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ARTICLE

Three-dimensional scanner with a modified evaluation method for measuring hand edema subtitle: an idea for accurate evaluation and preliminary fundamental and clinical validation

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ABSTRACT

Acute hand edema often results in loss of fine hand motor activities, especially without appropriate care. There is still no reliable and easy to use method to measure hand edema. In this study, we tested a handheld three-dimensional (3D) scanner on plastic male and female hand models using a whole hand measuring method (WM) and a modified method (MM) which excluded fingers. We evaluated the intra-rater reliability and inter-rater reliability and compared the measured volumes to computed tomography (CT) findings. Statistical analysis showed that the 3D scan method was valid and reliable for both WM and MM methods. In WM, intra-rater and inter-rater reliability were 0.97 and 0.84, with 95% confidence interval (CI) of 0.87–1.00 and 0.61–0.94, respectively. In MM, intra-rater and inter-rater reliability were 0.96 and 0.83, with 95% CI of 0.84–1.00 and 0.61–0.94, respectively. In comparison to the CT, the differences between 3D scan and CT in the male model volumes were $30.35 \pm 2.70\,cm^3$ (mean ± standard deviation) for WM and $11.60 \pm 2.07\,cm^3$ for MM. In the female model, the differences were $18.92 \pm 2.66\,cm^3$ and $11.18 \pm 2.35\,cm^3$, respectively. In both models, MM was significantly more accurate than WM ($p < 0.001$). When used in a clinical case, the scanner recorded changes in actual volume through the course of treatment. This cost-effective handheld 3D camera can be a reliable tool for evaluating hand edema even in cases of acute injury.

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KEYWORDS
Hand edema; handheld three-dimensional (3D) camera; compartment syndrome

Introduction

Upper limb edema is a common complication following hand surgery or injury and effective treatment is crucial, both esthetically and functionally. Edema is a key independent factor that determines prognosis and treatment approach. Along with destruction of tissue in cases of severe acute tissue damage, the development of edema can lead to irreversible paralysis and contractures, with or without compartment syndrome [1]. Furthermore, the hand is composed of small, complicated structures including the thumb, fingers, web spaces, and intrinsic muscles, which are critical for the delicate functions of the hand. This complexity limits the establishment of a standard volume-measuring method—especially for acute and subacute cases—that is accurate, reliable, efficiently performed even at bedside, and requires less time. Almost all the reported hand volume-measuring methods such as water replacement method and 3D stereogram method require large sets of costly machines and ample time for precise measurements. In addition, the appropriate measurement device for the intrinsic muscles of the hand remains unclear.

As a solution to the problems, we propose the application of a three-dimensional (3D) camera as a scanner and a tablet device to measure hand volume. This study aimed to evaluate the validity and reliability of a new volume measurement approach for clinical use in patients with hand edema. Life-sized plastic hand models were used for the evaluation of our 3D scanning methods. Additionally, we applied this scanning method to a case of prolonged hand edema following injury and estimated the usability of this method.

Materials and methods

In this study, we used a handheld battery-operated 3D camera (Structure Sensor (ST01), Occipital Inc., Boulder, CO, USA) as a scanner with a tablet (iPad Mini 2®, Apple Inc., Cupertino, CA, USA) (Figure 1(a)) combined with our original measurement method. For our measurements, five life-sized plastic hand models, with or without small plastic cases, were used as 10 different hand models (Figure 1(b)). The total cost of the latest handheld 3D camera scanner and the tablet was $926 as of July 21, 2020. All other applications and the software were obtained free-of-cost for non-commercial use.

3D Scanning of hand

3D Scanning

The 3D scanner was held using both hands and carefully maneuvered 360° around the plastic hand model at a distance of ~50 cm, while avoiding blurring as much as possible. A minimum open and flat area of $1.5 \times 1.5\,m^2$ was required for this 3D scan (Figure 2). The 3D data with size information were obtained using the time-of-flight method by infrared light from the 3D camera

