**Comparison of a Semi-Automatic Protocol Using Plastering and 3D Scanning Techniques with the Direct Measurement Protocol for Hand Anthropometry**

**Abstract**

The present study aimed to compare a 3D semi-automatic measurement protocol (3D-SAMP) which measures hand dimensions using a plaster hand and a 3D scanner with the conventional direct measurement protocol (DMP). An experiment was conducted to measure 52 dimensions of one hand by 20 measurers with 3 repetitions. The locations of landmarks attached to the plaster hand were automatically identified and then measurements of the hand dimensions were automatically extracted in the 3D-SAMP. Significant measurement differences with a range of 2.1 to 4.4 mm between the 3D-SAMP and the DMP were observed in 13 out of the 52 dimensions and the 3D-SAMP showed better reliability than the DMP in terms of intra- and inter-measurer variability. The 3D-SAMP was found significantly faster and easier in hand measurement than the DMP (11.1 ± 3.5 min. for 3D-SAMP and 17.8 ± 4.5 min for DMP; 5.2 ± 0.8 for 3D-SAMP and 4.3 ± 0.8 for DMP using a 7- point scale with 1 for very dissatisfied and 7 for very satisfied for ease of measurement) when fabrication (about 1 hour 10 min.) and scanning (3 min.) of a plaster hand were not considered. The proposed 3D-SAMP is applicable only to plaster hands available in hand measurement.

**Keyword**: hand anthropometry, 3D scanning, semi-automatic measurement, direct measurement, performance evaluation

**1. Introduction**

Hand anthropometric data are of use to design the size and shape of a hand-held or hand-wearable device for proper fit, comfort, and motion economy. Comprehensive, in-depth hand anthropometric surveys have been reported by Greiner (1991) for the U.S. Army personnel (*n* = 2,307, 84 dimensions), M. Kwon, Choi, Chung, and Yang (2005) for Korean civilians (*n* = 265, 63 dimensions), Chandra, Chandna, and Deswal (2011) for the industrial workers of India (*n* = 878, 37 dimensions), and Mandahawi, Imrhan, Al-Shobaki, and Sarder (2008) for Jordanian civilians (*n* = 236, 24 dimensions). Examples of hand anthropometric data application to ergonomic design include a glove design study by Choi, Lee, Kang, and Kim (2006) and O. Kwon, Jung, You, and Kim (2009), a spoon for children by Liu, Tseng, Wu, and Liu (2008), and a grip design of vacuum cleaner by Lee, Jung, and You (2008) for better fit, comfort, and motion economy.

Measurement protocols including a direct measurement protocol (DMP), a photogrammetric method (PM), and a 3D scanning method (3D-SM) have been utilized to collect hand anthropometric data, each having pros and cons in terms of accuracy, reliability, availability of post-measurement, time efficiency, cost, and usability. First, the DMP (using tape measures, measuring rods, calipers, and thickness gauges) is simpler and less expensive (Son, Kim, Choi, Sohn, & Kim, 2003), but subject to measurement error due to skin deformation when a measurement instrument is applied to the hand (Han & Nam, 2004). Next, the PM (using a camera or a 2D image scanner) collects post measurements from a 2D captured image of the hand (Ozsoy, Demirel, Yildirim, Tosun, & Sarikcioglu, 2009), but subject to measurement error caused by camera lens distortion, parallax, and/or skin deformation due to use of a support for the hand. Furthermore, the PM is inapplicable to some dimensional types such as thickness and circumference (Jang, Kim, & Kim, 1989). Lastly, the 3D-SM which uses a 3D laser or optical scanner is more sophisticated, collects post measurements, and measures not only simple dimensions such as length and circumference but also complex dimensions such as shape, surface area, and volume (Chang, Li, Cai, & Dempsey, 2007; Lee et al., 2013; Lee, Yoon, & You, 2010, 2011; Weinberg, Scott, Neiswanger, Brandon, & Marazita, 2004). However, the 3D-SM is more expensive and subject to significant measurement error due to lack of scanner resolution for correct identification of fine lines and landmarks on the hand, occurrence of hidden hand regions (Figure 1.a), sway of the hand during scanning (Figure 1.b), and/or skin deformation from using a support for the hand (Choi et al., 2006; Kim & Nam, 2001; Li, Chang, Dempsey, Ouyang, & Duan, 2008).

