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Wonsup Lee, Xiaopeng Yang, Daehan Jung, Seikwon Park, Heeeun Kim, and Heecheon You*
* Corresponding author

Wonsup Lee; Faculty of Industrial Design Engineering, Delft University of Technology, Delft 2628CE, The Netherlands; Tel. +31-15-278-2879, w.lee@tudelft.nl

Xiaopeng Yang; Department of Industrial and Management Engineering, Pohang University of Science and Technology; 77 Cheonam-ro, Nam-gu, Pohang, Gyeongbuk, 790-784, Republic of Korea; Tel. +82-54-279-8247, Fax: +82-54-279-2870, yxp233@postech.ac.kr

Daehan Jung; Department of Mechanical Engineering, Korea Air Force Academy; PO Box 335-2, 635 Danjae-ro, Sangdang-gu, Cheongju, Choongbuk, 360-060, Republic of Korea; Tel. +82-43-290-6451, Fax: +82-43-297-0479, daehanj@afa.ac.kr

Seikwon Park; Department of Systems Engineering, Korea Air Force Academy; PO Box 335-2, 635 Danjae-ro, Sangdang-gu, Cheongju, Choongbuk, 360-060, Republic of Korea; Tel. +82-43-290-6494, Fax: +82-43-297-0479, ergoparks@gmail.com

Heeeun Kim; Department of Clothing & Textiles, Kyungpook National University, 80 Daehak-ro, Buk-gu, 702-701, Republic of Korea; Tel. +82-53-950-6224, Fax: +82-53-950-6219, hekim@knu.ac.kr

Heecheon You; Department of Industrial and Management Engineering, Pohang University of Science and Technology; 77 Cheonam-ro, Nam-gu, Pohang, Gyeongbuk, 790-784, Republic of Korea; Tel. +82-54-279-2210, Fax: +82-54-279-2870, hcyou@postech.ac.kr

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Abstract

A revised pilot oxygen mask design was developed for better fit to the Korean Air Force pilots' faces. The present study compared an existing pilot oxygen mask and a prototype of the revised mask design with 88 Korean Air Force pilots in terms of subjective discomfort, facial contact pressure, and slip distance on the face in high gravity. The average discomfort levels, facial contact pressures, and slip distance of the revised mask were reduced by 33% to 56%, 11% to 33%, and 24%, respectively, compared to those of the existing oxygen mask. The mask evaluation method employed in the study can be applied to ergonomic evaluation of full- or half-face mask designs.

Keywords: pilot oxygen mask, ergonomic evaluation, subjective discomfort, facial contact pressure, mask slip distance

1. Introduction

An oxygen mask worn over the face of a fighter pilot needs a proper fit to the face for safe and effective mission accomplishment. The pilot oxygen mask supplies oxygen to the pilot when a mission is conducted at a high altitude where oxygen is lacking and houses a microphone for communication (Alexander et al., 1979; Lee et al., 2013a). An inappropriate oxygen mask design can cause excessive pressure and/or oxygen leakage around the nasal root due to a lack of fit of the mask to the face (Lee et al., 2013a; Lee et al., 2013b). A pilot can be endangered during operation if moisturized exhalation air leaks through the nasal root and fogs up the visor.

A pilot oxygen mask designed for better fit to the Korean Air Force (KAF) pilots' face required an ergonomic evaluation. MBU-20/P pilot oxygen masks (Gentex Corporation, Simpson: PA, USA; Figure 1.a), worn by KAF pilots of F-15 or F-16 fighter, were initially designed using the face anthropometric data of 2,420 US Air Force personnel (Churchill et al., 1977) and then improved by applying the three-dimensional face scan data of 30 male and 30 female pilots (Gross et al., 1997). A survey conducted by KAF on the usability of the MBU-20/P mask identified that a significant percentage of KAF pilots suffered from excessive contact pressure and/or oxygen leakage around the nasal root due to a lack of fit of mask to the face (Lee et al., 2013a; Lee et al., 2013b). Lee et al. (2013b) revised the design of the existing oxygen mask as shown in Figure 1.b by applying 3D face anthropometric data of 336 KAF pilots collected by Lee et al. (2013a).

[Figure 1 about here]

Evaluations of performance, fit, and comfort of respirator designs for better safety and usability have been conducted. The performance of a respirator was evaluated in terms of leakage and discomfort (Arnoldsson et al., 2016; Burgess et al., 1970; Lam et al., 2016; Niezgoda et al., 2013), cognitive and psychomotor effects such as steadiness of work performance and accuracy of precision movement (Abeysekera and Shahnavaz, 1987; AlGhamri et al., 2013; Meyer et al., 1997; Zimmerman et al., 1991), physiological effects such as heart rate, respiratory rate, tidal volume, and blood oxygen saturation (Johnson, 2016; Roberge et al., 2010; West, 2013), and CO_2 rebreathing (Smith et al., 2013). Various mask fit testing methods have been proposed to assess air leakage into a respirator such as a qualitative method using aerosols (e.g., isoamyl acetate and sodium saccharin) and a quantitative method using equipment for detection of air density and flow (Coffey et al., 2002; Han and Lee, 2005; Han et al., 1997; Kolear et al., 1982; Majchrzycka et al., 2016; Rengasamy et al., 2014). Lastly, a contact pressure measurement method or a 3D virtual fit analysis between a respirator and a 3D scanned head based on finite element modeling has been utilized to evaluate the fit and pressure characteristics of a respirator design (Butler, 2009; Cai et al., 2016; Dai et al., 2011; Lei et al., 2012; Lei et al., 2014; Lei et al., 2013; Schreinemakers et al., 2014).

The present study compared the existing MBU-20/P pilot oxygen mask design with the revised mask design in terms of subjective discomfort, facial contact pressure, and slip distance on the face in high gravity. The existing and revised oxygen mask designs were evaluated in terms of subjective measures including discomfort, oxygen leakage, slippage, microphone-lip contact, and overall satisfaction. Next, the facial contact pressures of the existing and revised oxygen mask designs against the face were measured by a pressure indicating film. Lastly, the performance of the revised mask was evaluated in flight-like situations such as low atmospheric pressure and high gravity acceleration. The present study hypothesized that the revised oxygen mask design would provide better satisfaction and performance for KAF pilots than the existing oxygen mask design.

2. Materials & Methods

2.1. Participants

An ergonomic oxygen mask evaluation was conducted with KAF pilots wearing an MBU-20/P oxygen mask and KAF Academy cadets. While 83 KAF pilots (81 males and 2 females; age: 25 ~ 43) and 58 KAF Academy cadets (32 males and 26 females; age: 19 ~ 22) participated in the subjective and facial contact pressure evaluation of oxygen mask, 5 male pilots in the performance evaluation of oxygen mask in low atmospheric pressure and high-G situations. The purpose and procedure of the mask evaluation experiment were fully explained to the participants, their participation was voluntary, and informed consent was obtained.

2.2. Apparatus

MBU-20/P oxygen masks and prototypes of the revised oxygen mask design were used for ergonomic evaluation in the present study. Four sizes (small narrow, medium narrow, medium wide, and large narrow) of the revised oxygen mask, designed by Lee et al. (2013b) based on 3D face anthropometric data of KAF pilots, were provided to participants for selection in terms of best fit to their face. Of the MBU-20/P oxygen mask components only the designs of facepiece and hardshell were revised. Materials similar to those of the MBU-20/P facepiece and hardshell components were used to manufacture the prototypes of the revised oxygen mask design. The similarity of material properties (e.g., hardness, toughness, tension, and elasticity) between the MBU-20/P and the prototype mask were confirmed by the Aero Technology Research Institute of Korea Air Force.

