Validity and Reliability of a Depth Camera–Based Quantitative Measurement for Joint Motion of the Hand

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Purpose: Quantitative measurement of hand motion is essential in evaluating hand function. This study aimed to investigate the validity and reliability of a novel depth camera–based contactless automatic measurement system to assess hand range of motion and its potential benefits in clinical applications.

Methods: Five hand gestures were designed to evaluate the hand range of motion using a depth camera–based measurement system. Seventy-one volunteers were enrolled in performing the designed hand gestures. Then, the hand range of motion was measured with the depth camera and manual procedures. System validity was evaluated based on 3 dimensions: repeatability, within-laboratory precision, and reproducibility. For system reliability, linear evaluation, the intraclass correlation coefficient, paired t-test and bias were employed to test the consistency and difference between the depth camera and manual procedures.

Results: When measuring phalangeal length, repeatability, within-laboratory precision, and reproducibility were 2.63%, 12.87%, and 27.15%, respectively. When measuring angles of hand motion, the mean repeatability and within-laboratory precision were 1.2° and 3.3° for extension of 5 digits, 2.7° and 10.2° for flexion of 4 fingers, and 3.1° and 5.3° for abduction of 4 metacarpophalangeal joints, respectively. For system reliability, the results showed excellent consistency (intraclass correlation coefficient = 0.823; \( P < .05 \)) and good linearity with the manual procedures (\( r = 0.909–0.982 \), approximately; \( P < .001 \)). Besides, 78.3% of the measurements were clinically acceptable.

Conclusions: Our depth camera–based evaluation system provides acceptable validity and reliability in measuring hand range of motion and offers potential benefits for clinical care and research in hand surgery. However, further studies are required before clinical application.

Clinical relevance: This study suggests a depth camera–based contactless automatic measurement system holds promise for assessing hand range of motion in hand function evaluation, diagnosis, and rehabilitation for medical staff. However, it is currently not adequate for all clinical applications.

Quantitative evaluation of hand range of motion after impairment is essential in many fields, such as medical care, rehabilitation, or appraisals of working capability. Specialists often use hand-held goniometers to assess hand range of motion, which is the most commonly used and widely accepted method in clinical work. However, manual measurement techniques are time consuming and skill-dependent. Over the last 2 decades, automatic devices that use optical, electronic, or magnetic technologies to measure hand motion have shown rapid development. Most
of these devices are categorized under wearable and contactless devices. However, wearable devices, such as data gloves, might be incompatible and inconvenient because the possibility of measuring various impaired hands with malformation, open injury, or muscle weakness is high. Unlike wearable devices, contactless automatic measuring devices could solve these issues because hand motion can be measured automatically by optical cameras without direct contact.

Various methods have been proposed for contactless human activity measurement with the development of hardware and artificial intelligence (AI) algorithms. Many studies have also yielded encouraging data on capturing and recognizing full-body movement with virtual reality. There is a notable limitation in the simultaneous evaluation of 14 hand joints using optical motion capture tools, such as Leap motion (Leap Motion Inc) and Kinect (Microsoft Inc). Vicon (Vicon) is another optical system that can capture extreme dexterous motions. However, its multicamera system and marker-dependent accuracy are costly and inconvenient.

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**Figure 1.** A flowchart of the participant enrollment process. A The domains of hand motion. B-D The systematic setup and traditional goniometers. E The 5 hand skeletons obtained using the depth camera.
instruments in clinical applications.\textsuperscript{16,25,26} Besides, the anatomy of hand motion is still poorly understood. Thus, most studies experienced setbacks because of the lack of a supportive theoretical framework of medical knowledge.

To facilitate rehabilitation and treatment of patients and research in hand surgery, we proposed a depth camera–based quantitative hand range of motion evaluation system. Intel RealSense SR300 (Intel) is based on a triangulation algorithm in which coded light is projected and captured by an infrared sensor that generates the position information of hand motion. The cost of the camera is low (the price of a depth camera was approximately $223); it is portable, with high resolution and efficiency, which may be suitable for clinical application. In this study, we analyzed the validity and reliability of the proposed evaluation system against hand-held finger goniometers. We also explored the system’s potential benefits for clinical care and research in hand surgery.

