ARTICLE IN PRESS

Journal of Hand Therapy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Hand Therapy

journal homepage: www.elsevier.com/locate/jht

# A novel technique for digital assessment of hand volume

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A R T I C L E I N F O

*Article history:*
Received 20 December 2024
Revised 27 February 2025
Accepted 4 March 2025
Available online xxxx

*Keywords:*
Hand volume assessment
Hand swelling
Computer vision
Figure-of-eight
Water displacement
Digital

A B S T R A C T

*Background:* Swelling is an anticipated nonspecific response following hand trauma, arthritis, infection, or surgery, which can decrease range of motion and increase pain. Approaches to quantify swelling, typically performed through hand volume measurement, are lacking in routine clinical assessments. A hand volumetry technique that is quick, inexpensive, noninvasive, and reliable is still in demand. With advances in computer imaging, new technologies are increasingly gaining attention to enable the digital assessment of hand volume as a surrogate marker of swelling.
*Purpose:* This study aims to develop a webcam-based method using computer vision technology for digital hand volume assessment and compare its results with those from conventional water displacement and figure-of-eight techniques to evaluate its feasibility in healthy hands.
*Study Design:* Cross-sectional observational pilot study.
*Methods:* A novel algorithm was developed to process hand images captured through a webcam. Digital hand volume was computed using both palmar and lateral view area calculations. Thirty healthy participants were recruited. The volumes of their hands were measured using three methods: the proposed digital method ($V_D$), water displacement ($V_W$), and figure-of-eight taping ($C_{FOE}$). Digital volumes were compared to conventional approaches using Pearson correlation coefficients and Bland-Altman analysis.
*Results:* A strong correlation was observed between $V_D$ and $C_{FOE}$ (r = 0.89, $p < 0.00001$). Similarly, $V_D$ demonstrated a significant correlation with $V_W$ (r = 0.96, $p < 0.00001$). However, a systematic overestimation by $V_D$ was identified and subsequently adjusted using a calibration curve derived from regression analysis, resulting in the calibrated hand volume ($V_{D^*}$). Bland-Altman analysis between $V_{D^*}$ and $V_W$ indicated Limits of Agreement (LOA) of ± 33.6 mL, with percentage limits ranging from −9.5% to 9.3%.
*Conclusions:* This study demonstrates a novel approach to digital hand volume assessment. Our findings suggest that when LOA of ± 9.5% is considered clinically acceptable, the digital method can be used interchangeably with water displacement volumetry in nonpathological hands.


## Introduction

Hand swelling is commonly evaluated qualitatively, but quantification of swelling requires a more advanced technique to measure volume. Mitigating the amount of swelling in the hand can have positive impacts on both pain and improved range of motion. Its reliable measurement is an important first step to complement a suspected diagnosis (eg, infection, arthritis, lymphedema, ganglion, tumor, vascular malformation) and evaluate strategies to target swelling (eg, elevation, compression, medications, surgery) to optimize recovery.[1] The abundance of techniques described to measure swelling is a testament to both the importance and challenge of the problem. For a swelling measurement approach to be clinically impactful, it must be accurate, easy to perform, and require minimal equipment.

To date, several traditional and tech-based methods have been introduced to accurately measure hand and wrist volume, including water displacement, figure-of-eight tape, ring gauges, and technological advances (eg, 3D scanners). The gold standard of these techniques is water displacement, which serves as the benchmark against which other volumetric methods are evaluated.[2,3] Water volumetry provides accurate measures of swelling in the hand, arm, feet, elbow, and knee,[2,4] with specific studies reporting an error rate

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0894-1130/
https://doi.org/10.1016/j.jht.2025.03.001

of less than 1% for the hand volume measurement under standard conditions.[3,5,6] The required equipment for measurement is rather inexpensive and does not need special training. However, it cannot safely measure the volume of hands with open wounds or skin lesions, and the hand positioning required during the test may cause pain or discomfort for patients with pathological conditions.[1,6,7] Furthermore, the process is time-consuming due to the preparation, apparatus setup, and cleanup required, which can make it cumbersome and impractical for routine use in clinical settings.[7]

Additional traditional techniques such as the figure-of-eight tape measurement, which involves tracing a tape in a figure-of-eight pattern around the hand,[6] ring gauge method, which measures the size of the little finger using a ring gauge,[8-10] and geometric algorithm technique, which measures hand dimensions (width and depth) at several sections using a caliper,[7] are cost-effective, easy to acquire, and can produce accurate measures in certain situations. However, they rely heavily on the examiner's ability to identify bony landmarks, accurately and repeatably perform the measurement technique (eg, tape tension, caliper placement), and ensure correct joint positioning during the measurement process, with any deviations possibly resulting in inaccuracies and misdiagnoses of swelling.[8,10]

More recently, newer technologies, such as volumetric analysis through noninvasive morphological evaluation, which uses 3D scanners, Perometry, which utilizes infrared light beams to scan the limb, computed tomography scanning, and magnetic resonance imaging, have emerged as highly precise and accurate alternatives to the original technologies, while also reducing measurement time and user error.[1,11-17] However, these options can be extremely costly, difficult to obtain, and can be limited by radiation exposure risks to the patient.

While tech-based methods are accurate and safe for individuals with open wounds or infections, their high equipment costs and operational complexity can limit adoption in medical settings. On the other hand, traditional techniques, while more accessible, often come with notable limitations in patient comfort and rely on the examiner's skill and consistency. These constraints may impede frequent monitoring of swelling during recovery, potentially affecting the overall efficacy and outcomes of treatment. Leveraging advances in technology, specifically computer vision, offers new opportunities to address these gaps and approach swelling measurement through a fresh lens. Hence, using this technology, we introduce an inexpensive, valid, and patient-friendly alternative for measuring hand volume.

The primary objective of this study is to develop a digital method to assess hand volume, which is integrated with the previously established DIGITS web application.[18,19] Utilizing computer vision technology, this method enables healthcare professionals to evaluate hand swelling and monitor treatment progress remotely by simply having patients position their hands in front of a standard laptop webcam or cell phone camera. To examine the feasibility of this approach, a pilot study was conducted with a healthy hand population to assess the validity of the proposed method relative to the two well-established traditional techniques of water volumetry and figure-of-eight taping. To achieve this, the relationships between the digital method and the traditional ones were studied through regression analyses. The Bland-Altman analysis was also conducted to explore the degree of agreement between the proposed method and the gold standard water volumetry.

