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Chapter 56

Application of 3D scanning in design education

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1. Ergonomic design based on 3D scanning in our education

1.1 Insole design

One of our master's degree students had to design an insole for a Spanish company, Instituto de Biomecánica de Valencia (IBV). He did several biomechanical and anthropometrical experiments to find the best requirements for insoles and to add comfort to a shoe during walking. One extra requirement was to design an insole that did not fit in other shoe brands. Research included walking sessions with different insoles to measure the dynamic pressure distribution, size, 3D shape, and other biomechanical characteristics of the foot to analyze the physical interaction between the foot and the floor during walking in the IBV laboratories. The result was an innovative insole including up to six layers of different materials that create an upright foot and comfortable gait pattern (Pizá Padial, 2009) (Fig. 56.1).

1.2 EXO-L, ankle protector

Ankle sprain injury is a worldwide problem, and although the use of braces reduces the accident risk during sports, athletes often reject them as a preventive measure due to the introduced discomfort and inflexibility. A simple idea evolved during this graduation project into a tested proof of principle, accompanied by the application of a patent. The project's success depended on a thorough analysis of the functional ankle anatomy and the conventional brace market. This project resulted in the EXO-L company that produces 3D printed and made-to-measure products based on the 3D scan of the ankle of the customer (Fleuren, 2011; Moldenbroek, Fleuren, & Klein Rensink, 2013) (Fig. 56.2)

1.3 MI-TP cast

After 3 years of teaching master's degree students how to use 3D scanners for industrial design engineering (Molenbroek & Goto, 2015), a graduation project was initiated with the objective to make a hand−arm orthosis from 3D printed material based on a 3D scan. Traditional plaster material has some disadvantages, for example, the inside of the plaster bandage could be warm and humid, a surgical suture is not possible, taking shower is difficult, and all these discomforts remain during a considerable time. With the Grasshopper software, a plug-in for Rhino 3D (Robert McNeel & Associates, Seattle, WA, USA), an open structure of the hand−arm orthosis was created and 3D printed as a first prototype (Leon Loreto, 2016) (Fig. 56.3).

1.4 Customized bra

The goal of this project was to design a customized bra based on 3D scans of the bust area. The first idea developed during a masters' degree project was to use the 3D scan of the breast in an ideal position according to the female user. The 3D

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FIGURE 56.1 Insole of six-layers-different material (Pizá Padial, 2009).

FIGURE 56.2 EXO-L worn above the ankle and connected to a running shoe with a strong shoelace.

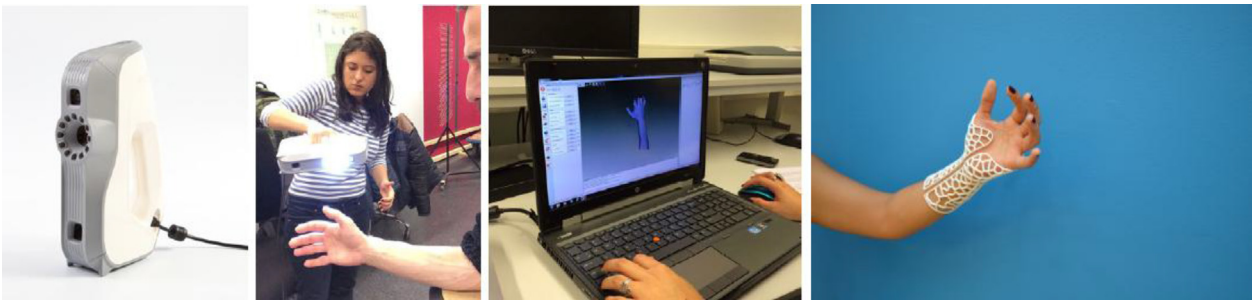

FIGURE 56.3 The usage of Artec-Eva 3D body scanner on the left picture, and at the right, an example of the 3D printed open-structured lower arm orthosis.

FIGURE 56.4 Model showing 3D printed Bra of Lidewij Twillert.

scanned image was systematically applied to produce a 3D printed part that was implemented for customizing a part of the bra. This idea was further developed in a business plan by a start-up company, MeshLingerie. However, the first idea seemed not yet profitable. Therefore, a second business plan is now used with an algorithm that matches a 3D breast scan with a variety of bras currently available on the market so that the user can find the most suitable bra that has good fit and is comfortable (Twillert, 2015) (Fig. 56.4).

1.5 Helmet design

In this master's degree project, the assignment was to design a helmet for adults with an attractive shape and good fit for a company, EGG, which was known as a producer of helmets for children. The student developed an algorithm using the Rhino 3D's Grasshopper plug-in, and the algorithm was able to compare large quantities of 3D scanning data of head shapes retrieved from the Civilian American and European Surface Anthropometry Resources (CAESAR) data. To analyze these scans to find a helmet liner that would fit a cluster of head forms, the student created an envelope around an overlay of these head forms and optimized the thickness of the foam accordingly to meet the safety regulations (Seggelen, 2015) (Fig. 56.5).