[Figure 1 about here]

Of the three measurement protocols the 3D-SM having the most prospective applicability to design the complex 3D shape of the hand-product interface, research is necessary to develop an effective method for better accuracy, reliability, and usability in 3D hand measurement. Enciso, Shaw, Neumann, and Mah (2003) established a gold standard for 25 head dimensions based on 47 landmarks manually identified on a mannequin head by two measurers with 10 repeated measurements using a MicroScribe 3D digitizer (Immersion Corporation, U.S.A.). Then, the 3D-SM was applied to measurement of the head dimensions using landmarks manually identified on a 3D digital head scanned from the mannequin head. The measurements using the 3D-SM were found quite similar (measurement differences < 1.55 mm) with the corresponding golden standard for all the 25 dimensions. Li et al. (2008) used a glass support in hand measurement to avoid a sway of the hand during scanning to increase the reliability of the 3D-SM. In their study, one measurer measured 64 hand dimensions with 10 repetitions through the 3D-SM and the DMP. The measurements using the 3D-SM were found reasonably similar with the corresponding measurements using the DMP: 61 out of the 64 hand dimensions showed their measurement differences ≤ 2 mm. However, Li et al.’s hand measurement method needs to be improved for better usability because the hand on the glass support is required to be stationary for about 8 min. Weinberg et al. (2004) applied the 3D-SM and the DMP to measurement of 19 facial dimensions for 20 participants by two measurers with two repetitions for one measurer and no repetition for the other. The 3D-SM was found more reliable (intra-measurer variability: SD = 0.12 ~ 1.25 mm; inter-measurer variability: SD = 0.03 ~ 1.33 mm) than the DMP (intra-measurer variability: SD = 0.49 ~ 1.30 mm; inter-measurer variability: SD = 0.51 ~ 1.39 mm).

The present study is intended to compare a 3D semi-automatic measurement protocol (3D-SAMP) which uses the 3D scanned image of a plaster hand with the DMP in terms of measurement difference, inter- and intra-measurer variation, time efficiency, and subjective satisfaction. A plaster hand was used in the present study for evaluation of the 3D-SAMP due to the aforementioned technical limitations of 3D scanning technology in hand measurement when a real hand is directly captured. The proposed 3D-SAMP was applied to measurement of 52 hand dimensions and compared with the DMP.

**2. 3D Semi-Automatic Measurement Protocol**

The 3D-SAMP applied in this study consists of four steps (Figure 2): (1) fabricating a plaster hand, (2) attaching landmarks on the plaster hand using marking stickers, (3) scanning the plaster hand with landmarks and automatically identifying the 3D locations of the landmarks, and (4) extracting measurements automatically for the hand dimensions based on the identified 3D landmark locations.

[Figure 2 about here]

*2.1. Fabricating a Plaster Hand*

A plaster hand is fabricated from the hand to be measured to prevent potential errors due to a sway of the hand and skin deformation due to the use of a hand support. The hand is molded in a container with alginate gel (water: alginate = 1: 2) for 3 minutes. Then, plaster mixed with water (water: plaster = 1: 3) is poured into the hand mold and solidified for 1 hour. Lastly, the coagulated plaster hand is carefully removed from the alginate mold for 5 minutes (see Figure 2.a). Plaster hands in two different extended postures (one with fingers together except the thumb and one with fingers apart) are prepared to measure various hand dimensions (Choi et al., 2006).