## Methods

### *Digital hand volume assessment technique*

To measure the digital volume of the hand, a computer-vision algorithm developed with OpenCV was integrated into the existing DIGITS platform. DIGITS is an augmented reality web application originally developed to remotely assess finger dexterity and range of motion in patients with hand pathologies.[18-20] This study extends its application by piloting DIGITS as a tool for assessing hand swelling.

In the proposed algorithm, the *digitally computed volume* ($V_D$) of the hand is calculated by capturing images and determining the areas from two perspectives: the front view (palmar perspective) and the side view (lateral perspective). These images are captured, and areas are calculated while the participant holds his/her hand in front of the webcam. To ensure accuracy, the hand must be positioned directly facing the camera, aligning optimally with the camera's field of view.

The algorithm calculates the hand area from both perspectives using real-time webcam frames and then computes the hand's volume based on these measurements. Figure 1 illustrates the steps of the proposed algorithm including preprocessing, segmentation, hand area and depth measurement, and volume calculation. The initial step within the algorithm includes noise removal and the application of filtering techniques to minimize noise and distortions. Next, the Gamma correction technique, along with brightness and contrast adjustment, is employed, and a sharpening filter is used to adjust the image's luminance and preserve essential visual data such as edges.[21,22] Together, these preprocessing stages enhance image quality, effectively preparing the captured frame for further processing and the segmentation phase.

To calculate the area, the hand is segmented from the captured frame, and its contour is outlined. For accurate segmentation of the hand, the Canny edge detection, recognized as one of the most effective and reliable edge detection techniques, has been employed to identify real and strong edges.[23,24] Since contrast limited adaptive histogram equalization (CLAHE) has proven to be the most effective preprocessing technique for edge enhancement,[25] it has been incorporated into our algorithm. Our studies under different lighting conditions have demonstrated that the consistency of the edge detection is significantly improved and becomes more robust in various environments when the CLAHE technique is applied to the grayscale version of the preprocessed frame.

In this study, we focused on measuring the volume of the palmar hand, defined as the area extending to the distal wrist crease. Therefore, to compute the digital volume ($V_D$), the output from the Canny edge detection process was cropped at the distal wrist crease. Hence, it is essential to ascertain the position of the wrist crease and the orientation of the hand to correctly extract the wrist line across various hand postures. A reliable method for determining wrist position and hand orientation involves using the pre-trained MediaPipe Hand Landmarker model.[26,27] This hand-tracking task utilizes a machine learning pipeline with two collaborative models: a palm detection model, which analyzes the full input image to locate the palms, and a hand landmarks detection model which processes the cropped hand image from the palm detector and outputs 21 precise landmarks in 2.5 dimensions, that is, $x$, $y$, and relative depth $z$ coordinates.[28] The MediaPipe Hands pipeline has been implemented in DIGITS as part of a study to evaluate hand dexterity and has demonstrated reliably accurate results.[20] Using hand landmarks, a line is drawn from the middle finger metacarpophalangeal joint to the wrist joint. The slope of this line representing the orientation of the hand is calculated. Subsequently, the equation of the wrist line, perpendicular to the hand's orientation, is obtained. Figure 2 depicts various orientations and postures of a hand with the landmarks identified by the MediaPipe Hand Landmarker model and the corresponding wrist line.

The subsequent steps to extract the hand's area from both the palmar and lateral views, which lead to the computation of the hand's digital volume, are illustrated in Figure 3. As shown, once a closed edge of the hand (cropped at the wrist) is obtained, a filled contour is extracted from the edges to create a stable mask. Subsequently, the final contour around the hand mask is drawn, and the area within this contour is calculated in pixels. To obtain the hand's volume, the area measured in pixels needs to be converted into square centimeters (cm²). This conversion necessitates a reference to

