Characteristics of Korean Children's Facial Anthropometry Evaluated by Three-dimensional Imaging

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ABSTRACT

There are few commercial respirators designed specifically for children because no three-dimensional anthropometric data exist for children's faces. As a first step, facial anthropometric dimensions need to be analyzed using a three-dimensional image capture device that can measure many dimensions accurately and easily in a short time. The aim of this study was to characterize the facial dimensions of Korean children using three-dimensional imaging for use in respirator design. Faces of children (n = 144, aged 5–13 years) were analyzed with three-dimensional imaging. We utilized Geomagic Capture, Geomagic Wrap, and Design X software (3D SYSTEMS, USA). Cluster analysis was performed for 16 facial dimensions to categorize them into different sizes. The geometric means were used to divide the groups using the K-means algorithm. Facial shapes were classified into three clusters: small, medium, and large. The face width and length for the first group were small with high protrusion of nose, while the face width and length for the second group were larger than those in the first and third groups. The facial dimensions for the third group showed medium dimensions but had the largest angle of the nose root to the gnathion (n-prn-gn). Children's facial dimensions increased with age, but not equally in all dimensions. Three clusters of small, medium, and large respirators were designed according to children's facial dimensions. We are in the process of developing an optimal mask size for each cluster based on the three-dimensional facial characteristics. This study showed that three-dimensional imaging can be useful for obtaining reliable and reproducible facial data.

Keywords: Anthropometric analysis, three-dimensional imaging, Child facial dimensions, Respirator design.

INTRODUCTION

With changes in social environments, increasing demand for new sizing systems and designs for industrial products calls for collecting three-dimensional (3D) anthropometric information (Kim et al., 2002). In modern society, the use of facial imaging has been expanded to various areas, including service systems and industries that use information from facial recognition and manufacturing industries that produce face-related products. In particular, since 3D facial modeling can be broadly applied to various areas, such as computer games, animation, 3D virtual cosmetic surgery of the face, and virtual hair salons, there has been a recent increase in the number of studies using 3D facial modeling (Lee et al., 2011a). In addition, medical researchers have also used 3D imaging (Kornreich et al., 2014), such as to obtain clinical measurements for aesthetic correction in dentistry or plastic surgery and to compare differences among ethnic populations (Liu et al., 2013; Weinberg & Kolar, 2005; Woelfel et al., 2014).

Advancements in 3D technology have revealed its growing importance in manufacturing sectors, including for respirators. Since the human body is composed of numerous irregular curves and convexo-concave angles, thereby making its measurement difficult, methods using computers and scanners have been developed to replace existing traditional measurement methods. The face has more diverse curves than other body parts do, and conventional methods that measure distances between landmarks or arc sizes have limitations in curvature measurements (Kim et al., 2003).

3D processing of facial images uses a combination of independently developed computer graphic and image processing technologies that has been shown to extract large amounts of data from collected image shapes with high accuracy and precision. However, while this method can quickly create realistic facial models, it requires additional work as well as expensive devices, which limits its applicability. In addition, 3D anthropometry data are inevitably fundamentally different from traditional directly measured values (Liu et al., 2013). These differences have been improved in recent years. For example, 3D images of people taken from various angles can be acquired through 3D photogrammetry technology, which quantifies and captures anthropometric dimensions of the head using a 3D imaging device, unlike the traditional method that uses a caliper to assess facial asymmetry, and facial asymmetry can be accurately compared based on a calculation of inter-landmark distances (Kornreich et al., 2014).

Respirators developed to protect workers from harmful substances need to be designed to provide close facial contact while minimizing gaps between the respirator and the face. Respirators should feature various osculating curves that contact the face and fit facial curves. However, respirators that are claimed to be manufactured to fit diverse facial morphologies often fail to provide sufficient protection when used in diverse worker populations. Therefore, 3D technology could be useful for respirator design. Han et al. (2004) classified Korean workers using 3D facial anthropometric dimensions and developed a half-mask that provides a better fit for Korean workers. Kim et al. (2003) reported that anthropometric dimensions and facial shapes differ among races, individuals, and sexes. Liu et al. (2008) developed a series of methods to design helmets based on 3D data of the head and constructed an efficient safety helmet design system. However, these studies were conducted in adults, and there have been few studies in children.

Recently, air pollution due to fine industrial particulates and yellow sand dust has emerged as a social issue in Korea (Kim & Lee, 2009). Fine industrial particulates, though in low concentrations, are suspected to cause more respiratory diseases in elderly, infirm, or pediatric populations than in adults (Kim et al., 2010). Since children have higher respiratory rates, their respiratory tracts reportedly have longer contact hours with pollutants. Children often breathe through their mouths and participate in more outdoor activities than adults do, leading them to be exposed to pollutants for longer periods of time. Since their immune systems are not fully developed, respiratory diseases are more likely to be exacerbated (Kim et al., 2010). Increasing respiratory and cardiac symptoms, diseases, and early death rates caused by yellow sand dust and fine particulates have recently been published in medical and environmental journals (Kim et al., 2006; Yu et al., 2007; Son et al., 2009).