*2.2. Landmarking the Plaster Hand*

Marking stickers (*φ* = 2.5 mm, thickness = 0.5 mm) are attached to locations on the plaster hand designated for a set of hand dimensions under measurement. Marking stickers are used in 3D optical scanning as reference points to merge images captured in multi viewpoints into one 3D digital hand. This study uses marking stickers not only for image merging but also for hand landmarking. As illustrated in Figure 3, two landmarks are used as reference points to measure hand dimensions of length, width/breadth, and thickness and four landmarks to measure hand dimensions of circumference. A pair of tweezers is used to exactly locate the center of a sticker onto a designated landmark location on the plaster hand (see Figure 2.b and Figure 4.a).

[Figure 3 about here]

[Figure 4 about here]

*2.3. Extracting 3D landmarks*

The landmarked plaster hand is scanned for 3 minutes to generate a digital hand and the 3D locations of landmarks are extracted automatically (see Figure 2.c) by the ezScan (Solutionix Corp., Seoul, South Korea) scanning program. Images of the 3D hand captured at various viewpoints are aligned and merged into a single digital hand by referencing to the attached landmarks using ezScan (see Figure 4.b). Then the 3D coordinates of the landmarks are automatically extracted and stored in a file for post processing. The 3D scanned hand is composed of around 400,000 ~ 500,000 point cloud data.

*2.4. Extracting Hand Measurements*

Measurements of hand dimensions are automatically extracted by a software program which identifies the landmarks and calculates distances and circumferences using the identified landmarks (see Figure 2.d). This study developed a hand measurement program using MATLAB™ 2010a (The MathWorks, Inc., Natick: MA, USA) which can automatically identify the landmarks for hand dimensions being measured (Figure 5) then extract measurements of the hand dimensions. Euclidean distances between landmarks were calculated for the measurement of length, width, and depth dimensions. Circumferences were measured based on point cloud along circumference landmarks using a convex hull algorithm (Lu & Wang, 2008).

[Figure 5 about here]

**3. Evaluation of the 3D-SAMP**

An experiment was administered to evaluate the proposed 3D-SAMP in comparison with the conventional DMP in terms of measurement difference, reliability, time efficiency, and subjective satisfaction.

*3.1. Participants*

A measurement experiment of hand dimensions on a real hand and its plaster hand was conducted with 20 measurers (12 males and 8 females). The right hand (length = 197.1 mm and breadth = 89.7 mm) and its plaster hand of a male (stature = 180 cm and weight = 77 kg) were measured in the experiment. The measurers were graduate students aged 23 to 30 (25.0 ± 2.2) without having experience with anthropometric measurement. They practiced measuring hand dimensions based on the DMP and 3D-SAMP for more than half an hour before the main experiment. Their participation was compensated.

*3.2. Apparatus*

In the DMP several measurement tools (digital caliper and tape measures) were used. Lengths, widths, and thicknesses of the hand were measured by a digital caliper (CP-20PS, Mitutoyo America Corp., Aurora: IL, USA). Circumferences were measured by appropriate tape measures selected by considering their features: hand circumference by a generic retractable tape measure, wrist circumference by the Baseline® Circumference Tape (Model 12-205; Fabrication Enterprises Inc., White Plains: NY, USA), and finger circumference by the Baseline® Finger Circumference Gauge (Model 12-1221; Fabrication Enterprises Inc., White Plains: NY, USA).

In the 3D-SAMP, plaster hands, marking stickers, tweezers, and a 3D scanner were used. Thirty replicates of the original plaster hand were prepared in the study for efficient experimentation. Plaster hands landmarked by the measurers were captured by the Rexcan 560 scanner (Solutionix Corp., Seoul, South Korea) and processed by the ezScan 4.5.7 scanning program; 3D scanning was conducted by an experimenter.