### Materials and methods

#### Participants

This was a cross-sectional study. The enrollment criteria for volunteers were as follows: (1) the participants could perform hand gestures in front of a depth camera independently and (2) the hand could be recognized as a “hand” by the built-in AI algorithms. In this study, we excluded people with a history of congenital deformity of the hand and those with space-occupying lesions in the hand that might make it difficult to perform tasks as instructed or might not be recognized by the AI. We also excluded people with more than 1 peripheral nerve involved and those with hand amputation and brachial plexus injury or central nervous system injury. Of the 96 volunteers reviewed, 71 participants met these criteria. We included 21 healthy adults and 50 patients who were
concluded to have upper-limb peripheral nerve injury (Fig. 1). Then, patients were further divided into 3 groups: (1) those with median nerve injury, (2) those with radial nerve injury, and (3) those with ulnar nerve injury. The demographic characteristics of participants are described in Table 1.

Participants were instructed to sit with their arm and elbow on the table to support the hand, 90° flexing elbow followed by neutral pronation of the forearm and wrist. Then, the palmar side of the hand was placed 30–40 cm in front of the camera and parallel to the camera plane until it was recognized and a steady hand skeleton image was generated (Fig. 1B1, B2). The hand skeleton consists of 22 measuring points representing the motion center of the hand joint (Fig. 2 A). Three-dimensional spatial coordinates for the 22 measuring points were collected for 10 seconds (3000 values and 125 measuring time points) at a resting interval of 2 minutes. Then, the mean values of the 125 measurements were analyzed as 1 set of replicates.

Manual measurement using a hand-held goniometer was carried out following the recommendations of a traditional dorsal technique by 2 trained senior hand surgeons in a blinded manner (Q.Z. and J.Y.). Measurement was taken after 2 minutes of rest. The mean of 3 readings for each measurement was considered as 1 replicate. Data acquired by manual procedures served as the gold standard in this study. The depth camera and manual procedures were coded and analyzed by another observer blindly.

To facilitate automatic measurement of hand range of motion using a depth camera, it is necessary to design a series of standard hand gestures (Fig. 1A, C). Our preliminary experiment revealed that the depth camera had difficulties in recognizing severely deformed or amputated hands and capturing all designed gestures.

Table 2
Hand Gestures and Corresponding Expert Knowledge

<table>
<thead>
<tr>
<th>Hand Function Module</th>
<th>Hand Gesture</th>
<th>Biomechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amputation (−)</td>
<td>Flat hand1/flat hand 2</td>
<td>-</td>
</tr>
<tr>
<td>(+)</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Finger Extension and hyperextension</td>
<td>Flat hand 1</td>
<td>EDC MCP joint, DIP joint</td>
</tr>
<tr>
<td>Flexion</td>
<td>Thumb-up</td>
<td>Lum, Int PIP joint</td>
</tr>
<tr>
<td>Abduction</td>
<td>Flat hand 1</td>
<td>Lum, Int MCP joint</td>
</tr>
<tr>
<td>Adduction</td>
<td>Flat hand 2</td>
<td>FDS PIP joint</td>
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<tr>
<td></td>
<td></td>
<td>FDP DIP joint</td>
</tr>
<tr>
<td>Thumb Extension and hyperextension</td>
<td>Thumb-up</td>
<td>EPB MCP joint</td>
</tr>
<tr>
<td>Flexion</td>
<td></td>
<td>EPL IP joint</td>
</tr>
<tr>
<td>Radial abduction</td>
<td>Thumb-up</td>
<td>FPR MCP joint</td>
</tr>
<tr>
<td>Adduction</td>
<td></td>
<td>FPL IP joint</td>
</tr>
<tr>
<td>Palmar abduction/opposition</td>
<td>Thumb-index pinch</td>
<td>APB Thumb</td>
</tr>
<tr>
<td></td>
<td>Thumb opposition</td>
<td>OP Thumb</td>
</tr>
</tbody>
</table>

ADM, abductor digiti minimi; AP, adductor pollicis; APB, abductor pollicis brevis; APL, abductor pollicis brevis; DI, dorsal interossei; EDC, extensor digitorum communis; EPL, extensor pollicis brevis; FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis; FPR, flexor pollicis brevis; FPL, flexor pollicis longus; Int, interossei; IP, interphalangeal; Lum, Lumbricals; MCP, metacarpophalangeal; MN, median nerve; OP, opponens pollicis; PI, palmar interossei; RN, radial nerve; UN, ulnar nerve.