Although respirators are needed for these reasons to protect the respiratory organs of children, no studies to date have examined the facial anthropometric dimensions of children in Korea, and no respirator with an optimal fit has been designed for children using such data. Although there are some commercialized masks marketed to children, no design specifications or research data are available for their products.

Therefore, the present study was conducted in Korean children less than 13 years of age to obtain fundamental data for designing respirators that would fit them accurately. 3D imaging was used for the measurements to save the time required for human body measurements, data reproduction, and repeated measurements with fewer errors. The 3D imaging also measures facial curvatures that cannot be measured by the existing direct-measurement method (Lee et al., 2004) and can obtain facial data from children in a short time. The 3D scanning data were further processed to generate a 3D image using a software program. With those images, facial anthropometric data were extracted and classified based on the children’s facial characteristics and shapes. The classification information will be used as baseline data in a future design of masks for children.

METHODS

Study subjects

Kindergartens, elementary schools, and middle schools that wished to participate in the study were selected in Seoul, Korea. Children were given explanations about the study goals and contents. Children who did not have surgical or facial scars and did not wear orthodontic braces were chosen. Children whose parents provided written consent were ultimately selected to participate. Recruiting regions were evenly distributed in the southern, northern, and western areas of Seoul to minimize regional bias. The final number of subjects in the present study was 144 children (72 boys, 72 girls) aged 5–13 years. The present study was approved by the institutional review board of The Catholic University (MC15OISI0029).

3D Scanning of Faces

Two Geomagic Capture devices (3D SYSTEMS, USA) for scanning the children’s faces were installed. The scanners were set at optimal angles to capture facial images of the subjects from the left and right sides simultaneously. A chair was used to support the neck and back to prevent movement of the head during scanning, since even slight movement of the face could cause noise in the scanning data, resulting in missing data and necessitating repeat scanning.

Once a participating child entered the scanning room (Figure 1), an elastic cap was put on his/her head to prevent hair from interfering with the facial scanning. A researcher placed several markers (Figure 2) on the pre-determined positions of facial landmarks (Liu et al., 2013; Luximon et al., 2010) for correct measurement. A cartoon character was affixed to the opposite wall for the subject to focus on while sitting in the chair.

Each subject was seated in the chair and instructed to remain still while looking straight ahead without moving during the scan, which took about 1 min. The scanner was a high-precision device with a light-emitting diode light source that had 0.08-mm resolution, 0.06–300-mm precision, and a 9,850,000 points/0.3 s/scan data acquisition rate (Geomagic Capture, 3D SYSTEMS, USA).

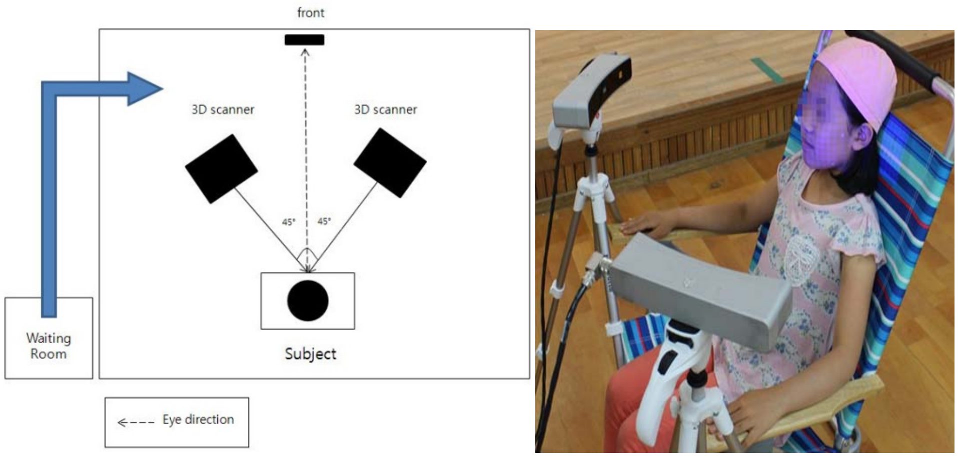


Figure 1. Schematic diagram of the scanning room (left) and a photo showing the setup of the scanners and the subject sitting on a chair (right).

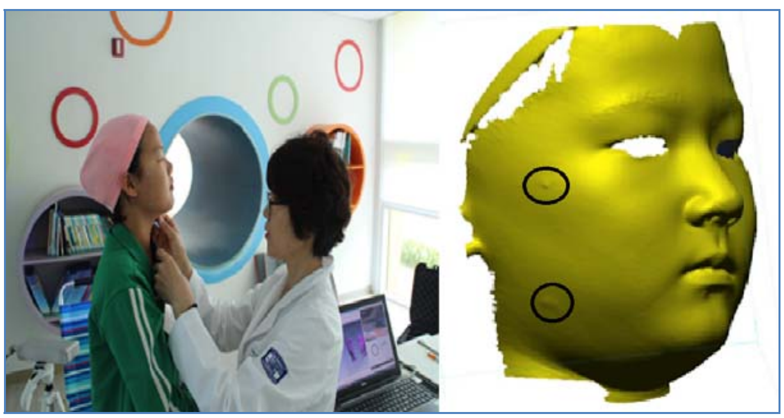


Figure 2. Placing landmarks on the subject’s face (left) and the land marks appeared after scanning (right).

