

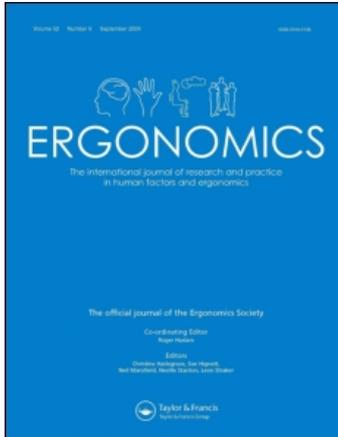
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Digital 3-D headforms with facial features representative of the current US workforce

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Existing headforms are based on anthropometric data collected over 30 years ago. In 2003, the National Institute for Occupational Safety and Health conducted an anthropometric survey of 3997 respirator users, of which 1013 subjects were scanned with a Cyberware 3-D Rapid Digitizer. The objective of this study was to create headforms representative of the current US workforce. 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 were then computed to target the ideal facial dimensions for each size category. Five scans in each category were chosen and averaged to construct a representative headform for each size category. Five digital 3-D headforms were developed: small, medium, large, long/narrow and short/wide. All dimensions are within 3 mm of the computed means for the sample population in each size category.

Statement of Relevance: This manuscript describes a new approach to constructing headforms that takes into account the facial form (size and shape) of the US workforce. These headforms could be incorporated into respirator research, certification standards and design in efforts to reduce the risk of injury or illness caused by inhalation hazards.

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

1. Introduction

Standard headform specifications exist globally and are used to test the efficacy of various types of personal protective equipment (PPE). However, specific designs vary depending on the PPE being tested as well as the country where the analyses take place. Two international standards have been drafted: ISO/R1511:1970 and ISO/DIS 6220:1983. 'Both of these documents were based upon the British Standard, BS 1869:1960, which itself was developed from the first set of test headforms produced by the UK Transport Road Research Laboratory in the 1950s' (British Standards Institution 2006). Neither draft was implemented as an international standard; nonetheless, many countries follow the guidelines presented in ISO/DIS 6220:1983, including Australia and Canada for helmet tests (Office of the Federal Register 1998). For headforms that require facial features, Canada follows CSA Z262.6–02, which was developed from data collected in '... studies undertaken by members of the Hospital for Sick Kids in Toronto, Ontario, and the School of Dentistry at the University of Toronto' (Canadian Standards Association 2002). In Great Britain, BS EN 960:2006, specifies headform sizes for testing protective helmets (British Standards Institution 2006). When

testing optical equipment, the standard headform has facial features and is based on the 50th percentile male headform developed by the UK Health and Safety Executive (European Committee for Standardization 1995a), which is the same standard headform used when testing equipment for eye and face protection for use during welding (European Committee for Standardization 1995b). Most European countries use standard headforms specified in EN 960:2006, a standard developed by correcting errors associated with ISO/DIS 6220:1983 draft. Internationally, 18 headform tests are required in eye and face protection standards being developed by ISO TC94/SC6.

In the US, consistency in headform construction between certification bodies has yet to be established. The headform specified by the American Society for Testing Materials for testing protective headgear and the headform specified by the American National Standards Institute for industrial head protection follow the ISO/DIS 6220:1983 draft (American National Standards Institute 1997, American Society for Testing Materials 2002). The National Operating Committee on Standards for Athletic Equipment uses headforms created from anthropometric

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measurements of army aviators published in 1971 (National Operating Committee on Standards for Athletic Equipment 2007). Crash test dummies used for testing automotive protection devices, follow the Federal Motor Vehicle Safety Standard No. 208, Occupant Crash Protection, which was published in 1972 and no substantial changes have been implemented since (Guizzo 2007). Recently, the Facial and Ocular Countermeasure Safety headform was designed to test the protective properties of helmets and goggles and is based on the 50th percentile male soldier from the Tri-Service US Army anthropometric study (Brozoski *et al.* 2008). Anthropometric data from the Tri-Service study were derived from multiple regression equations calculated from a 1967 survey of Air Force males (US Army Aeromedical Research Laboratory 1988). The Alderson 50th percentile male headform, used by the occupational and educational eye and face protective devices standard (American National Standards Institute 2003), is based on Health Education and Welfare data collected in the 1960s (First Technology Innovative Solutions, Plymouth, MI, USA). Much of the anthropometric data, used in the construction of the headforms discussed above, was collected over 30 years ago and since that time the demographics of the US population have changed.

Respirator certification tests conducted in the US by the National Institute for Occupational Safety and Health (NIOSH) use headforms to test resistance, air flow, oxygen and carbon dioxide levels, rated service time, positive pressure, gas flow, remaining service life indicator and field of view (National Institute for Occupational Safety and Health 2003). The future ISO may require the use of a number of headforms for evaluating the performance of respiratory protective devices. In an effort to account for the variability in face shape found across the American workforce, respirator fit test panels are used to select subjects who are representative of employees who use respirators. Currently, the Los Alamos National Laboratory (LANL) fit test panels are used in respirator design, certification testing and research. These panels were developed based on data collected during a 1960s military personnel anthropometric survey. Today's US workforce demographics are not reflected in the measurements collected from a survey sample dominated by young, fit Caucasian males. The contemporary workforce contains a higher proportion of African American and Asian employees, as well as an increase in the number of female workers compared to individuals employed during the 1960s and 1970s. Zhuang *et al.* (2004) demonstrated that the 1967–68 Air Force survey data are not reflective of the anthropometric distribution of the current US workforce.

