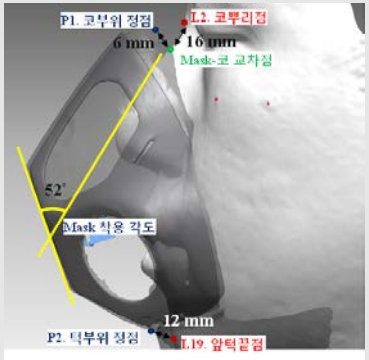
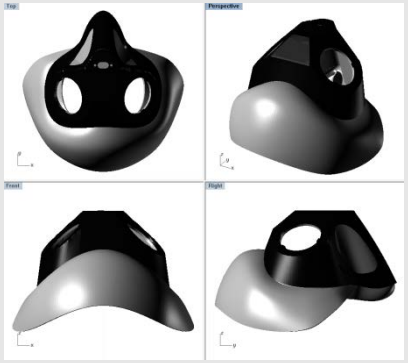
Development of a Methodology to Design a Pilot Oxygen Mask based on Virtual Fit Testing Method





[a]이원섭, [b]정정림, [c]손동훈, [c]박세권, [c]정대한, [d]김희은, [e]유민지, [e]박춘식 [a]유희천

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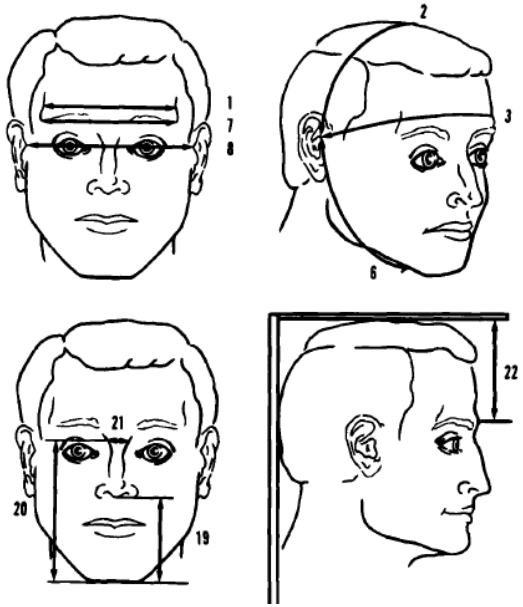
Agenda

- Background and Objectives
- Oxygen Mask Design Methodology
  - Face-Mask Interface Analysis
  - OM Design Strategy Development
  - OM Design Based on Virtual Fit Testing
  - Evaluation of Revised Oxygen Mask
- Discussion

Research Motivation

- Pilot oxygen mask which is designed based on US Air Force face data does **not fit to Korean pilots**
- Excessive **pressure** or oxygen **leaking** at nose (ROK Air Force, 2006)
  ⇒ cause pain and highly stressed situation



US Air Force
face anthropometric data
(Churchill et al., 1977)

MBU-20/P oxygen mask
for F-15, F-16 fighter
(Gentex corporation, USA)

Excessive pressure
for Korean pilots' nose
(illustrated)

General Differences Between Koreans and US Pilots

- **Required comparison between Korean and US pilots' facial characteristics to figure out the reason of unfitness of current mask to Korean pilots**
- **But, no facial anthropometric data of Korean pilots**

- ***cf.* Korean civilians' face is shorter (5.7 ~ 9.5 mm) and wider (1.8 ~ 3.8 mm) than US Pilots**

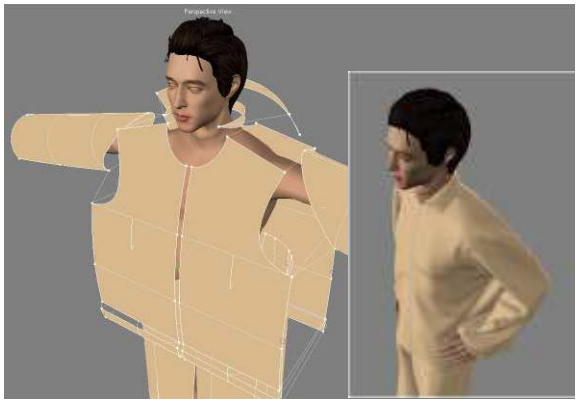
Comparison between Korean Civilians and US Pilots (age: 25 ~ 50, male)

no	face dimension	Korean civilians (Size Korea, 2004)		US pilots (Churchill et al., 1977)	mean difference (KC – USP)
1	face length	110.8	<	120.3	-9.5
2	lower face length	63.3	<	69.0	-5.7
3	face width (bitragion breadth)	144.3	>	142.5	1.8
4	nose width	39.2	>	35.4	3.8

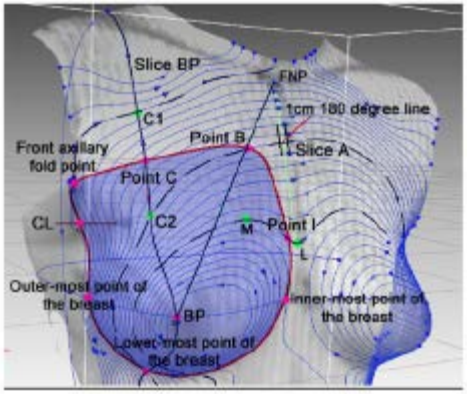
(unit: mm)

Product Design based on 3D Human Scan Data

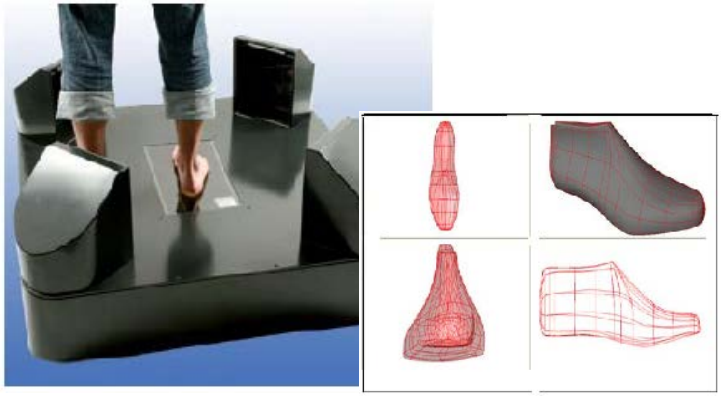
- **Wearable products** (e.g., cloths, shoes, helmets, masks) requires well-fitness
- Wearable products have designed based on **body size and shape**



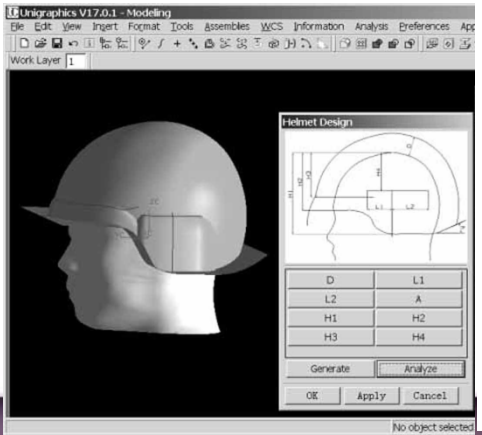
Clothing pattern design based on 3D human body (Park & Lee, 2012, etc.)



Innerwear design based on 3D scan data (Lee and Hong, 2007; Zheng et al., 2007)



Shoes customization based on 3D foot data (Lochner, 2009; Rout, 2010)



Helmet design based on 3D head (Liu et al., 2008)

Dustproof mask based on Korean face size and shape (Han et al., 2003, 2004)

Research Objectives

Design an Korean Pilot Oxygen Mask based on Virtual Fit Testing

1. **Measurement of Korean pilots' face**
   ⇒ figure out differences between Korean and US pilots' face

2. **Development of a mask design method based on 3D face scan data, mask wearing characteristics, and users' preferences**
   ⇒ systematically design the mask considering face-mask interface

3. **Development of a method for virtual mask fitting on 3D face**
   ⇒ virtually test a fitness of a revised mask on the early stage of design

4. **Evaluation of a revised mask prototype with Korean pilots**
   ⇒ validate proposed mask design method

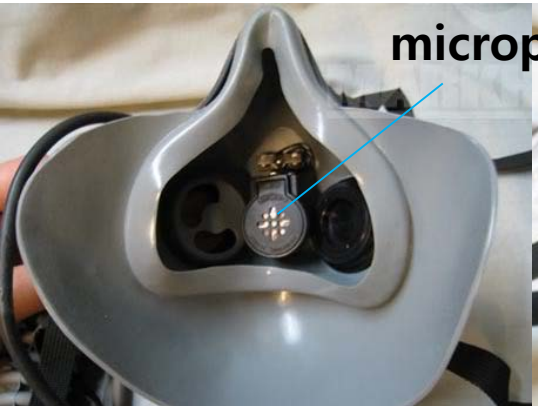
Pilot Oxygen Mask (MBU-20/P)

- MBU-20/P: oxygen mask for F-15 and F-16 fighter
- Half-face mask: covers nasal and oral part (*cf.* full-face mask)
- Supply oxygen on high altitude, high gravity, ejection, and ditching situation
- Support communication
- Size: extra small narrow (XSN), small narrow (SN), medium narrow (MN), medium wide (MW), large wide (LW)

design object of this study

Components of Pilot Oxygen Mask

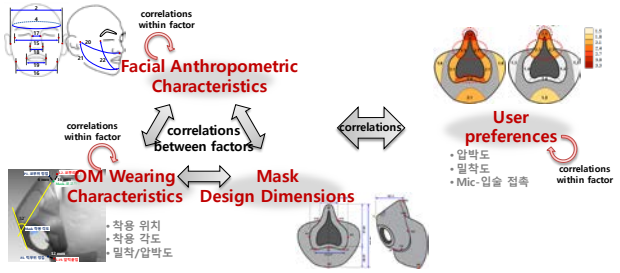
- Facepiece: preventing oxygen leaking (material: silicone rubber)
- Hardshell: preventing shape distortion of facepiece (material: polysulfone)



Oxygen Mask Design Process

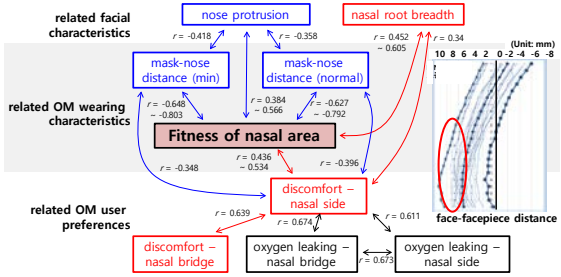
S1 Face-Mask Interface Analysis

- Facial characteristics
- OM wearing characteristics
- OM design dimensions
- OM user preferences



