

## Development of a New 3D Test Panel for Half-Mask Respirators by 3D Shape Analysis for Korean Faces

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### ABSTRACT

This study was performed to construct a new three-dimensional (3D) fit-test panel for respirator fit testing based on 3D face data. Three-dimensional surface data were obtained using a 3D laser scanner (Cyberware 3030RGC scanner with a PS platform, U.S.A.) from 102 volunteers (70 males and 32 females). The collected digitalized data were used for shape analysis utilizing the Procrustes algorithm. Face shapes between genders were statistically significantly different by discriminant analysis. The misclassification error rate was 2.99 %. Face shapes of all subjects including both genders were categorized into four different face types by cluster analysis. The new 3D fit-test panel was developed based on both face shape and size information. The panel was composed of the shape information on x-axis which were expressed as A, B, C, and D, and the size (length) information on y-axis that were classified into 4 groups ranged from 103.7 mm to 133.5 mm. The 3D approach for developing test panel can be applied for other ethnic groups having different face shapes.

**Keywords:** Procrustes algorithm, 3D laser scanner, Fit-test panel, Shape information, Length information

### INTRODUCTION

A fit-test panel should accurately represent current workers who rely on respirators to prevent work-related illness, injuries and death. Respirators designed to fit these panels are also expected to accommodate at least 95% of donned workers. Respirator certification standards in the United States, Australia and New Zealand, and many European countries require fit testing for respirator certification. In Korea, there is a respirator certification standard, but the standard does not require a fit test protocol or fit-test panel based on anthropometric data.

Los Alamos National Laboratory (formerly Los Alamos Scientific Laboratory, LANL) developed face dimension criteria made on military personnel for the design of oxygen and/or gas masks to be used for respirator design and suggests a five-size half-mask series (Hack & McConvill, 1978). These values were either the face length and face width for full-facepiece respirators, or the face length and lip width for half- and quarter- masks. But other studies (Liau et al., 1982; Oestenstad et al., 1990; Gross & Horstman, 1990) have reported that the face dimensions used for half masks (face length and lip width) show no relationship to the fit of half masks. Furthermore, since the results of previous studies were collected from military personnel, variability of the data in terms of age, weight, and height might have been much less

than that of civilians. Additionally, since past studies on respirator fit and anthropometric studies had focused on Whites, the results may not be applicable to Koreans or Asians.

Analysis of the results obtained in Kim *et al.* (2003) found significant differences between females and males in the 12 face dimensions measured except for nasal root. Gender differences in face dimensions have also been found in studies on American populations. Brazile *et al.* (1998) found that, in Americans, respirator fit was not associated with face dimensions based on race/ethnicity or gender and seemed to be associated with individual face characteristics.

The head and face are perhaps the most difficult body parts to adequately describe using traditional measurement techniques because of the great variability of head and face dimensions and their associated poor correlation. During the last few years, the measuring technology has advanced to the state that it is now possible to digitize the surface of biological forms faster and in much finer detail than was previously possible. For example, data are now being collected on the head and face and put into digital form in less than 15 seconds. The problems of how to describe the three-dimensional geometry of the human face are of interest here.

Penrose (1954) proposed 'shape' and 'form' as a simple linear formulation.

Form = Size + Shape

Size can be defined as a quantity that depends upon dimensional space. In a one-dimensional world, difference in size can be viewed as a difference in vector length. In two dimensions, linear measurements in combination (such as ratios) have proved to be inadequate and area becomes one definition of size. In three dimensions, volume would be the appropriate size quantity. Shape on the contrary, is a quantity that is difficult to adequately define, but has been characterized as 'residual' or what is left after controlling for size. A more technical definition for shape has been proposed as 'that which remains invariant under scaling, translation, rotation and reflection' (Lele, 1991). One can control or standardize for size by making the bounded area equal for all comparisons. This procedure effectively diminishes the influence of size close to zero. Then,

Form = Shape

Many statistical methods are in use for classifying size and shape in biological systems. Some of the current analytical methods used to analyze the biological form can be placed into two broad categories, which are: (1) homologous point (or landmark) methods and (2) boundary outline (or outline) methods. These two approaches can be further divided into techniques that can be applied to data sets (Lestrel, 1989, 1997 a, b). Landmark methods include: (1) Conventional metrical analysis (CMA); (2) Biorthogonal grids (BOG); (3) Finite element method (FEM); (4) Euclidean distance metric analysis (EDMA). (5) Thin plate spline (TPS). Subsumed under outline methods are: (1) medial axes analysis (MAA); (2) Eigen shape analysis; (3) elliptic Fourier functions (EFF). These are, by no means, the only methods, but represent those which to date have received the most attention (Chen *et al.*, 2000).

