

Three-Dimensional Shape Analysis of Commercial Half-Facepiece Respirators for Koreans: Structural Approach

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ABSTRACT

This study was performed to characterize shapes of Korean faces based on statistical shape analysis of three-dimensional (3-D) facial data, to identify design deficiencies of the facepieces of commercial half-facepiece respirators, and to suggest a new concept for constructing the test panel for respirator fit testing.

Three-dimensional surface data were obtained using a 3-D laser scanner from a group of 102 volunteers (70 males and 32 females) and surface data from the two foreign and two domestic models. The collected data was digitized and used for shape analysis utilizing the Procrustes algorithm.

Facial shapes between genders were statistically significantly different. The misclassification error rate was 2.99 %. Three-dimensional data of facial shapes of subjects and the surface contours of the four respirators tested showed a statistically significant difference. Specifically, significant gaps were found at nose and chin areas, while cheek area showed a relatively good fit.

The results of 3-D facial analysis showed that the facepieces of the commercial half-facepiece respirators tested, both imported and domestic, did not match with the facial shapes of Koreans. Principally, significant gaps were found around the nose and chin areas. These design deficiencies, as well as shape information of Korean faces, should be taken into consideration for the design of future half-facepiece respirators.

Keywords: Procrustes algorithm, 3-D laser scanner, Fit factor, Test panel, Facial shape

INTRODUCTION

It can be said that the human head or face is one of the most fascinating objects in nature. The fit requirements for personal protective equipment (respirators, eyeglasses and other head/face gear) are substantial. Measurements of the surface of the human head and face are necessary to design personal protective equipment. In the future, anthropologists and engineers will utilize remote imaging devices, such as lasers, video cameras, and holographic systems, to collect great quantities of 3-D shape information very rapidly.

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 facial dimensions and their associated poor correlation. In other words, the shape of the head and face is the most complicated one among the surfaces of the human body. The problems of how to describe the 3-D geometry of the human face are of interest here.

During the last few years the measuring technology has advanced to such a 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, head and face shape data are now being collected and put into digital form in less than 15s. However, statistical summary and clustering methods for the digitized 3-D data have not yet been developed. Penrose (1954) proposed 'shape' and 'form' as a simple linear formulation:

$$\text{Form} = \text{Size} + \text{Shape}$$

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 3-D, 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 and Richtsmeier, 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,

$$\text{Form} = \text{Shape}$$

Many statistical methods are in use for classifying size and shape in biological systems. Some of 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; Lestrel 1997A; Lestrel, 1997B). Landmark methods include: (1) Conventional matrix analysis (CMA); (2) Biorthogonal grids (BOG); (3) Finite element method (FEM); (4) Euclidean distance matrix analysis (EDMA); and (5) Thin plate spline (TPS). Subsumed under outline methods are: (1) medial axes analysis (MAA); (2) Eigen shape analysis; and (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).

The CMA was originally developed for measuring regular geometric objects and its application to irregular biological forms may not be the most appropriate, in spite of its ease of use. This method consists of linear measurements of distances, angles, and ratios. It is generally unsatisfactory because of difficulties in adequately standardizing for size. In spite of this limitation, previous studies for respirators were analyzed by CMA for faces (Hack *et al.*, 1974; Hack and McConville, 1978; Han and Choi, 2003; Kim *et al.*, 2003). Previous studies have been focused on distances, angles and ratios for irregular human face. The studies were not able to express the shapes properly. With relationship to respirators, Taylor (1994) used EDMA to investigate the size and shape of oxygen masks produced for the US Air Force. Ratnaparkhi *et al.* (1992) introduced Fourier analysis for respirator design.

Procrustes analysis was used for 3-D shape analysis of 4 commercial half-facepiece respirators and 102 faces in this study. The present study discovered the problems associated with the shape of current commercial half-facepiece respirators in Korea employing structural approaches using Procrustes analysis.

METHODS

1. Three-Dimensional Laser Scanning of Faces and Four Respirators

Three-dimensional surface coordinate data were obtained using a 3-D laser scanner (3030 RGB/PS, Cyberware, U.S.A.) from 102 volunteers (70 males and 32 females) and 4 half-facepiece respirators (2 foreign and 2 domestic).

The 3-D faces and 4 respirators length data were obtained by 3-D laser scanner. The lengths were measured and calculated a distance between sellion and gnathion from 3-coordinate data.

