ERGONOMIC DESIGN AND EVALUATION OF A PILOT OXYGEN MASK

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The present study developed a virtual fit assessment (VFA) method to design an oxygen mask which fits Korean Air Force (KAF) pilots. The VFA method used 3D face scan data of 336 KAF pilots to find the most proper shape of an oxygen mask for KAF pilots. The oxygen mask design revised in the study showed a 27% design improvement effect on average in terms of fit evaluated by the VFA method. Additionally, the present study evaluated the revised oxygen mask prototypes with 88 KAF pilots to experimentally verify the design improvement effect in terms of discomfort, pressure, and suitability for military equipment (slippage and stability in flight-like situations). The discomfort of the revised mask was 33 ~ 56% lower on average than the existing oxygen mask. In terms of the pressure, the revised mask showed 11 ~ 33% of improvement on average compared to the existing mask. Furthermore, on high gravity situation, the slippage distance of the revised mask was 24% shorter on average than the existing mask. The proposed VFA method can be applied to the design and evaluation of wearable products that require an ergonomically better fit for a target population.

INTRODUCTION

An oxygen mask is required to be designed to properly fit the facial characteristics (e.g., shape and size of face) of a target population to prevent users from the harmful atmosphere. The MBU-20/P (Gentex Corporation, U.S.A.) pilot oxygen mask, frequently used for the Korean Air Force (KAF) pilots, was originally designed using face anthropometric data of the U.S. Air Force (USAF) personnel collected by Churchill et al. (1977). A survey conducted by Lee et al. (2012b) on the usability evaluation of the MBU-20/P mask identified that more than 60 percent of KAF pilots suffered from excessive pressure and/or oxygen leakage around the nasal root due to the lack of fit from the oxygen mask to the face, which is most likely caused by a significant difference in facial shape and size between KAF pilots and USAF personnel.

Previous research on a respirator design used representative face models; however, those respirators didn't consider the facial characteristics of statistically significant amount of a target population in their research. Yatapanage and Post (1992), Gross et al. (1997), Han and Choi (2003), Han et al. (2004), and Song and Yang (2010) proposed respirator design methods based on an average face size or 1 ~ 3 of representative face models. However, the previous study didn't explain details of the respirator design method based on the 3D facial data. Also, there was a lack of systematical consideration for whether the proposed representative face models could significantly represent a target population.

Previous research proposed several methods for the evaluation of air penetration into a respirator; however, no study has evaluated pressure and subjective satisfaction of a respirator. Because of the importance of a respirator's fit, American National Standards Institute (ANSI), Occupational Safety and Health Administration (OSHA), and National Institute for Occupational Safety and Health (NIOSH) proposed standards for a manufacturing of industrial respirators (Han et al., 1997). Previous studies (Kolear et al., 1982; Han et al., 1997; Coffey et al., 2002) suggested quantitative or qualitative evaluation methods of a respirator's fit (e.g., flame photometric aerosol measurement, particle penetration, leak flow measurement, etc.). However, there is no experimental research that evaluates the pressure between a respirator and face; also, the previous respirator design study didn't conduct usability evaluations.

The present study developed an oxygen mask design method by using a virtual fit assessment and applied it to the design of an oxygen mask which fits KAF pilots. The oxygen mask appropriate to the facial characteristics of KAF pilots was designed by using 3D face scan data of all 336 KAF pilots. A prototype of the designed oxygen mask was ergonomically evaluated by 83 KAF pilots in terms of discomfort, pressure, and suitability for military equipment.

