applied sciences

Article

A Method for Generation of a Sizing System and Representative Models for a Facial Mask Design

Wonsup Lee [1,*], Baekhee Lee [2], Xiaopeng Yang [1] and Heecheon You [3,*]

1. School of Global Entrepreneurship and Information Communication Technology, Handong Global University, Pohang, Gyeongbuk 37554, Republic of Korea
2. Body Test Team 3, Hyundai Motor Company, Hwaseong, Gyeonggi 18280, Republic of Korea
3. Department of Industrial and Management Engineering, Pohang University of Science and Technology, Pohang, Gyeongbuk 37673, Republic of Korea

* Correspondence: w.lee@handong.edu (W.L.); hcyou@postech.ac.kr (H.Y.)

Abstract: A sizing system and representative face models (RFMs) need to be properly determined for the design of a facial mask. The present study proposed a novel approach for the generation of a sizing system and RFMs for a facial mask that considers not only the accommodation of the target population but also its applicability in practice (e.g., ease of use and economic efficiency). A custom sizing system with four unique sizing categories was generated by applying the proposed approach for a pilot oxygen mask for Korean pilots. Then, out of 336 faces, a face showing the minimum value of weighted sum of Euclidean distance (WSED) was identified as the RFM of each of the four sizing categories. The proposed approach can be applied to the development of a sizing system and the identification of representative human models for the design of wearable products associated with multiple body dimensions.

Keywords: pilot oxygen mask; sizing system; representative face model; ergonomic design

Citation: Lee, W.; Lee, B.; Yang, X.; You, H. A Method for Generation of a Sizing System and Representative Models for a Facial Mask Design. *Appl. Sci.* **2022**, *12*, 12387. https://doi.org/10.3390/app122312387

Academic Editor: Paolo Renna

Received: 31 October 2022
Accepted: 26 November 2022
Published: 3 December 2022

1. Introduction

An efficient sizing system for a facial mask is important to properly accommodate various users having different face sizes. As the purpose of a sizing system is to divide a diverse population into homogeneous subgroups based on body sizes [1], the understanding of the anthropometric characteristics of the target population is essential. Previous studies emphasized that the selection of appropriate key anthropometric dimensions is important to develop a good sizing system [2–5]. In addition to anthropometric dimensions, there are several more considerations for the development of an efficient sizing system, including (1) the number of sizing categories, (2) the accommodation range of each sizing category, (3) the overall accommodation percentage of the target population, and (4) economic efficiency for manufacturing and logistics [4,6].

A sizing system for a facial mask requires to be properly designed based on facial anthropometric measurements to accommodate different facial sizes of a target population. For example, Zhuang et al. [7] designed a sizing system consisting of five sizing categories (Small, Medium, Large, Long-Narrow, and Short-Wide categories) based on the principal component analysis (PCA) on 19 facial dimensions of 3997 US civilians (2543 males and 1454 females; age: 18 to 66) collected by Zhuang and Bradtmiller [8] for designing industrial masks (Figure 1a). Chen et al. [9] used the same PCA-based sizing system design method of Zhuang, Bradtmiller and Shaffer [7] for the Chinese population and found the sizing criteria for the Chinese population need to be different from each other due to anthropometric differences between the US and Chinese populations (Figure 1b). MBU-20/P pilot oxygen masks (Gentex Corporation, Simpson, PA, USA), widely used by F-15, F-16, and F-22 pilots of US Air Force (USAF), were designed by Gross et al. [10] and

Self et al. [11] in five sizes (Extra Small Narrow, Small Narrow, Medium Narrow, Medium Wide, and Large Wide) based on face measurements of 2420 USAF pilots surveyed by Churchill et al. [12] (Figure 1c). After the sizing system of the MBU-20/P was developed by Gross, Taylor, Mountjoy and Hoffmeister [10], Self, White, Diesel and Whitestone [11] divided the Small Narrow size into Small Narrow and Extra Small Narrow to accommodate female pilots having small faces, who might not be sufficiently considered in Gross, Taylor, Mountjoy and Hoffmeister [10]'s study.