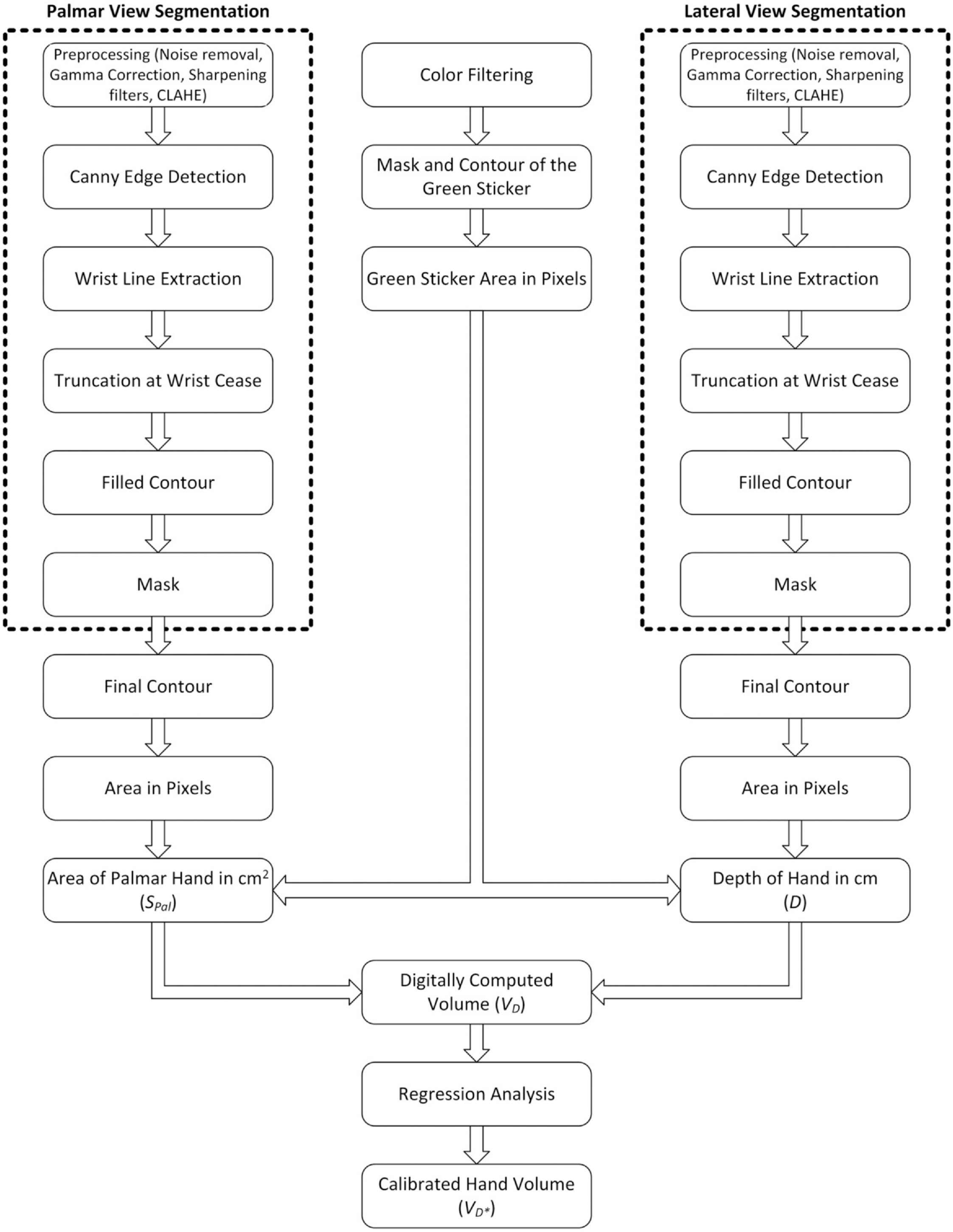


**Fig. 1.** The process chart of the digital algorithm to assess hand volume.

determine the pixel-to-centimeter ratio in the images. Accordingly, a commercially available circular fluorescent green sticker[a] with a radius of 0.95 cm is affixed to both the lateral and palmar surfaces of the hand and used as the reference for measurements. The area of this sticker is calculated in pixels using several steps in the algorithm (Fig. 1) to establish the pixel-to-centimeter ratio for both the hand and the green circle.

As depicted in the process chart outlined in Figure 1, the method for assessing the digitally computed volume ($V_D$) begins by calculating the area of the hand from the palmar view ($S_{Pal}$). Subsequently, the area from the lateral view ($S_{Lat}$) is determined. This area is divided by the hand's length ($L$) to estimate the depth of the hand ($D$), following the relation $D = S_{Lat} / L$. The length of the hand, $L$, is

[a] Blank inventory circle labels fluorescent green, 3/4" with the model number of S-3449G. Available at https://www.uline.ca/Product/Detail/S-3449G/Inventory-Labels/Blank-Inventory-Circle-Labels-Fluorescent-Green-3–4?keywords=S-3449G+Blank+Inventory+Circle+Labels+-+Fluorescent+Green%2C+3%2F4%22. Accessed December 12, 2024.

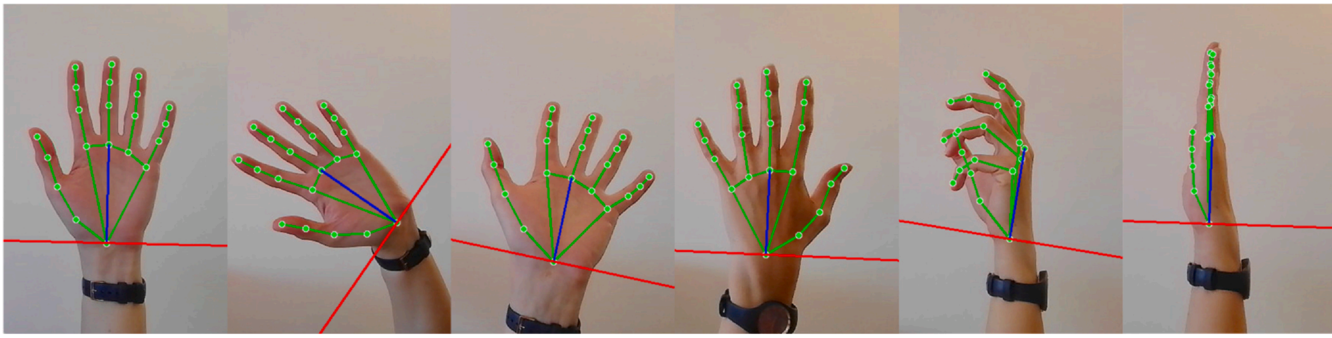

**Fig. 2.** Extraction of the wrist line in various hand postures; green dots and lines represent the hand landmarks identified by the MediaPipe Hands pipeline, while the blue line indicates the hand's orientation and the red line marks the wrist line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