OXYGEN MASK DESIGN METHOD

Virtual Fit Assessment Method

A virtual fit assessment (VFA) is a method which automatically fits the oxygen mask CAD on the 3D facial scan data and virtually evaluates mask wearing characteristics (e.g., fit, clearance). The present study used a VFA system developed by Lee et al. (2012a). The system evaluates the fit between the oxygen mask CAD and the 3D face. The actual oxygen mask is deformed when pilots wear the mask; however, the oxygen mask CAD infiltrates into the 3D face during virtual fitting (highlighted in red in Figure 1). Therefore, the present study identified the fit as an infiltration distance between the oxygen mask and the 3D face. Deep infiltration (e.g., infiltration distance > 10 mm) means an excessive pressure, and no infiltration (infiltration distance < 0 mm) can be explained as an oxygen leakage. The fit is analyzed by 1 mm according to the vertical location of the face. For instance, the oxygen mask is slightly fitted or not fitted at the nasal root area (vertical location = 0 ~ 10 mm), and deeply fitted (maximum infiltration distance = 20 mm) at the nasal side and zygomatic bone areas (vertical location = 10 ~ 60 mm) (Figure 2).

Figure 1. Illustration of a virtual fit analysis of an oxygen mask design on a pilot's face

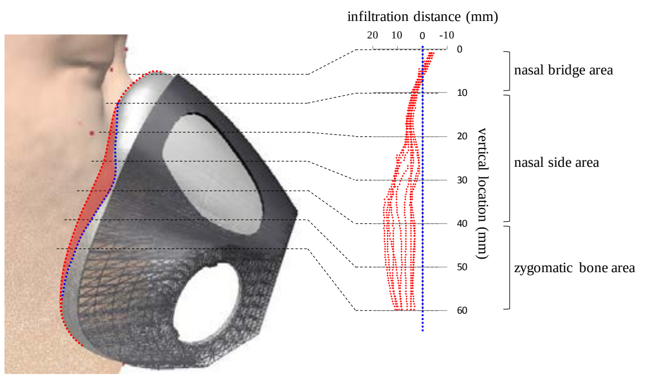


Figure 2. Fit of the oxygen mask according to vertical location

Oxygen Mask Design Based on the VFA Method

The present study designed the oxygen mask shapes (four sizes: small narrow, medium narrow, medium wide, and large wide) which were highly appropriate for the 3D facial data of 336 KAF pilots. The oxygen mask shape was revised through an iterative process between a design update using Rhino 3D (McNeel, U.S.A.), CAD software and an evaluation of its fit using the VFA system. The 3D faces of 336 KAF pilots were used to design the oxygen masks for KAF pilots. The sample size of KAF pilots was statistically identified based on ISO 15535 by Jeong et al. (2011). For an example of the medium narrow size (*n* = 113), the existing oxygen mask created less or no pressure on the nasal root area (see red circles in Figure 3.a), and an excessive pressure on the nasal side and zygomatic bone area, while the revised oxygen mask showed moderate fit at all locations on the face area (Figure 3.b).

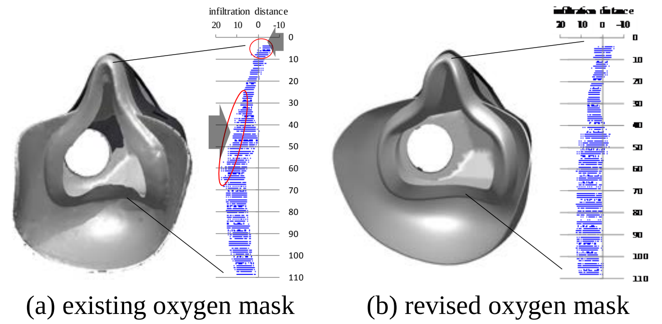


Figure 3. Fit analysis for the existing and revised oxygen mask

Evaluation of Oxygen Mask Shapes through the VFA Method

The revised oxygen mask showed an average 27% improvement in terms of design satisfaction ratio by facial area. The existing mask satisfied an average 55.3% (21 ~ 89% by facial area) of the sample population in terms of a fit criteria (indicated by red lines in Figure 4) identified by the present study, while the revised mask satisfied 82.3% (66 ~ 92% by facial area) on average (Figure 4).