Figure 3. Repeated measuring results for the length of 14 phalanges for 5 hand gestures of both hands using depth cameras. A–D The left hand. E–H The right hand. A and B The flat hand type 1 gesture. C and G The flat hand type 2 gesture. C and H The thumb-up gesture. D and I The thumb-index pinch gesture. E–J The thumb opposition gesture.
especially thumb flexion and abduction. Finally, 3 domains of hand function relating to 34 quantitative measurement items were assessed using 5 hand gestures in this study (Table 2; Fig. 2B–H). The 3 domains were finger extension/flexion, finger adduction/abduction and thumb radial abduction (extension), and thumb palmar opposition. The corresponding 5 hand gestures were as follows: (1) flat hand type 1 (complete extension and abduction of fingers), (2) flat hand type 2 (complete extension and adduction of fingers), (3) “thumb up,” (4) thumb-index pinch, and (5) thumb opposition.

System setup

The quantitative evaluation system for hand range of motion consisted of a RealSense SR300 device equipped with an red, green, and blue camera and an infrared camera.27 The camera was supported with a tripod and connected to a computer via a Universal Serial Bus 3.0 cable. A software development kit was initially installed, and three-dimensional spatial coordinates for the 22 measuring points of hand were obtained at 60 frames per second (Fig. 1B2). All items related to the hand range of motion involve angles or distances. They were calculated following algorithms, as described in Appendix 1 (available on the Journal’s website at www.jhsgo.org).

Experimental protocol

Validity

The experimental protocol was divided into 4 experiments. For the first part, a within-subject repeated measuring study was employed. A healthy volunteer was enrolled to perform all of the 5 hand gestures, each of which received 10 seconds of measurement per replicate. The independent variables of the experiment consisted of 3 replicates per run, 2 runs a day, with 2 depth cameras running for 5 days (3 × 2 × 5 protocol). The length of all 14 phalanges per hand gesture for each hand was measured using the depth camera.

For the second part, 5 healthy volunteers were invited to perform 3 hand gestures—flat hand type 1, flat hand type 2, and thumb-up. The independent variables of the experiment consisted of 3 × 10-second replicates at 2 runs a day for 5 days (3 × 2 × 5 protocol). Both depth camera and manual procedures collected the extension of 14 hand joints and flexion of 12 hand joints (joint flexion of the thumb was unavailable), and the abduction or adduction of 4 webs was collected separately.

Reliability

The third part was carried out to explore the linearity using the hand gestures of thumb-index pinch and thumb opposition. Thirteen pieces of transparent bars in preassigned length were used. The length of the bars increased gradually from 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 to 12 cm. For the thumb-index pinch (“OK” gesture), the bars were pinched by the thumb and index finger pulp from 0 to 12 cm. For the thumb opposition gesture, bars were pinched from the flexor crease of the thumb interphalangeal joint to the distal palmar crease over the third metacarpophalangeal joint. The distance increased gradually from 0 to 8 cm. Each test had 3 replicates per hand.

The fourth part was carried out in a clinical setting by 64 volunteers. Of the 83 hands studied, 28 belonged to 14 healthy volunteers and 55 belonged to 50 patients. All the volunteers were instructed to perform the following 3 hand gestures with 1 replicate protocol: flat hand type 1, flat hand type 2, and thumb-up. These hand gestures captured the extension of 14 hand joints, the flexion of 12 hand joints, and the abduction and adduction of the 4 webs using the depth camera and manual procedures.

Statistical analysis

A general linear model was used to conduct an analysis of variance (ANOVA) for the data from the first and second parts of the experiment to determine their main effects and interactions. The mean absolute error was the dependent variable. Before performing ANOVA, the sphericity assumption was identified using the Mauchly test or adjusted using the Greenhouse-Geisser test. For the first part, factors that influence the variation of the phalangeal length were analyzed, focusing on independent variables, such as the depth cameras, hand gestures, days, runs, and replicates. On the basis of the results of the ANOVA, system validity was evaluated on the basis of 3 dimensions: repeatability, within-laboratory precision, and reproducibility. For the second part, system validity was assessed with repeatability and within-laboratory precision. The system reliability of repeated measures was also analyzed using the intraclass correlation coefficient, Pearson’s product-moment correlation, and bias. For the third part, system linearity was determined using linear correlation and regression between the measurements. For the fourth part, bias was employed to evaluate system reliability, and the differences between measurements were tested using the paired t test. Five degrees were considered as an acceptable clinical threshold for repeatability, within-laboratory precision, and bias.28,29 All comparisons were performed at a 2-tailed significant level of .05. The definitions and calculation equations of the terms used in the statistical analysis can be found in Appendix 2 (available on the Journal’s website at www.jhsgo.org).

