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Measurement consistency and three-dimensional electromechanical anthropometry

David J. Feathers*, Victor L. Paquet, Colin G. Drury

Department of Industrial Engineering, School of Engineering and Applied Sciences, State University of New York,
342 Bell Hall, Buffalo, NY 14260-2060, USA

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Abstract

Two pilot studies investigated potential sources of error in static human body surface measurement for conventional anthropometry methods and three-dimensional electromechanical methods under different experimental conditions. In the first pilot study, two anthropometrists measured Humeral breadth, Radiale-Stylion length and Wrist breadth of a cadaveric arm repeatedly in nearly nude and lightly clothed conditions with conventional and electromechanical approaches in two separate, repeated measurement sessions. Analysis of variance (ANOVA) performed on these measurements demonstrated significant differences across measurers, methods, the interaction between measurer and clothing, and the interaction between measurer and methods, suggesting systematic error contributions for these variables. ANOVA performed on the standard deviation of data for each anthropometric dimension showed differences across methods and clothing conditions, demonstrating differences in measurement consistency for these variables. In the second pilot study, measurement consistency was evaluated for the conventional and electromechanical methods for anthropometric measurements of ten wheelchair users who were clothed and not capable of maintaining erect seated postures for the measurement session. The measurement consistencies for repeated measurements of acromion height, biacromial breadth, eye height, knee height and waist depth obtained with each method were compared to established standards. ANOVA showed differences between methods and measurers for some of the anthropometric dimensions, although the magnitude of the differences was relatively small. Relatively low variability in measurements within method for each dimension within condition was found in both studies. This suggests that conventional dimensions recorded with three-dimensional electromechanical approaches can be measured consistently, at least for the anthropometric dimensions and experimental conditions considered in these studies.

Relevance to industry

Anthropometric data provides a valuable source of information to ergonomists and designers who attempt to consider a range of body sizes and abilities in the design of occupational environments and products. These pilot studies investigate the reliability of anthropometric data collected with conventional and new three-dimensional measurement approaches.

Keywords: Anthropometry; Electromechanical measurements; Reliability; Wheelchair users

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*Corresponding author.
E-mail address: feathers@eng.buffalo.edu (D.J. Feathers).

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1. Introduction

There is no "correct" anthropometric measurement, as an anthropometric measurement is simply a construction of an observation or recording of an attribute, which can be affected by the measurers' characteristics, methods used in measurement and the measurement environment. Measurement consistency can be ascertained with repeated measurements across time. With continued repeated measurements, the concordant measurement results establish a measure of variability within measurement, measurer and methodology applied across time. Systematic effects across these variables can be studied similarly.

Some studies involving anthropometric measurements have investigated the topic of measurement consistency in relation to intrinsic qualities of variability within a given measurement. Gavan (1950) graded anthropometry dimensions in terms of consistencies seen though expert anthropometrists. Gavan's work investigated the potential sources of variance within a given measurement, and concluded that, "consistency increased as: The number of technicians decreased, the amount of subcutaneous tissue decreased, the experience of the technician increased, and as the landmarks were more clearly defined." (Gavan, 1950) Other works looked into the consistencies within and between measurers (Gordon and Bradtmiller, 1992; Gordon et al., 1989; Ulijaszek and Mascie-Taylor, 1994), and repeated measurement consistencies across groups of measurements (Relethford, 1994). These have lead to increased awareness about sources of measurement error in anthropometry, as well as "acceptable levels" of reliability.

In an attempt to improve measurement consistency within and across individuals who are measured, the postural conditions are usually standardized to a rigidly instructed, but proprioreceptively imbalanced and erect posture. Studies that take anthropometric measurements in controlled postures or conditions remain benchmarks for the fields of anthropometry and engineering anthropometry (Dempster, 1955; Dempster et al., 1959; Kroemer et al., 1997; Roebuck et al., 1975; Stoudt et al., 1965). Other studies emphasized the standard anthropometric position when studying adults (Annis et al., 1991; Damon and Stout, 1963; Molenbroek, 1987), workers of all types (Intranont et al., 1988; Rempel and Serina, 1995), and children (Donoso, 1987; Sunnegardh et al., 1988).