Recognising the inherent difficulties in using old military data and recognising the importance of updating the respirator fit test panels, NIOSH initiated a 2003 study to develop a head-and-face anthropometric database of civilian respirator users. Sampling included respirator users from all segments of the user population, including those in various types of industrial, health care and emergency response jobs. The researchers established a database containing anthropometric measurements that were weighted to be representative of the current US civilian workforce based on the race and age distributions from the 2000 US census. Measurements of the human subjects surveyed were obtained using two techniques: traditional measurement tools and a 3-D laser scanning system. Upon completion of the NIOSH survey, it was determined that the 25 subject (LANL) fit test panels do not adequately represent the current US workforce. Over 15% of NIOSH survey subjects were excluded from the full-face piece respirator fit test panel, resulting in the creation of new fit test panels (Zhuang *et al.* 2007).

Based on the data collected, NIOSH researchers developed two new fit test panels for half- and full-face piece respirator fit testing (Zhuang *et al.* 2007). One new panel (NIOSH bivariate panel) included the same linear measurements consistent with the LANL panel currently used for the NIOSH respirator certification programme. The other new panel was developed using principal component analysis (PCA) to identify the combination of facial dimensions that best represent facial variation in the dataset. Specific details regarding how PCA was used to create a new respirator fit test panel has been published previously (Zhuang *et al.* 2007). The PCA fit test panel accommodated 95% of the subjects surveyed and allowed for the categorisation of subjects based on the overall size of their head and shape of their face using 10 measured dimensions.

In addition to the traditional anthropometric data collected that led to the generation of the new fit test panels, 3-D scans of subjects were also collected. 3-D scans provide volumetric and contour data regarding face size and shape that is indeterminable from landmark coordinates. It is inadequate to design PPE, such as respirators, with traditional length, breadth and width dimensions without knowing the location of those landmarks in space (Coblentz *et al.* 1991). Linear measurements provide statistics on differences between age groups and gender, but these 1-D measurements cannot be used to define a 3-D relationship between landmarks that would enable surface generation (Kouchi and Mochimaru 2004).

This paper presents a new approach to developing headforms that uses both the NIOSH head-and-face

anthropometric survey data as well as the stereometric data collected with a 3-D scanner. To ensure the safety of US workers who use PPE, it is critical that all PPE worn on the head and face be certified on a series of standard headforms that are developed by incorporating both types of data.

2. Materials and methods

2.1. Subjects

A total of 3997 subjects were recruited from industries and public services in which workers routinely or occasionally use respirators. Equal sample sizes were collected by using a stratified sampling plan that consisted of three age strata (18–29, 30–44, 45–66 years), two gender strata and four ethnic group strata (Caucasian, African American, Hispanic and others). Although the sampling plan did not call for sampling specific geographic regions, subjects were obtained at 41 separate sites, located in eight states from the east to west coasts of the United States. A detailed description of the sampling plan has been previously published (Zhuang and Bradtmiller 2005).

2.2. Traditional measurements

A total of 21 anthropometric measurements were collected using spreading callipers, Lufkin Executive diameter steel tape 16 mm × 2 m (Cooper Tools, Apex, NC, USA) and sliding callipers (GPM Instruments, SiberHegner, Zurich, Switzerland). In total, 10 of the collected dimensions were selected for the development of the new headforms: minimal frontal breadth; face width; bigonial breadth; face length; interpupillary breadth; head breadth; nose protrusion; nose breadth; nasal root breadth; nose length. Zhuang *et al.* chose these same features for the development of new respirator fit test panels primarily because they are directly related to respirator fit, can be measured consistently and have been shown to be correlated with other facial dimensions. Additional criteria for their relevance have been described elsewhere (Zhuang *et al.* 2007). Prior to data collection each landmark was identified and marked with a round sticker. Each dimension is a straight line linear distance measured between two landmarks (Figure 1).

The technicians collecting the measurements were trained by Anthrotech, Inc. (Yellow Springs, OH, USA). In order to ensure accuracy of the measurements, the absolute difference between two repeated measurements by each technician could not exceed 2 mm. 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.

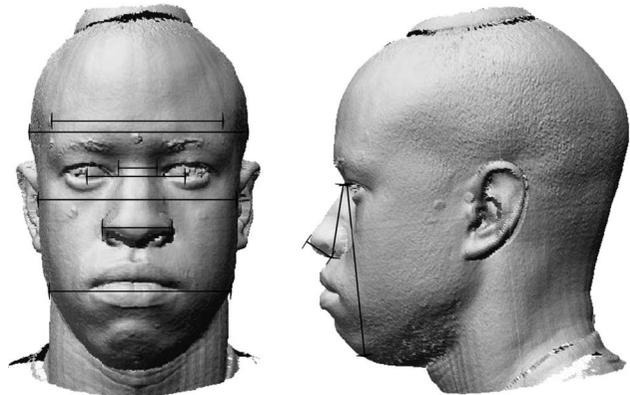


Figure 1. Facial characteristics are determined by measuring the linear distance between specific landmarks. The frontal view indicates the width measurements, from top to bottom: minimal frontal breadth (right and left fronto-temporale), head breadth (maximum width found level above the ears), nasal root breadth (width of the nose level with the sellion), interpupillary breadth (right and left pupil), face width (right and left zygomatic arch), nose breadth (right and left alare) and bigonial breadth (right and left gonion). The side view indicates nasal measurements and face length from left to right: nose protrusion (pronasale to subnasale), nose length (subnasale to sellion) and face length (menton to sellion).