FIGURE 56.5 Picture of a helmet design showing inside–outside cut on the left, and on the right, the chosen helmet with two different prints.

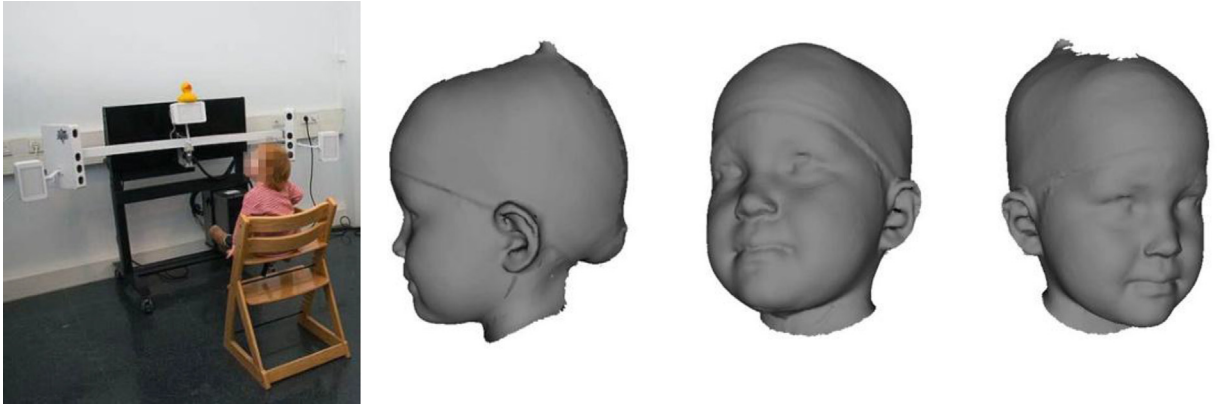

FIGURE 56.6 3dMD head scanner with the test person as an example showing how the investigation was done (left), and an example of the outcome of 3D scanned head forms (right).

1.6 Anthropometry of children's face for face mask design

As part of a PhD research project, a survey was conducted to collect anthropometric data of children's heads and faces for the development of a medical ventilation mask for young children. A total number of 303 Dutch children (128 girls and 174 boys) aged 0.5–7 years were recruited through health centers, primary schools, and the university. Traditional anthropometric measurement techniques were combined with the 3D scanning of children's heads and faces captured using the 3dMD 3D scanning system (3dMD Ltd., London, UK). By combining these two techniques, it is possible to study the shape variation of the children's faces as well as mapping the variation of the relevant dimensions for mask design (Goto, Molenbroek, & Goossens, 2013) (Fig. 56.6).

1.7 Aerodynamic recumbent bicycle (human power team)

Each academic year, a team of master's degree students attempt to develop the fastest human-powered vehicle to compete in an annual international contest: Human Powered Vehicle Challenge. The maximum speed in 2013 was 134 km/h with only the power of one person with a bullet-shaped bike. In this project, we tried to optimize the room, called the foot box, which is the minimum space required for a complete peddling cycle. The boot box requires comfortable movement of the legs and feet while the athlete is in almost lying position. The foot box was designed based on 4D scanned images of the leg movement of the athlete captured by the 3dMD full-body scanner with 40 frame-rates per second (Fig. 56.7).

1.8 Virtual fit mapping

Fit mapping is a method that measures the relationship between the body and product so that ease of use and adaptations are scientifically based (Robinette & Veitch, 2016; Wright-Patterson et al., 2009). Fit mapping can be performed to ensure a product design is properly designed in terms of comfort, efficiency, and safety to make decisions including form and

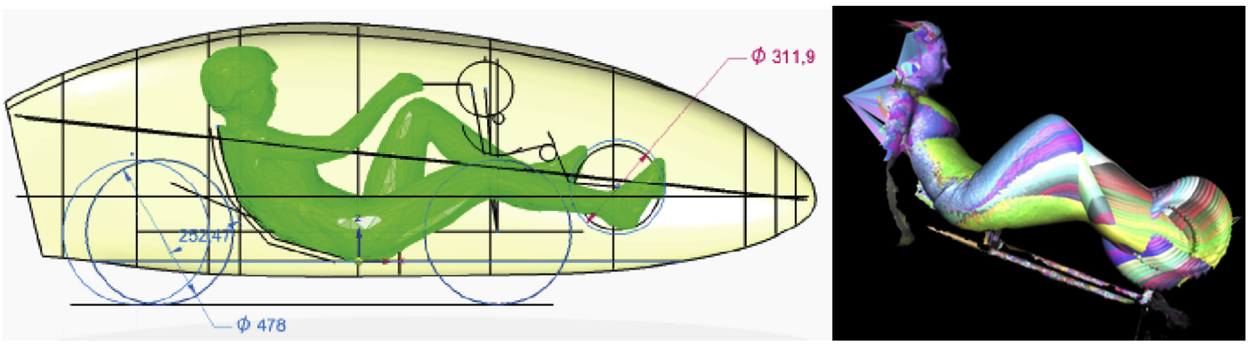

FIGURE 56.7 The posture of the pilot in the human-powered vehicle (HPV) bike (left). The image of the superimposed 4D scans showing the required leg room for the HPV pilot (right).