*3.3. Experiment Design*

The measurers collected measurements of 52 hand dimensions 3 times on different days with the same real hand by following the DMP and with a plaster hand by following the 3D-SAMP. The 52 hand dimensions (length: 27, width: 11, thickness: 7, and circumference: 7) were selected among 169 hand measurement dimensions (length: 116, width: 18, thickness: 17, and circumference: 18), which were identified from a review of 8 articles (Choi et al., 2006; Garrett, 1970; Greiner, 1991; Hidson, 1991; M. Kwon et al., 2005; Lim, 2005; Robinette & Annis, 1986; Ryu & Suh, 2004), because they were commonly measured in previous studies. Graphical charts of the selected hand dimensions and their corresponding landmark positions (45 landmarks on the hand with fingers apart and 8 landmarks on the hand with fingers together) were provided for the DMP and 3D-SAMP as illustrated in Figures 6 and 7.

[Figure 6 about here]

[Figure 7 about here]

The experiment was conducted by following a four-step procedure: (1) introduction to the experiment and signing an informed consent form, (2) practice of the DMP and 3D-SAMP, (3) administration of the main experiment, and (4) evaluation of subjective satisfaction in terms of ease of measurement. The experiment was separated into two 20-minute sessions of the DMP and 3D-SAMP and a 10-minute break was provided between the sessions. Graphical charts of the selected hand dimensions and their corresponding landmark positions were provided for the DMP and 3D-SAMP as illustrated in Figure 7. Hand breadth, wrist breadth, hand circumference, and wrist circumference were measured on the hand with fingers together and the others on the hand with fingers apart. The experiment was repeated on three different days with an interval of more than 24 hours to examine the reliabilities of the DMP and 3D-SAMP. The measurement order of the DMP and 3D-SAMP was counterbalanced among measurers, sessions, and repetitions.

*3.4. Evaluation Method*

The 3D-SAMP and DMP were compared by four criteria: measurement difference, reliability, measurement time, and subjective satisfaction. The measurement difference refers to the subtraction between the measurements by the 3D-SAMP and DMP. The reliability of each measurement method was evaluated by the intra- and inter-measurer variations in SD and coefficient of variation (CV). Weinberg, Scott, Neiswanger, and Marazita (2005) and Li et al. (2008) suggested 2 mm of SD and 5% of CV as criteria of satisfactory reliability for hand measurement. The completion time of measuring the 52 hand dimensions was recorded for each measurement method. The times of fabrication and scanning of a plaster hand were not included in measurement time because they were performed by the experimenter. Lastly, ease of measurement was evaluated by a 7- point scale (1: very dissatisfied; 7: very satisfied).

**4. Results**

*4.1. Measurement Difference*

Significant differences of measured values between the 3D-SAMP and the DMP appeared on 13 out of 52 hand dimensions (Table 1). The measurement differences were analyzed by the paired *t*-test at *α* = 0.05. Significant differences were observed more in thickness dimensions (6 out of 7 dimensions) but no significant differences in circumference dimensions. In addition, the measured values of the 3D-SAMP were found smaller on average by 2 to 3.5 mm in length dimensions but larger by 2 to 4.5 mm in width and thickness dimensions than those of the DMP. Also 1.7% of measurement error due to use of plaster hand was identified by comparing the diameter (30.0 mm) of an aluminum cylinder with that (30.5 mm) of the corresponding cylinder plaster.

[Table 1 about here]

*4.2. Reliability*

The intra- and inter-measurer reliabilities of the 3D-SAMP were far better than the DMP (see Table 2). In terms of intra-measurer SD, 10 dimensions of the DMP exceeded the satisfactory SD reliability criterion (SD = 2 mm), while any dimension of the 3D-SAMP was not greater than the SD reliability criterion. In terms of inter-measurer SD, 16 dimensions (SD = 2.2 ~ 11.1 mm) of the DMP and only 1 dimension (digit 3 proximal phalanx link length, SD = 2.02 mm) of the 3D-SAMP exceeded the SD reliability criterion. Moreover, in terms of intra-measurer CV, 4 dimensions (CV = 5.5% ~ 7.1%) of the DMP and only 1 dimension (digit 1 proximal phalanx link length, CV = 7.1%) of the 3D-SAMP were greater than the CV reliability criterion (CV = 5%). Lastly, in terms of inter-measurer CV, 13 dimensions (CV = 5.2% ~ 14.9%) of the DMP and only 1 dimension (digit 1 proximal phalanx link length, CV = 6.0%) of the 3D-SAMP exceeded the SD reliability criterion.

