Computer-AidedDesign

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A design and evaluation tool using 3D head templates

Yan Luximon ⬥, Roger M. Ball ⬥ and Eric H.C. Chow ⬥

School of Design, The Hong Kong Polytechnic University, Hong Kong

ABSTRACT
Product fit greatly depends on the human anthropometric information. Traditional anthropometric dimensions do not describe the 3D shape of the human body that is required by product designers, especially for head fitting products. With the development of CAD software and 3D scanning technology, 3D human modeling is becoming more important in design area. Based on SizeChina database, a 3D digital design and evaluation tool that allow designers to easily access Chinese head and face shape data in the Solidworks CAD environment has been developed in this study. The various sizes of 3D head templates are generated in using reference dimensions. This digital design tool can be used to visualize, evaluate and correct product fit on screen during the development process. This method allows the creation of better fitting products for the head and face.

1. Introduction

The design of body fitting products relies on accurate anthropometric data on human body shape [7]. The complex geometry of the head and face poses a difficult challenge for designers of head mounted products. Traditional 1D anthropometric dimensions are most commonly used [7,10,11]. In recent years, 3D whole-body digital mannequins has been used in developing products in the field of automotive, machinery, and garment design [8,13,14]. Chan and Jiao [6] attempted to develop a computerized anthropometric database, from which CAD users can easily look up statistics of Chinese body size. However, this database only includes body dimensions such as shoulder breadth, sitting eye height and elbow rest height, which are only suitable for workplace and furniture design. The design of face fitting products like eyeglasses, helmets and facemasks does not gain insight from simple 1D dimensions as they fail to accurately describe the complex 3D geometry of the head and face.

With the advent of 3D laser scanning technology, 3D head and face scans with high resolution of facial geometry are readily available. The CAESAR project (Civilian American and European Surface Anthropometry Resource Project) [19], provides large amount of 3D body scan, which includes high quality head and face scan data. However, the data set is from American and European population, not from the Chinese population. The 3D human modeling based on scan data starts to take

the role in simulation, animation and anthropometry [5,9,15,22,27]. Various computational modeling algorithms have been created [5,18,24,25] and 3D headforms were developed [20,26].

Product designers use tools to visualize product fit in design practice. With the increasing use of CAD software in product design, an easy and intuitive way method of designing head and face products in 3D software is required [20]. A practical and user-friendly 3D design tool is needed for designers to visualize their creative ideas and satisfy the fitting principles at the same time. The rapidly growing requires a design tool that uses sophisticated 3D body data to design "china-fit" products for the, optical, medical and sports industries. Such a tool will reduce product design lead times, with improved fit, and most importantly create safer products for the Chinese consumer. In light of this, a digital CAD design tool to enable designers to create "china-fit" head and face products in the 3D CAD environment has been developed in this study.

2. 3D head templates

2.1. 3D Chinese head scan database

The SizeChina 3D anthropometric survey collected the first 3D head scan database for Chinese adults in 2006 [4]. In this database, there are more than 2000 high resolution Chinese adults' head scans from six locations in north, south, west and east China.
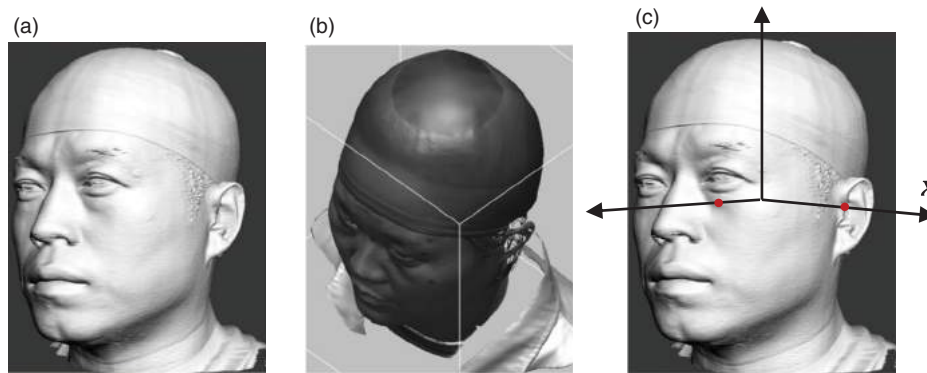
Figure 1. Data processing: (a) Point cloud data (b) Data cleaning (c) Frankfurt plane alignment.