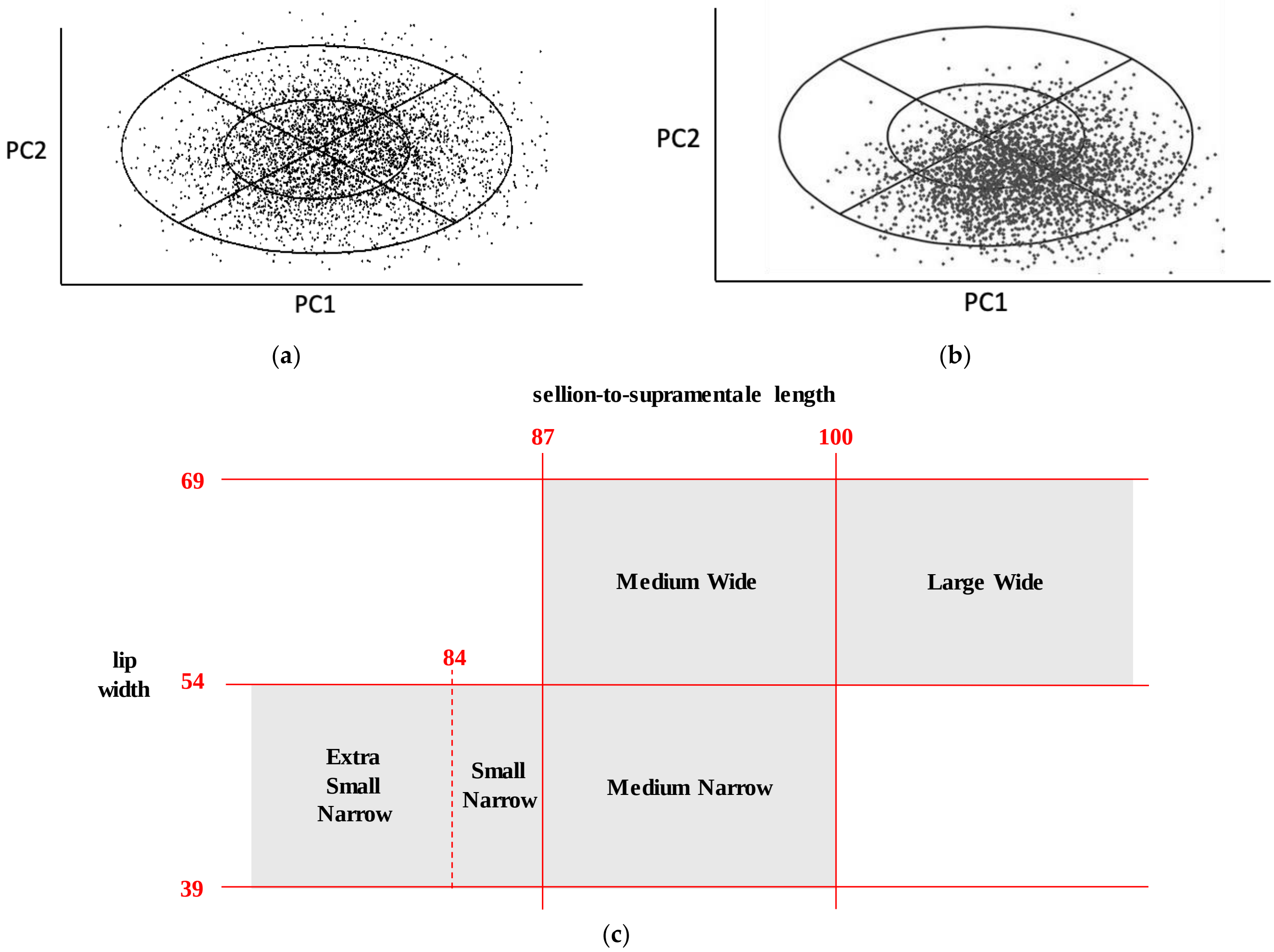


Figure 1. Sizing system for facial masks (illustrated). (**a**) Sizing system of industrial masks for US workforces generated based on the principal component analysis on facial anthropometric measurements [7]; (**b**) Inappropriateness of the sizing system for US workforces to Chinese workforces [9]; (**c**) Sizing system of MBU-20/P pilot oxygen mask.

A sizing system for a face mask is generally designed by considering a few key anthropometric facial dimensions. Previous studies in mask design [6,10,13–17] proposed some key facial anthropometric dimensions such as face length, lower-face length, lip width, and bigonial breadth for a mask sizing system. For example, Gross, Taylor, Mountjoy and Hoffmeister [10] used sellion-to-supramentale length (SSL; similar to face length) and lip width (LW) as key dimensions for the sizing system of MBU-20/P. As shown in Figure 1c, the sizing system of MBU-20/P consists of five sizing categories by combinations of extra small (SSL < 84 mm), small (84 mm ≤ SSL < 87 mm), medium (87 mm ≤ SSL < 100 mm) and large (SSL ≥ 100 mm) in length and narrow (39 mm ≤ LW < 54 mm) and wide (54 mm ≤ LW < 69 mm) in width.

As the pilot oxygen mask is an essential device for the safe and effective accomplishment of a flight mission, the pilot oxygen mask and its sizing system need to be designed based on the facial characteristics of the specific pilot population. For example, the pilot oxygen mask for Republic of Korea Air Force (KAF) pilots is required to be designed based on the facial data of KAF pilots. However, the MBU-20/P designed based on USAF pilots does not appropriately accommodate KAF pilots due to the anthropometric difference of the face between USAF and KAF populations [5]. Lee, Jeong, Park, Jeon, Kim, Jung, Park and You [5] identified that KAF male pilots showed significantly longer face length ($\bar{d}$ = 4.7 mm), narrower lip width ($\bar{d}$ = -2.4 mm), and wider nasal root breadth ($\bar{d}$ = 5.2 mm) on average than USAF male personnel. A survey by Lee [18] on the usability of the MBU-20/P mask conducted with 490 KAF pilots identified that 68% of KAF pilots had experienced significant discomfort from excessive pressure and/or oxygen leakage around the nasal root due to a lack of fit to the KAF pilots' faces.

3D facial models representing each sizing category in a sizing system have been utilized for the design of facial masks. Representative models are commonly used in designing a product having multiple sizes [3,4,6,7,19–21]. For example, Zhuang et al. [22] generated five representative 3D head models to design a respirator based on their sizing system shown in Figure 1a. Han et al. [23] designed an industrial respiratory mask of three sizes (small, medium, and large) for Korean industry workers using 3D representative head models identified based on facial measurement data of Korean faces. Lastly, Ball [24] created ten representative headforms for use in designing head-related products for the Chinese population based on the Size China anthropometric survey conducted by Ball and Molenbroek [25].

This study introduces ergonomic considerations (e.g., ease-of-use, ease-of-management, economic efficiency, accommodation ratio and representativeness) and practical strategies for designing a sizing system and representative face models (RFMs) based on facial anthropometric measurements with a case study on the MBU-20/P oxygen mask for KAF pilots. A new sizing system of the MBU-20/P for KAF pilots having six sizing categories was initially created based on the anthropometric facial measurements of KAF pilots. Then, the initial sizing system was modified by considering the usability and economic efficiency of the sizing system. The number of sizing categories and accommodation range of each sizing category were determined by a panel of discussion with ergonomists and stakeholders of KAF. RFMs showing better representativeness were derived by applying weighted sum of Euclidean distance (WSED) and normalized Euclidean distance (NED) suggested in this study.

2. Development of a Sizing System of a Pilot Oxygen Mask for KAF Pilots

2.1. Facial Anthropometric Data of KAF Pilots

3D facial anthropometric data (Table 1) of 336 KAF pilots (male: 278, female: 58) collected by Lee, Jeong, Park, Jeon, Kim, Jung, Park and You [5] were used for the development of a mask sizing system in this study. In their study [5], the number of participants were determined based on the formula for estimating minimum sample size provided in ISO 15535 and the gender composition of the KAF pilot population. 3D facial images of the pilots were obtained by scanning their faces using a Rexcan 560 3D scanner (Solutionix Co., South Korea) and processed by the ezScan software accompanied with the 3D scanner. The scanned 3D facial images were edited using image alignment, hole-filling, and smoothing functions in the ezScan software. Fourteen anthropometric landmarks were marked with stickers on a face by palpation before the face was scanned, then those stickers were identified automatically by the ezScan software. Eighteen facial dimensions (eight vertical length dimensions, one horizontal length dimension, six width dimensions, and three circumference and arc dimensions) closely related to pilot oxygen mask design were measured based on the facial landmarks. Descriptive statistics (e.g., mean, SD, minimum, maximum, and percentiles) of Lee et al.'s study regarding the 18 facial dimensions of the KAF pilots are presented in Table 1.

Table 1. Descriptive statistics of face dimensions derived by Lee et al. [5] (unit: mm).