sizing of the system. This method is relevant for products that need to fit close to the body, for example, helmets, masks, goggle, or wet suits for surfers. For fit testing in the traditional way, many participants who represent the widest variability of the target group may be needed, besides prototypes or samples of each size of the product. With the availability of 3D scan data from populations, a virtual fit mapping becomes useful and convenient for fit testing.

The steps of this method will be described based on a test with Samsung VR Glasses and the Decathlon's Easybreath mask for snorkeling. Fit mapping starts with the definition of fit. For the virtual reality (VR) glasses, it starts with the question how tight the product needs to fit to prevent light leakage into the glasses, which can cause unwanted reflections. The Easybreath mask needs to fit watertight, which is an even more strict demand of fit. Contrary, both the glasses and the mask need to provide a certain level of comfort, which means that the straps cannot be too tight which could cause too much pressure on certain areas on the face. Anatomical knowledge is important to understand which places of the head can bear some pressure and which places are more sensitive (superficial arteries, nerves, etc.). What also needs to be done is to find the dimensions of the product which determine the range of accommodation for each size. For the Easybreath mask, it is the face length (distance between the sellion and menton); the key sizes are necessary to be able to select the (3D scans from) the persons who represent the target group (widest variability).

It is important to place the scanned VR glasses or the Easybreath mask on the 3D scan of the face in such a way that the product is placed in a natural way. To build up experience with virtual fit mapping, we first tried to copy a real-life situation in the digital world. We used the following procedure (Fig. 56.8): scan the product, scan the face with the product, scan this face without the product, place identical markers on both faces, and align the "face-only" to the "face-with-product" scans. Later, the "product-only" scan is aligned, and the face with the product can be deleted; this will end up with the product virtually placed on the face in a natural way. Now the distances between the face and product can be measured as the fit mapping was carried out using Artec Studio (Artec 3D, Luxembourg) and Geomagic Design X (3D Systems, Rock Hill, SC, USA) (Fig. 56.9). Further study is ongoing to find the appropriate fit characteristics between a product and the face for comfortably wearing a product.

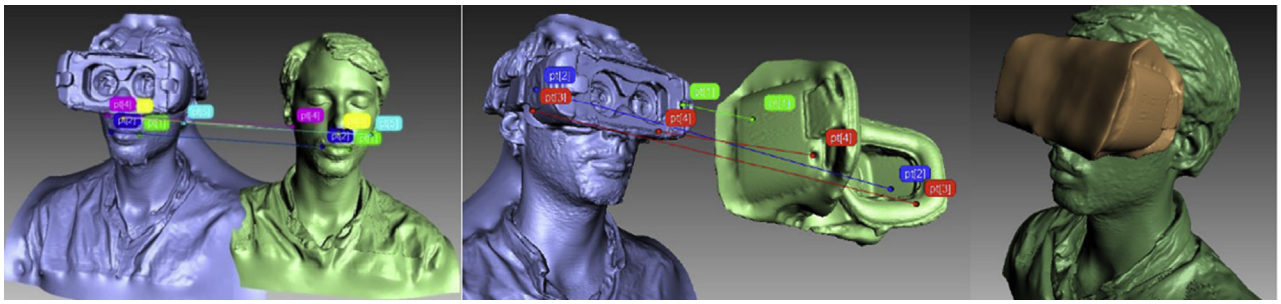

FIGURE 56.8 Example of student work when trying to virtual fit the Samsung VR glasses. From left to right, align face-only to face-with-product scan, align product-only to face-with-product scan, delete the face-with-product scan, and finally, you end up with product-only scan aligned to the face-only scan.

