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Original Article

Interrater reliability and criterion validity of the hand-held three-dimensional scanning method for evaluating hand volume in patients with stroke

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ABSTRACT

Objectives: This study aims to assess the interrater reliability and criterion validity of a three-dimensional (3D) scanning method in evaluating hand volume in patients with stroke.

Patients and methods: This observational study was conducted with 20 stroke patients (11 males, 9 females; mean age: 59.5±13.3 years; range, 28 to 74 years) between February 2023 and June 2023. Two trained therapists (Operators A and B) used a hand-held 3D laser scanner to measure bilateral hand volumes sequentially to assess the consistency of measurements between operators. Operator A also used a split cup to measure bilateral hand volumes to assess the accuracy of measurements between 3D scanning and the gold standard water displacement (WD) method.

Results: The intraclass correlation coefficient between the two operators was 0.923 ($p<0.001$) for the volume of the non-affected hand measured using the 3D scanning method and 0.945 ($p<0.001$) for the affected hand. The volume of the non-affected hand measured by Operator A using the 3D scanning method highly correlated with the volume measured by the WD ($r=0.938$, $p<0.001$), and the volume of affected hand measured by using the 3D scanning method highly correlated with the volume of that measured by the WD ($r=0.927$, $p<0.001$).

Conclusion: The 3D scanning method has good interrater reliability and criterion validity in the measurement of hand volume of affected and non-affected hands in patients with stroke.

Keywords: Hand volume, reliability, 3D scanning method, validity, water displacement method.

Poststroke hand swelling occurs in 37% of individuals who experience chronic stroke and in up to 18.5% of individuals with acute stroke.[1] Hand swelling may lead to limited range of motion, pain, and increased spasm in the hand and wrist, affecting the recovery of the upper limb motor function and sensory function after stroke. Prolonged swelling has an impact on the joint range of motion, soft tissue mobility, quality of scar tissue formation, function, strength, and aesthetics of the hand. These factors may delay the patient's recovery and return to normal activities of daily living.[2] In clinical setting or for research purposes, the accurate measurement of hand volume is necessary to determine the severity of hand swelling and to evaluate the effectiveness of the treatment.

At present, the commonly used methods for measuring limb volume mainly include the water displacement (WD) method, circumference measurement method, and figure-of-eight method. The WD is the gold standard of human body volume

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measurement based on Archimedes' principle, with good reliability and validity.[3] Nevertheless, the disadvantage of the WD is that the patient needs to be able to vertically place the hand of the affected side into the water, which may make it difficult for some stroke patients to maintain this position, and the water temperature may cause discomfort in some patients with sensory disorders. On the other hand, there was only a moderate correlation between the WD and the figure-of-eight method, and the correlation coefficient between the WD and circumference measurements was weak.[4] The ideal objective tool for evaluating the limb volume of hemiparetic stroke patients should be efficient, noninvasive, easy to use, fast, and patient friendly.

The three-dimensional (3D) scanning method utilizes a 3D scanner to scan the target object in three dimensions, and after processing by software, a model is obtained. We can also use software to calculate the surface area and volume of an object. More recently, the 3D scanning method has been applied to measure the volume of the affected limbs of patients with postoperative lymphedema due to breast cancer[5] and other conditions.[6] Our previous study confirmed that the 3D scanning method had good intrarater reliability for evaluating the volume of the upper limb in healthy subjects and was less time consuming.[7] This study aimed to assess the interrater reliability and criterion validity of a 3D scanning method in evaluating hand volume in patients with stroke.

