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An anthropometric study of manual and powered wheelchair users

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Abstract

The purpose of this study was to evaluate the structural anthropometric dimensions of adult wheelchair users as part of a larger project that involved developing a database of the structural characteristics and functional abilities of wheelchair users. Measurements were made on 121 adult manual and powered wheelchair users with an electromechanical probe that registered the three-dimensional locations of 36 body and wheelchair landmarks. Thirty-one body and wheelchair dimensions (e.g., heights, breadths, depths) were calculated from the three-dimensional coordinate data. Tests of distributional normality showed that less than 1/3 of the dimensions were not normally distributed. ANOVA showed significant differences between powered and manual chair users, and women and men for only some of the anthropometric dimensions. The results of this study provide anthropometric information for a small and diverse group of wheelchair users using new measurement methods that may have value for three-dimensional human modeling and CAD applications.

Relevance to industry

Anthropometric data of wheelchair users can be applied toward the universal design of occupational environments and products that afford greater usability for wheelchair mobile user populations that are usually not considered in the design process.

Keywords: Anthropometry; Wheelchair users; Three-dimensional human modeling

1. Introduction

Anthropometry, the measurement of physical characteristics and abilities of people, provides information that is essential for the appropriate design of occupational and non-occupational environments, as well as for the design of consumer products, clothing, tools and equipment. The most comprehensive anthropometric studies to date have focused on non-disabled adults, with much of the data based on military personnel (e.g., Anthropology Research Staff, 1978a, b; Gordon et al., 1989; Kennedy, 1986).

Anthropometric studies of the elderly or individuals with disabilities generally have involved much smaller sample sizes and fewer

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measurements than military studies (e.g., Das and Kozey, 1999; Goswami et al., 1987; Hobson and Molenbroek, 1990; Jarosz, 1996; Laubach et al., 1981; Molenbroek, 1987; Stoudt, 1981; Ward and Kirk, 1967). Studies involving disabled subjects have tended to focus on specific disability groups, and this, coupled with the lack of standardized dimensional definitions and measurement methods, has made combining information from previous studies very difficult (Bradtmiller and Annis, 1997). The physical characteristics of individuals have also been shown to be quite different across disability populations (e.g., Annis, 1996; Goswami et al., 1987; Jarosz, 1996). The general lack of anthropometric information about individuals who are wheelchair mobile limits the ability of designers to create environments and products that can be used effectively and safely by this diverse set of users.

Many of the previous anthropometric studies of wheelchair users have employed conventional methods of data collection, which include the use of anthropometers, spreading and sliding calipers, cylinders, and cones to measure body segment lengths, and grip circumferences. These measures allow percentile estimates for individual body dimensions that can be used in the design of living and workspaces. Newer approaches to engineering anthropometry stress the simultaneous consideration of multiple dimensions through various types of multivariate analyses that include human modeling (Reed et al., 1999). However, conventional anthropometric measurement approaches do not provide three-dimensional information that may facilitate the development of more realistic human models (Steinfeld et al., 2002).

Anthropometric data collection methods that allow an individual's body position to be recorded in three-dimensional space have been described previously (Annis, 1989; Brooke-Wavell et al., 1994; Hoekstra, 1997), and may overcome some of the limitations of conventional anthropometric measurement methods. Three-dimensional surface anthropometry already appears to have practical value in medical applications, the development of clothing and personal protective equipment, and the design of constructed environments (Jones and Rioux, 1997).

The objective of this paper was to evaluate some key structural anthropometric dimensions of adult wheelchair users, as part of a larger project that involved developing a database of the three-dimensional structural characteristics and functional abilities of wheelchair users. Of particular interest in this study was how anthropometry differed by gender and wheelchair type.

2. Methods

2.1. Participants

Manual and powered wheelchair users with disabilities that included arthritic disorders, CNS disorders, spinal cord injuries, amputations, paralysis, cardio-pulmonary conditions and stroke were recruited through a local Independent Living Center, a VA Medical Center, a United Cerebral Palsy Association location, and local hospitals. In addition, advertisements were posted in local newspapers and flyers placed in retail stores. Only those who relied on a wheelchair for their primary means of mobility were allowed to participate. A deliberate attempt was made to select a diverse group of wheelchair users, rather than just individuals who possessed a specific set of physical capabilities, so that the results obtained could be extended more generally to wheelchair user populations.

2.2. Measurement protocols

The measurement protocol required the collection of wheelchair specifications, demographic information, structural anthropometric information and functional anthropometric information for each participant. The make, model, types of accessories and other wheelchair specifications were obtained by inspecting each wheelchair. Demographic information about the participant such as age, disability type, and years of experience with a wheelchair was obtained through a structured interview. Three-dimensional locations of body and wheelchair landmarks were collected. Additionally, photographic records of each participant in a variety of positions were recorded.

Other data that were collected but not described in this paper included quantitative information about objective moving capabilities, wheelchair maneuvering abilities and grip strength.

The measurement protocol used for this study differed from conventional anthropometric data collection protocols. Some have noted the importance of using alternative measurement methods for wheelchair users (Hobson and Molenbroek, 1990). Physically disabled individuals may not be able to maintain standard anthropometric reference positions during data collection. Additionally, unclothed conditions may not be practical due to thermoregulatory issues, and assistance required to change out of and into clothes. The physical characteristics of the wheelchair can influence the maneuverability and reaching abilities of an individual. Therefore, individuals in this study wore light clothing and were measured while seated in a comfortable position while remaining in their own wheelchair.