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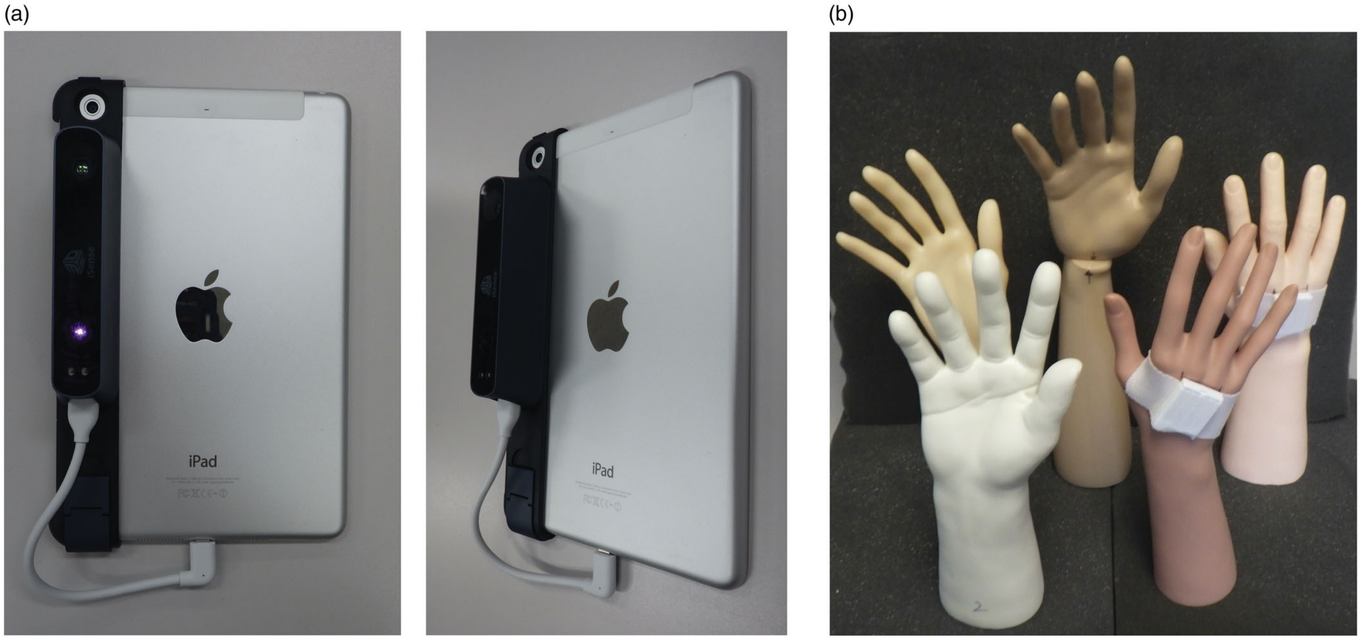

Figure 1. Three-dimensional (3D) scanner and plastic models of male and female hands. (a) An infrared 3D camera and iPad Mini 2® were used in this experimental and clinical study. The 3D scanner system measures 135 × 200 × 40 mm, weighs 450 g, and can operate for 3–4 h of active scanning using the internal battery. (b) Plastic hand models, representing male and female hands, were used in this study.

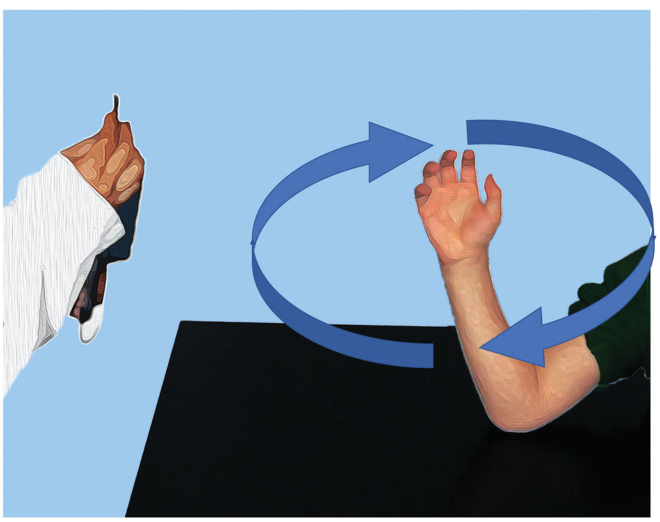

Figure 2. Three-dimensional (3D) scanning of the hand models. The 3D scanner was held by the examiner using both hands and moved carefully 360 degrees around the hand (model) at a distance of approximately 50 cm, with care taken to minimize blurring.

and were synthesized into a computed 3D model in the tablet adjusted by a gyro-sensors. According to the manufacturer's datasheet, its precision at a depth of 40 cm is 0.5% [2,3].

Data assessment

Whole hand measurement method

The 3D data from the camera were imported into a personal computer. Thereafter, the volumes of the hand and forearm (up to 10 cm proximal to the wrist crease; Figure 3(a), red range) were calculated using Netfabb 2017® (Autodesk Inc., San Rafael, CA, USA). We defined this section as the ideal range of interest for evaluating the volume of hand edema, and once the wrist crease on the Netfabb software was set, this area of interest up to 10 cm proximal to the crease was easily measured by the software.