2.3. 3-D scanning

A Cyberware rapid 3-D digitizer (Monterey, CA, USA), with its associated computer and data processing software, was used to scan a subset ($n = 1013$) of the total subject population. Scans were collected in San Diego, CA and Houston, TX. CyScan, one functional module of the Cyberware software package, was used to accomplish the initial scan. Subjects were scanned after all landmarks were labelled. During the 360° scan, a class I laser was projected, in a thin line, on to the subject, which followed the contour of the face and head. The duration of each scan was approximately 45 s, during which time subjects were required to maintain a stable posture. In an effort to ensure the least amount of movement and to properly position each individual, a reference post was placed on the top of the head. To ensure the accuracy of the scanner, calibration procedures were performed routinely. Additional processing and measurements of the images was accomplished using Polyworks version 10.1.6 (InnovMETRIC™, Québec, QC, Canada). Polyworks permits the user to create various features such as points and distances. Points were placed manually on each individual scan in the same locations as the labelled landmarks and linear distances were defined by those technician-defined points.

2.4. Subject selection criteria for creation of new headforms

Although headforms can be sculpted with some key facial dimensions, the representativeness of the design is limited if only the traditional data are used to construct the headforms. Automated surface anthropometry (3-D scan data) has many advantages over the traditional measurement methods; however, the applications of the 3-D data are still in early exploratory stages. The sample size of the subjects with scan data may not be representative of the worker population. Therefore, the approach to developing new headforms representative of the current US workforce was to first use the traditional data to define the target facial features of the headforms and then select subjects with scan data and facial features close to the target facial features. The scan data for the selected subjects were used to construct the digital 3-D headforms.

The criteria for choosing an individual 3-D head scan was based on calculations of principal components one and two (PC1 and PC2 respectively). PCA was performed based on correlation matrix of 10 dimensions (Zhuang *et al.* 2007). The selection of the 10 dimensions to include in PCA was based on four criteria: (1) the dimensions are relevant to respirator fit; (2) the dimensions excluded from PCA have good correlation with, and can be predicted by, the dimensions included in the PCA; (3) the number of dimensions is reasonable so that users of the PCA fit test panel can realistically make the measurements without undue burden on the test subjects; (4) dimensions that are difficult to obtain and/or highly variable are excluded. The number of principal components to use in developing the PCA model was selected based on the following criteria: (1) retaining any component with an eigenvalue greater than 1.00 (Kaiser criterion); (2) the proportion of variance accounted for; (3) interpreting the substantive meaning of the retained components; (4) practicality. Based on these criteria, the first two principal components were selected. The value of each principal component was calculated as follows:

$$\begin{aligned}
 \text{PC1} = & 0.343264 \times (\text{minimum frontal breadth}) \\
 & + 0.426498 \times (\text{face width}) + 0.372717 \\
 & \times (\text{bigonial breadth}) + 0.329648 \times (\text{face length}) \\
 & + 0.363474 \times (\text{interpupillary distance}) \\
 & + 0.372241 \times (\text{head breadth}) + 0.113578 \\
 & \times (\text{nose protrusion}) + 0.301125 \\
 & \times (\text{nose breadth}) + 0.202311 \\
 & \times (\text{nasal root breadth}) \\
 & + 0.193650 \times (\text{nose length}) \quad (1)
 \end{aligned}$$

$$\begin{aligned}
 \text{PC2} = & -0.152951 \times (\text{minimum frontal breadth}) \\
 & - 0.039087 \times (\text{face width}) - 0.093279 \\
 & \times (\text{bigonial breadth}) + 0.359799 \\
 & \times (\text{face length}) - 0.173099 \\
 & \times (\text{interpupillary distance}) + 0.013306 \\
 & \times (\text{head breadth}) + 0.551842 \\
 & \times (\text{nose protrusion}) - 0.210833 \\
 & \times (\text{nose breadth}) - 0.341235 \\
 & \times (\text{nasal root breadth}) + 0.584261 \\
 & \times (\text{nose length}) \quad (2)
 \end{aligned}$$

The headform dimensions for each size category were determined from the traditional data collected on 3994 of the 3997 surveyed subjects. Two individuals had missing values for face width and the third subject had a missing value for interpupillary breadth. Subjects were placed into the PCA fit test panel based on the scores for PC1 and PC2 and using an algorithm that was published previously (Zhuang *et al.* 2007). The first principal component accounts for the overall size of an individual face. If PC1 is low, the subject has smaller facial features in general and if PC1 is high the facial features are larger. The second principal component reflects the width of the face and the shape of the nose. Small PC2 values indicate shorter, wider faces with broad noses while large values represent individuals with longer faces with large narrow 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 (Figure 2). The mean values for the 10 facial dimensions were calculated for each size category, including subjects who fell outside the PCA panel. Table 1 provides a breakdown of subjects by head size and shape characteristics. In total, 50% of the US population has medium sized heads, while the distribution falls close to 11% for each of the remaining head size categories.