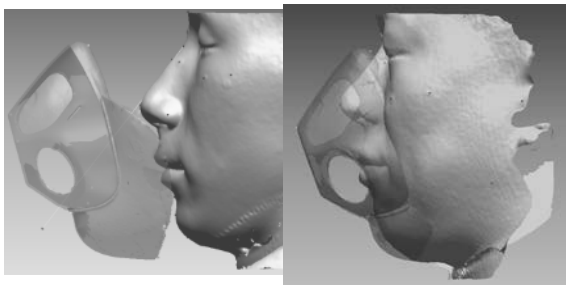
S2 OM Design Strategy Development

- Correlation analysis
- Technical model development
- Design directions determination



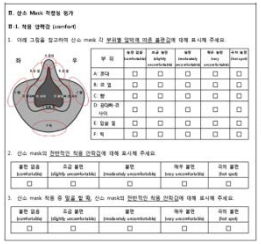
S3 OM Design Based on Virtual Fit Testing

- Virtual fit testing method development
- Design revision values determination
- OM design revision
- Design effect analysis & iterative design

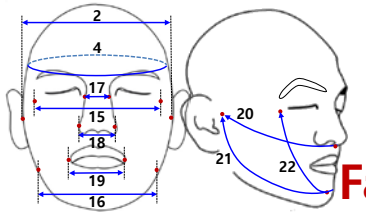


S4 Evaluation of Revised Oxygen Mask

- Virtual fit testing
- Ergonomic experiment

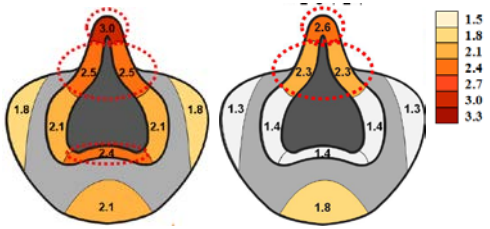


S1. Face-Mask Interface (FMI) Analysis



correlations within factor

Facial Anthropometric Characteristics



correlations within factor

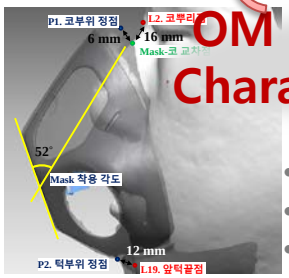
correlations between factors

correlations

User preferences

- Discomfort
- Oxygen leaking
- Mic-lip clearance

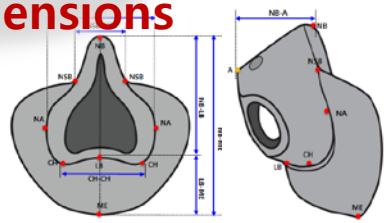
correlations within factor



OM Wearing Characteristics

- Wear position
- Wear angle
- Fitness

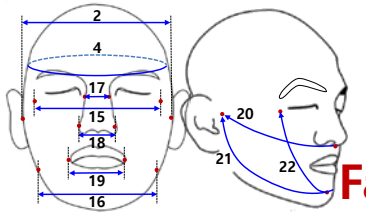
Mask Design Dimensions



Preferred/non-preferred design criteria

Design revision strategy & design improvement

FMI Factor: Facial Anthropometric Characteristics



correlations within factor

Facial Anthropometric Characteristics

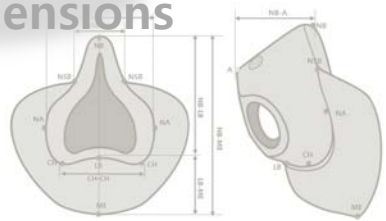
correlations between factors

correlations within factor

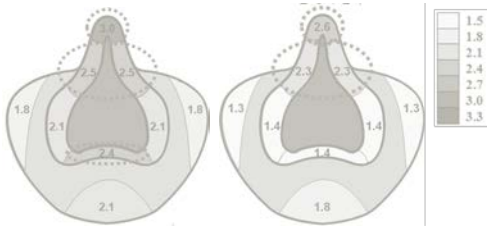
OM Wearing Characteristics

- Wear position
- Wear angle
- Fitness

Mask Design Dimensions



correlations



User preferences

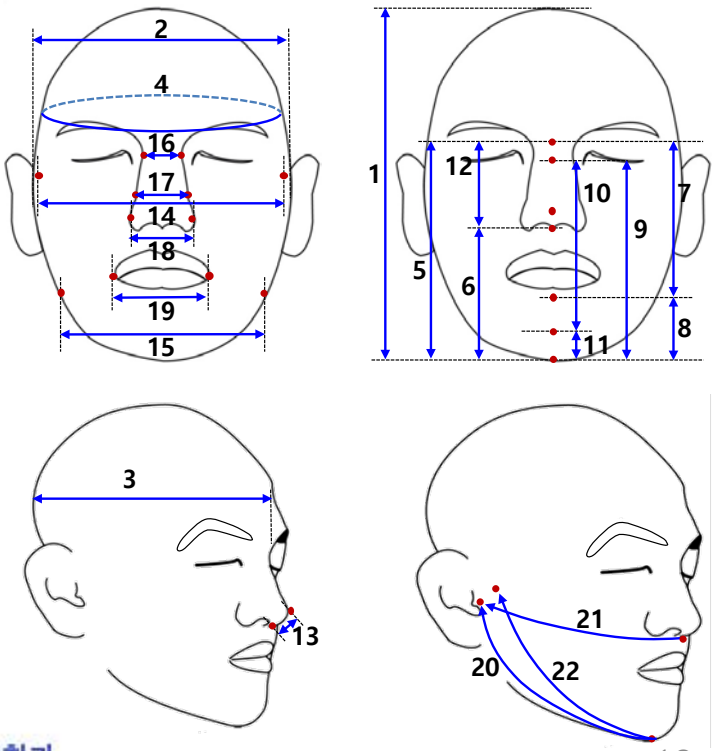
- Discomfort
- Oxygen leaking
- Mic-lip clearance

correlations within factor

Measurement Dimensions

(정정림 외, 2011)

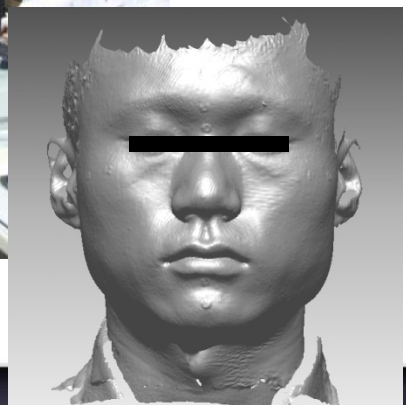
- Reviewed **15 previous studies** related to facial anthropometry or oxygen mask design
- Comprehensively gathered **109 head & facial dimensions**
- **Selected 22 facial dimensions** related to half-face mask design (length: 11, width: 7, circumference: 4)



	Face dimension	Importance
1	head height	L
2	head breadth	L
3	head length	L
4	head circumference	L
5	face length	H
6	lower face length	M
7	sellion-bottom lip length	M
8	bottom lip-menton length	L
9	nasal bridge-menton length	M
10	nasal bridge-chin length	H
11	chin-menton length	L
12	nose length	M
13	nose protrusion	L
14	face width	L
15	chin width	L
16	nasal root breadth	H
17	maximum nasal bridge breadth	H
18	nose width	H
19	lip width	H
20	bitragion-menton arc	L
21	bitragion-subnasal arc	L
22	bizygomatic-menton arc	L

