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Contact Pressure Analysis for Wearable Product Design

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Abstract. 3D body scanning has been used broadly including digital human modeling, simulation, ergonomic product design, and so forth. This research used template-registered faces of 336 Koreans in order to use them to design an oxygen mask that provides good fit to Korean faces. The finite element analysis method is applied onto the template-registered faces to predict the contact pressure of a mask design onto different faces. The average and variation of the estimated contact pressure values among all the Korean faces were analyzed for evaluation of the appropriateness of a mask design for Koreans. The proposed method can be usefully applied to find an optimal shape of wearable products for a specific target population.

Keywords: 3D face scanning · Finite element analysis · Pressure estimation Ergonomic product design

1 Introduction

3D body scanning and its analysis technologies have been usefully applied in studies on the ergonomic design of a form of a product. A 3D scanned image of a human body contains not only anthropometric dimensions (e.g., length, width, circumference) but also complex dimensions such as arcs, cross-sectional curves, surfaces, areas, and volumes. A product design based on those 3D shape characteristics of the human body has resulted in gaining a better fit and increased comfort, satisfaction, and safety for the users. Especially, a wearable product such as an oxygen mask, a full-face mask for snorkeling, or a VR headset needs to have an ergonomically designed shape, which can fit well to a certain amount of a target population.

An optimal shape of a design component can be determined by analyzing contact pressure occurring between the design component and 3D models. Lee et al. [1, 2] proposed a method for virtual fit analysis to find an optimal design of a pilot oxygen mask which accommodates the Korean Air Force pilots (n = 336). However, the contact pressure was not systematically considered with the virtual fit analysis method in their study. The finite element (FE) analysis techniques have been introduced for the

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contact pressure estimation of a product using 3D body scan images [3–5]. However, the previous FE studies used only a few body models (say, one or two) for the pressure estimation of a product, while various shape of the human body which can occur different contact pressure characteristics was not fully considered.

This study is aimed to develop a design method of an ergonomic wearable product based on numerous 3D body scan database and finite element (FE) analysis technology which is applied for estimation of contact pressure between a 3D body scan image and a design of a product.

2 Methods

2.1 3D Face Scans

3D face scan images of Korean Air Force pilots collected by Lee et al. [6] were used in this study. 3D faces of 336 pilots (male: 278, female: 58; age: 20 s to 40 s) were scanned using the Rexcan 560 (Solutionix Co., South Korea) 3D scanning system.

Landmarking and alignment were applied on 3D face images. 14 anthropometric landmarks were identified on the 3D face area to measure 22 facial dimensions related to designing the medical face mask. All 3D heads were aligned with the origin point at the sellion landmark, then aligned with two vectors (one vertical vector parallel to the Y axis and passing through sellion and supramentale and one horizontal vector parallel to the X axis and passing through left and right tragion) [2].

2.2 Template Model Registration

A template face model having appropriate mesh structure was prepared with considering the FE analysis, then all the 3D faces were template-registered using a non-rigid ICP registration method. Template registration, a computer graphic method, is one of useful technique that makes different 3D body scans having same vertex points and mesh structure. In this study, first, a symmetrized template face model having 1,340 vertex points was sophisticatedly generated by hand based on an average-sized face (see Fig. 1) using the RapidForm 2006 (INUS Technology, Inc., Korea) image processing software. Facial area related to the mask design (e.g., around nasal bridge, nasal side, chin) has denser vertex points than the other facial areas. Deformation and template model registration methods were applied to earn template-registered face images using the Matlab (MathWorks, Inc., Natick, MA, USA) programming. A hybrid registration approach proposed by Lee et al. [7, 8], which is using the bounded biharmonic weights (BBW) mesh deformational algorithm and non-rigid iterative closet point (ICP) registration to individual 3D head scans was used in this study. The hybrid registration approach which consider landmark's location by the mesh deformation algorithm and the registration methods could provide the accurate correspondence of mesh topology across all template-registered faces.