Traditional anthropometric dimensions including head circumference, head length and head width were measured together with digital data capturing. A Cyberware 3030 Head & Face color 3D scanner was transported to different locations to collect all 3D head surface data. A nylon wig cap was used to tighten the hair and enable the laser scanning process for black color hair. Landmarks were identified and marked on the face so that they were able to be recorded by 3D scanner's texture capture function. In this study, we randomly selected 144 head scans from six locations (24 at each location with half males and half females) to create the head templates. Their age range was from 18 to 30 years old.
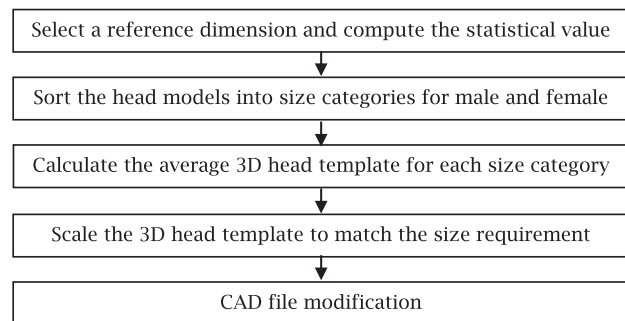
2.2. Build 3D parameterized head model

The original 3D head scan was point cloud data (Fig. 1(a).). The data was cleaned first in order to remove all extra data points ("noise") and fill the missing data ("hole") using Rapidform software (Fig. 1(b).). The 54 facial landmarks were used to determine the anatomical structure of human head and face according to previous anthropological studies [11,4,17]. The facial landmarks were manually indentified in Rapidform software. Then it was aligned based on Frankfurt plane using Matlab program (Fig. 1(c).). Frankfurt plane is formed by three landmarks including left infraorbitale, left and right tragions [17]. In order to increase the accuracy of the model, the virtual landmarks were sampled automatically in Matlab program. A parameterized modeling method based on the landmarks was used here to create a 3D head model which is consistent for every participant [17]. Triangulation approach was used to form a simple head and face model based on all landmarks. Then subdivision method was applied to create the detailed head model based on point cloud data for all participants. The parameterized head model had same alignment and same amount of vertices (= 5821)

which had comparable facial feature or meaning for all participants. For participant j the coordinates of the vertex $P_{ij} = \{(x_{ij}, y_{ij}, z_{ij})|i = 1, \ldots, N_P\}$, where N_P is the number of vertices.

2.3. Creation of 3D head templates

In order to create 3D head templates for different sizes, one possibility is to use statistical methods such as Principal Component Analysis to generate the 3D head shape data when the design tool software is in action [17,1,23]. However, these approaches are relatively new and still not widely accepted in practical setting. Most product designers find it confusing and hence are reluctant to use it. Therefore, simple 3D head template option based on percentile was adopted in this study (Fig. 2.). Product designers can simply select templates when using the software and computation duration can be saved significantly.

| Select a reference dimension and compute the statistical value |
| --- |
| Sort the head models into size categories for male and female |
| Calculate the average 3D head template for each size category |
| Scale the 3D head template to match the size requirement |
| CAD file modification |

Figure 2. Flow chart of head templates creation.

2.3.1. Dimension selection and calculation

Reference dimension method was used to select the 3D head scans. This method has been used for creating manikins and headforms for different products [15,21,12]. From parameterized head model, all head and

face dimensions can be calculated based on the landmarks and all vertices, and used as reference dimensions such as head circumference, face width and inter-pupil distance (Fig. 3.). Based on specific products, different reference dimensions would be selected to create the templates. For example, when designing eyewear, the face width and the nose bridge width could be the reference dimensions [23]. Different reference dimensions could cause different selection of size categories and hence affect the result of the head template [20]. From previous study [17], it was known that the dimensions of human head were positively correlated and general head size had largest variations among people. Therefore, single reference dimension was chosen for each size category selection in this study.
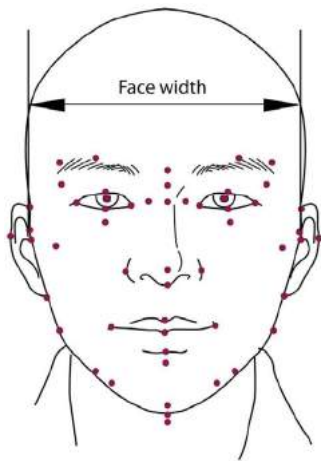

Figure 3. Head and face landmarks and an example of reference dimension.