Modified measurement method

The use of the 3 D-scan combined with the whole hand measuring method (WM) gave rise to overestimated volume measurements because scans of the web spaces were unclear, and this led to errors. Therefore, we developed a novel 'Modified method' (MM) by removing all four fingers from the 3D model on the computer (Figure 3(a), blue range) to avoid overestimation. Two palmar creases of the index and little fingers were marked, and the fingers were moved on this plane along the longitudinal axes. The thumb was used for measurements because it has the thenar muscle (an important measurement target) at its base and a large web space. Subsequently, volumes were calculated as described above.

Validity and reliability assessment of WM and MM

Intra-rater reliability of WM and MM

To assess the intra-rater reliability of WM and MM, three plastic hand models were scanned six times each by one rater using both the WM and MM. Thus, a total of 36 scans were performed by one rater. The intra-rater reliabilities were calculated using R (The R Foundation for Statistical Computing, Vienna, Austria). The results >0.8 were evaluated as excellent correlation [4].

Inter-rater reliability of WM and MM

Four trauma surgeons with a total of five years of clinical experience in this field performed the 3D scans. Each surgeon scanned the 10 hand models by both the WH and MM, thus providing 20 measurements per rater and a total of 80 scans by the four raters to evaluate inter-observer differences in the validity and reliability. Then, inter-rater reliabilities were calculated on R and evaluated as described above.

Accuracy of WM and MM compared to computed tomography value

Two life-sized plastic hand models were used to represent male and female hands for this evaluation, considering that their

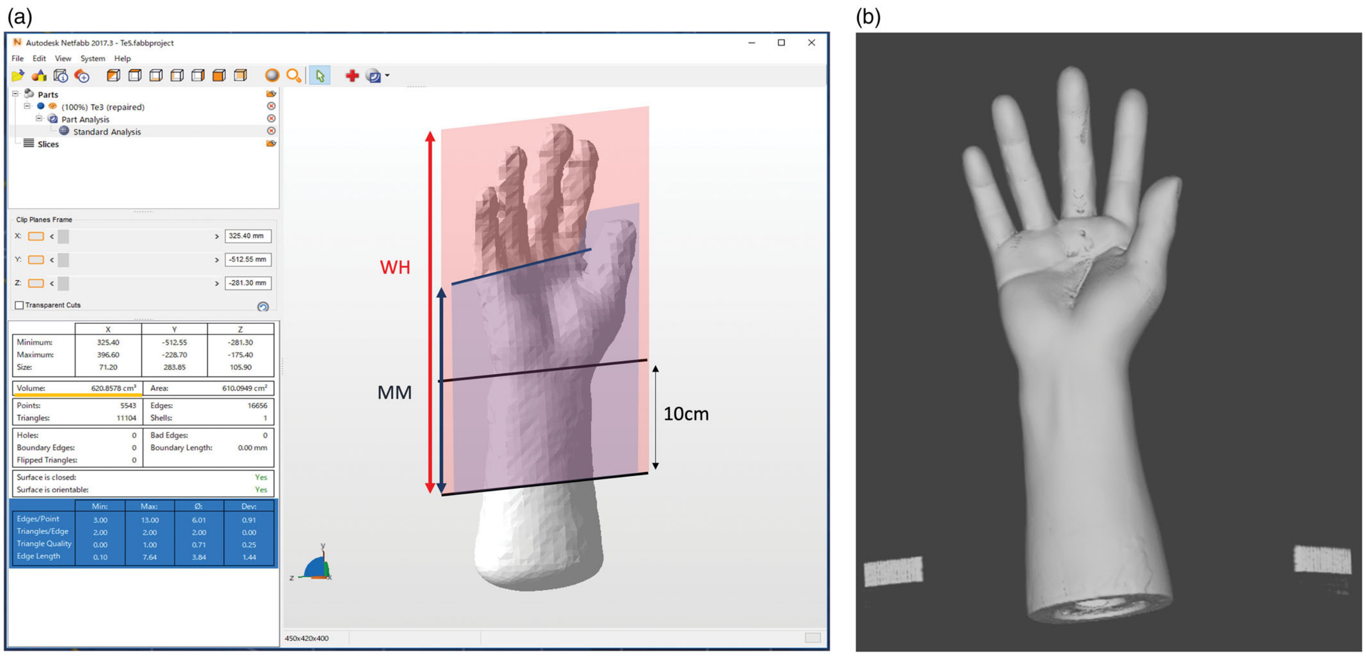

Figure 3. Evaluation of the hand volume on a computer and the range of evaluation using the modified method. In the whole hand method (WH), the volumes of the hand and forearm (from the tip of the fingers to 10 cm proximal to the wrist crease: illustrated as the red range) were calculated. The three-dimensional (3D) camera scan model was used in this figure (Figure 3(a)). In the modified method (MM), all the fingers except the thumb were excluded from the WH model (illustrated as the blue range). The scans of the web spaces were clear in the computed tomography scan model (Figure 3(b)). WH: whole hand method; MM: modified method.