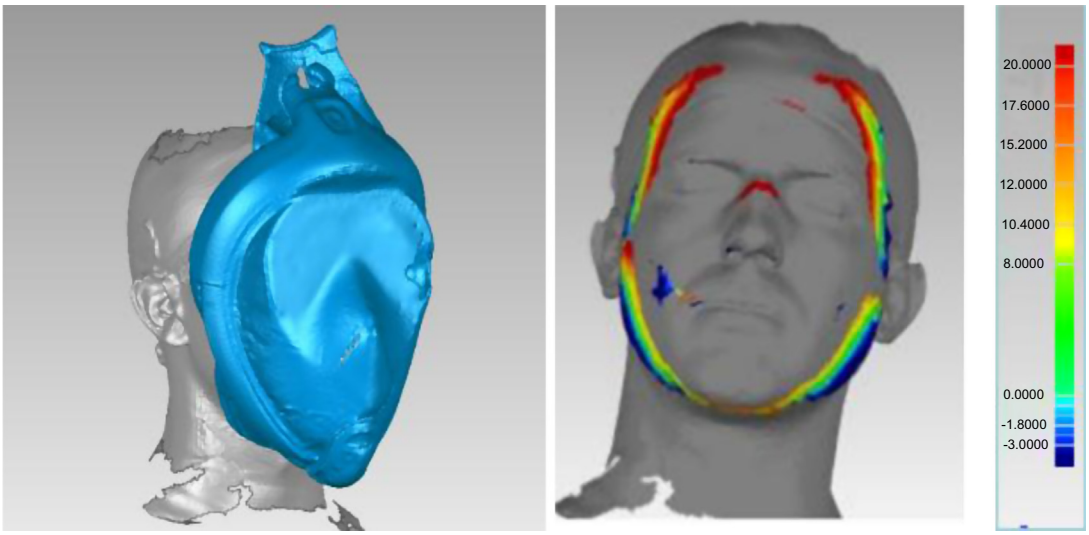

FIGURE 56.9 Example of student work when trying to virtual fit the Decathlon's Easybreath mask and calculate distances between the mask and face.

1.9 Three-dimensional hand scanner

Smakman was the first master's degree student working on the yet unfulfilled need for an affordable way to 3D scan human hands. After trying to 3D scan hands during the yearly ergonomics practicum using the Artec-Eva scanner (Artec 3D, Luxembourg), we identified as teachers that it was not student-friendly enough; however, it was possible for an experienced staff member to 3D scan hands. The idea was now to ask another master's degree student to create a new low-cost and student-friendly hand scanner so that no training will be necessary to make a perfect 3D hand scan. This resulted in a first working prototype and a graduation thesis (Smakman, 2015). The resulting proof of concept design was further developed in two additional graduation theses, one focusing on the core scanning technology and the other on the user experience (de Vries, 2016; Hilhorst, 2016). This has resulted in a prototype scanner design, a broad selection of insights into capturing a 3D model of the hand, and a user experience design concept that need to be further integrated. Thereafter, Weiss (Weiss, 2017) did further tests with the user interface and solved several software issues, resulting in a 3D scanned hand with an accuracy that can compete with the quality of our 3dMD scanner. While the 3D hand scanner study has been studied by multiple master's degree students in our faculty, a start-up company, Manometric (https://manometric.nl/), was started in 2018 by Smakman for 3D printed hand−arm orthoses using the invented hand scanner. More details of this hand scanner are provided in the upcoming paragraphs.

2. Three-dimensional hand scanner

In the past decades, 3D scanning enabled many new applications, such as for instance, aerial scanning and mapping cities in 3D, scanning products for quality control, and scanning of small insects for biological research. Among those applications, acquiring a fast and affordable 3D scan of human hands is to help industry and researchers in accelerating the anthropometric measure process, and developing personalized products. The hand is one of the most complex structures of the body. Consisting of 27 bones, of which 14 are located in the fingers (Taylor & Schwarz, 1995), it is very dexterous with 27 degrees of freedom (Elkoura & Singh, 2003) and has complicated functions. On the other side, the hand steadiness depends on age (Martin et al,. 2015), gender (Endo & Kawahara, 2011), and other factors. This poses challenges on 3D digitization techniques (Karatas & Toy, 2014), especially on low-cost 3D scanning, which always need several seconds, or even up to minutes, to measure a complete 3D scan.

Many techniques were developed for 3D scanning, ranging from structured light scanners to computed tomography (Das et al., 2017). Among those techniques, close-range photogrammetry has several distinct benefits such as the short data-acquisition time and contactless data acquisition, which make it especially suitable for scanning human hands (Fryer, Mitchell, & Chandler, 2007; Luhmann, 2010). Recent technology advancements in digital cameras, embedded systems (Raspberry Pi), and computational algorithms make 3D scanning on close-range photogrammetry more accurate, affordable, and salable. In this section, we introduce a dedicated hand scanner, which is built on the close-range photogrammetry technology. Fig. 56.10 presents the scanner. The scanner is designed around a light box, and 52 camera modules are installed. Each of this camera modules is a Raspberry Pi 2B computer with its camera module V2 (8 megapixels, Camera module) as shown in Fig. 56.10B. In Fig. 56.10C, the principle of the layout of the modules is presented where a typical human hand is placed in the center of two rings of cameras. On the hand, 140 points, which resemble critical features of the hand, are marked. The cameras are set in such a way that any of these 140 markers will be "seen" by at least three cameras, i.e., for each point, it is located in the depth of the view of at least three cameras to guarantee enough "redundancy" in the 3D reconstruction. Based on this principle, we identified that 52 camera modules were needed, and an extra Raspberry Pi 2B computer with a touch screen is used as the "Master Pi". The Master Pi interacts with the user through a touch screen user interface (the front screen in Fig. 56.10A). Those 52 camera modules and one master computer are connected by a network topology presented in Fig. 56.10C.