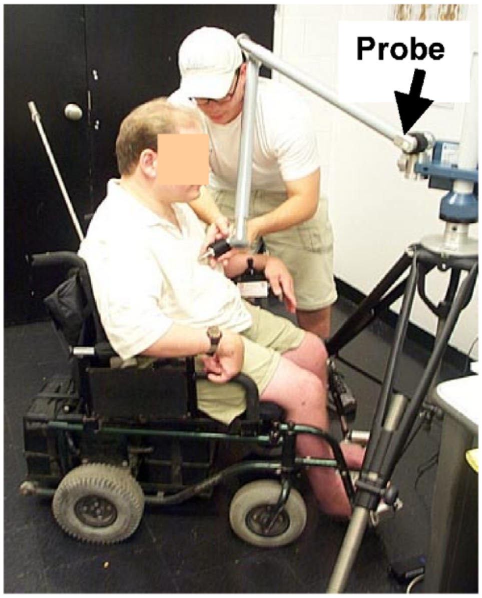

Fig. 1. Data collection with an electromechanical probe allows quick and accurate measurement of key mobility device and body dimensions.

2.3. Variables

2.3.1. Wheelchair characteristics

The following information about each chair was recorded: device type (e.g., manual or power chair), make, model, age, and presence/absence of armrests and footrests, drive wheels, controller, and seat support surfaces.

2.3.2. Landmarks, reference planes and dimensions

Body landmarks, wheelchair landmarks and reference planes were recorded with an electromechanical probe (Fig. 1). The probe was an articulating arm with six degrees of freedom and the location of the tip of the device had a precision of 0.3 mm. The three-dimensional coordinates of each landmark point were recorded by pressing the probe's activation button three times in rapid sequence. For the reference planes, a minimum of five points on different locations of the physical plane such as on the floor or on the top of a footrest were recorded to define the plane. Body and mobility device dimensions were obtained by calculating the distances between points or reference planes and used to derive estimated widths, heights, and depths of key chair and body dimensions. This method of obtaining anthropometric dimensions is reliable but measurements may differ from those obtained with conventional anthropometric measuring devices (Feathers et al., 2004). For this study, 36 body and wheelchair landmarks and seven reference planes were used in the calculation of 31 structural anthropometric dimensions (Tables 1 and 2).

2.4. Data analysis

Descriptive analyses were performed to evaluate the distributional characteristics of the dimensions, as well as the correlation of selected dimensions by gender and chair type. The mean, standard deviation, and 5th, 50th and 95th percentile values of the distribution for each dimension stratified by gender and wheelchair type were calculated. Kolmogorov–Smirnov goodness of fit tests were conducted to identify dimensional distributions that were non-normal. Analysis of variance (ANOVA) was used to test the effects of gender, chair type (manual vs.

Table 1
Body and wheelchair landmarks and reference planes used in this study

	Description
Landmarks	
Acromion*	Most lateral palpable point on the acromial process of the scapula on the outer aspect of the upper shoulder.
Abdominal point, anterior	Most protruding point of the abdominal region.
Anterior-most point	Forward-most portion of the individual's body or wheelchair. This includes the footrest edge, toe tip, etc.
Deltoid point, lateral*	Most lateral point on the surface of the shoulder covering the bulge of the deltoid muscles.
Ectocanthus*	Point at which both eyelids converge on the lateral edge of the eye.
Forearm point, lateral*	Most lateral point on the forearm.
Hip point, lateral*	Most lateral surface point in the hip region, different than ASIS left and right landmarks which are osteologically defined.
Knee point, distal*	Most distal portion of the knee when the knee is in or close to 90° flexion. The palpable osteological reference is the tibial tuberosity.
Lateral-most point*	Lateral most point of the individual and individual's wheelchair, including parts of the wheelchair and gear, including such as wheels (bottom—if with camber), elbow rests, communication hardware, trays, controls, pads, bags, etc.
Malleolus, lateral*	Lateral-most point on bony prominence at the distal end of the fibula. This landmark is lateral and superior to the talocrural joint.
Malleolus, medial*	Medial-most point on bony prominence at the distal end of the tibia. In relation to the malleoli, lateral this point is medial, slightly superior and anterior.
MCPII point, lateral*	Lateral-most point of the metacarpophalangeal joint II, which is located at the base of the index finger.
MCPV point, lateral*	Lateral-most point of the metacarpophalangeal joint V, which is near the hypothenar skinfold of the palm of the hand.
Popliteal point*	Center point of the fold resulting from knee flexion located on the dorsum of the knee area.
Posterior-most point	Backward-most portion of the individual's wheelchair. This may include wheelchair handles, wheelchair backpacks, wheel edges, etc.
Radial styloid*	Distal end of a bony prominence of the radius bone, located at the base of the thumb slightly inferior to the thenar eminence. In most cases, it is lateral to the 'anatomical snuff box' (a series of tendons that cross laterally from the forearm to the thumb).
Suprapatella*	Superior portion of the distal femur and patellar region on the knee when it is at or close to 90° flexion.
Thigh point, lateral*	Lateral-most point of the thigh between the knees and hips.
Waist point, lateral*	Lateral-most portion of the waist on the left and right side of the trunk between ASIS and ribs.
Vertex	Highest point of the head, regardless of head posture.
Planes	
Elbow rest plane*	Upper surfaces of the wheelchair elbow rests. Left and right are often at the same height above the floor, but in some cases, elbow rests may be at different heights.
Floor plane	The floor surface beneath the wheelchair.
Footrest plane*	Upper surfaces of the wheelchair footrests.
Seat back plane	Inner surface of the seatback the back, which supports the wheelchair user's back.
Seat pan plane	Horizontal plane passing through the lowest point of the compressed cushion surface of the seat of an individual's wheelchair.