A hypobaric aviation physiology training chamber and a high-G training facility at the Aero Medical Training Center of Republic of Korea Air Force were used in oxygen mask performance evaluation. The hypobaric aviation physiology training chamber can simulate various atmospheric pressure conditions by supplying three types of air (air with 20% oxygen for altitude < 25,000 ft., air with 100% oxygen for altitude ≥ 25,000 ft., and pressurized air with 100% oxygen for emergency mode at any altitude). The present study evaluated the stable functioning of the oxygen masks for the three air supply modes. Next, the high-G training facility can simulate various gravity acceleration conditions. The present study evaluated the slip distances of the existing and revised oxygen masks on the face at 9 G condition when the acceleration of the high-G training facility increased at a rate of 0.2 G/s. The pilot’s face was recorded by a video camera to analyze the slippage of oxygen mask in high-G.

2.3. Evaluation Methods

2.3.1. Subjective evaluation

The discomfort levels of the existing and revised oxygen masks were evaluated using a questionnaire as illustrated in Figure 2. The discomfort levels caused by contact pressure (0: no discomfort, 1: rare discomfort, 4: moderate discomfort, 7: extreme discomfort) and oxygen leakage (0: no leakage, 1: rare leakage, 4: moderate leakage, 7: extreme leakage) were evaluated at six facial areas (nasal root, nasal side, zygomatic bone, cheek, bottom lip, and chin). Furthermore, the discomfort levels caused by slippage (0: no slippage, 1: rare slippage, 4: moderate slippage, 7: extreme slippage) and microphone-lip contact (0: no contact, 1: rare contact, 4: moderate contact, 7: extreme contact), and overall satisfaction (-3: very unsatisfied, 0: neutral, 3: very satisfied) were evaluated. The mask evaluation questionnaire was prepared by referring to the combat edge fit assessment questionnaire which was developed by Gross et al. (1997) to find problems of oxygen masks for the US Air Force pilots.

[Figure 2 about here]

2.3.2. Facial contact pressure evaluation

The facial contact pressure of an oxygen mask against the face was evaluated using a 4LW Prescale™ pressure indicating film (Fujifilm Co., Japan) which can measure a pressure from 7.25 to 29 psi (0.05 to 0.2 MPa). The Prescale™ pressure film is composed by an A-film (coated with a particular micro encapsulated color forming material) and a C-film (coated with a specific color developing material) (Fujifilm, 2015). When a pressure is applied to the films, microcapsules of the A-film are broken depending on pressure distribution and magnitude and the broken microcapsules react with the color developing materials of the C-film.

The facial contact pressures of the existing and revised oxygen masks measured by pressure films were evaluated by a pressure analysis system developed in the present study. The contact pressure evaluation was conducted through a five-step procedure as shown in Figure 3. First, the film was prepared by considering the oxygen mask shape. Second, the pressure was measured by positioning the A- and C-films together between the oxygen mask and the pilot's face during 10 seconds. Third, the films were scanned as grayscale digital images (image size: 220 × 220 pixel) using a HP ScanJet 5370C scanner (Hewlett-Packard Company, Palo Alto: CA, USA). Fourth, cut edges, finger prints, and unexpected marks pressed onto the films were eliminated using Photoshop (Adobe Systems Incorporated, San Jose: CA, USA). Lastly, the pressure analysis system coded by Matlab 2008a (MathWorks, Inc., Natick: MA, USA) was applied to analyze the pressure distribution quantitatively.

[Figure 3 about here]

The facial contact pressure measured by the pressure film was quantitatively analyzed at facial areas in terms of average pressure and pressed area. The pressure magnitude is represented by darkness (white: no pressure; dark red: maximum pressure) as shown in Figure 4. The pressure magnitude was defined as pressure index (PI) which represents no pressure as PI = 0 and maximum pressure (29 psi) as PI = 100 (Figure 4.a). A PI was classified into low pressure (PI < 40), moderate pressure (40 ≤ PI < 70), and high pressure (PI ≥ 70) in the present study. The facial contact pressure was analyzed by the pressure analysis program at four facial areas (nasal root, nasal side, cheek, and bottom lip; Figure 4.b.) related to the facial areas in the questionnaire. An average PI and an excessively pressed area (PI ≥ 70; unit: number of pixels) were analyzed for each of the four facial areas.

[Figure 4 about here]

2.3.3. Performance evaluation in flight-like situations

The performance of the revised oxygen mask was evaluated in a low atmospheric pressure and a high-G condition, respectively. For the performance evaluation in the low atmospheric pressure situation, participants tested the revised oxygen mask in various air supply situations in a low atmospheric pressure (Figure 5.a), then reported noticeable problems in terms of stability, security, and usability. The performance of the oxygen mask in 9 G was evaluated in terms of mask slippage on the face using subjective questions (0 = no slippage, 1 = rare slippage, 4 = moderate slippage, 7 = extreme slippage) and a video analysis (Figure 5.b).

[Figure 5 about here]

2.4. Evaluation Procedure

The subjective evaluation and facial contact pressure evaluation were conducted by a four-step procedure (S1: introduction; S2: mask selection and fitting; S3: evaluation; and S4: debriefing) with the pilots and cadets as shown in Figure 6. First, the purpose and process of the mask design evaluation were introduced to a participant and an informed consent was obtained. Second, the participant chose one of the revised oxygen mask prototypes among the four sizes considering their face size and fit. Then, the selected prototype of the revised oxygen mask design was fitted to the participant's face by assistance of a technical sergeant. Third, his/her own MBU-20/P oxygen mask and the revised oxygen mask prototype were evaluated. The participant wore the existing or revised oxygen masks during 10 minutes and then answered the questionnaire. After the questionnaire survey, facial contact pressure was measured using a pressure film. The evaluation order of the existing and revised oxygen masks was counterbalanced. Lastly, a debriefing about the experiment was conducted and their participation was compensated. A similar evaluation protocol was applied to the cadets. However, because the cadets did not have their own oxygen masks, they selected both the existing and revised masks and fitted them to their faces. The pressure measurement was not applied for the cadets because the cadets did not exactly understand how they wear the oxygen mask in flight situations. Therefore, the cadets evaluated only their preferences by comparing the two masks with each other.

[Figure 6 about here]

The performance of the revised oxygen mask was evaluated in a low atmospheric pressure and a high-G situations by a four-step procedure (Figure 7): (1) introduction of the experiment and collection of a signed informed consent form, (2) selection and fitting of the revised oxygen mask to the face, (3) administration of the main experiment, and (4) debriefing. For the evaluation in a low atmospheric pressure situation, any noticeable problems of the revised oxygen mask in terms of stability, security, and usability were reported to the administrator. For the evaluation in the high-G situation, the face of a pilot was recorded during the main experiment and then a slippage of the oxygen mask at 9 G on the face was evaluated using a questionnaire. The experiment order of the existing and revised oxygen masks was counterbalanced and a 10-minute break was provided between the experiments. The experiment of the present study was conducted while complying with ethical standards and regulations of the affiliations of the authors and government agencies which participated in the study. The purpose and procedure of the mask evaluation experiment were fully explained to the participants, their participation was voluntary, informed consent was obtained, and their participation was compensated.

[Figure 7 about here]

3. Results

3.1. Subjective Evaluation

The discomfort of the revised oxygen mask was lower than that of the existing oxygen mask at all the facial areas. Selected were 32 out of 83 pilots and 24 out of 58 cadets whose discomfort score ≥ 3 (slightly discomfort) at the nasal root or nasal side areas of the existing oxygen mask to identify a design revision effect for the nose area of the oxygen mask. The average discomfort levels of the revised oxygen mask were 56% ~ 81% less for the pilots (Figure 8.a) and 33% ~ 60% for the cadets (Figure 8.b) than those of the existing oxygen mask at the facial areas.