2. Procrustes Analysis Algorithm

Shape analysis on the digitized data was done using the Generalized Procrustes Analysis (GPA) algorithm (Dryden and Mardia, 1998). The algorithm was as followed:

1. **Translations.** Center the configuration matrices to remove location. Initially let

$$X_i^P = X_i, i = 1, \dots, n.$$

2. **Rotations.** For the i th configuration let

$$\bar{X}_{(i)} = \frac{1}{n-1} \sum_{j \neq i} X_j^P$$

Then the new X_i^P is taken to be the ordinary Procrustes superimposition involving only rotation of the old X_i^P on $\bar{X}_{(i)}$. The n figures are rotated in turn. This process is repeated until the Procrustes sum of squares $D_{GPA}^2(X_1, \dots, X_n)$ (with $b_i = 1, v_i = 0 \forall i$) cannot be reduced further.

3. **Scaling.** Let Φ be the $n \times n$ correlation matrix of the $\text{vec}(X_i^P)$ (where $\text{vec}(X_i^P)$ = vector made of concatenation of rows of X_i and the usual roles of variable and observation labels are reversed) with eigenvector $\phi = (\phi_1, \dots, \phi_n)^T$ corresponding to the largest eigenvalue. Then take

$$b_i = \left(\frac{\sum_{k=1}^n \|X_k^P\|^2}{\|X_i^P\|^2} \right)^{\frac{1}{2}} \phi_i$$

repeated for all i .

4. **Repeat** steps 2 and 3 until the Procrustes sum of squares $D_{GPA}^2(X_1, \dots, X_n)$ cannot be reduced further.

3. Selection of 10 Facial Landmarks for Half-Facepiece Respirator Design

The 10 selected landmarks were sellion, right and left maxillofrontale, right and left maxillary point, right and left middle cheek point, right and left tuberculare and gnathion. The selection was based on the contact points between faces and respirators (Figure 1). These 10 landmarks were selected contacting points between faces and half-facepiece respirators and representative points for faces and respirators after discussed with an anatomist.

4. Statistical Shape Analysis

Three-dimensional landmark co-ordinates were scaled and aligned via Generalized Procrustes Analysis (GPA). The GPA was carried out using the program PAST (PAleological STatistics, v 1.12) (Hammer *et al.*, 2002). The residuals were then analyzed by discriminant analysis. The residual axis (x, y, z) data were classified by gender or human facial and respirator surface data. Statistical analysis was performed by using the Statistical Analysis System (SAS®) software (SAS Institute, Inc., 1999). Also the residuals were used to calculate stand-off distances between face and respirator on each landmark.

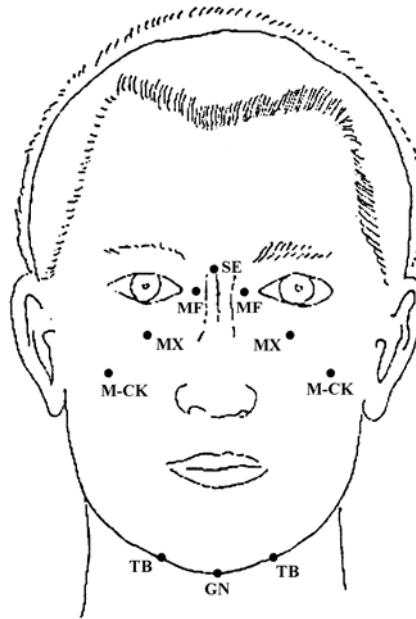


FIGURE 1. Facial landmarks selected for 3-D shape analysis. SE(sellion): the deepest landmark located on the bottom of the nasofrontale angle. MF(maxillofrontale): at the base of the nasal root medially from each endocanthion, close to the bony maxillofrontale of the medial margin of each orbit, where the maxillofrontal and nasofrontal sutures meet. MX(maxillary)point: the point which is located 1-cm below the midpoint of low 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.

RESULTS

Table I contains general information for 102 subjects and 4 respirators for the present study. The mean age of male and female subjects was 25.8 ± 6.2 years and 20.3 ± 3.4 years, respectively. The mean face length was 122.4 ± 5.5 mm for 70 males and 113.3 ± 4.8 mm for 32 females. The length of respirator matched on face length was 123.0 mm for the FM respirator, 112.9 mm for the FS respirator, 123.1 mm for the KG respirator and 118.6 mm for the KJ respirator.