2.3.2. Size categories and calculation of 3D head templates

Previous research showed that age groups did not have significant differences for adults, but gender group had significant difference for head dimensions [3]. Therefore, all male and female participants were separated first. Using the head and face reference dimensions, all head models were sorted into different size categories. In design practice, two values including 5 percentile (5%tile) and 95 percentile (95%tile) are commonly applied to determine the range of the design parameters, and 50 percentile (50%tile) size is often used as the median value of the design parameter [7]. Hence these three basic sizes were used as examples to explain the procedure. First, the statistical values of the reference dimensions for all head models including 5%tile, 50%tile and 95%tile were computed. Small size category (5%tile) included about 10% of the head models below 10%tile, and large size

category (95%tile) had about 10% of the head models above 90%tile. Median size category (50%tile) used all the head models from 10%tile to 90%tile. There are two advantages of this method for size category. The numbers of samples in small and large size categories are increased, and the calculated size can be close to the desired percentile when the average method is applied.

An example was explained in details using face width as the reference dimension for females. The face widths for 5%tile, 50%tile and 95%tile were 135.33 mm, 147.05 mm and 159.53 mm respectively from statistical analysis and plot (Fig. 4.). The 10% head models with face widths smaller than 10%tile (137.17 mm) were selected for small size category. The 10% head models with face widths larger than 90%tile (157.68 mm) were chosen for large size category. The median size category had all other 80% head models. Therefore, six size categories (2 genders * 3 sizes) based on the reference dimension were created.
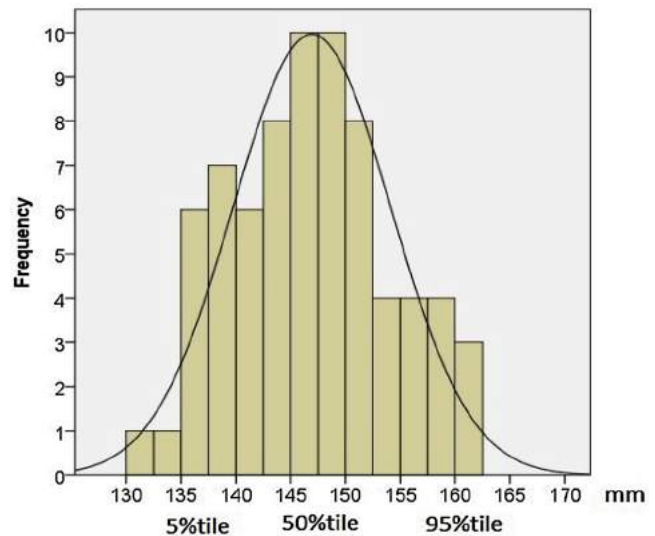
Figure 4. An example of statistics plot of the reference dimension (face width of female participants).

Once size categories were decided, the average method was then applied for x, y and z coordinates of all vertices of all 3D head models to create a head template in each size category (Eqn. (1)). Since the average method might not result exact equal measurement to percentiles, a linear scaling procedure (Eqn. (2)) was performed on x, y and z coordinates to calculate all head templates to match 5%tile, 50%tile and 95%tile measurements for the reference dimension. The result is a set of six 3D head templates with exactly measurements of percentile-value for the reference dimension (Fig. 5.). These six head templates represent the basic design range of the reference dimension from small to large for both genders. For a

(a)   (b)
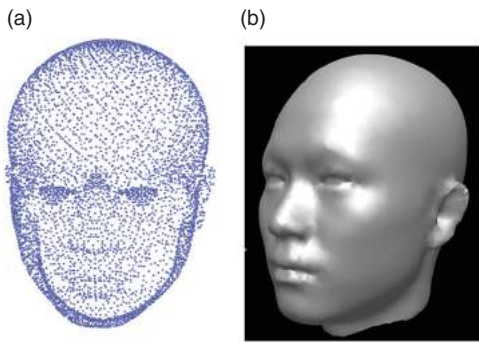
Figure 5. An example of the 3D head template (a) Vertices (b) Surface.