[Figure 8 about here]

The revised oxygen mask design was preferred in terms of oxygen leakage, slippage, microphone-lip contact, overall satisfaction, and preference. The oxygen leakage of the revised oxygen mask was 50% ~ 87% lower on average than that of the existing oxygen mask at the facial areas. The slippage and microphone-lip contact of the revised oxygen mask showed 43% and 70% lower on average than those of the existing oxygen mask (slippage: $t(78) = 7.32$, $p < 0.001$; microphone-lip contact: $t(78) = 4.08$, $p < 0.001$), respectively. The overall satisfaction of the revised oxygen mask was 80% higher than that of the existing oxygen mask ($t(76) = -8.48$, $p < 0.001$). Lastly, a preference survey of the oxygen masks during the debriefing session of the experiment showed that 74% of the pilots and 79% of the cadets preferred the revised oxygen mask to the existing one (Figure 9).

[Figure 9 about here]

3.2. Facial Contact Pressure Evaluation

The revised oxygen mask showed less contact pressure than the existing mask and more evenly fitted to the Korean pilots' face. According to the mask evaluation survey, 44 out of 83 pilots preferred to tightly wear an oxygen mask to their faces. The present study analyzed the pilots who tightly wear an oxygen mask (n = 44) because they might have a higher discomfort. The average PI and the excessively pressed area of the revised oxygen mask were 11% ~ 25%, 24% ~ 33%, and 8% ~ 40% less at the three facial areas (nasal root, nasal side, and cheek) than those of the existing oxygen mask, respectively, except for the bottom lip (Figure 10.a and 10.b). For the bottom lip area, the average PI and the excessively pressed area of the revised oxygen mask were 14% and 23% higher than those of the existing oxygen mask, respectively (Figure 11). Significant differences were found at the nasal root, nasal side, and cheek areas, while no significant difference was found at the bottom lip area.

[Figure 10 about here]

[Figure 11 about here]

3.3. Performance Evaluation in Flight-Like Situations

The revised oxygen mask showed better performance for military use in both low atmospheric pressure and high-G situations. No noticeable problems on stability, security, and usability were reported on the revised oxygen mask under all the oxygen supply types in a low atmospheric pressure. The revised oxygen mask showed less slippage in the 9 G situation. According to the questionnaire survey for performance evaluation in the high-G situation, the average slippage of the revised oxygen mask was 86% less than that of the existing oxygen mask with a significant difference at $\alpha = 0.05$ by the Mann-Whitney test ($W = 38$, $p = 0.037$). Furthermore, the mask slippage distance between the sellion (anthropometric landmark on a nasal root) and the top of the mask in the 9 G condition were measured by the video analysis (Figure 12). The slippage distance of the revised oxygen mask was 31% ~ 83% shorter than that of the existing oxygen mask with a significant difference at $\alpha = 0.05$ ($W = 26$, $p = 0.030$).

[Figure 12 about here]

4. Discussion

An ergonomic evaluation protocol was developed for examining the satisfaction and performance of the revised oxygen mask in terms of subjective satisfaction, contact pressure of the mask against the face, and performance in flight-like situations. Questionnaires were developed for subjective satisfaction survey in terms of discomfort, oxygen leakage, slippage, and contact of a microphone to the lip which might occur during flight operation. A facial contact pressure evaluation method using a pressure film was proposed for the quantitative analysis of pressure characteristics of a mask to the face. Lastly, qualitative and quantitative evaluation protocols in extreme flight-like situations (e.g., low atmospheric pressure and high gravity acceleration) were proposed for evaluating the stable functioning of the revised mask design. The proposed evaluation methods can be applied to various full- and half-face mask designs for military and/or industry use.

A pressure film was effectively utilized to measure pressures at contact areas of the mask against the face. Schreinemakers et al. (2014) used DigiTacts pressure sensor (Pressure Profile Systems Inc., Los Angeles: LA, USA) for analysis of a mask's contact pressure to flight pilots' face, but analyzed only the pressure at the nasal root. The present study introduced a novel protocol to measure and analyze a mask's contact pressure on the face to understand the fit characteristics of a mask design for better fit and comfort to mask users. An average contact pressure and an excessively pressed area were measured and analyzed by facial areas using pressure index converted from the pressure film. The contact pressure analysis program was developed in the present study to efficiently compare the existing and revised oxygen masks. The facial contact pressures of the revised oxygen mask were found lower on average than those of the existing mask at the facial areas, which supports the discomfort evaluation results.

KAF pilots with narrow nasal root breadths preferred the existing oxygen mask. Two KAF male pilots and nine cadets (4 males and 5 females) out of 131 participants answered that the existing oxygen masks were more appropriate to their faces than the revised oxygen masks. Their nasal root breadth (17.4 ± 2.2 mm) was 2.6 mm narrower on average than that of the KAF pilots (20.0 ± 2.8 mm) and closer to that of the US Air Force male personnel (15.4 ± 1.9 mm) collected by Churchill et al. (1977). The discomfort score of those 11 participants on the nasal root area (1.1 ± 1.5) was lower on average than that of the KAF pilots (1.8 ± 1.4) and cadets (1.5 ± 1.7).

The design improvement effect of the revised masks for KAF pilots was validated through a comparison of the existing and revised oxygen masks with KAF pilots. The revised oxygen mask was found better fit to KAF pilots' faces, less discomfort at the nasal area, better prevention of oxygen leakage at the nasal root, less slippage in the high-G situation, and less interference of a microphone to the lip than the existing mask. It was found that 92%

of KAF pilots and cadets were satisfied with the revised design; thus, the revised oxygen mask can increase safety and satisfaction KAF pilots in their successful mission accomplishment by reducing their physical and mental workloads caused by excessive pressure or oxygen leakage.

The present study was intended to provide the usability evaluation results of the pilot oxygen mask designs by KAF pilots. As designed for better fit to the KAF pilots' faces, the revised oxygen mask design required an ergonomic evaluation by KAF pilots to validate its effectiveness. The present study found that the revised design was suitable to 97.6 % of 83 KAF pilots. The number of pilots participating in the ergonomic mask evaluation study was limited due to limited use of military facilities and availability of pilots. However, the trend of preference identified in the present study can be generalizable to KAF pilots because they reported similar experience and opinion of discomfort and/or leakage at the nasal bridge with the existing oxygen mask (Lee et al., 2013a; Lee et al., 2013b).

5. Conclusions

The evaluation results of the revised mask design indicates that a customized design for pilots in different ethnic groups may be necessary. MBU-20/P pilot oxygen masks are used by F-16 fighter pilots in various countries including, but not limited to, Belgium, Chile, Denmark, Egypt, Indonesia, Israel, Italy, Jordan, Morocco, Norway, Oman, Pakistan, Poland, Portugal, Romania, Singapore, South Korea, Taiwan, Thailand, the Netherlands, Turkey, United Arab Emirates, and USA (Lockheed Martin Corp., 2015). Discomfort, nasal disorders, and/or oxygen leakage issues with the MBU-20/P oxygen mask have been reported in studies in USA (Bitterman, 1991; Gross et al., 1997; Liptak, 1998), the Netherlands (Schreinemakers et al., 2013), and South Korea (Lee et al., 2013a). Fit problems of MBU-

20/P oxygen mask to Air Force pilots in various countries could occur due to facial anthropometric differences among ethnic groups (Ball et al., 2010; Du et al., 2008; Farkas et al., 2005; Kim et al., 2003; Lee and Park, 2008; Lee et al., 2013a). Therefore, a customized oxygen mask design by referring to facial characteristics of a target population can help resolve problems due to lack of fit of a mask to the face.

The present study presented a novel method to measure and evaluate the contact pressure between the face and a facial mask using a pressure film. The results of the contact pressure analysis supplemented the results of subjective satisfaction in the present study. The concept of the contact pressure evaluation method can be usefully applied in usability evaluation studies to analyze fit characteristics between the human body and a product that needs to remain in contact with pressure to the body during its use.