In the present study, three dimensional surface data were obtained using a 3D laser scanner to develop a new 3D fit test panel. The collected digitalized data were used for shape analysis utilizing the Procrustes analysis.

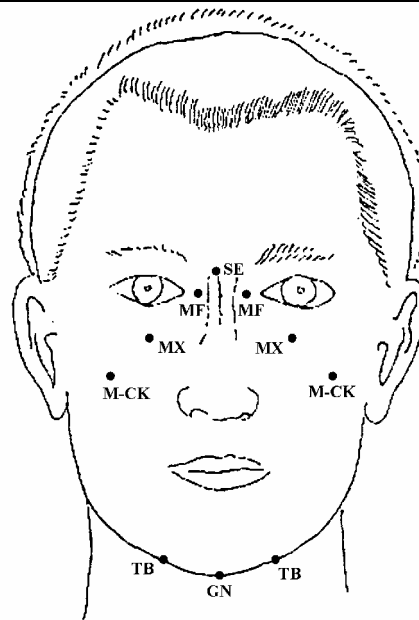
## MATERIALS AND METHODS

### Acquisition of Three-Dimensional Digitized Data of Facial Shape

Cyberware 3030RGC scanner with a PS platform (U.S.A.) was used to scan 102 subjects (70 males: age  $25.80 \pm 6.15$  years, face length  $122.38 \pm 5.54$  mm; 32 females: age  $20.31 \pm 3.35$  years, face length  $113.25 \pm 4.79$  mm). The 3D coordinates of 10 landmarks that characterize contacting parts of face and respirator shape were extracted from the laser scan on AutoCAD 2000.

## Selecting of 10 Landmarks on Face for Half-Mask Respirator Design

The extracted 10 landmarks were sellion (SE), right and left maxillofrontale (RMF and LMF), right and left maxillary point (RMX and LMX), right and left middle cheek point (RMCK and LMCK), right and left tuberculare (RTB and LTB) and gnathion (GN). The 3D coordinates of the landmarks extracted from the laser scans are illustrated in Figure 1.



**Figure 1. Selected landmarks of face for three dimensional shape analysis.**

### Definition of landmarks

SE(sellion): the deepest landmark located on the bottom of the nasofrontale angle.

MF(maxillofrontale): at the base of the nasal root medially from each endocanthion, close to the bony maxillofrontale of the medial margin of each orbit, where the maxillofrontal and nasofrontal sutures meet.

MX(maxillary point): the point which is located 1-cm below the midpoint of lower margin of orbit.

M-CK(middle cheek) point: the mid-point of zygomaticomaxillary suture.

TB(tuberculare): the point of mandibular tubercle.

GN(gnathion): the lowest median landmark on the lower border of the mandible. It is identified by palpation and is identical to the bony gnathion. This landmark is the lowest point used in measuring facial height.

## Three-Dimensional Shape Analysis of Faces and Statistical Analysis

In this study, 3D landmark coordinates were scaled and aligned via Generalized Procrustes Analysis (GPA) (Rohlf, 1999). The GPA was carried out using PAST program (version 1.12). Cluster analysis was chosen as the multivariate procedure to detect natural groupings among the input shape data. The Ward's hierarchical method was used for the cluster analysis procedure (SAS 8.01) to develop a hierarchical tree (dendrogram). Discriminant analysis was carried out to determine if face shapes showed difference between genders.

## RESULTS

### Shape Differences between Genders by Discriminant Analysis

Figure 2 summarizes Procrustes superimposition of 10 landmarks for 70 male (A) and 32 female faces (B). The 10 landmarks were illustrated in figure 1. The discriminant functions are visualized in Figure 3. The percentage misclassifications for males (n=70) and females (n=32) were found to be 3.13 % for females, 2.86 % for males, and 2.99 % for both.