accurate volume could be easily measured using computed tomography (CT). One CT scan and five 3D camera scans by the four raters were performed on each plastic model to confirm the validity and reliability of WM and MM.

CT scan data

The Digital Imaging and Communications in Medicine (DICOM) data of the hand models with 1 mm slice CT scan (AQUILION 64®, Toshiba®, Japan) were imported into OsiriX Lite® (Pixmeo SARL, Switzerland). The corresponding 3D-CT modeling data were procured, and the defined volume was estimated on a personal computer as described above (Figure 3(b)).

3D Scan data

Three-dimensional camera scans on two hand models using the WM and MM were performed five times by four raters producing a total of 20 cycles of 3D scans per rater. Subsequently, the data from the 3D camera were imported into a personal computer, and the volumes were calculated as described above.

Differences in volumetric measurements from CT and 3D scan data

The differences in volume between CT and 3D scan data were calculated for each method and rater. All data were subjected to normality tests based on the Shapiro–Wilk method. Statistical analyses were performed using two-way repeated-measure analysis of variance (ANOVA) on methods and raters. *P*-values of 0.05 or less were considered statistically significant. All statistical analyses were performed using R statistical software.

Clinical validity

A clinical case study was included to evaluate the usability and initial validation of this method. A 70-year-old male patient presented with a high-pressure oil injection injury on his right palm. The hand had been swollen like a catcher's mitt and had gradually improved (Figure 4). At his first visit to our clinic six weeks

Figure 4. Clinical images of a high-pressured oil injection injury hand. A 70-year-old male suffered a high-pressured oil injection injury on the right palm. The clinical image at his first visit to our outpatient clinic (6weeks after the injury). Refractory edema on the right hand was observed, and the fingers could not be fully extended due to both edema and stiffness.

after the injury, the range of motion of his fingers had decreased due to edema and stiffness. We evaluated the changes in volume using WM and MM during 13 weeks of our treatment and

Table 1. The intra-rater and inter-rater reliability of 3D scanner.

	ICC	F value	P value	95%CI H	95%CI L
The intra-rater reliability					
WM ICC (1, 6)	0.97	222	<0.001	1.00	0.87
MM ICC (1, 6)	0.96	153	<0.001	1.00	0.84
The inter-rater reliability					
WM ICC (1, 2)	0.84	42	<0.001	0.94	0.61
MM ICC (1, 2)	0.83	27	<0.001	0.94	0.61

ICC: Intraclass correlation coefficient, WM: Whole hand measurement method, MM: modified method, ICC (1, 6): intra-rater reliability, ICC (1, 2): inter-rater reliability.
The intra-rater reliability of WM and MM
To assess the intra-rater reliability of WM and MM, three plastic hand models were scanned six times each by one rater using both the WM and MM. Thus, a total of 36 scans were performed by one rater. All the ICCs showed almost perfect correlation.
The inter-rater reliability
Four trauma surgeons with a total of 5 years of clinical experience in this field performed the 3D scans. Each surgeon scanned the ten hand models by both the WH and MM, thus providing 20 measurements per rater and a total of 80 scans by the four raters to evaluate inter-observer differences in the validity and reliability. All the ICCs showed almost perfect correlation.

Table 2. The differences in the volumes (cm^3) between CT and a 3D scanner.