3D Modeling

3D scan data from the faces of children aged 5–13 years were subjected to a modeling process using software (Design X or Geomagic wrap. 3D SYSTEMS, USA). Scanned data with holes caused by noise were corrected and subsequently merged for optimization and registration to transform different sets of data into one coordinate system. The facial scanning data of all subjects were edited to 3D models for the purpose of obtaining measurements (Figure 3).

Although modeling methods based on 3D scanning can produce highly precise and realistic models, modeling is disadvantageous because of difficulties in collecting 3D facial data and the large workload required to construct each model with a long processing time (Kim et al., 2013b). Nevertheless, it has the advantages of being associated with fewer operator errors, shorter time with less effort required by subjects, and various measurement values, thereby making it useful for obtaining children's facial measurements.

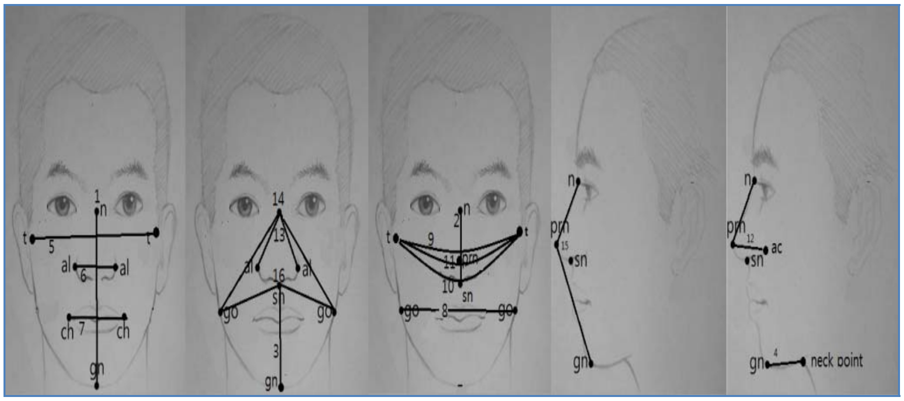
Figure 3. 3D Modeling processes showing merging and registration of scanned data.

3D Facial Anthropometry Data

For facial anthropometry measurements using completed 3D modeling data, a total of 16 items, including facial length, width, arc, and angles, were measured, as shown in Table I. The landmarks placed on the subject's face were utilized for measuring points, as in previous studies (Liu et al., 2013; Luximon et al., 2010). Based on landmarks by Kim et al. (2013a), facial measurements were performed, as shown in Figure 4. The actual measured 3D anthropometry data using Design X software are shown in Figure 5.

Table I. List of 3D Facial Anthropometry Used for the Study

	Name	Measurements	Number (in Figure)
Length	Face length	n-gn	1
	Nose length	n-prn	2
	Subnasale - chin length	sn-gn	3
	Menton length	gn-neck point	4
Width	Face width	t-t	5
	Nose width	al-al	6
	Lip width	ch-ch	7
	Gonion width	go-go	8
	Face curvature width	t-t curvature	9
Arc	Bitragion - subnasale arc	t-sn-t	10
	Bitragion - pronasale arc	t-prn-t	11
Angle	Nose protrusion angle	n-prn-ac	12
	Alare - nasal root angle	al-n-al	13
	Gonion - nose root angle	go-n-go	14
	Nose root - pronasale - gonion	n-prn-gn	15
	Gonion - subnasale angle	go-sn-go	16



Land marks	
n	Nasion
gn	Gnathion
prn	Pronasale
sn	Subnasale
t	Tragion
ch	Cheilion
go	Gonion
ac	Alar curvature point
al	Alare

Figure 4. Landmarks used and facial dimensions measured for the study.

Figure 5. Extraction of 3D Anthropometry data using the software.

Data Analysis

SPSS (version 18, SAS Institute Inc. USA) was used for the statistical analysis of the anthropometric data. A total of 16 facial dimensions were measured, including face length, face width, face curvature width, nose width, nose length, nose protrusion angle, nose root - pronasale - gonion angle, alare - nasale root angle, gonion - nose root angle, bitragion - subnasale arc, bitragion - pronasale arc, gonion - subnasale angle, gonion width, subnasale - chin length, lip width, and menton length.

The correlations between facial dimensions and age were analyzed by a correlation analysis, and an independent t-test was performed to determine differences in facial dimensions between sexes. In addition, the facial shapes were classified by characteristics using cluster analysis.

RESULTS

General characteristics

A total of 144 subjects (72 boys, 72 girls) participated in this study, which included 16 subjects for each age from 5 to 13 years (11.1%). Thus, there were 32 kindergarten students (22.2%) 5–6 years old, 96 elementary school students (66.7%) 7–12 years old, and 16 middle school students (11.1%) 13 years old (Table II).

