Heliyon 8 (2022) e11732

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Establishment of open web platform based on 3D head model for product adaptability analysis and evaluation

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ARTICLE INFO

Keywords:
Chinese head
Percentile
Headwear product
Adaptability
Gender difference

ABSTRACT

With improved living conditions, the demand for wearable products has increased, particularly for headwear. Traditionally, the dimensions of headwear products are designed according to 1D anthropometric data, such as head length, width, and eye width. However, this design method, applied to fit the 3D human head, results in differences in adaptability, which affect the wearing comfort of the user. Hence, this study aimed to develop an aided design platform based on a three-dimensional standard head shape to evaluate the virtual wearing of headwear products and adaptability testing. Specifically, a WebGL-based service, named the Chinese Headwear Adaptability Testing (CHAT) platform, was established. Validation and user studies were then conducted using an eye massager device. After the product was redesigned according to evaluation by the proposed system, the results show that the comfort and adaptability of the redesigned eye massager were significantly improved. The findings suggest that using the CHAT platform to design headwear products can help achieve a better wearing fit for the products.

1. Introduction

Head shape adaptability is essential for the comfort and functional effectiveness of headwear products [1]. Headwear is often used for protection, treatment, and health care purposes. A suitable matching feature is necessary to design headwear products that are in line with the principles of ergonomics to increase the comfort of the wearer. Skals et al. [2] reported that wearing improper headwear products for a long time causes injury, pain, and discomfort. A common way to improve the adaptability of headwear products is to apply proper head anthropometric data to the design [3]. At present, many anthropometric databases and software have been developed for the demonstration and evaluation of such products. These databases, which provide an average value for each body dimension, have been applied to product design. However, these datasets still lack in the use of product suitability evaluation methods [4].

Nowadays, designers in the headwear product industry face difficulties when using anthropometric data. First, designers apply traditional 2D anthropometric data to the design of 3D products, which can cause poor adaptability between the headwear and the head because of the complexity of the head surface [5]. Second, only a few 3D standard head-shape models are available for use in designs. Furthermore, the representative data are questionable because updated data have not been collected [6]. Third, some designers refer to European and American anthropometric datasets (e.g., CAESAR project) for the design of their products, because local head anthropometric data tend not to be open source and therefore cannot be freely used in the industry. However, the effect of ethnicity on anthropometry should be considered in headwear design. Products designed based on inappropriate data often have serious adaptability problems [7].

The rapid growth of China's consumer market has created a huge demand for wearable products. Future product design requires accurate data on Chinese heads and faces, especially for 3D visual modes transformed from 2D head data [4]. However, most anthropometric network platforms provide head data only in terms of basic statistics, such as the mean, 5%lie, and 95%lie. On the other hand, in-depth data use modes and user interaction experiences are not yet well developed. Hence, the aim of this study was to establish a user-friendly network graphics platform for the design and service of head-wear products. The contribution of the current study is in providing an easy-to-use platform with Chinese 3D head models for designers to use in evaluating the adaptability of

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https://doi.org/10.1016/j.heliyon.2022.e11732
Received 27 February 2022; Received in revised form 6 July 2022; Accepted 10 November 2022

headwear products, particularly for the early stage of designing a new product.

2. Literature review

Many institutions around the world have conducted research studies related to human head-shape anthropometric technologies and methods. The design and analysis of head-wearing products were also conducted according to the related head anthropometric data. In this section, the traditional design methods for headwear products are introduced. Subsequently, the state of the art in the head model databases of different countries is summarized. In addition, product designs based on digital head model and adaptability analyses are demonstrated. Finally, data on recent headwear product service design platforms from around the world are collected.

2.1. Traditional design method for headwear products

The traditional process for headgear product design is composed of six primary stages: creative sketch, engineering drawing, 3D modeling, sampling, user testing, and mass production. In the creative sketch stage, designers work to understand the demand from product management and customers, and then draw sketch schemes according to their own creativity. In the engineering drawing stage, designers analyze the product structure, size, and proportion, and complete their drawings based on their work experience, with the use of reference materials. In the sampling stage, prototypes of the selected products are produced based on 3D models created in the 3D modeling stage. Finally, in the user testing stage, validation of the products is conducted. Target users are invited to evaluate the prototypes and report their feedback regarding the user experience for use as a reference in redesigning and optimizing the product features. This cycle of redesign and validation is then repeated several times until a relatively reasonable product is created for mass production [8].

However, in the aforementioned process, the designers rarely apply anthropometric data to the repetitive user testing to determine a relatively reliable product shape. Thus, head shape determination still results in serious wearing problems because the number of recruited subjects is not sufficiently large to represent the entire target user group. Therefore, the modified modeling scheme fulfills the needs of only a small group of users.

2.2. Construction of head model database

Recognizing the importance of head anthropometric data, many researchers have begun to investigate and collect head models for design purposes. In China, during the last decade, two-dimensional head measurement data were obtained using conventional handmade size-measuring instruments. To create the GB/T 2428-1998 standard, 29 measuring points were defined, and 41 head and face measurement dimensions were collected to describe the morphological structures of heads among the adult population [9]. Meanwhile, Ball et al. [10] combined traditional anthropometric methods and three-dimensional scanning to collect data on head shapes. In that study, a total of 270 participants from seven different areas in China were recruited for scanning, to obtain three-dimensional coordinates of the head point cloud, creating a high-resolution 3D scanning database of Chinese head shapes. In the GB/T 23461-2009 project, computed tomography (CT) and magnetic resonance imaging (MRI) were used to collect 3D scanning data from 1261 Chinese adult male heads to establish a hierarchical-description 3D model. The results indicated that the head shapes of Chinese males can be divided into seven standard categories based on head width, height, and length. These seven types of head shapes have since been widely applied in the design of headwear products [11]. Yan et al. [12] proposed a method of building a digital model based on 3D scanning data of Chinese heads, with the aim of designing various products that perfectly fit the human body. They selected the head feature points, connected them two by two, and built a head mesh model based on triangles. However, the limitation of that study was that the final head model framework could not fully express the complex surface features of the head and face. On the other hand, Wang et al. [13] collected 3D scanning data from 2200 people from seven representative cities in China, whereas Kuo et al. [6] established a 3D head anthropometric database of the population of Taiwan and obtained several head shapes using a two-step clustering method and two-level self--organizing mapping (SOM) with a coverage rate of 80%. Compared with traditional two-dimensional measurements, high-resolution 3D scanning data show more detailed head geometry information.

With regard to similar efforts outside of China, the CAESAR 3D anthropometric database [14] consists of 3D body scanning data from people aged 18–65 in the United States, the Netherlands, and Italy, and includes high-quality data on heads and faces. The database was developed in 1997. Furthermore, the CAESAR project developed a 3D model database management system, which the users can query for 3D shapes, and anthropometric and demographic data. For better use of anthropometric data, Lee et al. [15] manually repaired 2299 head models from the CAESAR database by marking 26 measuring points in a 3D head to collect 30 head dimensions related to the design of headwear products. The results of the study indicated that there are a variety of key human head sizes for a number of target products, population, and size categories. Subsequently, a grading system was generated for the identification of representative head models. Lee et al. [16] collected 3D scanning data of heads, faces, and ears, and generated a hierarchical system and representative model using statistical analysis methods, such as factor and principal component analysis. Ellena et al. [17] obtained measurement data from 222 teenager cyclists in Melbourne, Australia, and distinguished the heads based on three standards (minimum, average, and maximum) according to the head shape and size. Wood et al. [18] proposed a method of developing a head model based on in vivo imaging data obtained using magnetic resonance imaging. Subsequently, the detail and accuracy of the model anatomy were analyzed. The model that was developed accounted for the thickness of the human soft tissue, enabling its use in simulating experiments on human anatomy. Meanwhile, the Netherlands recently obtained descriptive statistics based on detailed measurements of the heads and faces of Dutch children. To develop an ergonomic head and face suitable for children, they conducted an anthropometric survey using traditional anthropometrics and 3D-imaging-derived measurement technologies to obtain measurements from children between the ages of 6 months and 7 years. The different data sets were arranged according to the genders and ages of the children to provide a reference for the future design of products for children [19]. On the other hand, the US Army conducted an army-wide anthropometric survey, namely the ANSUR II, which included 94 traditional manual measurements and 3D scanning data from approximately 12000 US Army soldiers from 12 military facilities. The data generated were then used to design and evaluate clothing and personal equipment for the US Army. The study showed that there were significant differences in the quantitative sizes between male and female personnel. Furthermore, gender differences were manifested not only in the absolute sizes (male > female) but also in the proportions, which affected the potential designs of head protection devices [20].