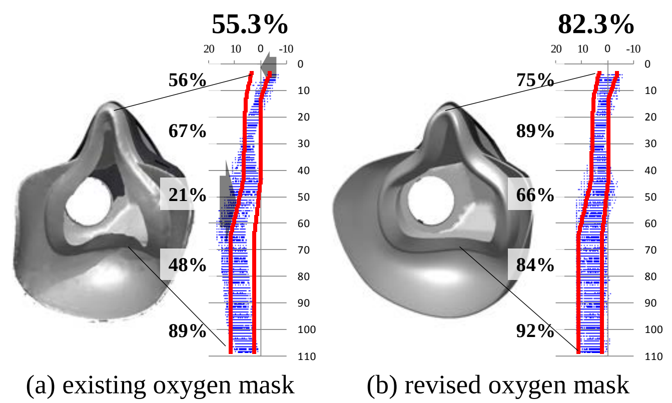


Figure 4. Evaluation of design satisfaction by virtual fit assessment (*n* = 336)

OXYGEN MASK EVALUATION METHOD

Participants

An ergonomic usability evaluation between the existing and revised oxygen masks was conducted with 83 KAF pilots (81 males and 2 females) who currently use the MBU-20/P oxygen mask. An additional 5 KAF male pilots participated for evaluation of the revised mask's suitability for military equipment.

Oxygen mask prototypes

The present study manufactured prototypes of the revised oxygen masks (4 sizes). To evaluate the oxygen masks under similar conditions, the present study used the similar materials as the MBU-20/P mask to make prototype.

Evaluation protocol

A usability evaluation was conducted in terms of discomfort and pressure through a five-step protocol (Figure 5). Pilots used their own MBU-20/P mask to evaluate the existing oxygen mask. For the revised mask evaluation, they selected one of prototypes among four sizes considering fit to his/her face shape and size. Pilots wore the existing or revised mask for 10 minutes, and then evaluated discomfort and pressure of the mask. The evaluation order of the existing and revised oxygen mask was counterbalanced.

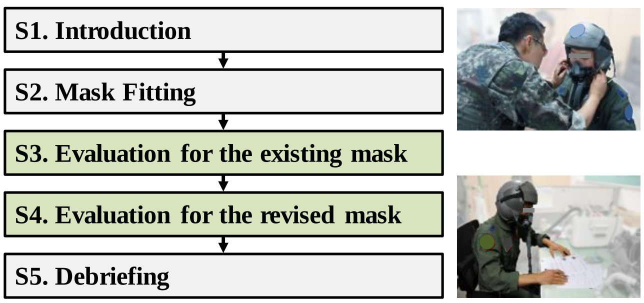


Figure 5. Oxygen mask evaluation protocol

The discomfort of the existing and revised oxygen masks were evaluated for six facial areas (nasal root, nasal side, zygomatic bone, cheek, bottom lip, and chin) by a 7-point scale (0: no discomfort, 1: rarely uncomfortable, 2: somewhat uncomfortable, 3: slightly uncomfortable, 4: moderately uncomfortable, 5: quite uncomfortable, 6: very uncomfortable, and 7: extremely uncomfortable) using a questionnaire developed by the present study.

The pressure of the existing and revised oxygen masks were measured by prescale pressure indicating film (Fujifilm, Japan) and analyzed by a pressure analysis system developed by the present study. The film shows amount of pressure between the oxygen mask and face, and is represented by a darkness (white: no pressure; black: maximum pressure) according to amount of pressure. After scanning the film (image size: 220 × 220 pixels), the system analyzes the amount of pressure (0: no pressure; 100: maximum pressure) on four facial areas (nasal root, nasal side, cheek, and bottom lip) (Figure 6). An average was used for an analysis of the pressure (a mean pressure value at each facial area); also, a pressed area (pressure ≥ 40; unit: number of pixels) and an excessively pressed area (pressure ≥ 70; unit: number of pixels) were defined by the present study.