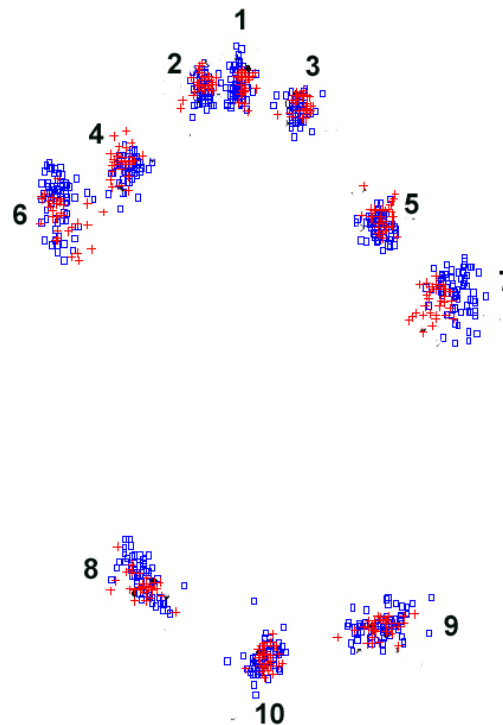


Figure 2. Procrustes superimposition of 10 landmarks for 70 male (□) and 32 female (+) faces.

### Classification of Face Type by Cluster Analysis

As illustrated in figure 4, face shapes could be classified into four types in this study. Type A consisted mainly of females and type B was mainly males. Type C was mixed males and females, but type D contained mainly males and few females.

Figure 5 summarizes four face types for designing and developing fit-test panel for half-facepiece respirators by cluster analysis. The four types were as follows; Type A is flat round elliptic faces, type B is bendy long elliptic faces, type C is round elliptic faces, and type D is flat chin and long elliptic faces.

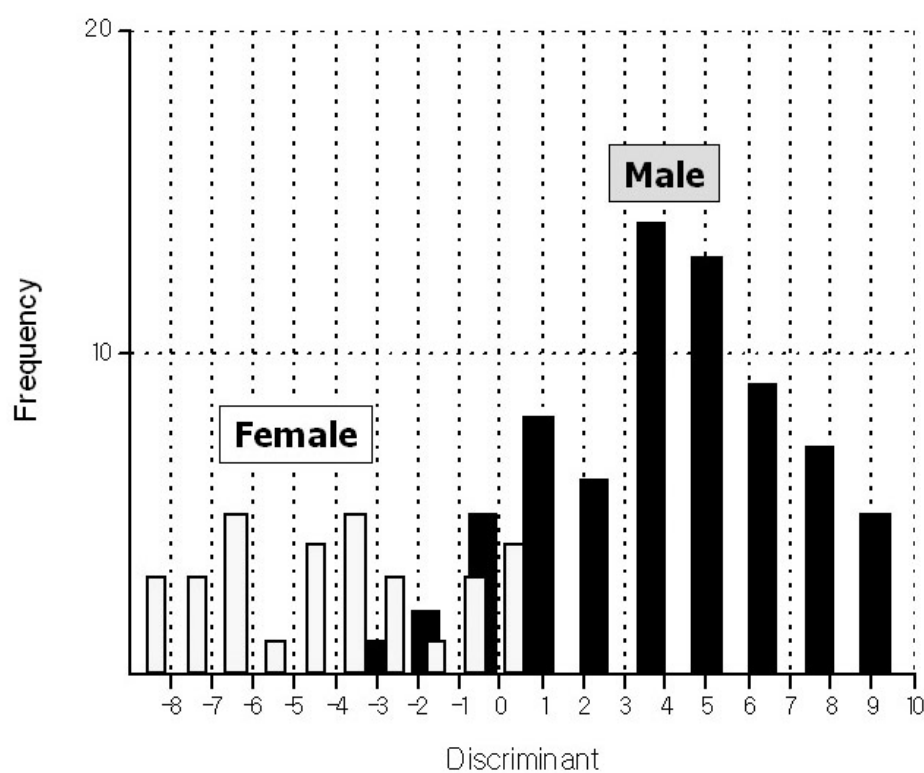


Figure 3. Comparison of face shapes of 70 males and 32 females by discriminant analysis.