Details on past studies on head measurement databases are summarized in Table 1. Although large amounts of anthropometric data concerning the head have been collected, most of these head databases are not available to the design community. Therefore, designers continue to face difficulties in gathering accurate data, which lead to problems with the fitness and comfort of the relevant products.

2.3. Product design based on digital head models

Many studies have investigated the relationship between the use of collected 3D head-shape data and product design. For example, Lee et al. [21] 3D scanned the faces of 336 Korean Air Force pilots and designed an

Table 1. Head databases constructed through research studies worldwide.

Database name	Acquisition year	Researchers or institutions	Number of samples	Country of samples
GB/T 2428-1998	1998	China Technical Committee of ergonomics standardization	1150 males & 1150 females	China
SizeChina	2008	Ball & Molenbroek	1620 subjects in 6 cities	China (Guangzhou, Huangzhou, Chanquin, Lanzhou, Beijing, Shenyang)
GB/T 23461-2009	2009	China National Standardization Administration Committee	1261 males	China
Chinese Head Database	2018	Hunan University (Wang H et al.)/Georgia Institute of Technology (Roger BALL)	2200 subjects in 7 cities	China (Guangzhou, Hangzhou, Changsha, Chengdu, Xi'an, Beijing, Harbin)
Taiwanese Head Database	2019	Kuo et al.	1010 males	Taiwan, China
CAESAR	1999	Robinette et al.	4000 subjects in USA	USA, Netherlands, and Italy
			10,900 subjects in Netherlands & Italy	
Mass Customization	2018	Ellena et al.	222 cyclists	Melbourne, Australia
Dutch Children Database	2019	Goto et al.	302 children (128 female)	Dutch
ANSUR II	2019	U.S. Army CCDC Soldier Center	~12000 US Army soldiers	USA, Netherlands, and Italy

oxygen mask based on 3D head models to improve the fit of the mask on the faces of the target users. Their experimental results showed that the comfort of the oxygen mask designed in this manner was significantly better than that of a mask designed without a 3D data reference. In addition, Lee et al. [22] proposed a 3D head scanning method based on the reverse engineering of the heads of soldiers through the fast surface method, which resulted in an ideal free-form surface with a satisfactory tolerance range (±0.2 mm). Furthermore, combat helmets for the army were produced according to the 2D and 3D head anthropometric data. Through reliability comparison, the use of 3D data was verified to be and selected as the better method for helmet design. Therefore, 3D scanning was proven to be a fast and accurate technology for obtaining head models necessary for personal helmet design. On the other hand, Wang et al. [23] developed a fitting algorithm based on the progressive scanning of different facial feature regions and on contouring sampling performed on the scanning layers, which were reconstructed and fitted using 3D software. The researchers created standard digital head models in different percentiles of head circumference and used them as a design service tool for physiological comfort optimization in wearable product design and other ergonomic evaluation programs. Pang et al. [24] created a 3D head-shape database based on 20 volunteers via 3D scanning and developed a new custom helmet liner to map head sizes and profiles into conventional medium (m) and large (L) sizes. Dynamic stability tests were then conducted to compare the new customized helmet with commercially available products. At the same time, Pang et al. [24] performed measurements for the transverse direction of the customized helmet and evaluated the feedback of participants to the helmet on different areas of the head. The evaluation results showed that the overall comfort, especially in the top area of the new helmet, was significantly improved.

Meanwhile, during the COVID-19 pandemic, many medical workers were exposed to infectious air because of a shortage of medical resources. In response to this problem, Swennen et al. [25] devised a reusable customized 3D-printed mask based on the characteristics of the human face. The mask fits the contour surfaces of the heads and faces of medical staff, which can help maintain their safety, whereas the modular component design method used to create the mask can save on medical resources. On the other hand, Loja et al. [26] used CT imaging to obtain 3D anthropometric data and applied these to the modeling of a head-fixed thermoplastic mask for patients undergoing radiotherapy. The results showed that the improved fixed-mask structure based on anthropometric data provided patients with better health care, comfort, and lower facial pressure.

The research results presented herein have shown that the comfort of products designed using 3D head models is significantly improved compared to those of products based on 2D data. However, these important 3D head-shape data based on different populations are not completely open for industry use, whereas the fitness evaluation software are currently private. Moreover, systematic tools for the design of headsets, including for the adaptability evaluation of designed products, remain to be established.

2.4. Adaptability analysis

After obtaining their representative digital head models, researchers shifted their focus to the adaptability evaluation of designed products. For example, Kang et al. [27] conducted research on helmet mold designs and, based on the standard normal distribution theory, proposed an algorithm that divides the data into a number of groups according to size. A representative model of each group is then generated automatically. An interactive interface was also developed, enabling users to modify the mold shape via the free deformation method. With the interface, the product can be exported as a 3D printable file with an arbitrary gap and thickness for adaptability evaluation. Meanwhile, Luximon et al. [28] randomly selected 144 head models from the Chinese head database and created head templates for the 5%, 50%, and 95% percentiles of head models. These head templates can be interacted with by designers, who can draw curves directly on the surfaces during the headwear design process, transform the designed head products into a visually translucent state, and cut the heads and products into slices for adaptability analysis. Stijn et al. [29] proposed a workflow that involves using an accurate 3D human body shape model in product design, and their findings indicated that the model closely matched the features of the head of the user and resulted in good wearing comfort. Furthermore, the researchers introduced rich head shapes, and new data that include dense geometric information and classic anthropometric data. The study also emphasized that using rich shape models to create personalized products, as an extension of the use of univariate anthropometric data, can become an important driving force for mass customization. However, despite the advancements listed herein, there are currently only a few fitting analysis methods for the design of headwear products, because of limitations in the functions and sharing modes of the design software.

2.5. Headwear product service design platform

Table 2 presents an analysis of three headwear product service design platforms that are presently available. Existing platforms are expected to exhibit some functional defects. Because of these defects, such platforms cannot directly reflect variations in head feature size among different percentiles and the corresponding relationship between headwear products and the head. Therefore, the adaptability of the designed headwear products could not be tested. With regard to interaction, existing platforms lack accurate control over the 3D model parameterization and registration interaction between the

Table 2. Analysis of presently existing headwear product service design platforms.

Platform interface	Function	Interaction	Development environment
SizeChina service design platform [30]	Different head models can be imported according to age, head feature size (head circumference, width, etc.), and facial features (face width, pupil spacing, etc.). User can select head shapes in the 5%, 50%, and 95% percentiles. A number of feature size values of the model head display in real time. The designed product model can be imported into the platform for visual adaptability analysis.	User can view and take control of the model using a mouse, and divide the different functional modules using tabs. Under the different tabs, there are drop-down lists and sliders set for the user to select the corresponding constraints.	Plug-in in SolidWorks
Chinese database [12]	This platform consists of six modules: home page, percentile of head shape, search bar, model, statistical summary, and database introduction. Users can access and interact with large-scale, personal-level head and face anthropometric data in different modules, including the original 3D scanning model, and view the statistical analysis results.	A large amount of data is displayed mainly in static charts. Users can rotate and zoom the 3D model to view the details via clicking, dragging, and scrolling a mouse.	Web page
Three-dimensional head shape grading system [16]	The key dimensions were determined via regression, factor analysis, principal component analysis, and other statistical analysis methods. These dimensions help product developers determine the best grading system and the standard head shape for product design through comparisons based on multiple grading systems.	Users can quickly identify the options from the product and head feature images. The analysis results are presented in charts and data tables. The layout of each module in the interactive interface is visually clear.	Client application

product and head shape. In addition, cloud design requires the service platforms of a website to be useable over a wider range of technologies and be able to adapt to different devices and systems in a variety of scenarios.

3. Requirement analysis and function research for proposed system

This section summarizes the steps involved in developing the Chinese Headwear Adaptability Testing (CHAT) platform. First, the requirements of designers for designing headwear were analyzed. Subsequently, the functions of the CHAT platform were built according to the needs of designers. Because typical head shapes are key elements for the design and evaluation, typical Chinese head shapes (small, median, and larger) were developed for this study. A module for adaptability analysis was also established for further use. Finally, a WebGL-based service was used to integrate the aforementioned functions into a platform and to visualize the results of the headwear evaluation in terms of adaptability. The newly developed CHAT system is able to help designers complete the adaptability analysis of headwear products in the early stage of the design without requiring the installation of any software or plug-ins. More importantly, the CHAT platform will be an open resource after publication.