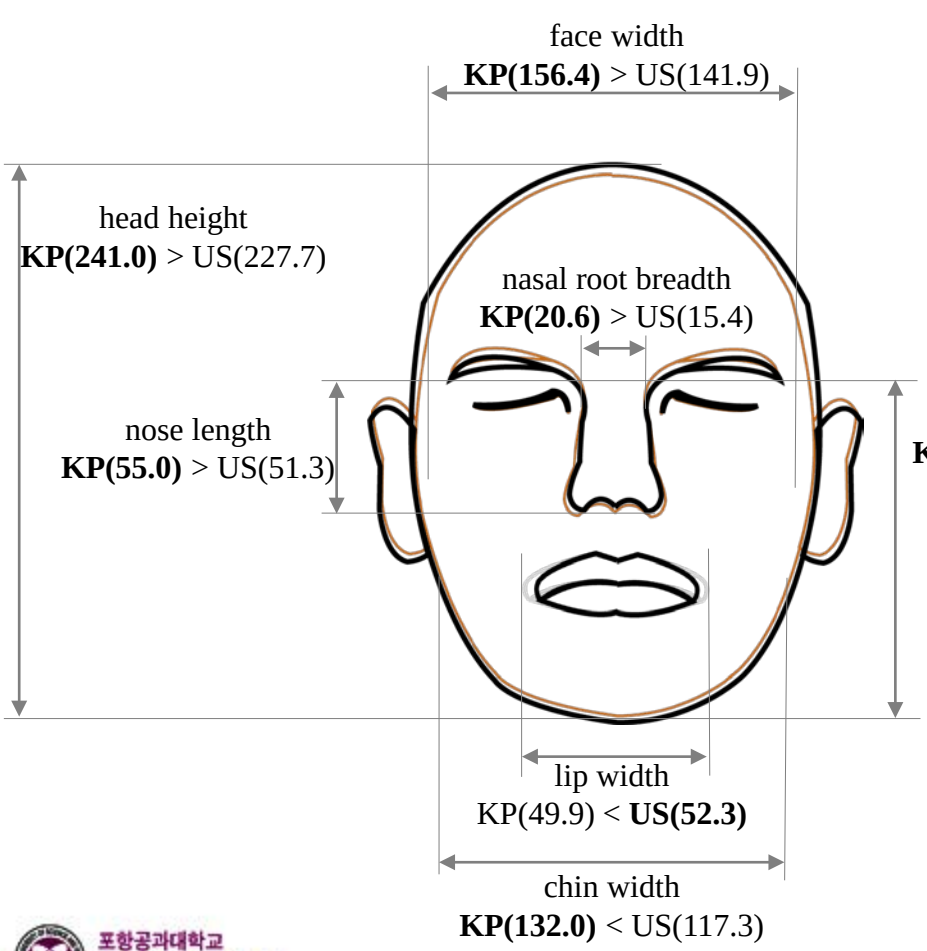
Facial Measurement Survey

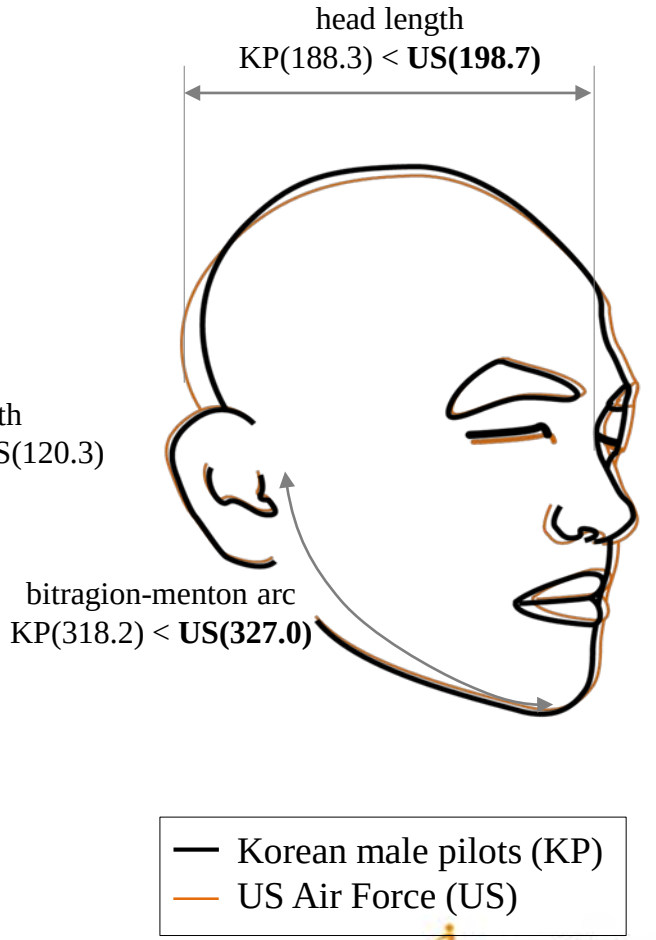
- **Participants**
  - ✓ 278 male pilots
  - ✓ 6 female pilots and 52 female Air Force Academy cadets
- **Survey period: Dec. 2010 ~ Feb. 2011**
- **Measurement method: direct measurement & 3D measurement**



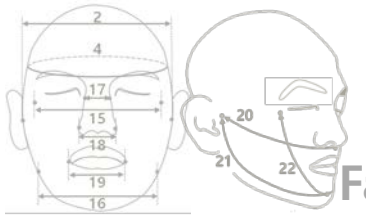
Korean Pilots vs. US Pilots

- **In general, Korean pilots' face is longer and wider than US pilots on average** ($p < 0.05$)
- **nasal root breadth: Korean pilots (20.6 mm) > US pilots (15.4 mm)**



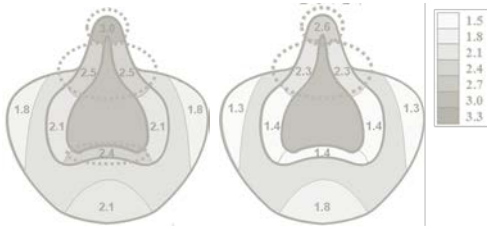


FMI Factor: Oxygen Mask Wearing Characteristics



correlations within factor

Facial Anthropometric Characteristics



correlations within factor

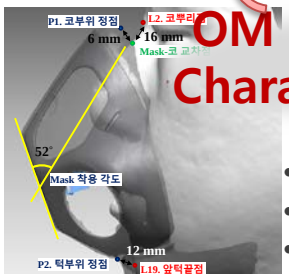
correlations between factors

correlations

User preferences

- Discomfort
- Oxygen leaking
- Mic-lip clearance

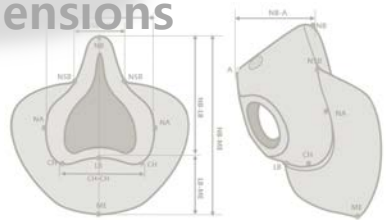
correlations within factor



OM Wearing Characteristics

- Wear position
- Wear angle
- Fitness

Mask Design Dimensions

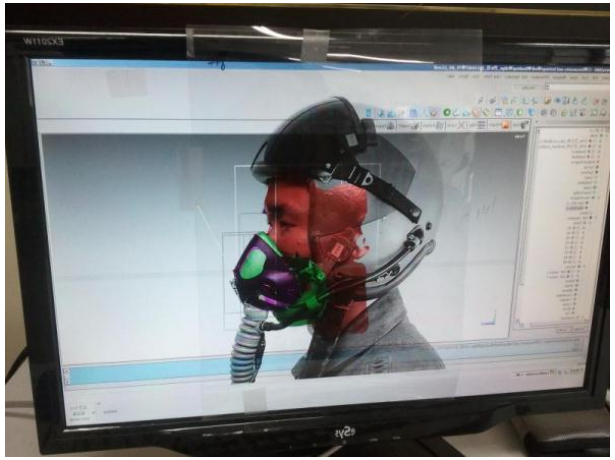


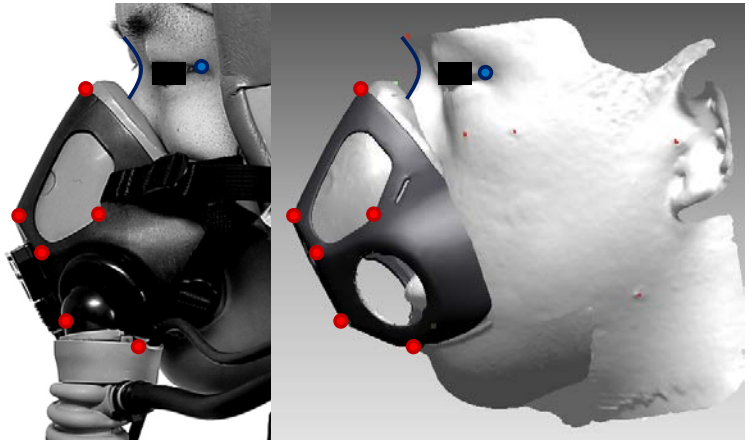
Analysis Method

(이원섭 외, 2011)

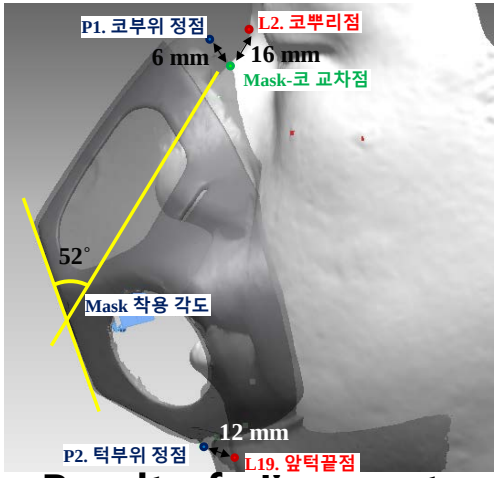
- **Gather photos of mask wearing (print on transparent film)**
- **Alignment of face and mask on display using 3D face & mask scan data**
- **References for alignment**
  - ✓ face features (e.g., shape nose and eyes)
  - ✓ feature points on mask
- **Reliability evaluation: inter- & intra-experimenter variability < 2 mm (*n* = 3)**

(Weinberg et al., 2005)





Alignment face & mask on 3D (3D face scan data & mask CAD)

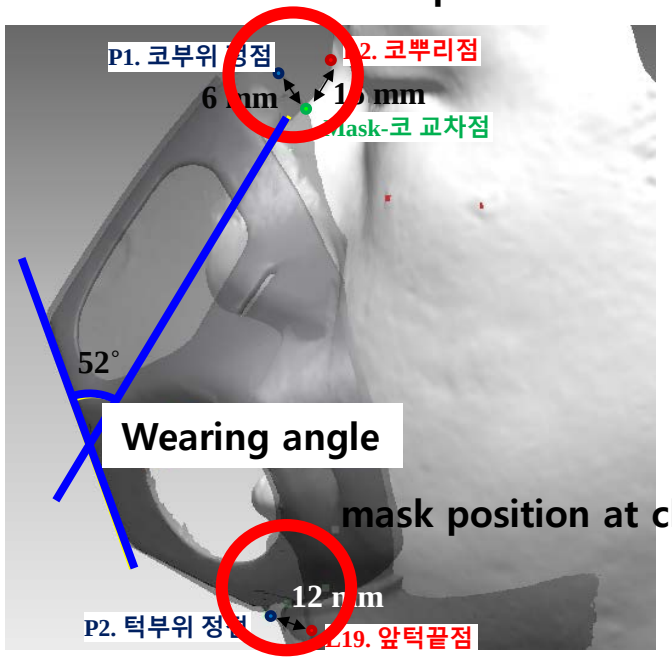


Result of alignment

Mask Wearing Characteristics

(1) wear position, (2) wear angle, (3) clearance (e.g., microphone-lip)
(4) fitness (distance between face & facepiece)

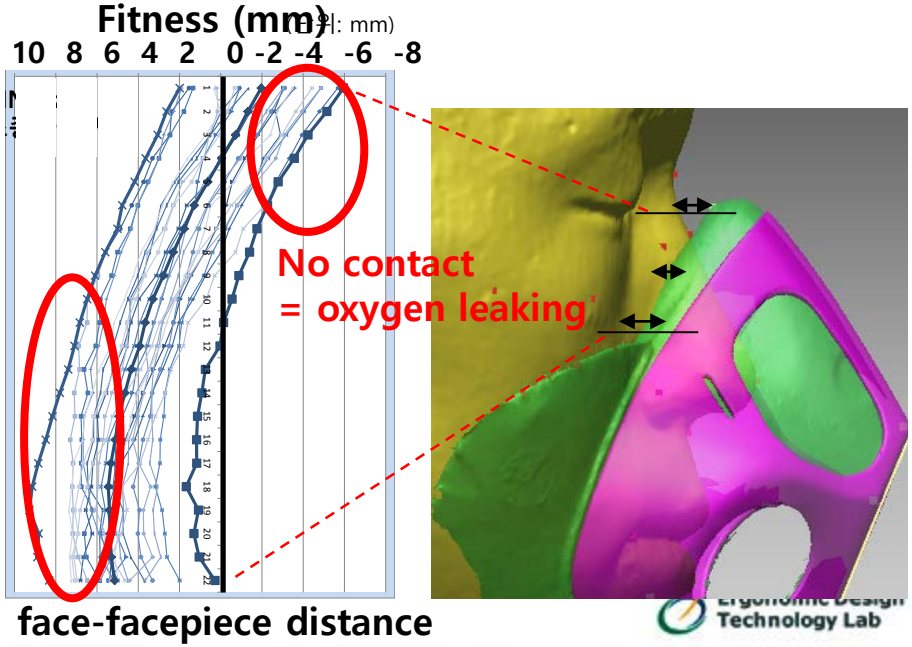
mask position at nose



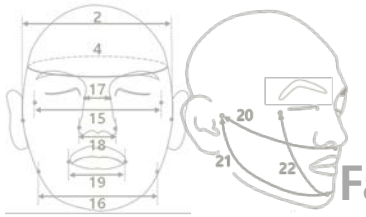
mask wear position & angle

Penetration of facepiece into face (back view)