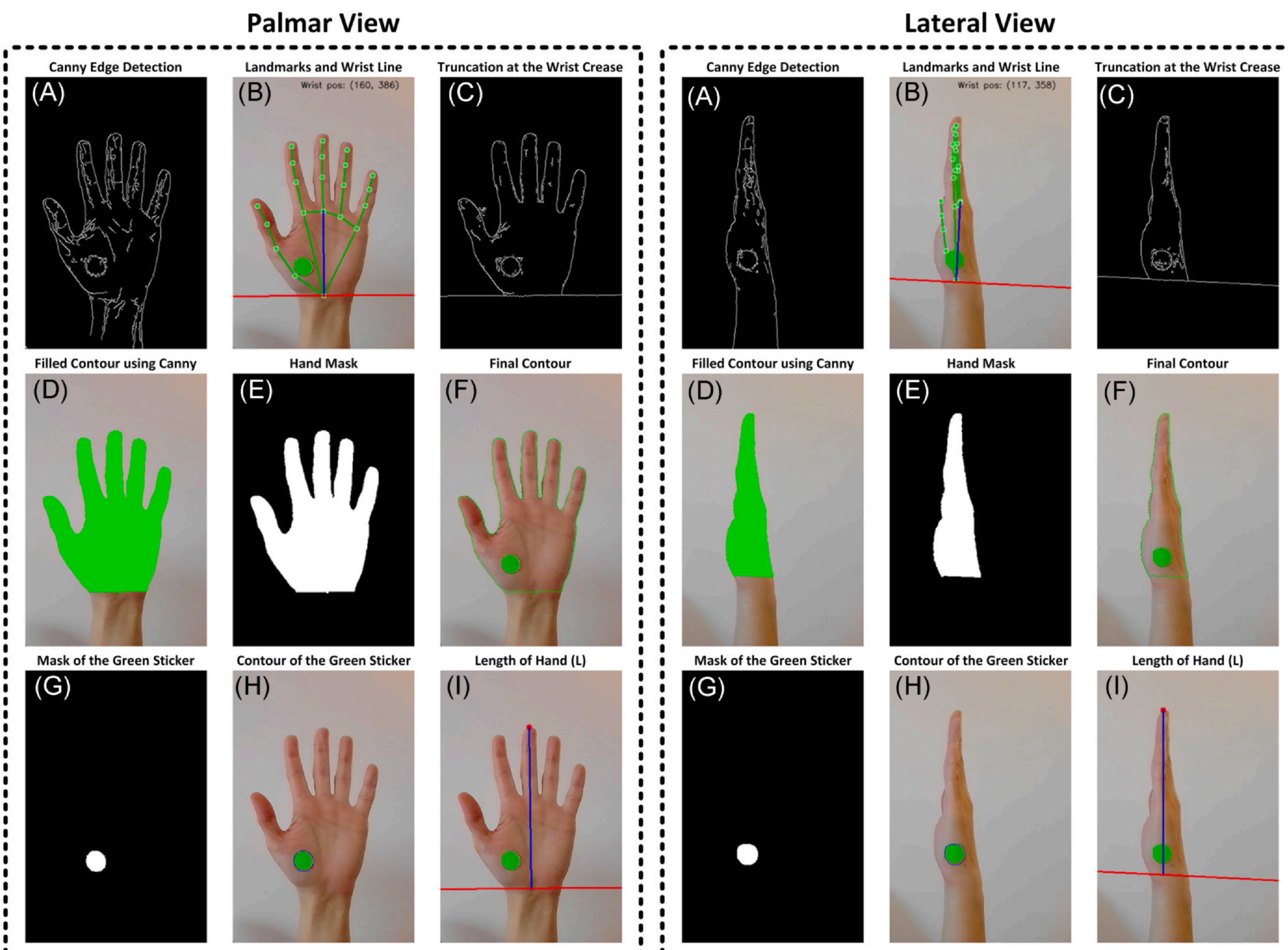


**Fig. 3.** Stages of hand segmentation, contour extraction, and calculation of palmar area and depth of the hand in the palmar and lateral views, (**A**) initial result from the Canny edge detection, (**B**) localization of hand key points using MediaPipe landmarks and extraction of the wrist line, (**C**) truncation at the wrist crease using the wrist line, (**D**) filled contour drawn around the closed edges, (**E**) hand mask after Canny processing, wrist truncation, and morphological operations, (**F**) final contour drawn on the original hand image, (**G**) mask of the green sticker derived from color detection, (**H**) contour extraction for the green sticker, (**I**) calculation of the hand's length to assess the hand's depth. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

defined as the distance from the distal wrist crease to the tip of the middle finger, as illustrated by the blue line in Figure 3I. The depth of the hand, $D$, is assumed to be uniform along its length, given that the hand's region in the side view is modeled geometrically as a rectangle. The digitally computed volume ($V_D$) is then estimated by multiplying the area from the palmar view ($S_{Pal}$) by the calculated depth, according to the formula $V_D = D \times S_{Pal}$.

It is worth mentioning that, though the palmar view only captures the area of the palmar hand, measuring the hand area in the lateral view to estimate depth allows us to account for potential swelling on either the dorsal or volar aspect of the hand, as this swelling alters the area visible from the side.

Applying this technique dynamically, whether it is a real-time sequence of frames captured by the webcam or a sequence of frames in a video file, the algorithm calculates the area and depth for each frame. However, measurements could be compromised by factors such as the hand being out of frame or noisy segmentation due to unintended rapid movements. To detect these anomalies, the interquartile range method (IQR) is applied in the algorithm to filter out outlier data, ensuring that only consistent and logical data are retained.[29,30] Once the outliers are removed from the data, the average values for hand area and depth are calculated from all the filtered frames.

### Participants

In this study, 30 healthy participants were recruited through university social media advertisements and word of mouth. The inclusion criteria included age 18+, no documented hand pathology, no allergies to adhesives, no subjective hand swelling, and the ability to communicate in English. Any participant with open wounds on their hands or wrists was excluded from the study. After recruitment, all participants were informed about the details and tasks of the study. They provided informed consent by signing the necessary forms via the Lawson Research Institute's Electronic Data Capture system (REDCap).[31,32] Basic demographic data including age, sex, race, occupation, and hand dominance were recorded on this platform. This study was approved by the Health Sciences Research Ethics Board at Western University with project ID: 125359.

### Pilot study protocol

In this study, 30 nonpathologic adult right hands were assessed using three different approaches. For each participant, we first assessed the volume of the hand using the proposed digital volume algorithm. Subsequently, the hand volume was measured using the figure-of-eight method, and finally, by water displacement volumetry. Only the right hand was measured for each participant, irrespective of hand dominance. All measurement techniques were performed by a single examiner.

### Digital volume measurement

The digital volume ($V_D$) measurement was conducted using the algorithm described above based on the integration with the DIGITS web application. A circular fluorescent green sticker was affixed to both the palmar and lateral surfaces of the participant's right hand. The participant then held their hand in front of a laptop webcam so that two video frames could be captured from different perspectives: one from the palmar view with fingers extended and abducted, and the other from the lateral view with fingers extended and adducted, with the thumb adjacent to the index finger, as depicted in Figure 3. Participants were instructed to position their hands directly facing the camera, square to the lens, to ensure optimal alignment with the camera's field of view. The captured frames were analyzed in real-time by the specially developed algorithm to determine the palmar hand area and estimate the hand's depth, thereby computing the hand volume. Additionally, video files were recorded from each perspective to enable later verification and confirm the accuracy of the values computed in real-time.