No.	Face Dimensions	*n*	Mean	SD	Min	Max	Percentile			
							1st	5th	95th	99th
1	face length	336	123.4	6.1	106.7	140.4	108.0	113.1	133.2	136.6
2	lower face length	336	69.1	4.5	57.5	83.6	58.6	61.8	76.3	79.4
3	sellion-to-supramentale length	336	97.1	5.2	80.7	114.1	85.3	88.3	104.7	109.4
4	supramentale-to-menton length	336	26.4	3.0	18.6	36.2	19.7	21.4	31.0	34.6
5	rhinion-to-menton length	336	109.1	5.5	93.2	124.3	95.8	99.8	117.7	120.8
6	rhinion-to-promentale length	336	95.8	5.6	78.2	108.9	83.7	86.7	104.9	108.1
7	promentale-to-menton length	336	13.3	2.5	4.9	20.6	7.9	9.5	17.6	19.1
8	nose length	336	54.3	3.4	43.2	62.2	46.6	48.6	60.3	61.9
9	nose protrusion	336	18.4	1.9	12.9	23.9	14.2	15.3	21.6	23.0
10	face width	336	154.8	6.4	132.4	171.5	138.6	144.0	164.2	168.2
11	chin width	336	130.3	8.6	105.4	156.7	112.5	116.5	144.6	150.8
12	nasal root breadth	336	20.0	2.8	12.3	27.7	14.0	15.2	24.6	26.8
13	maximum nasal bridge breadth	336	30.5	2.8	22.3	37.7	24.2	25.6	35.3	36.7
14	nose width	336	37.6	2.7	30.3	45.8	31.8	33.4	42.4	43.8
15	lip width	336	49.1	3.8	38.5	58.2	40.7	42.6	55.5	57.4
16	bitragion-menton arc	336	313.7	16.2	269.0	361.1	273.5	284.1	339.1	347.3
17	bitragion-subnasale arc	336	283.0	12.9	234.9	319.6	252.1	263.1	304.5	312.1
18	bizygomatic-menton arc	336	304.8	14.5	261.3	339.6	267.0	277.8	327.6	336.2

2.2. Existing Sizing System of MBU-20/P Pilot Oxygen Mask

The existing sizing system for the MBU-20/P was not applicable to KAF pilots due to the differences between KAF pilots and USAF personnel in the key facial dimensions, SSL and LW. The average SSL of KAF pilots (97.1 ± 5.2 mm) was 6.5 mm longer than that of USAF personnel (90.6 ± 7.0 mm) measured by Gross, Taylor, Mountjoy and Hoffmeister [10]. The average LW of KAF pilots (49.1 ± 3.8 mm) was 6.5 mm narrower than that of USAF personnel (51.6 ± 3.3 mm). The accommodation percentage of the existing sizing system for KAF pilots was 73%. The scatter plot of KAF pilots' faces in the existing MBU-20/P's sizing system showed a highly unbalanced distribution in the existing sizing categories (Extra Small Narrow: 0%, Small Narrow: 3%, Medium Narrow: 61%, Medium Wide: 5% and Large Wide: 4%) (Figure 2).

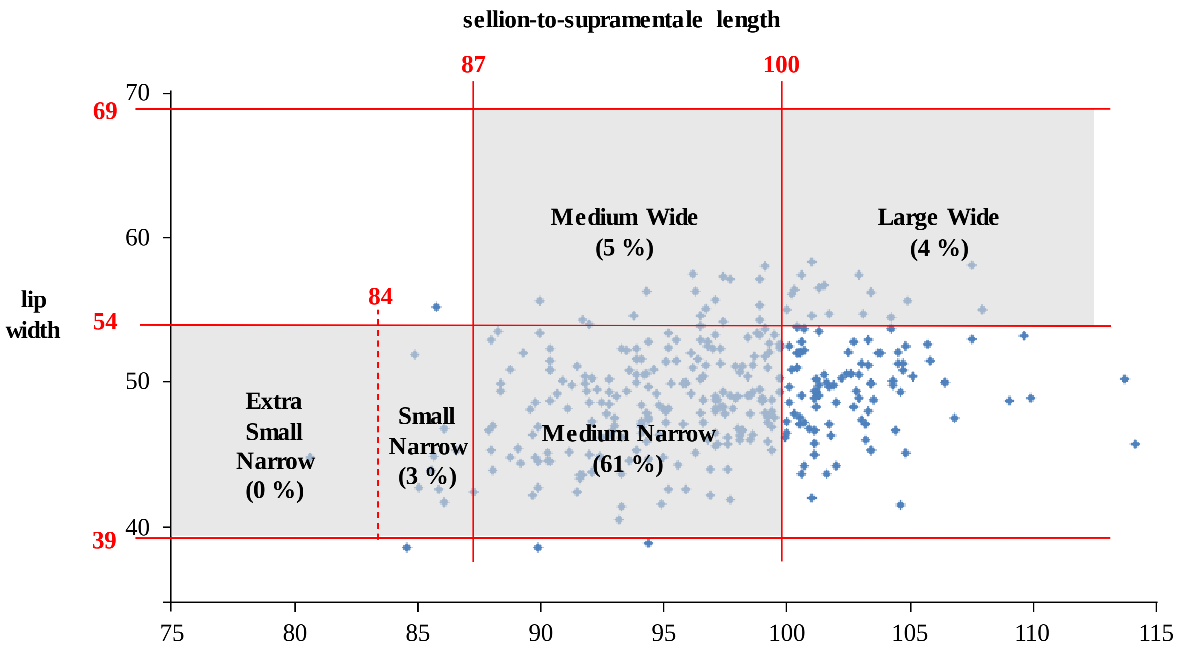
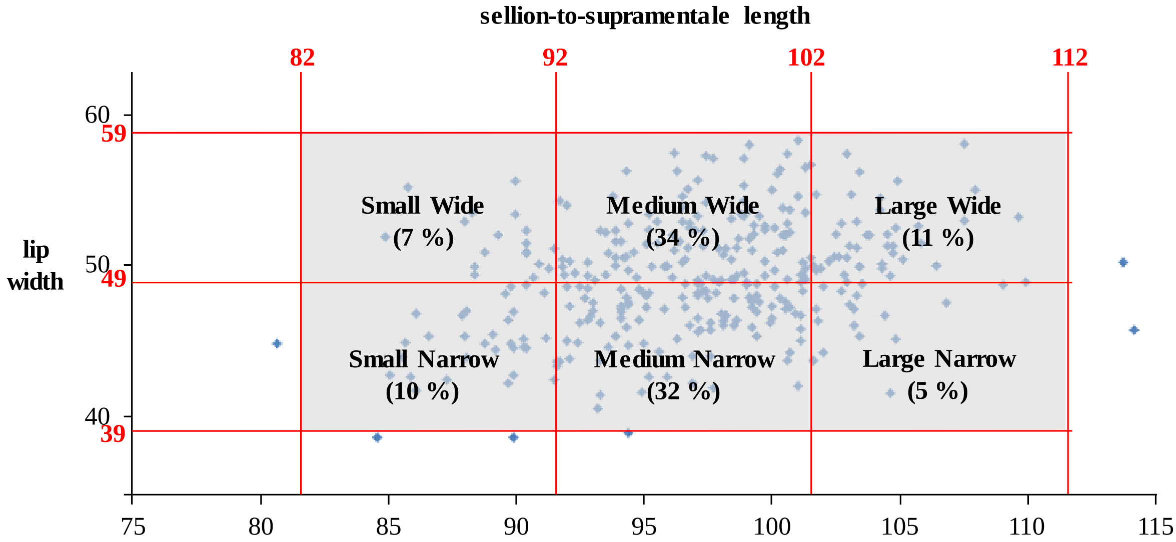