Lastly, application of contact pressure analysis results can be considered as future research in a virtual fit evaluation. The contact pressure between a mask design and 3D face scan images can be estimated by the finite element analysis method and then estimated contact pressures can be compared with those of the film-based contact pressure measurement. A sophisticated algorithm of contact pressure estimation for a mask design to the face can be developed and applied to design of a mask shape for a target population using their 3D face scan images.

Conflict of Interest

The authors declare no conflicts of interest.

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References

Abeysekera, J.D. and Shahnavaz, H., 1987. Ergonomics assessment of selected dust respirators: Their use in the tropics. Appl Ergon 18(4), 266-272.

Alexander, M., McConville, J.T., and Tebbetts, I., 1979. Anthropometric Sizing, Fit-Testing, and Evaluation of the MBU-12/P Oral-Nasal Oxygen Mask. Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, OH.

AlGhamri, A.A., Murray, S.L., and Samaranayake, V.A., 2013. The effects of wearing respirators on human fine motor, visual, and cognitive performance. Ergonomics 56(5), 791-802.

Arnoldsson, K., Danielsson, S., and Thunell, M., 2016. A method for evaluating aerosol leakage through the interface between protective suits and full-face respirators. J Occup Environ Hyg 13(5), 319-328.

Ball, R.M., Shu, C., Xi, P.C., Rioux, M., Luximon, Y., and Molenbroek, J.F.M., 2010. A comparison between Chinese and Caucasian head shapes. Appl Ergon 41(6), 832-839.

Bitterman, B.H., 1991. Application of Finite Element Modeling and Analysis to the Design of Positive Pressure Oxygen Masks. The Air Force Institute of Technology, Wright-Patterson Air Force Base, OH.

Burgess, W.A., Hinds, W.C., and Snook, S.H., 1970. Performance and acceptance of respirator facial seals. Ergonomics 13(4), 455-&.

Butler, K.M., 2009. Using 3D head and respirator shapes to analyze respirator fit, 13th International Conference on Human-Computer Interaction (HCII 2009), LNCS 5620, San Diego, CA, pp. 483-491.

Cai, M., Shen, S.N., Li, H., Zhang, X.T., and Ma, Y.Z., 2016. Study of contact characteristics between a respirator and a headform. J Occup Environ Hyg 13(3), D50-D60.

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

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.

Dai, J.C., Yang, J.Z., and Zhuang, Z.Q., 2011. Sensitivity analysis of important parameters affecting contact pressure between a respirator and a headform. Int J Ind Ergonom 41(3), 268-279.

Du, L.L., Zhuang, Z., Guan, H.Y., Xing, J.C., Tang, X.Z., Wang, L.M., Wang, Z.L., Wang, H.J., Liu, Y.W., Su, W.J., Benson, S., Gallagher, S., Viscusi, D., and Chen, W.H., 2008. Head-and-face anthropometric survey of Chinese workers. Ann Occup Hyg 52(8), 773-782.

Farkas, L.G., Katic, M.J., Forrest, C.R., Alt, K.W., I, B., Baltadjiev, G., Cunha, E., Cvicelova, M., Davies, S., I, E., Gillett-Netting, R., Hajnis, K., Kemkes-Grottenthaler, A., I, K., Kumi, A., Kgamphe, J.S., Kayo-Daigo, N., Le, T., Malinowski, A., Negasheva, M., Manolis, S., Ogeturk, M., Parvizrad, R., Rosing, F., Sahu, P., Sforza, C., Sivkov, S., Sultanova, N., Tomazo-Ravnik, T., Toth, G., Uzun, A., and Yahia, E., 2005. International anthropometric study of facial morphology in various ethnic groups/races. Journal of Craniofacial Surgery 16(4), 615-646.

Fujifilm, 2015. Prescale presure film. Retrieved March 31, 2016 from: http://www.fujifilm.com/products/prescale/prescalefilm/.

Gross, M.E., Taylor, S.E., Mountjoy, D.N., and Hoffmeister, J., 1997. Antropometric Research on the Sizing of the MBU-20/P. Human Effectiveness Directorate, Crew System Interface Division, Wright-Patterson Air Force Base, OH.

Han, D. and Lee, J., 2005. Evaluation of particulate filtering respirators using inward leakage (IL) or total inward leakage (TIL) testing - Korean experience. Ann Occup Hyg 49(7), 569-574.

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.

Johnson, A.T., 2016. Respirator masks protect health but impact performance: a review. J Biol Eng 10(

Kim, H., Han, D., Roh, Y., Kim, K., and Park, Y., 2003. Facial anthropometric dimensions of Koreans and their associations with fit of quarter-mask respirators. Ind Health 41(1), 8-18.

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.

Lam, S.C., Lui, A.K.F., Lee, L.Y.K., Lee, J.K.L., Wong, K.F., and Lee, C.N.Y., 2016. Evaluation of the user seal check on gross leakage detection of 3 different designs of N95 filtering facepiece respirators. Am J Infect Control 44(5), 579-586.

Lee, H. and Park, S., 2008. Comparison of Korean and Japanese Head and Face Anthropometric Characteristics. Human Biology 80(3), 313-330.

Lee, W., Jeong, J., Park, J., Jeon, E., Kim, H., Jung, D., Park, S., and You, H., 2013a. Analysis of the facial measurements of Korean Air Force pilots for oxygen mask design. Ergonomics 56(9), 1451-1464.

Lee, W., Kim, H., Jung, D., Park, S., and You, H., 2013b. Ergonomic design and evaluation of a pilot oxygen mask, Human Factors and Ergonomics Society 57th Annual Meeting. The

Human Factors and Ergonomics Society, San Diego, CA.

Lei, Z., Yang, J., and Zhuang, Z., 2012. Headform and N95 filtering facepiece respirator interaction: contact pressure simulation and validation. J Occup Environ Hyg 9(46-58.

Lei, Z.P., Yang, J., and Zhuang, Z.Q., 2014. A Novel Algorithm for Determining Contact Area Between a Respirator and a Headform. J Occup Environ Hyg 11(4), 227-237.

Lei, Z.P., Yang, J., Zhuang, Z.Q., and Roberge, R., 2013. Simulation and evaluation of respirator faceseal leaks using computational fluid dynamics and infrared imaging. Ann Occup Hyg 57(4), 493-506.

Liptak, L., 1998. Advanced Aircrew Oxygen Mask Insert Evaluation. Human Effectiveness Directorate, Flight Stress Protection Division, Systems Research Branch, Brooks Air Force Base, TX.

Lockheed Martin Corp., 2015. F-16 Fighting Falcon. Retrieved March 31, 2016 from: http://www.lockheedmartin.com/content/dam/lockheed/data/aero/documents/f16/f16_product_card_a11-34324g.pdf.

Majchrzycka, K., Okrasa, M., Skora, J., and Gutarowska, B., 2016. Evaluation of the Survivability of Microorganisms Deposited on Filtering Respiratory Protective Devices under Varying Conditions of Humidity. Int J Environ Res Public Health 13(1).

Meyer, J.P., Hery, M., Herrault, J., Hubert, G., Francois, D., Hecht, G., and Villa, M., 1997. Field study of subjective assessment of negative pressure half-masks. Influence of the work conditions on comfort and efficiency. Appl Ergon 28(5-6), 331-338.

Niezgoda, G., Kim, J.H., Roberge, R.J., and Benson, S.M., 2013. Flat fold and cup-shaped N95 filtering facepiece respirator face seal area and pressure determinations: a stereophotogrammetry study. J Occup Environ Hyg 10(8), 419-424.

Rengasamy, S., Eimer, B.C., and Szalajda, J., 2014. A Quantitative Assessment of the Total Inward Leakage of NaCl Aerosol Representing Submicron-Size Bioaerosol Through N95 Filtering Facepiece Respirators and Surgical Masks. J Occup Environ Hyg 11(6), 388-396.