3.1. Data usage requirement analysis

Information concerning the design process for various headwear products and the usage of head data was obtained from five experienced designers in the headwear product industry. Among the participants, the average working experience relevant to headwear was 9.53 ± 2.11 years. The topics of the interviews were divided into the following steps: (1) design of the headwear product, (2) access and usage of head data, (3) product adaptability analysis, and (4) expected functions in aided design platforms.

The interview and research results show that head data are required throughout the entire process of product design, as shown in Figure 1. In the early stage of product design, designers analyze the user information, product size, and structure to determine the approximate proportions and to develop the sketch scheme design. During the modeling, the designers ask for more accurate product size information and communicate with engineers with rich working experience to determine the details of the structure. In other words, the product characteristics are determined in detail by the experience of producers, designers, and manufacturers. A prototype is then generated. A number of users are selected for the wearing test, and the user responses on their experience and physical feedback are recorded and analyzed for use in product redesign. The steps are repeated until the products have a relatively reasonable structure and feedback. We have inferred that an accurate model or platform for testing can fill the gaps in practical implications. Because head-shape data are required throughout the entire design process, it is necessary to use data with high reliability and ease of use.

3.2. Function definition and implementation of platform

Based on to the design platforms and user interviews mentioned in this paper, this study analyzed the interaction process for when designers use head data to improve product adaptability, and defined the function and interface hierarchical relationship involved in the proposed aided design platform for headwear products. The hierarchical relationship of the platform page is shown in Figure 2.

3.2.1. Construction of digital head shape

In this study, 3D models of Chinese adult male and female heads were constructed using acupoints attached to the head.

3.2.1.1. Construction of adult male head model. Based on the GB/T 23461-2009 standard, this study constructed a 3D head model for a Chinese adult male. This standard measured the head anthropometric data from 1261 males aged from 16 to 36 years. The male's 3D model was collected by computer tomography and magnetic resonance method. More specifically, a 3D head parametric model was defined with 56 layers of circumference and 12-order Fourier series description parameters for each circumference layer. The following parameter was defined as follows (1):

$$\rho i(\theta) = ai,0/2 + \sum_{n=1}^{12} ai,n\cos n\theta \tag{1}$$

where i is the serial number of the circumference, and a_i and n are the description parameters for each circumference of the head type [6].

In the rectangular coordinate system, the coordinate values of the points on the circumference are defined as $(X_{i,\,j}, Y_{i,\,j}, Z_{i,\,j})$:

$$\begin{cases} Xi,j = \rho i,j\cos\theta j + X0 \\ Yi,j = \rho i,j\sin\theta j \\ Zi,j = Zi \end{cases} \tag{2}$$

In Eq. (2), i is the serial number of the weekly line, and j is the serial

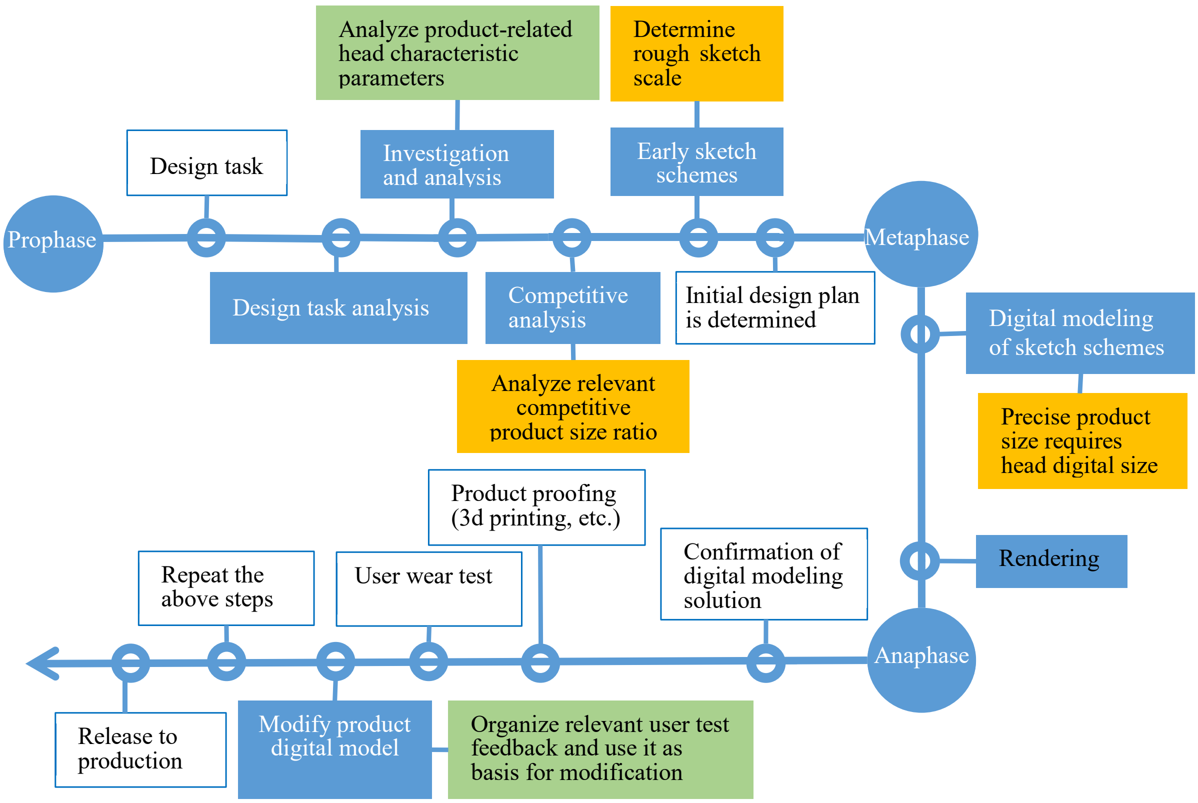


Figure 1. Data usage in early design stage (green color was used to identify physical phase, and orange color was applied for digital phase).

number of the point on the weekly line. The values of X_0 and Z_i are listed in Table A2.

Based on Eqs. (1) and (2), this study established the hierarchical perimeter of the head form using MATLAB 2013, and triangulated the adjacent perimeter to reconstruct three-dimensional mesh models of five standard head forms with high coverage: round high head, normal round head, middle high head, middle round head, and super round high head. The sample coverage was 93.58%. In Figure 3, the side views and front views of the five aforementioned types of 3D head models were shown.

3.2.1.2. Construction of female head model. Because of the lack of Chinese national standard 3D head size data for adult women, this study constructed a 3D adult female head model. First, 3D head data of 15 women aged from 18 to 25 were collected by this study. The equipment used was a Reeyee Pro 2x handheld 3D scanner (Wiiboox company, China) with an accuracy of 0.05 mm. The key processing of the scanned head data is shown in Figure 4. Informed consent was obtained from all participants prior to the survey, and the study protocol was ethically approved by a university institutional ethics committee as per the Helsinki declarations.