### Figure-of-eight measurement

A 1/4-inch wide retractable tape, pre-cut at the 70-cm mark for easier handling, was utilized (similar to the protocol described by Maihafer et al[6]). The participant's arm was positioned in supination with the hand extended over the table edge. The wrist was maintained in a neutral position with fingers adducted. The measurement process began by positioning the tape's zero mark just past the ulnar styloid on the wrist's ulnar side, stretching it across the volar side of the wrist to a position just distal to the radial styloid. Subsequently, the tape passed diagonally across the dorsum to the fifth metacarpophalangeal joint, continued across the volar aspect of the palm to the second metacarpophalangeal joint, and finally, was drawn diagonally over the dorsum to return to the starting point, where the measurement was recorded in centimeters ($C_{FOE}$). Care was taken to ensure no tension was applied to the tape while wrapping it around the hand to avoid measurement errors.

### Water displacement volume measurement

Water displacement measurement was conducted for each participant using a standard volumeter set,[b] with all procedures carried out by the same examiner. The setup began by filling the tank with tap water until it overflowed from the spout, then waiting for any excess overflow to cease. Participants were instructed on the proper hand immersion technique for the water volumetry method; each stood parallel to the volumeter, maintaining their wrists in a neutral position. The participant's right hand was then slowly immersed in the water up to the distal wrist crease, previously marked with a marker to ensure precise immersion depth and prevent inaccuracies due to excessive or insufficient submersion. The displaced water that overflowed was collected in a dry beaker until the overflow stopped. This water was then carefully transferred to a graduated cylinder, which was placed on a level surface. After allowing the water to settle into equilibrium, the water level at the meniscus was recorded as the hand volume obtained by water displacement ($V_W$). A thermometer was used throughout the setup to maintain the water temperature within the range of 22°C-32°C, ensuring both the reliability and consistency of the volumetry and the comfort of the participant.[2] Throughout the data collection, it was ensured that fresh water was used for each participant and the volumeter tank was sanitized between participants. Given that hand volume may increase immediately postimmersion due to biological responses, water volumetry measurements were conducted after assessing the virtually computed volume and tape measurement.

### Data analysis

The results of hand volumetry, using three techniques; digital volume method, figure-of-eight taping, and water displacement measurement were evaluated. Descriptive statistics, including means and standard deviations, were extracted and compared for results obtained from the three methods. Regression analyses were conducted between each pair of measured values and correlations were investigated to examine the validity of the digital volume approach against the established conventional methods (figure-of-eight and water displacement). A calibration curve was also developed from the derived regression equation to adjust the systematic overestimation of the digitally computed volume ($V_D$), resulting in the *calibrated volume* ($V_{D^*}$) of the hand. A Bland-Altman analysis was conducted to assess the degree of agreement between the digital method and the gold-standard water volumetry.

[b] Baseline hand volumetric edema gauge (3"W × 5"L × 9"H) with the model number of 12-3500 obtained from Fabrication Enterprises. Available at https://www.fab-ent.com/evaluation/size-edema/baseline-volume-and-edema-gauges/#123500. Accessed December 12, 2024.

**Table 1**
Means and standard deviations for hand volume obtained from three methods of digital volume, water displacement, and figure-of-eight ($n$ = 30)

| Method | Mean | Standard deviation |
|---|---|---|
| Digitally computed volume, $V_D$ (mL) | 373.4 | 67.61 |
| Calibrated volume, $V_{D^*}$ (mL) | 332 | 57.74 |
| Water displacement measurement, $V_W$ (mL) | 332 | 55.14 |
| Figure-of-eight tape measurement, $C_{FOE}$ (cm) | 41.6 | 2.37 |

## Results

### Participant demographics

Overall, 30 participants with healthy hands were included in this study, comprising 15 males and 15 females. The average age was 32.97 ± 5.35 years. 93.3% of the participants were right-hand dominant, while 6.7% were left-hand dominant. The participants represented various races and had diverse skin tones. None of the participants reported any recent severe injuries or trauma to their hands or wrists, meeting the study's inclusion and exclusion criteria.

### Hand volumetric methods and correlations

Table 1 summarizes the aggregated results for hand volume as determined by the digital volume method, water displacement, and figure-of-eight tape measurements. The discrepancies between the mean and standard deviation of digitally computed volumes ($V_D$) and those obtained via water displacement ($V_W$) indicate a systematic overestimation of hand volume by the digital method. This overestimation can be attributed to the algorithm used for computing the digital volume, which models the depth of the hand uniformly across its surface and neglects the palmar concavity. This systematic bias can be adjusted through a calibration process.

To determine the calibration equation and evaluate the correlation between digitally computed volume ($V_D$) and conventional methods ($V_W$ and $C_{FOE}$), regression analyses were employed. Figure 4 graphically illustrates the correlations between each pair of volumetric measurement methods. The correlation coefficient between tape measurement ($C_{FOE}$) and water displacement ($V_W$) was recorded at 0.97, consistent with findings reported by Maihafer et al.[6] Additionally, significant positive correlations were observed: between digitally computed volume ($V_D$) and water displacement ($V_W$), with a