Interaction with the scanner itself is designed to be very straightforward. Before a capture, the user is able to input key information about their personal details. Then top and side live previews are presented on the screen, as shown in Fig. 56.10A. These two views help the user to align their hand to the center of the scanner as illustrated in Fig. 56.11A. After proper alignments, the user is able to start scanning by pressing a button (with the other hand), and then Master Pi synchronizes all 52 camera modules to ensure that 52 images are captured simultaneously. The 3D reconstruction is conducted in several steps. Images are registered together based on featured points (Fig. 56.11B), and the matched feature points are used to generate a sparse point cloud. The sparse point cloud is then iteratively optimized toward a dense point

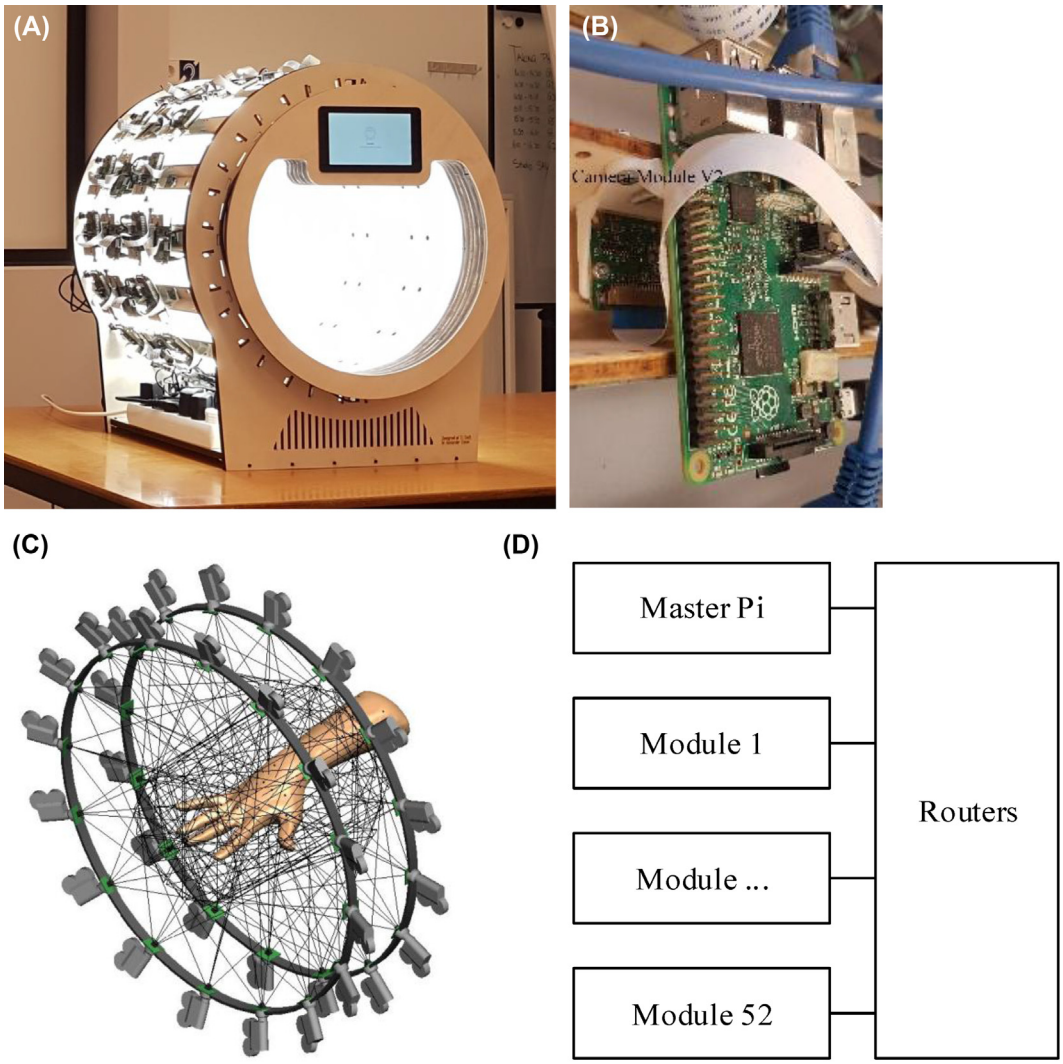

FIGURE 56.10 Hardware setup of the hand scanner. (A) The scanner, (B) the camera module, (C) the design principle, and (D) topology of the connection.

cloud, which generally contains one to two million points. Finally, a mesh can be generated based on the point cloud. Implementation of the 3D reconstruction software program is based on the application programming interface (API) of Agisoft PhotoScan. On average, the process takes 10−15 min with an Intel Core i7 2.6-GHZ processor; however, it varies a lot among different types of images, i.e., the skin properties of the hand. The 3D reconstruction results of different subjects with various skin properties can be found in Fig. 56.11C. The results show relatively good and consistent scan quality. Major defects may occur with very fair skin and younger participants (Fig. 56.11C). The user can improve the quality of a mesh by postprocessing, e.g., by using Geomagic Design X.