product targeting to satisfy 90% sample range in terms of face width, the design should be able to fit the small and the large templates for both female and male.

$$T_i = \left\{ \left(\frac{\sum_j^{Ns} x_{ij}}{N_S}, \frac{\sum_j^{Ns} y_{ij}}{N_S}, \frac{\sum_j^{Ns} z_{ij}}{N_S} \right) \middle| i = 1, \ldots, N_P; j \right.$$
$$\left. = 1, \ldots, N_S \right\}, \tag{1}$$

where N_P is the number of vertices of the template and N_S is number of samples in a size category

$$T_i = k \times T_i, \ k \text{ is the scaling parameter} \tag{2}$$

More size categories can be created based on the sizing parameters and size increments (allowances) for a specific product. When a designed product has a small allowance, that is to say that the sizing parameter cannot be adjusted in a large range, more sizes are needed for better fitting [16]. For example, helmet circumference normally cannot be adjusted much in most of helmet designs. In order to satisfy the 10 mm helmet circumference size increment between two sizes, 10 size categories are needed for Chinese population in order to cover the whole range of the head circumference dimension [2].

2.3.3. CAD file modification

In order to smooth the surface and clear the detail, some fine modifications were carried out on the 3D head templates using software Rapidform and Alias (Fig. 6.). The details of both ears were rebuilt. Fig. 7. shows some examples of final 3D head templates for face width dimension.

3. The digital design tool

3.1. User interface design

In order to allow product designers to easily access 3D head templates data in a CAD environment, a user-friendly interface has to be developed.

There are several major 3D CAD software for product design on the market. Rhinoceros is low cost basic software while Autodesk Alias is a high cost with complex functionalities. On the other hand, Solidworks is the industry-standard product design software because of its moderate pricing and functionality, as well as its ease-of-use and user-friendly interface. Therefore, it was decided that the digital design tool is targeted for Solidworks CAD environment. The design tool software essentially inserts the 3D head template as a layer, on which the designers can directly draw and design their products in Solidworks CAD environment with slider and drop-down menu user-interface.

The design tool software was developed in Microsoft C# programming language, and interacted with Solidworks CAD environment through the Solidworks API (Application Programming Interface). It was fully tested and functional on Solidworks 2012 under the Windows XP or Windows 7 environment. Fig. 8. shows the software installed and running in the Solidworks 3D CAD environment.

The user-interface of the design tool consists of three main tabs (Fig. 9.). One tab labeled "Head Shape" is for working with the head dimensions, and another tab for working with the face dimensions ("Face Shape" tab).

