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Three-dimensional human head modelling: a systematic review

Parth Shah and Yan Luximon

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

ABSTRACT

Human head is one of the most important parts of the body, as it houses brain and other sensory organs, which controls functioning and working of the whole body. The products used for head and face are designed for functions like protection, information transfer, healthcare or to improve the aesthetic appearance. In order for them to serve their purpose, they need a close fit and in order to make it more ergonomic, user's comfort also needs to be addressed, thereby making it necessary to acquire accurate anthropometric data for ergonomic product design. Traditional techniques involve manual measurement using tapes, callipers and scales which normally have low reliability and low accuracy. With the advancement in image processing and computer aided designing and modelling techniques it has become possible to develop highly accurate and reliable 3D head and face model. Following paper presents a systematic review of different approaches that have been proposed for developing 3D head and face model and also the techniques used in processing and analysis of 3D data and their limitations. The paper also presents application of head and face models for ergonomic product design.

KEYWORDS
3D modelling; human head; 3D scanning; anthropometry; alignment

Relevance to human factors/ergonomic theory

With the advent of 3D modelling techniques, it has become easier for product designers to use 3D anthropometric data to design and develop ergonomic products with improved comfort and with better fit. In this manuscript, the authors have tried to conduct a systematic review of existing technologies and parameters which are considered for 3D modelling of human head and face. The paper also explains the analysis techniques and methods used to study shape variation amongst head models which can help in deciding of optimal sizing and grading parameters for a product.

Introduction

Human head is considered to be one of the most important regions of the body as it houses the brain, which controls and monitors working of the whole body. It also houses various sensory organs (Farkas 1994; Waugh and Grant 2010). Most of the products related to head and face are designed for the purpose of protection like the helmets, mask, etc., or for healthcare application like the respirators, hearing aid, etc., or for information transfer for example earphones or for aesthetics purpose like the spectacles, caps etc. These products need to have a close fit with the body in order to serve their purpose effectively. Also if the product needs to be worn for a long duration of time, user comfort has to be considered. Hence for designing of ergonomic products related to head and face, highly accurate anthropometric data of head and face is required. Anthropometric measurements can also be useful in understand morphology of certain medical conditions (Farkas and James 1977; Hammond et al. 2004) and can help in developing customised ergonomic orthotic products. Traditionally anthropometric data was acquired using measurements which were manually recorded using tapes (Zhuang and Bradtmiller 2005; Vasavada, Danaraj, and Siegmund 2008), scales, callipers (Yokota 2005), Hertel exophthalmometer (Quant and Woo 1993) etc., which are time consuming and consist of human errors as the soft tissues get deformed while measurement procedure (Fourie et al. 2011). The ability of accurately locating landmark and measurements depend on the expertise of the technician using the equipment and hence may lead to less reliable results (Kouchi and Mochimaru 2011). Also with the complexity in the contour of human body surface it is very difficult to acquire accurate anthropometric data using traditional techniques (Shah et al. 2016). With the advancement in image processing techniques it has been made possible to develop three-dimensional (3D) head and face models by using multiple images clicked from different angles or by using images acquired from medical imaging techniques which are more easy, robust and accurate (Bubb 2004; Ozsoy et al. 2009) like computed tomography (CT) and magnetic resonance imaging (MRI). Also with advent of 3D scanning systems and advances in computer-aided designing (CAD) it has been possible to develop highly accurate 3D head and face models. Large database of individual head models can be used to develop a generalised head model depicting a specific ethnic group or a group of people belonging to same nationality or location. This can be helpful in developing customised ergonomic products for people belonging to specific group or location in order to achieve good fit and better comfort.

Many researchers have used 3D anthropometric data for designing of various products (Niu and Li 2012) since this can provide accurate shape and contour of the head and face. In order to design a product for a large target population it is essential to understand the variance in the shape and size amongst the population to acquire the optimal product dimensions for sizing and grading of the product, making it necessary to analyse the shape variation amongst the target user population.

While analysing the shape variance for a set of 3D point cloud data the type of alignment technique used for the process plays a major role. Many different alignment methods have been used by researchers like modified principal component analysis (PCA) method (Venkatesh, Kassim, and Murthy 2009), alignment based on Frankfurt plane (Luximon, Ball, and Justice 2010) and iterative close point (ICP) alignment technique (Luximon et al. 2016). Alignment techniques have been used for applications like 3D face recognition (Amor et al. 2005). Accurate alignment can help in developing a better and accurate 3D generalised head and face model for designing products, making it an essential parameter to be considered.