To verify the accuracy of the proposed hand scanner, a mannequin hand was scanned using an Artec Spider (accuracy up to 0.05 mm) as the baseline. Then the same mannequin hand was scanned 8 times using the proposed hand scanner. For each scan, the mannequin hand was held in a different position within the scanning volume. This is similar to the procedure defined in ISO Standard, 20685-2 (ISO, 2015). The acquired images were processed following the designed procedure, using background-based masking, and then converted into meshes. The root mean square (RMS) of the absolute distances between the two surfaces (i.e. the error) was calculated as 0.42 ± 0.07 mm. For the signed distance, it was 0.21 ± 0.19 mm (Fig. 56.12).

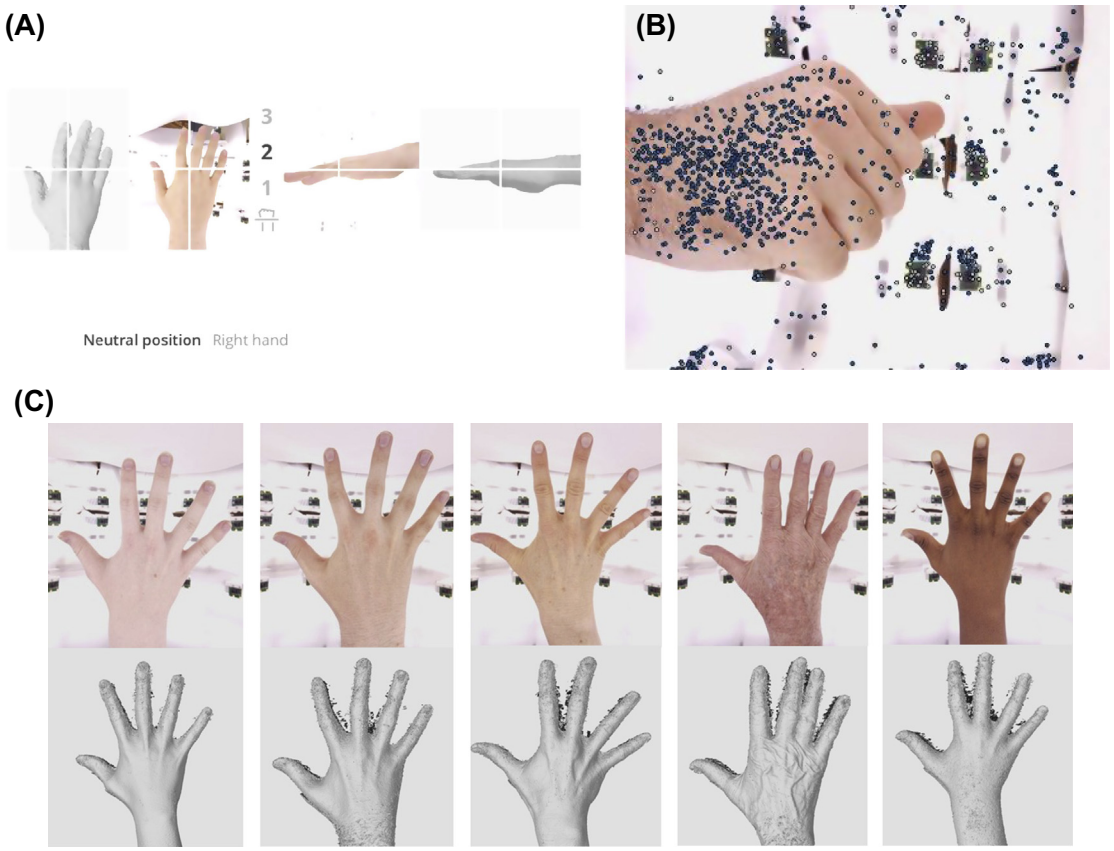

FIGURE 56.11 Reconstruction of hand shapes. (A) The user interface helps the user to position their hand. (B) Feature points extracted from one image (without mask). (C) The 3D scans of different subjects with different skin properties.