Measurement over clothing is generally not recommended due to a potential increase in systematic error (Roebuck et al., 1975), and most large-scale anthropometry studies have strict guidelines regarding clothing (Gordon et al., 1989). Investigators who have evaluated the effects of clothing on measurements found that measurements taken with clothing were systematically larger than measurements made with no clothing (Paquette et al., 1999). Pett and Ogilive (1957) also found that clothing impacted correlations of height and weight. However, information about the size and abilities of clothed people has useful applications. For example, studies have sought to measure persons while in clothing to obtain measurements that were realistic in the setting to which the measurements would be applied (Anthropology Research Project (Ed.), 1978; Roebuck et al., 1975).

Despite the multitudes of studies using and reporting anthropometric data, there are few studies that have reported concerns on capturing anthropometric data and the variable nature of its results. The 1988 US Army ANSUR study offered guidelines for acceptable error estimates for a specific set of measurement conditions that include nude individuals who were measured while in erect standardized postures using conventional measurement approaches (Clauser et al., 1989). Additional efforts are needed to assess the viability of error checking mechanisms for different clothing conditions, postural considerations, and measurement approaches.

Three-dimensional anthropometry has been in use for well over a decade. Authors have described devices that have enabled this new measurement approach to be used (Annis, 1989; Brooke-Wavell et al., 1994; Coblentz et al., 1985; Hoekstra, 1997). Methods may range from manual collection of three-dimensional locations of body landmarks via electromechanical probe or electromagnetic sensing systems to three-dimensional scanning of entire body surfaces. To date, however, there has been little published literature on the measurement consistency of three-dimensional anthropometry approaches. Nor has there been literature that chronicles the differences and similarities between two- and three-dimensional anthropometry measurement approaches and output data. Only a few studies have documented how three-dimensional data can be used in designing, although it appears that three-dimensional anthropometry has some important advantages over conventional measures that include, for example, data that can be more readily used for three-dimensional human modeling (Reed et al., 2000).

The two studies reported here have investigated some potential sources of error in anthropometric measurement for conventional methods (i.e., use of anthropometers and calipers) and an electromechanical method. Of particular interest were sources of error associated with clothing, and non-standardized seated postures. The research questions included:

1. How reliable are the three-dimensional methods of data collection, as compared to the conventional approaches that employ the use of anthropometers and calipers?
2. For the three-dimensional measurement methods, will clothing lead to a systematic over-estimation of body dimension size or will it lead to greater variability in the measurements?
3. What effects do non-standardized postures assumed by users of wheelchairs have on the consistency of the anthropometric measurements obtained with conventional and electromechanical methods?

2. Study 1: measurement consistency for a cadaveric arm

2.1. Methods

Two participants with knowledge of anatomy and anthropometry laboratory experience performed repeated measures on a human cadaveric arm (male, age 68). One of the participants was a physical anthropologist with 8 years of formal coursework in musculoskeletal anatomy and research experience in the measurement of osteological features of the forearm using conventional anthropometric measurement devices. The other participant was an industrial engineer who had coursework in gross anatomy, and some experience in the collection anthropometric data using conventional anthropometric measurement tools such as anthropometers and calipers. Differences between measurers in terms of reliability were hypothesized to decrease with the repeated use of the three-dimensional approach since both participants had very little experience with the electromechanical device (three-dimensional approach).

Measurements of Bihumeral Epicondylar breadth, Radiale-Stylion length, and Wrist breadth were made. These were chosen because they are typical measurements that are widely distributed in terms of measurement consistency (Gavan, 1950). Bihumeral breadth and Wrist breadth were thought to be obtained more easily and more consistent than Radiale-Stylion length, since it requires locating body landmarks that were less prominent.

Three measurement approaches were used by each of the measurers: Conventional, an electromechanical approach that required manually identifying the specific point of interest, and an electromechanical approach that required scanning a body surface area. In the conventional approach, a sliding caliper was used to collect the Bihumeral Epicondylar breadth and the Wrist breadth measurements, and an anthropometer to collect the Radiale-Stylion length. The electromechanical device used in this study was the FaroArm™ (Faro Technologies, Florida). The device is an articulating arm with six degrees of freedom and a probe tip of 0.25 in and a reported precision of 0.3 mm. With this device, the measurer is required to manually manipulate the tip of the probe to the desired body point or area, and the device records the three-dimensional coordinates of the desired point (Fig. 1). The first electromechanical approach required the measurer to manipulate the probe tip to the desired body location, and the three-dimensional coordinates of the probe tip were recorded ("point and click" method). In the second electromechanical condition, the measurer was required to use the probe to