TABLE I. General Characteristics of 102 Subjects and Four Respirators

Characteristics	Sub-classification		Results
Subject	Age (yrs.)	Male	25.8 ± 6.2
		Female	20.3 ± 3.4
	Face length (mm)	Male	122.4 ± 5.5
		Female	113.3 ± 4.8
Half-facepiece respirator	Length (mm)	FM	123.0
		FS	112.9
		KG	123.1
		KJ	118.6

FM, FS: imported half-facepiece respirators; KG, KJ: domestic half-facepiece respirators

The full Procrustes superimpositions of the 70 male (A) and 32 female (B) faces with 4 commercial half-facepiece respirators registered in the coordinate system as recorded by a digitizer. The 10 landmarks are sellion, right-maxillofrontale, left-maxillofrontale, right-maxillary point, left-maxillary point, right-middle cheek point, left-middle cheek point, right-tuberculare, left-tuberculare, and gnathion (Figure 2).

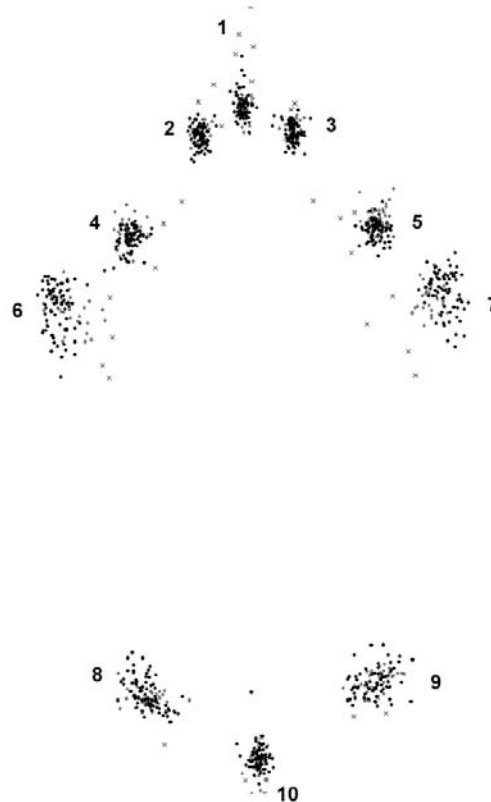


FIGURE 2. Procrustes superimposition of 10 landmarks for 70 male (dark dot) and 32 female faces (grey dot) with 4 commercial half-facepiece respirators (cross).

To summarize Korean facial shape of 70 males and 32 females, discriminant analysis was performed in this study (Figure 3). Based on the statistical results, the shape of male and female faces was shown to be different. The error rate of females and males were 3.13 % and 2.86 %, respectively. The average error rate was 2.99 %.

Discriminant analysis was performed to determine the shape differences of 102 Korean faces and the four respirators. According to the results, shape analysis of 102 faces and 4 respirators was significantly different. The error rate was 0.00 % (Figure 4) which means shapes of 102 faces and 4 respirators not overlapped. Therefore, it can be said that faces and respirators are designed different shapes. The shape difference shown implies that the respirators were not designed based on Korean face shape.

Figure 5 illustrates stand-off distances between each face and the foreign FM respirator at 10 landmarks. The shortest distances were on maxillary and middle cheek point (cheek area), and the longest distances were nose (sellion and maxillofrontale) landmarks and chin (tuberculare and gnathion) landmarks. The widest range of distance was found on the right maxillary point, right middle cheek point and tuberculare.

