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Digital 3-D Headforms Representative of Chinese Workers

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Headforms are useful for designing and testing various types of personal protective equipment used to protect millions of workers from occupational hazards in China. Although the Chinese national standard of head-and-face dimensions for adults was first published in 1981, headforms based on those dimensions were never developed. In 2006, an anthropometric survey of 3000 Chinese civilian workers was conducted. As part of the survey, 350 subjects were scanned with a Cyberware 3D Rapid Digitizer. The manual measurements and 3-D digital scans from this survey were used to develop 3-D digital headforms that represent Chinese workers.

Objective: The objective of this study was to develop headforms that represent today's Chinese workers.

Methods: Ten facial dimensions relevant to respirator fit were chosen for defining a principal component analysis model which divides the user population into five face size categories. Mean facial dimensions from manual measurements were then computed to target the ideal facial dimensions for each size category. Five scans were chosen from each face size category to be used in the construction process. Selected scans were then averaged to construct a representative headform for each face size category.

Results: Five digital 3-D headforms were developed: small, medium, large, long/narrow, and short/wide. These distinct sizes of digital 3-D headforms take into account the linear distance between landmarks as well as the surface contours captured during the 3-D scan. The dimensions of constructed headforms were within ~4 mm between the corresponding computed means and manual measurements of anthropometric landmarks for the sample population in each size category.

Conclusions: These new headforms represent the facial size and shape distribution of current Chinese workers and may be useful for respirator research and development. The Chinese medium headform has a wider face width, shorter face length, and smaller nose protrusion when compared with the current U.S. standard headforms. Upon validation, it may be useful to incorporate these dimensions into Chinese and international respiratory protective devices standards.

Keywords: anthropometrics; facial dimensions; headforms; respirator; sizing

INTRODUCTION

China has the largest population in the world and millions of Chinese workers rely on personal protective equipment (PPE) such as respirators, helmets, and safety glasses to reduce the risk of injury and limit occupational exposure to hazardous agents. Prior to human subject testing, headforms are used to design and test PPE in order to determine its efficacy. The International Organization for Standardization (ISO) has developed >20 headform tests for

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respiratory protection and eye and face protection standards (ISO TC94 SC6 and SC15).

In China, the first head-and-face anthropometric survey was conducted in 1958 on 43,173 military personnel (She, 2002). Then, in the 1970s, measurements from 2458 civilians were added to the database (She, 2002). An additional survey of 9392 civilians was conducted in 1980 (CNIS, 1981). These three data sets were used to create the Chinese national standard of head-and-face dimensions for adults (CNIS, 1981) that was published in 1981. In this standard, 13 head sizes, based on 29 head-and-face dimensions, were defined for males and females separately (Xiao, 1994; Yu, 2002). In 1998, a new database of Chinese human body dimensions was established from 22,300 adults. The database included seven head-and-face dimensions: full-head length, sagital arc, bitragion coronal arc, head breadth, head length, head circumference, and face length (CNIS, 1998). Since only seven head-and-face dimensions were collected in the 1998 survey, a pilot study of 393 Chinese adults was conducted to measure 41 facial dimensions to create regression equations to predict 34 head-and-face dimensions from the 7 facial dimensions measured in the 1998 survey (CNIS, 1998). The 7 dimensions measured and the 34 dimensions calculated from the predicted regression equations were added to Chinese national standard of head-and-face dimensions for adults in 1998 (CNIS, 1998).

Currently, Chinese respirator certification standards follow the European standards, requiring total inward leakage tests on 10 subjects (CNIS, 2006). Chinese respirator manufacturers, however, design respirators according to Los Alamos National Laboratory fit test panels, which are based on data collected from an anthropometric survey of US Air Force personnel in the 1960s (Yang *et al.*, 2007). Zhuang *et al.* (2004) have demonstrated that anthropometric data collected from US military personnel in the 1960s is no longer reflective of the head-and-face anthropometric distribution of the current US work force. In addition, it has been reported that Chinese civilian adults have shorter face length and nose protrusion, and larger face width and lip length in comparison with the facial dimensions of US subjects (Zhuang and Bradtmiller, 2005; Du *et al.*, 2008). There is a pressing need to develop headforms that represent the current Chinese civilian workers.

Headforms are used for designing and testing various types of PPE that protect millions of workers from occupational hazards. Although the Chinese national standard of head-and-face dimensions for adults was first published in 1981, appropriate headforms were never developed. Rapid economic growth and the pattern of food intake over the last 30 years brought changes in the physical characteristics of the population. For example, the height of Chinese youths increased 2 cm every 10 years (Xie *et al.*, 2006). To accommodate these changes, a head-and-face anthropometric survey of 3000 civilian workers was conducted in 2006 in China.