After the scan, the model was processed using Netfabb, Meshmixer, and other software to fill in vulnerabilities, and to modify and reduce the mesh, as shown in Figure 4(a). The width and depth of the head were reduced by approximately 15 mm and 20 mm, respectively, to eliminate the thickness of the hair and nylon cap. To maintain the high quality of the model and to compress the file at the same time, the model grid was

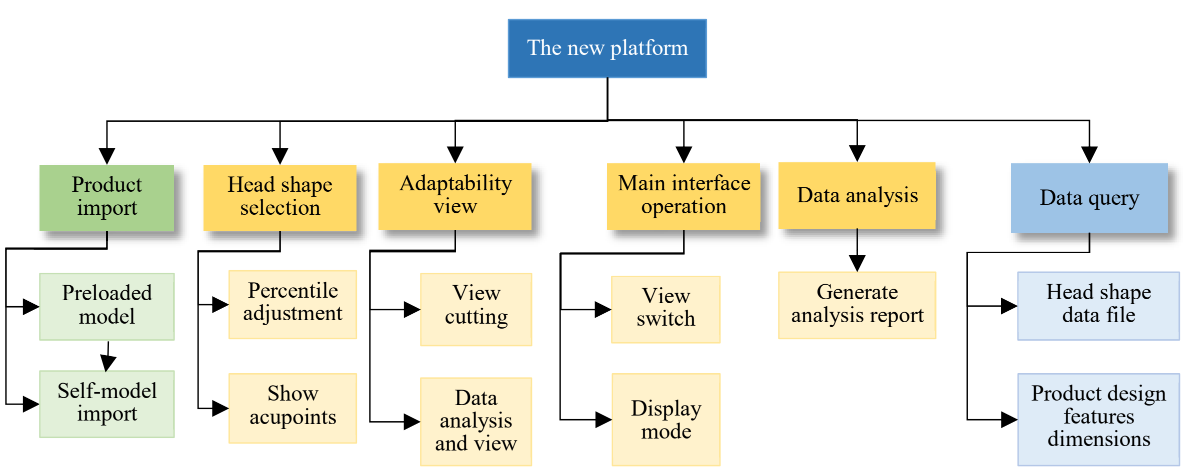


Figure 2. Platform page hierarchy diagram.

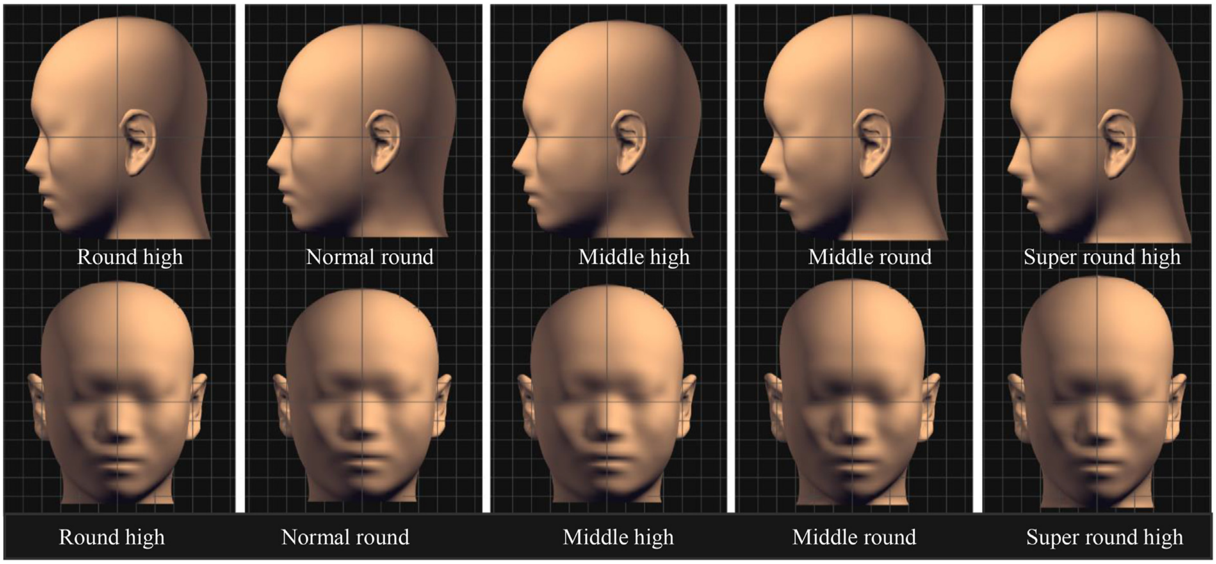


Figure 3. Five Chinese male 3D head models generated by the proposed system.

reduced to approximately 8000, and the head position was adjusted based on a coordinate system with the Frankfurt plane as the XY plane and the midpoint of the screen point on the left and right ears as the coordinate origin, as shown in Figure 4(b) [31]. After post-processing the sample data, we started to build the average three-dimensional head shape for women due to the average women head model is lacking. According to GB-T 23461-2009, the perimeter of each layer is parallel to the Frankfurt plane and grouped by the characteristic perimeter, and the inner perimeters of the groups are equidistant, as shown in Figure 4(c). The vertical section was constructed such that it intersected with the perimeter; in this way, the perimeter reaches an intersection point at every 30° interval, corresponding to 12 points in total. Subsequently, the XYZ coordinates of the intersection were obtained. Specifically, the XY coordinates were obtained directly from the model, as shown in Figure 4(d).

The corresponding data for the 15 head models were then recorded. To obtain the coordinates of each intersection point, this study averaged the points for the 15 models and marked them in a coordinate system to construct an average head shape with a smooth surface. The standard head shape of young women was adjusted according to the seven main head dimensions in the GB/T 2428-1998 standard to construct a female head model as the median (50th percentile) head model. The model was adjusted based on the scaling factors for the small (5th percentiles) and large (95th percentiles) head shape. Finally, three average female head models for the 5th, 50th, and 95th percentiles were established, as shown in Figure 5.

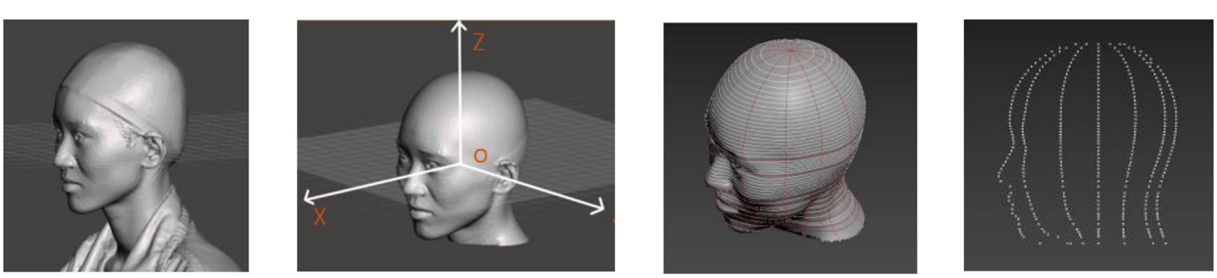
3.2.2. Adaptability analysis

To perform adaptability analysis, the product and the digital head model were subjected to cutting plane analysis, and the gap between them was analyzed.

In cutting plane analysis, which is a common method for evaluating the adaptability of a given product, the model is cut parallel to the coordinate plane. A continuously cut model shows, in an intuitive manner, the gap and interference between the head shape and the product contour on the cutting section, with which designers can identify any structural problems. The ranging function supports drawing the head and product contour lines and calculating the gap distribution between them in real time, as shown in Figure 6. Point P_1 is on the bridge of the nose, point P_2 and P_3 in is on the cheek (see Figure 6(b). The adaptability analysis result between product and head is visualized as a distribution curve, as shown in Figure 6(c). The gap is about 7.5 mm between head and massage product at Point P_1. The gap is about -1 mm at both point P_2 and $P_{3.}$ With this function, designers and engineers can learn the adaptability of products and use the platform for their quantitative evaluation.

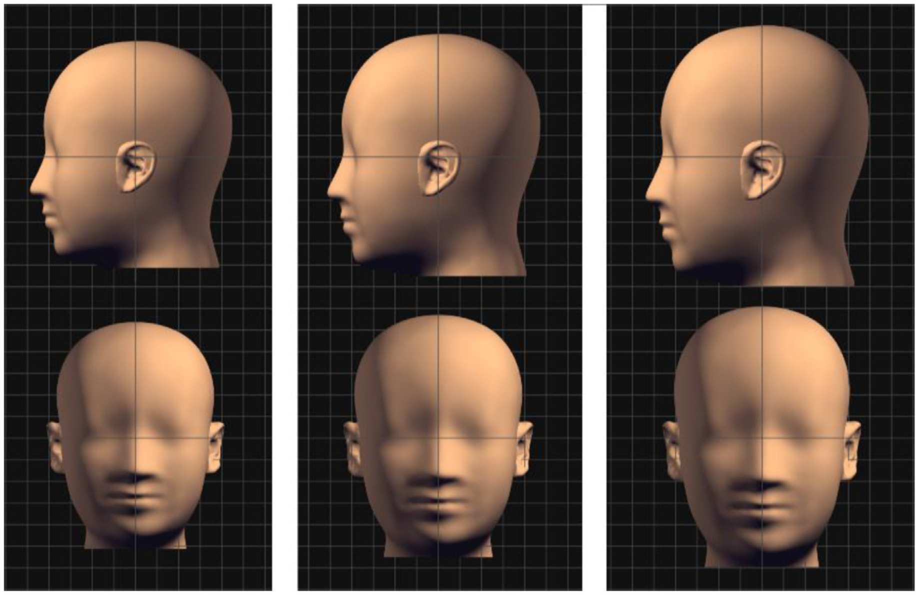
3.2.3. Platform development

A WebGL-based service design platform with a user-friendly interface was developed to help designers share their standard head information and to encourage more effective use of the Chinese standard head model and human–machine dimension specification for product adaptability analysis and design. The design platform uses Three js as a 3D engine and



a) Scan to obtain model   b) Filling / model correction/ coordinate adjustment   c) Obtain intersection of feature lines of head mold   d) Mark feature points of 3D space.