*Measurements made on left and right side of body.

powered), and gender × chair type on the anthropometric dimensions. ANOVA was conducted on all dimensions since the test is robust even when the distribution of the measured variable does not exactly follow a normal distribution for sample sizes such as the ones used in this study

Table 2
Calculated anthropometric dimensions derived from the landmarks in Table 1

Dimension	Description
Abdominal extension depth	Shortest perpendicular distance from seat back plane to abdominal point, anterior.
Acromion height*	Vertical distance from floor plane to acromion landmark.
Biacromial breadth	Point to point distance between right and left acromion landmarks.
Bideltoid breadth	Point to point distance between right and left deltoid point, lateral landmarks.
Bimalleolar breadth*	Point to point distance between malleolus, lateral and malleolus, medial landmarks of the ankle.
Buttock–knee length*	Shortest perpendicular distance from seat back plane to knee point, distal.
Buttock–popliteal length*	Shortest perpendicular distance from seat back plane to popliteal point.
Elbow rest height*	Vertical distance from floor plane to elbow rest plane.
Eye height*	Vertical distance from floor plane to ectocanthus.
Forearm to forearm breadth	Point-to-point distance between right and left forearm point, lateral landmarks.
Hand breadth*	Point-to-point distance between the MCPII point, medial landmark and MCPV point, lateral landmark.
Hip breadth	Point-to-point distance between the right and left hip point, lateral landmarks.
Knee height*	Vertical distance from floor plane to suprapatella landmark.
Knee to footrest height*	Shortest perpendicular distance from footrest plane to suprapatella landmark.
Overall depth	Distance between parallel vertical planes that cross the anterior-most point and posterior-most point of wheelchair or occupant.
Overall height	Vertical distance from the floor plane to the vertex.
Overall breadth	Distance between parallel vertical planes that cross the left and right lateral-most point landmarks.
Sitting height	Vertical distance from the seat pan plane to vertex.
Thigh breadth	Point-to-point distance between the left and right thigh point, lateral landmarks.
Waist breadth	Point-to-point distance between the left and right waist point, lateral landmarks.
Wrist height*	Vertical distance from the floor plane to the radial styloid.

*Measurements made on left and right side of body.

(Kleinbaum et al., 1988). Since the correlation of dimensions is useful in the application of anthropometric data in design, Pearson's correlation coefficients (r), stratified by gender and chair type, were calculated for height dimensions. Analyses were completed using the statistical analysis system (SAS) statistical software program for the personal computer (SAS Institute, 2002).

3. Results

3.1. Study sample

The study sample consisted of 75 males and 46 females who used wheelchairs as their primary means of mobility on a regular basis. The average age (standard deviation) for participants was 51 (16) years, with a range of 22–94 years. The average years (standard deviation) with disability was 25.2 (17.2) years with a range of one half year to 69 years. The number of male and female manual and powered wheelchair users for different categories of disability is shown in Table 3. Almost half of the sample (46%) used powered wheelchairs. Of those that used powered wheelchairs, more than half reported their primary disability to be a disorder of the central nervous system such as cerebral palsy. The sample overall had a larger proportion of powered wheelchair users with more severe physical limitations than what might be expected in the United States population of wheelchair users (Jones and Sanford, 1996).

3.2. Wheelchair characteristics

One-third of all wheelchairs sampled had a headrest, trunk lateral support, thigh lateral support or other positioning support. A majority of the postural supports (81%) were found on powered wheelchairs, with the trunk lateral

Table 3
Number of study participants by disability category, chair type and gender

Disability	Males		Females		Total
	Manual chair	Powered chair	Manual chair	Powered chair	
Spinal cord injury	9	11	1	0	21
CNS disorder	8	18	15	13	54
Orthopedic injury or deformity	10	3	7	1	21
Cerebral vascular disease	2	3	4	0	9
Respiratory or cardiovascular disorder	4	1	0	0	5
Other	4	2	1	4	11
Total	37	38	28	18	121

supports being the most common postural support for all powered wheelchair types. Trunk lateral support accounted for almost half of all postural supports (47%). One half of the armrests on manual chairs were height adjustable. The swing-away footrest was the most common type of footrest on the manual chair. For powered chairs, rear wheel drives accounted for 66% of the drive wheels, and middle wheel drives accounted for 28% of the drive wheels. A hand controller accounted for almost 97% of all controllers. Over half of the participants in this study carried at least one piece of luggage such as a backpack or satchel on their wheelchair. Luggage was most often carried on the back of the chair (69%). The wheelchair type most likely to have luggage was the power wheelchair (67%). Only 6% of all participants carried more than one piece of luggage. Of those who did, the side and back combination accounted for 75% of the luggage combinations.

3.3. Structural dimensions

The structural dimensions of the manual and powered wheelchair users by gender are summarized in Tables 4 and 5. Goodness of fit tests on the overall sample and samples of women and men indicated that less than 1/3 of the dimensions were not normally distributed ($p<0.05$). Often distributions found to be non-normal had median (50th percentile) values that were close to the mean values. In some cases, the median approximated the middle of the 5th and 95th percentile values of the dimensions, suggesting fairly symmetrical distributions for these dimensions. Standard deviations of non-normally distributed dimensions have been left in the tables to allow direct comparisons of the variability in dimensions for different groups, but should not be used to estimate dimensional values of specific percentiles in the distribution.