Results

Internal validity of the depth camera measurements

The results indicated that the type of hand gesture may have an important effect on the measured length of phalanges (P < .001). Besides, there was a significant interaction between the effects of gesture and the depth camera (P < .05). When measuring the phalangeal length, data from the overall measurement validity revealed low to moderate dispersal: the mean percentage coefficient of variation of repeatability was 2.63% ± 0.29%, the within-laboratory precision was 12.87% ± 1.87%, and the reproducibility was 27.15% ± 4.70% (Figs. 3, 4; Supplementary Table S1, available on the Journal’s website at www.jhsgo.org). Data from the second part of the experiment showed that when measuring hand range of
motion, the overall repeatability and within-laboratory precision were 1.8° and 5.8°, respectively. The mean repeatability and within-
laboratory precision were 1.2° and 3.3° for extension of 5 digits, 2.7° and 10.2° for flexion of 4 fingers, and 3.1° and 5.3° for abduction of 4 metacarpophalangeal joints, respectively (Fig. 5).

Comparison of depth camera measurements with manual goniometer measurements

The linear experiment showed that the measured distances of thumb opposition and thumb-index pinch had positive linear correlation with the actual distances. Although these correlations were statistically significant, they could not fully satisfy the evaluation of the total range of motion of thumb opposition/pinch. This was because the measurements for relatively small distances (0–2 cm for thumb-index pinch gesture and 0–4 cm for thumb opposition gesture) were less reliable than those for larger distances (Fig. 6).

The repeated measuring experiment revealed that the depth camera provided excellent consistency in evaluating the hand range of motion compared with the consistency provided by the manual procedures (intraclass correlation coefficient = 0.823; \( P < .05 \)). The overall association between the 2 measurements showed a significant positive correlation \( (r = 0.970; \ P < .001) \) (Figs. S1, S2, available on the Journal’s website at www.jhsgo.org). The repeated measuring experiment showed that 78.3% of the measurements that differed from the manual measurements were <5° (clinically acceptable).

Data from the fourth experiment of reliability indicated that the overall measured hand range of motion with the depth camera was lesser than that with manual procedures. However, only the differences in the flexion of the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints between the manual procedures and depth camera were statistically and clinically significant \( (P < .05) \). For the 4 groups of participants (healthy, median nerve injury, ulnar nerve injury, and radial nerve injury), a larger hand deformity resulted in an overall reduced hand range of motion, as measured by the depth camera, and a lower measurement reliability (Fig. 7; Supplementary Table S2, available on the Journal’s website at www.jhsgo.org).

Discussion

Unlike traditional manual procedures, which are highly dependent on professional staff, hand gestures are the key to analyzing hand motion using contactless activity capture devices, such as depth cameras. The participants can take photographs in front of the camera without the help of observers. Capturing hand gestures is the first step in hand recognition, only after which the depth camera can generate hand position information. Thus, we analyzed 5 well-designed and clinically accepted hand gestures to facilitate the automatic measuring of hand range of motion. Measurements of hand motion were collected by corresponding hand gestures or a combination of different hand gestures. Because most hand gestures are simple and conveniently recognized, depth cameras can be expected to be valid and reliable in evaluating hand range of motion.

The first and second experiments systematically investigated the internal validity of the depth camera system and its influencing factors. The findings of this study indicated that internal validity was satisfactory when the phalangeal length and hand range of motion were repeatedly measured, based on the analysis of more than 3 million items of data output from the depth camera–based measurement system. It is important to note that the time taken to collect those data using the depth camera was <2 hours, which was highly efficient compared with the manual procedure. The results of the internal validity of the depth camera and ANOVA indicated that all the variances were expected to be derived from the system because the length of each phalanx of the same participant’s hand is unchangeable during the measurement. Among these, hand gestures had the greatest effect on the source of measurement variance. Further analysis showed that thumb opposition and thumb-up gestures had the lowest and highest variance, respectively (Fig. 3). Our data also agreed with the previous finding that...
classified hand gestures can achieve a more valid measurement of hand range of motion.