(a)   (b)   (c)   (d)   (e)
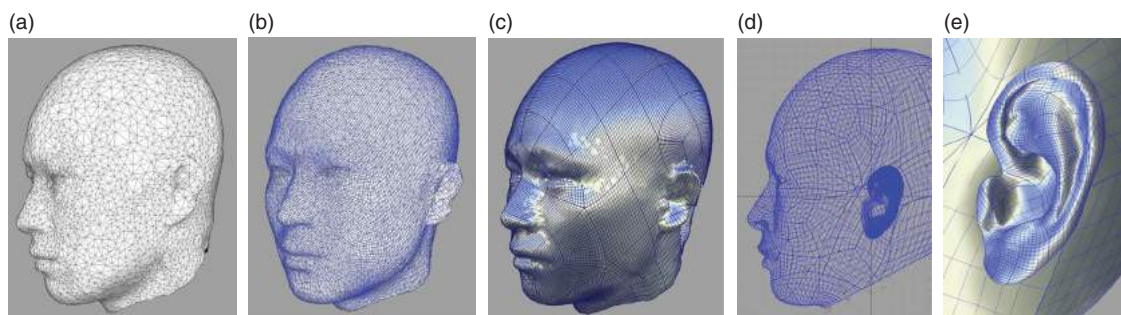
Figure 6. Modification of the 3D head template: (a) Vertices (b) Surface fitting (c) Surface modification (d) Detail clearance (e) Ear modification.
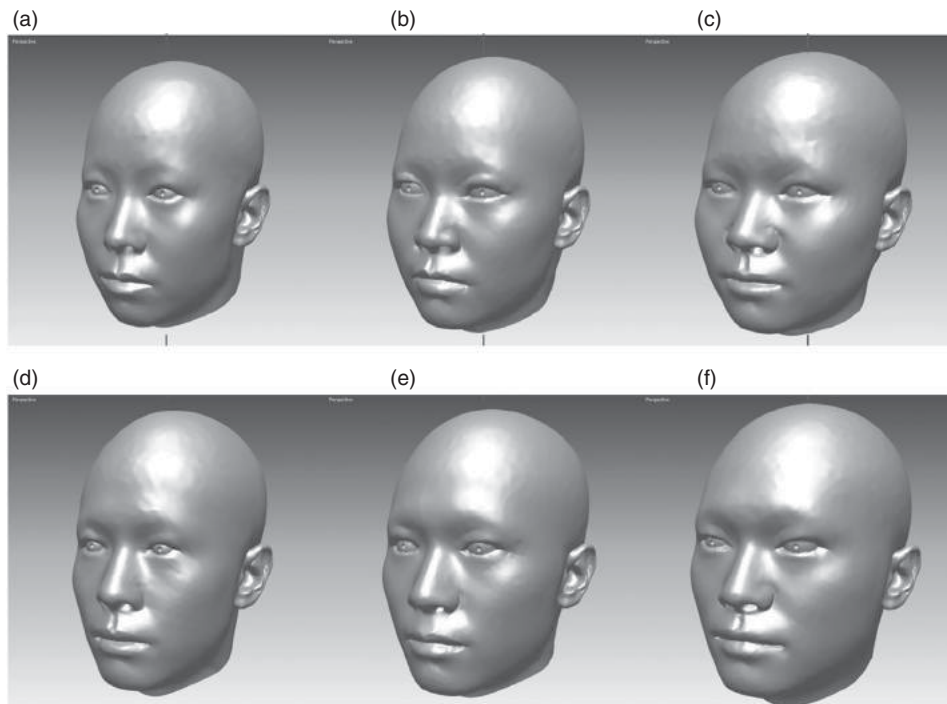
Figure 7. Examples of final 3D head templates using face width as the reference dimension: (a) Small female (b) Median female (c) Large female (d) Small male (e) Median male (f) Large male.
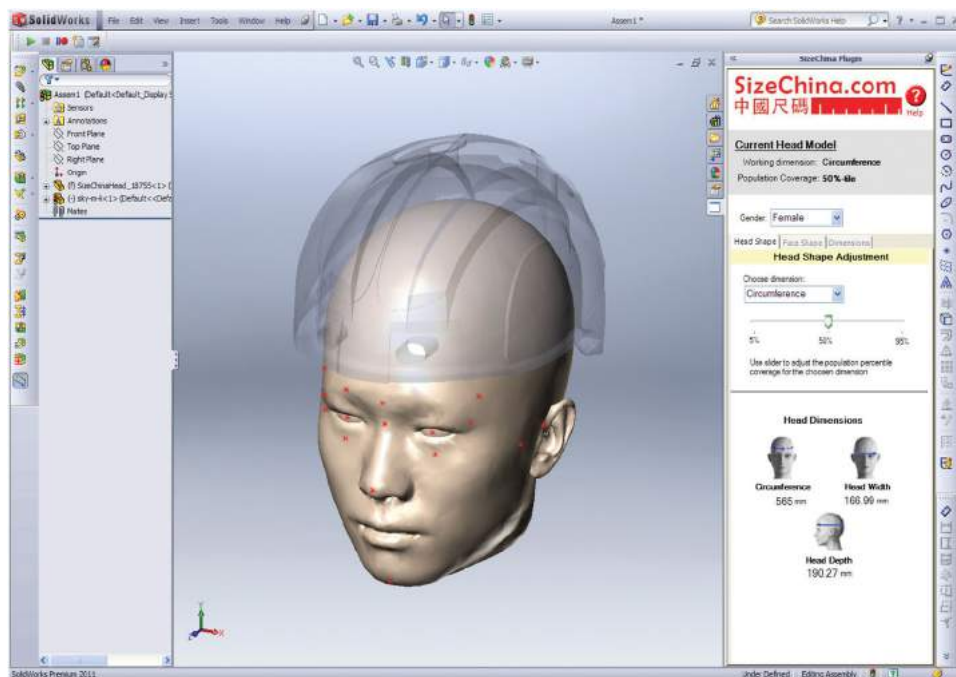

Figure 8. The design tool running in Solidworks 3D CAD environment.