Face-facepiece distance = fitness

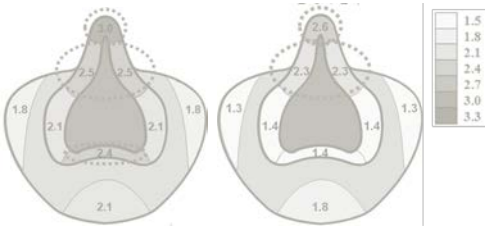


FMI Factor: Oxygen Mask Design Dimensions



correlations within factor

Facial Anthropometric Characteristics



correlations within factor

correlations between factors

correlations

User preferences

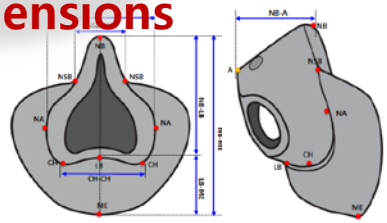
- Discomfort
- Oxygen leaking
- Mic-lip clearance

correlations within factor

OM Wearing Characteristics

- Wear position
- Wear angle
- Fitness

Mask Design Dimensions

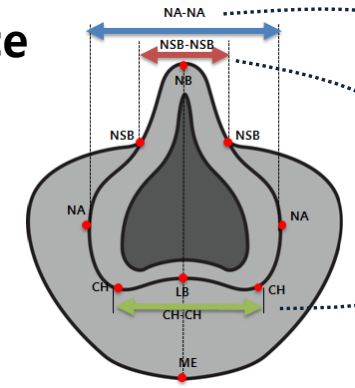


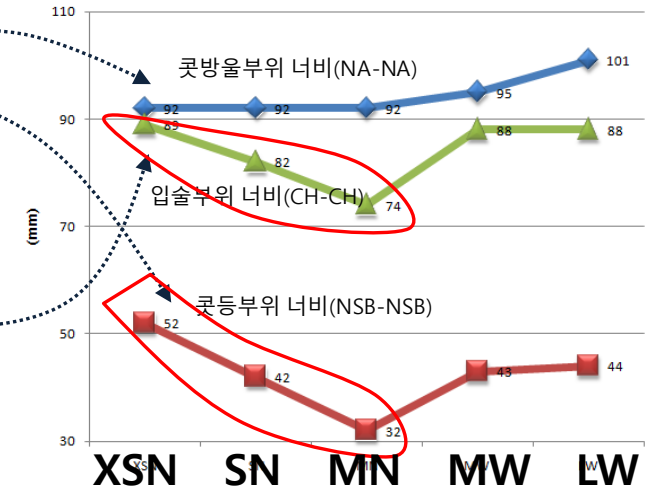
Method & Results (Illustrated)

(Immersion MicroScribe® 3D Digitizer, Revware Inc., USA)

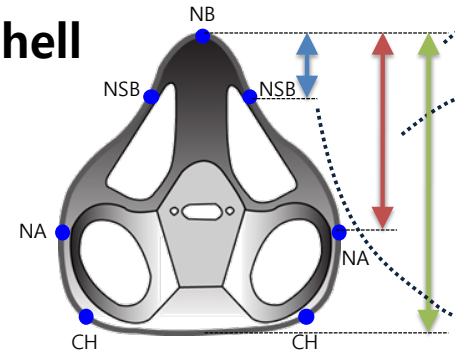
- **Measurement of facepieces and hardshells using 3D digitizer (5 sizes)**

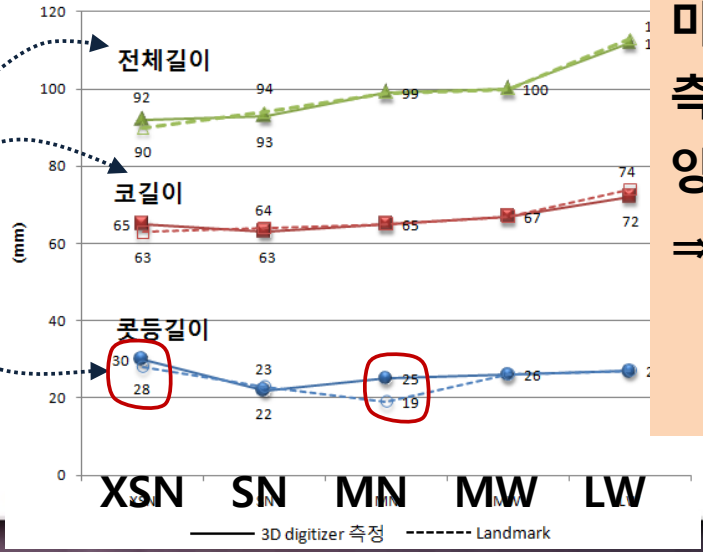
facepiece





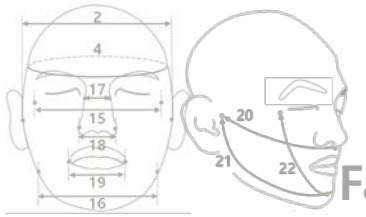
hardshell





현행 산소마스크는
일부 측정항목에서
마스크 size 증가에 따른
측정 부위별 크기 증가
양상을 보이지 않음
⇒ 산소마스크 설계 개선 시
마스크 size 간의
설계 합리성 고려 필요

FMI Factor: Oxygen Mask User Preferences



correlations within factor

Facial Anthropometric Characteristics

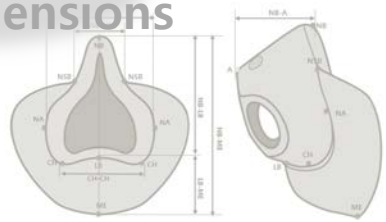
correlations between factors

correlations within factor

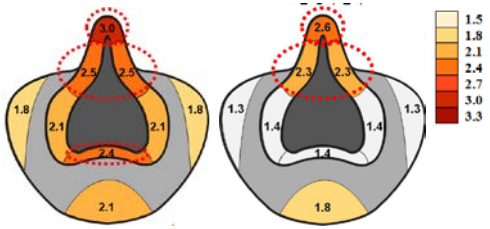
OM Wearing Characteristics

- Wear position
- Wear angle
- Fitness

Mask Design Dimensions



correlations



User preferences

- Discomfort
- Oxygen leaking
- Mic-lip clearance

correlations within factor

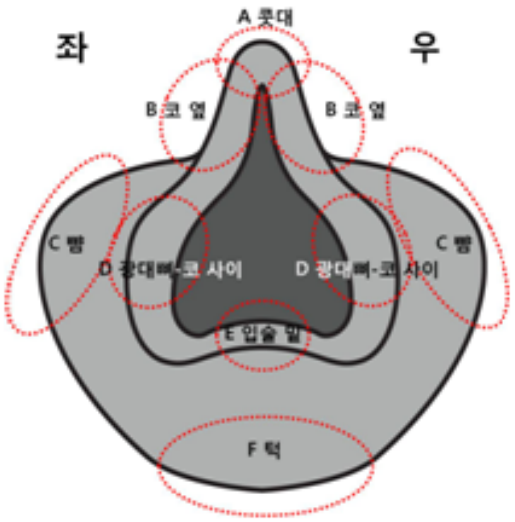
Information of User Preferences Survey

- **Survey period: 2010. 12 ~ 2011. 02**
- **Participants: around 500 military pilots**
- **Survey method: interview & intranet**
- **Example of questionnaire**

Ⅱ. 산소 Mask 적합성 평가

Ⅱ-1. 착용 안락감 (comfort)

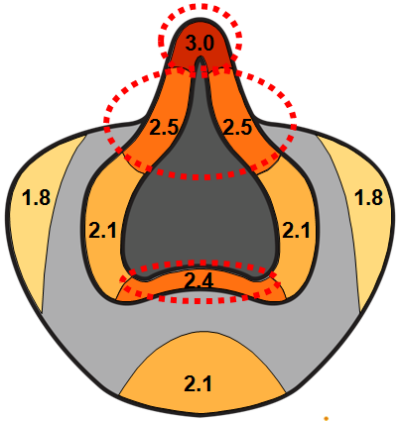
1. 아래 그림을 참고하여 산소 mask 각 부위별 압박에 따른 불편감에 대해 표시해 주세요.



