3D human head and face model is needed by industry in order to design better fit and safer products.

The 3D modeling of the human body has progressed rapidly in recent years with the fast development of the computer technology. More and more new algorithms have been applied to achieve flexible and realistic human models in the simulation and animation area [10–12]. Some researchers used feature based models or landmark-free models to create parameterized human body or head models [10,13,14]. The non-uniform rational B-splines (NURBS) method was applied to reconstruct the 3D human heads [15]. The methods of fitting a template or generic model to scan data have also been proposed [16–18]. However, they did not specify the accuracy of the model and the methods were comparatively complex. Most of these methods were not aiming to create a parametric model for anthropometric purpose. Therefore, the 3D features of one person might not correspond to another one in detail. In this case, the model could not be used for statistical analysis. In addition, most of these studies were based on few human scans and did not provide very useful statistical results. Thus the models could not represent the population variations. Other researchers have created a 3D model from landmarks to analyze the face shape and to evaluate the fit of spectacle frames [19]. Homologous shape modeling method was applied [19] and the model provided consistent statistical shape information. However, this model was only for spectacle frames test and there was a lack of 3D details due to the digitizing technology used.
A method that can accurately represent 3D head and face shape with corresponding anatomical features is needed.

The recent development of 3D laser scanning technology provides an opportunity to create a more accurate human model for product design and evaluation. High resolution 3D scans record a massive amount of detailed geometrical information of the human body shape. Studies have tried to build human models using several large-scale scan databases including the Civilian American and European Surface Anthropometry Resource (CAESAR) project, the University of South Florida (USF) Human ID 3D database and the National Institute of Occupational Safety and Health (NIOSH) head and face database [20–24]. However, only a few small scale 3D scan surveys have focused on the Chinese population. Computerized Tomography (CT) technology and digitizer were applied to capture the 3D head shape [25,26]. These surveys had relatively low resolution compared to high density laser scans therefore the data was not suitable to build a highly accurate model. In addition, their participants were mainly adult males in the military which did not cover a broad cross-section of the Chinese population. Designing products for the Asian market, especially China, has become a strategic plan for many international enterprises. But the accurate and advanced head and face models have not been built for the Chinese.

The objective of this study is to develop an accurate 3D head and face model for the Chinese and provide meaningful statistical results of 3D head and face shapes. The procedure of model development is presented (Fig. 1). The accuracy of the model is calculated and applications on product design is discussed.

2. Methodology

2.1. Data collection

In order to create an accurate head and face model for the Chinese, the head 3D information has to be collected first. Therefore, the SizeChina anthropometric survey was conducted and high resolution laser scanning technology (Cyberware 3030 Color 3D scanner) was applied to create a first 3D head digital database of Chinese population [27,28]. The scanning resolution or sampling pitch of scanner set in the survey was 1° on theta, 0.7 mm on the vertical axis and a minimum 0.1 mm on diameter (www.cyberware.com). Before scanning, an expert put fourteen landmarks physically on participant’s face in order to identify the critical bone structure for further processing. There was a nylon wig cap fitted to each participant’s head in order to flatten the hair and allow the scanner to record the head shape more accurately. The scanning takes 17 s and the 3D shape was captured as point cloud data automatically through the scanner (Fig. 2). In total, 144 participants’ scans which included 72 males and 72 females all aged from 18 to 30 years old were selected randomly and processed to create Chinese head and face 3D model in this study.

2.2. Model construction

2.2.1. Data preprocessing

Since the original laser scan data has some extra data points or missing data on top of the head, nose holes and ear region, these noise data points were cleaned and the holes were filled with a “curvature” function based method in Rapidform2006 software (www.rapidform.com) before further data processing (Fig. 3). Let us assume that S represents the head and face surface. Then $H_S \subset S$, is a set of estimated points on the surface of the head and face. The elements of $H_S$ are the points $P_{Si} = \{(X_{Si}, Y_{Si}, Z_{Si}) | i = 1, \ldots, N_p\}$.