The data from the 2006 survey of 3000 Chinese civilian workers were used to develop two new respirator fit test panels for half- and full-facepiece respirators (Du *et al.*, 2008; Chen *et al.*, 2009). The bivariate approach used face length and face width measurements that were weighted to match age and gender distributions of the Chinese population from the 2005 census. The principal component analysis (PCA) panel was developed using the first two principal components obtained from a set of 10 facial dimensions. Both panels accommodated >95% of the subjects who were surveyed. In addition to the traditional anthropometric data, 3-D scans of 350 subjects were also conducted during the survey. The 3-D scans could collect volumetric and contour data regarding head-and-face size and shape that are indeterminable from landmark coordinates.

Zhuang *et al.* (2010) developed digital 3-D headforms specific to the US workforce based on data from the survey of US workers (Zhuang and Bradtmiller, 2005). In that study, selected scans collected using the Cyberware Rapid 3-D ditigizer, based on the manual measurement survey, were then averaged together using Polyworks, to create 3-D headforms.

The primary objective of this study was to develop representative headforms for Chinese workers using traditional anthropometric survey data and the 3-D data collected with a 3-D head scanner using the same methodology developed by Zhuang *et al.* (2010). The secondary objective was to compare the newly developed Chinese headform series to the current Chinese standard headforms, the National Institute for Occupational Safety and Health (NIOSH) headforms, as well as headforms identified for use in testing in various PPE standards.

MATERIALS AND METHODS

Subjects

An anthropometric survey of Chinese civilian workers was conducted in 2006 (Du *et al.*, 2008). In that survey, a total of 3000 subjects (2026 males and 974 females) between the ages of 18 and 66 years old was measured using traditional techniques. A stratified sampling plan of three age strata (18–29, 30–44, 45–66) and two gender strata was implemented. In order to obtain a representative sample, subjects were measured in five geographical regions in China: north, south, central, east, and west.

Traditional manual measurements

Anthropometric measurements were collected using a Lufkin steel measuring tape (Cooper Tools, Apex, NC, USA), a spreading caliper, a sliding caliper (GPM Instruments, Zurich, Switzerland), and a pupilometer. Measurements were made according to methods described by Zhuang and Bradtmiller (2005) and the 'China national standard basic human body measurements for technological design' (CNIS, 1999). Technicians were trained before conducting the study and practiced with each other until their measurement errors were less than allowable errors, e.g. the difference of two measurements <5 mm (Gordon *et al.*, 1989). Before data collection began, a 6-mm diameter sticker was placed on each landmark. Each dimension is a straight line linear distance measured between two landmarks. Custom computer software was used to ensure that values collected were within the expected range of a given dimension, and if values fell outside of this range, the measurements were repeated. Measurements and the quality control methods have been described previously (Du *et al.*, 2008). Ten dimensions directly related to respirator fit were selected to develop new headforms. These 10 dimensions are shown in Fig. 1.

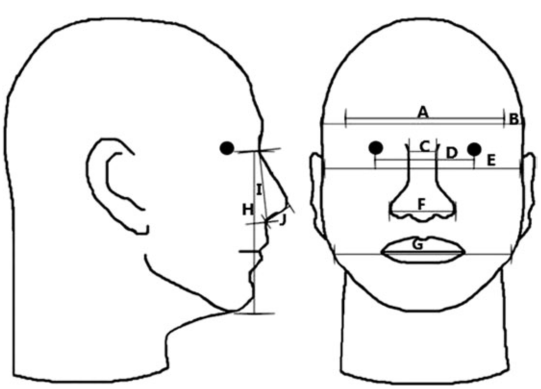

Fig. 1. Facial characteristics are determined by measuring the linear distance between specific landmarks. The frontal view indicates the width measurements, from top to bottom: (A) minimal frontal breadth (right and left frontotemporale), (B) head breadth (maximum width found level above the ears), (C) nasal root breadth (width of the nose level with the sellion), (D) interpupillary breadth (right and left pupil), (E) face width (right and left zygomatic arch), (F) nose breadth (right and left alare), and (G) bigonial breadth (right and left gonion). The side view indicates nasal measurements and face length from left to right: (H) face length (menton to sellion), (I) nose length (subnasale to sellion), and (J) nose protrusion (pronasale to subnasale).

Three-dimensional scanning

During the 2006 survey of Chinese workers, 350 of the 3000 subjects were also scanned. A Cyberware rapid 3-D digitizer (Monterey, CA, USA), with its associated computer and data processing software, was used to collect 3-D facial surface data from subjects within three age strata and two gender strata. The subject was asked to sit calmly prior to the scan. Then, technicians used stickers to indicate all landmark locations when the subject looked straight ahead, holding his/her teeth slightly occluded. During each scan, a Class I laser beam was projected onto the subject's head and face for 360°. Each scan lasted for ~45 s and subjects were asked to maintain a stable posture at all time. To ensure scan data were accurate, the head scanner was calibrated every 2 weeks. Polyworks version 10.1.6 (InnovMETRIC™, Québec, QC, Canada) was used to process and measure the images.

Selection of digital scans for construction of headforms

Constructing headforms from 3-D scan data is more advantageous than solely using linear distance values between landmarks acquired from traditional anthropometric techniques. The 1-D data is void of information regarding the contours of the surface between those two landmarks, whereas a scan provides the distance and the surface between the points. Traditional landmark data were used to set the target facial features of the headforms and scan data that most closely matched those target values were selected to be averaged to get digital 3-D headforms.