Figure 4. Data post-processing for the scanning head model.



(a) 5th percentiles of head (b) 50th percentiles of head (c) 95th percentiles of head

Figure 5. The three female head models of different percentiles of head size.

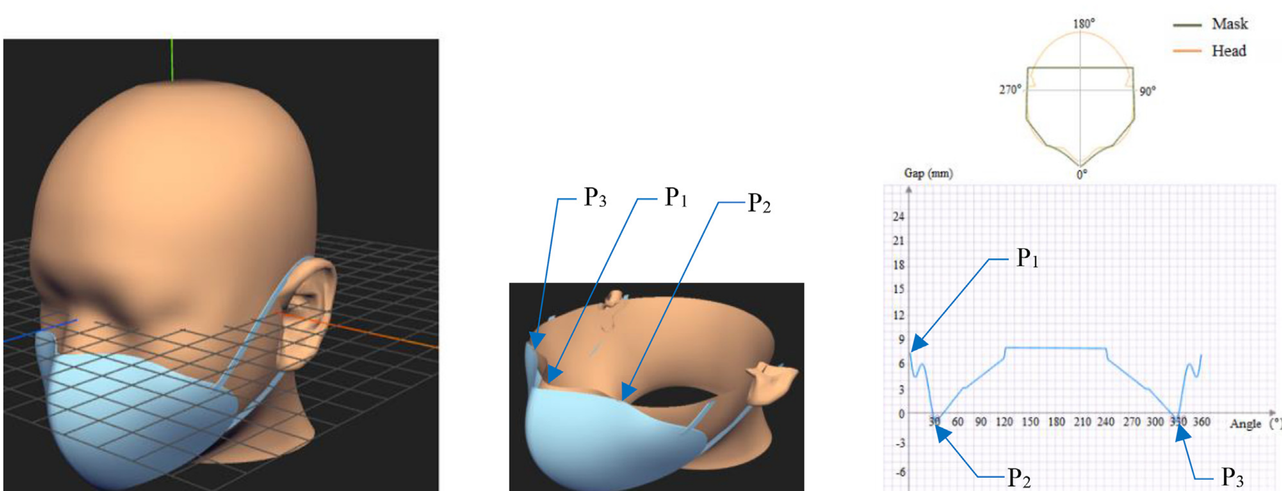
loads the Chinese standard head information into a web page. Designers can directly operate the platform using a web browser to choose the head shape, perform acupoint selection, and adjust the percentile. The web page displays the head feature points and feature sizes relevant to the product in real time. The most important function of the platform is adaptability evaluation, with which designers can intuitively see the gaps and interferences between the standard head shape and the contour of the product for a given section. Based on the analysis data, designers can then apply better dimensions in developing the structure of the product. Furthermore, in addition to the pre-selected digital products available in the platform for functional testing, users are also allowed to import their own three-dimensional models for adaptability analysis. The platform realizes the online preview and analysis of 3D head shapes and digital products mainly through the following technologies.

Based on past user research, competitive product analysis, and user usability principle, the platform provides a set of UIs for designers in the headwear industry, as shown in Figure 7. The proposed platform can be used through www.head3d.net.

The left column of the platform interface displays real-time data on the current head shape, whereas the right side of the platform interface contains the model control column. With this platform, users can intuitively observe matches between the modeling product and standard head shape, perform a series of operations on the model and head shape using the right column, and complete corresponding interactive operations, as shown in Figure 7.

4. Validation

This platform provides 3D head and face data for the design of headwear products, such as eye massagers, masks, and hats. To verify the usability of the service design platform for headwear products, this study selected one popular eye massager for user experience testing.



(a) Wearing mask (b) Create section view by cutting plane (c) Gap curve at cutting plane

Figure 6. The gap curve between the head shape and the product contour on the cutting section.

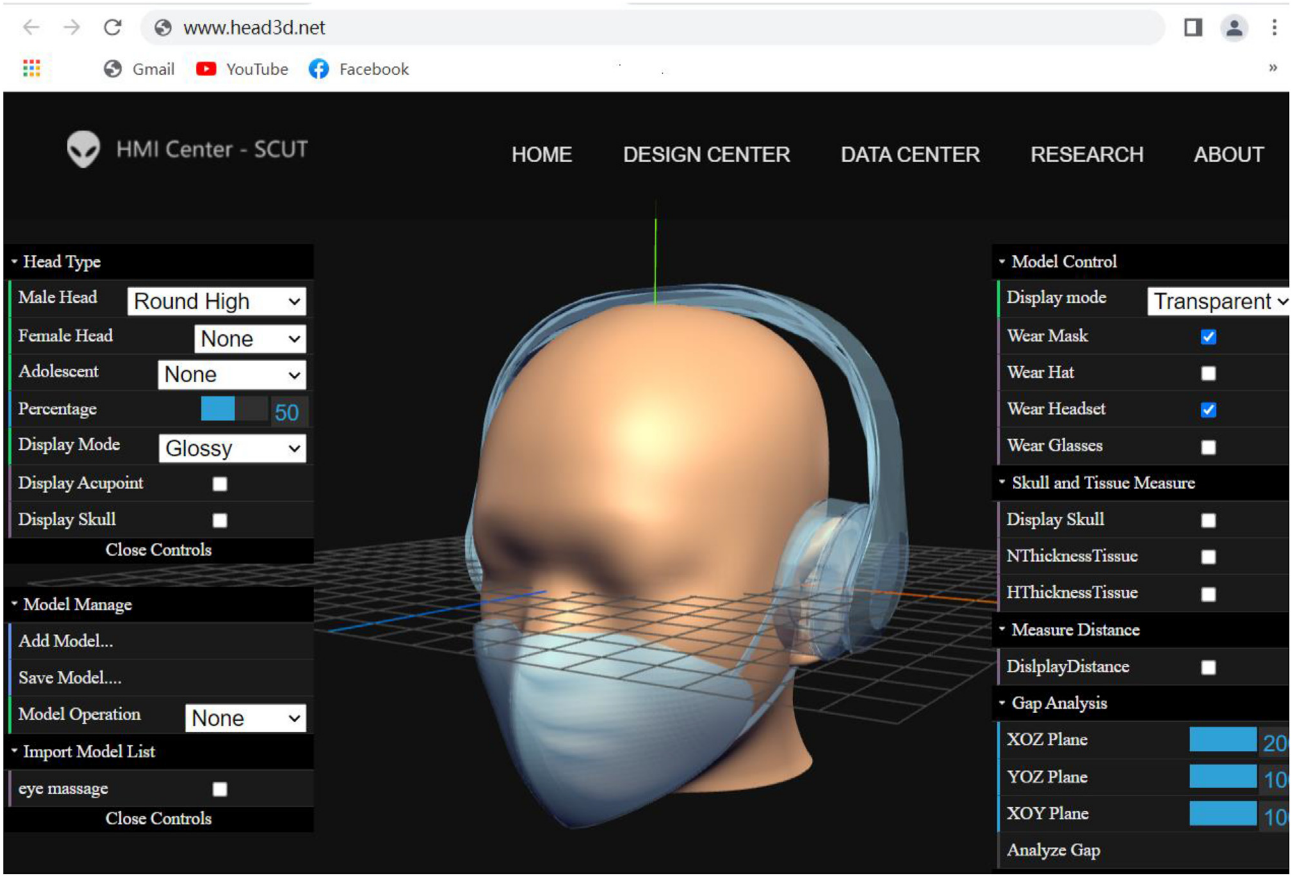


Figure 7. Snapshot of the interface of the propose system.