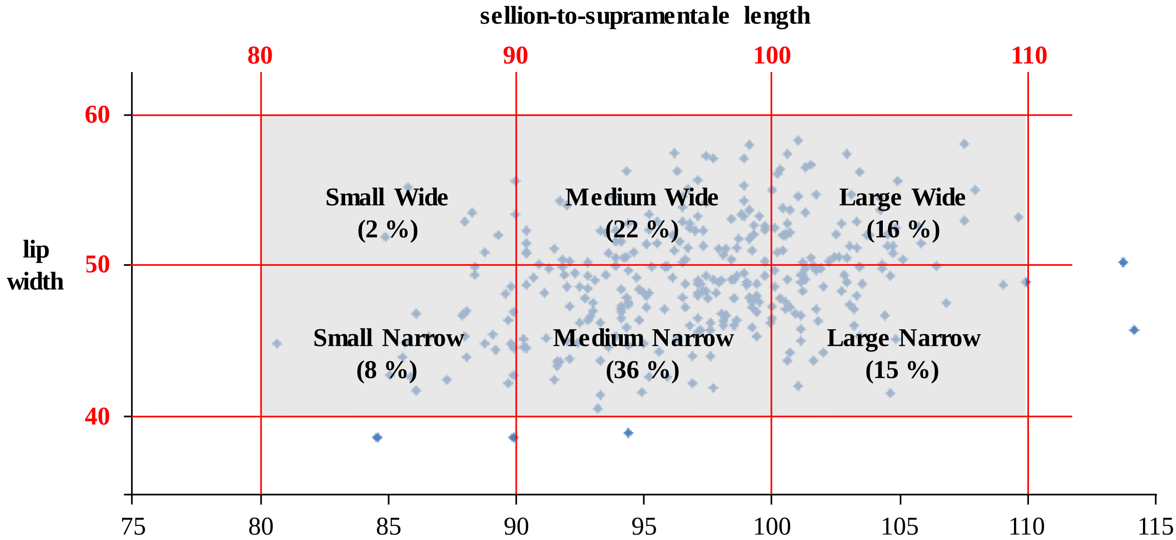
Figure 2. Scatter plot of Republic of Korea Air Force (KAF) pilots in the existing MBU-20/P's sizing system (accommodation percentage = 73%; dots: 336 KAF pilots).

2.3. Development of an Oxygen Mask Sizing System for KAF Pilots

The present study developed a new sizing system of oxygen masks for KAF pilots by the following approach. First, an initial sizing system was generated through a grid formation method proposed by Lee, Jung and You [19]. The initial sizing system consisted of six sizing categories generated based on predefined constraints: (1) a size interval of 10 mm for the key dimensions SSL and LW, (2) an accommodation percentage of 95%, and (3) a minimum presence percentage of 5% for a sizing category. The 10 mm sizing interval for SSL and LW (smaller than 13 mm for SSL and 15 mm for LW in the existing mask) was determined by considering the variations of SSL (range: 80.7 mm~114.1 mm) and LW (range: 38.5 mm~58.2 mm) of KAF pilots. Additionally, the interval of 10 mm was set as its ease-of-read and rememberability compared to the existing sizing system of the MBU-20/P. A sizing system having six sizing categories (Figure 3a) was formed automatically by the distributed representative human model generation and analysis system (DRHM-GAS) proposed by Lee, Lee, Yang, Jung and You [4]. The DRHM-GAS automatically formed the initial sizing system by inputting the sizing interval (10 mm in this case) and the number of sizing categories (6 categories in this case). The initial sizing system with 98% of accommodation percentage was generated with the sizing criteria of 82, 92, 102, and 112 mm in SSL and 39, 49, and 59 mm in LW. Then, the sizing criteria were adjusted to 80, 90, 100, and 110 mm in SSL and 40, 50, and 60 mm in LW, as shown in Figure 3b to provide an easy perception of size cut-off values. The adjusted sizing system showed 99% of the accommodation percentage.



(**a**)



(**b**)

Figure 3. Generation of a revised oxygen mask sizing system for KAF pilots. (**a**) initial sizing system (accommodation percentage = 98%); (**b**) adjusted sizing system (accommodation percentage = 99%).

2.4. Modification of the Oxygen Mask Sizing System

The proposed sizing system was adjusted through a panel of discussion with stakeholders of KAF to consider the economic and managerial efficiencies in military equipment logistics while maintaining a reasonable accommodation percentage. First, the two sizing categories Small Wide and Large Narrow were eliminated from the proposed sizing system as the existing sizing system of the MBU-20/P also does not contain Small Wide and Large Narrow sizes (Figure 1c) based on anecdotal recommendations from the expert personnel in the USAF [10]. The reasons for the exclusion of those two sizing categories from the existing sizing system could include (1) low presence rates of the two sizing categories and (2) economic efficiency for mask manufacturing and logistics after cutting the two sizing categories. For the same reasons, this study excluded Small Wide (presence rate = 2%) and Large Narrow (presence rate = 15%) from the proposed sizing system (Figure 4). Second, the sizing criteria of Small Narrow and Large Wide sizes were adjusted to effectively accommodate the user population with the remaining four sizing categories. The range of SSL of Small Narrow size was set as 85 to 90 mm (initial range: 80 to 90 mm) in order to find a better RFM for the Small Narrow size. The range of LW of Large Wide size was decided to be 45 to 55 mm (initial range: 50 to 60 mm) to accommodate more pilots. The accommodation percentage of the adjusted sizing system was decreased to 90% from 99% but still acceptable to accommodate a sufficient number of Korean pilots. Additionally, the material elasticity (as silicon rubber) of the oxygen mask was considered as it can increase the accommodability [26]. Besides, the economic efficiency of the adjusted sizing system (number of sizing categories = 4) will be comparably better than that of the sizing system having six sizes. The four-category sizing system will have better practicality in terms of managerial efficiency as the sizing category names are the same as the existing ones, but the shapes of each sizing category are dualized if new oxygen masks are used in KAF.