PCA is a technique for defining a new coordinate system based on a linear combination of original variables. The Chinese PCA respirator fit test panel was based on a correlation matrix of the 10 dimensions relevant to respirator fit (Chen *et al.*, 2009) and can predict other dimensions which were not included (Zhuang *et al.*, 2007). The first (PC1) and second (PC2) principal components were used to select head-and-face dimensions. The overall size of the face is determined from PC1, while PC2 accounts for the overall length of the face and the shape of the nose. Small PC1 values are indicative of an individual with small facial features, whereas small PC2 values indicate shorter faces with broader noses. Individuals with small heads fall into Cell 1, medium heads in cells 2, 4, 5, and 7, large heads in Cell 8, long/narrow heads in Cell 6, and short/wide heads in Cell 3 (Fig. 2). The value of each principal component was calculated as follows:

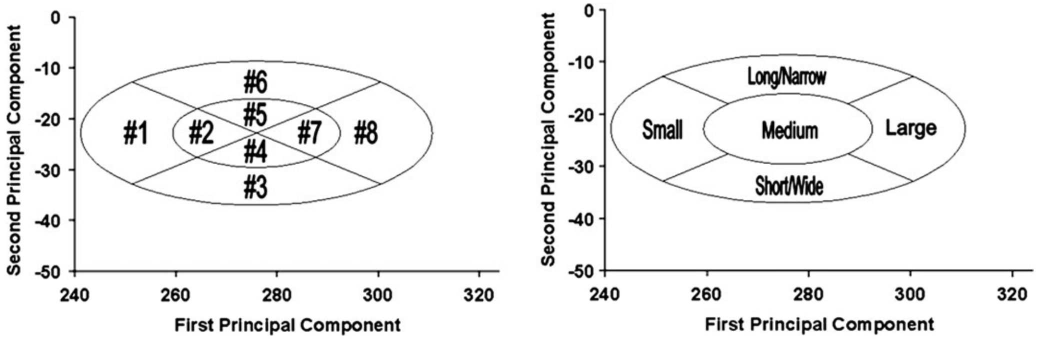

Fig. 2. The Chinese PCA respirator fit test panel (left) and the five face size categories (right).

$$\begin{aligned} PC1 = {} & 0.322260(\text{minimum frontal breadth}) \\ & + 0.422051(\text{face width}) + 0.328562(\text{bigonial breadth}) \\ & + 0.244826(\text{face length}) + 0.370307(\text{interpupillary distance}) \\ & + 0.373045(\text{head breadth}) + 0.237882(\text{nose protrusion}) \\ & + 0.321181(\text{nose breadth}) + 0.159204(\text{nasal root breadth}) \\ & + 0.297905(\text{nose length}) \end{aligned} \quad (1)$$

$$\begin{aligned} PC2 = {} & -0.388836(\text{minimum frontal breadth}) \\ & - 0.140757(\text{face width}) - 0.227790(\text{bigonial breadth}) \\ & + 0.568632(\text{face length}) - 0.159748(\text{interpupillary distance}) \\ & - 0.132683(\text{head breadth}) + 0.308739(\text{nose protrusion}) \\ & - 0.079405(\text{nose breadth}) - 0.173192(\text{nasal root breadth}) \\ & + 0.528574(\text{nose length}) \end{aligned} \quad (2)$$

The scores for PC1 and PC2 were calculated for all 3000 subjects. For each size category except the medium size, the arithmetic mean values for the 10 facial dimensions were calculated based on both subjects whose PC1 and PC2 scores fell in the category and outside the PCA panel and adjacent to each corresponding category. A breakdown of subjects by face size category is provided in Table 1. The medium size category has ~50% of the population, while each of the other four categories has ~11 and 12% of the population.

The individual PC1 and PC2 values calculated with the 10 measurements acquired from the digital 3-D scan with Polyworks were sometimes different from the PC1 and PC2 vales determined from the 10 traditional measurements. The PC1 and PC2 coordinates based on computer measurement are mainly distributed in the large and short/wide face size categories. The differences between these two measurement methods may be due to facial tissue characteristics of the human being. During a manual measurement, the facial tissue is pliable and can deform when the technician holds spreading or sliding calipers on the landmarks. The depression of facial

Table 1. Subject distribution by face size category

Face size	*n*	Percentage of population		
		Male (%)	Female (%)	Total (%)
Small	241	1.7	22.6	12.2
Medium	1479	46.5	53.5	50.0
Large	463	23.3	0.5	11.8
Long/narrow	372	16.5	6.6	11.5
Short/wide	327	7.1	14.9	11.0
Outliers	118			3.5

skin during manual measurements of bigonial breadth resulted in manual measurements smaller than the measurement taken with Polyworks. On the other hand, the landmarks for head breadth and face width are located beneath hair and sideburns. Polyworks measures the distance from surface to surface, in other words the top of the hair, whereas calipers can slide under the hair and be placed directly on the bony landmarks. The manual measurements for these dimensions are consistently smaller in comparison to those values measured with Polyworks. Regression equations were generated to correct the differences between measurements collected with Polyworks and those collected using traditional anthropometric techniques (Table 2). New PC1 and PC2 scores were calculated using the predicted manual measurement values for head breadth, face width, and bigonial breadth, as well as the remaining seven dimensions collected with Polyworks (Fig. 3). Only three equations were chosen to calculate corrected values based on relatively large values for these three dimensions and the large coefficients for these three dimensions in the equations (1) and (2). *P*-value also needs to be <0.05.