Following paper aims at presenting a systematic review in the area of 3D head and face modelling considering all the key parameters explained above. The paper evaluates the advantages and limitations of techniques currently used for development of 3D head and face models for product design and also the different processing and analysis techniques involved. Paper also summarises the applications of 3D head and face modelling in ergonomic product designing and other fields.

Methodology

Search strategy

For the study PubMed database, PMC database, ScienceDirect database and OVID database were searched and reviewed. Articles consisted of articles from peer reviewed journals, technical reports, conference proceedings, reviews and case studies. The timeline selected for the study was from January 1980 to December 2016. Articles accepted for publication in upcoming edition of peer reviewed journals were also included in the search. The initial search was carried out using ‘3D modelling', ‘Anthropometry', ‘Human head' keywords. No language specification was specified during initial search. A data base was developed by articles collected from the search.

Inclusion and exclusion criteria

The database developed was first checked for any duplication. Duplicate copies were excluded from the database. A language check was performed to exclude all the articles which were not in English. Current study was focused on articles related to head and face. Titles and abstracts of the retrieved articles were analysed at the first stage. The inclusion criteria selected for the first stage was: studies related to 3D modelling of human head and face and its applications. The full text of retrieved articles was thoroughly read. The inclusion criteria at the second stage included relevance to one of the following focused key areas: 3D modelling techniques, alignment techniques, 3D data processing techniques, shape variation study and application design. Exclusion criteria at this stage included study of 3D modelling of specific regions or organs like ear and lip; studies based on simulation models; studies based on skeletal models. The reference list of every selected article was hand searched to check for any relevant article which could be included in the study, resulting into addition of one article.

Results

Total sixteen articles met the inclusion criteria for the study. Figure 1 depicts the flow diagram of the process followed for systematic review. All the articles included for the study focused on one of the decided key areas. An overview of all the selected articles is provided in Table 1.

From the list of selected articles six articles discussed different 3D modelling techniques including CT, MRI, fusion of CT and MRI, use of two images, stereophotogrammetry and 3D scanning techniques. Two articles described most commonly used alignment techniques based on selection of three points on the Frankfurt plane and ICP technique. Two articles focused on 3D data processing, one of which described PCA which was found to be most commonly used in the studies, whereas the second article described usage of