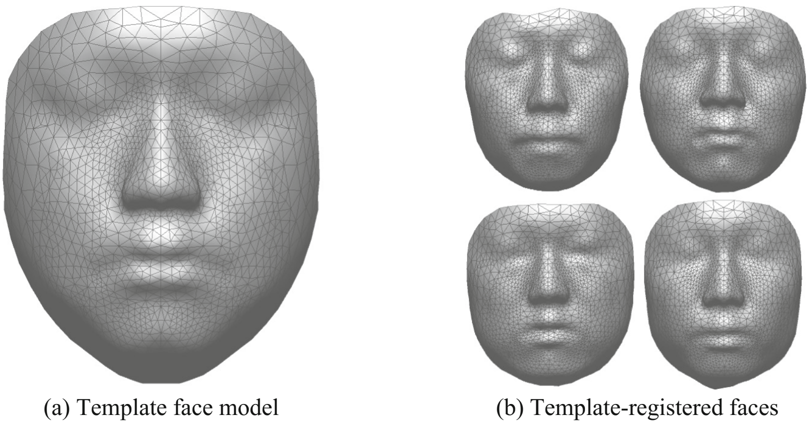


Fig. 1. The template face and the template-registered faces (illustrated)

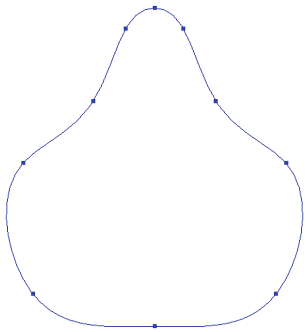
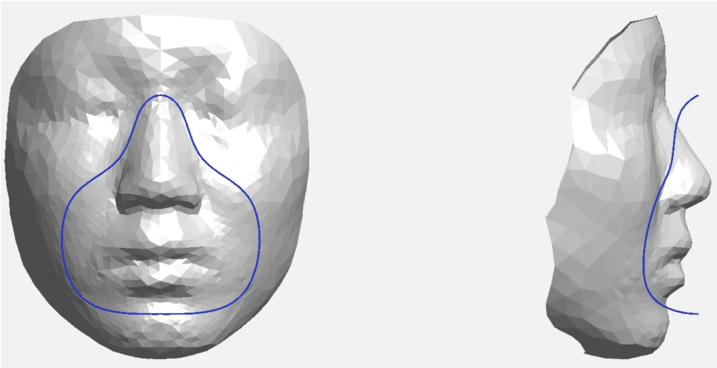


Fig. 2. The curvy shape of a mask's part that is contacting to the face

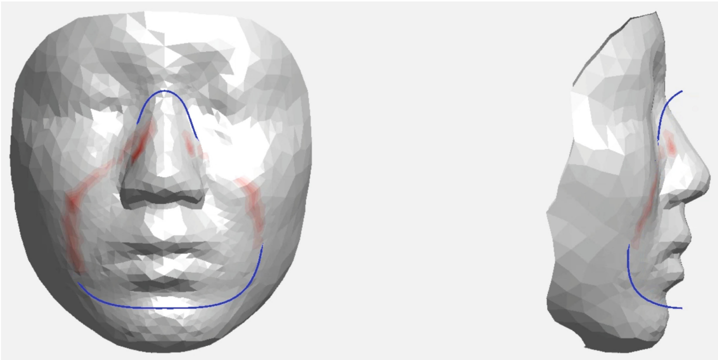
2.3 Contact Pressure Estimation Using Finite Element Analysis

From 3D scanned image of a product, a curvy shape that is contacting to a facial area was saved as a spline curvature. The curvature was defined as a spline curve consisted with 10 points as shown in Fig. 2. While the curvature is virtually aligned to all template-registered faces, the pressure of the curvature towards a 3D face was predicted using finite element analysis [9]. In this work, we applied triangular shell elements for the 3D facial modeling based on the 3D scanned image data as shown in Fig. 1. 2,624 elements and 1,340 nodes were then used. Since the contact pressure estimation of the facial skin with small deformation was mainly focused on, the simple linear elastic material properties were applied on the nodes except all the boundary nodes which are fixed and unmovable. For static analysis, the following equation was used:

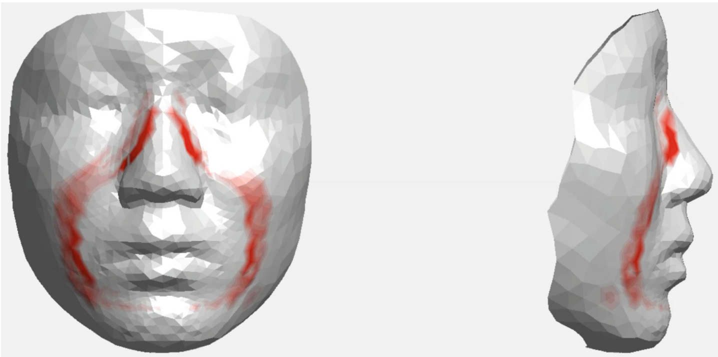
$$f = Ku \tag{1}$$



(a) face without contacting to the mask curvature: no pressure.



