DEVELOPMENT OF A 3D SEMI-AUTOMATIC MEASUREMENT PROTOCOL FOR HAND ANTHROPOMETRIC MEASUREMENT

Wonsup Lee, Sunghye Yoon, and Heecheon You

Division of Mechanical and Industrial Engineering, Pohang University of Science and Technology, Pohang, South Korea

Measurement protocols for hand anthropometry have been studied for ergonomic product design. The present study developed a 3D semi-automatic measurement protocol (3D-SAMP) which semi-automatically measures various hand dimensions using a 3D scanner. The 3D-SAMP was compared with the conventional direct measurement protocol (DMP) to examine its effectiveness. The 3D-SAMP consists of (1) fabricating a plaster cast of the hand, (2) placing landmarks on the plaster hand, (3) scanning the plaster hand with a 3D scanner, (4) automatically identifying the positions of the landmarks on the digital hand, and (5) automatically extracting hand anthropometric measurements (lengths, widths, thicknesses, and circumferences). An evaluation experiment was conducted and found the 3D-SAMP preferred to the DMP in terms of reliability, efficiency, and ease of measurement.

INTRODUCTION

Hand anthropometric data are of great use in designing the physical size and configuration of a hand-held device. Hand anthropometric data have been applied to the ergonomic design of various hand-operated or wearable products such as a computer mouse, a control stick, and gloves.

Several hand measurement protocols have been developed to efficiently collect hand anthropometric data, each showing pros and cons in terms of ease and usefulness of measurements. Hand measurement protocols include a direct measurement method, a photogrammetric method, and a 3D scanning method. The direct measurement protocol (DMP) is an easy and inexpensive method to measure the hand (Son et al., 2003); however, errors can be caused by skin deformation when measurement instruments are applied (Han & Nam, 2004). The photogrammetric method measures hand dimensions using a photo of the palm. This method can take additional measurements afterward (Ozsoy et al., 2009). However, measurement errors can be caused by the distortion of a camera lens when capturing the palm, and circumference cannot be measured (Jang et al., 1989). The 3D hand measurement method generates a 3D digital hand using a 3D scanner, and then computer software measures 3D hand dimensions from the digital hand. The generated 3D digital hand with its several dimensions can be directly applied to design of product shape (Chang et al., 2007). However, measurement errors can be caused by a quality deterioration when capturing a 3D scan.

3D hand measurement data is useful for its application, but there are some limitations in terms of the quality of 3D data and ease of measurement. The 3D measurement can measure various hand dimensions of a 3D digital hand simultaneously, so they can be directly applied to product design. However, three limitations of 3D hand measurement exist. First, because the hand moves significantly during 3D scanning compared to other body parts (e.g., foot and face), the scanned 3D hand can be different from the real hand (Kim et al., 2001; Choi et al., 2006). Second, if a hand support is used to prevent hand movement while 3D scanning, measurement errors can occur by skin deformation which caused by touching the support (Chang et al., 2007; Li et al., 2008). Lastly, the 3D hand measurement method should be improved to equal the ease and intuitive measurement of DMP.

The present study developed a 3D semi-automatic measurement protocol (3D-SAMP) to compensate for the lack of usability with existing 3D scanning measurement methods. The 3D-SAMP was compared with the DMP in terms of measurement difference, reliability, time efficiency, and ease of measurement.

(a) S1. Fabricating plaster hand (b) S2. Landmarking on plaster hand (c) S3. Extracting 3D landmarks (d) S4. Extracting hand measurements

Figure 1. 3D semi-automatic measurement protocol

3D SEMI-AUTOMATIC MEASUREMENT PROTOCOL

A 3D semi-automatic measurement protocol (3D-SAMP) is conducted through a four-phase process as illustrated in Figure 1. The measurement process consists of (1) fabricating a plaster hand, (2) indicating landmarks on the plaster hand using marking stickers, (3) automatically extracting 3D locations of the landmarks by 3D hand plaster scanning, and (4) automatically measuring the hand dimensions (lengths, widths, thicknesses, and circumferences) based on the 3D locations of the landmarks.