(a)

	Ave	SD	Median	95%CI H	95%CI L
All WM	24.63	13.28	25.95	28.88	20.39
All MM	11.39	9.92	12.06	14.56	8.22
M WM	30.35	2.70	32.53	31.62	29.09
M MM	11.60	2.07	11.74	12.57	10.63
F WM	18.92	2.66	21.06	20.16	17.67
F MM	11.18	2.35	12.30	12.29	10.08

(b)

Examiner	Ave	SD	Median	95%CI H	95%CI L
1 WM	28.72	14.20	33.70	38.88	−9.91
1 MM	14.96	15.71	16.19	26.20	4.13
2 WM	23.24	12.53	24.77	32.20	−5.19
2 MM	9.63	13.60	15.94	19.36	2.20
3 WM	22.58	13.76	23.47	32.43	−3.02
3 MM	12.01	13.55	11.79	21.70	5.12
4 WM	16.36	6.45	15.64	20.98	−4.73
4 MM	3.60	2.92	3.44	5.69	0.46

(data are shown as mean ± standard deviation).
CT: computed tomography; 3 D: three-dimensional; WM: Whole hand measurement method; MM: modified method; M: male model, F: female model.
Two life-sized plastic hand models were used to represent male and female hands for this evaluation, considering that their accurate volume could be easily measured using computed tomography (CT). One CT scan and five 3D camera scans by the four raters were performed on each plastic model to confirm the validity and reliability of WM and MM.
(a) In the Male model, volume on CT by WM was 507.51 cm^3. In the Female model, volume on CT by WM was 356.36 cm^3. The volumes were largely overestimated in WM, and the standard deviation was small in both MM and WM. Due to different position of each hand model, the standard deviations in the All model showed more variance than that of each model.
(b) Some differences, probably due to experience in this method, were observed, especially in MM, because MM needed additional procedures for calculating on computer. Only five times of 3D scanning were performed for WM and MM in this study, which may contribute to the large standard deviations.

rehabilitation program to investigate the validity and clinical use of our technique.

A small bedside table was used when performing the 3D camera scans. The patient placed his elbow on the table in an arm-wrestling position (Figure 2). The scanning was easily performed within 5 min in the outpatient clinic.

The institutional review committee of our hospital approved this study, and the patient gave informed consent.

Results

Time for 3D scanner measurements

The measurement time to scan the hand model was 1–2 min using the 3D camera scanner, ~5 min using the WM, and 8 min using MM on a personal computer.

Validity and reliability assessment of WM and MM

In the intra-rater reliability test of WM and MM, a total of 36 3D scan measurements were competently performed by one rater. In WM, the intra-rater reliability was 0.97 and 95% confidence interval (CI) was 0.87–1.00 (Table 1). In MM, the intra-rater reliability was 0.96 and 95% CI was 0.84–1.00.

In the inter-rater reliability test, a total of 80 3D scan measurements were performed by four raters without any issues. In WM, the inter-rater reliability was 0.84 and 95% CI was 0.61–0.94 (Table 1). In MM, the inter-rater reliability was 0.83 and 95% CI was 0.61–0.94.

Accuracy of WM and MM compared to the CT value

The CT and 3D camera scan results by each examiner, including both WM and MM, are summarized in Table 2 and Figure 5. In the Male model, volume on CT by WM was 507.51 cm^3 and the volumetric differences between CT data and 3D scan data using WM and MM were 30.35 ± 2.70 (mean ± standard deviation) and 11.60 ± 2.07 cm^3, respectively. In the Female model, the volume on CT using WM was 356.36 cm^3, and the differences were 18.92 ± 2.66 and 11.18 ± 2.35 cm^3, respectively. The volumes were largely overestimated by WM, and the standard deviation was small in both MM and WM.

The normality for all these data was proved using the Shapiro–Wilk test. Analysis of two-way repeated-measures ANOVA on the methods (WM and MM) and raters of all the models showed significant difference in the method ($p < 0.001$) but not in the rater ($p = 0.134$). No interaction was found between the method and the rater ($p = 0.715$). Taken together, the validity of MM (2–3% error) was better than that of WM (5–6% error), and the reliability was consistent between multiple raters.

Evaluation of clinical usability and validity

All the measurements were performed at an outpatient clinic smoothly and comfortably with the patient. The 3D scan volume values were compatible with the impressions of the treating doctor and occupational therapist (Figure 6). The patient performed less rehabilitation at home in the 7–9th week post-injury, and the edema worsened in both WM and MM. A discrepancy between the WM and MM on the 15th week postinjury was observed along with better active range of motion of fingers.

Discussion

The validity and reliability assessment of the WM and MM showed that both the intra- and inter-rater reliability had excellent correlation. Although the four raters had different experiences using the 3D scanners, high validity and reliability were observed. Due to the blunt description of finger web in WM, MM was used for a more accurate evaluation of hand edema, and the accuracy of the 3D scan was assessed for both WM and MM.