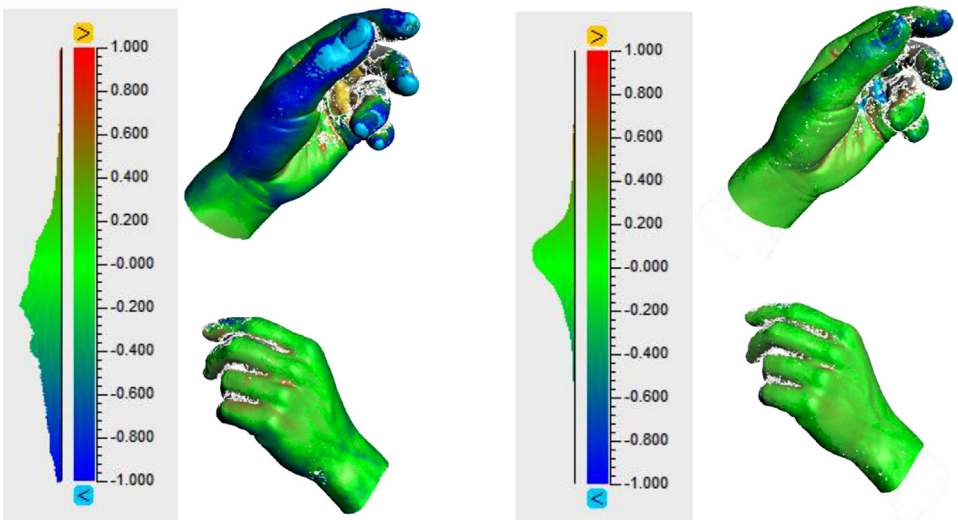

FIGURE 56.12 Distance maps between the 3D scans and the baselines (left: first scan, right: third scan).

3. Processing of 3D scans for the application in product design

Once 3D body scan images are gathered, the images are processed and analyzed for a certain design purpose. A raw 3D scan image generally has incomplete features such as uncaptured areas, noise, or nonoptimal mesh structure that need to be edited in order for the raw 3D image to become more useful for product design (Goto et al., 2015; Lee, 2013; Lee, Jung, & You, 2013; Lee et al., 2017). Editing is conventionally done by using one or more image-editing software programs such as Geomagic (3D Systems, commercial), Artec Studio (Artec 3D, commercial), GOM Inspect (GOM GmbH, noncommercial), MeshLab (Institute of Information Science and Technology, noncommercial, open source), and MeshMixer (Autodesk, noncommercial) and by applying functions such as hole filling, noise reduction (or smoothing), and mesh optimization (or remesh) that are generally provided in these types of software programs. Because each software package has pros and cons, we recommend students to try out different types of software programs depending on their design work.

After image editing is completed, the size and shape of 3D body scan images are analyzed. First, anthropometric landmarks are normally marked on the 3D images by referring to ISO in which the landmarks locations are defined (Goto et al., 2015; Lee, 2013; Lee et al., 2013, 2017). Those landmarks are necessary for the extraction of anthropometric measurements as well as the analysis of shape and its variations. Based on the landmarks, different types of anthropometric dimensions are often measured: point-to-point distance (e.g., biacromion length), surface distance (e.g., bitragion−menton length), or circumference/arc (e.g., waist circumference). Most of aforementioned 3D image-processing software programs provide features for measurements on 3D images. Computer programming is very helpful to measure thousands of 3D scan images efficiently (Lee, 2013). Matlab codes for the anthropometric measurements are shared by one of the authors for educational purposes at https://github.com/HandongHCI/3D_Anthro. The summary statistics (e.g., mean, standard deviation, minimum, maximum, and percentile) of the anthropometric measurements have been conventionally used in classroom to understand the body size of a targeted population as well as to define product sizes. To efficiently analyze anthropometric measurements and to easily find representative models from the CAESAR database, which consists of 2D and 3D anthropometric data of more than 4000 people, a sizing analysis tool (Fig. 56.13A) was developed and has been used for education. The website www.dined.nl (Fig. 56.13B) offers a system that can provide Web-based anthropometric analysis. A sizing system (e.g., small, medium, large, or extra-large sizes for clothes) is often considered to separate the size and shape of a designated product into appropriate categories. Accommodation percentage, number of sizing categories, sizing formation methods, and tolerance of each sizing category of a sizing system are important factors that need to be considered for product design (Lee, 2013; Lee, Jeong, Park, 2013).

Sometimes, one or more of 3D images among the 3D scan database are chosen and used in a product design. Those selected 3D images are also known as representative human models (RHMs). These 3D images represent the 3D scan database in terms of size and shape (Lee, 2013; Lee et al., 2016). The RHMs simply can be average models of each sizing category. To assist students in determining the RHMs from CAESAR and to apply these RHMs into their product design, we developed a software program that can calculate RHMs in terms of a few body dimensions related to their product design. The RHMs are useful for determining the size and shape of a designated product through a computer-aided design (CAD) software program such as Rhino 3D and SolidWorks (Dassault Systèmes SolidWorks Corporation, Waltham, MA, USA). Next to the RHMs, all the 3D images in a 3D scan database can be used in the product design process to find an optimal design that fits as many individuals as possible. Surface curvatures (e.g., cross-sectional arcs of the wrist) extracted from all the 3D images in a database can show the variation of the shape and size of the body part in a different way (Lee, 2013; Lee, Lee, Kim, 2015a, 2015b). For example, the shape and size variations of the wrist provide information of how a wrist-band−type product should be shaped.