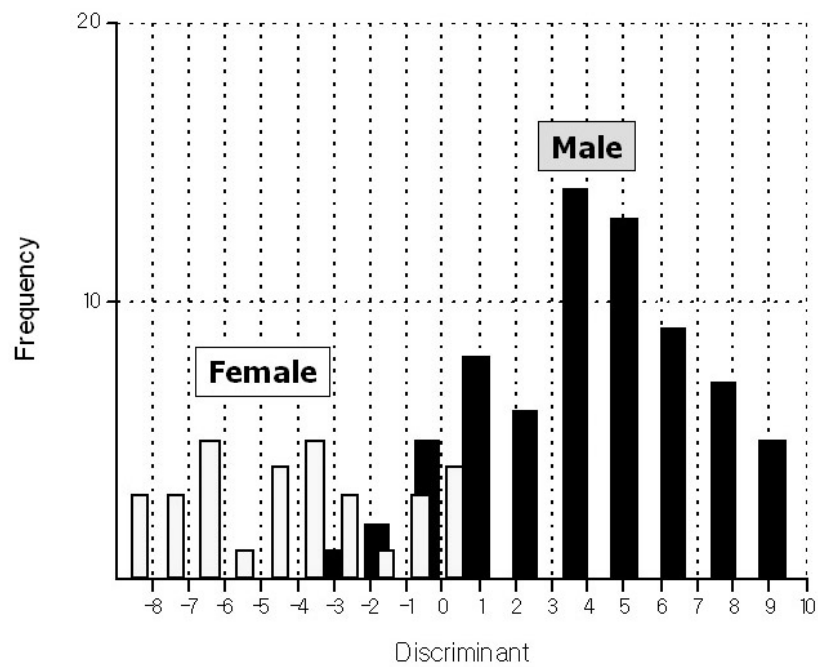


FIGURE 3. Comparison of facial shapes of 70 males and 32 females by discriminant analysis.

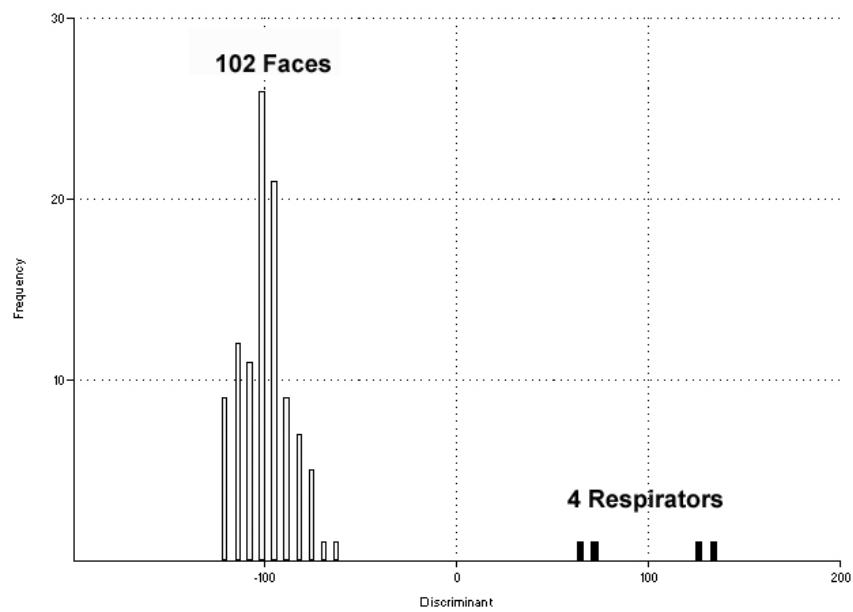


FIGURE 4. Comparison of 102 faces and 4 respirators by discriminant analysis.

