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Ergonomic evaluation of pilot oxygen mask designs

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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%–56%, 11%–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.

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, 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; Fig. 1a), worn by KAF pilots of F-15 or F-16 fighter, were initially designed using the face anthropometric data of 2420 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, 2013b). Lee et al. (2013b) revised the design of the existing oxygen mask as shown in Fig. 1.b by applying 3D face anthropometric data of 336 KAF pilots collected by Lee et al. (2013a).

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, 2014, 2013; Schreinemakers et al., 2014).

The present study compared the existing MBU-20/P pilot oxygen

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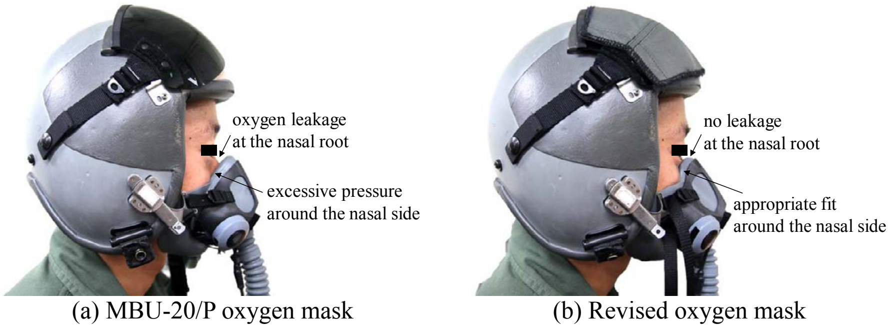


Fig. 1. Comparison of existing and revised pilot oxygen masks.

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

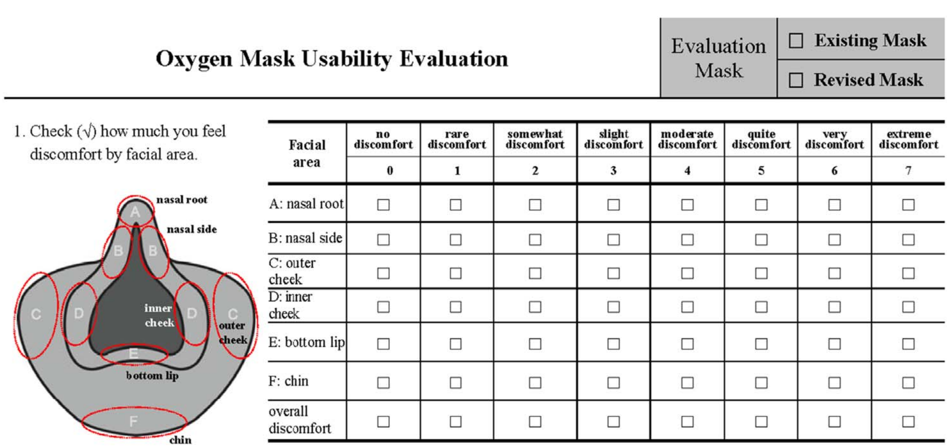
MBU-20/P oxygen masks and prototypes of the revised oxygen mask design were used for ergonomic evaluation in the present study. Four sizes (small narrow, medium narrow, medium wide, and large narrow) of the revised oxygen mask, designed by Lee et al. (2013b) based on 3D face anthropometric data of KAF 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 $\geq$ 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 Fig. 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



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

Fig. 2. Subjective evaluation questionnaire (illustration).