In this study, the 3-D scans of 5 subjects whose facial dimensions from computer measurement (3 of 10 were corrected, i.e. predicted manual measurement) most closely matched the 10 calculated

Table 2. Regression equations to predict manual measurements from computer measured dimensions

Dimension	Equation	R^2	P-value
Minimal frontal breadth	$Y = 0.716X + 28.96$	0.671	<0.001
Face width	$Y = 0.722X + 40.70$	0.735	<0.001
Bigonial breadth	$Y = 0.541X + 45.80$	0.499	<0.001
Face length	$Y = 0.751X + 28.59$	0.777	<0.001
Interpupillary distance	$Y = 0.483X + 28.95$	0.537	<0.001
Head breadth	$Y = 0.677X + 47.08$	0.713	<0.001
Nose protrusion	$Y = 0.544X + 8.24$	0.256	<0.001
Nose breadth	$Y = 0.773X + 6.97$	0.630	<0.001
Nasal root breadth	$Y = 0.399X + 10.07$	0.279	<0.001
Nose length	$Y = 0.683X + 14.28$	0.656	<0.001

Y = predicted manual measurement, X = dimension measured with Polyworks, and $n = 145$ which is different from 350 because some subjects had missing demographic data and poor scan data and were not used in this analysis.

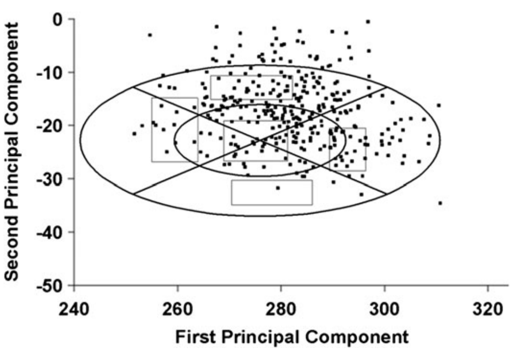

Fig. 3. Scanned subject distribution of PC1 and PC2 calculations based on the seven Polyworks dimensions and regression values for head breadth, face width, and bigonial breadth.

mean values of the manual measurements were then selected to develop new headforms for each face size category. The five subjects for each size category with the exception of short/wide category had calculated PC1 and PC2 values based on the computer Polyworks and corrected measurements within 1 SD of the calculated mean PC1 and PC2 values based on the traditional manual measurements. The five subjects selected from each size category were shown in Fig. 4. Table 3 provides the Polyworks measurements for each subject.

Scan data processing

Once 3-D scans of interest were selected, Polyworks was used to review and process the 3-D scans. The next step was to align each scan using the Frankfurt plane and a vertical plane which was formed from three midpoints of the right and left landmarks: tragion, zygomatic arch, and ectocanthus. Once five scans were in proper alignment, they were averaged together into a single digital headform.

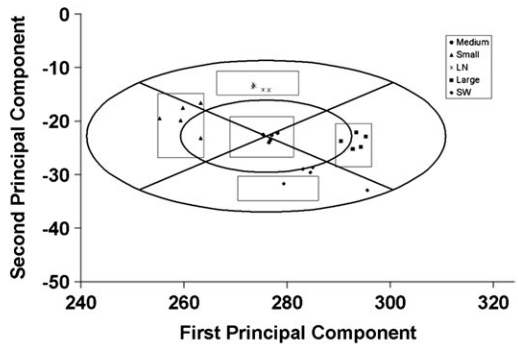

Fig. 4. The distribution of PC1 and PC2 values calculated with Polyworks and regression values for head breadth, face width, and bigonial breadth for the subjects selected for the creation of the five headforms. The boxes represent 1 SD above and below the computed means of the traditional measurements.