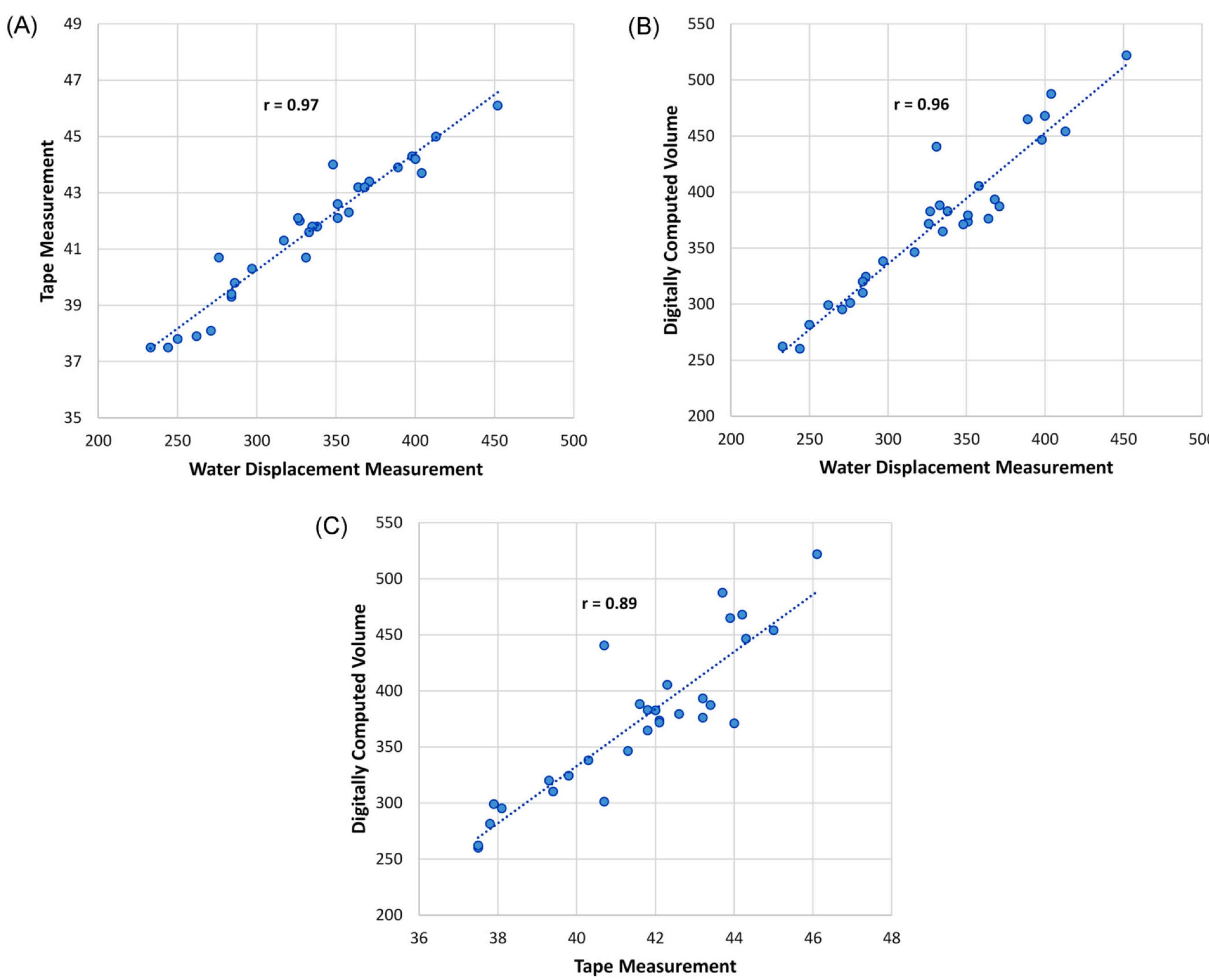


**Fig. 4.** Correlations between hand volumetric methods for the 30 participants; (**A**) figure-of-eight tape measurements ($C_{FOE}$) and water displacement ($V_W$), (**B**) digitally computed volume ($V_D$) and water displacement ($V_W$), (**C**) digitally computed volume ($V_D$) and figure-of-eight taping ($C_{FOE}$).

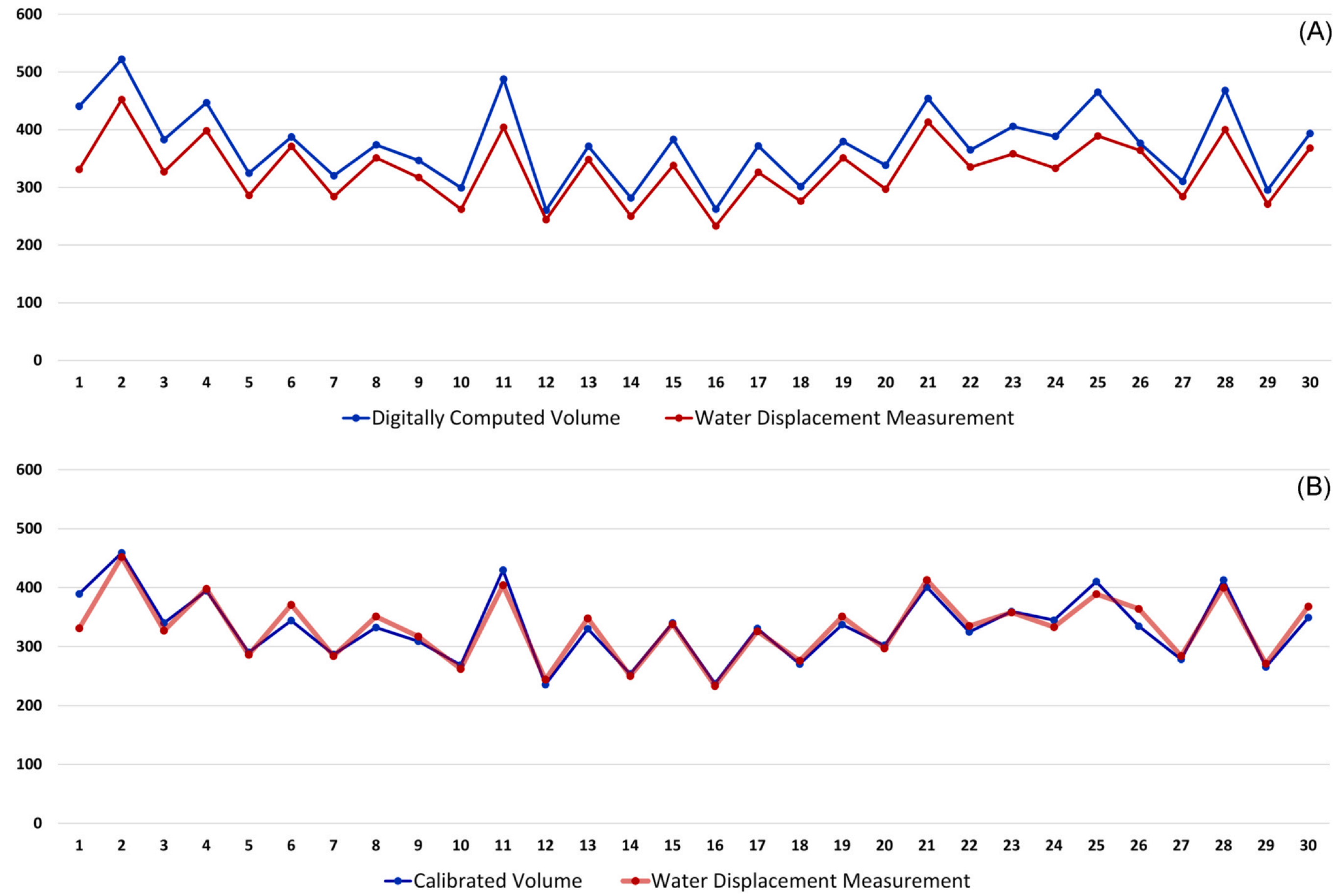


**Fig. 5.** (**A**) Comparison between digitally computed volumes ($V_D$) depicted by the blue dots and volumes measured by the water displacement method ($V_W$) marked in red for 30 asymptomatic hands; (**B**) comparison between the calibrated volumes ($V_{D^*}$) represented by the blue dots and the water displacement measurements ($V_W$) illustrated by the red markers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