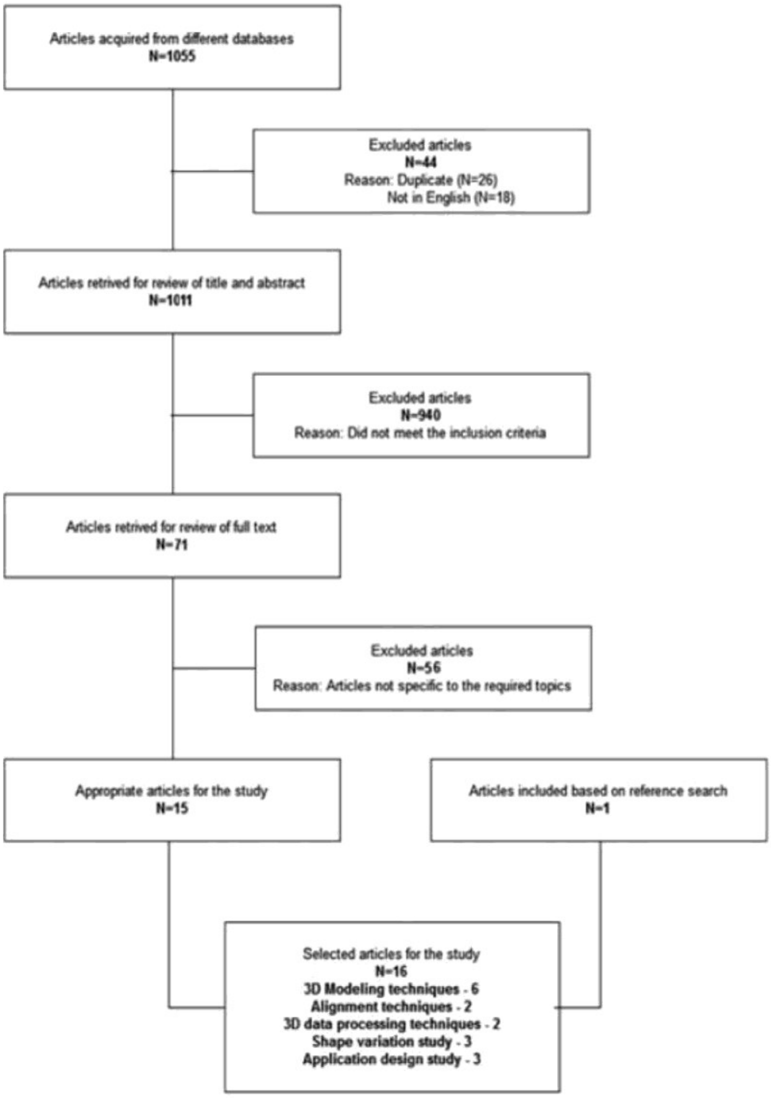

Figure 1. Flow chart of the systematic review process.

bi-cubic B-splines techniques based on laser scanning technique. Proposed study also included three articles on study of shape variation in Chinese population and U.S. civilian workers. It also included an article comparing Chinese and Caucasian face. The study also included three articles based on use of 3D model for designing of ergonomic products with better fit and comfort, and applications involving use of 3D head and face model for face recognition and finite element analysis to understand the impact of head injuries.

Discussion

In the age of user centre product design, they have been a keen interest in considering ergonomics and human factor parameters while designing products. Traditional

Table 1. Overview of sixteen articles selected for the study.

Author	Technique used for data collection	Equipment used	Technique used for data processing	Application/ Purpose of the study	Population studied	Number of subjects/scans
3D modelling techniques:						
Xia et al. (2000)	CT + three 2D images	GE® Pace CT scanner, camera with Medical-Nikkor® lens	Polygonal surface rendering algorithm	Surgical planning and simulation		10
Lin and Wang (2012)	Two 2D images	Digital camera	Feature extraction, body shape deformation	Development of 3D body models		30
Yang et al. (2014)	CT + MRI	Not specified	Reconstruction using Segmentation, Manual alignment	To develop Finite Element head model for study of impact head injury	Singapore Chinese	1
Galantucci et al. (2014)	Stereophotogrammetry	5 DSLR cameras	PCA	To study correlation between PCA results for beauty and results of beauty contest	Italian	64
Lacko et al. (2015)	MRI	Philips ACSIII 1.5T Scanner	PCA	Study of male and female head scalp anthropometry, design of BCI headset	Western	100
Liuetal. (2015)	3D scanning	Cyberware rapid 3D digitiser	PCA	Manufacture of better fit respirators	Chinese	350
Alignment techniques:						
Kouchi and Mochimaru (2004)	Plaster mould + 3D digitiser, 3d scanning	FaroARM Bronze digitiser, VOXELAN 3D scanner	Alignment using Frankfurt plane, MultiDimensional scaling	To analyse 3Dface form variation, to show usefulness of 3D data for product design - spectacle frame	Japanese	56
Luximon et al. (2016)	3D scanning	Cyberware 3030 3D colour laser scanner	Alignment by ICP method	To develop an accurate head model including ear shape	Chinese	10
3D data processing techniques:						
Zhang and Molenbroek (2004)	3D scanning	3D laser scanner	bi-cubic B-splines technique	To design a new interpolation techniques for 3D point data to develop 3D model		1 (CAESAR database)
Gotoa et al. (2015)	3D scanning	3dMD face system	PCA	To study variation in the children's face, helpful for designing applications	Dutch	307
Shape variation study:						
Ballet al. (2010)	3D scanning	Cyberware 3030 3D colour laser scanner	PCA	To study shape variation between Chinese and Caucasian head shape	Chinese and Caucasian	1200 scans (CAESAR & SizeChina database)

(continued)

Table 1. *(Continued)*

Author	Technique used for data collection	Equipment used	Technique used for data processing	Application/ Purpose of the study	Population studied	Number of subjects/scans
Luximon, Ball, and Justice (2012)	3D scanning	Cyberware 3030 3D colour laser scanner	Alignment by plane created by 3 reference points	Development of 3D homologous head and face model	Chinese	144
Zhuang et al. (2013)	3D scanning	Cyberware rapid 3D digitiser	Alignment by using landmark points, PCA	To study shape variation in US. Civilian workers, helpful for designing respirators with better fit	American	1169
Application of 3D head model:						
Amor et al. (2005)	2.5D images	Not specified	ICP method	3D face recognition		Database of 20 3D models
Bai k, Jeon, and Lee (2007)	3D scanning	Vivid 900 laser scanner	Software based 3D anthropometric measurements	Facial soft tissue analysis	Korean	60
Skals et al. (2016)	3D scanning	Artec Eva ™ 3D scanner	Alignment by using three planes	Designing of bicycle helmet liners for improvised fit	Multiple ethnic groups	122