Users can also see the dimensions of currently selected and displayed head template through "Dimension" tab. Help file can also easily be accessed from the top of the user-interface. In the "Head Shape" tab, users can choose the head dimensions such as head circumference and head width through a drop down list, based on which

users can import the respective head template of different sizes (such as 5%tile, 50%tile and 95%tile). The sizes can be selected through a slider widget. Similarly, the "Face Shape" tab let users select the sizes based on the face dimensions such as face width and inter-pupil distance. In addition, at anytime during the software usage, users
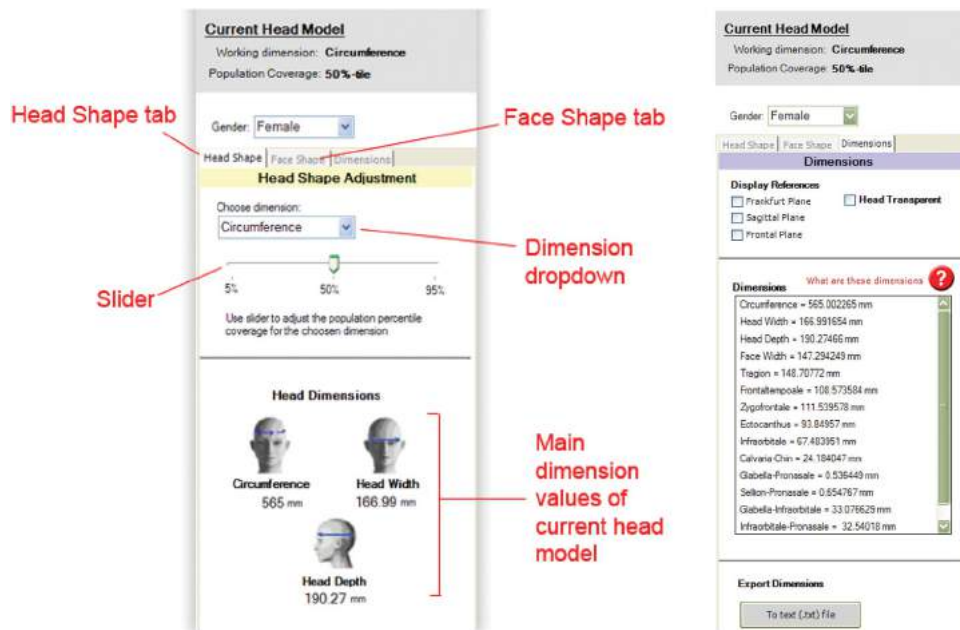
**Figure 9.** Main user-interface of the design tool.
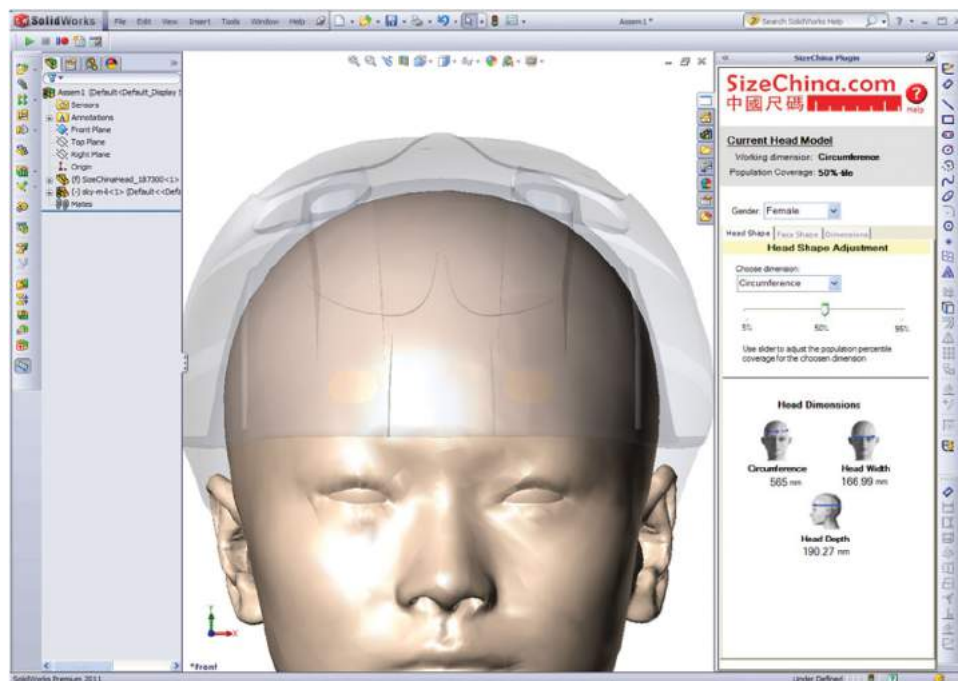
Figure 10. Product fitting test between head template and product in a semi-transparent view.