When PC1 and PC2 values were calculated using measurements acquired with Polyworks from the digital 3-D scan, the individual values of PC1 and PC2 changed. The values for the sample population shifted towards the large and short/wide face size categories. The differences found between the two measurement techniques with human subjects may be explained by the tissue characteristics of the human head and face. Spreading callipers are used to collect the majority of width measurements. Facial tissue is pliable and liable to become depressed when the technician holds the spreading callipers on the facial landmarks during a measurement. Some regions of the face (bigonial breadth) are more pliable and the surface of the skin depresses more easily than others, resulting in

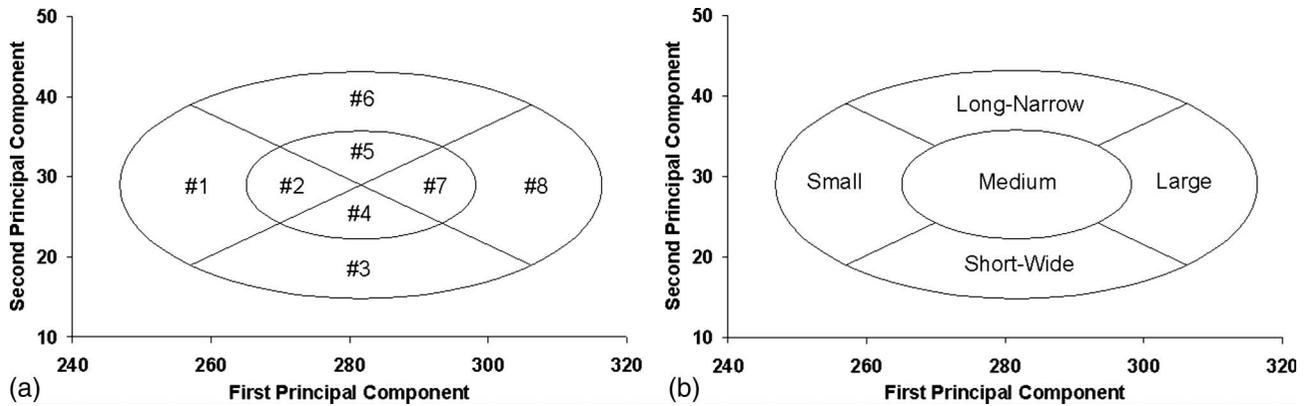


Figure 2. The principal components analysis respirator fit test panel (a) and the five face size categories (b).

Table 1. Subject distribution by face size category.

Head size	n	Percentage of population			Outlier n
		Male (%)	Female (%)	Total (%)	
Small	248	1.1	22.0	11.6	11
Medium	1934	49.9	50.3	50.1	0
Large	620	20.8	1.0	10.8	82
Long/narrow	351	5.6	17.8	11.7	45
Short/wide	557	17.9	6.6	12.2	146

manual measurements that are found to be smaller than those collected with Polyworks. Conversely, head breadth and face width are landmarks found beneath the subject's hair and sideburns respectively. When compared, manual measurements of these dimensions are consistently smaller than values obtained using Polyworks. There is no way to remove the hair and leave a reliable computerised surface to measure, so values collected from these landmarks using Polyworks are inflated. In order to account for the discrepancy between values collected with Polyworks and those collected manually and to select subjects for constructing headforms with the targeted facial characteristics, regression equations were obtained and used to correct three dimensions: head breadth; face width; bigonial breadth (Table 2). Using the calculated values for these three dimensions, as well as the remaining seven dimensions collected with Polyworks, new digital PC1 and PC2 values were determined (Figure 3).

Subjects chosen for the construction of a headform for a given size category had digital PC1 and PC2 values within 1 SD of the calculated mean of the traditional manual measurements. Five subjects from each size category were chosen (Figure 4). The digital measurement of every dimension, including the three

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

Dimension	Equation	R ²	p value
Minimal frontal breadth	$Y = 0.538 X + 45.24$	0.481	<0.001
Face width	$Y = 0.586 X + 52.22$	0.579	<0.001
Bigonial breadth	$Y = 0.596 X + 37.96$	0.567	<0.001
Face length	$Y = 0.903 X + 11.07$	0.705	<0.001
Interpupillary distance	$Y = 0.540 X + 27.76$	0.479	<0.001
Head breadth	$Y = 0.364 X + 91.00$	0.240	<0.001
Nose protrusion	$Y = 0.610 X + 8.93$	0.338	<0.001
Nose breadth	$Y = 0.864 X + 1.08$	0.815	<0.001
Nasal root breadth	$Y = 0.373 X + 9.23$	0.144	<0.001
Nose length	$Y = 0.882 X + 6.04$	0.604	<0.001

Y = predicted manual measurement; X = dimension measured with Polyworks; n = 927, which is different from 1013 because some subjects had missing demographic data and poor scan data and were not used in this analysis.

regressed dimensions, for each chosen subject, is provided in Table 3. Although these subjects do not appear to be the most representative observations for each face size category, they have computer measurements that are the closest to the computed means of the traditional data.