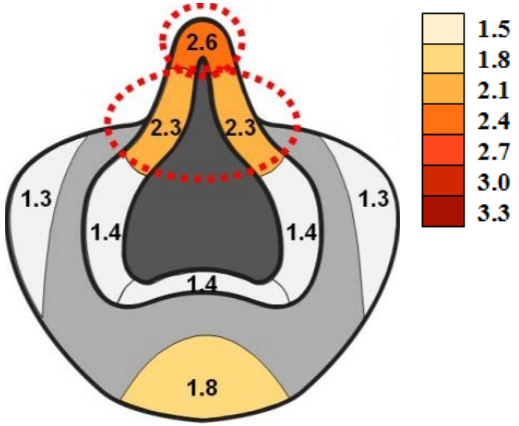
부 위	불편 없음 (comfortable)	조금 불편 (slightly uncomfortable)	불편 (moderately uncomfortable)	매우 불편 (very uncomfortable)	극히 불편 (hot spot)
A: 콧대	☐	☐	☐	☐	☐
B: 코 옆	☐	☐	☐	☐	☐
C: 뺨	☐	☐	☐	☐	☐
D: 광대뼈-코 사이	☐	☐	☐	☐	☐
E: 입술 밑	☐	☐	☐	☐	☐
F: 턱	☐	☐	☐	☐	☐

Results

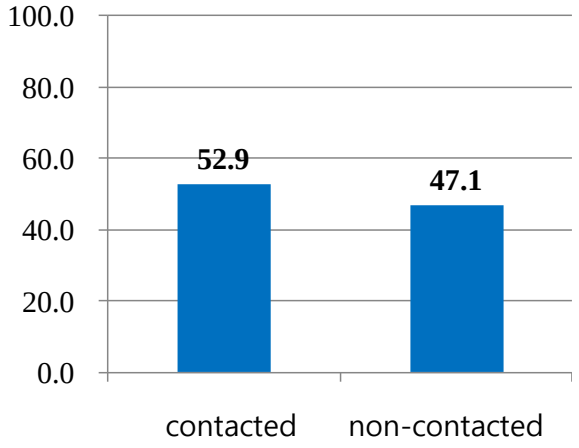
- Highly uncomfortable on nasal part
- Microphone is contacted to lip on half of pilots (53%)



pressure

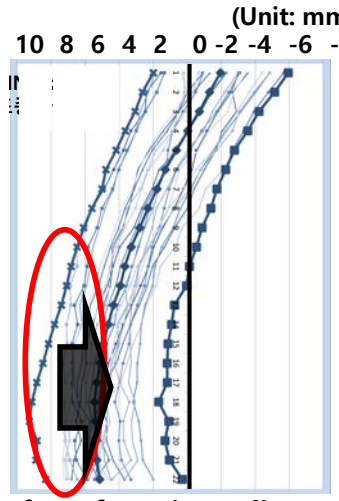


oxygen leaking

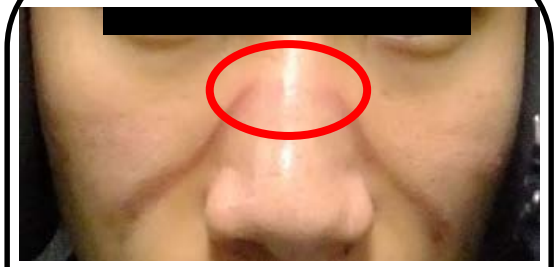


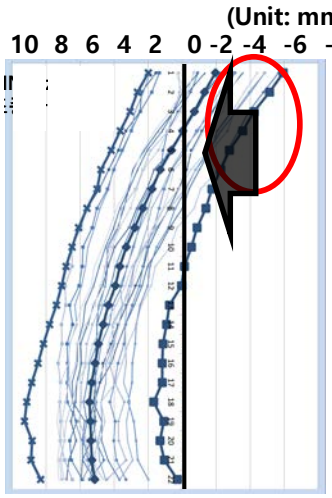
Microphone-lip contact

Needs of Design Improvement

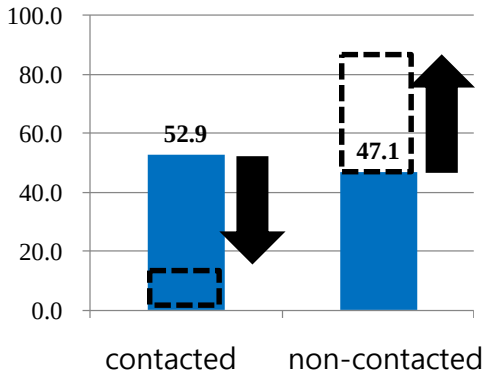


prevent high pressure on nasal area





prevent oxygen leaking on nasal area



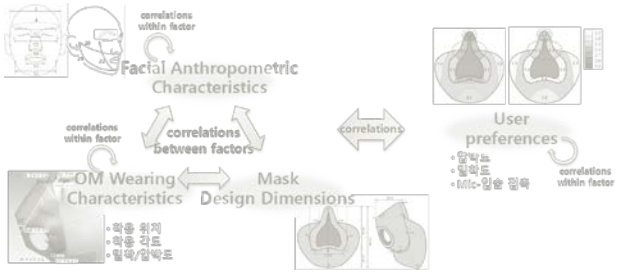
Microphone-lip contact

prevent microphone-lip contact

S2. OM Design Strategy Development

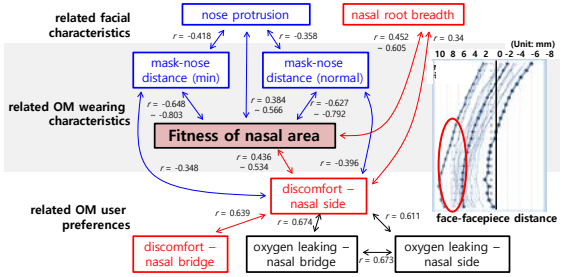
S1 Face-Mask Interface Analysis

- Facial characteristics
- OM wearing characteristics
- OM design dimensions
- OM user preferences



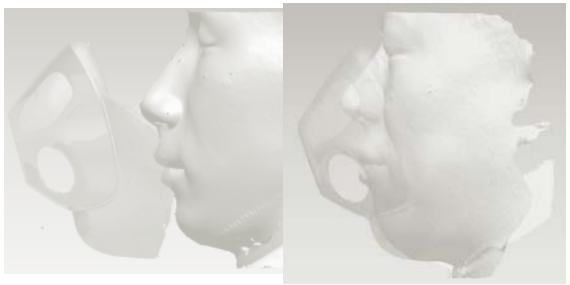
S2 OM Design Strategy Development

- Correlation analysis
- Technical model development
- Design directions determination



S3 OM Design Based on Virtual Fit Testing

- Virtual fit testing method development
- Design revision values determination
- OM design revision
- Design effect analysis & iterative design

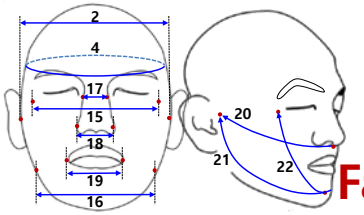


S4 Evaluation of Revised Oxygen Mask

- Virtual fit testing
- Ergonomic experiment

Correlation Analysis Between and Within FMI Factors

- Facial characteristics × OM wearing characteristics × OM user preferences (2775 items)
- Mask design dimension: constant for MN size
- **Selected 57 items** highly related to OM design



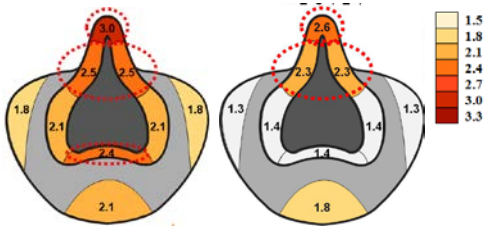
correlations within factor

Facial Anthropometric Characteristics

correlations within factor

correlations between factors

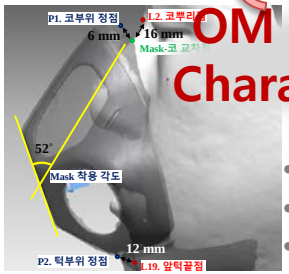
correlations



User preferences

- Discomfort
- Oxygen leaking
- Mic-lip clearance

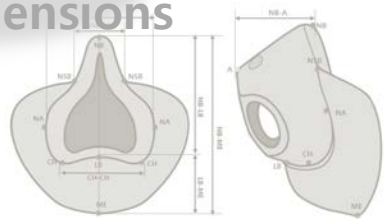
correlations within factor



OM Wearing Characteristics

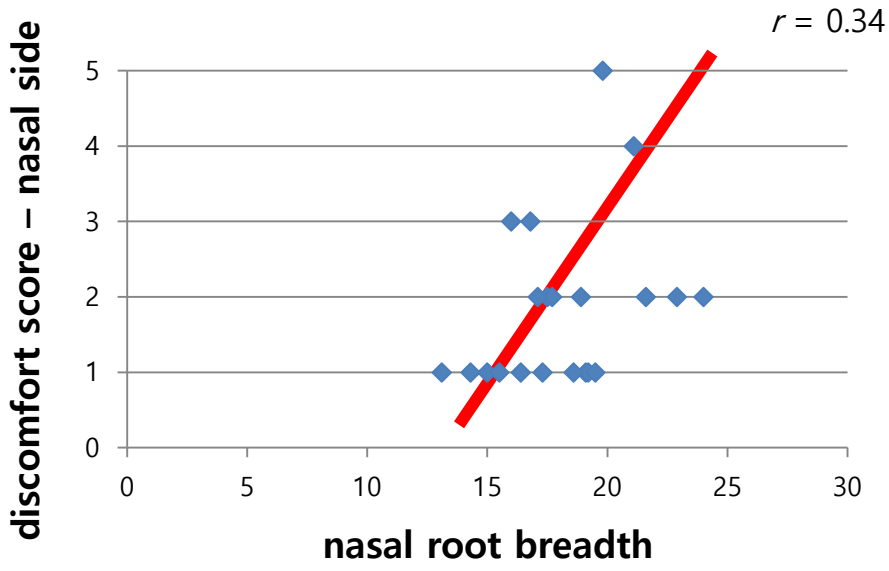
- Wear position
- Wear angle
- Fitness

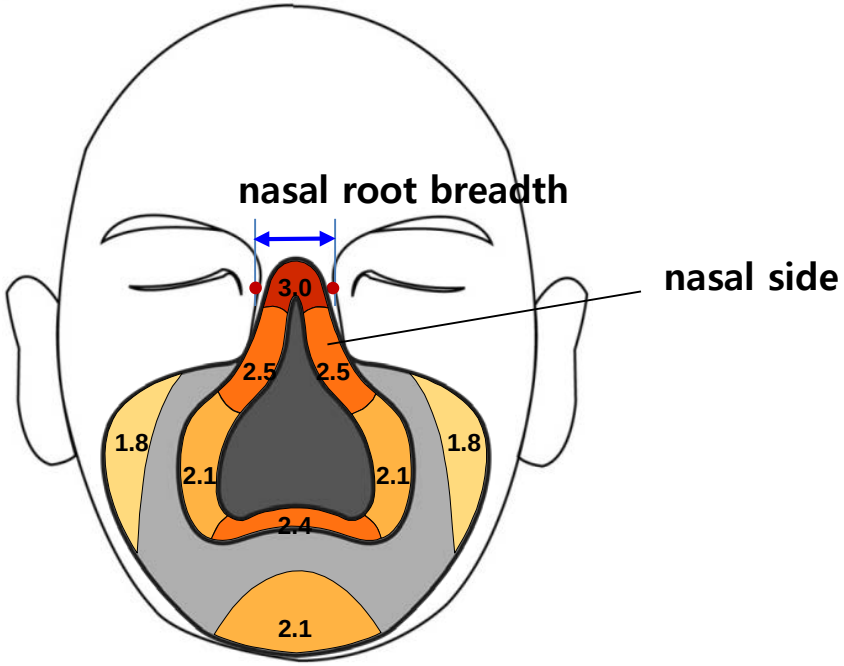
Mask Design Dimensions



Results of Correlation Analysis (Illustrated)