[Table 2 about here]

*4.3. Measurement Time*

The completion time of the 3D-SAMP was significantly faster than the DMP (*t*(59) = 13.23, *p* < 0.001). The average measurement time of the 3D-SAMP was 11.1 minutes (SD = 3.5), while that of the DMP was 17.8 minutes (SD = 4.5).

*4.4. Subjective Satisfaction*

The satisfaction of the 3D-SAMP for ease of measurement was significantly higher than the DMP (*t*(19) = 2.85, *p* = 0.01). The average value of subjective satisfaction of the 3D-SAMP was 5.2 (SD = 0.8), while that of the DMP was 4.3 (SD = 0.8).

**5. Discussion**

The present study proposed a semi-automatic hand measurement protocol and found the proposed protocol superior to the DMP in measuring hand dimensions. The proposed 3D-SAMP uses a 3D digital hand by scanning a plaster hand instead of a real hand due to errors from a sway of the hand during hand scanning. A plaster hand was fabricated using an alginate mold which can elaborately duplicate the real hand. By using the plaster hand, problems of the previous measurement protocols (Chang et al., 2007; Choi et al., 2006; Kim & Nam, 2001; Li et al., 2008) such as instability and skin deformation of the hand could be resolved. Furthermore, by using marking stickers for landmarking, the 3D-SAMP could automatically extract the 3D locations of the landmarks and corresponding hand measurements (lengths, widths, thicknesses, and circumferences).

The 3D-SAMP was found more reliable and efficient than the DMP when the times of fabrication and scanning of a plaster hand are not considered; but, the opposite can become true for time efficiency and subjective satisfaction. Out of the 52 hand dimensions, only two (digit 1 proximal phalanx link length and digit 3 proximal phalanx link length) of the 3D-SAMP exceeded the satisfactory reliability criteria (SD = 2 mm and CV = 5%), while 16 dimensions of the DMP did not meet the satisfactory reliability criteria. This high reliability of the 3D-SAMP was achieved from the use of a plaster hand which prevents errors from skin deformation and posture instability caused by scanning a real hand. Exceeding of the satisfactory reliability criteria on digit 3 proximal phalanx link length (intra-measurer SD = 2.1 mm) and digit 1 proximal phalanx link length (intra-measurer CV = 7.1%; inter-measurer CV = 6.0%) might be caused by ambiguous landmark locations of the middle of the digit 3 knuckle and the middle of the digit 1 first crease. However, the reliabilities of the two dimensions can be improved by clear identification of corresponding landmarks. Furthermore, the present study more precisely examined intra- and inter-measurer variabilities using measurements collected by multiple measurers (*n* = 20) with 3 measurement repetitions than other studies such as Li et al. (2008) and Weinberg et al. (2004) which analyzed measurements collected by one or two measurers without repetition or with 2 measurement repetitions. Lastly, the 3D-SAMP required 62% shorter time compared to the DMP in measuring the 52 hand dimensions.