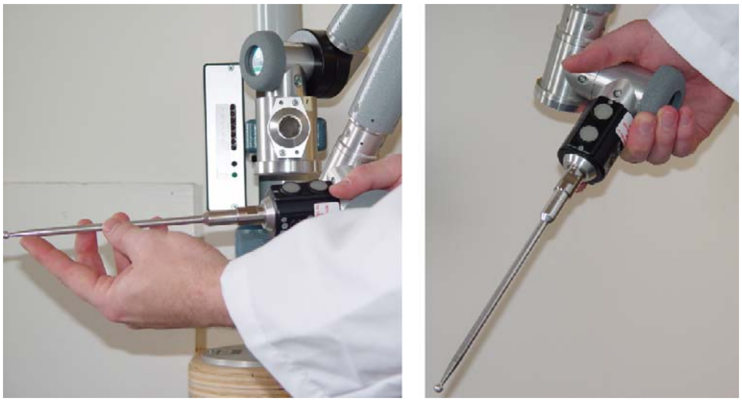

Fig. 1. The electromechanical arm used in this study had six degrees of freedom, a working radius of 2 m and accuracy of 0.3 mm. The probe tip is shown here.

manually scan a surface area that included the body location of interest. For this condition an extreme point thought to represent the body location (i.e., most inferior, superior, distal or proximal point within the scan) was automatically identified with the electromechanical device (“scan” method). The scan function was thought to automate the identification of an extreme point of interest similar to the way a caliper is swept over a body region when measuring breadths. (Fig. 2).

Measurers were blinded to the outcomes of the measurements to reduce learning effects associated with repeated measurements. The measurement marks on the calipers and anthropometers were covered throughout the measurement trials. For these measurements, the measurer adjusted the tool to the desired setting while remaining blinded to the value of the measurement and the experimenter recorded the value and readjusted the measurement device off of the desired setting. In both electromechanical conditions, the measurers were blinded to the three-dimensional coordinates of the body points that were measured, as well as the dimensions (e.g., lengths and breadths) that were calculated from the three-dimensional coordinate data.

The anthropometric measurements were calculated as the point-to-point distances between the body landmarks. Epicondylar breadth was defined as the distance between the Medial Humeral Epicondyle and the Lateral Humeral Epicondyle. Radiale-Stylion length was defined as the distance between the Radiale landmark of the Radius and the Radial-Styloid landmark of the Radius. Wrist breadth was defined as the distance between the Radial Styloid of the Radius and the Ulnar Styloid of the Ulna.

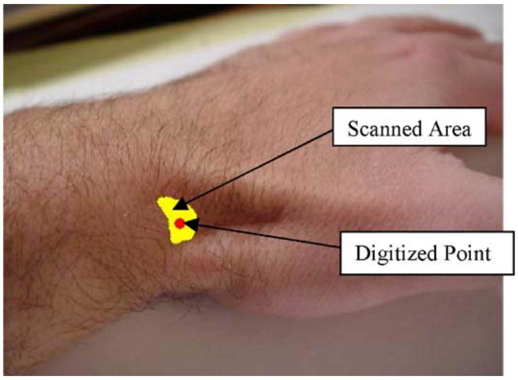

Fig. 2. An example of the area scanned with the probe and the extreme point that is digitized (Radial-Styloid) automatically.

Training was provided for all measurement approaches, anatomical landmarks and anthropometric measurements. Trial measurements were performed to introduce the participants to the measurement approaches, ensure the measurement tasks were practiced, and obtain a baseline measurement of each measurer’s ability with respect to the task. Repeated measurement sessions were conducted to evaluate the effects of measurer, measurement approach and clothing on the reliability of the measurements.

An overview session was first provided to orientate the participants to both conventional and electromechanical approaches. The session opened with a brief overview of the study. The participants were then asked to handle the instruments and take practice measurements of objects in the laboratory for approximately 2 h. This was the only time in which the participants saw the measurement marks on the conventional tools. For the remainder of the study, instrument measurement marks were covered to minimize any learning effect that could occur within method because of the repeated measurements.

Two days after the orientation session, participants returned to the laboratory and performed an initial series of measurements for attaining baseline error estimates of their respective performances. Two trials with repeated measures were performed. First, a steel bar (FaroArm Certification bar, Faro Technologies, Florida) with a rounded end was measured to allow the participants to become reacquainted with the measurement tools and methods. In the second trial, Bihumeral Epicondylar breadth, Radiale-Stylion length, and Wrist breadth were made on a skeletal arm.