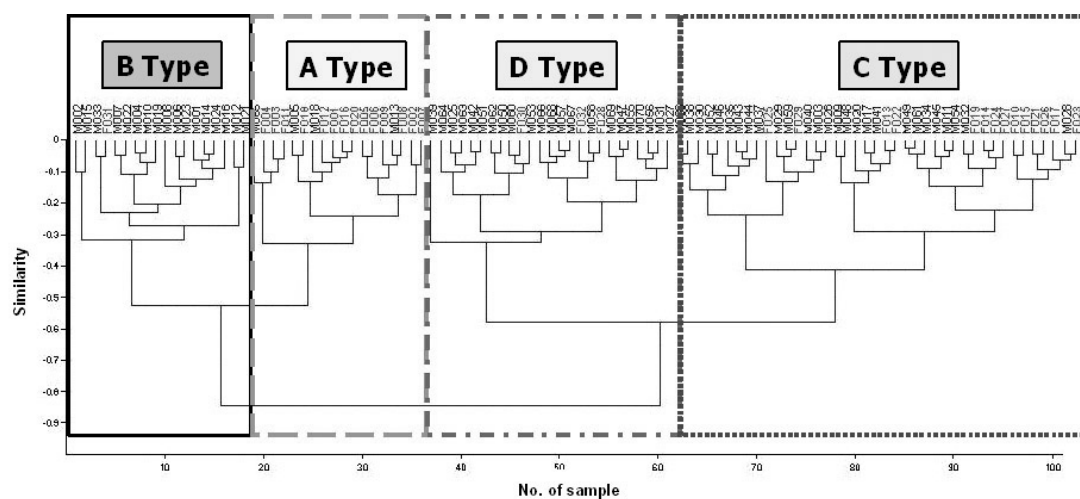
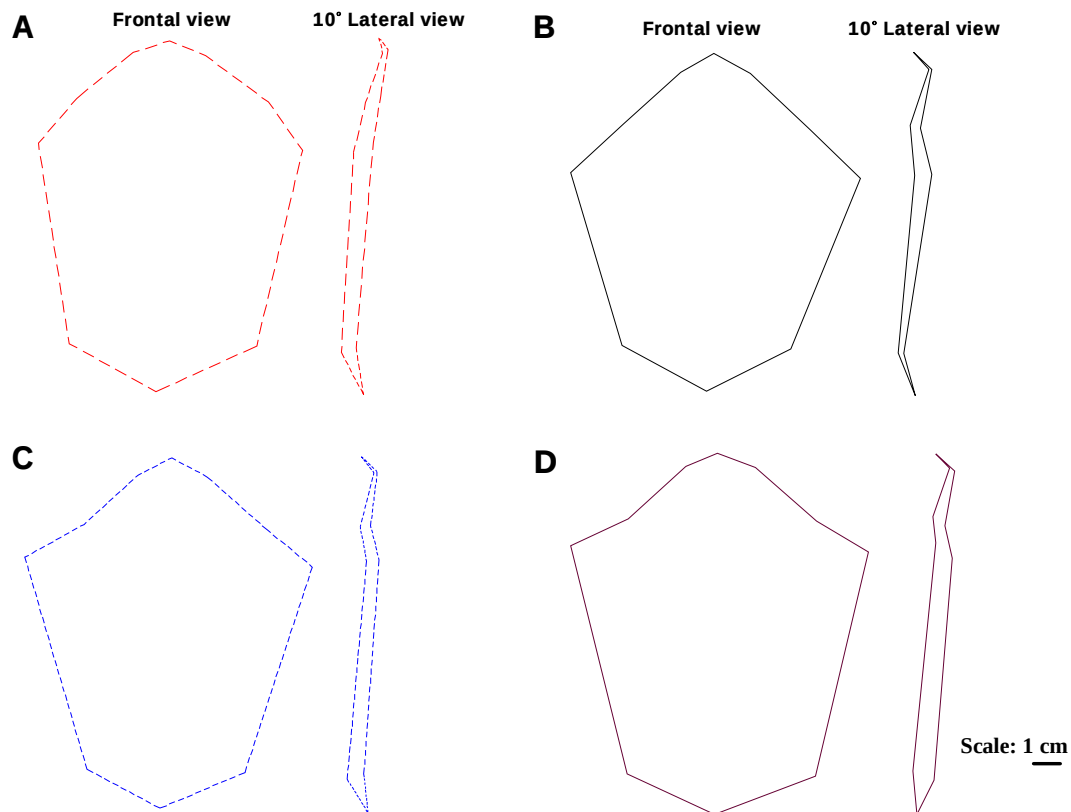


Figure 4. The results of cluster analysis for classifying 102 subjects.