For accuracy analysis of anthropometric measurement methodologies, not only true values of the hand dimensions but also comprehensive understanding about measurement errors are required. The differences of measured values between the 3D-SAMP and DMP were significant on 13 dimensions (length: 3, width: 4, thickness: 6) out of the 52 dimension. Of the dimensions showing significant differences, 3 length dimensions (base of digit 1 to wrist crease center, base of digit 4 to wrist crease center, and base of digit 5 to wrist crease center) of the DMP were larger by 2.1 to 3.5 mm than the 3D-SAMP, which might be caused by a movement of the hand in flexion/extension and/or abduction/adduction during measurement. On the other hand, width and thickness dimensions of the DMP were smaller by 2.1 to 4.4 mm than the 3D-SAMP, which might be caused by skin deformation due to the application of measurement tools (digital caliper and tape measure) on the hand. However, the accuracy of the 3D-SAMP could not be analyzed in this study because the true values of the hand dimensions are unavailable. The measurement differences can be explained by various reasons such as different measurement methods (e.g., 3D-SM vs. DMP), skin deformation caused by the use of an anthropometer or a glass support, error of reading gradation, distortion of a plaster hand during fabrication, error of a 3D scanning system, and/or error of aligning and merging 3D images of the hand (Aldridge, Boyadjiev, Capone, DeLeon, & Richtsmeier, 2005; Bougourd, Dekker, Ross, & Ward, 2000; Enciso et al., 2003; Lee et al., 2010; Li et al., 2008; Weinberg et al., 2004). Skin deformation errors caused by the use of an anthropometer can be analyzed by comparing measurements of a real hand with those of its plaster hand using the DMP. About 1.7% of distortion error caused by plaster hand fabrication was identified by comparing the diameter (30.0 mm) of an aluminum cylinder with that (30.5 mm) of the corresponding cylinder plaster.

The subjective satisfaction about ease of measurement of the 3D-SAMP (average = 5.2, SD = 0.8) was found higher than the DMP (average = 4.3, SD = 0.8). Previous studies did not conduct a subjective satisfaction analysis to investigate the usability of anthropometric measurement methods. The 3D-SAMP which uses a plaster hand was preferred to the DMP because locating landmarks on the plaster hand is easier than direct measurement of hand dimensions and hand measurements are automatically obtained by scanning the plaster hand with landmarks. Furthermore, the 3D-SAMP would be more preferred to Li et al.’s 3D-SM by requiring a shorter interaction time with a participant: 2 ~ 3 min for hand fabrication in the 3D-SAMP versus about 8 min for keeping the hand stationary during scanning in Li et al.’s 3D-SM. However, the DMP can be preferred to the 3D-SAMP if the times of fabrication and scanning of a plaster hand are considered.

Lastly, further research is needed to improve performance and capabilities of the 3D-SAMP for efficient hand measurement. This study compared the 3D-SAMP with the DMP on 52 out of 169 hand dimensions and thus a comparative evaluation study is needed for the unmeasured hand dimensions with various hand sizes. And the 3D-SAMP can have a limited application to a large-scale anthropometric study of the hand due to time and cost required for fabrication and 3D scanning of a plaster hand. However, if an advanced 3D scanner which enables to capture a real hand with high accuracy is developed, a pre-landmarked human hand will be directly scanned and measured in a short time by applying the automatic landmark identification and measurement extraction processes employed in the 3D-SAMP. The 3D-SAMP would be more effective than the DMP in case of measurement of a large number of hand dimensions (say, over 50 dimensions) and complex dimensions such as curvature, arc, and circumference.

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**List of Figures**

Figure 1. Examples of hand scans with improper quality due to (a) occurrence of hidden hand regions and (b) sway of the hand during scanning

Figure 2. The process of 3D semi-automatic measurement protocol (3D-SAMP)

Figure 3. Figure 3. Landmarking (illustrated): (a) hand length, (b) hand breadth, (c) hand thickness, and (d) distal circumference of middle finger

Figure 4. Hand landmarked, scanned, and of which landmarks automatically identified: (a) photo of plaster hand with landmarks; (b) screen capture of a hand scan with 3D coordinates of landmarks automatically identified by a 3D scanning system

Figure 5. Automatic hand landmark identification process, *i* = {3, 2, 4, 5, 1}

Figure 6. Hand dimensions measured

Figure 7. Hand landmarks for 3D semi-automatic measurement: (a) palm and (b) dorsal

**List of Tables**

Table 1. Hand dimensions showing significant measurement differences between the 3D-SAMP and DMP

Table 2. Frequencies of hand dimensions by the reliability measures SD and CV