Results of 3D Facial Measurements

During analysis of the modeling results from 3D scanning data in 144 children, several with missing data caused by ambiguous borders due to missing landmarks or by excess adipose tissue in the neck were excluded during the 3D measurement process; ultimately, measurement values of 137 children were used for the actual analysis.

For the correlation analysis, results of age and each of the 16 facial dimensions, including face length, face width, lip width, nose length, face curvature width, nose width, gonion width, subnasale - chin length, bitragion - subnasale arc, and bitragion - pronasale arc showed positive correlations, indicating that length and width items significantly increased ($p < 0.05$) with age.

In contrast, nose protrusion angle, alare - nasale root angle, gonion - nose root angle, and gonion - subnasale angle had negative correlations, indicating that angles significantly decreased with age ($p < 0.05$). On the other hand, age had no correlation with the nose root - pronasale - gonion angle ($p = 0.325$) or menton length ($p = 0.438$) (Table III).

An independent t-test performed to identify sex difference in facial dimensions showed no statistically significant difference for the majority of variables, although boys had higher anthropometric values than girls did. Only three of the 16 items showed statistically significant differences by sex; face length ($p = 0.0473$), face width ($p = 0.0037$), and the bitragion - pronasale arc ($p = 0.0482$).

Anthropometric values were higher for boys by 2.71 mm for face length, 4.33 mm for face width, and 6.14 mm for the bitragion - pronasale arc (Table IV). Since most of the facial variables were not statistically significantly different by sex in children, only the age variable, regardless of sex, was further analyzed for size classifications.

Classification by 3D Facial Morphology

Cluster analysis of the facial anthropometric values of 144 children resulted in three groups. A hierarchical clustering method was used to determine the optimal cluster number for the classification of facial shapes, from which the optimal cluster number was determined as three based on a dendrogram (Figure 6). To classify facial morphologies into three clusters, a non-hierarchical clustering method (k-mean clustering) was performed using the squared Euclidean distance, and the clusters were classified from the closest center after standardized processing of each anthropometric value for minimum variance divided into clusters 1, 2, and 3 (Figure 7).

Fig. 8 shows the three clusters of standardized face length (Z score), in which the group with the short face length was classified into cluster 1, followed by cluster 2 for the group with the long face length, and cluster 3 for the group with the medium face length. A figure connecting clusters 1, 2, and 3 with the centroid is shown in the right panel of Figure 8.

Table II. General Characteristics of the Study subjects

(N = 144)

Classification		N (%)
Sex	Male	72 (50%)
	Female	72 (50%)
Age	5	16 (11.1%)
	6	16 (11.1%)
	7	16 (11.1%)
	8	16 (11.1%)
	9	16 (11.1%)
	10	16 (11.1%)
	11	16 (11.1%)
	12	16 (11.1%)
	13	16 (11.1%)
Grade	Kindergarten	32 (22.2%)
	Elementary school	96 (66.7%)
	Middle school	16 (11.1%)

N: Number of subjects (%)

Table III. Results of Correlation Analysis

	Name	Mean	Standard Deviation	Pearson Correlation	Sig	N
Length	Face length	96.26	8.34	0.751	0.000*	143
	Nose length	33.37	3.74	0.740	0.000*	143
	Subnasale - chin length	57.29	5.48	0.622	0.000*	143
	Menton length	21.88	4.57	0.67	0.438	143
Width	Face width	129.06	9.01	0.446	0.000*	143
	Nose width	33.02	2.72	0.609	0.000*	143
	Lip width	38.62	4.49	0.632	0.000*	143
	Gonion width	104.77	8.23	0.429	0.000*	143
	Face curvature width	171.09	17.55	0.410	0.000*	142
Arc	Bitragion - subnasale arc	169.93	17.61	0.325	0.000*	142
	Bitragion - pronasale arc	174.23	18.52	0.344	0.000*	142
Angle	Nose protrusion angle	85.86	6.77	-0.359	0.000*	143
	Alare - nasal root angle	53.23	5.54	-0.168	0.045*	143
	Gonion - nose root angle	63.77	4.47	-0.317	0.000*	143
	Nose root – pronasale - gonion	133.11	4.09	-0.83	0.325	138
	Gonion - subnasale angle	84.80	7.81	-0.278	0.001*	143

*significant at the 0.05 level (two-tailed)