Phase 1. Fabricating a plaster hand

A plaster hand is fabricated to prevent the deterioration of image quality which is caused by movement or skin deformation during the scanning of a real hand. The plaster hand is fabricated of mixed plaster (water: plaster = 1: 3) using the mold of the hand which is cast in mixed alginate (water: alginate = 1: 2). The coagulated plaster hand (coagulation time = around 15 minutes) should be carefully detached from the alginate mold (see Figure 1.a). While casting the mold of the hand in alginate, the participant was asked to pose a designated posture for hand measurement.

Phase 2. Landmarking on the plaster hand

Landmarking for 3D hand measurement is conducted by attaching marking stickers on the plaster hand. Typically, marking stickers (ϕ = 2.5 mm) are used as reference points while merging multi-viewpoint 3D scanned images into a 3D digital hand. This study uses marking stickers not only as reference points for 3D image integration but also for 3D hand landmarks. The center of each individual sticker indicates the landmark location of the hand. Therefore, the measurer uses tweezers to exactly locate the center of the sticker onto the landmark location of the plaster hand (see Figure 1.b).

Phase 3. Extracting 3D landmarks

The landmarked plaster hand is scanned to generate a digital hand in order to extract all 3D landmark locations automatically. The 3D scanned digital hand is composed of around 400,000 ~ 500,000 3D point cloud data. These 3D landmark locations are simultaneously identified with the digital hand (see Figure 1.c). The list of 3D landmark locations is automatically extracted by running 3D scanning software which captures the plaster hand and generates the digital hand.

Phase 4. Extracting hand measurement

Hand measurement dimensions are automatically extracted based on calculation of distances between the 3D landmarks. At first, each 3D landmark is automatically identified to correspond with the same landmark of the plaster hand. Next, hand measurement dimensions (lengths, widths, thicknesses, and circumferences) are automatically calculated based on identified 3D landmarks (see Figure 1.d). The present study developed a hand measurement system based on MATLAB^{TM} (The MathWorks, Inc., USA). This system automatically identifies 3D landmarks and simultaneously measures hand dimensions. To identify 3D landmarks, the system's algorithm uses geometrical characteristics among 3D landmarks (e.g., distances between the landmarks, located patterns among landmarks, and finger tip locations).

EVALUATION OF 3D-SAMP

Participants

The measurement experiment was conducted with 20 measurers for one hand. The measurers (12 males and 8 females) were 26 years old on average (SD = 2.2). All measurers were non-experienced with anthropometric measurement. They practiced measuring hand dimensions based on the 3D-SAMP and DMP for half an hour before the main experiment. Every participant was compensated for their participation.

Apparatus

Several measurement tools (digital caliper, baseline circumference tape, finger circumference gauge, and body measurement tape) were used in the DMP. Lengths, widths, and thicknesses of the hand were measured by a digital caliper (CP-20PS, Mitutoyo Corp., USA). Circumferences were measured by appropriate measurement tapes according to hand dimensions: hand circumference by a body measurement tape, wrist circumference by a Baseline Circumference tape (Fabrication Enterprises Inc., USA), and finger circumference by a Finger Circumference gauge (Patterson Medical Products Inc., USA).

The 3D-SAMP utilized plaster hands, marking stickers, tweezers, and a 3D scanner. Thirty duplications of one plaster hand were prepared for efficient experimentation. Each landmarked plaster hand was captured by the Rexcan 560 scanner (Solutionix Corp., South Korea) and analyzed by ezScan (Solutionix Corp., South Korea) to generate a 3D digital hand.

Experiment design

The measurers measured 52 hand dimensions three times with plaster hand and the real hand using the 3D-SAMP and DMP, respectively. 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 gathered by referring to previous studies (Annis, 1986; Choi et al., 2006; Garrett, 1970; Greiner, 1991; Hidson, 1991; Kwon et al., 2005; Lim, 2005; Robinette and Ryu and Suh, 2004). The experiment was conducted through a four-step process composed of (1) introduction to the experiment and signing an informed consent form, (2) practice of the 3D-SAMP and DMP, (3) administration of the main experiment, and (4) evaluation of subjective satisfaction in terms of ease of measurement. The experiment was separated into two sessions; a 10-minute break was provided between the sessions. The measurement order of the 3D-SAMP and DMP was counterbalanced among the measurers, measurement trials (three times with an interval of more than 24 hours), and sessions of an experiment.