correlation coefficient (r) of 0.96, and between digitally computed volume ($V_D$) and hand sizes measured by the figure-of-eight method ($C_{FOE}$), with a correlation coefficient of 0.89. Our findings indicate strong positive linear relationships, confirming that the correlations between the proposed method and both established conventional methods are statistically significant ($p < 0.00001$).

*Calibrated hand volume*

Considering the high accuracy of the water displacement method, with a reported error of less than 1%,[3,5,6] it is recognized as providing the true value for hand volume. This true value served as a benchmark for calibrating the digitally computed volume ($V_D$). Based on the regression equation derived from the analysis, $V_D = 1.17\ V_W - 15.42$, a calibration curve was developed to align digitally computed volumes more closely with the highly accurate volumes obtained from water displacement. The calibrated volume ($V_{D^*}$) for each participant was subsequently extracted using this calibration curve. As presented in Table 1, the mean and standard deviation of these calibrated volumes demonstrate the adjustment of systematic bias relative to the water volumetry. Figure 5 also shows the alignment between the calibrated volumes ($V_{D^*}$) and the water displacement measurements ($V_W$) after calibration using the regression line equation.

*Limits of agreement between digital volume and water displacement methods*

The mean absolute percentage error of the calibrated volume relative to water volumetry was 3.6%. However, neither this low mean absolute percentage error value nor the high product-moment correlation coefficient ($r = 0.96$, $p < 0.00001$) is an indicator of agreement between the two methods. As Bland and Altman have discussed, investigating the correlation between two methods measures the strength of the relationship between them, rather than their level of agreement which is crucial for determining whether traditional methods can be replaced by newly proposed ones.[33,34] In this study, Bland-Altman analysis was employed to assess the agreement between the digital volume method and water displacement, as well as to investigate the significance of variations in calibrated volume relative to water volumetry. This analysis included data from 30 participants, examining both the absolute and percentage differences between the two methods. Figure 6 illustrates the differences in volume measurements between the calibrated volume ($V_{D^*}$) and the water displacement method ($V_W$) plotted against the average of the two $(V_{D^*} + V_W)/2$; Part (a) depicts the absolute differences $(V_{D^*} - V_W)$, and Part (b) displays these differences as a percentage of their average, providing a normalized view of the differences between the methods. The central dashed red line in each plot represents the mean difference, while the solid blue lines, set at ± 1.96 standard deviations from the mean, establish the limits of agreement (LOA). The data pertinent to these analyses are detailed in Table 2. The near-zero mean difference between $V_{D^*}$ and $V_W$ of $6 \times 10^{-7}$ mL (−0.1%) indicates a negligible consistent bias between the two methods. The obtained LOA suggests that if a difference of up to 33.57 mL (9.5%) in estimating hand volume is acceptable from a medical standpoint, the digital method can serve as an alternative to water volumetry for measuring hand volume.