ANOVA revealed significant differences ($p<0.05$) between men and women, and manual and powered wheelchair for some, but not all dimensions (Table 6). Significant differences between men and women were found for many of the height dimensions, as well as for biacromial breadth and hand breadth ($p<0.05$, d.o.f $=1$, 117). As expected in these cases, the heights and breadths were larger for men than for women. Differences between powered and manual wheelchair users were found for elbow rest and wrist heights as well as several of the breadth and depth dimensions. The correlations of the height dimensions also varied, to a certain extent, by gender and wheelchair type (Appendix A).

4. Discussion

4.1. Measurement considerations

In this study, three-dimensional surface anthropometric measurement methods were used to capture body and wheelchair landmarks that were

Table 4
Body and wheelchair dimensions (cm) of female wheelchair users[a]

Dimension	Overall sample ($n=46$)					Manual chair users ($n=28$)					Power chair users ($n=18$)				
	Mean	SD	5th	50th	95th	Mean	SD	5th	50th	95th	Mean	SD	5th	50th	95th
Age (years)	49.5	15.0	28	48.5	74	53.1	15.2	33	51	82	44.0	15.0	22	41	72
Heights															
Overall height	125.1	6.3	113.9	125.8	134.3	125.4	5.8	113.9	125.5	134.3	124.6	7.0	113.2	126.1	135.5
Eye height, left	113.9	6.3	104.3	114.7	123.7	113.6	5.4	104.8	114.7	123.7	114.3	7.6	99.6	115.4	124.1
Eye height, right	114.2	6.5	103.0	115.0	125.5	114.0	5.6	104.6	114.9	125.5	114.7	7.9	102.0	116.1	125.7
Acromion height, left	99.7	5.2	91.3	100.5	106.9	99.3	4.9	91.8	99.4	106.9	100.3	5.7	88.6	100.7	109.9
Acromion height, right	99.8	5.4	92.0	99.6	109.7	99.5	5.1	92.3	98.9	109.9	100.3	5.9	90.3	100.9	109.7
Elbow rest height, left	73.4	4.9	65.8	73.4	80.5	71.9	3.9	65.8	73.0	77.6	75.6	5.5	64.3	76.6	86.2
Elbow rest height, right	72.9	4.1	66.4	73.7	80.1	71.8	4.0	65.8	72.4	76.0	74.6	3.8	68.7	74.2	81.3
Wrist height, left	77.1	6.6	64.9	77.0	88.2	75.7	6.5	62.6	76.8	87.2	79.4	6.3	70.2	79.7	90.6
Wrist height, right	78.2	9.5	63.3	77.4	93.1	75.1	8.1	62.2	75.4	90.1	83	9.6	66.6	84.9	101.6
Sitting height	73.6	6.3	62.1	74.1	83.3	75.3	4.9	66.3	74.9	83.3	71	7.3	58.9	73.0	86.8
Knee to footrest height, Left[m]	45.3	7.5	30.8	45.8	55.8	47.8	6.4	32.8	48.4	56.2	41.3	7.6	23.0	42.0	55.5
Knee to footrest height, right[o,m]	44.8	7.8	30.0	45.0	55.5	46.8	7.5	30.0	47.4	55.5	41.7	7.4	25.4	42.4	56.6
Knee height, left[p]	62.1	5.4	53.9	61.4	70.8	60.4	5.2	53.8	59.4	70.4	64.6	4.6	58.3	63.9	74.1
Knee height, right	62.8	5.8	54.6	62.3	71.5	61.2	5.3	53.2	60.9	71.0	65.2	5.7	55.5	64.3	81.0
Breadths															
Overall breadth[o,m]	70.8	7.9	61.3	68.9	85.2	69.6	7.6	60.8	67.5	84.4	72.8	8.2	61.6	72.1	90.6
Bideltoid breadth	50.6	6.8	39.2	49.9	63.2	51.2	6.5	39.1	50.6	62.0	49.6	7.4	39.2	48.4	63.9
Biacromial breadth	33.5	4.1	26.9	33.7	40.5	33.6	4.3	26.9	33.8	40.6	33.4	4.0	25.5	33.3	40.5
Forearm to forearm breadth	59.9	8.1	44.8	59.7	72.6	58.5	7.8	44.9	59.2	72.6	61.0	8.5	42.4	61.2	76.5
Hand breadth, left	8.0	0.8	6.6	8.1	9.4	8.1	0.8	7.1	8.1	9.5	7.9	0.7	6.2	7.9	9.3
Hand breadth, right	8.1	0.6	7.0.	8.1	8.8	8.1	0.6	7.0	8.1	8.8	8.1	0.6	6.9	8.2	9.1
Hip breadth[o,p]	27.7	5.2	21.6	26.1	38.3	27.9	5.2	21.6	26.8	38.3	27.4	5.4	21.2	25.3	41.8
Waist breadth	43.1	5.1	36.6	43.0	51.9	43.1	4.6	36.6	42.7	50.8	43.2	6.0	32.4	43.7	53.8
Thigh breadth	44.4	8.2	33.8	43.2	60.3	43.6	7.6	33.8	42.8	59.6	45.5	9.1	31.7	43.6	65.5
Bimalleolar breadth, left	8.1	1.4	6.3	7.9	10.5	7.9	1.4	6.2	7.7	10.5	8.4	1.4	6.5	8.2	11.5
Bimalleolar breadth, right	8.4	1.4	6.7	8.1	10.6	8.2	1.4	6.4	7.9	10.6	8.6	1.3	6.7	8.4	10.7
Depths and lengths															
Overall depth	119.0	10.0	104.8	118.9	134.0	116.8	9.3	102.5	116.1	132.9	122.4	10.4	106.8	122.2	152.9
Abdominal extension depth	36.5	5.6	28.4	35.8	45.7	36.1	5.8	26.4	34.9	45.7	37.2	5.5	27.3	36.5	46.3
Buttock–knee length, left[p]	62.5	6.8	55.2	62.9	76.0	63.5	4.9	55.2	63.7	69.2	60.9	9.1	34.7	61.0	76.1
Buttock–knee length, right[o]	62.4	6.2	54.8	62.5	74.4	62.8	4.0	56.5	62.8	67.4	61.9	8.7	38.7	61.3	77.9
Buttock–popliteal length, left	52.1	5.2	45.1	51.9	58.9	52.7	4.1	46.9	51.8	58.9	51.2	6.7	35.1	51.8	65.4
Buttock–popliteal length, right[o,m]	52.8	7.2	41.5	52.6	46.4	53.6	6.7	43.4	52.9	64.6	51.5	8.0	31.7	52.6	67.2