techniques have been found to be less efficient as compared to 3D modelling for acquiring 3D anthropometric data. Since products related to head and face need to be in close contact for making sure their purposes are served, a good fit is one of the most important requirement. Along with fit, user's comfort is also one of the key parameters which need to be considered. Use of highly accurate data can help increase the comfort and improve the fit, which can affect user experience. A study by Luximon and Shah (2017) elaborates on the change in user perception of comfort and fit for head related products based on the accuracy and precision of the 3D scanners.

Bubb (2004) describes the need of use of 3D models. He explains how it can be used not only for anthropometric measurements, but also for contact-less body posture measurements and simulation studies to understand various effects of forces applied on the area. This can help in evaluating prototypes of designed products before testing it with users. One such example is Joint Prosthesis Design (JPD) conducted by Testi (2005), where they developed software to simulate the prosthetic stem and host femur to understand the compatibility. In addition, while considering applications in medical science, where there is need of customisation, patient specific models are required. In such situation usage of 3D models can be of great help. Hence, 3D models have found their use in the fields of ergonomic studies, making it necessary to explore in details the different parameters associated with it.

The most widely used techniques for developing 3D human models include use of either medical imaging data like CT and MRI, use of multiple 2D images taken in different planes or use of 3D point cloud data obtained from 3D scanning using different 3D scanners. Several studies have been conducted using fusion and combination of two or more of the above techniques.

CT data consist of accurate skeletal information of a region. It is acquired in form of slices and can be reconstructed using various 3D image processing software like MIMICS and Slicer. Various studies have been carried out using CT data to develop 3D models of various parts of human body like head and foot. The accuracy of CT data depends on the slice width and distance between two slices. The acquired images are very high quality images but it consists of use of ionising radiation hence it is can be harmful to other cells of the body. Also since it can provide only 3D data of the bone structure, it has to be used in combination with other techniques like MRI (Yang et al. 2014) or along with using multiple 2D images or using surface images obtained from the structured-light scanning (Qiu et al. 2011) so as to acquire an accurate 3D head model. Whyms et al. (2013) used CT data of a mandible to understand the effect of CT scanner parameters and 3D volume rendering techniques on the accuracy of its measurement.

MRI provides detailed information about the soft tissues of the body which is acquired using magnetic field and radio waves. It does not involve use of ionisation radiation hence is preferable over CT. But MRI cannot be performed on people who have metallic implants or pacemaker in their body. Badin et al. (2002) came up with a technique to develop 3D linear articular models of tongue, lips and face based on MRI and video images. Also Lacko et al. (2015) used MRI data to develop a head model which they used to evaluate human scalp anthropometric model.

Both CT and MRI data fail to provide textural details of the body region and also details about human hair. For acquiring accurate CT and MRI images the individual needs to be stable and avoid any movement. Since the time for scanning is long there are chances of change in facial expressions, leading to artefacts in the data. Hence it is very difficult to use this technique for developing 3D head models for children. Time taken for rendering CT and MRI based DICOM image files to develop a 3D model is longer as compared to other techniques. CT and MRI are costlier than other techniques and are mostly used for medical scenarios for planning or simulation of surgeries. Many researchers have used existing database of CT and MRI for their studies. But the existing number of databases are very limited and mainly consist of data obtained from adults, hence it is very difficult to generalise them and use them while working on children (O’Connor 2005).

Various studies have been carried out using either two or three 2D images taken in different planes at the same time to develop 3D models. These techniques use detection of key reference anatomical landmark and helps in measurement of key anthropometric data useful for development of 3D models (Hammond et al. 2004). Such studies use techniques similar to Free Form Deformation (FFD) (Mochimaru, Kouchi, and Dohi 2000) and use of localised deformation (DeCarlo, Metaxas, and Stone 1998) to develop 3D model based on acquired data and by using a generic 3D human body model template. Similar technique was proposed by Tang and Huang (1996) based on a template matching algorithm and use of geometric transforms on the generic head model. This can help in generating of 3D models with hair and proper textural details. Li et al. (2013) developed 3D head model with the hair style details and also soft tissue details like wrinkles. But it is very difficult to acquire an accurate 3D model as most of the data of the shadowed region like the area beneath chin, area behind ear is lost. Human face is not completely symmetrical, hence there are some errors introduced while trying to use one front image and one side image. This technique takes very less time for obtaining the data, but it takes a large amount of time for processing the data to obtain 3D model.