2.5. Scan data processing

Designing a single headform is a multi-step process. Below is a description of how the digital headforms were constructed using the medium size as an example. After subjects with scanned heads of the size and shape of interest were selected, their 3-D scans were aligned using Polyworks, a program that allows the user to edit 3-D scans. In order to obtain the optimum average of the five subjects, each head scan was aligned using the Frankfurt plane and a vertical symmetry plane

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

	Subject	Minimal frontal breadth	Face width*	Bigonial breadth*	Face length	Inter-pupillary breadth	Head breadth*	Nose protrusion	Nose breadth	Nasal root breadth	Nose length
Small	1	97	131	103	111	56	143	18	33	18	47
	2	94	129	100	115	62	145	19	31	21	48
	3	101	129	99	108	58	141	19	33	18	50
	4	97	133	103	110	55	143	20	35	16	47
	5	93	128	103	108	60	145	19	29	19	48
Medium	1	103	135	110	124	63	148	19	37	18	52
	2	106	136	110	121	59	146	20	33	20	50
	3	107	130	105	127	65	143	17	43	23	53
	4	101	138	112	118	60	149	19	38	18	49
	5	104	136	110	117	60	146	16	33	21	53
Large	1	117	146	118	131	66	155	19	40	20	54
	2	110	148	122	130	68	152	21	40	22	53
	3	111	143	115	135	68	153	20	44	24	57
	4	110	145	122	131	68	154	18	37	23	54
	5	115	148	118	127	67	156	20	39	21	48
Long/ Narrow	1	104	132	109	139	60	144	17	34	20	58
	2	97	136	112	126	59	148	19	36	15	58
	3	99	132	108	129	62	147	23	36	18	54
	4	101	131	110	128	58	150	20	34	18	55
	5	94	135	115	126	52	146	21	38	19	56
Short/ Wide	1	106	136	107	114	64	150	19	39	21	45
	2	104	140	111	107	65	153	18	39	18	48
	3	95	136	116	109	68	152	17	43	20	44
	4	100	136	108	114	63	148	15	38	20	46
	5	104	139	115	111	66	148	17	37	20	50

*Indicates the three dimensions corrected for tissue pliability. The equations used for this correction are found in Table 2.

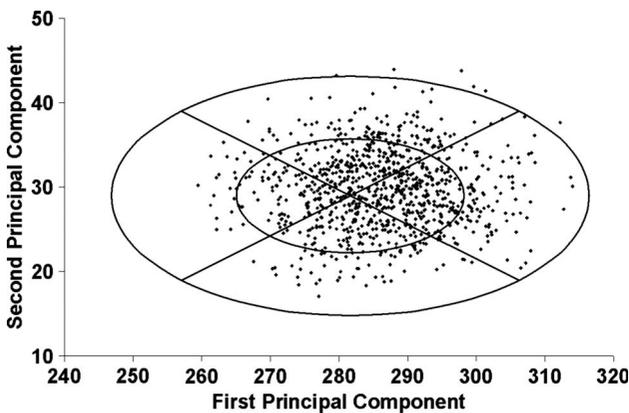


Figure 3. Scanned subject distribution of principal components one and two calculations based on the Polyworks dimensions including regression values for head breadth, face width and bigonial breadth.

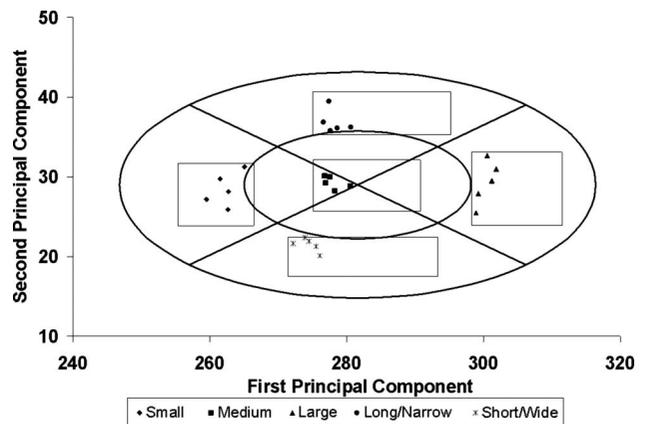


Figure 4. Subjects selected for the creation of five headforms from principal components one and two values calculated with Polyworks and regression values for head breadth, face width and bigonial breadth. The boxes represent 1 SD above and below the computer means of the traditional measurements.

constructed from the midpoint distance between six landmarks (right and left trignon, right and left zygomatic arch, right and left ectocanthus) for each scan. Once in proper alignment, Polyworks was used to create a single averaged headform from all five digital scans.

The resultant averaged headform may contain regions of missing information around important

facial features such as the mouth, nose and eye regions. However, the forehead, cheeks and chin regions provide a smooth average. The auricular was not detailed, only the location of the ear was noted. The medium average was missing surface information for the eyes that required a simple patching procedure,

but the average mouth surface was distorted. Aligning heads using the Frankfurt plane does not guarantee that specific facial features will line up so the resultant average provided a face with three lips. The average lips for the medium headform was developed from a separate average of the lips themselves. As shown in Figures 5 and 6, one of the subjects had a moustache. Polyworks was used to remove the hair and to create a smooth surface above the upper lip. Then all five lips were aligned with each other and an average lip was created with Polyworks. The resultant surface was then inserted into the averaged medium headform at the centre of the lip surface created from the original average. When necessary, subsequent alignments, such as the one described for the medium lips, were used for individual facial features: the nose, lips, and each eye. Once all individual features were in position, any remaining holes were patched. Patching the headform included the removal of the noisy ear regions, as well as the creation of a smooth scalp. Developing a scalp from the scans used to make a given sized headform was challenging because the individuals scanned had hair and wore wig caps. However, some subjects were bald and those scalps were used to create contours that were reflective of an actual human head. Constructed headforms were given scalps with head lengths and head breadths that matched the average values for



Figure 5. Images of the scan subjects chosen to construct the medium headform.