Evaluation and Analysis

The present study selected four evaluation criteria (difference of measured values, reliability, measurement time, and subjective satisfaction) to compare the usefulness and the efficiency of the 3D-SAMP and DMP. The difference of measured values refers to the subtraction between the measurements by the 3D-SAMP and DMP (3D-SAMP – DMP). The reliability of each measurement protocol was evaluated by the intra- and inter-variabilities of measurers. Weinberg et al. (2005) suggested 2 mm of SD and Li et al. (2009) proposed 5% of coefficient variance (CV) as an evaluation criterion of reliability for hand anthropometry. The completion time of measuring 52 dimensions was recorded for each measurement protocol. Lastly, ease of measurement was evaluated by a 7- point scale (1: very dissatisfied, 7: very satisfied).

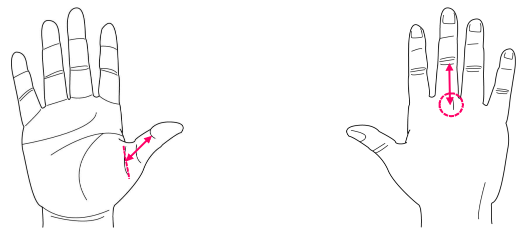
RESULTS

Measurement Difference

Significant differences of measured values between the 3D-SAMP and DMP (3D-SAMP – DMP) appeared on 11 out of 52 hand dimensions. The differences in measurement were analyzed by the paired *t*-test (α = 0.05). As shown in Table 1, the differences were observed more on thicknesses (6 out of 7 dimensions). The differences of lengths showed that the measured values of the DMP were larger than the 3D-SAMP. There were no significant differences between the 3D-SAMP and DMP on circumferences.

Reliability

The intra- and inter-variabilities of the measurers of the 3D-SAMP were lower than the DMP, which indicates that the reliability of the 3D-SAMP is higher. In terms of intra-measurer variability of SD, the measured values of 10 dimensions of the DMP exceeded the evaluation criterion (SD = 2 mm), while no dimension of the 3D-SAMP was greater than the evaluation criterion (see Table 2). In terms of inter-measurer variability of SD, 15 dimensions of the DMP and only 1 dimension (digit 3 proximal phalanx link length) of the 3D-SAMP exceeded the evaluation criterion. Moreover, in terms of intra-measurer variability of CV, 4 dimensions of the DMP and only 1 dimension (digit 1 proximal phalanx link length) of the 3D-SAMP were greater than the evaluation criterion (CV = 5%). Lastly, in terms of inter-measurer variability of CV, 14 dimensions of the DMP and only 1 dimension (digit 1 proximal phalanx link length) of the 3D-SAMP exceeded the evaluation criterion (see Figure 2).



(a) Digit 1 proximal phalanx link length (b) Digit 3 proximal phalanx link length

Figure 2. Dimensions of the 3D-SAMP which exceeded the evaluation criteria

Table 1. Significant dimensions in terms of difference of measured value

Category	Number of measured dimensions	Number of significant dimensions	Hand dimensions	Difference of measured values (mm)
Length	27	3 (11%)	Base of digit 1 to wrist crease center	-2.1
			Base of digit 4 to wrist crease center	-2.4
			Base of digit 5 to wrist crease center	-3.5
Width	11	2 (18%)	Digit 2 distal interphalangeal (DIP) joint width	2.5
			Digit 3 DIP joint width	2.5
Thickness	7	6 (86%)	Digit 1 DIP joint thickness	3.2
			Digit 2 DIP joint thickness	2.1
			Digit 3 DIP joint thickness	2.6
			Digit 3 DIP joint thickness	3.1
			Digit 3 DIP joint thickness	2.8
			Wrist thickness	4.4
Circumference	7	0	-	-
Total	52	11 (21%)	-	-