[a] Non-normal distribution ($p<0.05$) indicated by **o** for overall sample, **m** for manual wheel chair users, **p** for power wheelchair users.

then used in the calculation of standard anthropometric dimensional values. Descriptions of the anatomical landmarks used therefore had to be modified from those often used in conventional anthropometric studies. Each participant enrolled in this study was allowed to assume a comfortable seated posture while wearing light clothing, which may have added to the variability of dimensional values within categories of gender and chair type (Feathers et al., 2004). While our measurement methods deviated from others, the value of measuring the user and wheelchair together in such a way has been described by others (e.g., Jarosz, 1996).

Table 5
Body and wheelchair dimensions (cm) of male wheelchair users[a]

Dimension	Overall sample ($n = 75$)					Manual chair users ($n = 37$)					Power chair users ($n = 38$)				
	Mean	SD	5th	50th	95th	Mean	SD	5th	50th	95th	Mean	SD	5th	50th	95th
Age	52.0	15.6	23	52	80	57.3	15.6	33	57	81	46.5	13.8	22	46	70
Heights															
Overall height	130.9	6.0	121.6	131.2	139.4	130.6	4.7	123.6	131.0	137.9	131.2	7.1	121.4	131.2	149.4
Eye height, left	119.6	5.7	111.0	119.5	127.2	119.2	4.4	111.8	119.5	126.0	120.0	6.7	110.9	119.9	137.8
Eye height, right	119.4	5.8	110.5	119.3	127.0	118.8	4.7	112.5	119.0	126.6	120.0	6.6	109.8	120.0	136.7
Acromion height, Left[o]	104.2	5.4	94.1	104.6	114.0	103.8	3.8	94.1	104.6	109.6	104.6	6.6	93.6	104.4	120.3
Acromion height, right[o,p]	104.3	5.0	94.6	104.6	113.4	103.8	4.2	93.0	104.3	109.9	104.8	5.6	94.6	104.7	119.1
Elbow rest height, left	74.1	5.8	63.9	73.5	84.0.	73.1	5.1	63.9	73.3	80.4	75.1	6.2	62.3	75.8	84.8
Elbow rest height, right	74.1	4.9	64.7	73.7	83.7	72.8	4.1	64.2	72.8	79.3	75.2	5.3	65.7	73.9	85.1
Wrist height, left	77.7	7.2	66.7	77.7	91.5	76.5	6.6	66.4	76.2	94.3	78.9	7.7	67.9	78.3	91.5
Wrist height, right	77.5	7.7	64.8	77.0	89.2	75.4	6.3	63.5	74.9	87.3	79.5	8.5	64.8	79.3	90.2
Sitting height[o]	77.3	6.0	67.8	78.6	85.0	79.6	4.7	69.4	80.3	86.7	75.0	6.3	60.1	75.6	84.5
Knee to footrest height, left[o,m]	50.5	7.1	37.8	52.5	59.0	51.9	7.4	37.8	53.2	59.4	49.1	6.6	37.8	50.3	57.8
Knee to footrest height, right[o,m]	49.6	8.1	35.9	51.6	57.3	49.7	9.8	22.5	52.7	58.9	49.6	6.2	38.2	50.8	56.8
Knee height, left	62.8	6.0	53.7	63.5	73.5	61.4	6.2	51.5	61.0	72.4	64.2	5.5	56.3	63.6	75.2
Knee height, right[o,m]	64.5	6.7	55.0	64.2	74.8	63.9	7.8	52.1	63.9	85.7	65.0	5.4	55.0	64.9	74.8
Breadths															
Overall breadth[o,m]	71.3	8.2	60.4	70.9	83.9	69.8	6.8	58.9	69.0	83.9	72.8	9.2	60.8	72.6	88.5
Bideltoid breadth	52.2	6.0	41.5	52.1	61.1	53.4	5.2	46.7	52.5	63.3	51.0	6.5	39.7	51.9	60.4
Biacromial breadth	37.1	3.6	30.6	37.5	42.3	38.6	2.8	33.8	39.0	42.4	35.75	3.8	27.7	36.6	42.2
Forearm to forearm breadth	60.1	8.2	47.5	59.3	73.7	59.0	6.5	49.2	57.9	70.1	61.2	9.5	39.1	60.7	74.7
Hand breadth, left	8.9	1.0	7.0	8.9	10.6	9.0	0.9	7.2	9.0	10.4	8.8	1.1	6.8	8.7	10.9
Hand breadth, right[m]	9.0	0.9	7.2	9.1	10.5	9.2	0.8	7.2	9.3	10.4	8.8	0.9	7.1	8.8	10.5
Hip breadth	27.0	4.1	20.7	26.7	33.9	26.3	3.9	22.4	28.0	38.7	25.8	4.0	18.4	25.5	32.8
Waist breadth	42.9	6.1	30.4	43.5	53.0	44.3	5.4	30.8	44.7	53.6	41.7	6.6	29.2	42.0	53.0
Thigh breadth	44.1	9.1	27.0	44.0	62.5	45.1	6.7	30.8	46.1	52.9	43.2	11.0	25.2	42.5	69.6
Bimalleolar breadth, left[o,m]	8.5	1.3	6.6	8.4	11.0	8.6	1.3	7.1	8.4	11.0	8.5	1.4	6.4	8.4	11.2
Bimalleolar breadth, right[o,m]	8.8	1.5	6.9	8.5	11.2	9.0	1.4	7.2	8.6	12.3	8.7	1.5	5.7	8.5	11.1
Depths and Lengths															
Overall depth[p]	122.5	10.1	109.2	123.0	141.9	123.5	10.9	107.1	124.0	146.5	121.6	9.4	109.6	118.9	138.1
Abdominal extension depth	37.1	5.5	28.2	36.1	47.4	35.6	5.0	27.0	35.5	43.7	38.5	5.7	30.6	37.6	48.8
Buttock–knee length, left[o,m]	62.3	7.4	48.9	63.8	73.2	62.4	6.1	51.1	63.8	71.2	62.2	8.5	44.9	63.8	73.6
Buttock–knee length, right	62.5	7.0	51.4	62.8	73.6	63.2	5.0	54.7	63.2	70.5	61.8	8.5	47.0	62.1	74.3
Buttock–popliteal length, left	51.8	7.1	39.4	52.4	62.6	51.7	5.8	40.5	52.7	59.8	51.8	8.2	34.6	52.0	63.9
Buttock–popliteal length, right[o]	52.0	7.4	37.0	53.0	62.9	52.2	6.8	39.2	53.1	60.9	51.8	7.9	35.1	53.1	63.1