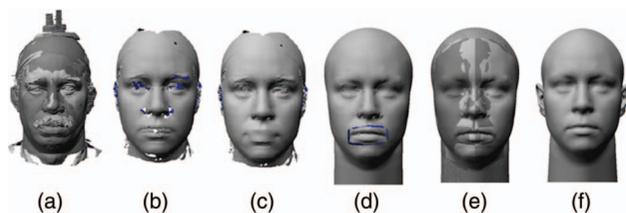


Figure 6. The intermediate steps from the point of the initial average of the scans to the completed headform with ears, neck, and smooth scalp: (a) alignment of all headforms using a symmetry plane and the Frankfurt plane; (b) initial headform after the averaging; (c) patching of the eyes and smoothing 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; (f) final average headform with ears and neck attached.

each size category. In addition, necks were placed on the headforms following the contour of the average nape of the neck with the appropriate neck circumference values for each size category. Once the entire headform was patched, it was duplicated and mirrored so that a symmetric average of the headform could be created. The surfaces of the ears were obtained from Direct Dimensions Inc. (Owings Mill, MD, USA). Those ears, a neck and a 5 mm hole at the centre of each mouth were added to complete each headform. Figures 5 and 6 show the original scans of the subjects chosen to create the medium headform, and the remaining steps leading to a completed digital model.

3. Results

Five digital 3-D headforms (small, medium, large, long/narrow and short/wide), representing the five face size categories, have been created (Figure 7). Table 4 provides the calculated mean values from the traditional manual measurements for the 10 dimensions critical to respirator fit, as well as the computer measurements of the digital headforms. All dimensions of the constructed headforms are within 3 mm of the corresponding computed means, which corresponds to the tolerances associated with manual measurements of anthropometric landmarks.

Facial dimensions measured from 3-D scans of four existing standard headforms are provided in Table 5. The PCA fit test panel is considered to be representative of the current US workforce and Figure 8 shows the distribution of the NIOSH series of headforms as well as four currently used standard headforms. The Alderson 50th percentile and Sheffield headforms fall into the large size cell, while the Sierra and the National Operating Committee on Standards for Athletic Equipment (NOCSAE) headforms are located along the boundary between the long/narrow cell and the medium cell. According to the NIOSH bivariate panel, all standard headforms fall within a cell that represents individuals with medium sized faces

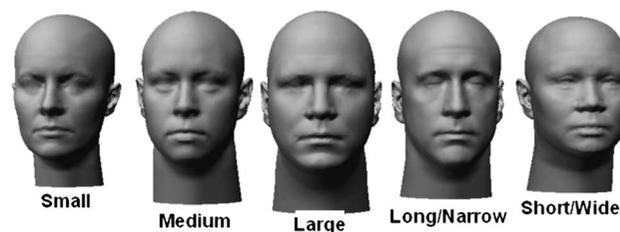


Figure 7. Five digital 3-D headforms representing the five face size categories for the US workforce: small, medium, large, long/narrow and short/wide.

Table 4. Summary of the computed mean (AVE) and SD for the manual measurements of 3997 subjects, and the mean (3-D) and SD from five independent measurements of the constructed headforms using Polyworks.

Dimensions	Face size category																								
	Large					Medium					Small					Long/Narrow					Short/Wide				
	Traditional		Computer			Traditional		Computer			Traditional		Computer			Traditional		Computer			Traditional		Computer		
AVE	SD	3-D	SD	AVE	SD	3-D	SD	AVE	SD	3-D	SD	AVE	SD	3-D	SD	AVE	SD	3-D	SD	AVE	SD	3-D	SD		
Minimal frontal breadth	110	5.0	112	1.8	104	4.6	105	1.8	98	4.7	101	1.3	103	5.3	101	2.1	106	5.5	108	1.1	106	5.5	108	1.1	
Face width	151	5.0	154	0.5	140	5.4	141	0.2	128	4.1	131	0.2	140	6.4	139	0.9	141	6.6	140	0.2	141	6.6	140	0.2	
Bigonial breadth	131	9.3	130	0.8	115	7.8	118	1.2	101	4.9	102	2.1	113	8.2	116	0.8	118	9.8	117	1.0	118	9.8	117	1.0	
Face length	127	6.0	127	1.3	119	5.6	120	1.0	110	5.1	111	0.8	127	6.3	125	0.6	112	5.6	113	1.1	112	5.6	113	1.1	
Inter-pupillary distance	68	3.5	71	1.2	64	3.2	62	1.8	59	2.9	59	1.9	63	3.4	62	1.3	65	3.8	67	2.8	65	3.8	67	2.8	
Head breadth	158	5.1	158	0.9	150	5.2	152	0.2	142	4.5	144	0.2	151	5.5	153	0.2	149	6.2	146	0.7	149	6.2	146	0.7	
Nose protrusion	21	2.5	20	0.6	20	2.5	21	0.4	19	2.5	18	0.3	23	2.5	21	0.4	17	2.1	17	0.2	17	2.1	17	0.2	
Nose breadth	41	4.9	43	0.2	36	4.4	37	0.5	32	3.4	32	0.3	35	3.8	36	0.4	39	4.6	41	0.4	39	4.6	41	0.4	
Nasal Root breadth	18	2.2	19	0.7	16	2.0	17	0.8	15	1.9	18	0.5	15	1.5	16	0.8	17	2.0	19	1.1	17	2.0	19	1.1	
Nose Length	52	3.8	55	0.5	50	3.2	52	0.6	47	3.2	49	0.6	56	3.0	56	0.6	44	2.7	47	1.0	44	2.7	47	1.0	

All values are shown in millimetres.