In the final session of this study, measurements were made repeatedly on a cadaveric arm, which was measured while nearly nude (i.e., placed in clear shrink-wrap to maintain the integrity of the tissue) and lightly clothed. A cadaveric arm was used rather than that of a live person since the forearm was secured firmly to a tabletop throughout the experiment to minimize movement between measurements. The two participants completed all of the trials. A series of four measurements was taken per dimension and clothing condition within each of the three measurement conditions. The order of the dimensions measured was randomized within the two measurers to control for learning effects across the experiment. The method of measurement was counterbalanced.

Before beginning data collection, participants reviewed a booklet of anatomical landmarks and suggested methods of measurement. This summarized their previous training that was at their disposal for the entire measurement session. The participants then palpated and landmarked the cadaveric arm, in both clothed and unclothed conditions, with small adhesive dots and clear tape to secure the dot. The measurement session began after all landmarks were placed and secure.

Analysis of variance (ANOVA) was performed on the raw data and standard deviation of the repeated measurement trials of each dimension for the main effects and interactions of method, measurer, and clothing conditions. Method and clothing condition were treated as fixed effects, and measure was treated as a random effect. The analysis of the raw data allowed systematic effects on the measured values to be evaluated across conditions, while the analysis of the standard deviation within dimension allowed the differences in measurement consistency to be identified across conditions.

2.2. Results

In the initial measurement session used to establish baseline error estimates, both of the participants completed measurements on a skeletal forearm that secured in place. As shown Table 1, the raw data showed that measurements on a particular dimension were repeatable between 1 and 4 mm, regardless of the method used, and measurer, and statistically significant differences in measurements or measurement consistency across methods or between measurers were not found ($p > 0.05$).

In general, measurements made across conditions were relatively similar, and measurements within condition had standard deviations that were generally less than 0.2 cm. However, there were significant differences across methods ($F(2, 143) = 35.3$, $p < 0.001$) and between measurers ($F(1, 143) = 11.5$, $p < 0.001$) in the values of the anthropometric measurements. Values of dimensions for the electromechanical approaches were slightly greater than those obtained with conventional instruments. Statistically significant differences were found in measurement consistency between measurement method ($F(2, 35) = 5.6$, $p < 0.05$) clothing conditions ($F(1, 35) = 10.4$, $p < 0.001$) with the electromechanical “point and

Table 1
Measurements for initial trial measurements of a model arm (in cm)

Method	Dimension								
	Radiale-stylion length			Humeral epicondyle breadth			Wrist breadth		
	T	*P*	*S*	*T*	*P*	*S*	*T*	*P*	*S*
Measurer 1	24.4	24.8	24.2	6.0	6.5	6.4	4.6	4.7	4.8
	24.5	24.8	24.3	6.0	6.1	6.3	4.5	4.6	4.9
Measurer 2	24.6	25.1	25.2	6.2	6.3	6.2	4.7	4.0	4.3
	24.3	24.5	25.0	6.3	6.7	6.3	4.7	4.2	4.2

Note: *T* = conventional method, *P* = "point and click", *S* = scan.

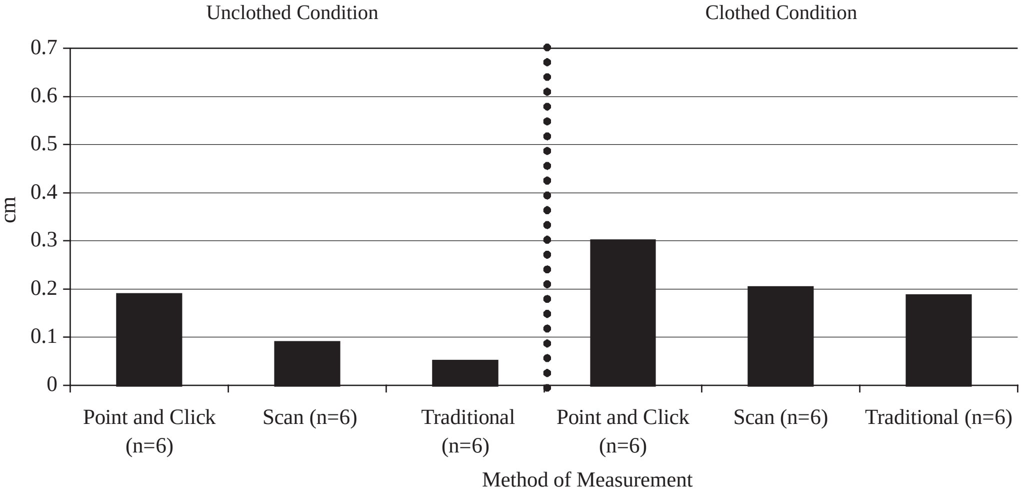

Fig. 3. Mean standard deviation for cadaveric trials under two clothing conditions for each of the measurement conditions.

click" method and the lightly clothed conditions showing the least measurement consistency (Fig. 3).