Table IV. Independent t-test for Gender

	Name	Total Mean(SD)	Boy Mean(SD)	Girl Mean(SD)	p-value	N
Length	Face length	96.26(8.34)	97.60(8.31)	94.89(8.21)	0.0473*	143
	Nose length	33.38(3.74)	33.73(3.92)	33.03(3.55)	0.2656	143
	Subnasale-chin length	57.30(5.48)	58.11(5.53)	56.49(5.35)	0.0776	143
	Menton length	21.89(4.57)	21.41(4.36)	22.33(4.75)	0.2376	143
Width	Face width	129.06(9.01)	131.24(8.7)	126.91(8.8)	0.0037*	143
	Nose width	33.02(2.73)	33.46(2.91)	32.59(2.49)	0.0585	143
	Lip width	38.62(4.49)	39.07(4.10)	38.18(4.83)	0.2393	143
	Gonion width	104.78(8.23)	105.97(7.8)	103.60(8.4)	0.0853	143
	Face curvature width	171.09(17.6)	173.95(17.9)	168.32(16.9)	0.0556	142
Arc	Bitragion - subnasale arc	169.94(17.6)	172.48(17.6)	167.47(17.4)	0.0900	142
	Bitragion - pronasale arc	174.24(18.5)	177.35(18.5)	171.21(18.2)	0.0482*	142
Angle	Nose protrusion angle	85.86(6.78)	86.24(6.71)	85.48(6.87)	0.5059	143
	Alare - nasal root angle	53.23(5.54)	53.26(5.05)	53.21(6.02)	0.9582	143
	Gonion - nose root angle	63.78(4.48)	63.72(4.20)	63.83(4.76)	0.8829	143
	Nose root – pronasale- gonion angle	133.12(4.09)	133.43(4.4)	132.81(3.8)	0.3683	138
	Gonion - subnasale angle	84.80(7.81)	84.29(7.63)	85.31(8.01)	0.4382	143

*Significant at the 0.05 level

Table V shows the classification results of 137 anthropometric data points into three clusters by facial shape characteristics. Seven extreme values were excluded. Children in cluster group 1 had short face length and face width, a protruding nose, and the largest gonion angle; children in cluster group 2 had faces with predominantly larger anthropometric values for face length and width; and children in cluster group 3 had medium face sizes and the largest nose root – gnathion angle.

The three clusters from the cluster analysis were validated by ANOVA, and the items with high F values, including face curvature width, bitragion - subnasale arc, bitragion - pronasale arc, face length, and face width, explained the significant differences noted in the cluster classification variations. All items, excluding nose protrusion angle ($p = 0.075$), alare - nasale root angle ($p = 0.262$), gonion - nose root angle ($p = 0.018$), and nose root - pronasale - gonion angle ($p = 0.753$), differed significantly among clusters ($p < 0.01$), indicating that all items of length, width, and arc were clustered significantly differently and that there was no significant difference in the facial angle items of children among clusters, excluding the gonion - subnasale angle ($p = 0.000$). Facial shapes of children in clusters 1, 2, and 3 were classified as shown in the 3D image in Fig. 9. The distribution of ages within the three clusters is summarized in Table VI. As expected, a wide distribution of ages was observed within a cluster. Within clusters, however, we noticed a trend toward a higher frequency of the occurrence in certain ages, such as for ages 5 to 7 years in the small group, 8 to 10 years in the medium group, and 11 to 13 years in the large group, indicating that age was the predictive variable for classification of children's faces.

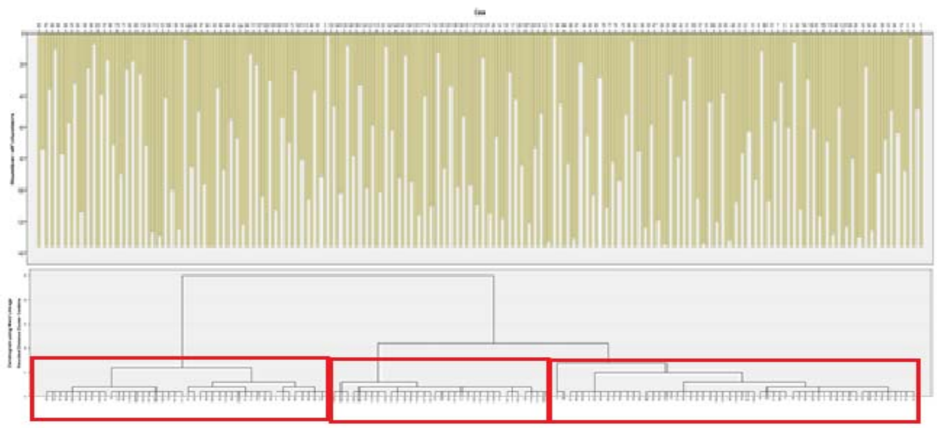


Figure 6. Dendrogram of the clusters combined showing three clusters.