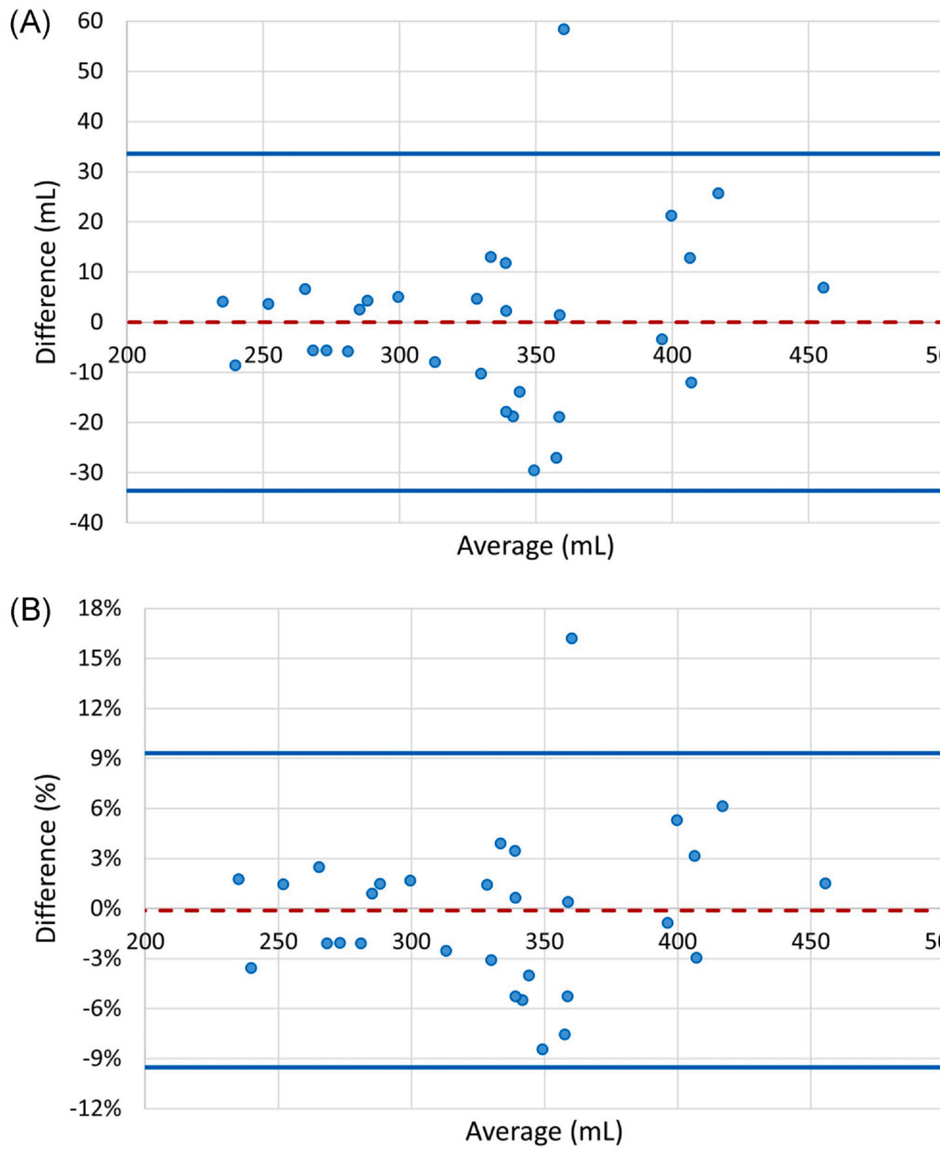


**Fig. 6.** Bland-Altman plots displaying the absolute differences (**A**) and percentage differences (**B**) between $V_{D^*}$ and $V_W$, plotted vs the average $(V_{D^*} + V_W)/2$ for 30 participants.

**Table 2**
LOA between digital volume and water displacement methods

| | Mean difference | LOA |
|---|---|---|
| $V_{D^*} - V_W$ (mL) | $6 \times 10^{-7} \pm 17.13$ | − 33.57 to + 33.57 |
| $(V_{D^*} - V_W)$/Average (%) | − 0.10 ± 4.80 | − 9.52 to + 9.31 |

LOA = limits of agreement.

## Discussion

Accurate measurement of hand volume is crucial for assessing swelling, which is essential for monitoring recovery and rehabilitation progress following surgery or trauma. It is also vital for diagnosing and evaluating the efficacy of treatments for upper limb conditions such as arthritis and lymphedema. Various established methods have been used for this purpose, ranging from traditional techniques like water displacement and circumferential measurements to sophisticated tech-based methods such as volumetry using 3D scanning, magnetic resonance imaging or computed tomography imaging, and Perometry. However, these methods often present challenges; some of them are time-consuming and/or impractical for patients with open wounds or skin lesions, thus hindering the frequent assessment of hand edema in clinical environments. Others are invasive or require expensive, specialized equipment. Therefore, a reliable, quick, affordable, and easy-to-perform method is still in demand. In this feasibility study, a novel method was proposed based on computer vision technology, which does not require special imaging equipment. This method can be conducted remotely, requiring patients to simply present their hands in two views in front of a standard webcam or camera found on most laptops and cell phones.

The proposed method was compared with the established gold standard, water displacement volumetry, and the figure-of-eight method across 30 healthy hands, demonstrating significant correlations with both. However, a systematic overestimation of the digitally computed volume ($V_D$) relative to the water displacement measurement ($V_W$) was observed. This discrepancy was adjusted through a calibration curve derived from regression analysis, resulting in the calibrated volume ($V_{D^*}$). In the comparison between $V_{D^*}$ and $V_W$, the LOA, defining an interval wherein approximately 95% of all differences between two measurements reside, were determined to be ± 33.6 mL (LOA% = −9.5% to 9.3%). Therefore, our findings suggest that when differences of approximately ± 9.5% are deemed clinically acceptable, the digital volume method can be used interchangeably with water displacement.

Although the proposed method appears promising, it is not without limitations. Despite including participants of diverse races, the small sample size in this study significantly limits the generalizability of the results and impacts the accuracy of the calibration process. Additionally, one of the reasons for the wide interval observed in the Bland-Altman plots is the limited number of participants.[33] Furthermore, this study only utilized healthy, asymptomatic hands, and the method's accuracy has not yet been verified for clinical applications. To extend these results to a broader population, future research should include medically diverse participants with mobility limitations, hand deformities, and anomalies. Moreover, before validating the proposed method as an effective tool for assessing hand swelling in clinical settings, studies should be conducted on patients with hand edema.

Another important limitation of the proposed method is its sensitivity to the hand's orientation relative to the camera. The accuracy of volume measurements is compromised if the hand is not directly facing the webcam or is positioned at a substantial angle relative to the camera. While minor deviations may be acceptable, excessive angulation can affect the results. Consequently, the method's effectiveness still relies to some extent on the user's correct actions. As can be seen in Figures 4B and 6, one data point indicates a substantial overestimation of hand volume, significantly diverging from other samples. Upon investigation, this discrepancy was attributed to improper hand angulation relative to the webcam during the experiment. Although this data could have been excluded as an outlier due to video frame corruption, we chose to retain it to underscore the methodological limitation. This decision, while resulting in a reduction of the correlation coefficient and a widening of the LOA, clearly demonstrates that the method can still yield acceptable results despite this limitation. To address it, further research could incorporate the implementation of relative depth analysis, as provided by *z* coordinate determination in the MediaPipe Hand Landmarker model.[28] This enhancement would enable the application to guide the user in correct hand positioning through real-time feedback. Additionally, incorporating augmented reality cues on the user interface may further mitigate positioning errors, thus improving the accuracy of the measurements.

Finally, since all video capturing, processing, water volumetry, and tape measurements were conducted in a single session without repeated examinations by the same examiner, intra- and inter-rater reliability was not evaluated.

Despite the limitations discussed above, the obtained results indicate that with further development, the proposed method could serve as an effective alternative to conventional techniques. This method is inexpensive, easy to perform, and requires less than 2 minutes to complete. Importantly, it eliminates the need for physical contact, which is advantageous in case of injury or when dealing with a painful limb. Furthermore, given the growing demand for telemedicine and telerehabilitation, the remote applicability of this method could enable continuous monitoring of hand swelling.

## Author Contributions

**Nastaran Katouzian**: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Claire A. Parent**: Writing – review & editing, Project administration, Formal analysis. **Roy Eagleson**: Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis. **Caitlin Symonette**: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

## Funding

The study was supported by New Frontiers in Research Fund Exploration Grant (NFRFE-2021-00671).

## Declaration of Competing Interest

The authors declare that they have no known competing interests or personal relationships that could influence the study reported in this article.

## Acknowledgments

The authors wish to express their gratitude to all individuals who participated in this study, with special appreciation to Farzad Monsefpur, Niloofar Davoodvandi, Atena Atashfaraz, Saeed Karimi, and Farshid Karbassian for their invaluable support to the research team during the data collection phase.

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