Table 2. The number of measurement dimensions according to the evaluation criteria of reliability (SD and CV)

Evaluation criteria of reliability		SD (mm)			CV (%)					
		0~1	1~2	>2	0~1	1~2	2~3	3~4	4~5	>5
3D-SAMP	Intra-variability of measurers	42	10	-	11	18	13	8	1	1*
	Inter-variability of measurers	37	14	1*	12	24	11	3	1	1*
DMP	Intra-variability of measurers	27	15	10*	1	13	11	18	5	4*
	Inter-variability of measurers	22	14	16*	-	5	13	16	8	14*

*: The number of dimensions which exceeded the evaluation criteria (SD = 2 mm, CV = 5%)

Measurement time

The completion time of the 3D-SAMP measurement 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).

Subjective satisfaction

The satisfaction score for ease of measurement of the 3D-SAMP was significantly higher than the DMP ($t(19) = 2.85$, $p = 0.01$). The average value of subjective satisfaction of the 3D-SAMP was 5.18 (SD = 0.83), while that of the DMP was 4.30 (SD = 0.82).

DISCUSSION

The present study developed a 3D semi-automatic measurement protocol (3D-SAMP) which is comparatively accurate and time efficient. The 3D-SAMP uses a 3D scanned digital hand derived from a plaster casting instead of a real hand. The plaster hand was fabricated using an alginate mold which can elaborately duplicate the human hand shape into the plaster one. By using the plaster hand, problems of previous research during real hand 3D scanning, such as instability or skin deformation, were minimized. Also, by using marking stickers for landmarking, the 3D-SAMP could semi-automatically extract 3D locations of the landmarks. Also, hand measurement dimensions (lengths, widths, thicknesses, and circumferences) were automatically calculated based on the identified 3D landmarks using a MATLAB program. For these reasons, the 3D-SAMP can measure hand dimensions more easily and efficiently than the DMP or the previous 3D measurement protocols.

The 3D-SAMP was more useful in terms of reliability and its measured values were more consistent compared to the DMP. Because the 3D-SAMP used the plaster hand which minimized skin deformation and posture distortion, measured values of the hand dimensions were highly consistent. Among the measured values, only 2 dimensions (digit 1 proximal phalanx link length and digit 3 proximal phalanx link length) of the 3D-SAMP exceeded the evaluation criterion. The intra- and inter-measurer variabilities of CV of digit 1 proximal phalanx link length exceeded the evaluation criterion (intra-CV = 7.1%; inter-CV = 6.0%). It is possible that the measurers misjudged the location of the middle of the digit 1 first crease when landmarking. Additionally, the intra-measurer variability of SD of digit 3 proximal phalanx link length exceeded the evaluation criterion (intra-SD = 2.1 mm). It is possible that the measurers misjudged the location of the middle of the digit 3 knuckle when landmarking; however, these differences were quite small. For these reasons, to generalize the 3D-SAMP, some ambiguous landmark locations need to be more clearly identified according to characteristics of landmark location.

The differences of measured values between the 3D-SAMP and DMP were significant on 11 dimensions (length: 3, width: 2, thickness: 6) out of 52 dimensions, but the accuracy of measurement was difficult to evaluate. Among the significant dimensions, 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 (2.1 ~ 3.5 mm) than the 3D-SAMP; it seems that these differences came from wrist movement (flexion/extension, abduction/adduction) during measurement. Width and thickness dimensions of the DMP were smaller (2.1 ~ 4.4 mm) than the 3D-SAMP; it seems that skin deformation was caused by measurement tools (e.g., digital caliper). A high portion of the differences of measured values (6 out of 7 dimensions) were caused on the dimensions of thicknesses. It also seems that these differences occurred by the measurement tool. However, because we cannot know the true values of the hand dimensions, it is difficult to find a more exact method by analyzing the differences of measured values between the 3D-SAMP and DMP.