PATIENTS AND METHODS

In this observational study, 20 stroke patients (11 males, 9 females; mean age: 59.5±13.3 years; range, 28 to 74 years) were recruited from the Department of Rehabilitation Medicine, Huashan Hospital, Fudan University between February 2023 and June 2023. The time of stroke onset was at an average of 5.1±5.7 (median: 3.0; range, 1.2 to 24.0) months. The inclusion criteria were as follows: *(i)* aged 18 to 75 years; *(ii)* diagnosed with stroke confirmed by computed tomography or magnetic resonance imaging; *(iii)* stroke course of more than two weeks; *(iv)* stable vital signs; *(v)* being able to cooperate with the measurement. The exclusion criteria were as follows: *(i)* severe cognitive impairment and mental illness that could impair cooperation with the operator; *(ii)* resting tremor or postural tremor; *(iii)* upper limb thrombosis; *(iv)* patients who were unable to maintain their hand position for the WD method; *(v)* severe infection erysipelas; *(vi)* local fracture or mutilation of the upper limb. Written informed consent was obtained from each patient. The study protocol was approved by the Huashan Hospital Ethics Committee (Date: 27.10.2020, No: 2020). The study was conducted in accordance with the principles of the Declaration of Helsinki. Clinical Review No. (1167).

For the 3D scanning method, participants were assisted in lying supine. An assistant helped maintain the patient's elbow at approximately 90° flexion. Two trained rehabilitation therapists (Operators A and B) sequentially used a hand-held EinScan-Pro 2X 3D scanner (SHINING 3D Science and Technology Co., Ltd., Hangzhou, Zhejiang, China) to scan both hands (from the distal forearm to the wrist at the transverse carpal line) of the subjects at 360°. To avoid stroboscopic flashes of laser light, which may cause discomfort, the subjects were told to wear an eye patch. During scanning, the operator kept the scanner perpendicular to the surface of the hand (Figure 1a). The distance between the 3D scanner and the limb was automatically calculated by computer software, and the computer would sound an alarm if the effective scanning range was exceeded. After scanning, optimized 3D point cloud data would be generated (Figure 1b). The scanning image was regarded as complete if no missing data were observed. We intercepted the point cloud data and removed stray points, and a 3D model was built through EXScan Pro3.7.3.0 software (SHINING 3D Science and Technology Co., Ltd., Hangzhou, Zhejiang, China) (Figure 1c). Volumetric measurements were measured using the self-contained tool of the software.

For the WD measurement, we prepared a split cup, a measuring cup, and an electronic scale. After 3D scanning, Operator A performed volume measurements of both hands by WD. Before measurement, the measuring cup was placed under the spout, the split cup was filled with water above the level of the spout, and the measuring cup was used to catch spilled water. The value of the electronic scale was reset to zero before the overflow. An assistant helped the subject to hold the hand perpendicular to the surface of the water and slowly immersed into the water (Figure 2a). When the operator visually observed that the transverse stripe of the wrist had reached the horizontal plane of water, the subject was asked to remain still. When the water stopped overflowing, the hand could be removed from the split cup. The mass of the spilled water was weighed to calculate the volume of the hand (Figure 2b).