Roberge, R.J., Coca, A., Williams, W.J., Powell, J.B., and Palmiero, A.J., 2010. Physiological impact of the N95 filtering facepiece respirator on healthcare workers. Resp Care 55(5), 569-577.

Schreinemakers, J.R., Boer, C., van Ameronge , P.C., and Kon, M., 2014. Exerted pressure by an in-flight oxygen mask. Aviat Space Environ Med 85(7), 745-749.

Schreinemakers, J.R.C., Westers, P., van Amerongen, P., and Kon, M., 2013. Oxygen mask related nasal integument and osteocartilagenous disorders in F-16 fighter pilots. Plos One 8(3).

Smith, C.L., Whitelaw, J.L., and Davies, B., 2013. Carbon dioxide rebreathing in respiratory protective devices: influence of speech and work rate in full-face masks. Ergonomics 56(5), 781-790.

West, J.B., 2013. A strategy for in-flight measurements of physiology of pilots of high-performance fighter aircraft. J Appl Physiol 115(1), 145-149.

Zimmerman, N.J., Eberts, C., Salvendy, G., and Mccabe, G., 1991. Effects of respirators on performance of physical, psychomotor and cognitive tasks. Ergonomics 34(3), 321-334.

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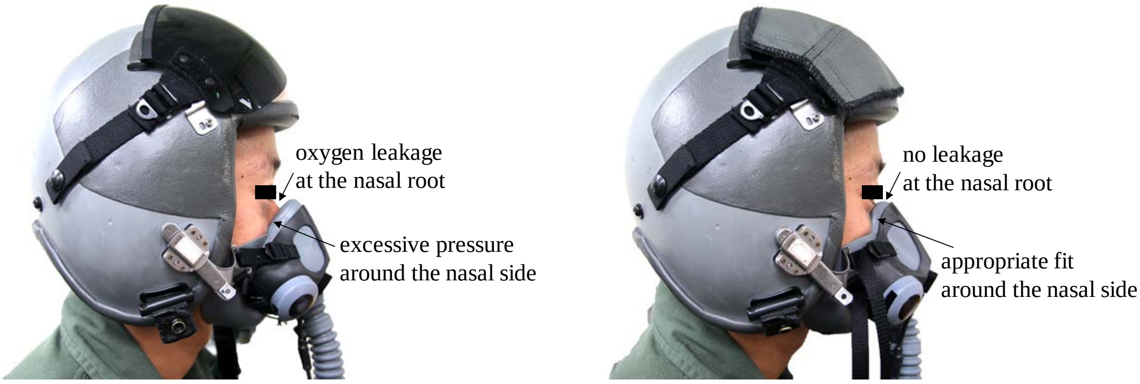
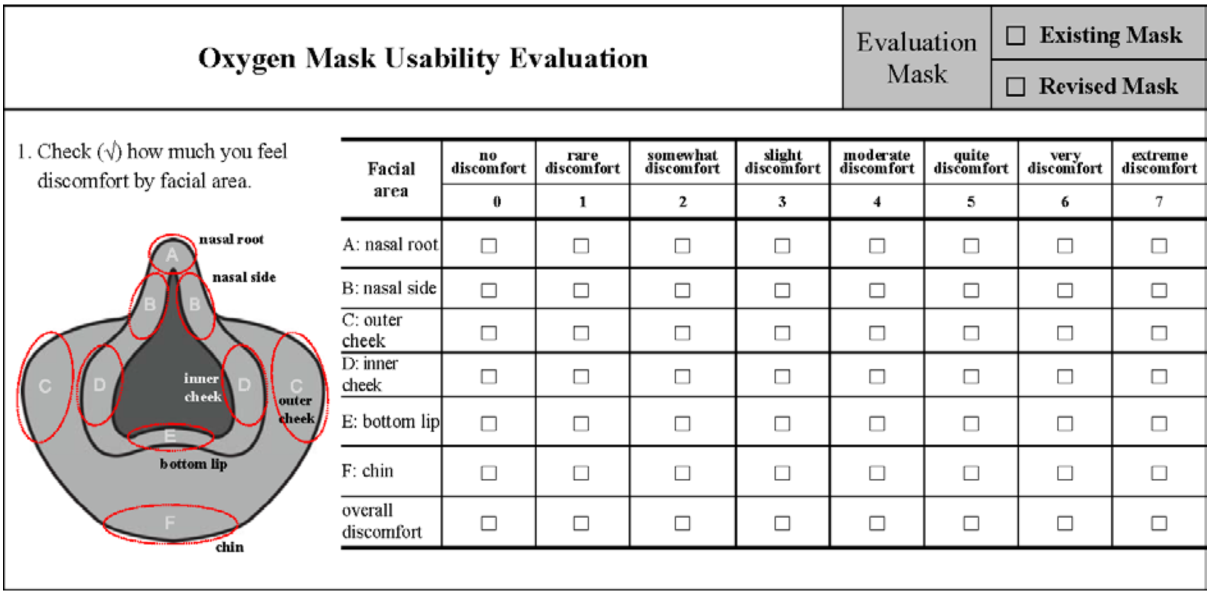


(a) MBU-20/P oxygen mask

(b) Revised oxygen mask

Figure 1. Comparison of existing and revised pilot oxygen masks



Oxygen Mask Usability Evaluation | Evaluation Mask | ☐ Existing Mask | ☐ Revised Mask

1. Check (√) how much you feel discomfort by facial area.

Facial area	no discomfort	rare discomfort	somewhat discomfort	slight discomfort	moderate discomfort	quite discomfort	very discomfort	extreme discomfort
	0	1	2	3	4	5	6	7
A: nasal root	☐	☐	☐	☐	☐	☐	☐	☐
B: nasal side	☐	☐	☐	☐	☐	☐	☐	☐
C: outer cheek	☐	☐	☐	☐	☐	☐	☐	☐
D: inner cheek	☐	☐	☐	☐	☐	☐	☐	☐
E: bottom lip	☐	☐	☐	☐	☐	☐	☐	☐
F: chin	☐	☐	☐	☐	☐	☐	☐	☐
overall discomfort	☐	☐	☐	☐	☐	☐	☐	☐

Figure 2. Subjective evaluation questionnaire (illustration)

