Materials and Methods for ISO Digital Headforms

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).

Traditional Measurements

A total of 21 anthropometric measurements were collected using spreading calipers, Lufkin Executive diameter steel tape 16 mm x 2 m (Cooper Tools, Apex, NC, USA) and sliding calipers (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).

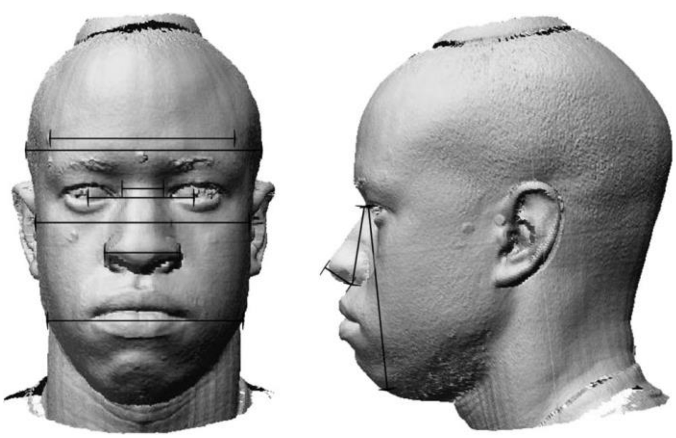

Figure 1. Facial characteristics are determined by measuring the linear distance between specific landmarks. The frontal view indicates the width measurements, from top to bottom: minimal frontal breadth (right and left frontotemporale), head breadth (maximum width found level above the ears), nasal 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).

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 = 1,013) 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™, Que´bec, 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.

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:

PC1 = 0.343264 x (minimum frontal breadth) + 0.426498 x (face width) + 0.372717 x (bigonial breadth) + 0.329648 x (face length) + 0.363474 x (interpupillary distance) + 0.372241 x (head breadth) +

0.113578 x (nose protrusion) + 0.301125 x (nose breadth) + 0.202311 x (nasal root breadth) + 0.193650 x (nose length)

PC2 = -0.152951 x (minimum frontal breadth) – 0.039087 x (face width) – 0.093279 x (bigonial breadth) + 0.359799 x (face length) – 0.173099 x (interpupillary distance) + 0.013306 x (head breadth) + 0.551842 x (nose protrusion) – 0.210833 x (nose breadth) – 0.341235 x (nasal root breadth) + 0.584261 x (nose length)

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.

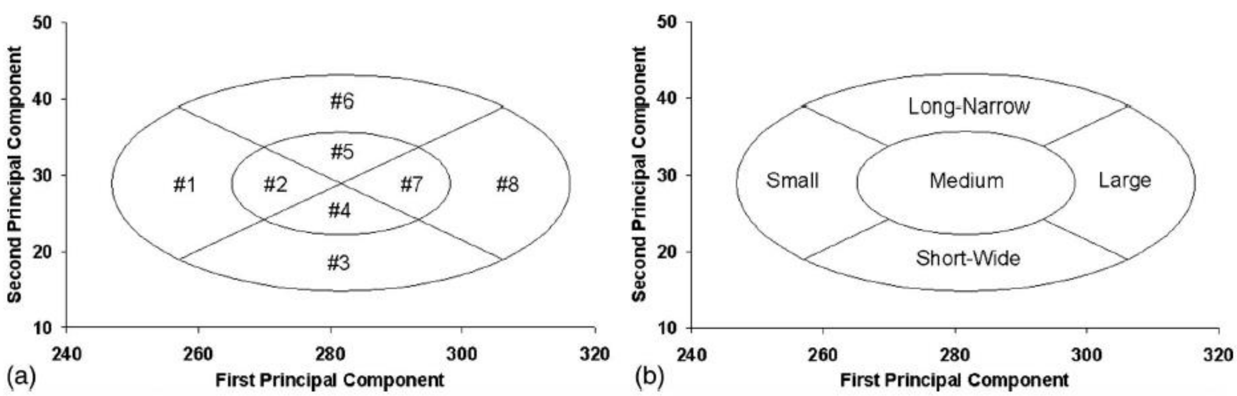

Figure 2. The principal components analysis respirator fit test panel (a) and the five face size categories (b).

Table 1. Subject distribution by face size category.

Head size	n	Percentage of population Male (%)	Female (%)	Total (%)	Outlier n
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

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 calipers are used to collect the majority of width measurements. Facial tissue is pliable and liable to become depressed when the technician holds the spreading calipers 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 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 computerized 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).

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.

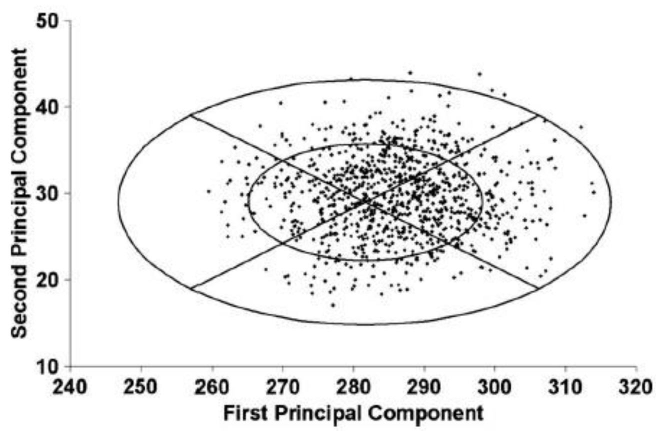

Figure 3. Scanned subject distribution of principal components one and two calculations based on the Polyworks dimensions including regression values for head breadth, face width and bigonial breadth.

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 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.

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.

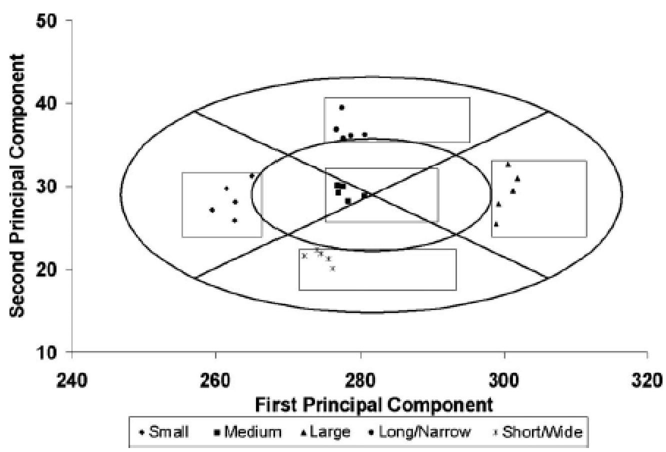

Figure 4. Subjects selected for the creation of five headforms from principal components one and two values calculated with Polyworks and regression values for head breadth, face width and bigonial breadth. The boxes represent 1 SD above and below the computer means of the traditional measurements.

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 constructed from the midpoint distance between six landmarks (right and left tragion, 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 center 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 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 center 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.

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.

References

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