can also select the gender of the head templates. The "Dimension" tab displays the dimensions of the current head template. Also, all important facial dimensions and measurements for each template model can be exported into text files for print-out reference in the "Dimension" tab.

### 3.2. Application on product fitting and product design

After selecting the appropriate head shape template from the "Head Shape" or "Face Shape" tab, user can then import existing headwear product design 3D CAD file
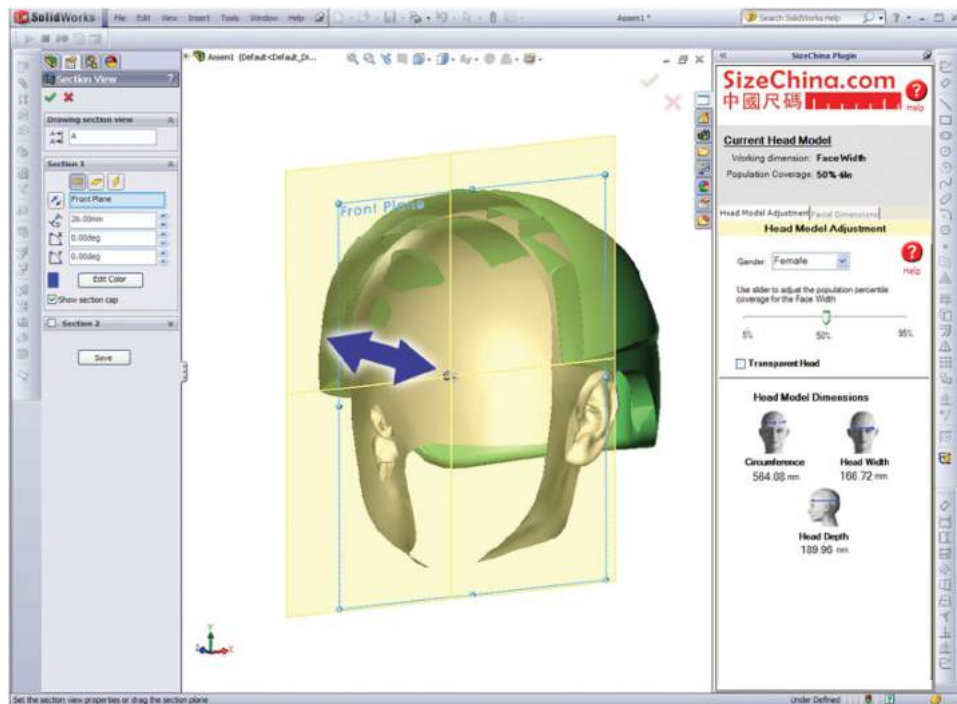
Figure 11. Use of Section View to examine product fit.

directly onto the head shape model using simple drag-and-drop operation. The 3D CAD file imported into SolidWorks CAD environment can be turned into a visually semi-transparent state. Users then can clearly examine how well the inner surface of a product is fitted to the head shape (Fig. 10.). The visual evaluation allow users to identify where on product 3D CAD file needs to be physically modified in order to fit the Chinese head shape. In addition, users can make use of the section tool in the software to examine the product fit with respect to the head model "section-by-section". Using this method, users can visually examine the intersection between the head shape and the product from within the head template model (Fig. 11.).