[a] Non-normal distribution ($p < 0.05$) indicated by **o** for overall sample, **m** for manual wheel chair users, **p** for power wheelchair users.

4.2. Sampling considerations

Significant differences in dimensional values between men and women, and powered and manual wheelchair users were found for only some of the dimensions. This is most likely the result of the small sample sizes, diversity of the participants and diversity of chair models within chair types, as well as factors related to the measurement protocol. The sample sizes for categories of gender and chair type were relatively small, and a wide range of disabilities was represented in each category. Additionally, there are different types of manual and powered wheelchairs, along

Table 6
Summary of significant effects for the ANOVA on gender and chair type for the anthropometric dimensions ($p<0.05$, d.o.f = 1, 117)[a]

Dimensions	Differences between women and men	Differences between manual and powered chair users
Overall height	√	
Eye height, left and right	√	
Acromion height, left and right	√	
Elbow rest height, left and right		√
Wrist height, left and right		√
Sitting height		√
Knee to footrest height, left	√	√
Knee to footrest height, right	√	
Knee height, left and right		√
Overall breadth		√
Biacromial breadth	√	√
Hand breadth, left and right	√	
Hip breadth		√
Abdominal extension depth		√

[a] √ indicates statistical significance ($p<0.05$, d.o.f = 1, 117).

with different types of accessories that would add to the variability of dimensional values within chair type.

While significant differences between men and women, and manual and powered wheelchair users were found for some dimensions, the 5th, 50th and 95th values of dimensions between user groups in these cases still often remained within 5 cm of each other. While the differences are meaningful from a theoretical perspective, and may be important in biomechanical or kinematic modeling, differences of this magnitude may have limited practical significance to designers.

The sample described in this study was not representative of the US wheelchair user population in terms of gender, wheelchair type and disability status. For example, there is a greater proportion of powered wheelchair users included in this sample than the 7% of powered chair users estimated in US population of wheelchair users (Jones and Sanford, 1996). However, a wide range of disabilities was sampled within wheelchair type, and the results summarized in Tables 4 and 5, if used cautiously, may be useful in the design of environments that accommodate power and manual wheelchair users. Data collection efforts are continuing to increase the size and diversity of the sample to improve the quality and utility of the data set.

4.3. Comparisons with previous studies

When selected dimensions of body size are compared with other recent studies of wheelchair users, there are differences in the dimensional values. For example, in this study sitting height and biacromial breadth appear to be smaller, while bideltoid breadth appears to be larger (Table 7). Differences in the measurement methods and characteristics of the study population may explain these differences. Individuals in the current study were allowed to maintain a relaxed sitting posture during the measurement sessions and often abducted their shoulders to rest their arms on the wheelchair's arm support. Such postures would likely result in a reduction of sitting height and biacromial breadth, and an increase in bideltoid breadth when compared to those measurements recorded during erect seated postures. Additionally, the definitions of the landmarks and dimensions used in this study were slightly different than those used in previous studies. Finally, the types of disabilities represented in

Table 7
Comparison of selected dimensions (cm) for three anthropometric studies of wheelchair users

Dimension	Gender	Current study ($n = 121$)			Jarosz (1996) ($n = 169$)			Das and Kozey (1999) ($n = 62$)		
		Percentile								
		Mean	5th	95th	Mean	5th	95th	Mean	5th	95th
Biacromial breadth	Women	33.5	26.9	40.5	35.2	31.0	39.4	35.5	29.1	41.8
	Men	37.1	30.6	42.3	39.2	35.3	42.5	39.6	35.4	43.9
Bideltoid breadth	Women	50.6	39.2	63.2	n/a	n/a	n/a	46.9	38.3	55.6
	Men	52.2	41.5	61.1	n/a	n/a	n/a	51.0	45.2	56.8
Sitting height	Women	73.6	62.1	83.3	78.1	66.8	89.4	75.2	64.7	85.7
	Men	77.3	67.8	85.0	86.4	76.9	96.0	84.8	73.4	96.3

the studies also differed, potentially contributing to the observed differences.