(Figure 9). The NIOSH medium headform has a narrower and shorter face than the current standards.

3-D comparisons between the NIOSH medium headform and the four standard headforms referenced above were performed after aligning all heads with the Frankfurt plane. The overall size and shape of the entire headform, including facial depth, was inspected after adjusting the headforms so the tragion midlines overlapped one another (Figure 10). A dark border was placed around the profile of the NIOSH medium headform and the darker shading indicates where the two transparent 3-D headforms intersect. The NIOSH medium headform sits completely inside the NOCSAE headform when the ear locations are matched. The remaining standards have similar facial depth while scalps, brow ridges and chin contours vary.

4. Discussion

There is a difference in the location of a subject in the PCA panel depending on which measurements, traditional manual or computer are used for the PC1 and PC2 calculations. Upon discovering the discrepancy between the two measurements, a plastic replica of the human skull was scanned. The skull was measured with traditional sliding and spreading callipers for 10 dimensions similar to those measured on the human subjects. Polyworks was used to collect digital measurements of the same dimensions and regression analysis between the manual dimensions and those collected using Polyworks resulted in $R^2 = 0.999$, slope = 1.0017 and $p < 0.001$. The scanner in conjunction with Polyworks provides accurate measurements of hard, inanimate objects.

However, human subjects are not inanimate objects with solid surfaces. Skin tissue deforms the moment it interacts with an external force. It is difficult to collect traditional anthropometric measurement without causing depressions in landmark locations. The gonion is the lateral point on the posterior angle of the jawbone, a fleshy point on the face. Collecting bigonial breadth, the linear distance between the right and left gonion, may be difficult on certain subjects. During the measurement, the pressure exerted on the calliper may depress the skin, resulting in a distance less than expected by up to 6 mm or more. Using computer scans of the subject's head may provide a more accurate measurement of this dimension because the computer views the surface of the face as a solid. Depression cannot occur and results obtained on the computer are larger and may be more consistent than results obtained with traditional techniques. The opposite is true regarding head breadth; a measure across the largest width of the head above the ears. This region provides a consistent measurement using

Table 5. Facial dimensions (mm) of scanned standard headforms measured with Polyworks.

Variables	NIOSH, M	Sheffield	Alderson 50	Sierra	NOCSAE
Minimum frontal breadth	103	97	112	105	103
Face width	139	146	141	140	143
Bigonial breadth	113	124	125	120	117
Face length	117	122	121	127	126
Interpupillary distance	63	70	69	62	61
Head breadth	150	164	161	156	152
Nose protrusion	20	26	19	22	22
Nose breadth	34	37	38	36	35
Nasal root breadth	18	19	22	22	18
Nose length	51	54	54	56	55

NIOSH = National Institute for Occupational Safety and Health; NOCSAE = National Operating Committee on Standards for Athletic Equipment.

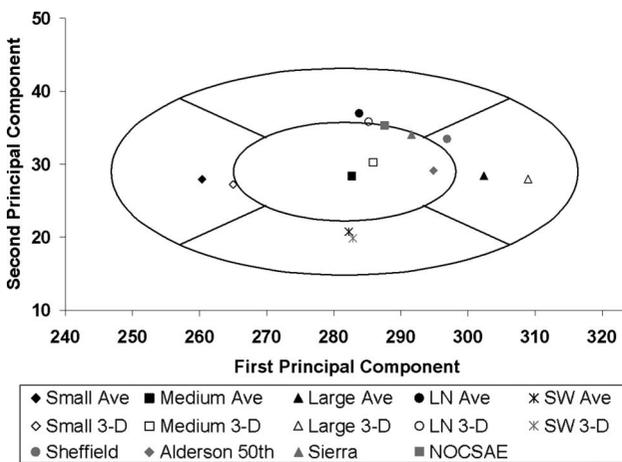


Figure 8. The location of the newly constructed headforms (suffix 3-D) and computed mean of the traditional manual measurements (suffix Ave) in the National Institute for Occupational Safety and Health principal component analysis panel. Four current standard headforms were also included. NOCSAE = National Operating Committee on Standards for Athletic Equipment.

traditional techniques because the landmark is bony and hair can be moved out of the way. When subjects are scanned in their natural state, with hair exposed, the scan usually results in a clear view of the face and neck, but data are missing from the top and back of the head. To prevent such a dramatic loss of information, subjects were asked to don a nylon cap so that the curvature of their scalp could be captured during the scan. This results in head breadths larger than actual values because hair captured under the nylon cap is added to the head breadth dimension. Once again, the computer sees the surface as a solid and head breadth is measured larger than it would be when measured traditionally.