When designing products, users can also trace curves (3D splines) directly onto the surface of the 3D head templates to create Chinese fit products. The designed product can be matched set with the reference points or selected landmarks in the digital head template to create human shape dependent and ruled based product design. For example, one can use 3D projection method in Solidworks to trace a curve on the face of the 3D template (Fig. 12.). The result is 3D spline that can serve as a basis for creating a facemask (Fig. 12.). In this way, the designed product can have better fitting from the beginning of design process, not at the final evaluation stage (Fig. 13). Product evaluation and modification time can be greatly improved. This method can be also used for customized design for individual consumer.
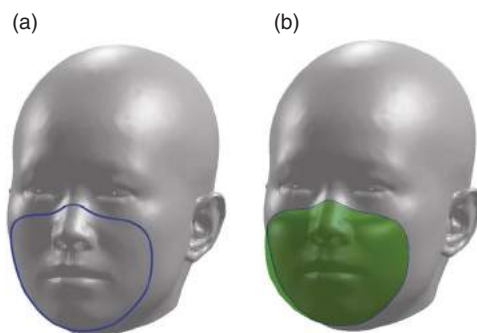
Figure 12. Designing a product using a head template: (a) Tracing of 3D spline on the head template (b) Create 3D product surface.
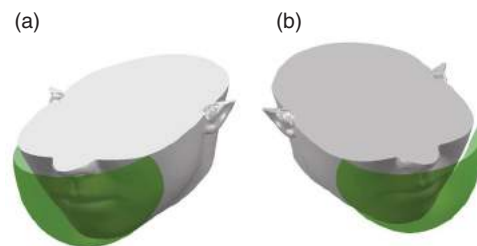
Figure 13. Product fitting test in section view (a) A good fitting product (b) A poor fitting product.

In order to evaluate the fit of the product that designed using 3D head templates, a facemask has been designed based on median female head template (Fig. 12.) and

3D printed. Seven female participants were tested. A 7-point Likert scale questionnaire was used for evaluation on overall satisfaction (1-extremely unsatisfied, 4-neutral and 7-extremely satisfied) and regional fit (1-extremely tight, 4-neutral and 7-extremely loose). Results showed that participants felt satisfied for overall fit (average 4.7). Although hard 3D printing material (ABS plastic) was used in this test, two participants had a good fit and their average perceived fitness was 4.3. Other participants felt that nose region was tight (average 2.0) and cheek regions were loose (average 5.1). Results showed that an adjustable design using softer fabric, or more sizes should be applied to improve the fit for the experimental face-mask. Small and large size head templates could be used to check the adjustable design.

4. Conclusion and discussion

Significant differences between Chinese and Caucasian head shape have been found [5]. Chinese heads are rounder than Caucasian counterparts in general. Thus product designers need to use an Asian head model in order to design better fitting products for the Asian markets. A method that allows designers easy access to accurate 3D Chinese head and face shape data in the Solidworks CAD environment has been developed in this study. The different sizes of 3D head templates are created from reference dimensions. This design tool can be used to visualize, evaluate product fit, and correct designs on screen during the design process. In addition, the 3D head template can be further developed for finite element analysis when simulating the load distribution and deformation. Due to computational time limits, software users can only select existing 3D head templates based on reference dimensions. However, more 3D head templates based on more dimensions for different head and face related products can be calculated using same method when it is needed. In addition, the variations of poses should be considered in future studies so that dynamic fit can be evaluated. Further development of the design tool is possible for other parts of the human body, such as ears for headphone design, hands and wrists for wearable products or feet for footwear design. Using the same method, anthropometric data from other ethnics groups can also be included in future development.

Acknowledgement

ORCID

Yan Luximon ⓘ http://orcid.org/0000-0003-2843-847X
Roger M. Ball ⓘ http://orcid.org/0000-0002-0539-3654
Eric H. C. Chow ⓘ http://orcid.org/0000-0003-2654-2097

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