The 3D body scan images are applied not only for the product design but also for evaluation of a design. As mentioned previously, virtual fit mapping is one of the methods used for design evaluation (Lee, 2013; Lee et al., 2015a; Lee & Jung, 2016; Lee & Yang, 2016). The fit of a form of a product (e.g., a shape of a 3D scanned image of an existing product, a CAD model newly designed by students) can be virtually evaluated by fitting them onto 3D scan images using the Artec Studio or Geomagic software. A fit map, which shows the fit characteristics in different colors, is often assessed to visually check the fit or design appropriateness (Fig. 56.14).

www.dined.nl

FIGURE 56.13 Computerized tools for efficient analysis and visualization of huge amount of anthropometric data. (A) A computerized tool for sizing analysis and representative model search for the CAESAR database, (B) www.dined.nl.

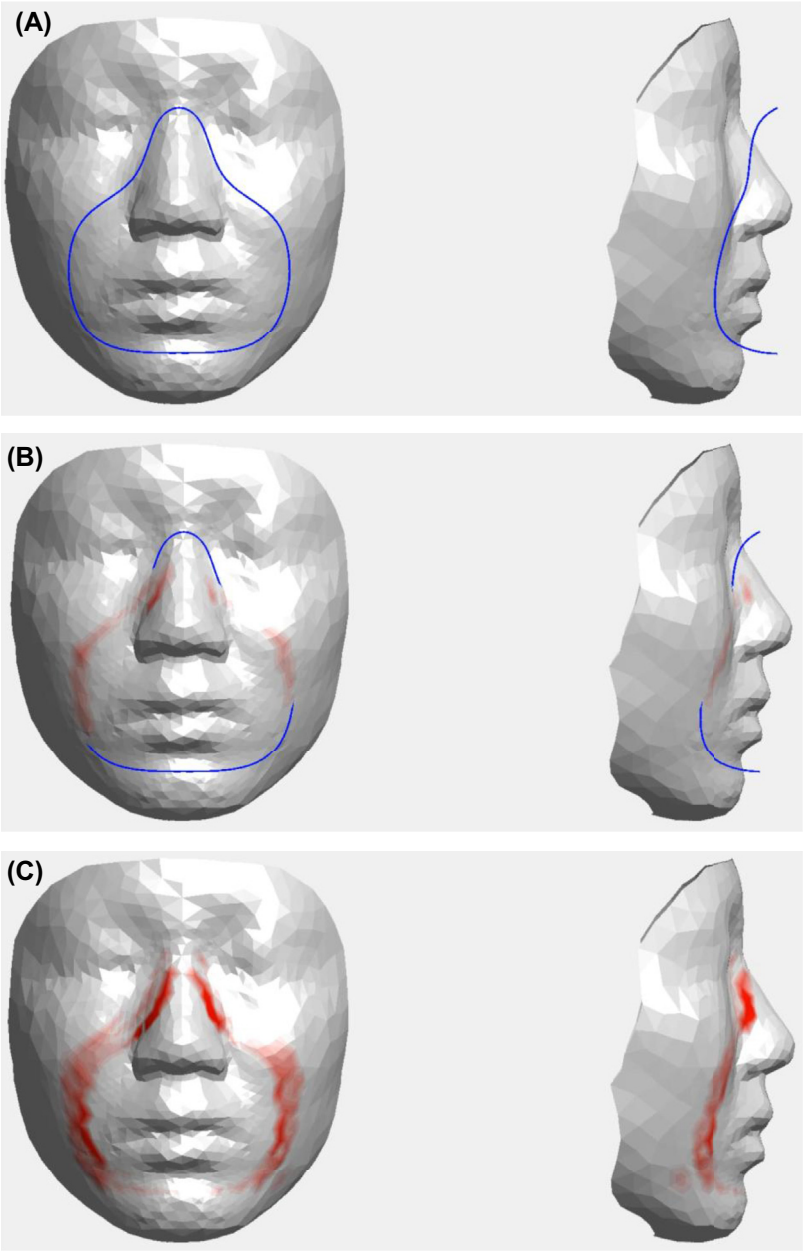

FIGURE 56.14 The estimated contact pressure between the template-registered face and the mask defined as a curvy shape (illustrated). (A) A face not in contact with the mask curvature: no pressure. (B) A face partially in contact with the mask. (C) A face fully in contact with the mask.

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