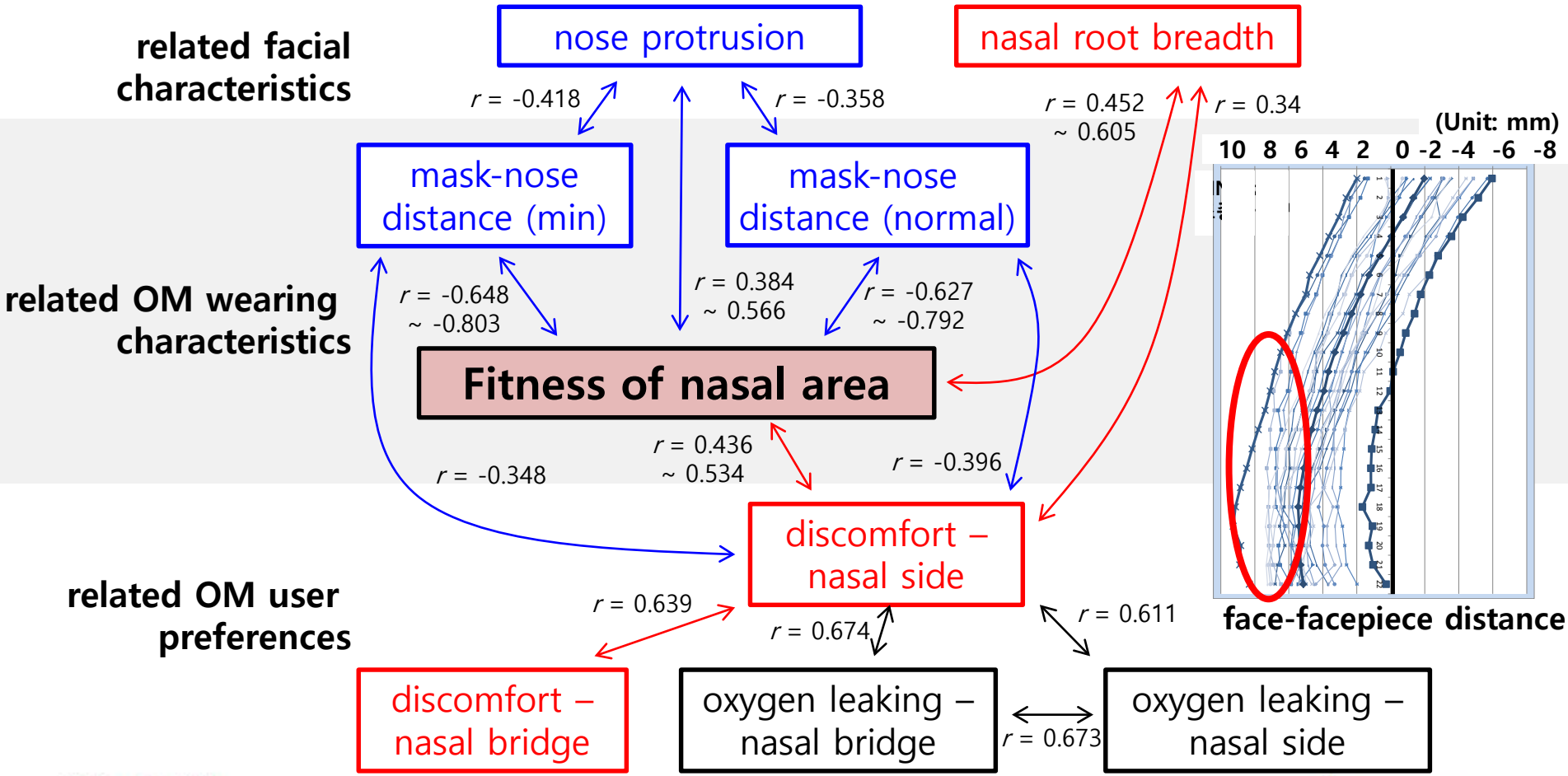
- **Nasal root breadth ↑ than discomfort score of nasal side ↑**
- **Required design revision on breadth of nose part of oxygen mask**
- ***cf.* Nasal root breadth of Korean pilots (20.6 mm) > US pilots (15.4 mm)**





Development of Technical Models (Illustrated)

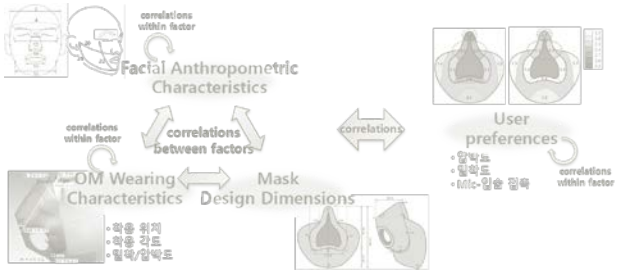
- **Overall relationship between FMI factors about fitness of nasal area**



S3. OM Design Based on Virtual Fit Testing

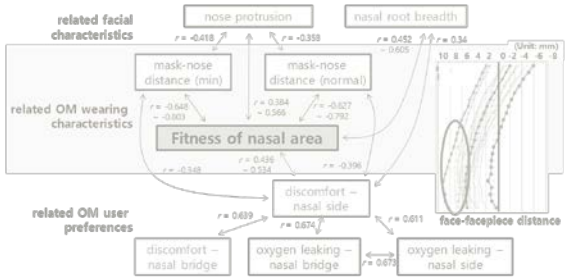
S1 Face-Mask Interface Analysis

- Facial characteristics
- OM wearing characteristics
- OM design dimensions
- OM user preferences



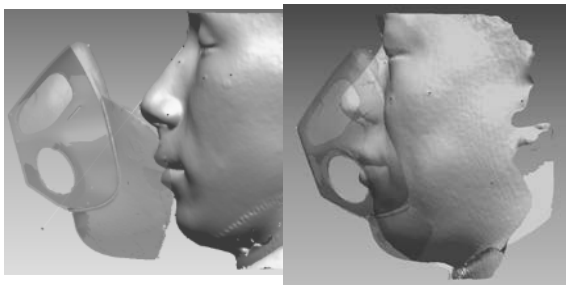
S2 OM Design Strategy Development

- Correlation analysis
- Technical model development
- Design directions determination



S3 OM Design Based on Virtual Fit Testing

- Virtual fit testing method development
- Design revision values determination
- OM design revision
- Design effect analysis & iterative design

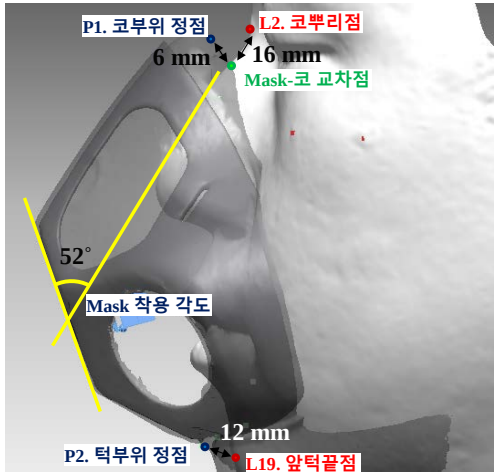


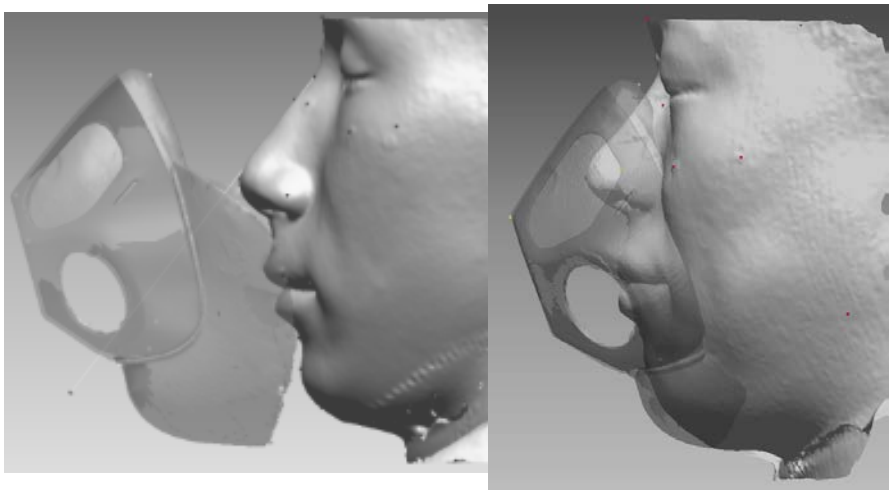
S4 Evaluation of Revised Oxygen Mask

- Virtual fit testing
- Ergonomic experiment

Virtual Fit Testing

- Developed **virtual fit testing system** using Matlab™ based on results of **OM wearing characteristics** analysis (*n* = 23)
- Applied virtual fitting to other 107 pilots