Currently available optical cameras have a universal limitation: the camera’s view of the digit of interest might often be blocked by other digits. Thus, a well-designed hand gesture is perhaps a major solution to solve the issues. It would improve the measurement validity by reducing the blocking. The findings of this study provide insights into the hand gestures used and lay the ground for better gestures that are static and intransitive and have maximum extension and abduction while performing step-by-step flexion and adduction, which can be conveniently measured using a single camera from a special angle of view.

The linear analysis of the third experiment showed that the depth camera loses its reliability when measuring a relatively small or narrow distance (<2 cm for the thumb-index pinch gesture and <4 cm for the thumb opposition gesture). However, the performance of the depth camera becomes acceptable when the tapping distance increases. These findings can be partly explained by the fact that the finger pulps of both the thumb and the index finger/palm were not rigid. The objects pinched by the thumb and index finger/palm might exert a force on the soft tissue and cause a certain level of elastic deformation, which might have substantially shorten the measured distances compared with the actual distances. As mentioned earlier, the thumb might be self-blocking when pinching or opposing to the minimum extent. Thus, further development is required to improve the depth camera’s performance in measuring short distances.

One of the most important aspects of this study was to quantitatively analyze the repeated measurement reliability of a depth camera-based measurement system for hand range of motion. Most of the angles obtained using the depth camera were generally smaller than those obtained using manual procedures. This result might be because the manual hand measurement is commonly obtained using dorsal techniques, whereas the depth camera usually obtains hand motion from the palmar view. Therefore, the depth camera’s views might be another potential source of measurement variance. Although the paired differences between the measurements were stable, part of the variance might derive from systematic errors and can be rectified through an improved system. After comparing with the standard method of manual procedures, the hand range of motion information collected by the depth camera can be further calculated and analyzed for hand physio-pathologic status classification or prediction intelligently. These analyses cannot be conducted with the information gathered from manual procedures.

In addition, measurement reliability was assessed in clinical applications, especially in patients with upper-limb peripheral nerve injury. Data on hand range of motion showed that most of the measurements were reliable, except for the flexion of PIP and DIP joints that were below the clinical assessment requirement. This
Figure 7. Paired comparison of hand range of motion between 2 measurements in 4 groups of people. A and E Healthy control group. B and F The median nerve injury group. C and G The ulnar nerve injury group. D and H The radial nerve injury group. A–D The extension/hyperextension and adduction for finger joints. E–H The flexion and abduction for finger joints. Andrew’s curve is included in each figure part at the upper right corner, which was triangulated from the 2 measurements and may indicate the overall difference between the 2 measurements. I, index finger; IP, interphalangeal joint; L, little finger; M, middle finger; MCP, metacarpophalangeal; R, ring finger; T, thumb
outcome differs from previous findings that verified the system reliability for the flexion of PIP and DIP joints using digital image capture devices, such as Leap motion and Creative Sen2D (Intel).28,36 However, these studies were broadly consistent with earlier studies, which indicated similar measurement bias with the Leap motion device.31 In addition, the system bias increased as the earlier studies, which indicated similar measurement bias with the hand motion analysis devices but choosing hand-held goniometers.

The findings might help prioritize the system with more accurate hand motion analysis in complicated clinical applications. When measuring the 3 domains of hand amputation, thumb flexion, and adduction, our preliminary experiment revealed that the AI algorithms of the depth camera could neither recognize the hand nor provide output position information for the whole hand. Amputation of finger or phalanges is related to impairment percentage of hand function; however, it has nothing to do with the range of motion of a healthy hand. Flexion and adduction are only part of the thumb’s range of motion. Thus, the absence of these 3 domains of hand range of motion has a limited impact on the overall reliability and validity of this modality.

Another limitation of this study was not choosing other optical hand motion analysis devices but choosing hand-held goniometers as the gold standard. Despite the disadvantages of the traditional hand-held finger goniometer, it is the clinical standard, and its reliability and validity have been established. Thus, the depth camera--based measurement system should be compared with the clinical standard before using it in clinical applications.

In conclusion, this study investigated the validity and reliability of a depth camera--based quantitative measurement system for hand range of motion, especially in clinical settings. The proposed system provides acceptable measurement validity and reliability for evaluating most hand range of motion, potentially benefiting clinical care and research in hand surgery. Before clinical application, there is a need to improve the measurement reliability for flexion of DIP and PIP joints and system validity in recognizing severely deformed hands (including amputated hands) because the system performance reduced with more severe pathology of the hand.

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References