While measurements made with the electromechanical approaches were, on average, slightly greater than those obtained with the conventional approaches (e.g., Fig. 4), there were no significant effects ($p > 0.05$) across measurement methods within any given dimension.

3. Study 2: measurement consistency for wheelchair users

3.1. Methods

The conventional and electromechanical methods used in the first study were to collect anthropometric measurements for five female and five male wheelchair users. The average age (standard deviation) of the participants was 46.2 (9.8) years for the females and 47 (5.8) for the males.

For each wheelchair user, two measurers who did not participate in the first study collected two sets of measurements using the conventional approach and the electromechanical approach that employed the use of the "point and click" function. Measurers were blinded to all measurement outcomes during data collection, and the order in which the measurements were made as well as the measurement method used by each measurer was randomized across the ten participants.

During the measurement session, the wheelchair users remained in light clothing and were asked to

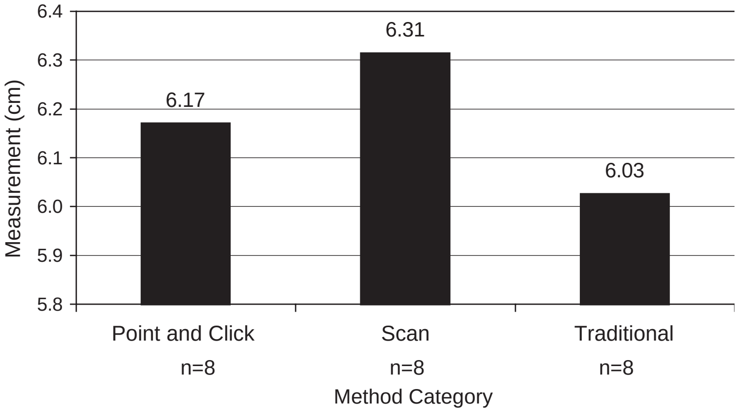

Fig. 4. Mean wrist breadth obtained with each of the methods during the cadaveric trials.

maintain a comfortable seated posture for the duration of the measurements. Each measurer performed each measurement twice with each of the measurement tools. Six dimensions were recorded and analyzed: Acromial height, Biacromial breadth, Bimalleolar breadth, Eye height, Knee height and Waist depth. Acromial height was defined as the height of the left Acromion of the seated individual to the floor. Biacromial breadth was defined as the distance of the left Acromion to the right Acromion. Bimalleolar breadth was the horizontal distance between the Medial Malleolus and the Lateral Malleolus of the left ankle. Eye height was the vertical distance of the left Ectocanthus of the seated participant to the floor. The Knee height was defined as of the vertical distance of the Suprapatella of the left Knee to the floor. Waist depth was defined as the horizontal depth of the Abdominal point (Omphalion) to the seat back in the mid-sagittal plane. These measurements were selected because they represent a range of measurement difficulty (Gavan, 1950) and are different in terms of what might be expected in terms of their consistencies (Gordon et al., 1989).

ANOVA was used to identify systematic differences between methods (fixed effect) and measurers (random effects) in terms of measurements and measurement consistencies. The absolute value of the difference between the two measurements within condition (i.e., mean absolute difference) was compared to guidelines of acceptable values previously established for anthropometric studies of nearly nude military personnel (Clauser et al., 1989).

3.2. Results

Statistically significant effects between methods and measurer on the anthropometric dimensions were found, but the magnitude of the differences was relatively small. ANOVA showed statistically significant differences in measurements between methods for Acromion height ($F(1, 9)=5.6$, $p<0.05$), Biacromial breadth ($F(1, 9)=11.2$, $p<0.01$) and Eye height ($F(1, 9)=7.1$, $p<0.05$). In these cases, the electromechanical method registered measurements that were approximately 0.3 cm smaller than those made with the conventional instruments. Significant effects for measurers were also found for Biacromial breadth, with average differences of 0.5 cm between measurers. Differences between measurers for other dimensions were not significant and averaged approximately 0.2 cm.

The mean absolute differences between measurements within dimension recorded for each of the measurement methods suggest that the reliability of the methods is similar but not always within the maximum tolerable error suggested by Clauser et al. (1989) (Table 2).