**Figure 5. Four half-mask respirator shapes modeled by cluster analysis for the face shapes of Koreans (type A: Flat round elliptic faces, type B: Bendy long elliptic faces, type C: Round elliptic faces, type D: Flat chin and long elliptic faces).**

### Development of a New 3D Test Panel Using 3D Face Data

The present study was performed to develop a new 3D test panel using shape information from clustering of 3D shape analysis and size information of face length (Figure 4). Face types on x-axis were based on figure 4 and face lengths on y-axis were defined from sellion to gnathion (Figure 6). Based on Hack *et al.* (1974), face lengths on y-axis were defined as follows. The upper limit of 133.5 mm was set as the mean (122.4 mm) of male measurements plus two standard deviations. The lower limit of 103.7 mm was set as the mean (113.3 mm) of the female measurements minus two standard deviations.

Figure 6 shows that 21.7% of males were type C with face lengths between 118.6 mm and 126.1 mm while 25% of females were type A and 25% were type C with face lengths between 111.2 mm and 118.6 mm. Traditional fit-test panel is consisted of 25 people (13 males and 12 females). The new fit-test panel developed in this study is also consisted of 25 people (13 males and 12 females). However this test panel removed 6 of the 16 boxes which consisted of less than 3 % population among 102 subjects as in Figure 7.

Figure 8 is the 3D fit-test panel of only 16 males; most workers are males in Korean manufacturing factories. Face shapes of Korean males can be summarized by type B, type C, and type D on x-axis and removing the small-sized boxes from the test panel for 25 people on y-axis. Eventually the test panel of 16 males is consisted of 8 boxes after removing type B and 126.1 mm-133.5 mm where no measurements existed.

|                  |       | Face shape  |                           |                            |                           |
|------------------|-------|-------------|---------------------------|----------------------------|---------------------------|
|                  |       | A           | B                         | C                          | D                         |
| Face length (mm) | 133.5 | 2M (2.90%)  | 2M (2.90%)                | 8M (11.59%)                | 5M (7.25%)                |
|                  | 126.1 | 2T (1.98%)  | 2T (1.98%)                | 8T (7.92%)                 | 5T (4.95%)                |
|                  | 118.6 | 2M (2.90%)  | 8M (11.59%)               | 15M (21.74%)<br>2F (6.25%) | 9M (13.04%)               |
|                  | 111.2 | 2T (1.98%)  | 8T (7.92%)                | 17T (16.83%)               | 9T (8.91%)                |
|                  | 103.7 | 8F (25.00%) | 7M (10.14%)<br>1F (3.13%) | 4M (5.80%)<br>8F (25.00%)  | 7M (10.14%)<br>2F (6.25%) |
|                  |       | 8T (7.92%)  | 8T (7.92%)                | 12T (11.88%)               | 9T (8.91%)                |
|                  |       | 6F (18.75%) |                           | 2F (6.25%)                 | 3F (9.38%)                |
|                  |       | 6T (5.94%)  |                           | 2T (1.98%)                 | 3T (2.97%)                |

Figure 6. Distribution of 101 subjects by face sizes and shapes.

|                  |       | Face shape |    |          |          |
|------------------|-------|------------|----|----------|----------|
|                  |       | A          | B  | C        | D        |
| Face length (mm) | 133.5 |            |    | 2M       | 1M       |
|                  | 126.1 |            | 2M | 3M<br>1F | 2M       |
|                  | 118.6 | 4F         | 1M | 1M<br>3F | 1M<br>1F |
|                  | 111.2 |            |    |          |          |
|                  | 103.7 | 3F         |    |          |          |

Figure 7. Male and female, 3D test panel of 25 members for half-mask respirator.

|                  |       | Face shape |   |   |
|------------------|-------|------------|---|---|
|                  |       | B          | C | D |
| Face length (mm) | 133.5 | 0          | 2 | 1 |
|                  | 126.1 | 2          | 4 | 2 |
|                  | 118.6 | 2          | 1 | 2 |
|                  | 111.2 |            |   |   |

Figure 8. 3D test panel of 16 males for half-mask respirators.