4.4. Applications in design

The dimensions summarized in this paper have been presented in a way that allows for conventional univariate analysis for design. However, the three-dimensional information recorded in this study may improve our ability to consider multiple dimensions simultaneously, provide human models that are more lifelike, and improve location estimates of joint centers of rotation in human models (Reed et al., 1999). Perhaps one of the most valuable uses of this type of information involves allowing three-dimensional CAD designs of environments to be tested against three-dimensional human models that are derived directly from the three-dimensional coordinate data of individual participants. Use of realistic three-dimensional models and animations may also allow designers to present plans to users in a way that is easy to understand and encourages participation in the design process by user groups (Eriksson and Johansson, 1996).

The approach taken in this study towards data collection, management and display was specifically intended to address the needs of designers. Through conference presentations, workshops, surveys and interviews, new ways of presenting data in human models and in graphical and numerical displays have been developed. For this, software packages such as Microsoft Access and Microsoft Visual C++ and Open Graphics Library (OpenGL) have been used to display demographic, structural anthropometric and functional anthropometric data, and render body dimensions in three-dimensional space. Information that can be accessed easily includes photographs and videos of an individual and wheelchair, as well as the sample statistics for groups of individuals such as mean, range and standard deviation of measurements, which are calculated automatically for the overall sample or subgroups that are of interest.

Fig. 2 shows examples of early versions of a database prototype. On the left, the distribution of an anthropometric dimension, Biacromial Breadth, is displayed. The vertical bars shown in the histogram are used to mark the portion of the distribution included for a given design parameter (inside the bars). Participants falling outside the bars are listed by in the window to the left. The individual that falls outside of the bars can be selected for further study (circled). On the right is an example of an interface displaying the demographic information and structural dimensions and human model of the selected individual. The visualization of the human and chair is derived from the three-dimensional coordinates of the body and wheelchair landmarks. The human model can then be exported to CAD environments to test the fit of designs and specific individuals in this database.

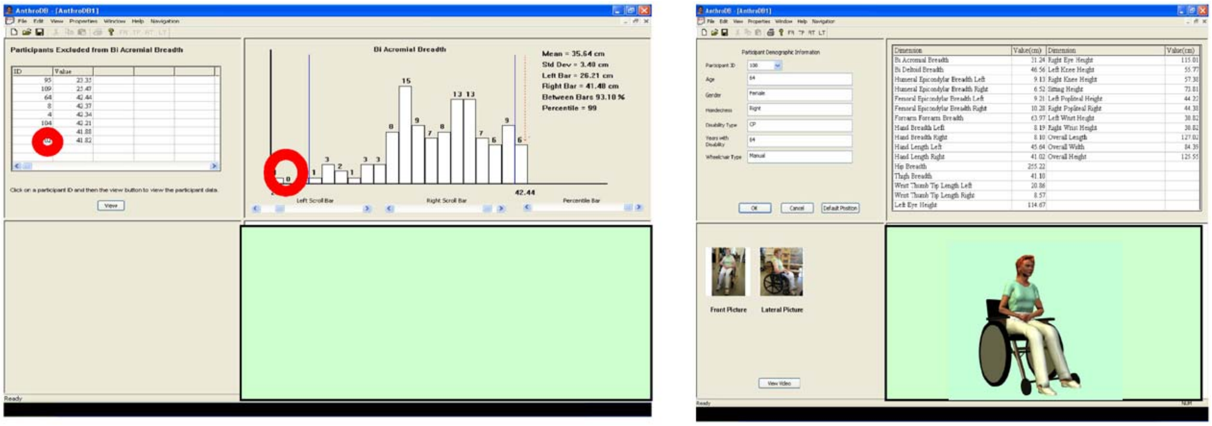

Fig. 2. Left: display showing the distribution of an anthropometric dimension. Right: display showing the demographic information, structural dimensions, sample photographs and human model of a selected individual derived from the three-dimensional coordinates of the individual's body and wheelchair landmarks.

Steinfeld et al. (2002) in summarizing key findings of a workshop held to discuss the current state of the knowledge about research and design practices related to anthropometry and disability, found that the available databases were not providing the information that designers need in a form that is easy to use. Furthermore, they concluded that using conventional anthropometric measurement techniques would adequately improve our knowledge of the anthropometry of disabled populations. While the study described here is ongoing, it attempts to address these limitations by providing data that can be used not only with conventional anthropometric methods, but introduces a prototype interface that may allow designers to use information more readily and effectively in simple ways that involve using three-dimensional human models in design.

5. Conclusion

This paper summarized the structural anthropometric dimensions of 121 male and female wheelchair users. There is a need for continued efforts that will improve our understanding of the anthropometry of wheelchair users. It appears that new measurement and data presentation methods will soon offer promising new ways to apply anthropometry in design for this important segment of the population.

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Appendix A

Correlation matrices of height dimensions by gender and chair type (see Tables 8–11).