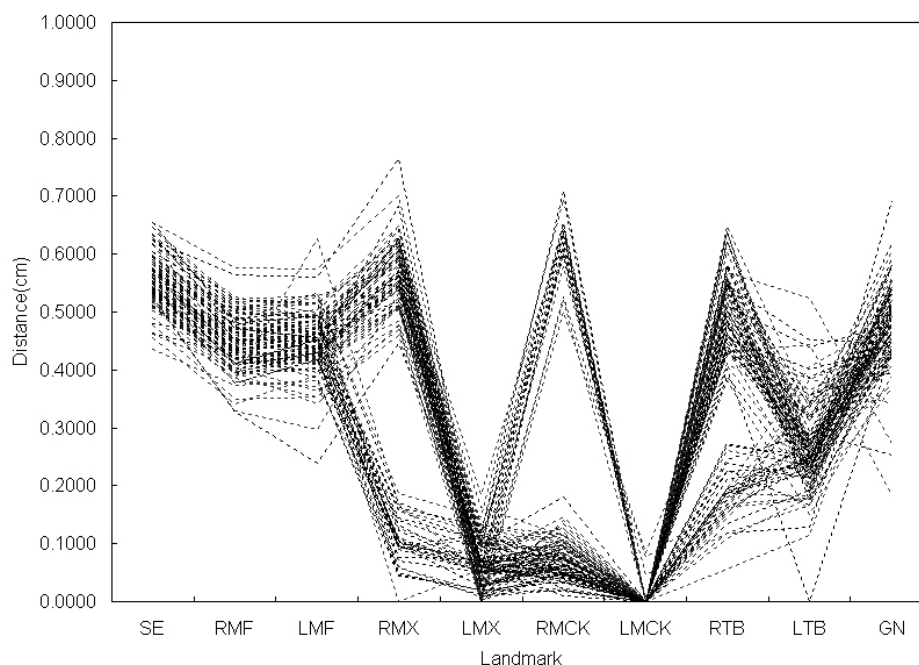


Figure 5. Stand-off distances between each face and the FM respirator on 10 landmarks (SE: sellion, RMF: right maxillofrontale, LMF: left maxillofrontale, RMX: right maxillary point, LMX: left maxillary point, RMCK: right middle cheek point, LMCK: left middle cheek point, RTB: right tuberculare, LTB: left tuberculare, GN: gnathion).

Figure 6 illustrates stand-off distances between each face and the foreign FS respirator of 10 landmarks. The trend of short and long distances was the same as with the FM respirator, but the absolute length was shorter than that of the FM respirator. In addition, the widest range of distance was found at right maxillary point, right middle cheek point, left & right tuberculare and gnathion.

Figure 7 illustrates the stand-off distances between each face and the domestic KG respirator for each of 10 landmarks. The overall shortest distances were on maxillary point and middle cheek point (cheek area). The longest distances were on sellion, maxillofrontale (nose area), tuberculare and gnathion (chin area). The widest range of distance was shown at left maxillary point, right middle cheek point and left & right tuberculare.

Figure 8 illustrates stand-off distances between each face and the domestic KJ respirator for each of 10 landmarks. The overall shortest distances were at the maxillary point and middle cheek point (cheek area). The longest distances were at sellion, maxillofrontale (nose area), tuberculare, gnathion (chin area) and right middle cheek point. The right middle cheek point was different from FM, FS and KG respirators. As was shown with the above 3 respirators, subjects who have the longest distances were mostly a part, while the longest distance was shown greater parts of subjects in the KJ respirator. The widest range of distance was found at the left maxillofrontale point, right middle cheek point, and left & right tuberculare points.

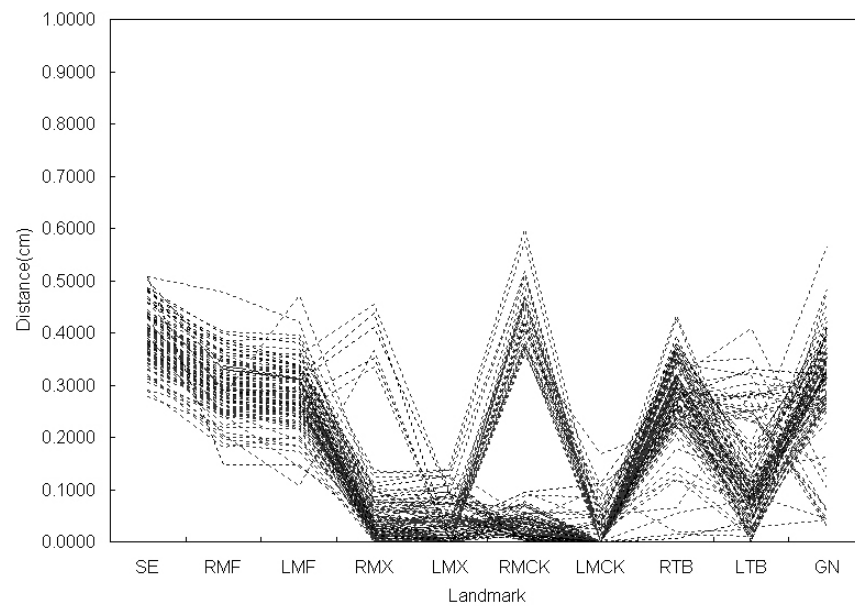


Figure 6. Stand-off distances between each face and the FS respirator on 10 landmarks (SE: sellion, RMF: right maxillofrontale, LMF: left maxillofrontale, RMX: right maxillary point, LMX: left maxillary point, RMCK: right middle cheek point, LMCK: left middle cheek point, RTB: right tuberculare, LTB: left tuberculare, GN: gnathion).