2.2.2. Data alignment

Since the coordinates of point cloud data for different subjects might not be consistent due to head rotation and shifts from subject to subject, the point cloud data was aligned based on the plane created by three reference points (Left infraorbitale; left tragion; right tragion) using programs written in Matlab (Fig. 4). The plane is called the Frankfurt plane which is the XY-plade after alignment. All points $P_{Si}$ were first translated to the new zero point which is located at the midpoint of left and right tragiens. Then two rotations were performed along Z and Y axes so that the left and right tragiens lie along the X axis. The last rotation was carried out along the X axis so that left infraorbitale lie on the XY-plane. After data alignment, the data was transformed, let $H_i$ represents the scanned head and face data points. The alignment procedure transformed all points $P_{Si}$ in $H_S$ into the set $H_i$ with new elements $P_{Ai} = \{(X_{Ai}, Y_{Ai}, Z_{Ai}) | i = 1, \ldots, N_p\}$.

2.2.3. Landmarks selection

Since the human features vary from person to person, landmarking is a common method for data representation [19,29]. Researchers have tried to locate features automatically but the accuracy and reliability of these methods still need to be tested [30, 31]. In order to create a consistent head and face model landmarks were selected in this study.

Anatomical landmarks were first picked up manually in Rapidform2006 software. These landmarks include fourteen manually-marked landmarks and forty physical landmarks (Fig. 5). Manually-marked landmarks are the landmarks which were put on each subject’s face before scanning, while physical landmarks are selected from the face after scanning. Manually-marked landmarks are Chin, Glabella, Frontotemporale (left and right), Infraorbitale (left and right), Pronasale, Sellion, Tragion (left and right), Zygofrontale (left and right) and Lateral zygomatic (left and right). The selection of the landmarks was mainly based on the study of anthropology and head-and-face survey [21,27]. $H_i$ represents the landmark set with $N_i$ number of
landmarks. Let \( P_{Li} = \{ (X_{Li}, Y_{Li}, Z_{Li}) | i = 1, \ldots, N_i \} \) represent the landmarks in \( H_i \). \( H_M \subset H_i \) represents the anatomical (Manually-marked and Physical landmarks) with elements \( P_{M} = \{ (X_{M}, Y_{M}, Z_{M}) | i = 1, \ldots, 54 \} \).

\[
\begin{align*}
\theta_{Li} &= a \tan 2(Y_{Li}, X_{Li}) \\
\varphi_{Li} &= a \tan 2(Z_{Li}, \sqrt{X_{Li}^2 + Y_{Li}^2}) \\
r_{Li} &= \sqrt{X_{Li}^2 + Y_{Li}^2 + Z_{Li}^2}
\end{align*}
\]

where \( i = 1, \ldots, N_i \). (1)

In order to obtain the whole head shape, virtual landmarks were sampled on the head’s surface besides the anatomical landmarks. These landmarks are also called mathematical landmarks and Pseudo landmarks [32]. This is essential since we did not have anatomical landmarks on the forehead and the head surface. In order to create virtual landmarks, a surface \( S_i \) was created. Trials on parameterization of the surface based on spherical, cylindrical and Cartesian coordinate system have indicated that a spherical coordinate transformation and surface fitting for the head and face is sufficiently accurate for product design.

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Therefore, the coordinates \( (X_{Li}, Y_{Li}, Z_{Li}) \) of aligned points \( P_{Li} \) were transformed into spherical coordinates \( (\theta_{Li}, \varphi_{Li}, r_{Li}) \) using Eq. (1).

A smooth surface \( S_i \) was generated using the griddata function in Matlab with triangle-based cubic interpolation method [33]. The \( r \) value of any point on the surface \( S_i \) is determined by \( r = f(\theta, \varphi) \). The 130 virtual landmarks were chosen to have distributed sampled points at the cheeks, top head and front neck area (Fig. 6). \( H_M \subset H_i \) represents the virtual landmarks with elements \( P_{ML} = \{ (\theta_{ML}, \varphi_{ML}, r_{ML}) | i = 1, \ldots, 130 \} \).