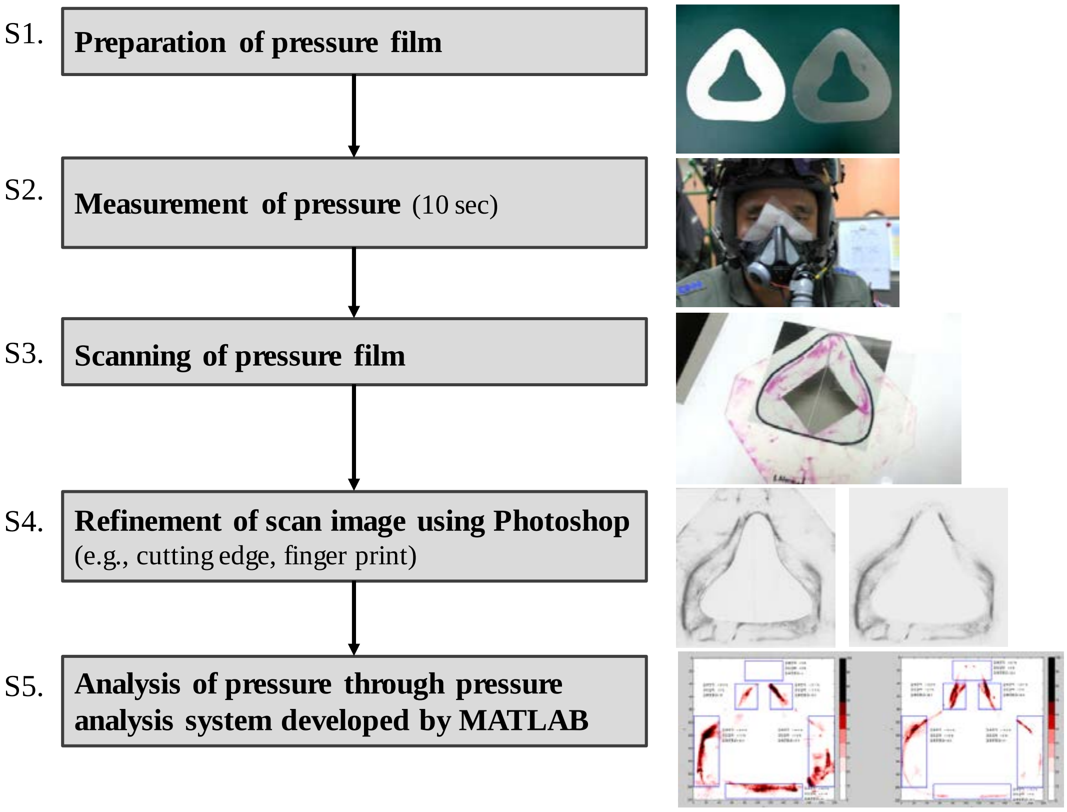
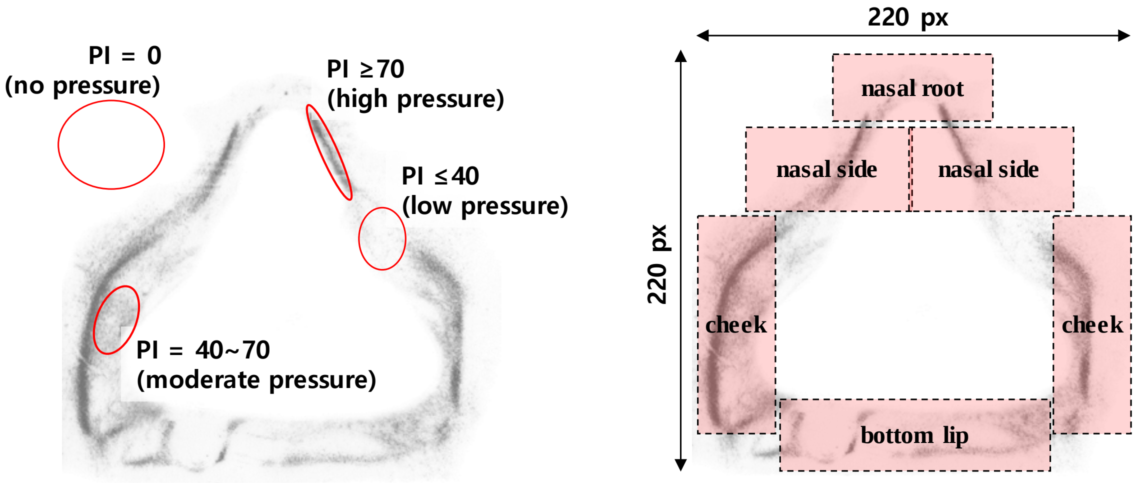


Figure 3. Facial contact pressure measurement and analysis protocol



(a) Pressure index (b) Facial areas for pressure analysis

Figure 4. Example of pressure index and facial areas for pressure analysis

(a) Evaluation in the low atmospheric pressure situation

(b) Evaluation in 9-G situation

Figure 5. Evaluation of performances of the revised oxygen mask in flight-like situations

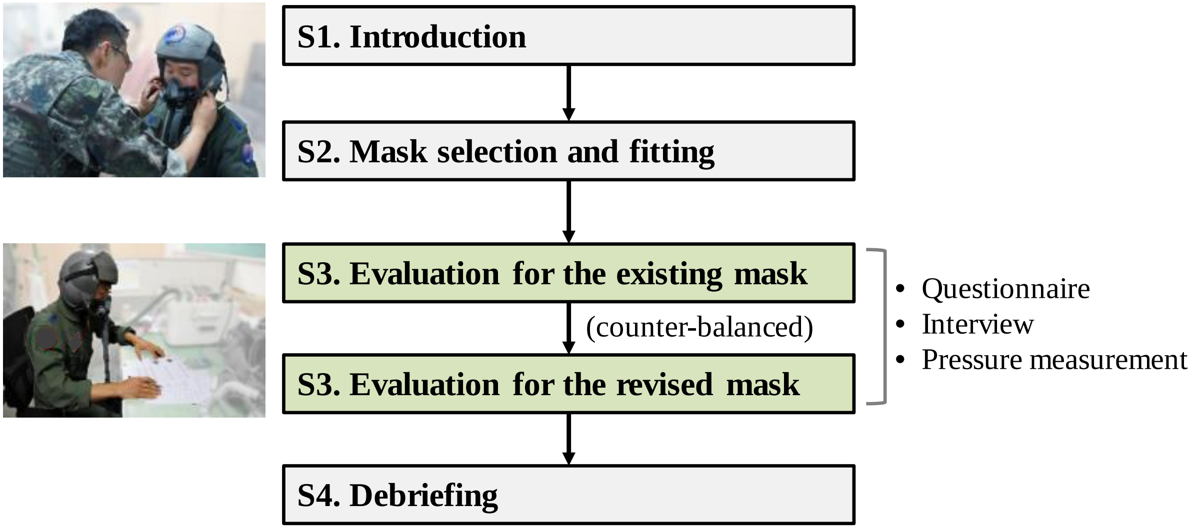
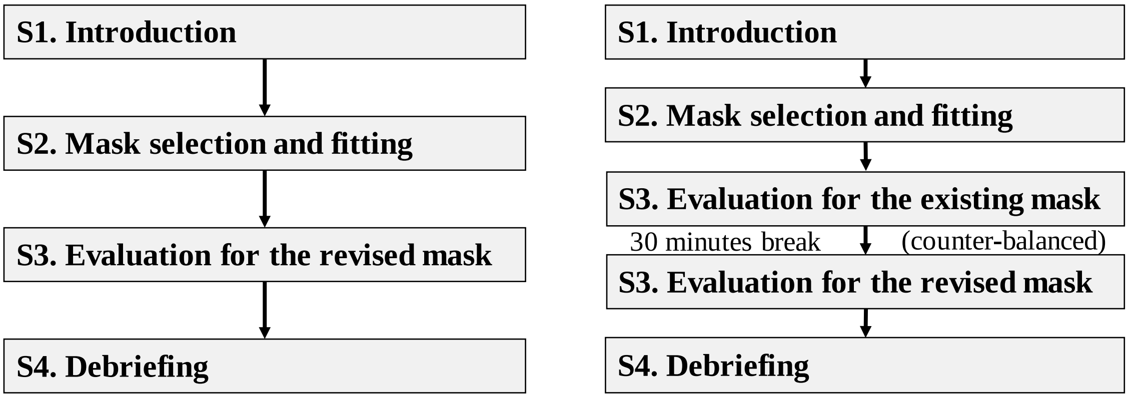