Even though there is a discrepancy between the two measurement techniques, a relationship exists between

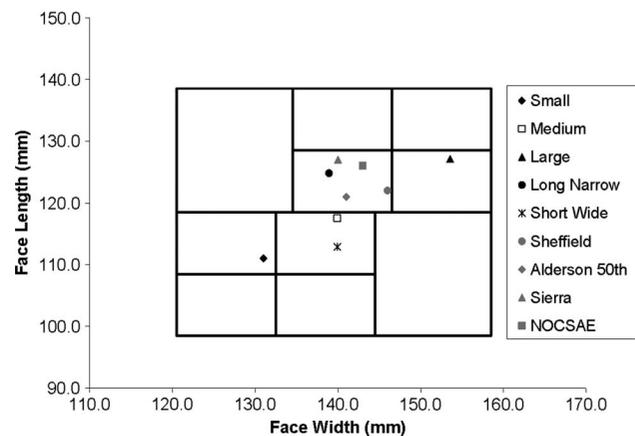


Figure 9. Location of the newly constructed headforms and the current standard headforms in the National Institute for Occupational Safety and Health bivariate panel. NOCSAE = National Operating Committee on Standards for Athletic Equipment.

the two (Table 2). The majority of the dimensions have R^2 values greater than 0.477, with $p < 0.001$. Nasal root breadth and nose protrusion are the smallest facial dimensions and are most sensitive to minute variations in measurement values. Head breadth has a low R^2 value for the entire population due to the distribution of hair under the nylon cap. Analysis of bald subjects, $n = 95$, reveals that there is a relationship between the two measurements techniques resulting in an R^2 value of 0.505, $p < 0.001$.

When subject heads are chosen based strictly on their manual measurements, their placement in the PCA panel is as shown in Figure 2. As discussed previously, the 3-D point cloud of those same subjects results in a shift down and to the right in the PCA panel due to the nature of the scanning technology. Polyworks performs an average of the scanned point clouds. If subjects are chosen strictly from the Polyworks dimensions they are shifted by factors

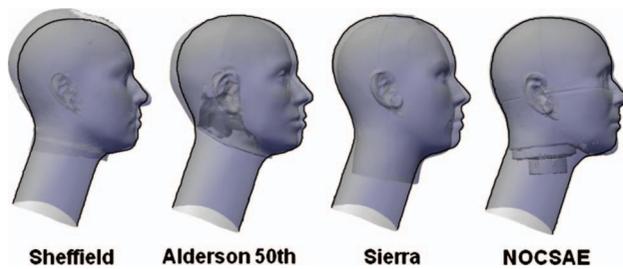


Figure 10. Comparison of the overall size, shape and depth of the current standard headforms in relation to the National Institute for Occupational Safety and Health (NIOSH) medium headform with the ears in alignment. The dark outline follows the contours of the NIOSH medium headform. NOCSAE = National Operating Committee on Standards for Athletic Equipment.

greater than necessary due to the large difference in the width measurements for head breadth, face width and bigonial breadth. By using corrected values for three dimensions, the chosen point clouds will land in the appropriate location to create a headform in the desired face size category with the appropriate facial characteristics. The new headforms are smaller so that the scan-derived measurements are close to compressed (traditional) measurements.

New headforms were developed using 3-D scans of subjects whose facial dimensions most closely matched the 10 calculated mean values of the manual measurements for each face size category. The technique used to average five heads into one representative head resulted in constructed headforms that were within 3 mm of the calculated means. The NIOSH medium is smaller than all currently used headforms, which may be due to the contribution in facial characteristics from a larger proportion of women and minorities found in the NIOSH survey than the data used to construct the four standard headforms listed above. Those headforms were developed from anthropometric surveys dominated by white males, collected between the 1950s and the 1970s.

Increasingly available 3-D scanning devices and data have generated active research and development in digital human modelling. Allen *et al.* (2003) developed a novel method for fitting high-resolution template meshes to detailed human body range scans with sparse 3-D markers. Li *et al.* (2008) also developed a method to generate average or targeted head models from 3-D scans. Li *et al.*'s method aligns 3-D head scans and corresponding anatomy at a few critical levels and performs surface synthesis on cross-sectional curves. Niu *et al.* (2009) recently proposed a 3-D anthropometric sizing method based on clustering algorithm combined with a multi-resolution description. These methods may be easier than the method

used in this study. However, the method used in this study took advantage of using the traditional measurement data for a much larger sample size of 3997 subjects. This method also attempted to solve the problems associated with the scan data, such as hair, tissue pliability, inflated computer measurements, etc., as described above. When respirators are put on to the headforms for a design and certification test, the fitting is similar to putting the respirator on the wearer because the respirator will compress and deform the wearer's face.

In addition, the method developed by Li *et al.* (2008) was used to generate an average head model for the five subjects selected to develop the medium headform in this study. The average head model from Li *et al.*'s method is comparable to the medium headform developed in this study. The differences in key dimensions and between the two surfaces are less than 2 mm.

5. Conclusions

Using anthropometric data gathered during the 2003 NIOSH survey, parameters for new headforms in five size categories were developed. 3-D scans of five individuals, who most closely represented a given size category were averaged together. The resulting models include facial features not found on current standard headforms. Five distinct sizes (small, medium, large, long/narrow and short/wide) of digital 3-D headforms have been created, taking into account the overall size and shape of the face. The NIOSH headforms are symmetric and represent the facial size and shape distribution of current US respirator users. In addition, the ears have been placed on the headforms to match the average position for the chosen heads of a given size. In the future, both half- and full-face piece respirators need to be tested on the headforms to assess the quality of fit. In addition, steps will be taken to minimise the discrepancy between the two measuring techniques.

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