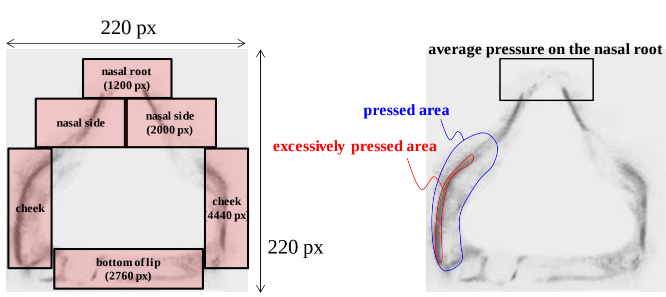
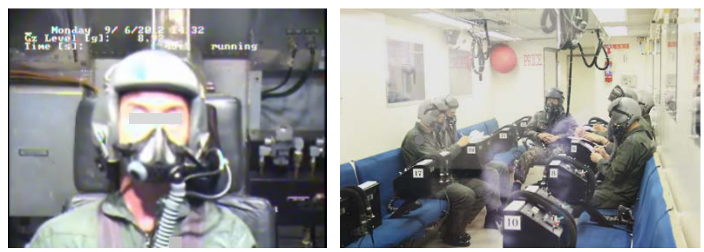


Figure 6. Areas for pressure analysis

Separately from the usability evaluation, the revised mask's suitability for military equipment was evaluated in situations of high gravity acceleration and low atmospheric pressure at the Aerospace Medical Center of KAF with 5 pilots. The evaluation of high gravity acceleration (9G) was conducted by using a high-G training equipment to identify a slippage of the oxygen mask at the face (Figure 7.a). The slippage of the mask was evaluated by questionnaire (0: no discomfort, 7: extremely uncomfortable due to slippage) and video inspection. The evaluation of low atmospheric pressure was conducted by using an aviation physiology training chamber which supplies various types of air (e.g., atmospheric pressure at < 25,000 feet situation: supplement of air with 20% oxygen, atmospheric pressure at ≥ 25,000 feet situation: supplement of 100% oxygen) to the pilot through the oxygen mask (Figure 7.b). Pilots subjectively evaluated the stability of the revised oxygen mask according to the various types of air supply.

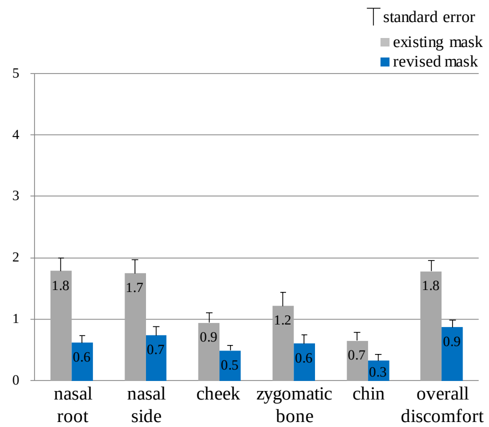


(a) evaluation in high gravity (b) evaluation in low atmospheric pressure

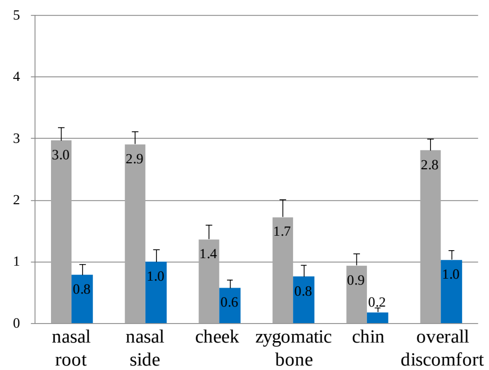
Figure 7. Evaluation of suitability for military equipment

Results

The KAF pilots preferred the revised oxygen mask over the existing mask in terms of comfort. The discomfort of the revised mask was 33 ~ 56% lower on average than the existing mask by facial areas (Figure 8.a). Specifically, the present study selected 43 pilots who felt the high discomfort (discomfort score > 3) at nose (nasal root or nasal side area) in the existing mask, and found that the discomfort of the revised mask among them was 56 ~ 81% lower on average than the existing mask by facial areas (Figure 8.b). Additionally, 73% of pilots (n = 61) chose the revised mask as the one they preferred for own face (Figure 9).