4.1. User experience analysis

4.1.1. Subject

Fifteen subjects participated in the user experience test. Based on the differences between male and female head shape data, and the fact that the product was optimized based on female head data, all 15 subjects for this test were female. Most of the participants had a bachelor's degree and design-related knowledge background. Thus, they were able to provide professional user-experience feedback. Their average height was 163.22 $\pm$ 3.52 cm, whereas their average head circumference was 49.54 $\pm$ 4.88 cm. Informed consent was received and the study protocol was approved by a university institutional ethics committee based on the Helsinki declarations.

4.1.2. Test product introduction

The selected test product was an eye massager, of brand Nuotai, with dimensions of 180 (L) $\times$ 100 (W) $\times$ 60 (H) mm^3. This product is known to work effectively, looks simply, and enjoys a good reputation and sales.

4.1.3. Data collection type

In this user test on the eye massager, three different dimensions of user experience were tested: eye distance matching degree, nose bridge comfort, and cheek extrusion. After completing the test, the subjects scored the dimensions based on a scale of 0–10 points. The higher the score, the better the experience of comfort. A simple user interview was then conducted to learn the feelings of the users about the product and their expectations for product improvement.

4.1.4. Experimental process

The experimental procedure is summarized as follows:

1) Prior to the experiment, the participants were informed about the objective of the experiment, the content of the evaluation record, and the scoring standard. Afterward, the participants observed and learned the operation of the glasses and the buttons before wearing the glasses. In turn, each user utilized the product according to instructions.
2) Operation instruction: put on the eye protector → turn on → function experience → turn off. This takes about 5 min.
3) Evaluation procedure: After the test, the participants filled in a scoring table, providing scores of 0–10 points for the eye massager based on the three dimensions. The participants provided scores (0–10) for the product with 0 indicated extreme dissatisfaction/discomfort and 10 points indicated extreme satisfaction/comfort. Problems during the user experience raised by participants were also recorded.

4.1.5. Test result

Table 3 shows that the average test scores of the product for all three test dimensions were not high. From observing the behaviors of the users in the process of wearing and fixing the product, and in getting a massager, the study observed that the wearing problems of the users were caused by the poor adaptability of the product. Specifically, the eye massager had support points only for the head. There were no support points on the nose tip and on the three-dimensional surface of the face, and thus the product slid forward or behind after a period of time. Furthermore, some of the participants did not feel an effective massage on the right part of the eye. Some head shapes were also squeezed over a large area, inducing an oppressive and uncomfortable feeling among the users.

Table 3. Product experience test results.

Test dimension	Score (mean ± standard deviation)
Eye distance compatibility	6.667 ± 1.291[#]
Comfort of nose bridge	6.533 ± 1.642
Cheek comfort	6.533 ± 1.807

[#] scores are ranged from 0 (extreme dissatisfaction/discomfort) to 10 (extreme satisfaction/comfort).

4.1.6. Platform fitting analysis

A Reeyee desktop 3D scanner (Wiiboox company, China) with an accuracy of 0.1 mm was used to collect point cloud data of real product. Then, the point cloud data was be denoised, filled with loopholes, and revised models by using software REEYEE PRO. The triangle mesh model of original eye massager was obtained, as shown in Figure 8(b). Based on surface shape and dimension of mesh model of the original massager, a new eye massager was designed, as shown in Figure 8(c). The mesh file of the new massager was converted into the GLB file by using software Blender2.8. The GLB file was imported into the platform for virtual wearing and gap analysis, as shown in Figure 8(d) and (e).

For the sake of convenience in the explanation, this case uses only section plane S for the illustration, as shown in Figure 8(d). In practical application, the user of the software can analyze any gaps for different sections of the product. The gap analysis results on cutting position plane S for the three percentiles (5%, 50%, and 95%) of the female head shape are shown in Figure 9.

According to Figure 8, which shows a result of the virtual wearing of the product, there was a large gap between the product and head, which resulted in a low comfort score. Figure 9 shows that, on section plane, the maximum gap distance between the product and the head shapes of the women for the three different percentiles was 23 mm, whereas the minimum was −3 mm. These gaps caused interferences between the head and the product and led to poor user experience. These data can be used as a reference for the optimization of the product.

The evaluation results for the platform system show that the gap between the product and the head was excessively large, which sometimes caused interferences between the product and the head. The scores for this product test were not high. Therefore, according to the user experience test results and the female 3D model of the headwear product design platform, the product needs to be improved.

4.2. Product optimization design

Based on product structure analysis and feedback regarding user experience, it was determined that there are three main contact parts between the eye massager and the face, namely, the part around the eyes A_1, between the eye massager and the bridge of the nose A_2, and the part between the elastic band and the ear A_3, as shown in Figure 10(a).

Details concerning these three parts in the context of product design are as follows:

(1) The eyepiece setting range of the product is designed based on an adult female pupil distance range of 52–68 mm. In actual use, users can adjust the eyepiece as desired to make the device fit their eyes as far as possible.
(2) To fit the majority of adult female groups, the product is based on the standard female head shape for three different percentiles of head size (5th, 50th, and 95th percentiles).
(3) The overall structure of the product has different pressure effects on the head. The improved product is supposed to disperse the device structure and make the product into a "U" shape to prevent great burden to the face due to the "one line" structure.

In view of the aforementioned problems, the eye massager was optimized, as shown in Figures 10(b) and (c).

4.3. User experience test on optimized product

In this section, information on the user test is divided into two parts: platform virtual wearing evaluation and user experience test.

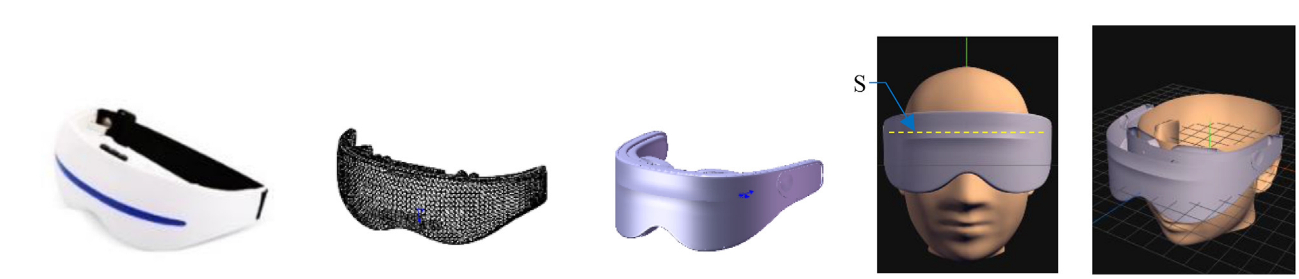
4.3.1. Evaluation and analysis of aided platform

The optimized eye massager model was imported into the aided design platform for headwear products to analyze its fitting. As an example, the cutting plane is same with Figure 8(d). The results are shown in Figure 11.

According to Figure 11, the profile curve of the product for section plane S fits those of the three female head shapes with different percentiles. There were almost no significant gaps or mutual interferences between the product and the head. Excluding a number of special curved surface positions, the gap distances of the three sections were within an acceptable range, with a maximum of 5 mm and a minimum of 0.2 mm. To verify the feasibility of this aided design analysis method, a second user test was conducted on the optimized product.

4.3.2. User experience test

In order to compare the levels of fitting effect of the original and optimized eye massagers. A prototype of optimized eye massager was made (Figure 12). The experimental procedure in Section 4.1 was repeated. The 15 testers who participated in the experiment presented in Section 4.1 were invited again to test and score the optimized product in terms of eye distance matching, nose comfort, and cheek extrusion degree. The results of the analysis processed using SPSS software are shown in Table 4.



(a) Original eye massager (b) Trilateral Mesh model of original eyes massager (c) New eye massager (d) Cutting position of section plane S (e) Gap analysis as wearing product

Figure 8. New massager design and virtual wear analysis.