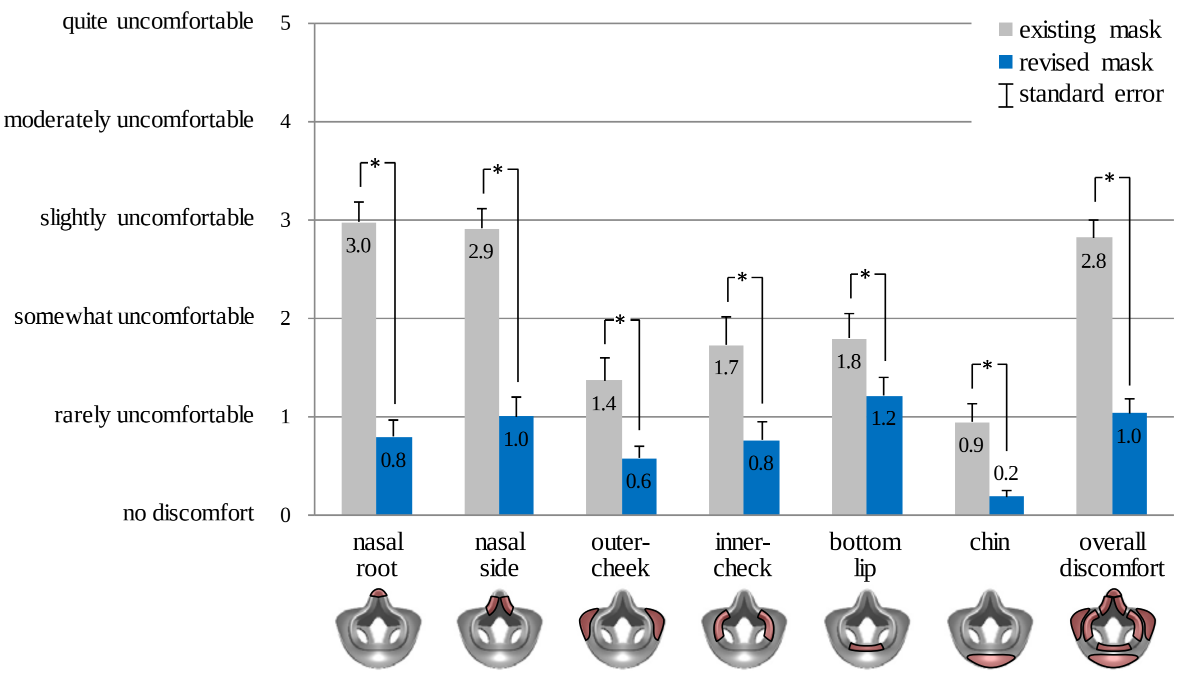
Figure 6. Protocol for subjective and pressure evaluation



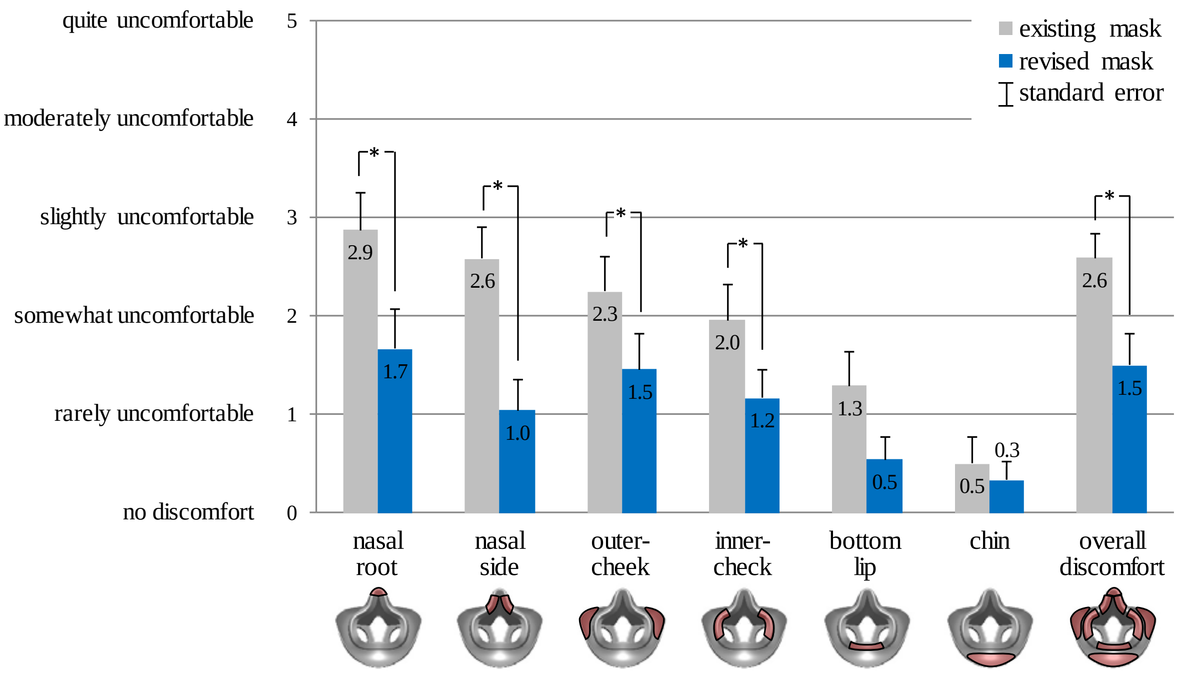
(a) Evaluation process for the low atmospheric pressure situation

(b) Evaluation process for the high-G situation

Figure 7. Evaluation process for performance evaluation in flight-like situations



(a) Discomfort of pilots (n = 32)



(b) Discomfort of cadets (n = 24)

Figure 8. Discomfort of pilots and cadets (p < 0.05)