Averaging multiple scans together sometimes leads to an incomplete surface. For example, some areas of the mouth, nose, and eye are missing. On the other hand, averaging the forehead, cheeks, and chin areas leads to smooth surface. Therefore, the initial average of medium scans resulted in a surface with the eye region requiring a simple patching procedure. However, the resultant average had three lips and the lips needed to be analyzed independently. The five lips from the five subjects were aligned with each other to obtain an average of just that region. The new lip was then patched onto the average medium headform. When necessary, similar aligning procedures were used for other facial features such as the nose and each eye. Because the selected 3-D scans usually had hair and a wig cap, the scalps of bold subjects were used to create contours representative of an actual human head. Scalps with head length and head breadth that matched the target calculated mean values were used to replace the averaged scalps. The ears of the scanned subjects were usually noisy and had missing information. So surfaces for the ears obtained from Direct Dimensions Inc. (Owings Mill, MD, USA) were used. The ears do not represent the size and shape of the Chinese workforce. After completing all individual features, remaining holes were patched. In addition, a neck with the appropriate neck circumference was added on the headform following the contour of the average nape of the neck. Once the entire headform was developed, it was further duplicated and mirrored to obtain a symmetric average of the headform. A 5-mm hole at the center of the mouth was added to complete each headform. Figure 5 shows the original

Table 3. Polyworks measurements in millimeter of all subjects chosen for the averaging procedure

	Subject	Minimal frontal breadth	Face width[a]	Bigonial breadth[a]	Face length	Interpupillary breadth	Head breadth[a]	Nose protrusion	Nose breadth	Nasal root breadth	Nose length
Small	1	98	134	108	107	61	146	18	35	17	47
	2	104	125	119	106	61	151	18	38	15	48
	3	104	133	104	113	64	145	17	37	19	50
	4	86	134	111	104	60	151	15	33	16	46
	5	102	136	101	110	62	147	17	34	15	49
Medium	1	105	142	122	111	61	155	20	39	19	50
	2	110	144	112	115	62	158	17	37	19	50
	3	101	142	125	112	60	153	18	38	20	51
	4	106	142	121	116	69	152	19	34	19	51
	5	99	140	128	111	66	155	15	42	15	49
Large	1	118	149	126	123	70	160	17	39	18	52
	2	102	149	138	119	66	163	21	37	17	50
	3	117	151	117	120	73	166	17	39	18	55
	4	111	150	115	119	75	164	20	43	22	54
	5	106	153	134	124	72	161	18	39	18	52
Long/narrow	1	101	134	119	121	66	153	17	38	15	53
	2	96	139	123	117	63	152	18	41	18	55
	3	109	139	108	127	66	148	16	36	18	51
	4	98	143	114	119	65	154	17	40	21	53
	5	108	138	107	121	68	145	21	42	17	51
Short/wide	1	112	148	133	117	69	151	15	35	16	49
	2	111	152	125	115	65	157	15	37	20	48
	3	113	149	136	115	72	164	19	43	19	48
	4	111	147	138	114	61	150	18	38	17	48
	5	110	142	133	111	63	154	16	36	19	46

[a]The dimensions corrected for hair and tissue pliability. The equations used for this correction are found in Table 2.

Fig. 5. Images of the scans for subjects chosen to construct the medium headform.

scans of the subjects chosen to create the medium headform. The remaining steps used to complete the digital model are illustrated in Fig. 6.

RESULTS

The five finished digital 3-D headforms representative of the Chinese workforce are shown in Fig. 7. These headforms represent the five face size categories: small, medium, large, long/narrow, and short/wide. The mean and standard deviation (SD) of 3000 subjects for the 10 dimensions from traditional manual measurements are summarized for each face size category in Table 4. The mean and SD of the same 10 dimensions from 5 independent measurements of the finished digital headforms using Polyworks are also shown in Table 4. All 10 dimensions of the constructed headforms except for short/wide are within 4 mm of the target computed means for the 3000 subjects with manual

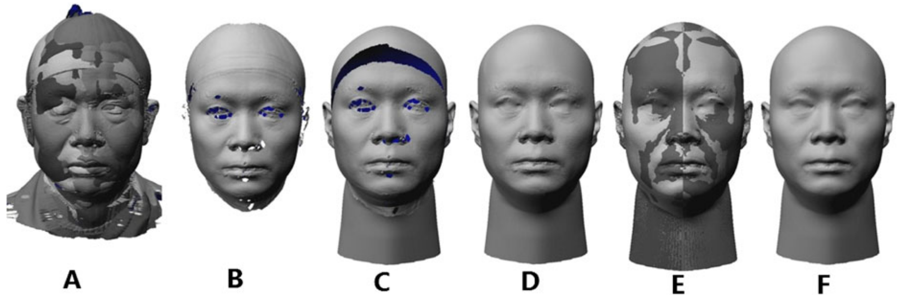

Fig. 6. The intermediate steps from the point of the initial average of the scans to the completed headform with ears, neck, and smooth scalp: (A) alignment of all headforms using a symmetry plane and the Frankfurt plane, (B) initial headform after the averaging, (C) patching of the eyes and smoothing of the lips, (D) removal of the original average of the lips with the new average lips in the desired location, (E) alignment of the smooth headform with the mirror of itself, and (F) final average headform with ears and neck attached.