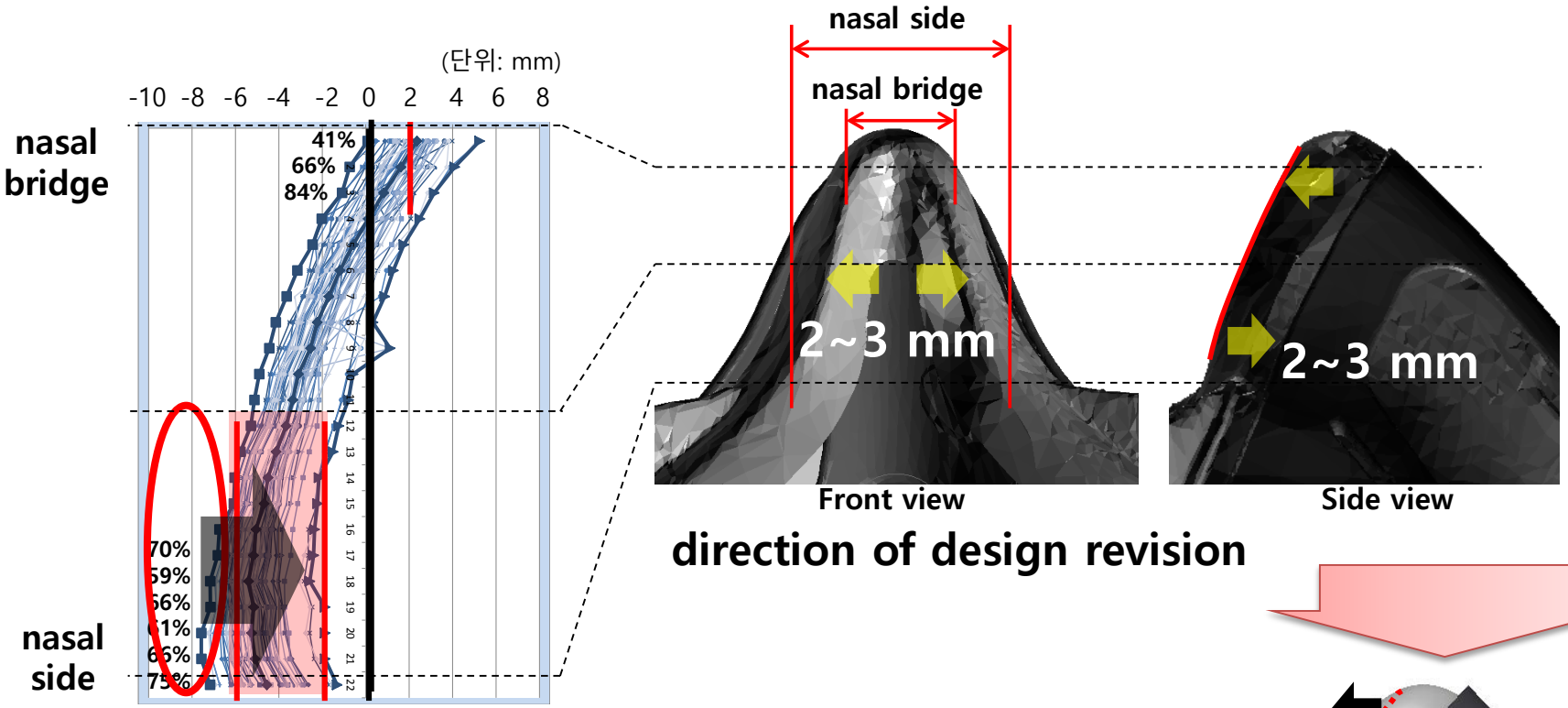
Analysis of OM wearing characteristics by photo
- 23 pilots (MN size)
- Wear angle: 52˚ (range: 47 ~ 57˚)
- Wear position

Analysis of wearing characteristics by virtual fitting
- 107 pilots (MN size)

- **Fitness** (pressure or oxygen leaking)
- **Microphone-lip clearance**

Determination of Design Revision Values (Illustrated)

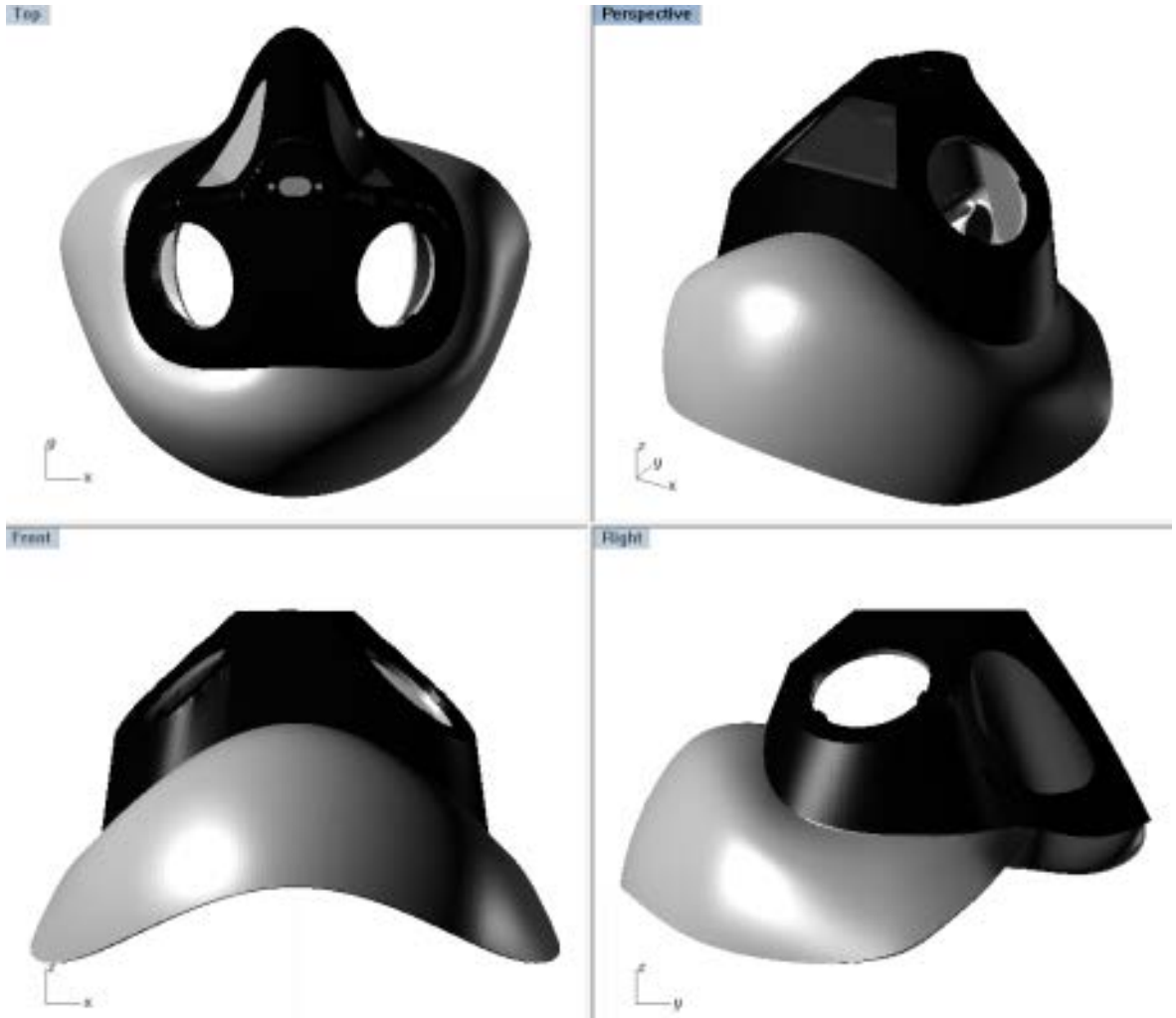
- Determined **numerical values for design revision** through virtual fit testing



Face-facepiece distance
(design criteria: -2 ~ -6 mm)

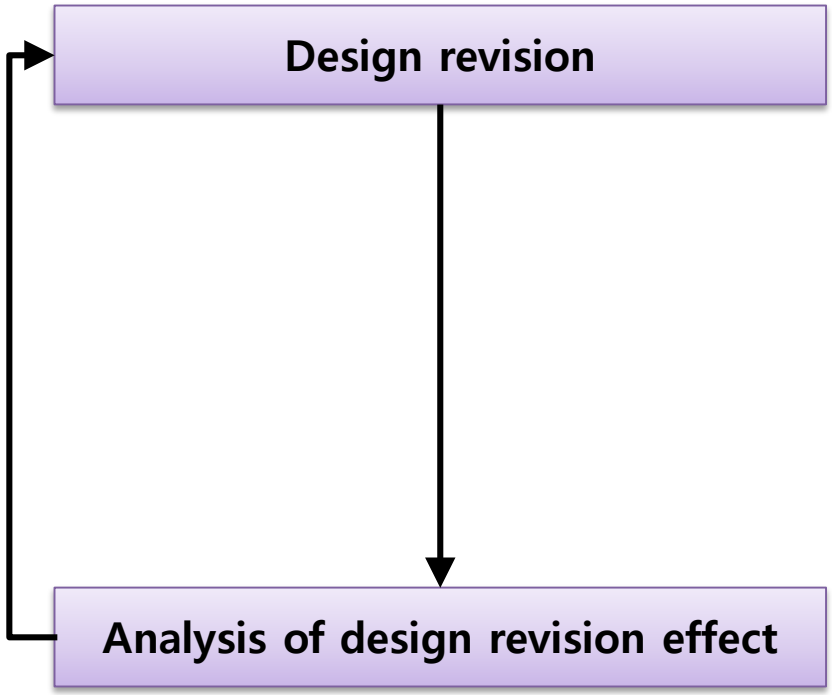
Design Revision – Drawing CAD

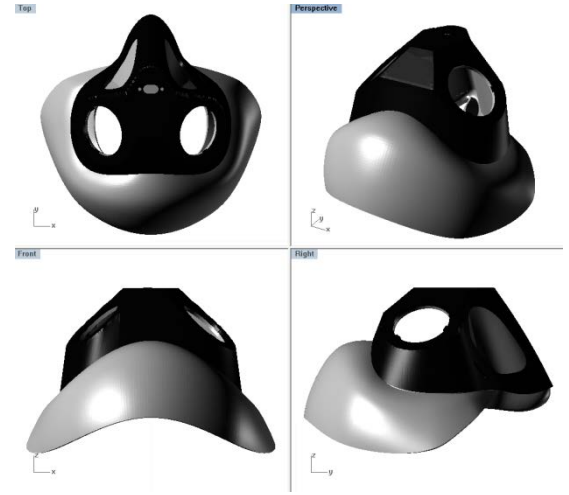
- **Improvement of OM CAD using Rhino 3D**