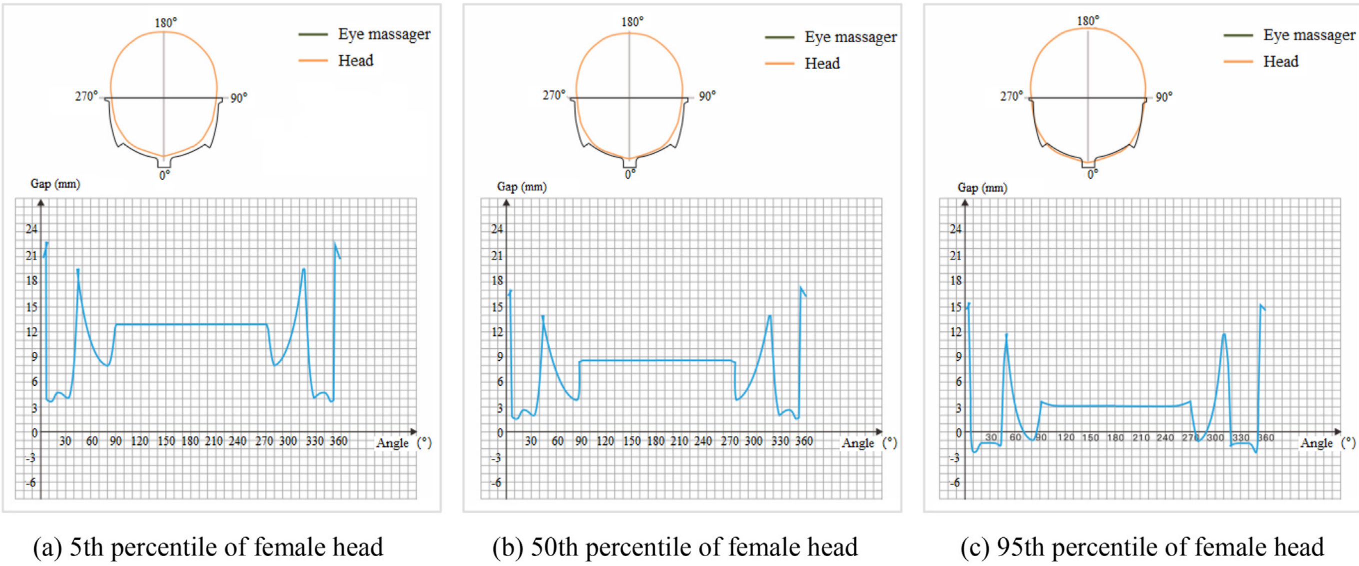


Figure 9. Section gap analysis of new eye massager wear by the three head shapes.

Based on the K–S single sample test statistical analysis in SPSS, the p values of the original and improved products all surpassed 0.05. The data were in accordance with an approximately normal distribution. According to the table, the average test scores for the three dimensions in the two tests had evident differences, and the product scores of the optimized product were significantly improved.

The aforementioned tables show the paired sample t-test results for the three dimensions of the original and improved products. The probability of the t-test on eye distance compatibility was $p < 0.001$, that of the nose bridge comfort was $p < 0.05$, and that of the cheek comfort level was $p < 0.002$. It can be inferred that the evaluation and analysis results from the headwear product design platform had a significant effect on the optimized product in terms of the eye distance compatibility and the comfort of the nose bridge and cheek. Therefore, this study was able to demonstrate that the evaluation analysis results produced by the proposed platform resulted in effective improvements in the adaptability of the product.

4.3.3. Results

It is feasible to optimize a product based on analysis results produced by the aided platform for headwear. The cases presented previously have demonstrated that the eye protector optimized using the platform fits more closely with the head shapes of the users even when the sizes are adjusted. Therefore, the product optimization was able to solve the adaptability problem of an existing product and effectively improve the user experience.

5. Discussion

5.1. 3D head-shape database

The Chinese 3D head-shape database created in this study includes adult male and female head shapes stored in a 3D visualization data format. Users can intuitively observe the differences among different head shapes and those among head shapes of the same category but for different percentiles of head dimensions. The adult male head shape is a digital head shape constructed using 3D modeling software based on the GB 23461-2009 standard issued by the China National Institute of Standards in 2009. This category of head shapes includes 18 types of basic head shapes that are commonly used in product design. Designers can choose the corresponding reference head shape according to the actual design requirements [11]. At present, many universities and research institutions in China have been creating their own head-shape databases. For example, Ball and Molenbroek of Hong Kong Polytechnic University obtained measurements from 135 males and 135 females between the ages of 18 and 70 from seven different places in China and created a high-resolution 3D scanning database of Chinese head shapes [10]. Wang et al. of Hunan University collected three-dimensional scanning data from 2200 people from seven representative cities in China [13]. However, the databases established by the aforementioned research teams still have certain regional limitations. The numbers of samples were relatively small, and these databases are not accessible to the public. Therefore, individual designers have had difficulties in obtaining relevant data

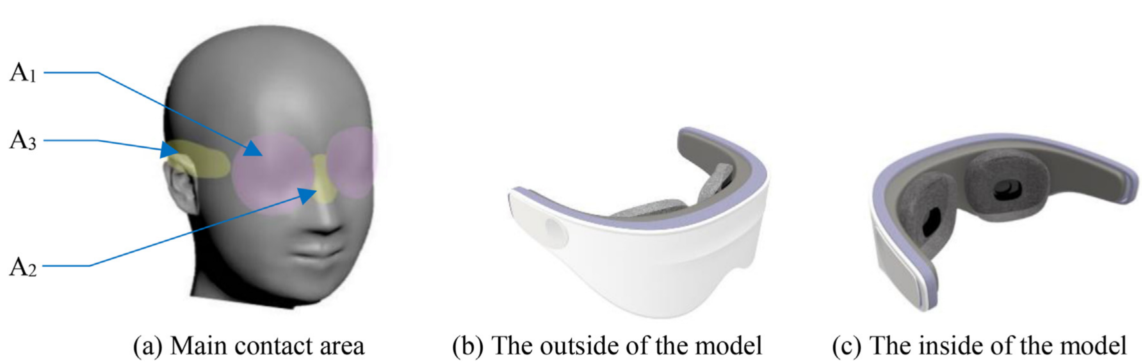
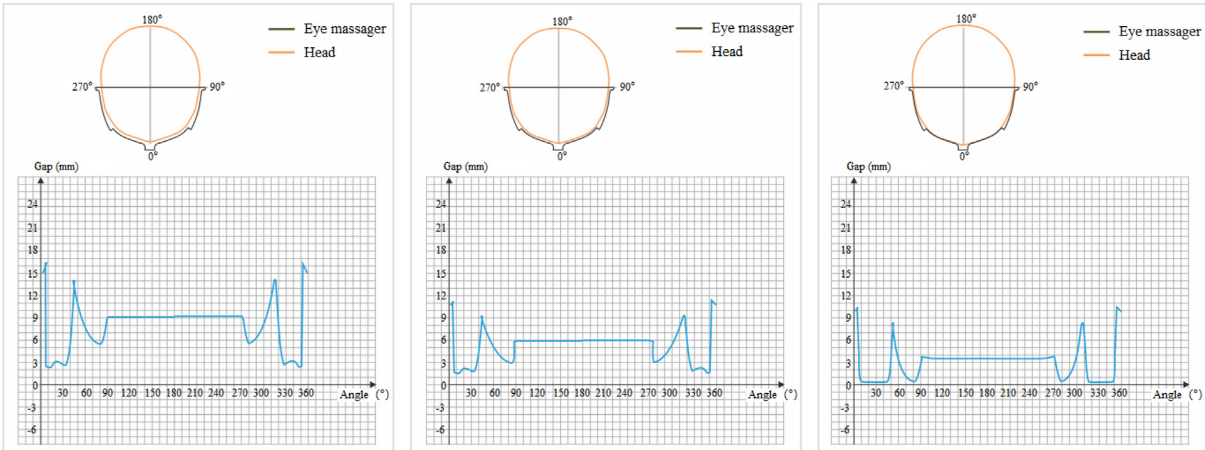


Figure 10. Main contact area and the optimized eye massager.



(a) 5th percentile of female head (b) 50th percentile of female head (c) 95th percentile of female head

Figure 11. Section gap analysis of optimized eye massager based on three head shapes.

(a) Prototype of optimized massager (b) Tester

Figure 12. User experience test on optimized product.

and applying them to actual design work. By contrast, this study collected samples from 15 adult female models between the ages of 20 and 24 years and created a digital model based on the average size of the heads of the 15 subjects. Based on the findings of this research, we will continue to improve on different types of adult female digital models.