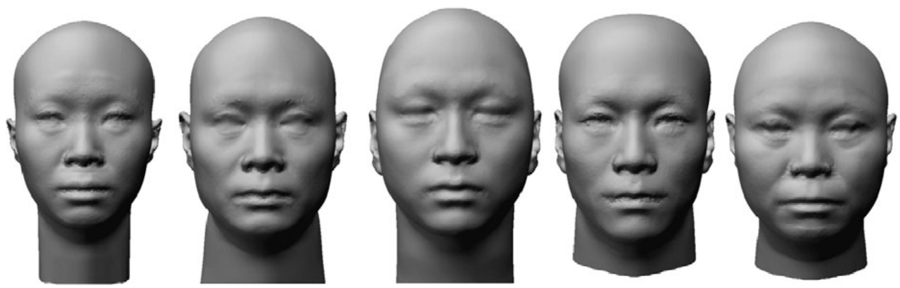

Fig. 7. Five digital 3-D headforms representing the five face size categories for the Chinese workers: small, medium, large, long/narrow, and short/wide, from left to right.

measurements in each size category. This may be due to only one scan in the box within 1 SD of the target computed mean of the traditional manual measurements and limited number of scans available near the box for short/wide faces (Fig. 3). Figures 8 and 9 show the distribution of the Chinese series of headforms in the Chinese PCA panel and the Chinese bivariate panel.

Facial dimensions measured from 3-D headforms of this study, mean facial dimensions of Chinese national standard in 1998, two existing U.S. standard headforms, and the newly developed NIOSH headforms representative of US workers are provided in Table 5. In comparison with facial dimensions of China National Institute of Standardization of 1998, the minimum frontal breadth of this study is smaller and face width and interpupillary distance are larger. The differences in other facial dimensions between this study and the 1998 Chinese standard are within 2 mm. When compared with the existing U.S. standard headforms, this study showed that Chinese people have wider face widths or minimum frontal breadth, shorter face lengths, and smaller nose protrusions. NIOSH medium headform and Alderson 50th percentile headform fall within cell #7 of the Chinese bivariate panel which represents individuals with medium-sized faces. The Sierra headform and the headform developed by the National Operating Committee on Standards for Athletic Equipment (NOCASE, 2007) are located in cell #9 of the Chinese bivariate panel (long/narrow). The Chinese medium headform has a wider and shorter face than NIOSH medium headform.

DISCUSSION

During the new headform construction, differences were found between manual and computer measurement techniques for certain facial dimensions: head breadth, face width, and bigonial breadth as observed by Zhuang *et al.* (2010). Facial skin tissue is pliable and liable to deform during manual measurements. Traditional anthropometric measurements are usually taken while the skin in landmark locations is pressed. For example, bigonial breadth is the linear distance between the right and left gonion. The pressure from the caliper exerted by the measurer on the gonion during the measurement may result in a distance less than those measured on the computer by up to $\geq$6 mm (Du *et al.*, 2008). The linear

Table 4. Summary of the computed mean (AVE) and SD for the manual measurements of 3000 subjects, and the mean (3-D) and SD from 5 independent measurements of the constructed headforms using Polyworks. All values are listed in millimeters

Dimensions	Face size category																			
	Large				Medium				Small				Long/narrow				Short/wide			
	Traditional		Computer		Traditional		Computer		Traditional		Computer		Traditional		Computer		Traditional		Computer	
	Average	SD	3-D	SD	Average	SD	3-D	SD	Average	SD	3-D	SD	Average	SD	3-D	SD	Average	SD	3-D	SD
Minimal frontal breadth	113	3.6	115	0.6	107	4.5	106	1.5	102	5.6	99	0.6	103	4.3	105	2.1	113	4.4	113	3.0
Face width	152	3.3	156	0.4	143	4.7	146	0.4	135	4.6	137	0.2	143	4.6	144	2.9	145	5.4	151	0.2
Bigonial breadth	127	6.5	128	1.0	116	7.1	116	2.3	107	7.9	106	3.1	111	6.4	114	2.9	122	7.7	123	0.9
Face length	119	4.7	122	1.2	113	5.1	114	1.6	108	6.0	108	0.6	122	5.1	120	1.3	107	4.1	112	1.1
Interpupillary distance	66	2.5	68	1.1	62	2.7	61	0.7	59	2.9	60	0.3	62	2.9	62	1.4	63	3.0	65	1.2
Head breadth	162	4.3	158	0.7	153	5.2	150	0.5	145	5.1	144	0.2	153	5.6	152	0.9	156	5.8	157	1.0
Nose protrusion	20	1.9	18	0.3	18	2	19	0.9	17	2.2	17	0.3	19	2.1	18	0.8	18	2.1	16	0.9
Nose breadth	41	2.6	39	0.3	37	2.8	39	0.3	35	2.6	36	0.4	38	2.5	39	0.2	38	2.9	37	0.2
Nasal root breadth	19	2.2	19	0.6	18	2.2	18	0.9	17	2.2	19	0.8	17	1.7	19	1.4	18	2.3	21	0.3
Nose length	53	2.6	54	1.2	49	2.8	51	0.5	46	3.6	49	0.5	52	2.8	53	0.8	46	3.1	47	0.9

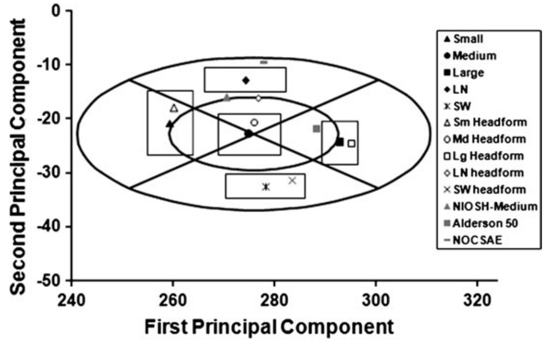

Fig. 8. The distribution of the newly constructed headforms (e.g. large headform) and computed mean of the traditional manual measurements (e.g. large) in the Chinese PCA panel.