To improvise the accuracy of the scan various researchers have tried to use stereophotogrammetry technique in their studies (Galantucci et al. 2014; Dong et al. 2010; Heike et al. 2010; Harder et al. 2013) for developing 3D models. In this technique multiple high resolution cameras are arranged in a fixed setup and images from all the cameras are taken at the same time. Using different algorithms, the images taken from different angles are projected over each other, overlapping of these images help in development of a 3D model. To improvise the accuracy of the 3D, model the number of cameras need to increased, but with the increase in number of images the time taken for rendering of data increases considerably. The loss of the data in the shadowed region can be reduced by better positioning of the cameras and designing a proper posture for acquiring the data, in order to achieve the best possible images for reconstruction. Dong et al. (2010) performed an anthropometric analysis of Chinese nose using data acquired using stereophotogrammetry. One of the limitations of this technique is complex arrangement. Due to use of multiple cameras and other required system there are multiple wires which need to be taken care of, hence the setup requires a proper laboratory arrangement. Any change in the camera position can lead to artefacts while developing a 3D model. The accuracy of this technique would also be affected by the ambient lighting in the room. This technique can be very useful in developing 3D head models of children as it consumes very less time (Harder et al. 2013). Heike et al. (2010) developed a guide for facial image acquisition using stereophotogrammetry which systematically analysed different issues faced during use of stereophotogrammetry techniques and possible practical solutions for the same.

3D scanning has been extensively used in various studies (Bush and Antonyshyn 1996; Kovacs et al. 2006; Liu et al. 2015) for developing 3D models. The accuracy and the precision of the data depend on the type of scanner used for the study. Different types of 3D head scanners are available. The older version scanners like Cyberware 3030 laser scanner consist of a rotating scanner arrangement where the person to be scanned sits in the centre and the scanners rotates to acquire a complete 360-degree view of the individual. The scanning time for such scanners is approximately 1-2minutes. The data acquired is of very high quality but the problem with this scanner is it cannot scan the shadowed areas and also the hairs. Other scanners like the structural scanners or scanners like Artec Eva are hand held and depending on the efficiency and skills of the user can help acquire an accurate 3D head model. These hand held scanners can help in acquiring data even in the shadowed regions. But being optical scanners they cannot scan human hairs, hence the individual to be scanned needs to wear a tight fit cap so as to acquire the scalp data. Structural scanners are less accurate as compared to optical and laser scanners. Artec Eva hand held scanners impounds flashing light while scanning which can be uncomfortable and needs to be avoided for scanning people with epilepsy. The scanning time for these scanners is around 2-5minutes. The textural information can also be acquired by using this technique. This can be further processed to develop 3D model. Shah and Luximon (2017) reviewed the different types of 3D scanners used for scanning head and face. Since the data acquired is quite huge in size (in Giga bytes) the data processing time is comparatively larger as compared to any other techniques. The limitation of 3D scanning is errors introduced due to movement of the person to be scanned but many 3D processing software have algorithm to remove or reduce such artefacts. Tomaka et al. (2005) evaluated the accuracy of 3D scanning and defined the conditions for its usability in the field of orthodontics.

The 3D data acquired by most of the above stated techniques are in the point cloud format. Most of the 3D modelling software use triangulation (Luximon, Ball, and Justice 2010) or polygon based techniques to develop 3D model. The accuracy and the precision of the model are proportional to the number of triangles or the polygons. Zhang and Molenbroek (2004) designed a technique using bi-cubic B-spline interpolation method to develop 3D head model from the raw point cloud data.

To study multiple 3D head models to understand the shape variance and to develop generalised head model for a specific ethnic group or based on countries or region, there is a need of proper alignment of all the 3D head models. Manual alignment is time consuming and leads to errors. Many studies use multiple reference anatomical landmarks or use reference planes to achieve a better alignment. Most commonly used plane is Frankfurt plane consisting of 3 anatomical landmarks including left infraorbitale, left and right tragions (Luximon, Ball, and Justice 2010; Kouchi and Mochimaru 2004). This is implemented using 3D modelling software. The other technique used to achieve accurate alignment uses ICP method (Luximon et al. 2016; Amor et al. 2005). ICP method consists of two set of point cloud data where one set acts as a reference set, whereas the second point cloud data set tries to iteratively transform to minimise the difference between the two sets to achieve the best match or overlapping. To achieve ICP-based alignment coding can be done in software like MATLAB for simplification.