The anatomical landmarks mainly represent the facial features while the virtual landmarks represent the forehead and head features. The reason to have more landmarks on cheeks was that this area has relatively fewer anatomical landmarks. Since the hair had large noise, the virtual landmarks were sampled only above the Frankfurt plane at the back of the head. In this study the region was not separated, hence for all further analyses the landmarks are not differentiated.

In the spherical coordinate system the landmarks are represented as \( P_{Li} = \{ (\theta_{Li}, \varphi_{Li}, r_{Li}) | i = 1, \ldots, N_i \} \). \( N_i = 130 + 54 = 184 \).

2.2.4. Triangulation and subdivision

Triangulation was executed to create a simple model first based on the landmarks. Then triangular subdivision was performed to form the detailed model. In order to have a consistent triangular mesh among all participants, the average landmark position was calculated based on all the 144 participants. The new set \( H_{MS} \) representing the average landmarks \( P_{LM} = \{ (\theta_{LM}, \varphi_{LM}, r_{LM}) | i = 1, \ldots, N_i \} \) in the spherical domain. Delaunay triangulation was used [33]. After Delaunay triangulation, some modifications were done manually to make symmetrical triangles for left and right sides of the face. These triangles are called first-level triangles. The same triangular mesh was used for all participants. Since the landmark set \( H_i \) does not accurately represent the head and face surface \( S \), triangular subdivision was carried out for each participant’s face.

Fig. 7 shows an example of triangular subdivision algorithm based on landmarks \( P_{25}, P_{26} \) and \( P_{28} \). \( P_{M1}, P_{M2} \) and \( P_{M3} \) are the middle points of three edges of triangle. \( P_{MC} \) is the center point of the triangle. By connecting all these points together, one triangle is subdivided into six second-level triangles (Fig. 7). The \( \theta, \varphi \) and \( r \) values for \( P_{M1}, P_{M2} \) and \( P_{M3} \) and \( P_{MC} \) can be calculated based on Eq. (2). The same hierarchy procedure can be completed for each of the second-level triangles to form six third-level triangles in order to obtain more points. The new points together with landmarks make up the vertices \( V_i = \{ (\theta_{Vi}, \varphi_{Vi}, r_{Vi}) | i = 1, \ldots, N_i \} \) of the head surface model \( S_i \) (Fig. 8). Here \( N_i \) represents the number of total vertices on \( S_i \). When three-level triangles are applied, the number of total vertices is 5821. Once all vertices were sampled, the spherical coordinates \( \theta, \varphi \) and \( r \) were transformed back to \( X, Y, Z \) coordinates \( V_i = \{ (X_{Vi}, Y_{Vi}, Z_{Vi}) | i = 1, \ldots, N_i \} \) by using Eq. (3).

\[
\begin{align*}
\theta_{M1} &= (\theta_{25} + \theta_{26})/2; \quad \varphi_{M1} = (\varphi_{25} + \varphi_{26})/2; \\
\theta_{M2} &= (\theta_{26} + \theta_{28})/2; \quad \varphi_{M2} = (\varphi_{26} + \varphi_{28})/2; \\
\theta_{M3} &= (\theta_{25} + \theta_{28})/2; \quad \varphi_{M3} = (\varphi_{25} + \varphi_{28})/2; \\
\theta_{MC} &= (\theta_{25} + \theta_{26} + \theta_{28})/3; \quad \varphi_{MC} = (\varphi_{25} + \varphi_{26} + \varphi_{28})/3; \\
r_{MC} &= f(\theta_{MC}, \varphi_{MC})
\end{align*}
\]

\[
\begin{align*}
X_{Vi} &= r \cos(\varphi_{Vi}) \cos(\theta_{Vi}) \\
Y_{Vi} &= r \cos(\varphi_{Vi}) \sin(\theta_{Vi}) \quad \text{where } i = 1, \ldots, N_i. \\
Z_{Vi} &= r \sin(\varphi_{Vi})
\end{align*}
\]
2.3. Accuracy of model