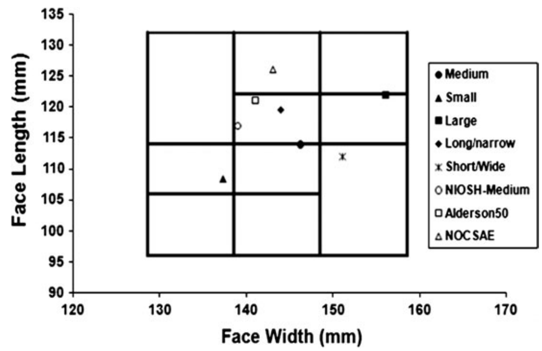

Fig. 9. The distribution of the newly constructed headforms and US standard headforms in the Chinese bivariate panel.

measurement from scans of the subjects using Polyworks may provide a more accurate measurement of the bigonial breadth because Polyworks views the face as a solid surface and there is no depression. On the other hand, the traditional measurement technique is better for some dimensions such as the head breadth which is a measure across the largest width of the head above the ears. Measurement of the head breadth using traditional technique is more accurate because the spreading caliper can be placed under the hair to reach the scalp. When subjects are scanned without a wig cap, the scans usually have missing data on the top and in the back of the head. Subjects were asked to wear a nylon wig cap to prevent such a dramatic loss of data. The surface of the top and back of the head was enlarged and did not represent the real curvature of the scalp. The head breadth measurement using Polyworks was larger than actual value from manual measurement because hair captured under the nylon cap is added to the head breadth dimension. To resolve these problems, regression equations were established to predict manual measurement from computer measurement.

Table 5. Facial dimensions (millimeter) of different scanned headforms measured with Polyworks

Variables	This study medium	1998 Chinese standard	NIOSH medium	Alderson 50	NOCSAE
Minimum frontal breadth	106	114	103	112	103
Face width	146	141	139	141	143
Bigonial breadth	116	115	113	125	117
Face length	114	114	117	121	126
Interpupillary distance	62	59	63	69	61
Head breadth	152	152	150	161	152
Nose protrusion	18	18	20	19	22
Nose breadth	39	36	34	38	35
Nasal root breadth	19	—	18	22	18
Nose length	51	50	51	54	55

Moderate relationships with R^2 values >0.499 and with $P < 0.001$ were found between the manual and computer measurements (Table 2). The corrected computer values based on regression equations, for head breadth, face width, and bigonial breadth, were used in the selection of scans for the development of the new headforms.

When compared with facial dimensions of China National Institute of Standardization of 1998, the minimum frontal breadth of this study is smaller and face width and interpupillary distance are larger than those in the standard. These differences might have been due to different measuring techniques used in the 1998 and current studies. Face length and head breadth are very close to the reported results in the Chinese standard, which were obtained from direct measurement. The other facial dimensions of Chinese Standard listed in Table 5 were calculated using regression equations which were obtained from facial measurements of 393 adults. The small number of people measured may have affected the accuracy of the regression equations.

The medium headform of this study has a wider face width, shorter face length, and smaller nose protrusion when compared with current US standard headforms or NIOSH medium headform. The Alderson 50th percentile male headform, used by the American National Standards Institute for occupational and educational eye and face protective devices (ANSI, 2003), was based on Health Education and Welfare data collected in the 1960s (First Technology Innovative Solutions, Plymouth, MI, USA). The National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform was created from anthropometric measurements of US army aviators published in 1971 (NOCSAE DOC [ND] 001-06m07, 2007). Therefore, one possible reason for this difference between Chinese headforms and US headforms is that face-and-head dimensions of Asian people are different from those of Americans. The other reason is that our facial dimension data included ~32% women and the four standard US headforms were developed from anthropometric survey data collected between the 1950s and the 1970s and dominated by Caucasian males.

Another recent survey (SizeChina) was conducted to collect 3-D data for >2000 subjects to characterize the shape of the Chinese head (Ball and Molenbroek, 2008). Using SizeChina digital data and another recent 3-D anthropometric survey data (CAESAR; Robinette *et al.*, 2002), Ball *et al.* (2010) applied geometric morphometrics to the 3-D data to quantify and characterize the shape differences. Significant differences between head shapes of Chinese and Caucasians were found in that study. That study also characterized the Chinese heads as generally rounder than their Caucasian counterparts, with a flatter back and forehead. The authors concluded that using Western anthropometric data to design head-related products such as helmet may not fit the Chinese head well. This finding is similar to the findings reported in this study.