## DISCUSSION

Traditionally, anthropometric measurements have been made with tapes and calipers and are referenced to coordinate systems dependent upon anatomical landmark locations. There are two problems inherent with the use of traditional anthropometry for the design of protective equipment or fit-test panel. First, an infinite number of contours can be derived from these linear measurements and therefore, items produced by different manufacturers meeting the same specifications can produce very different products in terms of shape and ultimately, fit. Second, many measurements are entirely dependent upon orientation of the body segment. It is possible to lose that size data if it is not able to be expressed as complicated curved face data. The previous LANL test panel is not appropriate to represent to current workers who rely on respirators to prevent work-related illness, injuries and death.

According to NIOSH (2002), the respirator fit-test panels currently used are 25 subject panels, developed by Los Alamos National Laboratory (LANL) based on data from the 1967-1968 survey of U.S. Air Force men and women. The half-mask panel is based on face length and lip length and full-facepiece panel is based on face length and face width. These panels were established to represent the working population. The fit of respirators on these subject panels is assumed to be representative of the fit of respirators in the user populations. Respirators designed to fit these panels are also expected to accommodate at least 95 % of the wearers. However, NIOSH research indicated that the LANL panel for full-facepiece respirators included only 84 % of current civilian subjects.

The previous studies of fit-test panels used only length (size) data. The present study developed a new 3D test panel based on length and shape data. This study performed shape analysis by Procrustes algorithm to provide 3D information of faces.

Discriminant analysis was used to determine if there was any gender difference in face shape. Cluster analysis was used to classify 102 subjects by face types. In the results, differences between males and females were shown by discriminant analysis, and 102 subjects were classified into four types by cluster analysis. The classified 4-type face shapes would be useful for respirator design and fit-test panel construction.

Traditional test panel for full-facepiece respirators is defined by face length on y-axis and face width on x-axis. The panel for half-facepiece respirators is defined by face length on y-axis and lip length on x-axis (Hack *et al.*, 1974; Han, 1999). In the present study, however, the new 3D test panel for half-facepiece respirators was developed face length on y-axis and face type from shape analysis on x-axis.

In this study, the subjects face lengths were  $122.4 \pm 5.5$  mm for males and  $113.3 \pm 4.8$  mm for females. According to previous studies of Korean populations (Han *et al.*, 1997; KRISS, 1998; Yoon & Jung, 2002; Kim *et al.*, 2003), the females had face lengths ranging from 109.5-111.0 mm and the males had face lengths ranging 120.1-120.6 mm. The face lengths data of the previous study was not significantly different from of the present study ( $p > 0.05$ ).

The test panel for Koreans developed by Han (1999) was based on the LANL test panel. Han (1999) showed that this anthropometric data differed from LANL anthropometric data. Also Kim *et al.* (2003) showed that Korean anthropometric data were different from western anthropometric facial data. The study suggested that different face characteristics need to be considered in the design of quarter mask respirators to improve respirator fit for Koreans.

To overcome the shortcomings of the previous test panel, 3D data must be adopted. Summarization of 3D face data is an important processes as well as data acquisition. The 3D test panel was developed by data summarization and acquisition. The developed 3D test panel will be valuable for half-facepiece respirators designed to be used by a Korean population.

This 3D test panel can also be used for respirator certification. To use this 3D test panel, subjects are first scanned using a 3D scanner. The 3D-coordinate extraction of 10 landmarks from the digitized 3D scan data is then carried out. The extracted data are further analyzed to determine face shape (Types A, B, C, or D). With the face length measurement, subjects are assigned to appropriate cells of the 3D panel representing Korean population. However, the classification technique will be needed to improve for the 3D test panel. The face recognition and identification technique is not confirmed in this respirator field yet.

The limitations of this study are that this 3D test panel could be applied only Korean and half-facepiece respirators. However, 3D test panels can be developed for other ethnic groups and full-facepiece respirators by 3D anthropometric data acquisition and summarization such as Procrustes algorithm. Validation study of this panel will be needed in the near future. Also it will be necessary to develop the 3D test panel for full-facepiece respirators.

## CONCLUSIONS

The LANL fit-test panels are based on only size (length) information. Length information is not sufficient to adequately represent face anthropometry. A new 3D fit test panel for Koreans was developed utilizing shape information as well as length information in this study. The 3D approach for developing test panel can be applied for other ethnic groups having different face shapes.

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