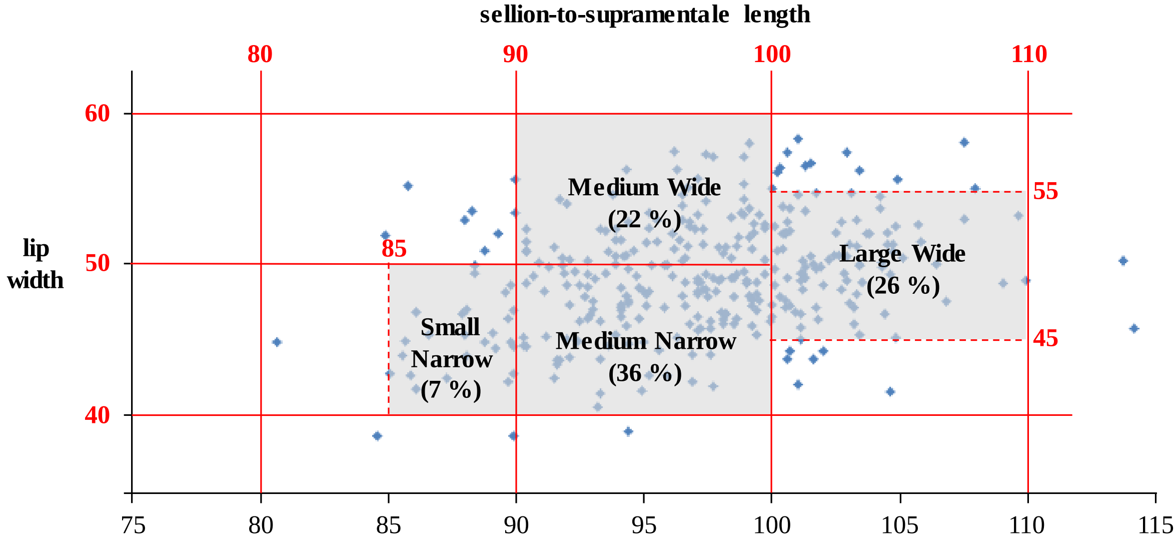


Figure 4. The final mask sizing system for KAF pilots with four sizing categories, updated by considering economic efficiency (accommodation percentage = 90%).

3. Comparative Selection of RFMs for a Pilot Oxygen Mask for KAF Pilots

After the sizing system was established, RFMs were identified among KAF pilots based on the weighted sum of Euclidean distance (WSED; Equation (1)), which is the weighted sum of distances between the facial measurements of a pilot and the averages (or medians) of facial measurements of a sizing category. The medians were used as the center of sizing categories drawn based on two key dimensions, SSL and LW; while the averages were used for the other 16 non-key dimensions as their sizes were not categorized and, in consequence, their medians are unknown. Table 2 shows the averages of facial measurements of KAF pilots by sizing category for 18 face dimensions considered in pilot oxygen mask design. The weight of each facial dimension can be defined according to their relevance (e.g., H: high; M: medium; and L: low) in designing an oxygen mask (Lee, Jeong, Park, Jeon, Kim, Jung, Park and You [5]. The WSED of each pilot's face can be calculated under four different analysis conditions by considering types of measurement value (measured value or normalized value) and weight (equal weight or unequal weight). The *z*-score normalization was applied to obtain normalized values of facial dimensions for each pilot. For the condition of unequal weights, weight values (e.g., H = 9, M = 3, and L = 1) were assigned to facial dimensions. Table 3 presents the identification numbers of KAF pilots selected as RFM candidates having the smallest WSED in each sizing category under the four analysis conditions.

$$WSED_j = \sqrt{\sum_{i=1}^{18}\left\{w_i \times \left(m_{ij} - \bar{m}_{ij}\right)^2\right\}} \quad (1)$$

where

w_i = weight of facial dimension *i*,

m_{ij} = measurement (measured value or normalized value) of facial dimension *i* of a single face in sizing category *j*, and

$\bar{m}_{ij}$ = average (or median) of the measurements (measured value or normalized value) of facial dimension *i* of all faces in sizing category *j*.

Table 2. The medians (key dimensions) and averages of face measurements by mask sizing category (unit: mm).

No.	Face Dimension	Importance	Grand Mean	Centroid of Mask Sizing Category			
				Small Narrow	Medium Narrow	Medium Wide	Large Wide
1	face length	H	123.4	114.5	121.7	122.7	129.4
2	lower face length	M	69.1	64.3	68.3	68.3	72.6
3	sellion-to-supramentale length †	M	97.1	87.5	95.0	95.0	105.0
4	supramentale-to-menton length	L	26.4	26.3	26.2	26.6	26.6
5	rhinion-to-menton length	M	109.1	102.0	107.4	108.8	113.9
6	rhinion-to-promentale length	H	95.8	88.0	94.1	95.8	100.3
7	promentale-to-menton length	L	13.3	14.0	13.3	13.0	13.6
8	nose length	M	54.3	50.1	53.5	54.4	56.8
9	nose protrusion	M	18.4	17.8	17.9	18.5	19.0
10	face width	M	154.8	148.6	153.5	157.2	156.5
11	chin width	L	130.3	123.1	129.3	133.7	131.0
12	nasal root breadth	H	20.0	17.7	19.6	20.9	20.6
13	maximum nasal bridge breadth	H	30.5	27.4	30.0	31.4	31.4
14	nose width	H	37.6	35.1	37.1	38.4	38.5
15	lip width †	H	49.1	45.0	45.0	55.0	50.0
16	bitragion-menton arc	L	313.7	295.3	310.1	318.5	319.5
17	bitragion-subnasale arc	L	283.0	269.9	280.5	286.0	287.6
18	bizygomatic-menton arc	L	304.8	288.9	301.5	308.4	311.5

† Two key dimensions of the sizing system were calculated as the median value of each sizing category, while the other 16 non-key dimensions were calculated as the average value of each sizing category.

Table 3. Representative pilot identification numbers showing the smallest weighted sum of Euclidean distance (WSED) for each sizing category for different WSED calculation conditions.