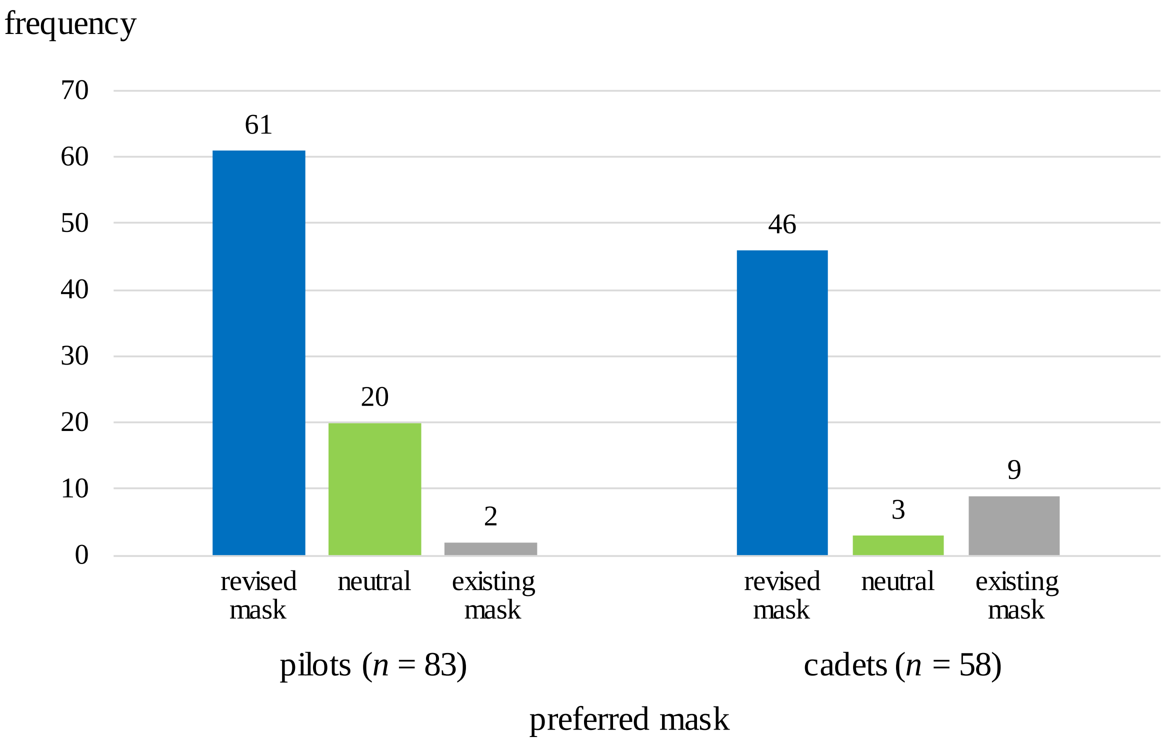
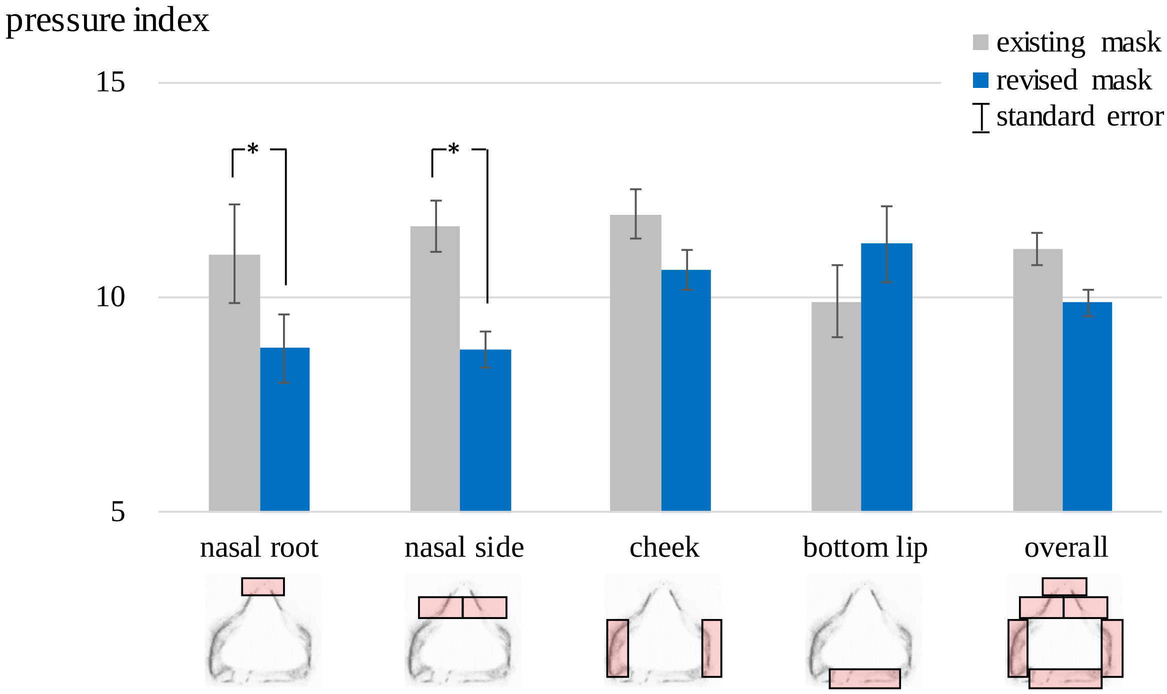
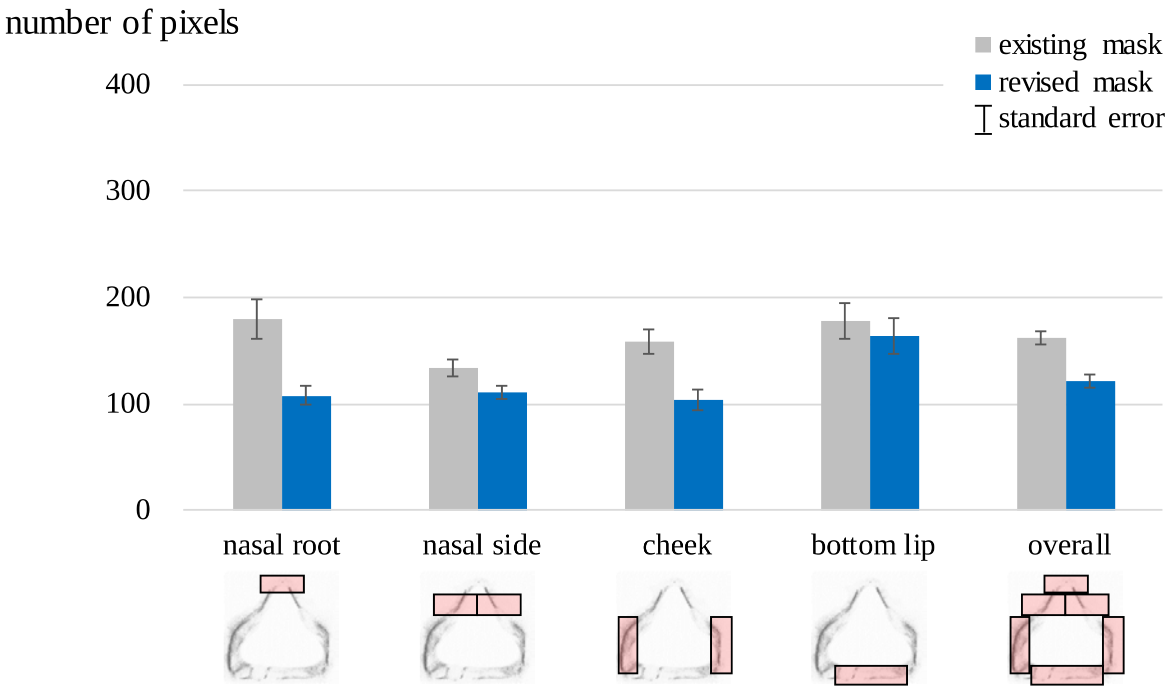


Figure 9. Preference results



(a) Pressure analysis results for average of pressure



(b) Pressure analysis results for excessively pressed area (PI ≥ 70)

Figure 10. Facial contact pressure analysis results (p < 0.05)

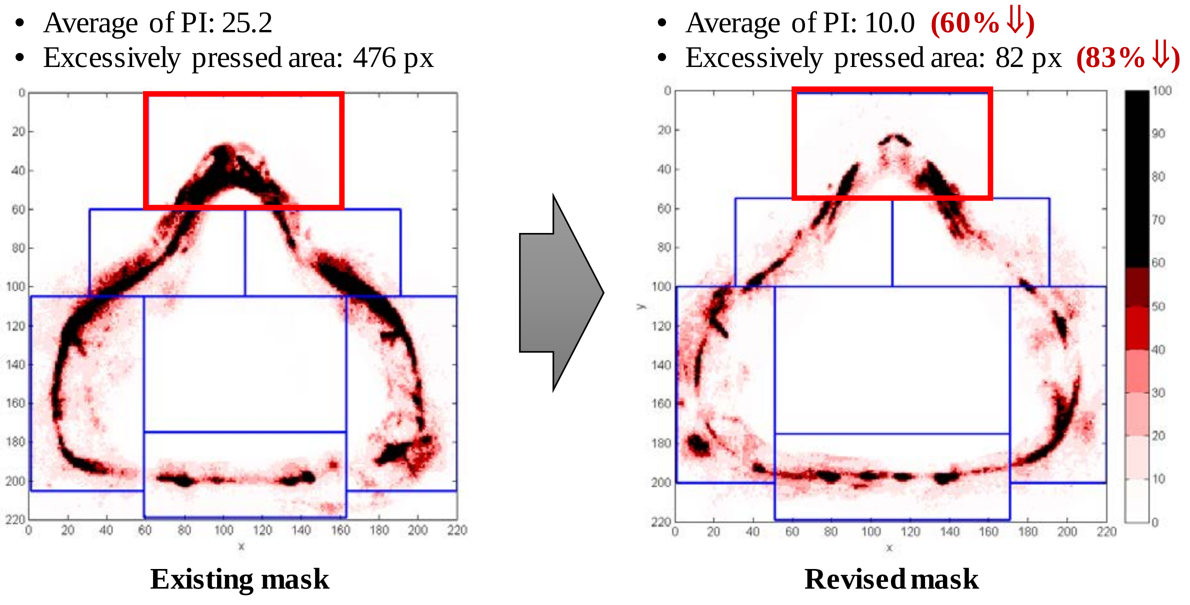


Figure 11. Illustration of the facial contact pressure analysis result at nasal root

(a) Existing mask (b) Revised mask

Figure 12. Illustration of the video analysis results