(a) results of all 83 pilots



(b) results of 43 pilots who felt high discomfort at the nose

Figure 8. Discomfort analysis results

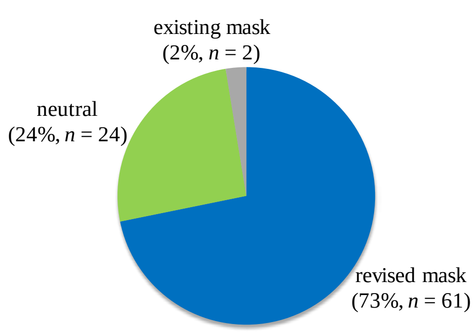
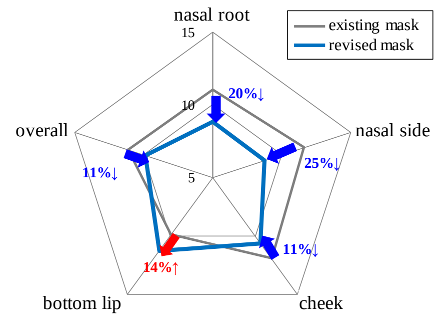
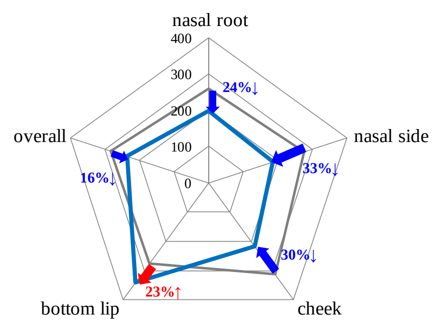


Figure 9. Preference results (n = 87)

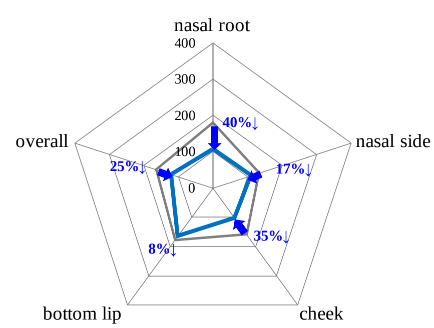
The revised mask showed less pressure than the existing mask, and evenly fitted to the pilots' face. The average pressure of the revised mask was 11 ~ 25% lower on average than the existing mask by facial areas (Figure 10.a) except the bottom lip. And the pressed area of the revised mask was 24 ~ 33% lower on average than the existing mask by facial areas (Figure 10.b) except the bottom lip. In terms of the bottom lip area, the average pressure and the pressed area of the revised mask were 14% and 23% higher on average than those of the existing mask. However, this can be interpreted as a better fit instead of excessive pressure, because the discomfort of the revised mask was lower than the existing mask at the bottom lip area. Lastly, the excessive pressed area of the revised mask was 8 ~ 40% lower on average than the existing mask by facial areas (Figure 10.c).



(a) average of pressure



(b) pressed area



(c) excessively pressed area

Figure 10. Pressure analysis results (n = 83)

The discomfort due to slippage of the revised mask (score = 0.4 on average) was 14 % lower on average than the existing mask (score = 2.8 on average). A slippage distance was measured by video inspection; and the slippage distance of the revised mask was shortened by 24% on average compared to the existing mask. And, all five pilots reported that there were no problems with the revised mask in various air supply situations that varied according to atmospheric pressure.

DISCUSSION

The present study developed the VFA method to design an ergonomic oxygen mask shape which is highly appropriate for KAF pilots. The previous studies used an average or a few representative faces for a respirator design; however, the present study considered how the mask would be more effectively applied to the specific target population (KAF pilots). And, the previous study did not verify a representativeness of the face models; this means a respirator shape design based on the face models may not be fitted to a large number of a target population. On the other hand, the present study could validate the design improvement effect of the revised oxygen mask with the statistically significant number (n = 336) of the target population through the VFA method.