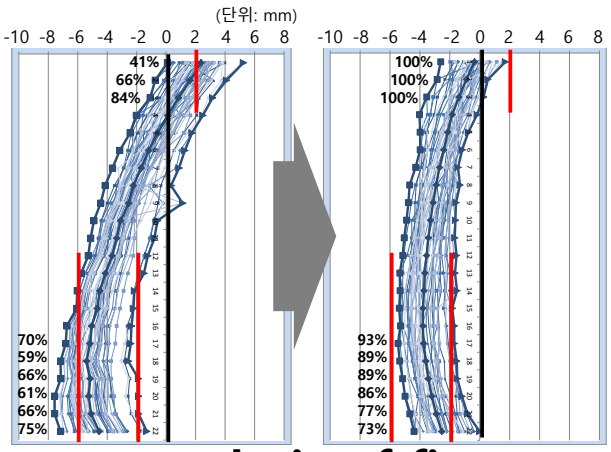


Analysis of Design Revision Effect & Iterative Design

- Analysis of **design revision effect** through virtual fit testing







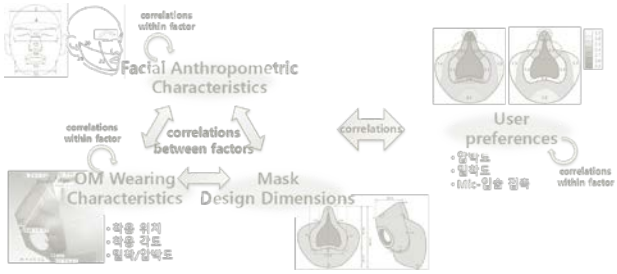
e.g., analysis of fitness

Concept of iterative design based on virtual fit testing

S4. Evaluation of Revised Oxygen Mask

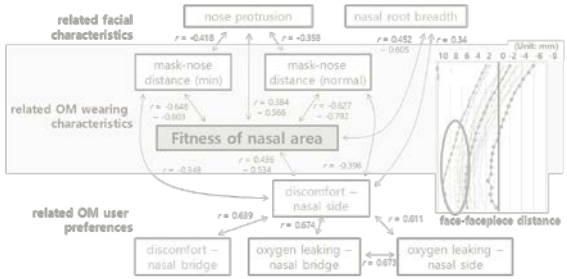
S1 Face-Mask Interface Analysis

- Facial characteristics
- OM wearing characteristics
- OM design dimensions
- OM user preferences



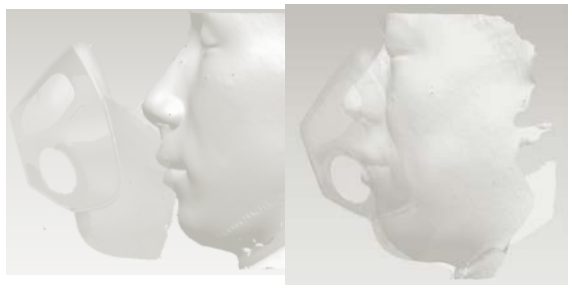
S2 OM Design Strategy Development

- Correlation analysis
- Technical model development
- Design directions determination



S3 OM Design Based on Virtual Fit Testing

- Virtual fit testing method development
- Design revision values determination
- OM design improvement
- Design effect analysis & iterative design

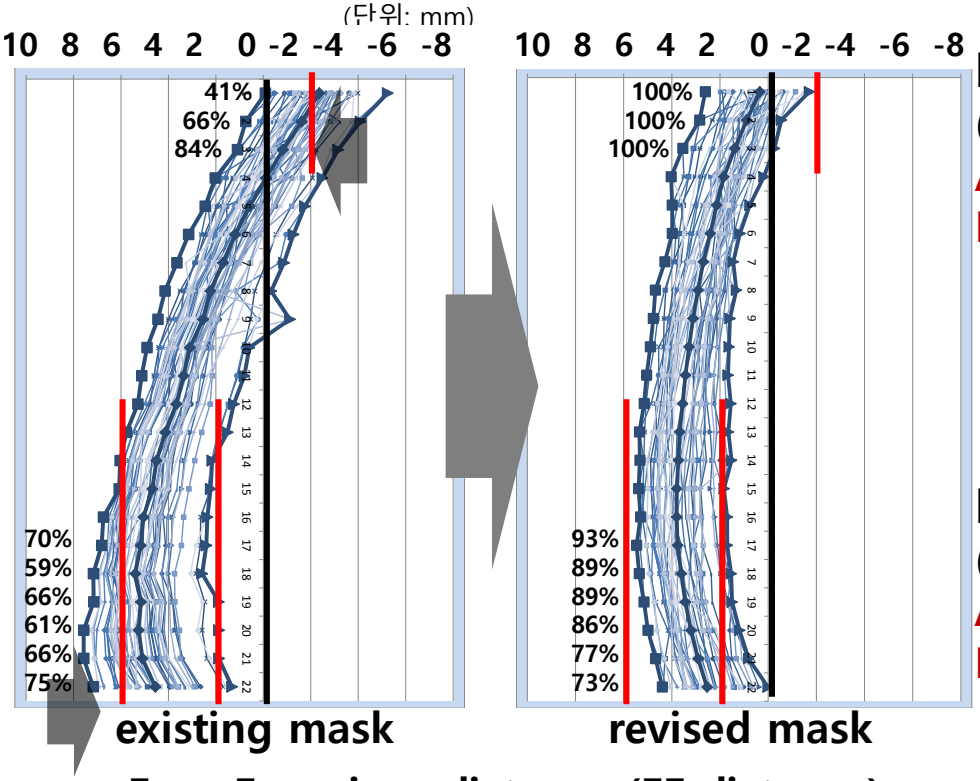


S4 **Evaluation of Revised Oxygen Mask**

- Virtual fit testing
- Ergonomic experiment

Evaluation of Design Revision Effect by Virtual Fit Testing

(1) Fitness



Nasal bridge
(design criteria: FF distance = -2 mm)
Accommodation rate: 41 ~ 84% ⇒ 100%
Revision effect: 16 ~ 59% fitness ↑
(oxygen leaking ↓)

Nasal side
(design criteria: FF distance = 2 ~ 6 mm)
Accommodation: 59 ~ 75% ⇒ 73 ~ 93%
Revision effect: 11 ~ 30% fitness ↑
(pressure ↓)

(2) Microphone-lip contact: 34% ⇒ 100% (revision effect: 66% ↑)

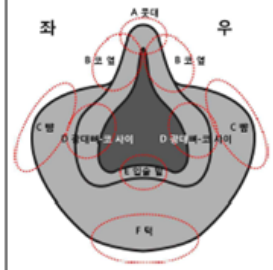
Experiment for Mask Usability Evaluation

	Subjective Evaluation	Objective Evaluation
index	Discomfort, oxygen leaking, microphone-lip clearance, overall satisfaction (7-point Likert scale)	• Pressure • Oxygen leaking
Example	Questionnaires (illustrated)	Prescale Pressure Indicating Film Combined Aircrew Systems Tester (CAST)

Ⅱ. 산소 Mask 적합성 평가

Ⅱ-1. 착용 안락감 (comfort)

1. 아래 그림을 참고하여 산소 mask 각 부위별 압박에 따른 불편감에 대해 표시해 주세요.



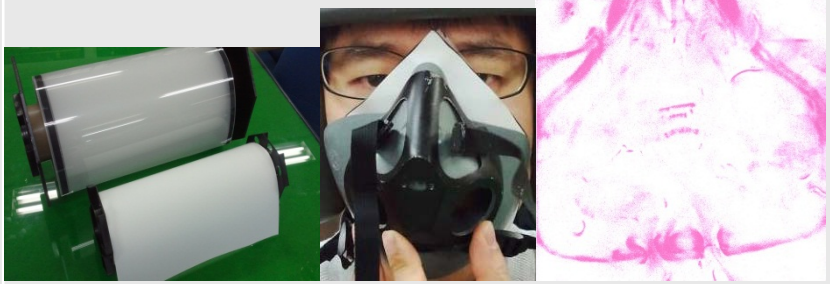
부 위	불편 없음 (comfortable)	조금 불편 (slightly uncomfortable)	불편 (moderately uncomfortable)	매우 불편 (very uncomfortable)	극히 불편 (hot spot)
A: 콧대	☐	☐	☐	☐	☐
B: 코 옆	☐	☐	☐	☐	☐
C: 뺨	☐	☐	☐	☐	☐
D: 광대뼈-코 사이	☐	☐	☐	☐	☐
E: 입술 밑	☐	☐	☐	☐	☐
F: 턱	☐	☐	☐	☐	☐

2. 산소 mask의 전반적인 착용 안락감에 대해 표시해 주세요.

불편 없음 (comfortable)	조금 불편 (slightly uncomfortable)	불편 (moderately uncomfortable)	매우 불편 (very uncomfortable)	극히 불편 (hot spot)
☐	☐	☐	☐	☐

3. 산소 mask 착용 중 말을 할 때, 산소 mask의 전반적인 착용 안락감에 대해 표시해 주세요.

불편 없음 (comfortable)	조금 불편 (slightly uncomfortable)	불편 (moderately uncomfortable)	매우 불편 (very uncomfortable)	극히 불편 (hot spot)
☐	☐	☐	☐	☐



Evaluation Protocol

S1. Introduction

S2. Evaluation for existing mask

(counter-balanced)

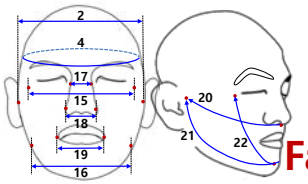
S3. Evaluation for revised mask

- Questionnaire
- Pressure test
- Oxygen leaking test

S4. Debriefing

Discussion

1. Developed **OM design method** based on **face-mask interface (FMI) analysis**
   - **Systematic method** considering relationships between FMI factors
   - Identified **preferred or non-preferred design features**
   - Developed **virtual fit testing system** based on mask wear characteristics



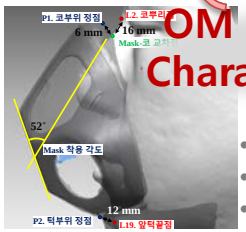
correlations within factor

Facial Anthropometric Characteristics

correlations between factors

correlations within factor

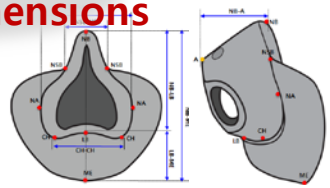
OM Wearing Characteristics

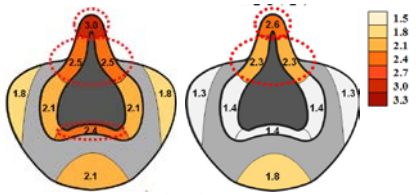


- Wear position
- Wear angle
- Fitness

correlations

Mask Design Dimensions





User preferences

- Discomfort
- Oxygen leaking
- Mic-lip clearance

correlations within factor

Discussion

2. Developed design revision method based on virtual fit testing
   - Identified numerical values for design improvement
   - Identified design revision effect quantitatively
   - Iteratively improved OM design to find better alternatives

3. Revised pilot oxygen mask to fit to Korean pilots
   - Evaluated by virtual fit testing
     - ✓ Accommodation rate: 73 ~ 100%
     - ✓ Revision effect: 11 ~ 66%
   - Well-fitness ⇒ no or low pain, no oxygen leaking, safe flight

Further Studies

- Conduct mask wearing experiment with Korean pilots
- Validate the proposed mask design method by usability experiment
- Apply the method to design other size (MW, LW, SN)

- Applicable to design industrial half-face masks (e.g., dustproof mask)

Thank You