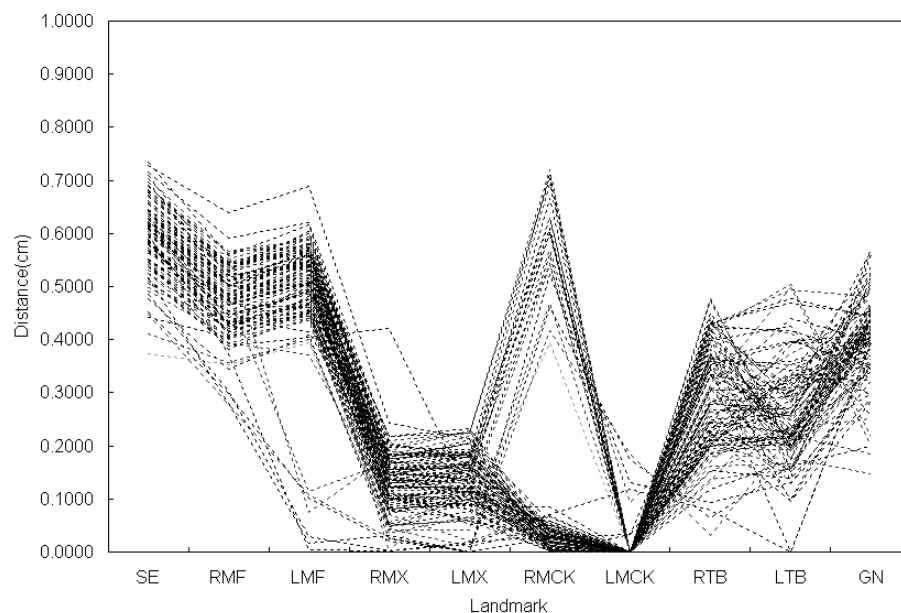


Figure 7. Stand-off distances between each face and the KG respirator on 10 landmarks (SE: sellion, RMF: right maxillofrontale, LMF: left maxillofrontale, RMX: right maxillary point, LMX: left maxillary point, RMCK: right middle cheek point, LMCK: left middle cheek point, RTB: right tuberculare, LTB: left tuberculare, GN: gnathion).

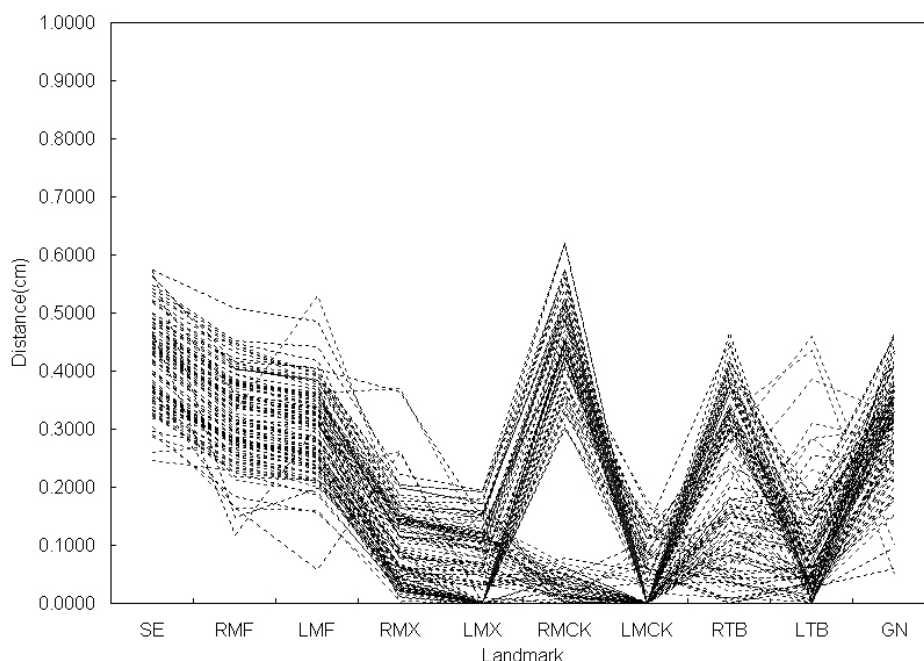


Figure 8. Stand-off distances between each face and the KJ respirator on 10 landmarks (SE: sellion, RMF: right maxillofrontale, LMF: left maxillofrontale, RMX: right maxillary, LMX: left maxillary, RMCK: right middle cheek, LMCK: left middle cheek, RTB: right tuberculare LTB: left tuberculare, GN: gnathion).