As one of our future objectives was to evaluate hand volume for intrinsic muscle survival in patients with acute injury, the accuracy of the 3D scan method must be compared with that of CT. Volumes were largely overestimated *via* WM, although the standard deviation was small in both MM and WM. Due to the

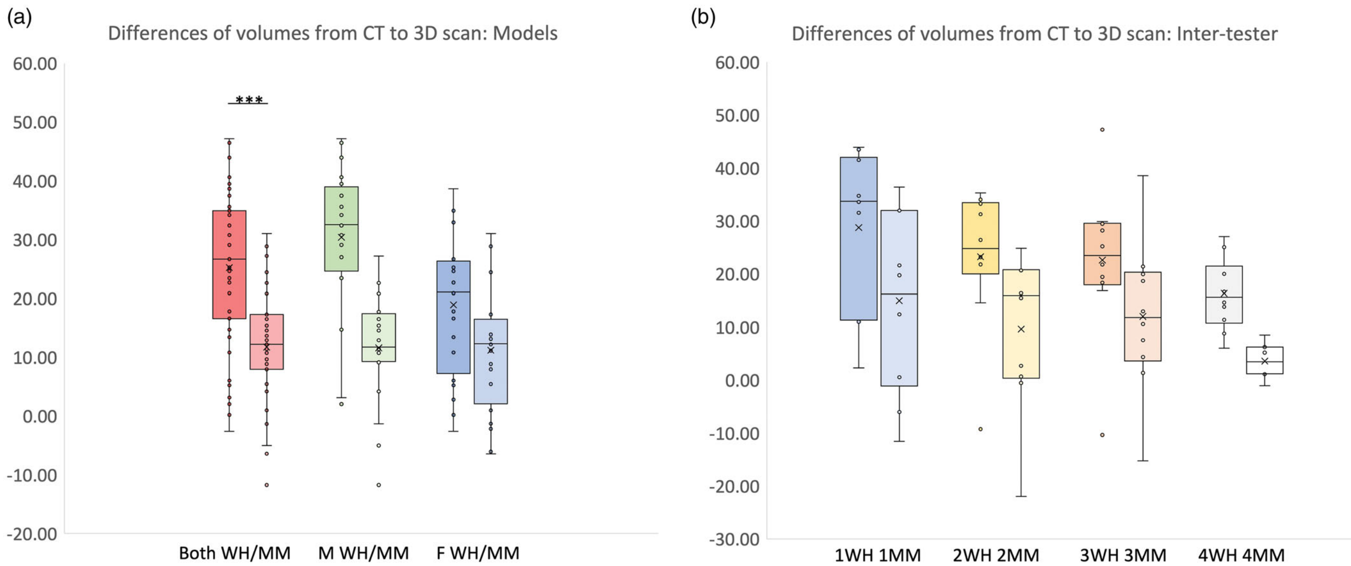

Figure 5. The differences in volume between CT data and 3D scan by WH and MM. (a) The box plot shows that the volumes were largely overestimated by WH in all models. (b) Some variances between examiners, probably due to experience in this method, were observed, especially in MM, because MM needed additional procedures for calculating on computer. WH: whole hand method; MM: modified method.

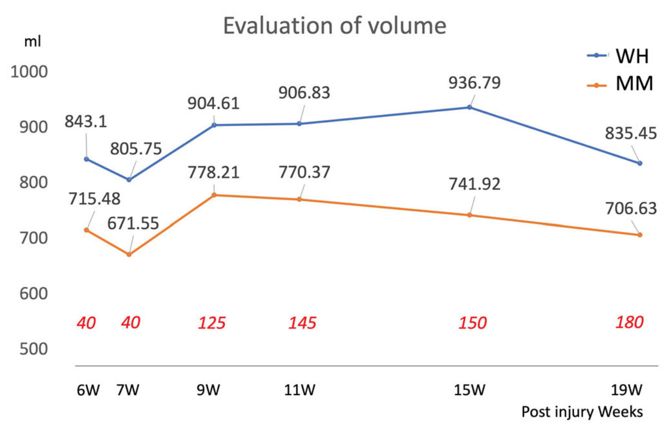

Figure 6. A chart of the hand volumes measured throughout the clinical course. The whole hand method (WH) and the modified method (MM) were used to evaluate the edema measurements. Changes in values were similar between the methods; however, at 15 weeks, moderate error, which is supposed to be from the finger and finger webs, was observed in WH. The total active range of motion (red letters) was calculated by adding the total active flexion and total active extension deficit of the middle finger joints (metacarpophalangeal joint, proximal interphalangeal joint, distal interphalangeal joint).

different hand positions of each model, the male models had narrower web spaces than the female hand models, and the female hand models had greater ulnar wrist flexion that the male models did. The standard deviations in both WM and MM models combined showed greater variance than that of male and female models alone (Figure 5(a)), highlighting the importance of hand position when using this method.