Table 8
Female manual chair users ($n = 28$)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Overall height	1	0.87	0.95	0.88	0.81	0.37	0.44	0.11	0.16	0.70	0.42	0.34	0.28	0.39
2	Eye height, left		1	0.94	0.83	0.65	0.35	0.43	0.04	0.16	0.61	0.31	0.34	0.28	0.37
3	Eye height, right			1	0.85	0.71	0.35	0.43	0.05	0.18	0.63	0.31	0.31	0.30	0.38
4	Acromion height, left				1	0.88	0.49	0.59	0.19	0.30	0.60	0.28	0.21	0.38	0.51
5	Acromion height, right					1	0.43	0.46	0.13	0.20	0.59	0.33	0.08	0.26	0.38
6	Elbow rest height, left						1	0.93	0.53	0.68	0.10	0.10	0.01	0.55	0.56
7	Elbow rest height, right							1	0.50	0.68	0.13	0.09	0.10	0.57	0.58
8	Wrist height, left								1	0.79	−0.08	−0.02	−0.03	0.36	0.45
9	Wrist height, right									1	−0.08	−0.12	−0.12	0.53	0.57
10	Sitting height										1	0.51	0.47	−0.03	0.11
11	Knee to footrest height, left											1	0.84	0.09	0.15
12	Knee to footrest height, right												1	0.11	0.20
13	Knee height, left													1	0.90
14	Knee height, right														1

Values exceeding 0.46 are statistically significant ($p<0.01$).

Table 9
Female powered chair users ($n = 18$)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Overall height	1	0.93	0.91	0.95	0.94	0.78	0.64	0.37	0.45	0.92	0.42	0.40	0.40	0.41
2	Eye height, left		1	0.93	0.92	0.88	0.83	0.73	0.40	0.68	0.83	0.42	0.38	0.56	0.53
3	Eye height, right			1	0.86	0.88	0.85	0.78	0.39	0.51	0.80	0.42	0.35	0.54	0.50
4	Acromion height, left				1	0.95	0.86	0.62	0.40	0.55	0.86	0.50	0.48	0.49	0.47
5	Acromion height, right					1	0.85	0.56	0.54	0.54	0.85	0.53	0.51	0.46	0.48
6	Elbow rest height, left						1	0.72	0.45	0.61	0.64	0.33	0.31	0.62	0.52
7	Elbow rest height, right							1	0.20	0.54	0.55	0.18	0.07	0.38	0.21
8	Wrist height, left								1	0.51	0.25	0.24	0.34	0.32	0.42
9	Wrist height, right									1	0.33	0.26	0.22	0.53	0.47
10	Sitting height										1	0.57	0.58	0.27	0.35
11	Knee to footrest height, left											1	0.96	0.33	0.43
12	Knee to footrest height, right												1	0.31	0.48
13	Knee height, left													1	0.92
14	Knee Height, Right														1

Values exceeding 0.58 are statistically significant ($p<0.01$).

Table 10
Male manual chair users ($n = 37$)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Overall height	1	0.93	0.94	0.78	0.76	0.31	0.20	0.02	0.12	0.65	0.35	0.00	0.41	0.38
2	Eye height, left		1	0.98	0.72	0.73	0.33	0.19	0.10	0.11	0.59	0.30	0.00	0.34	0.33
3	Eye height, right			1	0.74	0.73	0.33	0.20	0.09	0.15	0.62	0.33	0.01	0.34	0.32
4	Acromion height, left				1	0.76	0.44	0.52	0.20	0.30	0.63	0.43	0.04	0.26	0.24
5	Acromion height, right					1	0.61	0.20	0.07	0.34	0.39	0.37	−0.16	0.33	0.44
6	Elbow rest height, Left						1	0.51	0.40	0.50	0.14	0.04	−0.46	−0.06	0.37
7	Elbow rest height, right							1	0.48	0.52	0.34	−0.04	−0.09	−0.13	0.16
8	Wrist height, left								1	0.73	0.01	−0.09	−0.21	−0.01	0.13
9	Wrist height, right									1	0.16	−0.05	−0.37	−0.12	0.33
10	Sitting height										1	0.29	0.14	0.01	0.07
11	Knee to footrest height, left											1	0.54	0.33	0.27
12	Knee to footrest height, Right												1	0.26	−0.23
13	Knee height, left													1	0.38
14	Knee height, right														1

Values exceeding 0.42 are statistically significant ($p<0.01$).

Table 11
Male manual powered chair users ($n = 38$)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Overall height	1	0.97	0.95	0.85	0.90	0.65	0.66	0.55	0.40	0.74	0.31	0.27	0.36	0.26
2	Eye height, left		1	0.98	0.87	0.91	0.67	0.70	0.53	0.39	0.68	0.35	0.31	0.36	0.28
3	Eye height, right			1	0.84	0.89	0.66	0.67	0.52	0.40	0.65	0.35	0.33	0.31	0.24
4	Acromion height, left				1	0.92	0.74	0.72	0.46	0.45	0.55	0.42	0.34	0.44	0.33
5	Acromion height, right					1	0.75	0.63	0.46	0.42	0.56	0.34	0.32	0.45	0.35
6	Elbow rest height, left						1	0.73	0.36	0.45	0.19	0.18	0.14	0.56	0.40
7	Elbow rest height, right							1	0.53	0.44	0.28	0.24	0.09	0.47	0.34
8	Wrist height, left								1	0.71	0.30	0.24	0.15	0.50	0.45
9	Wrist height, right									1	0.08	0.27	0.15	0.54	0.47
10	Sitting height										1	0.18	0.11	−0.12	−0.22
11	Knee to footrest height, left											1	0.78	0.41	0.41
12	Knee to footrest height, right												1	0.35	0.48
13	Knee height, left													1	0.92
14	Knee height, right														1

Values exceeding 0.42 are statistically significant ($p < 0.01$).

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