5.2. Adaptability analysis

The analysis method proposed in this paper is to first analyze current design methods for a number of mainstream headwear products, summarize the way that they are used, and then analyze how research institutions around the world use human body-size data in the field of product design. Through comparative analysis, it was determined that, at present, most research institutions focus on how to obtain accurate digital human models, but leave some gaps in the classification of human model data and in the application of digital models, which are able to represent a user group, to the actual design work. The method proposed based on this platform can effectively help designers to optimize their products. With the proposed platform, designers will be able to import their designed products into the system, perform virtual wearing, and intuitively see any gaps and interferences between the head shape and the product contour on the cutting section. With these data, they will be able to determine any structural design problems and devise necessary improvements. In addition to the pre-selected digital products available in the platform,

Table 4. User experience test results.

Serial number		Score (points)	P value of K–S test	t	SIG (two tailed)
Eye distance matching	Original massager	6.667 ± 1.291	0.101^{c}	−6.820	0.000
	Optimized massager	8.533 ± 0.915			
Nose point comfort	Original massager	6.533 ± 1.642	0.101^{c}	−4.380	0.001
	Optimized massager	8.067 ± 1.223			
Cheek comfort	Original massager	6.533 ± 1.807	0.060^{c}	−3.836	0.002
	Optimized massager	8.400 ± 1.056			

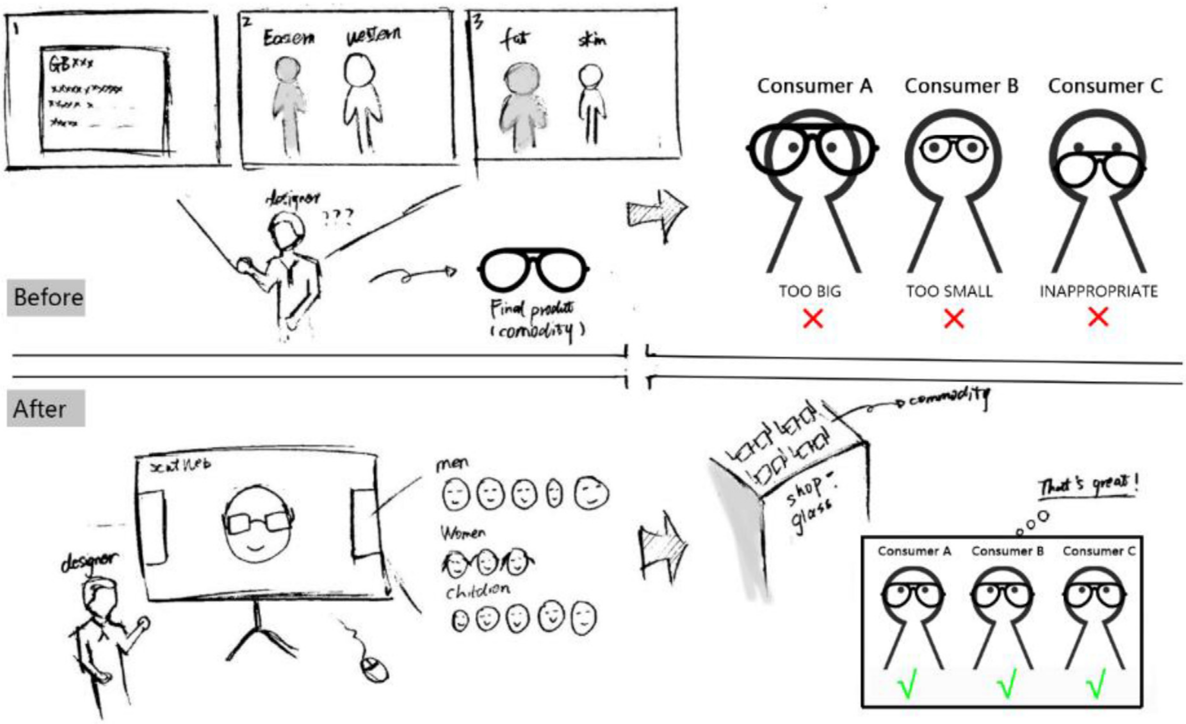


Figure 13. Example application display of proposed platform.

users are also allowed to import their own three-dimensional models for product adaptability analysis.

However, despite the good results demonstrated in this study, the type of user group represented by the digital model constructed in this study is presently limited. In follow-up research studies, we will have to include more representative models for the platform to fulfill the many design needs of product designers.

5.3. Resulting improvements

This paper proposes a user representative digital head model platform that can assist designers in optimizing and improving the adaptability of wearable products. In this study, an eye massage was used to demonstrate the usability of the platform. The results show that the improved product is more suitable for the human body curve. Unlike many other competitive products, this platform supports users in importing their own designed products. In this platform, designers can virtually wear their products on a Chinese standard human head mold. Furthermore, using the gap adaptability calculation function provided by this platform, designers can quickly check for product adaptability problems. Through continuous iterative optimization design, a final product design with improved user experience can be achieved. At present, the spacing function for fitness detection supports only one-way (YOZ axial) analysis, whereas the other axial position can be analyzed and viewed only through the sectioning function. This will be optimized in the subsequent version iteration.

5.4. Example application of platform

In the past, designers were limited to using two-dimensional data and national standard data. Thus, the resulting products were unable to fulfill the comfort requirements of most users. The auxiliary design platform constructed in this study for headwear products can help designers in the headwear industry improve the final user experience. The proposed platform, which will be made available online, provides standard three-dimensional human body data models and adaptability evaluation related functions. Several of the problems of most designers concerning the development of headwear products can be resolved using this platform. (1) Presently, the reference data are not intuitive, and most of them are presented in the form of words, which cannot be used directly by designers. (2) Much of the reference data are not accurate, and most designers still refer to western anthropometric data, which are often inapplicable to users of other ethnicities. (3) The characteristics of the crowd exhibit variations, whereas information regarding the human body found on the Internet is generally not accurate. Thus, the resulting models are not fully representative of the human race.

The online display of human body data and the online analysis function for product adaptability provided by the platform developed through this research, as shown in Figure 13, can effectively help designers improve the comfort of their products.

6. Conclusion

First of all, the base and category of the Chinese standard 3D head type measured and constructed in this research study are limited in terms of applicability. Therefore, future studies on this research topic are expected to include more head-shape data of different age groups and genders and to classify the head type varieties more systematically, such as adding more screening conditions (e.g., area, gender, and age) to fulfill the different needs of headwear product design. Furthermore, personalized design elements can be implemented on the platform at the same time.

In this study, we constructed a headwear product service design platform based on Chinese 3D head-shape data. Information regarding relevant research studies around the world and in-depth interviews with designers have shown that a number of fitting problems are caused by the inability of designers to use Chinese standard head shape data. In view of this problem, this study developed a platform with which virtual trial wearing of digital products can be performed online, and that provides a series of visual operations for product adaptability testing. Moreover, the newly developed service design platform is able to adapt to different client systems and terminal devices, dramatically improving the user experience. The platform is expected to contribute to the better management and sharing of Chinese standard digital head-shape data, the establishment of systematic service tools, and the more widespread use of Chinese 3D standard head shapes in product design.

However, there were some limitations in the current study. For example, we used only the Chinese head database in our validation. Thus, this study was conducted with a specific focus on a Chinese population, which may have limited the generalizability of the findings. To sufficiently investigate for a wider variety of products and consumer demographics, the inclusion of cross-cultural differences in anthropometry is recommended. To collected more 3D head data of Chinese females for updating the female's head models of the proposed platform can improve the representability. Moreover, the head models of the proposed system were developed according to Frankfurt plane. The proper alignment of the heads is important for headwear product design and fitting. Providing different alignment strategy of head for design different headwear products is needed. It should be noticed that the term “size” of the study was referred to a percentile of head circumference. The 5th and 95th percentile of head in this study might not been interpreted as a 5th or 95th percentile of all head dimensions, because of no human exists with all 5th or 95th percentile of head dimensions. If a real human has a 95th percentiles of head, that means he/she might have a few 95th percentiles dimensions on the headfrom but others would be lower the percentiles.

Declarations

Author contribution statement

Zhelin Li: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Xianghong Deng: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Yu-Chi Lee: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Lijun Jiang: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Guangzheng Yu: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Jiaxu Fan: Performed the experiments; Analyzed and interpreted the data.

Funding statement

Zhelin Li was supported by Natural Science Foundation of Guangdong Province [2021A1515010934] and the Fundamental Research Funds for the Central Universities [No. 2022ZYGXZR104].

Data availability statement

The data that has been used is confidential.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

We are grateful to all the students who participated in this experiment for providing us with valuable data.

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