DISCUSSION

Designing personal protective equipments for the head and face requires not only 3-D anthropometric information of the head and face, but also 3-D statistical description of anatomical geometry. The mathematical theory of statistical methods is not usually part of the standard equipment of the biologist or anthropologist. However, without this background, they are quite unprepared to deal effectively with a large sample.

Korean respirator studies have shown that the performance of domestic respirators advertised as designed for Korean workers, were inferior to that of foreign respirators (Han and Choi, 2003; Kim *et al.*, 2003; Hur and Kim, 1994; Han, 1999). The causes of the problem may be attributed to either the inadequacy of the respirator certification program in Korea, where no requirement for fit testing has been specified and no fit test panel was established, or improper design of respirators for Korean workers as well as poor choice of raw materials used in the manufacturing of Korean respirators (Kim *et al.*, 2003; Park and Kim, 1994).

The elasticity of rubber respirators would not cover individual anthropometric variation and facial expression variation hall of respirators donned in the workplace due to the restricted sizes and types of respirators. Therefore the respirators should be designed using Korean anthropometric facial data.

Shape in these studies has meant the location of and relative distances between these designs of equipment. However, for certain complex designs, this information though useful, is insufficient. The information regarding the contour of the face is needed. Procrustes analysis was used for 3-D shape analysis of half-facepiece respirators in this study. Four commercial half-facepiece respirators were selected for the study. The present study discovered problems with current commercial half-facepiece respirators' shapes in Korea using Procrustes analysis.

In the present study, the face lengths of males ($n=70$) and females ($n=32$) were 122.4 ± 5.5 mm, 113.3 ± 4.8 mm respectively. There was no statistically significant difference between the present data and the previous data where face lengths ranged from 120.1-120.6 mm for Korean males, and 109.5-111.0 mm for Korean females ($p>0.05$) (Km *et al.*, 2003; Han, 1999; KRISS, 1998; Yoon and Jung, 2002). According to this statistical result, we concluded that the subjects who volunteered to be in this study were representative of the Korean population.

As a result of shape analysis by superimposition of 3-D data using Procrustes analysis, there were statistically significant differences between males and females. The error rate was 2.99 %. The error rate means that one cannot distinguish between female or male facial shapes for 3 % of the Korean population. Therefore respirators for males and females should be specifically designed for each gender.

Discriminant analysis was carried out to determine if 3-D shapes were different when comparing facial shapes and respirator shapes. The error rate was 0.0 %. Per these results, the shapes were classified perfectly. This means that the four respirators used in this study were inappropriately designed for Koreans. Stand-off distances on each landmark were measured to describe inappropriate leak sites at 10 facial landmarks for each of the four candidate respirators. The present study demonstrated the same trend using the stand-off distances between each face and commercial half-facepiece respirator for 10 landmarks. Especially long distances were identified in nose and chin areas, while short distances were identified for the cheek area such as maxillary point and middle cheek point. Hur and Kim (1994) reported that 73.2 % of the leak sites were found in nose and chin areas based on the results of leak sites surveys using qualitative fit tests for half-facepiece respirators. Their results explained that the shapes of commercial respirators were not designed for Korean facial shape because the traditional respirator design was based on only facial size.

In the present study, stand-off distances of right middle cheek points among chin areas was relatively 20-40 % longer than left middle cheek points. In my opinion, the differences may be from errors caused by shape analysis or facial asymmetry. The former method superimposed each landmark using Procrustes analysis and then measured the distances between respirator and face. During the Procrustes analysis, it is possible that each landmark was arranged by both respirators and faces. Actually the faces and respirators used in this study did not allow for their skin flexibility and rubber elasticity respectively. Future studies will use finite element analysis in order to allow for material elasticity of respirators, skin flexibility and motion variability of faces. The latter takes into account the variability in right and left asymmetric faces due to cheek area as a matter of fact. In this case, two solutions are possible. The first solution is to make up for asymmetric face by using the elasticity of respirators, but it is questionable whether the elasticity of respirators is able to properly account for the asymmetric problems of faces. The second solution is to consider the use of custom-made respirators for persons with serious asymmetric faces.