The same modeling method was applied to process all the 144 Chinese head scans. The modeling error was calculated for each scan based on the shortest distance from all vertices in the head model \( S_M \) to the aligned point cloud data \( H_A \) [34]. For a given vertex \( V_k(\mathbf{X}_k, \mathbf{Y}_k, \mathbf{Z}_k) \), the shortest distance \( e_k \) was defined by Eq. (4). The average error distribution maps for male and female are displayed in Fig. 9. In general, the error was less than 1 mm and the average was 0.65 mm. The maximum error was found at the ear area since there was a lot of missing data at back of ears due to scanner limitations (Fig. 9).

\[
e_k = \min \left\{ \sqrt{(X_i - X_k)^2 + (Y_i - Y_k)^2 + (Z_i - Z_k)^2} \right\}
\]

where \( i = 1, \ldots, N_P \).

3. The 3D shape analysis

Since all vertices of the model for every scan have same anatomical or morphological meaning, the statistical analysis can be performed to create a general model and analyze the individual differences. Principal Component Analysis (PCA) was performed for male and female separately to find the largest variance among the individuals [18]. The input variables were the shape variables \((x, y, z)\) coordinates from all vertices. Eigenvalues, loading matrix and scores for principal components (PCs) were calculated. The PC scores were translated back into the shape variables through Eq. (5) by applying the PCA algorithm [35]. When all the cells of \( B \) are zero, \( D \) represents the average shape. If the value of one cell of \( B \) is changing but all the other cells are kept zero, the change of \( D \) will demonstrate the variation along that principal component axis.

\[
D = \overline{D} + EB
\]

where \( D \) is the new set of 3D coordinates of vertices; \( \overline{D} \) is the average 3D coordinates of vertices; \( E \) is the PC loading matrix; \( B \) is a column vector for each PC score.

After PCA analysis, a separate average male model and an average female model based on all vertices is displayed in Fig. 10. The head height, head width, head depth, face height, face width, mandible width, nasion depth and chin depth are computed and displayed in Table 1. The definition of these measurements can be referred to Table 1. The overall size of the average male head and face is larger than the average female’s head, especially in terms of head height, head depth and mandible width measurements.

For males, the first four PCs contained 63.09% of the total variation (PC1: 29.99%; PC2: 18.60%; PC3: 9.36%; PC4: 5.15%). The eigenvector loadings of males for PC1, PC2, PC3 and PC4 are shown in Fig. 11(a). The grey scale shows the loading values at different locations for that principal component. The PC1 is related to all the regions with the chin region having a high relative loading. The PC2 is associated to the head and chin region. The PC3 is related to the back of the head region and the jaw region. The PC4 is mainly related to the frontal and menton regions (under the chin). For females, the first four PCs contained 63.78% of the total variance (PC1: 32.10%; PC2: 17.19%; PC3: 8.50%; PC4: 5.99%). The eigenvector loadings of females for PC1, PC2, PC3 and PC4 are shown in Fig. 11(b). The loading distributions of females are similar but not same as that of males. The PC1 is associated to all the regions especially for the chin region. The PC2 is mainly related to the top of the head and chin and menton region. The PC3 is related to back of head and front face region. The PC4 is mainly related to frontal and menton region.

In order to visually view the amount of variations for each PC more clearly, the change of males’ head and face shapes are displayed in Fig. 12 using Eq. (5). The values of first four cells of \( B \) were set one by one from negative three standard deviations \((-3 \text{ Std})\), zero, and positive three standard deviations \((+3 \text{ Std})\). The variation of PC1 in Fig. 12 demonstrates that the general size of head and face give the largest difference among people. The head and face width and depth changes more than height (Table 1). With
the head width and head depth decreasing, people’s face width reduces and become a triangular face (small mandible width) and receding chin (small chin depth). The variation of PC2 has shown that the head height and width changes from large to small, but the face changes from receding chin to a prominent chin shape. The variation of PC3 demonstrates that a longer face has a square jaw but smaller head depth. The variation of PC4 displays that the forehead changes from forward to backward and menton and the jaw region becomes plumper.