The subjective satisfaction about ease of measurement of the 3D-SAMP was higher than the DMP. The DMP was less satisfying than the 3D-SAMP according to the debriefing in the study. The DMP needs a long time of meeting between the measurer and participants under measurement, and the DMP requires several measurement tools. Also, the subjective reliability for the measured result of the DMP was low because of continually changing measured values caused by skin deformation and hand movement. Conversely, the 3D-SAMP which uses the plaster hand was preferred to the DMP due to no meeting between participants and easy use of landmarking tools.

To generalize the 3D-SAMP, additional validation experiments are required to compare the measured results with other hand dimensions. The present study compared the 3D-SAMP with the DMP based on selected 52 out of 169 whole hand dimensions which were collected by referring eight previous studies. Lastly, there were dimensions showing a low reliability on the 3D-SAMP. Therefore, to generalize the 3D-SAMP, the additional unmeasured hand dimensions of this study need to be measured by the 3D-SAMP and then compared to the DMP.

REFERENCES

Chang, C. C., Li, Z., Cai, X., and Dempsey, P. (2007). Error control and calibration in three-dimensional anthropometric measurement of the hand by laser scanning with glass support. *Journal of the International Measurement Confederatio, 40*(1), pp.21-27.

García-Hernández, J., Heras, S., Juan, A., Paredes, R., Nácher, B., Alemany, S., Alcántara, E., and González, J. C. (2005). The MORFO3D foot database. In *Proceedings of Pattern Recognition and Image Analysis*.

Garrett, J. W. (1970). *Anthropometry of the Hands of Male Air Force Flight Personnel (Report AMRL-TR-69-42)*. Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command.

Greiner, T. M. (1991). *Hand Anthropometry of US Army Personnel*. U.S. Army Natick Research. Development and Engineering Center. Natick: MA. (NTIS No. ADA244533).

Han, H., and Nam, Y. (2004). The suitability of 3-dimensional body scan method in measuring body surface area. *Textile Science and*

Engineering, 41(3), pp.223-229.
Hidson, D. (1991). *Development of a Standard Anthropometric Dimension Set for Use in Computer-Aided Glove Design*. DREO Technical Note 91-22, Defense Research Establishment OTTAWA.
Jang, M., Kim, J., and Kim, C. (1989). A study on the non-contact body measurements using image processing. *Journal of the Ergonomic Society of Korea, 8*(2), pp.35-41.
Kim, M., and Nam, Y. (2001). Development of three dimensional scanner for anthropometric measurement. *Journal of the Ergonomic Society of Korea, 20*(3), pp.77-88.
Kwon, M., Choi, I., Chung, G., and Yang, M. (2005). A study on establishment of glove size system and hand shape. *Journal of the Korean Society of Costume, 55*(6), pp.24-37.
Li, Z., Chang, C. C., Dempsey, P. G., Ouyang, L., and Duan, J. (2008). Validation of a three dimensional hand scanning and dimension extraction method with dimension data. *Ergonomics, 51*(11), pp.1672-1692.
Lim, J. (2005). Classification of hand types for the development of glove patterns. *Journal of Korean Home Economics Association, 43*(8), pp.115-122.
Ozsoy, U., Demirel, B. M., Yildirim, F. B., Tosun, O., and Sarikcioglu, L. (2009). Method selection in craniofacial measurements: Advantages and disadvantages of 3D digitization method. *Journal of Cranio-Maxillofacial Surgery, 37*(5), pp.285-290.
Robinette, K. M. and Annis, J. F. (1986). *A Nine-Size System for Chemical Defense Gloves*. Technical Report (AAMRL-TR-86-029) (ADA173 193).
Ryu, K., and Suh, M. (2004). A study on the measurement of Korean women's hand: focusing on glove size. *The Research Journal of the Costume Culture, 12*(2), pp.262-278.
Son, H., Kim, H., Choi, C., Sohn, H., and Kim, C. (2003). A study on a measurement method for 2D anthropometry using digital camera. *The Research Journal of the Costume Culture, 11*(1), pp.11-19.
Weinberg, S. M., Scott, N. M., Neiswanger, K., and Marazita, M. L. (2005). Intraobserver error associated with measurements of the hand. *American Journal of Human Biology, 17*(3), pp.368-371.