The present study developed the ergonomic usability evaluation protocol and evaluated the fit of the oxygen mask in both qualitative and quantitative terms. The previous study mainly proposed some experimental methods for identification of air penetration, while the present study experimentally measured the pressure between the mask and face by using pressure indicating film. Also, the previous study didn't propose any subjective measures for the mask usability test, while the present study developed and applied the questionnaire which can evaluate the fit of the oxygen mask in terms of not only discomfort but also oxygen leakage, slippage, and overall satisfaction. Therefore, the present study could experimentally validate the design improvement effects of the revised oxygen mask and the oxygen mask design method simultaneously.

The proposed VFA method is an appropriate method to design and evaluate ergonomically wearable products in the early stage of the product development process. In the case of the oxygen mask, the present study made metal molds for the mask prototypes. However, because of cost, it is very difficult to make numerous molds to find the proper shape of the mask. Therefore, the VFA method proposed by the present study can be usefully applied for design and evaluation of the product shape at the stage prior to the prototype manufacturing.

ACKNOWLEDGEMENT

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REFERENCES

Churchill, E., Kikta, P., and Churchill, T. (1977). *The AMRL Anthropometric Data Bank Library: Volumes I-V* (AMRL-TR-77-1, ADA047314). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory.

Coffey, C. C., Lawrence, R. B., and Myers, W. R. (2002). Comparison of five methods for fit testing N95 filtering-facepiece respirator. *Applied Occupational and Environmental Hygiene, 17*(10), 723-730.

Gross, M. E., Taylor, S. E., Mountjoy, D. N., and Hoffmeister, J. (1997). *Anthropometric research on the sizing of the MBU-20P* (AFRL-HE-WP-TR-2002-0181). Wright-Patterson Air Force Base, OH: Human Effectiveness Directorate, Crew System Interface Division.

Han, D. and Choi, K. (2003). Facial dimensions and predictors of fit for half-mask respirators in Koreans. *American Industrial Hygiene Association Journal, 64*(6), 815-822.

Han, D., Rhi, J., and Lee, J. (2004). Development of prototypes of half-mask facepieces for Koreans using the 3D digitizing design method: A pilot study. *Annals of Occupational Hygiene, 48*(8), 707-714.

Han, D., Willeke, K., and Colton, C. E. (1997). Quantitative fit testing techniques and regulations for tight-fitting respirators: Current methods measuring aerosol or air leakage, and new developments. *American Industrial Hygiene Association Journal, 58*, 219-228.

Jeong, J., Lee, W., Park, J., Lee, B., Jeon, E., Son, D., Park, S., Jung, D., Kim, H., and You, H. (2011). Analysis of the Facial Anthropometric Data of Korean Pilots for Oxygen Mask Design. In *Proceedings of the 2011 Spring Conference of Ergonomics Society of Korea*.

Kolear, E. S., Cosgrove, D. J., de la Barre, C. M., and Theis, C. F. (1982). Comparison of respirator protection factors measured by two quantitative fit test methods. *Aviation, Space, and Environmental Medicine, 53*(11), 1116-1122.

Lee, W., Jeong, J., Son, D., Park, S., Jung, D., Kim, H., You, M., Park, C., and You, H. (2012). Development of a Methodology to Design a Pilot Oxygen Mask based on Virtual Fit Testing Method. In *Proceedings of the 2012 Spring Conference of the Korean Institute of Industrial Engineers*.

Lee, W., Park, J., Jung, J., Jeon, E., Kim, H., Park, S., and You, H. (2012). Analysis of the Facial Anthropometric Data of Korean Pilots for Oxygen Mask Design. In *Proceedings of the Human Factors and Ergonomics Society 56th Annual Meeting. Boston, MA: The Human Factors and Ergonomics Society*.

Song, Y. and Yang, W. (2010). Half-mask interface prototype design using Korean face anthropometric data. *Journal of Korea Safety Management and Science, 12*(4), 87-92.

Yatapanage, K. G. and Post, K. (1992). Measurement of 3-D facial contours for the design of half-face respirators. *American Industrial Hygiene Association Journal, 53*(1), 19-26.