To perform shape variance study PCA is implemented over a 3D head model database comprising of large sample size PCA is a statistical analysis technique used to identify the similarities and difference within a set of data. It can be used to identify pattern in a data and hence can be used to deduce an optimised model. The input variables for performing PCA comprise of the 3D coordinates of all the vertices, based on which Eigenvalues, loading matrix and score for principal components are evaluated. These are used to understand the variation amongst the head shape of multiple 3D head models. PCA has been successfully used by researchers to analyse the shape variation amongst Chinese population (Liu et al. 2015), American population (Zhuang et al. 2013; Zhuang, Benson, and Viscusi 2010), Caucasian population (Olsen 2003). The generalised model developed is specific for the selected database and cannot be termed accurately as the generalised model representing the whole population which is not covered in the study. PCA has also been used to understand variation between head shapes of Chinese and Caucasian individuals by Ball et al. (2010). Various surveys and databases related to head shape and sizes have been developed for African-American (Hu et al. 2007), American (Zhuang, Benson, and Viscusi 2010), Australian (Skals et al. 2016; Perret-Ellena et al. 2015), Chinese (Luximon, Ball, and Justice 2012; Ball 2011; Du et al. 2008), European (Hu et al. 2007), French (Coblentz, Mollard, and Ignazi 1991) and Korean (Baik, Jeon, and Lee 2007) population for designing and development of product specific to people belonging to a specific ethnic group or location. To study the head shape variation, Kouchi and Mochimaru (2004) used a distance matrix by calculating distance between landmarks and evaluated it using MultiDimensional Scaling using SPSS software to calculate independent variables (scales) that resolve the distance relationship between the subjects.

Most of the products manufactured by companies in the America and Europe use the anthropometric data of local population (Yang, Shen, and Wu 2007). Hence the products designed by these companies don't have a good fit for Asian population. With the advent of 3D scanning it has become easy to manufacture customised ergonomic products with better comfort and fit for people based on the use of 3D anthropometric data. Various products like helmets (Guo, Wang, and Dong 2009; Catapan et al. 2015), eyewear (Kouchi and Mochimaru 2004), mask (Gotoa et al. 2015), brain computer interface headset (Yokota 2005), electroencephalogram (EEG) headset (Lacko et al. 2017), apparels (D'apuzzo 2007) etc. have been designed for customised population based on the 3D anthropometric data. 3D head models have also be used for performing surgical simulations and planning (Farkas and James 1977). 3D face recognition is also one of the potential application of 3D head and face models (Amor et al. 2005; Zhang et al. 2014; Russ, Boehnen, and Peters 2006).

Also while designing products specific to a region it is reasonable to use partial head and face data related to that region instead of using the whole 3D head scan, so there is a need of developing localised 3D head and face model based on the products used for that region. There is a need to also study the difference in product designing based on localised head and face model and generalised head and face model.

Conclusion

Compared to traditional manual measurement techniques, 3D anthropometric measurements acquired from 3D models are more accurate, reliable and less time consuming. With the advances in 3D scanning systems and data processing techniques in last few decades, it has been seen that many designers have tried to use 3D models of human head and face to develop ergonomic products with better comfort and fit. The paper tried to present a systematic review of current scenario of 3D head and face modelling studies and evaluated different techniques and processing methods used at present. The paper described the advantages and limitations of all the techniques used in developing 3D model. With optimisation and further advancement in the field of CAD the scope for research and ergonomic product designing would be increased tremendously.

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Notes on contributors

Parth Shah is a PhD student working on 3D head and face modelling of Chinese people at the Asian Ergonomics Design Lab in School of Design at The Hong Kong Polytechnic University. His key areas of interest include Ergonomics, product design, biomechanics and orthotic and prosthetic design.

Yan Luximon obtained her PhD in ergonomics from The Hong Kong University of Science and Technology. She is currently an Assistant Professor and the Asian Ergonomics Design Lab leader in the School of Design at The Hong Kong Polytechnic University. She is also the Council member of the Hong Kong Ergonomics Society. She has been active in design research and teaching. She has published several book chapters, patents, international conference papers and peer-reviewed journal papers.

ORCID

Parth Shah http://orcid.org/0000-0002-2562-0578
Yan Luximon http://orcid.org/0000-0003-2843-847X

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