There were some differences between the examiners performing MM and WM, probably due to their previous experience of each method. This was especially true for MM, which requires the additional procedure of removing the fingers *via* the software to calculate the volume. 3D scanning was performed only five times for WM and MM each when we measured the accuracy of the WM and MM compared to the CT value; therefore, the small number of measurements may have contributed to the large standard deviations as shown in Table 1(b). Other factors regarding individual raters, such as the distance between the target and the 3D scanner, tablet's angle to target, or speed of moving the scanner around the model during the measurements, were considered to be the likely causes of the differences observed. However, as shown in intra-rater reliability test, correlation of repeated measurements was excellent in a single rater, meaning that the consistency of the rater's measurement settings could achieve excellent validity and reliability.

During the clinical evaluation at the outpatient clinic, 3D scan data were obtained quickly and painlessly. Though edema persisted to some extent, the range of motions of the patient's fingers gradually improved with rehabilitation. Such improvements may have led to discrepancies between WM and MM at 15 weeks due to the positions of the patient's fingers. The MM data objectively reflected the slight decrease in edema, which supported the effectiveness of our conservative treatment. It is worth noting that the variation in edema between each evaluation time point was <50 ml and was approximately 100 ml during the overall two-month clinical course. This small variance indicates the importance of accurate evaluation of hand and forearm edema.

Evaluating edema following an acute injury is critical, especially in unconscious patients with severe tissue damage in order to avoid compartment syndrome. The total volume of intrinsic muscles according to anatomical studies is less than 100 cm^3 [5]. Therefore, of the total hand volume of 900 cm^3 in our clinical case, to preserve future fine motor functions, emergent fasciotomy to the small intrinsic muscles should be considered in addition to conventional fasciotomy procedure. Additionally, even in cases of chronic hand lymphedema, accurate, reliable, and easy evaluation of edema is essential throughout its long treatment course. Regarding cases of acute or subacute hand trauma, previous studies rarely considered measuring the degree of edema. Most studies are on chronic edema and included the use of a 3D camera [6], stereo-photo technique [7], water displacement [8], ring-gauge [9,10], and hand circumference measurement methods [11]. However, the standard clinical method for quick assessment of hand edema remains unestablished. Practically, edema of the hand in such acute cases are estimated during physical examination to decide the emergent need for additional fasciotomy of the hand, as evaluation of the tiny intrinsic muscles of the hand using a needle manometer is not always feasible [12]. This problem is a future focus of our 3D scan method.

The water displacement method is known to be the most accurate method with less than 1% error [13]; however, it requires a large water tank and experienced examiners. Consequently, it is inappropriate for the evaluation of edema in such cases of acute or subacute trauma.

The ring-gauge method [9] is easy and cheap but can only measure the circumference of a finger. However, the results obtained may not directly reflect ongoing volume changes. Most circumference measurements of the hand and forearm face similar problems. Moreover, these methods require physical contact, including touching the painful hand for measurements with a certain risk of causing infection in these cases.

Some studies report the use of a stereo-photo technique [14,15] with an expensive large camera system and exclusive application to measure volume accurately with less than 1% of error. However, its applicability and accuracy in acute or subacute clinical cases remains unclear. A study on the use of 3D cameras, similar to our method, was poorly handled [16] and was attached to a PC using long cords [6]. Notedly, most of these studies require the use of specific complementary equipment for accurate measurement along with exclusive software, as well as elaborate preparations and workspaces.

In our method, 3D data and sizes of the hands were obtained using the time-of-flight method with infrared light from a handheld 3D camera and measured using conventional application with relatively low-cost equipment. Moreover, MM has the possibility to measure edema of the hand more accurately even at the bedside with less physical contact even in severe traumatic cases. Lastly, our method can evaluate hand edema more effectively, while many previous 3D scan methods require patients to clench their fist or exclude hands from measurement to avoid error [7,16]. In MM, the actual estimated error is approximately 2–3%, larger than that of other previously reported methods. Instead, we can quickly evaluate the volume of the edema at bedside, with a cost reduction of 10–20 times less than other medical 3D scanner systems.