The approach to developing headforms in this study is not the only approach. One alternative is to select scan subjects from the periphery of the ellipse of the PCA panel to develop headforms. These proposed headforms may collectively accommodate the percentage of the population that is enclosed between them. However, if only one individual scan is used to develop a headform, it has very little representation. The first version of the NIOSH medium headform was developed using one subject near the center of the PCA panel, but standard developers and users rejected it. If multiple scans were to be used, the current scan data do not have so many subjects to be averaged. New 3-D data need to be collected.

CONCLUSIONS

Five digital 3-D Chinese headforms were developed using anthropometric data from 3000 Chinese civilian workers and head scans for 350 of them gathered during the 2006 survey. The headforms take into account the linear distances between landmarks and the surface contours captured during the 3-D scan. They represent the face size and shape distribution of current Chinese workers and may be useful for respirator research and development. The outcomes showed that the Chinese medium headform has wider face width, shorter face length, and smaller nose protrusion when compared with the NIOSH medium headform and other current US standard headforms. Upon validation, it may be useful to incorporate these headforms and their dimensions into Chinese and international respiratory protective devices standards.

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REFERENCES

American National Standards Institute. (2003) ANSI Z87. 1–2003. American national standard for occupational and educational personal eye and face protection devices.

ANSI. (2003) ANSI Z87.1–2003. American National Standard for Occupational and educational personal eye and face protection devices. New York: American National Standards Institute, Inc.

Ball RM, Molenbroek JFM. (2008) Measuring Chinese heads and faces. Proceedings of the 9th International Congress of Physiological Anthropology, Human diversity: Design for life. Delft, the Netherlands, pp. 150–5.

Ball R, Shu C, Xi P *et al*. (2010) A comparison between Chinese and Caucasian head shapes. Appl Ergon; 41: 832–9.

Chen W, Zhuang Z, Benson S *et al*. (2009) New respirator fit test panels representing the current Chinese civilian workforce. Ann Occup Hyg; 53: 297–305.

CNIS. (1981) CNIS GB2428–81. Head styles of adults. Beijing, China: General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China.

CNIS. (1998) CNIS GB/T2428:1998. Head-face dimensions of adults. Beijing, China: General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China.

CNIS. (1999) CNIS GB/T5703–1999. China national standard basic human body measurements for technological design. Beijing, China: General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China.

CNIS. (2006) CNIS GB2626–2006. Respiratory protective equipment-non-powered air-purifying particle respirator. Beijing, China: General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China.

Du L, Zhuang Z, Guan H *et al*. (2008) Head-and-face anthropometric survey of Chinese workers. Ann Occup Hyg; 52: 773–82.

Gordon CC, Bradtmiller B, Clauser CC *et al*. (1987–1988) (1989) Anthropometric survey of U.S. army personnel: methods and summary statistics (TR-89-044). Natick, MA: US Army Natick Research, Development and Engineering Center.

NOCSAE. (2007) NOCSAE DOC (ND) 001–06m07. Standard drop test method and equipment used in evaluating the performance characteristics of protective headgear. Overland Park, KS: National Operating Committee on Standards for Athletic Equipment.

Robinette K, Blackwell S, Daanen H *et al*. (2002) Civilian American and European Surface Anthropometry Resource (CAESAR), Final Report, Volume I: Summary, AFRL-HE-WP-TR-2002-0169, Air Force Research Laboratory, Human Effectiveness Directorate, Bioscience and Protection Division, Wright-Patterson AFB, Ohio.

She QY. (2002) Practice book of knowledge and standard of individual protect equipment. Hubei Press of Science and Technology. pp. 14–16.

Xiao H. (1994) Head-face dimensions of Chinese adults and its application in protective equipments. Chin Labor Protective Equip; 1: 16–29.

Xie Z, Zeng X, Chen X *et al*. (2006) The comparison of student's growth and development in Quanzhou City from 1982 to 2002. Chin J Health Students; 27: 66–7.

Yang L, Shen HG, Wu G. (2007) Racial differences in respirator fit testing: a pilot study of whether American fit panels are representative of Chinese faces. Ann Occup Hyg; 4: 415–21.

Zhuang Z, Guan J, Hsiao H *et al*. (2004) Evaluating the representativeness of the LANL respirator fit test panels for the current U.S. civilian workers. J Int Soc Resp Protect; 21: 83–93.

Zhuang Z, Bradtmiller B. (2005) Head-and-face anthropometrics survey of U.S. respirator users. J Occup Environ Hyg; 2: 567–76.

Zhuang Z, Bradtmiller B, Shaffer R. (2007) New respirator fit test panels representing the current U.S. civilian work force. J Occup Environ Hyg; 4: 647–59.

Zhuang Z, Benson S, Viscusi D. (2010) Digital 3-D headforms with facial features representative of the current U.S. work force. Ergonomics; 53: 661–71.