No.	WSED Calculation Condition		Pilot Identification Numbers Showing the Smallest WSED			
	Type of Measurement Value	Weight	Small Narrow	Medium Narrow	Medium Wide	Large Wide
1	measured	equal	260	165	240	177
2	measured	unequal	11	307	189	139
3	normalized	equal	54	128	189	177
4	normalized	unequal	32	128	189	139

Representativeness of the identified RFMs derived through the four WSED calculation conditions was evaluated by the distance between the identified RFM in a sizing category and the average face of the same category. As different results of the calculated

WSEDs under different conditions, normalized Euclidean distance (NED; Equation (2)) considering the weight of the facial dimensions was used to find the best RFMs. From the NED calculation results, the RFM selection condition using normalized values generated more representative RFMs than that using measured values in general (Table 4). The RFM selection method using measured values and unequal weights was applied in the present study because of its smaller mean and SD values in NEDs than those of other conditions. The four RFMs of KAF pilots and their locations in the proposed mask sizing system are presented in Table 5 and Figure 5, respectively.

$$NED_j = \sqrt{\sum_{i=1}^{18}\left\{w_i \times \left(\frac{m_{ij} - \bar{m}_{ij}}{\sigma_{ij}}\right)^2\right\} \Big/ sum\ of\ weights} \quad (2)$$

where

w_i = the weight of facial dimension *i*,
m_{ij} = the measurements (measured value or normalized value) of facial dimension *i* of a representative face in sizing category *j*,
$\bar{m}_{ij}$ = the averages (or medians) of the measurements (measured value or normalized value) of facial dimension *i* of all faces in sizing category *j*, and
σ_{ij} = the standard deviation of the measurements (measured value or normalized value) of facial dimension *i* of all faces in sizing category *j*.

Table 4. Normalized Euclidean distance (NED) of the identified representative face by the weighted sum of Euclidean distance (WSED) calculation method (unit: mm; pilot identification numbers are indicated in parentheses).

No.	WSED Calculation Condition	NED of Representative Face Per Sizing Category				Mean	SD
		Small Narrow	Medium Narrow	Medium Wide	Large Wide		
1	Measured value & Equal weight	0.23 (260)	0.23 (165)	0.37 (240)	**0.13 (177)**	0.24	0.10
2	Measured value & Unequal weight	**0.20 (11)**	**0.21 (307)**	**0.14 (189)**	0.15 (139)	**0.18**	**0.04**
3	Normalized value & Equal weight	0.46 (54)	0.46 (128)	0.53 (189)	0.58 (177)	0.51	0.06
4	Normalized value & Unequal weight	0.58 (32)	0.49 (128)	0.53 (189)	0.66 (139)	0.56	0.07

Bold texts: the smallest values among the results of WSED calculation conditions.

Table 5. Selected representative face models (RFMs) of KAF pilots and their facial sizes (key dimensions of the sizing system are in bold; pilot identification numbers are indicated in parentheses; unit: mm).

No.	Face Dimension	Facial Measurements of the RFM Per Sizing Category			
		Small Narrow (11)	**Medium Narrow (307)**	**Medium Wide (189)**	**Large Wide (139)**
1	face length	116.5	121.7	124.8	127.4
2	lower face length	66.1	69.3	70.1	72.7
3	sellion-to-supramentale length *	88.1	94.4	96.5	102.6
4	supramentale-to-menton length	28.4	27.3	28.3	24.8
5	rhinion-to-menton length	102.9	107.4	113.3	111.9
6	rhinion-to-promentale length	85.7	95.0	99.4	98.0
7	promentale-to-menton length	17.2	12.4	13.9	13.9
8	nose length	50.4	52.4	54.7	54.7

9	nose protrusion	17.2	17.0	17.6	18.7
10	face width	144.8	150.5	157.6	156.1
11	chin width	118.4	127.1	135.6	129.9
12	nasal root breadth	19.1	18.6	20.5	21.3
13	maximum nasal bridge breadth	26.4	34.4	32.8	30.3
14	nose width	33.6	38.9	37.4	35.7
15	lip width *	46.9	44.6	54.5	50.5
16	bitragion-menton arc	293.4	305.7	323.3	320.6
17	bitragion-subnasale arc	266.7	278.1	292.9	292.9
18	bizygomatic-menton arc	285.2	296.6	306.5	314.6

* Key dimensions.

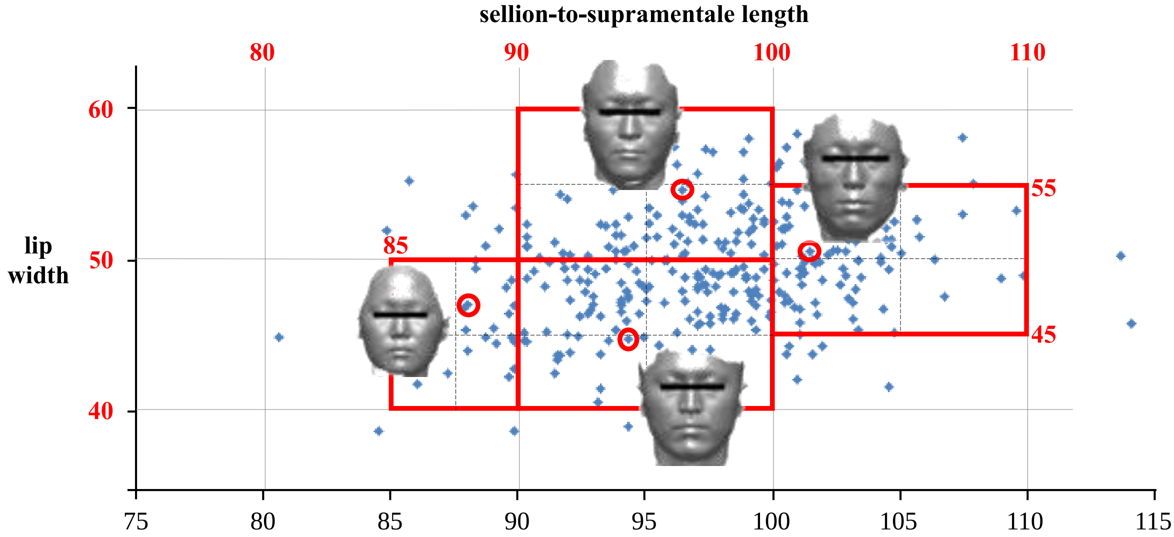


Figure 5. Representative face models for the proposed pilot oxygen mask sizing system of KAF pilots.

4. Discussion

The present study proposed a sizing system and RFMs of oxygen masks for KAF pilots with practical considerations including ease-of-use, ease-of-management, economic efficiency, accommodation ratio and representativeness. First, the initial sizing system consisting six categories formed by a combination of small, medium, and large sizes in SSL and narrow and wide sizes in LW. The size interval of 10 mm for SSL and LW and corresponding sizing cutoff criteria of 80, 90, 100, and 110 mm for SSL, and 40, 50, and 60 mm for LW in the initial sizing system were determined for ease-of-use of the sizing system. Second, based on stakeholders' considerations of economic efficiency (e.g., manufacturing and logistics costs) and equipment management (e.g., same sizing categories of the existing MBU-20/P), the number of sizing categories of the initially generated sizing system was reduced to four. Third, to increase the accommodation percentage with the reduced number of sizing categories, the sizing criteria for Small Narrow and Large Wide sizing categories were adjusted. The accommodation percentage of the adjusted sizing system (90%) showed 17% higher than that of the existing sizing system (73%) for KAF pilots. Lastly, the RFMs were found by considering the representativeness analysis methods (WSED and NED) proposed in this study.