Similarly, the variations for the first four PCs for the female are displayed in Fig. 13 using Eq. (5). The variation of PC1 demonstrates the general size of head and face changes from large to small, especially for head and face width and depth (Table 1). The variation of PC2 is mainly related to the head and face height. The head and face changes from very long to a very short shape. The variation of PC3 shows the head changes from small head depth with large face depth to the large head depth with small face depth. The variation of PC4 demonstrates that the menton region becomes plumper and face height increases when the forehead changes from forward to backward.

4. Discussion and conclusion

The human head and face have large variations among the population and within the population. Without any design tools, designers commonly use traditional 1D anthropometric dimensions in the 3D design process. This has resulted in a lot of fitting problems. On the other hand, due to advances in scanning technology 3D human modeling is becoming widespread. Although there are plenty of algorithms for digital human modeling, most studies focused on simulation and animation and are unable to provide statistical information for product design.

Table 1
The univariate measurements for PCA results (mm).

<table>
<thead>
<tr>
<th></th>
<th>Head height</th>
<th>Head width</th>
<th>Head depth</th>
<th>Face height</th>
<th>Face width</th>
<th>Mandible width</th>
<th>Nasion depth</th>
<th>Chin depth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Male Average</strong></td>
<td>243.29</td>
<td>172.50</td>
<td>199.17</td>
<td>129.96</td>
<td>154.44</td>
<td>133.90</td>
<td>96.71</td>
<td>88.93</td>
</tr>
<tr>
<td>PC1 (−3 Std)</td>
<td>248.96</td>
<td>187.57</td>
<td>219.13</td>
<td>133.93</td>
<td>171.56</td>
<td>150.92</td>
<td>108.80</td>
<td>112.20</td>
</tr>
<tr>
<td>PC1 (+3 Std)</td>
<td>237.61</td>
<td>157.42</td>
<td>179.22</td>
<td>125.98</td>
<td>137.31</td>
<td>116.89</td>
<td>84.63</td>
<td>65.66</td>
</tr>
<tr>
<td>PC2 (−3 Std)</td>
<td>264.55</td>
<td>186.80</td>
<td>210.39</td>
<td>135.42</td>
<td>162.10</td>
<td>138.48</td>
<td>100.84</td>
<td>75.38</td>
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<tr>
<td>PC2 (+3 Std)</td>
<td>222.02</td>
<td>158.20</td>
<td>187.96</td>
<td>124.49</td>
<td>146.77</td>
<td>129.33</td>
<td>92.58</td>
<td>102.49</td>
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<tr>
<td>PC3 (−3 Std)</td>
<td>240.59</td>
<td>175.46</td>
<td>200.15</td>
<td>127.81</td>
<td>154.95</td>
<td>132.33</td>
<td>103.20</td>
<td>85.25</td>
</tr>
<tr>
<td>PC3 (+3 Std)</td>
<td>245.98</td>
<td>169.53</td>
<td>198.20</td>
<td>132.11</td>
<td>153.48</td>
<td>135.48</td>
<td>90.23</td>
<td>92.61</td>
</tr>
<tr>
<td><strong>Female Average</strong></td>
<td>232.24</td>
<td>165.15</td>
<td>188.18</td>
<td>121.12</td>
<td>146.94</td>
<td>121.47</td>
<td>90.61</td>
<td>83.25</td>
</tr>
<tr>
<td>PC1 (−3 Std)</td>
<td>239.20</td>
<td>182.13</td>
<td>209.67</td>
<td>121.94</td>
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<td>137.90</td>
<td>102.27</td>
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<tr>
<td>PC1 (+3 Std)</td>
<td>225.28</td>
<td>148.18</td>
<td>166.70</td>
<td>120.30</td>
<td>130.09</td>
<td>105.03</td>
<td>78.96</td>
<td>62.18</td>
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<td>257.91</td>
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<td>230.85</td>
<td>168.86</td>
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<tr>
<td>PC4 (+3 Std)</td>
<td>233.63</td>
<td>161.45</td>
<td>190.82</td>
<td>127.96</td>
<td>146.81</td>
<td>122.47</td>
<td>87.41</td>
<td>86.89</td>
</tr>
</tbody>
</table>