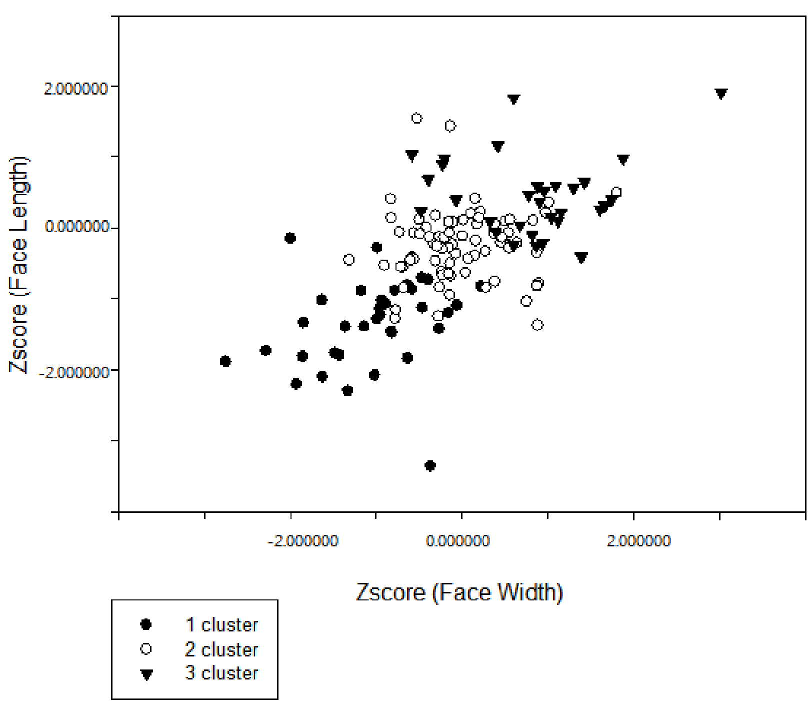


Figure 7. Plot of three clusters by Z scores.

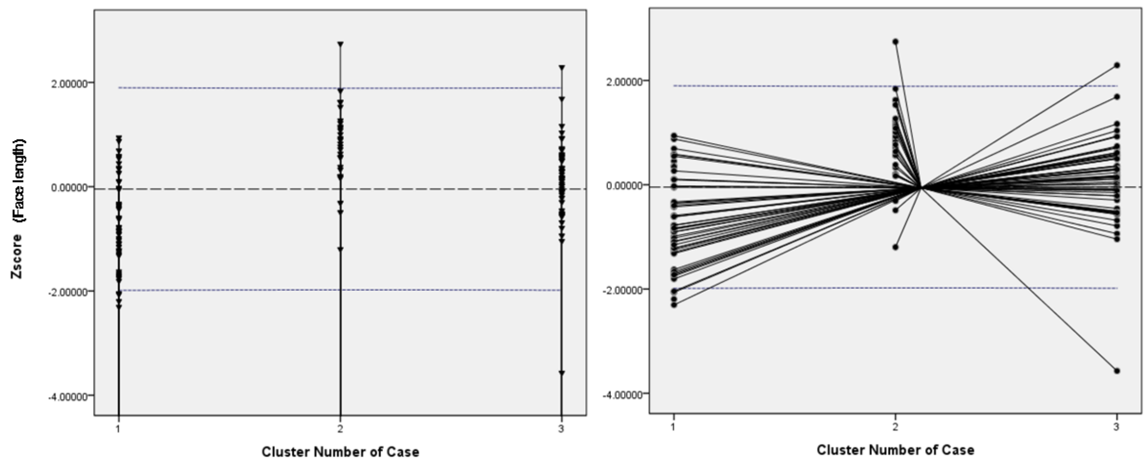


Figure 8. Plot of cluster number of cases by Z score.

Table V. Results of Clustering by Facial Anthropometry

Name	Cluster			F	Sig.
	1 (n = 49)	**2 (n = 28)**	**3 (n = 60)**		
Face length	-.70039	**.77120**	.10799	31.309	.000*
Nose length	-.59059	**.70793**	.06352	22.233	.000*
Subnasal - chin length	-.67409	**.40602**	.24063	20.789	.000*
Menton length	-.25647	.50457	-.01644	5.499	.005*
Face width	-.75918	**1.06917**	.13754	52.284	.000*
Nose width	-.51196	**.64809**	.06658	15.632	.000*
Lip width	-.54876	**.57232**	.07761	5.499	.005*
Gonion width	-.54381	**.92771**	-.04730	26.232	.000*
Face curvature width	-.98643	**1.35198**	.25825	212.149	.000*
Bitragion - subnasale arc	-.96743	**1.40201**	.22361	223.630	.000*
Bitragion - pronasale arc	-1.00701	**1.40280**	.25442	273.060	.000*
Nose protrusion angle	**.27746**	-.09348	-.14960	2.636	.075
Alare - nasal root angle	**.18185**	-.20505	-.00594	1.354	.262
Gonion - nose root angle	**30395**	-.25973	-.16454	4.150	.018
Nose root - pronasale - gnathion	-.04049	-.04121	**.08997**	.284	.753
Gonion - subnasale angle	**.53062**	-.61620	-.27879	19.166	.000*
Specific	Short face length and width, protruded nose, and the largest gonion angle	Long face length and width	Medium face sizes and the largest angle of nose root - gnathion		

*significant at the 0.01 level, ANOVA, F test

Table VI. Age Distributions within Cluster

N=137 (%)