The proposed sizing system does not include the Extra Small Narrow size, because the anthropometric characteristics of female pilots who may include small faces in KAF had been considered. The Extra Small Narrow size of the existing MBU-20/P was created after the four sizing categories were defined to consider female pilots having smaller faces.

In this study, the Extra Small Narrow was not necessary as a separated sizing category as the proportion (17%) of female KAF pilots was fully considered in the proposed sizing system. A usability evaluation conducted by Lee et al. [27] on the new oxygen mask designs for KAF pilots designed based on the proposed sizing system [26] showed that the KAF female pilots were sufficiently accommodated by the Small Narrow size.

The proposed RFM selection method considers multiple anthropometric dimensions rather than using only two key dimensions to increase the RFMs' representativeness. The RFMs found as the closest to the centroid of sizing categories generated by two key dimensions might not be representative for other body dimensions [6,7,28]. This study used all the 18 facial dimensions in the selection of RFMs closest to the average face of each sizing category. Not all the RFMs in this study locate close to the centroid of each sizing category drawn based on only the two key dimensions, but it might show better representativeness within the population than the RFMs close to the centroids. The representativeness was evaluated in this study by comparison between different RFM sets found based on different conditions. Types of measurement value (measured value or normalized value) and weight (equal weight or unequal weight: H = 9, M = 3, L = 1) of each facial dimension were considered as the analysis conditions for RFMs selection in this study. The normalized values in WSED calculation were used to consider the differences in measurement range by facial dimensions (e.g., nose protrusion = 12.9~23.9 mm; bitragion-menton arc = 269.0~361.1 mm) that can affect the results of RFM selection. The RFM selection conditions were evaluated using NED. RFMs showing better representativeness were found under the conditions using measured values with unequal weights in the case of the oxygen mask for KAF pilots. The RFM selection and representativeness analysis methods proposed in this study can be usefully applied to finding representative models for a multiple-size product design.

As the follow-up study, the RFMs having facial sizes that are exactly the same as the average (or median for the key dimensions) face would be created by applying the skin deformation technology. The present study found the RFMs among the existing faces of the KAF pilot data. Due to the limited amount of sample size (n = 336), an identified RFM could be located at a significant distance from the average/median face in the sizing category. This issue can be resolved by artificially creating 3D RFMs that have the average/median facial size in each sizing category by applying the skin deformation technology [29–32]. The 3D form of the selected RFM can be slightly deformed to have exact sizes of the average/median face by adjusting meshes around facial landmarks.

The sizing system and RFMs derived in this study were applied in the design of a pilot oxygen mask for KAF pilots. Four-sized oxygen masks were designed based on the proposed sizing system [6,26,28] and the RFMs. Prototypes of the oxygen masks for KAF pilots were manufactured with similar materials to the existing MBU-20/P mask. Then, the prototypes were compared to the MBU-20/P with 88 KAF pilots in terms of subjective and facial contact pressure analyses [27]. As a result, the discomfort level and facial contact pressure of the newly designed mask showed 33~56% and 11~33% lower on average than those of the MBU-20/P, respectively.

5. Conclusions

The present study tends to deliver ergonomic considerations for product sizing and design by introducing a case study of the sizing system and RFMs development for the oxygen mask for KAF pilots. The new sizing system of the oxygen mask was created with consideration of not only the key anthropometric dimensions and accommodation percentage but also ease of use and economic efficiency. Next, RFMs to develop an oxygen mask design for KAF pilots were selected based on all the facial dimensions under consideration by using the WSED and NED. The proposed method for the development of a sizing system and RFMs can be applied to the development of an ergonomic sizing system and design of not only face masks but also wearable products associated with multiple body dimensions.