This study has some limitations. We only evaluated life-sized plastic models and one clinical case of subacute edema of the hand as a preliminary study. To establish this method for clinical use, further evaluations are required, including an assessment of the relationship between edema and intra-muscular pressure in cases of acute injury. This would also allow us to see if our 3D scanner can be used as a clinical tool in chronic lymphedema, which needs long term treatment; therefore, we need to assess the long-term validity and reliability of this technique in the outpatient department. As the difference in variance between the male and female models revealed, the position of the hand also critically influences accurate evaluation of edema. Consequently, stabilizing the position of the hand must be critical in this method. In unconscious patients with severe injuries, additional use of a Chinese finger trap fixation might solve this position problem, especially during MM.

In future, we hope that this 3D scanner method can be used as the first non-invasive evaluation to identify indicators of fasciotomy in cases of acute compartment syndrome of the limbs. It can also be used in the evaluation of rehabilitation following injuries or conservative treatment of lymphedema [17].

Conclusion

We confirmed that our 3D scanning method had excellent validity and reliability. Moreover, after excluding the fingers and web spaces, there was a possibility to evaluate the hand volume more accurately, conveniently, and non-invasively even in cases of acute or subacute hand trauma. Our cost-effective method that applies a handheld 3D camera could be used efficiently and can identify small changes in hand volume painlessly in actual clinical settings. Although further evaluations are needed, we believe that our technique can be considered as a standard method for evaluating hand edemas.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

[1] Matsen FA, 3rd, Winquist RA, Krugmire RB. Jr. Diagnosis and management of compartmental syndromes. J Bone Joint Surg Am. 1980;62(2):286–291.

[2] Occipital I. What are the technical specifications of Structure Sensor (ST01)? https://support.structure.io/article/157-what-are-the-structure-sensors-technical-specifications2020.

[3] Occipital I. How precise is the original Structure Sensor (ST01)? https://support.structure.io/article/157-what-are-the-structure-sensors-technical-specifications2020.

[4] Cicchetti DV. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. Psycholl Assess. 1994;6(4):284–290.

[5] Linscheid RL, An K-N, Gross RM. Quantitative analysis of the intrinsic muscles of the hand. Clin Anat. 1991;4(4): 265–284.

[6] Bullas AM, Choppin S, Heller B, et al. Validity and repeatability of a depth camera-based surface imaging system for thigh volume measurement. J Sports Sci. 2016;34(20): 1998–2004.

[7] Landau MJ, Kim JS, Gould DJ, et al. Vectra 3D imaging for quantitative volumetric analysis of the upper limb: a feasibility study for tracking outcomes of lymphedema treatment. Plast Reconstr Surg. 2018;141(1):80e–84e.

[8] Beach RB. Measurement of extremity volume by water displacement. Phys Ther. 1977;57(3):286–287.

[9] Suzuki T, Sato Y, Sotome S, et al. Intra- and inter-tester reliability and validity of normal finger size measurement using the japanese ring gauge system. J Hand Surg Eur Vol. 2017;42(5):511–515.

[10] Yamazaki H, Sakurai T, Uchiyama S, et al. Reliability and concurrent validity of the ring gauge method and the metacarpal head tape measure method of measuring hand size. J Hand Surg Asian Pac Vol. 2018;23(3):382–387.

[11] Yamamoto T, Yamamoto N, Yoshimatsu H. Localized arm volume index: a new method for body type-corrected evaluation of localized arm lymphedematous volume change. Ann Plastic Surg. 2017;79(4):390–392.

[12] Wong JC, Vosbikian MM, Dwyer JM, et al. Accuracy of measurement of hand compartment pressures: a cadaveric study. J Hand Surg Am. 2015;40(4):701–706.

[13] Waylett-Rendall J, Seibly DS. A study of the accuracy of a commercially available volumeter. J Hand Ther. 1991;4(1): 10–13.

[14] Hameeteman M, Verhulst AC, Vreeken RD, et al. 3D stereophotogrammetry in upper-extremity lymphedema: an accurate diagnostic method. J Plast Reconstr Aesthet Surg. 2016;69(2):241–247.

[15] Batista BN, Baiocchi JMT, Fraga MFP, et al. Vectra 3D imaging for quantitative volumetric analysis of the upper limb: a feasibility study for tracking outcomes of lymphedema treatment. Plast Reconstr Surg. 2018;141(4): 616e–617e.

[16] Buffa R, Mereu E, Lussu P, et al. A new, effective and low-cost three-dimensional approach for the estimation of upper-limb volume. Sensors (Basel)). 2015;15(6): 12342–12357.

[17] Cau N, Galli M, Cimolin V, et al. Quantitative comparison between the laser scanner three-dimensional method and the circumferential method for evaluation of arm volume in patients with lymphedema. J Vasc Surg Venous Lymphat Disord. 2018;6(1):96–103.