Cluster	Age									Total
	5	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
Small	**14** **28.6**	**12** **24.5**	5 10.2	1 2.0	2 4.1	1 2.0	7 **14.3**	6 12.3	1 2.0	49
Medium	2 3.3	3 5.0	8 13.4	**12** **20.0**	**12** **20.0**	9 15.0	3 5.0	2 3.3	9 15.0	60
Large	0 0	0 0	2 7.1	3 10.8	2 7.1	**6** **21.4**	4 14.3	5 17.9	**6** **21.4**	28
Total	16	15	15	16	16	16	14	13	16	**137**

Bold letters represent higher frequency of occurrences within the cluster

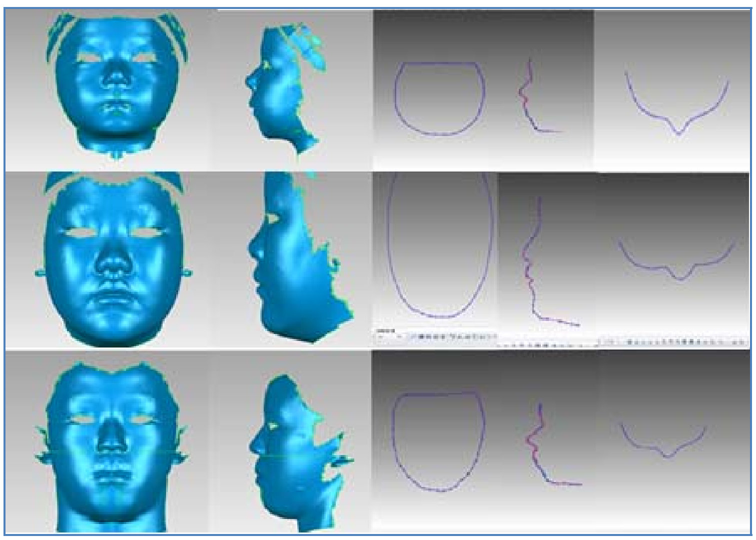


Figure 9. 3D Facial shapes of clusters 1, 2, and 3.

DISCUSSION

This study aimed to classify children's facial characteristics via anthropometric measurement of facial dimensions based on 3D imaging data. Although existing digital designs and assessment methods using 3D facial scanning data have been proposed (Gross et al., 1997; Han & Choi, 2003; Song & Yang, 2010), there is currently no objective standard for design or assessment standards.

Facial analyses of anthropometric data from adults using 3D methods are required to develop masks with an accurate fit or modeled contact areas of the face in three dimensions (Kim et al., 2003; Song & Yang, 2010). Luximon et al. (2010) reported that facial morphologies of Chinese adults were different from those of Americans, and that Chinese adult women had wider, shorter faces than did other Asians, including Koreans. Ballet al. (2010) measured and compared 3D facial anthropometric data of the face and head between Chinese and Caucasian individuals through the SizeChina Project, and recent studies not only measured anthropometric dimensions and analyzed images using 3D facial scanning data (Luximon et al., 2012; Zhuang et al., 2010a; Zhuang et al., 2010b) but also actively constructed models of adult facial morphologies from 3D images (Kim et al., 2013b; Lee et al., 2011a).

In contrast, few studies using 3D measurement or 3D analyses have targeted the faces of children. In a study investigating differences between age groups to design masks for delivering drugs to children (Amirav et al., 2014), the faces of 271 children ranging from 1 month to 4 years of age underwent 3D imaging, followed by facial image analyses that divided them into three cluster groups, including infants, toddlers, and children, and concluded that masks in small, medium, and large sizes were needed. Consistent with these findings, the present study also identified an increase in face length and width with age (Table III), and all items except for the nose root - pronasale - gonion angle and menton length showed significant differences with age.

Lee et al. (2011b) classified facial anthropometric dimensions and facial shapes through a review of published data from 3D facial studies for respirator designs and suggested that optimal designs for respirators and their evaluation could have significant effects on the development of various ergonomic products. It recently became possible to perform various detailed 3D analyses of the face comprising numerous pixels due to advancements in 3D imaging technologies and FEM-based analysis systems, but studies on children and the elderly are rarely performed. Since direct measurements can be difficult to obtain in elderly, disabled, and very young populations, 3D measurement devices are a desirable alternative since these can efficiently and safely obtain the desired measurements in a short period (Amirav et al., 2013; Weinberg & Kolar, 2005).

3D scanning devices refer to devices that read and digitize 3D images of objects for use in reverse engineering, mass-customization, character design, and reconstruction of remains and buildings and that can obtain highly precise measurements, in contrast to conventional direct measurement methods. Han et al. (2004) noted that the positions of each point and definition of landmarks could significantly affect measurement results and that the anthropometric measurement values of free curves, unlike linear distance, in independent facial morphologies differed greatly from directly measured values. In addition, advantages of 3D measurement include saving time for anthropometry and enabling the measurement of regions that are immeasurable using traditional direct measurement methods. However, hardware and software precision must be verified to acquire reliable and precise 3D data, for which a standardized 3D measurement method should be established (Lee et al., 2004).