CONCLUSIONS

The four commercial respirators were chosen based on facial length data. Traditional anthropometric data without face shape data was not sufficient to adequately express complete face information for perhaps the most difficult body part. Through 3-D shape analysis of Korean faces, stand-off distances between face and respirator in nose and chin area (sellion, maxillofrontale, tuberculare and gnathion) were found to be longer than with the other cheek area. The present study supports the previous study the commercial respirators usually leaked in the nose and chin area for Korean population.

Facial shape data found in the present study should be considered for use in designing respirators for Koreans. Further research is needed to find suitability for using face shape data for respirator design as well as facial length data.

REFERENCES

- Penrose, L.S.:** Distance, size and shape. *Ann of Eugenics*. 18:337-343 (1954).
- Lele, S., and J.T. Richtsmeier:** Euclidean distance matrix analysis: A coordinate-free approach for comparing biological shapes using landmark data. *Am J Phys Anthropol*. 86(3):415-427 (1991).
- Lestrel, P.E.:** Some approaches towards the mathematical modeling of the craniofacial complex. *J Craniofacial Genetics and Developmental Biology*. 9:77-91 (1989).
- Lestrel, P.E.:** Morphometrics of craniofacial form: a Fourier analytic procedure to describe complex morphological shapes. In: Dixon, A.D., Hoyte DAN, O. Rønning (eds) *Fundamentals of craniofacial growth*. CRC Press, New York. pp. 155-187 (1997).
- Lestrel, P.E. (ed):** Fourier descriptors and their applications in biology. Cambridge University Press, Cambridge, pp. 3-44 (1997).
- Chen, S.Y.Y., P.E. Lestrel, W.J.S. Kerr, and J.H. McColl:** Describing shape changes in the human mandible using elliptical Fourier functions. *European J of Orthodontics*. 22:205-216 (2000).
- Hack, A.L., E.C. Hyatt, B.J. Held, T.O. Moore, C.P. Richards, and J.T. McConville:** Selection of respirator test panels representative of U.S. adults facial size. Los Alamos Scientific Laboratory of the University of California, NM, 1974.
- Hack, A.L., and J.T. McConville:** Respirator protection factors: Part I - Development of an anthropometric test panel. *Am Ind Hyg Assoc J*. 39(12):970-9 (1978).
- Han, D.H., and K.L. Choi:** Facial dimensions and predictors of fit for half-facepiece respirators in Koreans. *Am Ind Hyg Assoc J*. 64:815-822 (2003).
- Kim, H.W., D.H. Han, Y.M. Roh, K. Kim, and Y.G. Park:** Anthropometric dimensions of Koreans and their associations with fit of quarter-masks respirators. *Industrial Health*. 41: 8-18 (2003).
- Taylor, S.:** Euclidean distance matrix analysis and MBU-20/P oxygen mask fit. In Mardia KV, Gill CA, Dryden IL, editors, *Proceedings in Image Fusion and Shape Variability Techniques*, pages 220-221, Leeds. University of Leeds Press 1994.
- Ratnaparkhi, M.V., M.M. Ratnaparkhi, and K.M. Robinette:** Size and shape analysis techniques for design. *Appl Ergo*. 23(3):181-185 (1992).
- Dryden, I.L., and K.V. Mardia:** *Statistical Shape Analysis*. Wiley. 1998, pp 81-108
- Hammer, Ø, Harper, D.A.T., and Ryan P.D.:** PAST - PAleontological STatistics. Available from: <http://folk.uio.no/ohammer/past/past.pdf> 2002.
- SAS Institute, Inc.** SAS/STAT User's Guide, Version 8.0, SAS Institute Inc., 1999, Cary, North Carolina
- Hur, J.Y., and H. Kim:** Identification and distribution of leak sites of half mask respirators. *Korean Ind Hyg Assoc J*. 4(2):180-188 (1994).
- Han, D.H.:** Fit testing for respirators and development of fit test panels for Koreans. *Korean Ind Hyg Assoc J*. 9(1): 1-13 (1999).
- Park, E.J., and H. Kim:** Quantitative respirator fit testing of half mask respirators. *Kor J Occup Health*. 34(4): 133-143 (1995)
- KRISS:** National anthropometric survey of Korea 1997. Korean National Institute Technology and Quality. 1998.
- Yoon, H.Y., and S.G. Jung:** A Study of measurement on the head and face for Korean adults. *IE interface*. 15(2): 199-208 (2002).