Table 2
Mean absolute differences (cm) between trials for each of the methods and researchers for dimensions taken in preferred and standardized seated postures

	Researcher 1		Researcher 2		Max. tolerable error (Clauser et al., 1989)
	Conventional	Electromechanical	Conventional	Electromechanical	
	Trial 1 vs. Trial 2	Trial 1 vs. Trial 2	Trial 1 vs. Trial 2	Trial 1 vs. Trial 2	
Acromial height	0.7	0.9	0.6	0.6	0.7
Biacromial breadth	0.9	0.6	1.0	0.9	0.8
Bimalleolar breadth	0.2	0.3	0.1	0.3	0.2
Eye height	0.8	0.8	1.0	0.7	0.8
Knee height	0.4	1.3	0.4	1.1	0.2

4. Discussion

The results of these pilot studies suggest that measurement method, clothing and measurer are sources of systematic and random error. Recordings made with the electromechanical approaches were on average 0.1–0.4 cm greater in the cadaveric trials, depending on the type of electromechanical approach and the body dimension, than those made with the conventionally instruments. The differences were greatest between the electromechanical "point and click" measurements and the conventional measurements. In the study of wheelchair users, the electromechanical measurements tended to be smaller than those made with the conventional approaches. While knowledge about the magnitude of the systematic differences for the different conditions studied here could be used to estimate "correction factors" that allow measurements collected with the electromechanical approaches to be made comparable to those collected with the conventional approaches, the results suggest that systematic corrections will be unique to different anthropometric dimensions. Interestingly, clothing did not introduce systematic increases in the measurements made with any of the approaches used in this study, which contradicts the findings of other researchers (e.g., Paquette et al., 1999). There may be a random measurement error due to covering the landmark that serves to mask the systematic measurement effect of clothing. As expected, some differences in the measurements between measurers were found, although measurer each in the pilot studies were able to record values with a relatively high degree of consistency.

In the pilot study of wheelchair users, with the exception of knee height, measurements were made consistently with both the conventional and the electromechanical measurement methods. For some dimensions, particularly knee height, the mean absolute difference of measurement values exceeded maximum tolerable errors that had been established in previous anthropometric studies of army personnel who were required to hold fixed erect postures (Clauser et al., 1989). This is not surprising since the wheelchair users in this study were clothed and were not necessarily able to hold the same posture between measurements. As shown in the first study, even light clothing appears to affect the consistency of measurements. Changes in posture between measurements would also result in inconsistent results.

A couple of limitations associated with the research should be mentioned. First, in each pilot study, only two measurers were included in the evaluation. While this may not have affected the statistical outcomes of the study, a much better understanding of the variance related to different measurers would have been obtained if more measures had been included. Additionally, analysis was performed only for a small set of anthropometric measurements intended to represent a range in difficulty, but how generalizable these results are to other anthropometric dimensions is not known.

The use of the electromechanical approaches has some inherent advantages of the conventional methods of measurement. The results of the studies demonstrate that novice users of the instrumentation can learn to collect measurements about as consistently as those made with conventional methods in a much shorter time period. Since the electromechanical measurements are derived from the three-dimensional locations of body points that are recorded, three-dimensional computerized models of the body features may be more directly and more easily constructed with the data.

The technology developed within the past 20 years has enabled three-dimensional anthropometry to be used in a variety of settings. As was pointed out in this paper, there appears to be systematic differences that exist between conventional and three-dimensional anthropometric data. One of the contributing factors might be caused by the complexities with rendering simple anthropometric dimensions from three-dimensional coordinate information, while another may have to do with differences in the task requirements between the measurement methods. Conventional definitions used for anthropometric dimensions and statistical considerations of acceptable margins of error tolerances may require modification prior to their use in three-dimensional anthropometry.

5. Conclusions

These pilot studies investigated the potential sources of error within anthropometry measurements collected for a cadaveric arm and a group of wheelchair users. There were some small systematic differences in measurements made between conventional and electromechanical methods. The reliability of the electromechanical methods was comparable to, but not better than, the conventional methods. Contrary to prior studies, clothing did not systematically increase the measurements but reduced measurement consistency for all of the methods used. Measurements made on lightly clothed wheelchair users seated in comfortable postures suffered slightly in their consistency but were generally at or within maximum tolerable errors established previously. Further work is needed to fully delineate all factors that play both an independent and interactive role in measurement consistency.

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