One study (Ball et al., 2010) showed that head shapes and characteristics differed among individuals and races and tended to differ among individuals in the same race. Cho and Choi (1999) classified facial types of Korean men and women into round faces (Group A) and narrow and long faces (Group B) and claimed that overall facial morphology should be stated as the ratio between face length and width. The present study found that facial length and width items significantly affected the three cluster standards (Table V) that classified the facial shapes of children. After interpreting facial images, Kim et al. (2003) classified Korean faces into four shapes (flat round elliptic faces, long elliptic faces, round elliptic faces, flat chin and long elliptic faces) by measuring distances using coordinate values from the nose root to the gonion protrusion. The anatomical characteristics of Korean faces belong to a general facial type (Cho and Choi, 1999), and a study on differences in children’s facial morphologies by region found no statistically significant difference in facial items by sex or region (Kim et al., 1992). However, a study on anthropometric facial dimensions by age reported that facial imbalance increased with age (Kim & Lee, 2010), and a study on the faces of children reported that mandibular growth took longer than did growth for other parts of the head and that mandibular growth was irregular and unpredictable (Chang, 1997).

Jung and Whang (1999) reported a significant increase in facial length with age from 10–11 years to 12–13 years and 14–15 years, a finding that was consistent with increases in facial sizes with age in the present study. Similar to the results of the above study that reported that changes in facial growth and morphological characteristics occur with age in children, the anthropometric data that affected classification of the children's facial shapes in the present study were face length, face width, face curvature width, bitragion - subnasale arc, and bitragion - pronasale arc.

Clustering of children's anthropometric facial data using 3D imaging resulted in classification of children's faces into three clusters according to facial size, including small, medium, and large faces, of which morphological characteristics of the face in cluster 1 were small facial sizes with protruding noses and the largest gonion angle, while those of cluster 2 were large face lengths and widths. Cluster 3, which included medium facial sizes, had characteristics of the largest angle of nose root - gnathion.

The present study obtained 3D images and precisely measured various anthropometric dimensions of children in the growth period in detail using 3D scanning data, including not only lengths and widths but also angles and curvature lengths. Since no statistically significant sex differences were found, only age was used to classify subjects. Three clusters were constructed, and wide variations in age within all clusters were observed. However, within a cluster, further groupings using frequency occurrences by age (e.g. 5–7 years, 8–10 years, and 11–13 years) were processed for easy application of the clusters (Table VI). These data can serve as fundamental information for children's mask sizes using 3D anthropometric facial data in the future as well as baseline data for a 3D mask design with an optimal fit for children's faces.

CONCLUSIONS

To obtain fundamental data for children's respirator designs, anthropometric facial dimensions of children were measured and classified based on facial characteristics. The faces of 144 boys and girls aged 5–13 years were scanned with 3D imaging, the scanned data were converted to 3D image data using software, and then 16 face dimensions were measured. In addition, the anthropometric facial dimensions of the items were statistically analyzed (with correlation analysis, independent t-test, and K-means clustering) and divided into three clusters, as follows:

1. The 144 study subjects (72 boys, 72 girls) were 5–13 years of age, and there were 16 children per age (11.1%).
2. A correlation analysis between age and each of the 16 face dimensions revealed statistically significant differences ($p < 0.05$) in face length, face width, lip width, nose length, face curvature width, nose width, gonion width, subnasal-chin length, bitragion - subnasal arc, bitragion - pronasal arc, nose protrusion angle, alare - nasal root angle, gonion - nose root angle, and gonion - subnasal angle, whereas the nose root - pronasal - gonion angle ($p = 0.325$) and menton length ($p = 0.438$) were not correlated with age.
3. An independent t-test to examine differences by sex showed no statistically significant differences for the majority of facial dimensions, except for face length ($p = 0.0473$), face width ($p = 0.0037$), and bitragion - pronasal arc ($p = 0.0482$). Boys showed higher values than girls in these items, with differences of 2.71 mm for face length, 4.33 mm for face width, and 6.14 mm for the bitragion - pronasal arc.
4. Optimal cluster numbering for facial shape classification was determined in three clusters based on hierarchical clustering. Characteristics of each facial shape were classified by the k-mean clustering method, which resulted in cluster 1, which included children who had small face lengths and widths, nasal protrusion, and the largest gonion angle; cluster 2, which included children who had large face lengths and widths; and cluster 3, which included children who had medium facial sizes and the largest nose root - gnathion angle.
5. High F values of face curvature width, bitragion - subnasal arc, bitragion - pronasal arc, face length, and face width indicated that these items had a great impact on the classification of clusters, and all items except the nose protrusion angle ($p = 0.075$), alare - nasal root angle ($p =$

0.262), gonion - nose root angle (p = 0.018), and nose root - pronasal - gonion angle (p = 0.753) showed significant differences ($p < 0.01$) between clusters.

In conclusion, this study classified the faces of Korean children aged 5–13 years into three clusters. The 3D measurement method used in the present study is expected to be useful in settings in which traditional measurement methods cannot be readily applied. In addition, data related to face clusters and morphological characteristics of children gathered in the present study will be of value for designing respirators for children.

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