Author Contributions: Conceptualization, all coauthors; methodology, W.L. and B.L.; software, W.L. and B.L.; validation, W.L. and B.L.; formal analysis, W.L. and X.Y.; resources, all coauthors; writing—original draft preparation, W.L.; writing—review and editing, all coauthors; visualization, W.L.; supervision, H.Y.; project administration, H.Y.; funding acquisition, H.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was jointly supported by Air Force Logistics Command grant funded by Republic of Korea Air Force, and by the National Research Foundation of Korea (NRF) grants funded by Korean Government (2020R1F1A1050076 and 2022R1A2C1013198).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. McCulloch, C.E.; Paal, B.; Ashdown, S.P. An optimization approach to apparel sizing. *J. Oper. Res. Soc.* **1998**, *49*, 492–499.
2. Zakaria, N. Body Shape Analysis and Identification of Key Dimensions for Apparel Sizing Systems. In *Anthropometry, Apparel Sizing and Design*; Gupta, D., Zakaria, N., Eds.; Woodhead Publishing: Cambridge, UK, 2014; pp. 95–119.
3. Jung, K.; Kwon, O.; You, H. Evaluation of the multivariate accommodation performance of the grid method. *Appl. Ergon.* **2010**, *42*, 156–161. https://doi.org/10.1016/j.apergo.2010.06.004.
4. Lee, B.; Lee, W.; Yang, X.; Jung, K.; You, H. Development of a distributed representative human model generation and analysis system (DRHM-GAS): Application to optimization of flight suit and pilot oxygen mask sizing systems. *Int. J. Ind. Ergonom.* **2019**, *72*, 261–271. https://doi.org/10.1016/j.ergon.2019.06.005.
5. Lee, W.; Jeong, J.; Park, J.; Jeon, E.; Kim, H.; Jung, D.; Park, S.; You, H. Analysis of the facial measurements of Korean Air Force pilots for oxygen mask design. *Ergonomics* **2013**, *56*, 1451–1464. https://doi.org/10.1080/00140139.2013.816376.
6. Lee, W.; Yang, X.; Jung, H.; You, H.; Goto, L.; Molenbroek, J.F.M.; Goossens, R.H.M. Application of massive 3D head and facial scan datasets in ergonomic head-product design. *Int. J. Digit. Hum.* **2016**, *1*, 344–360. https://doi.org/10.1504/ijdh.2016.084592.
7. Zhuang, Z.; Bradtmiller, B.; Shaffer, R.E. New respirator fit test panels representing the current U.S. civilian work force. *J. Occup. Environ. Hyg.* **2007**, *4*, 647–659. https://doi.org/10.1080/15459620701497538.
8. Zhuang, Z.; Bradtmiller, B. Head-and-face anthropometric survey of U.S. respirator users. *J. Occup. Environ. Hyg.* **2005**, *2*, 567–576. https://doi.org/10.1080/15459620500324727.
9. Chen, W.; Zhuang, Z.; Benson, S.; Du, L.; Yu, D.; Landsittel, D.; Wang, L.; Viscusi, D.; Shaffer, R.E. New respirator fit test panels representing the current Chinese civilian workers. *Ann. Occup. Hyg.* **2009**, *53*, 297–305. https://doi.org/10.1093/annhyg/men089.
10. Gross, M.E.; Taylor, S.E.; Mountjoy, D.N.; Hoffmeister, J. *Anthropometric Research on the Sizing of the MBU-20/P.*; AFRL-HE-WP-TR-2002-0181; Human Effectiveness Directorate; Crew System Interface Division, Wright-Patterson Air Force Base: Montgomery County Green, OH, USA, 1997.
11. Self, B.P.; White, C.; Diesel, D.A.; Whitestone, J. Development of an Extra Small Narrow MBU-20/P Oxygen Mask. In Proceedings of the 36th Annual SAFE Symposium, Phoenix, AZ, USA, 14–16 September 1998; pp. 466–472.
12. Churchill, E.; Kikta, P.; Churchill, T. *The AMRL Anthropometric Data Bank Library: Volumes I-V.*; AMRL-TR-77-1, ADA047314; Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base: Montgomery County Green, OH, USA, 1977.
13. Zhuang, Z.; Coffey, C.C.; Ann, R.B. The effects of subject characteristics and respirator features on respirator fit. *J. Occup. Environ. Hyg.* **2005**, *2*, 641–649. https://doi.org/10.1080/15459620500391668.
14. Oestenstad, R.K.; Perkins, L.L. An assessment of critical anthropometric dimensions for predicting the fit of a half-mask respirator. *Am. Ind. Hyg. Assoc. J.* **1992**, *53*, 639–644. https://doi.org/10.1080/15298669291360283.
15. Han, D.-H.; Choi, K.-L. Facial dimensions and predictors of fit for half-mask respirators in Koreans. *Am. Ind. Hyg. Assoc. J.* **2003**, *64*, 815–822. https://doi.org/10.1080/15428110308984877.
16. Hack, A.L.; McConville, J.T. Respirator protection factors: Part I—Development of an anthropometric test panel. *Am. Ind. Hyg. Assoc. J.* **1978**, *39*, 970–975.
17. Lee, B.; Lee, W.; Jeong, J.; Jeon, E.; Son, D.; Park, S.; Jung, D.; Kim, H.; You, H. An improvement in the sizing system of oxygen masks for Korean pilots. In Proceedings of the 2011 Fall Conference of Ergonomics Society of Korea, Cheonan, Republic of Korea, 21–22 October 2011.
18. Lee, W. *Development of a Design Methodology of Pilot Oxygen Mask Using 3D Facial Scan Data*; Pohang University of Science and Technology: Pohang, Republic of Korea, 2013.
19. Lee, B.; Jung, K.; You, H. Development of a distributed representative human model (DRHM) generation and analysis system for multiple-size product design. In Proceedings of the Human Factors and Ergonomics Society 57th Annual Meeting, San Diego, CA, USA, 30 September–4 October 2013.
20. Lacko, D.; Vleugels, J.; Fransen, E.; Huysmans, T.; De Bruyne, G.; Van Hulle, M.M.; Sijbers, J.; Verwulgen, S. Ergonomic design of an EEG headset using 3D anthropometry. *Appl. Ergon.* **2017**, *58*, 128–136. https://doi.org/10.1016/j.apergo.2016.06.002.

21. Ellena, T.; Skals, S.; Subic, A.; Mustafa, H.; Pang, T.Y. 3D digital headform models of Australian cyclists. *Appl. Ergon.* **2017**, *59*, 11–18. https://doi.org/10.1016/j.apergo.2016.08.031.
22. Zhuang, Z.; Benson, S.; Viscusi, D. Digital 3-D headforms with facial features representative of the current US workforce. *Ergonomics* **2010**, *53*, 661–671. https://doi.org/10.1080/00140130903581656.
23. Han, D.; Rhi, J.; Lee, J. Development of prototypes of half-mask facepieces for Koreans using the 3D digitizing design method: A pilot study. *Ann. Occup. Hyg.* **2004**, *48*, 707–714. https://doi.org/10.1093/annhyg/meh068.
24. Ball, R.M. 3-D design tools from the SizeChina project. *Ergon. Des.* **2009**, *17*, 8–13.
25. Ball, R.M.; Molenbroek, J.F.M. Measuring Chinese heads and faces. In Proceedings of the 9th International Congress of Physiological Anthropology, Human Diversity: Design for Life, Delft, The Netherlands, 22–26 August 2008; pp. 150-155.
26. Lee, W.; Jung, D.; Park, S.; Kim, H.; You, H. Development of a virtual fit analysis method for an ergonomic design of pilot oxygen mask. *Appl. Sci.* **2021**, *11*. https://doi.org/10.3390/app11125332.
27. Lee, W.; Yang, X.; Jung, D.; Park, S.; Kim, H.; You, H. Ergonomic evaluation of pilot oxygen mask designs. *Appl. Ergon.* **2018**, *67*, 133–141. https://doi.org/10.1016/j.apergo.2017.10.003.
28. Lee, W.; Kim, H.; Jung, D.; Park, S.; You, H. Ergonomic design and evaluation of a pilot oxygen mask. In Proceedings of the Human Factors and Ergonomics Society 57th Annual Meeting, San Diego, CA, USA, 30 September–4 October 2013.
29. Lee, W.; Goto, L.; Molenbroek, J.F.M.; Goossens, R.H.M. Analysis methods of the variation of facial size and shape based on 3D face scan images. In Proceedings of the Human Factors and Ergonomics Society 61st Annual Meeting, Austin, TX, USA, 9–13 October 2017.
30. Lee, W.; Molenbroek, J.F.M.; Goto, L.; Jellema, A.H.; Song, Y.; Goossens, R.H.M. Application of 3D Scanning in Design Education. In *DHM and Posturography*, Scataglini, S., Paul, G., Eds.; Academic Press: Cambridge, MA, USA, 2019.
31. Lee, W.; Jung, H.; You, H. Application of 3D human body template model for ergonomic product design. *J. Ergon. Soc. Korea* **2020**, *39*, 223–241.
32. Lee, W.; Jung, H.; You, H. Development of a 3D template-registered image database of Korean heads for ergonomic product design. *J. Ergon. Soc. Korea* **2020**, *39*, 437–451. https://doi.org/10.5143/jesk.2020.39.5.437.