Note:
- Head height: distance in Z axis from head top to Menton.
- Head width: widest distance in X axis for upper head.
- Head depth: distance in Y axis from Glabella to the most posterior point of head back.
- Face height: distance in Z axis from Nasion to Menton.
- Face width: distance in X axis from Zygion left to Zygion right.
- Mandible width: distance in X axis from Gonial left to Gonial right.
- Nasion depth: distance in Y axis from Nasion to Tragion.
- Chin depth: distance in Y axis from Chin to Tragion.
This study has provided a methodology from point cloud data to a 3D homologous head and face model which can be used for statistical analysis and the design of head and face related products. The 3D head and face model with consistent features was built using anatomical and virtual landmarks and surface modeling algorithm (triangulation and subdivision) based on point cloud data. Compared to other computer model for the human head, using landmarks guaranteed that the anatomical head and face features were same for all subjects and more landmarks preserved more anatomical information for further analysis which is especially useful for medical examination and anthropometrical measures. A surface modeling method was used to sample the details of the shape and increase the accuracy of the model. This method could be used to compare and analyze the shape differences and help improving the product design guidelines. In addition, the method is essential for future work in developing new sizing rules. The 3D anthropometric head and face models with different sizes could be used as design tools directly by designers instead of traditional 1D anthropometric dimension during the design process. In this study, the models were created for Chinese males and females using scans from the SizeChina 3D...
anthropometric survey. The same modeling method can be applied to other populations to develop 3D head and face models.

Having the same amount of vertices or shape vectors for each model, statistical analysis such as Principal Component Analysis could be performed. The numerical measurements of head and face height, width and depth (Table 1) were computed. The average models of Chinese males and females were calculated and the size of the male head and face is larger than the female model for all the measurements, especially in terms of head height, head depth and mandible width measurements. The 3D shape analysis using PCA demonstrated the first four components had counted for more than 60% of variance for both male and female models. The head and face shape varied a lot for different PCs. The general size of the head and face from small to large contributed to the largest variation, but head and face width and depth changes more than head and face height. Face height, back of the head, forehead, chin and jaw area were also important in terms of describing the head shape variations. An interesting result is that the variations of the face shape on PC1 and PC2 were consistent with a previous study [2] which applied a similar PCA on a simple face model of Chinese women. These results from the PCA showed that people’s head and face shapes did not vary proportionally in all directions and there are differences between male and female. It is suggested that products sizing systems using proportional grading from the average or a unisex system could cause more fitting problems.

The 3D shape analysis gave great information about the variations among Chinese and provided a useful computer-aided-design tool for future product design process. With the products like helmet-mounted displays or head sets integrated with multiple functions becoming more and more popular, it is expected that new designs could benefit from the results and are guided based on 3D information rather than traditional anthropometric measures in the future. However, the face measurements in this study were slightly different from some of the traditional measures on the Chinese [8]. The reason might be the differences between the laser-scanning method and the traditional method. The traditional method is operated manually and the error of measurements can be caused by physical contact of skin [24]. In addition, the nylon cap was used to fix the hair on the head in order to get a close shape of the skull. However, the head size measured in this way will be different from that measured by the traditional method. A validation study has been completed to compare the laser-scanning method to the traditional method using the SizeChina database. Results showed that head width from the laser-scanning method was 22.07 mm (for women) and 15.31 mm (for men) larger than the traditional method. Head depth
from the laser-scanning method was 20.04 mm (for women) and 11.52 mm (for men) larger than the traditional method. These gender differences were determined by the thickness of hair since Chinese women usually have long hair compared to Chinese men.

The distance error of the model was sufficiently small with less than 1 mm in general. Most of regions including face and head top showed low errors. However, in order to create this accurate model for complex geometry of human face, a lot of anatomical landmarks were located manually in this study and it was relatively time consuming. Further studies should find out the relationships among the anatomical landmarks and reduce the number of landmarks in order to improve the efficiency of processing the 3D point cloud data. In addition, the ear region had a relatively high modeling error, due to the missing data caused by scanner limitations. More research has to be conducted to improve the ear shape.

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