(b) face partially contacting to the mask



(c) face fully contacting to the mask

Fig. 3. The estimated contact pressure between the template-registered face and the mask defined as a curvy shape (illustrated) (Color figure online)

where K is a global stiffness matrix, u is a displacement vector for all nodes, and f is a force vector for all nodes, respectively. The elastic modulus and Poisson ratio which are necessary for calculation of the K are defined as 0.3 and 0.5 in this study. After the curvature was aligned at the required position by referring to Lee's study [10],

The displacement vector u was derived as the Euclidean distance between the curvature and each node. By solving Eq. (1), the contact pressure f was calculated. In this work, only z-translation at the nodal coordinates was simply considered with the stiffness matrix K to compute the force. The contact pressure is defined as the force exerted on a surface divided by the area (m^2) over which that force is applied. However, instead of the contact pressure, this study used the force which is proportionally equivalent to the contact pressure if the area is unconsidered. As illustrated in Fig. 3, the estimated contact pressure was shown as intensity of the red color. The pressure calculation process was implemented by MATLAB environment.

3 Results

As results, the average and variation of the predicted facial contact pressure between all the template-registered faces and a mask design were analyzed. Figure 4 is showing one average face with two different patterns of the average contact pressure calculated

Mask design A

Mask design B

Fig. 4. Average contact pressure derived by two different mask designs (illustrated).

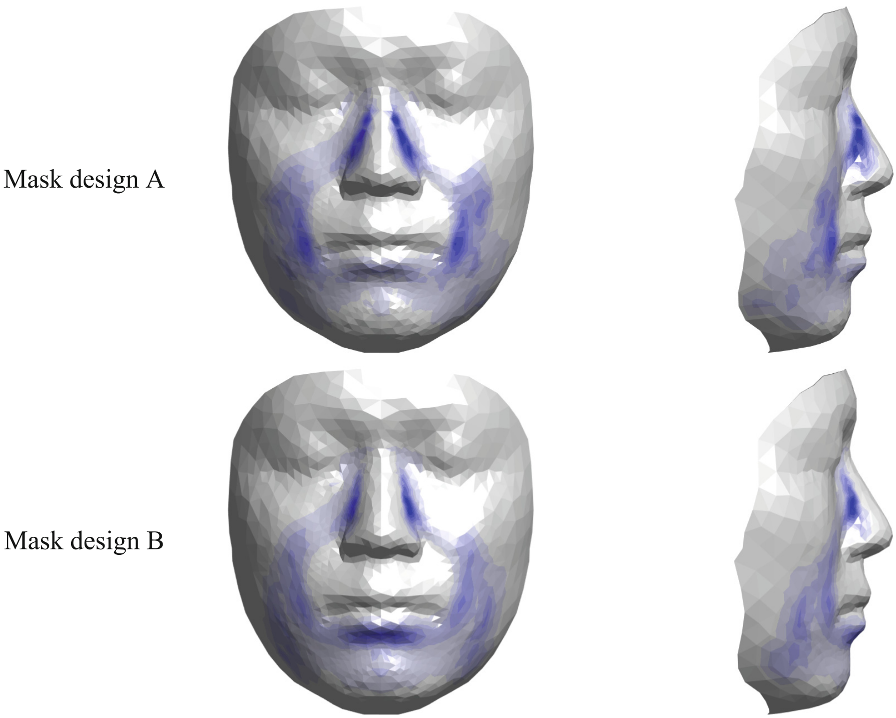


Fig. 5. Standard deviation analyzed by two different mask designs (illustrated).

using different shape of the mask. The Figs. 4 and 5 are showing that the lower image presents a better result in terms of the average and standard deviation of the contact pressure estimation. The average contact pressure of the lower image is smaller as well as more equally-distributed than that of the upper image. And the standard deviation of the contact pressure of the lower image is smaller than that of the upper image.

4 Discussion

Compare to the previous FE studies, this study used hundreds of face images in order to analyze variation of contact pressure characteristics that are different by people. Instead of making the realistic FE model, this study assumed that the material properties and face-to-mask contacting context are same by people. Since the validity of FE model needs to be further improved to be more realistic and robust, but the proposed method provides differences regarding the contact pressure that is useful for design of a wearable product.

The further study is needed for validation of the method. The estimated contact pressure illustrated as red color in Fig. 3 need to be compared to the actual contact pressure that can be measured by a pressure film [11]. Also, a study to investigate the elastic modulus and the Poisson ratio need to be conducted to sophisticate the proposed method.

The FEA-based contact pressure analysis method proposed in this study can be usefully applied to find an optimal shape of a product's part that contacts the human body. Different body parts and different product designs will be further considered in order to investigate an applicability and usefulness of the developed method.

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