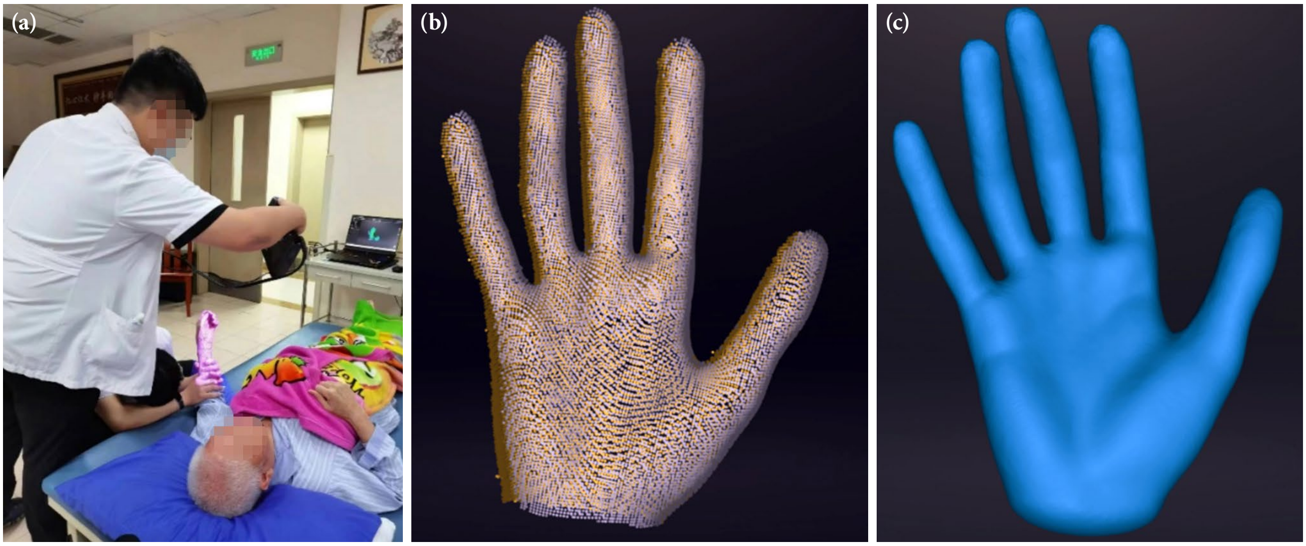

Figure 1. **(a)** The operator used a hand-held 3D scanner to scan the hands of subjects at 360°. **(b)** After scanning, optimized 3D point cloud data are generated. **(c)** A 3D hand model was built to calculate the volume.
3D: Three-dimensional.

Statistical analysis

The data were analyzed using IBM SPSS version 20.0 software (IBM Corp., Armonk, NY, USA). The intraclass correlation coefficient (ICC), based on the model two-way mixed effects, absolute agreement, and single measurement, was used for interrater reliability.[8] The consistency of the results of the two operators according to the 3D scanning method was analyzed using the ICC; the correlation analysis of the results between the two different methods was analyzed using Pearson correlation analysis. The level of statistical significance was set to $p<0.05$. A Bland-Altman plot was also used to visualize the consistency of the two methods. GraphPad Prism 7 (GraphPad Software Inc., La Jolla, CA, USA) was used to construct the plots.

RESULTS

Measurements by Operator A and Operator B using the 3D scanning method showed

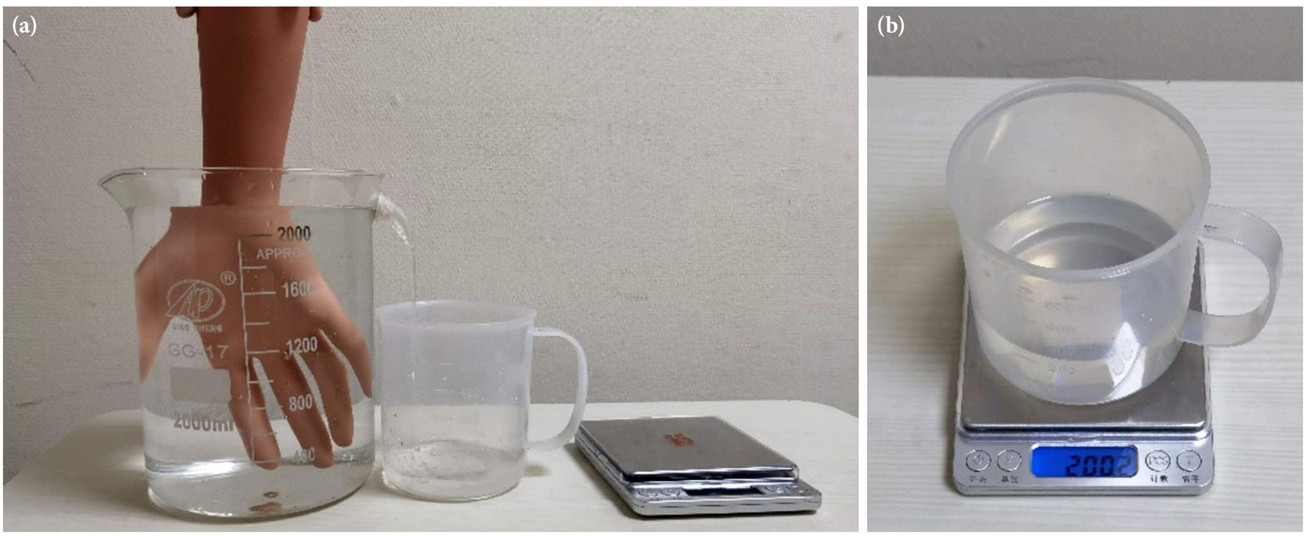

Figure 2. **(a)** An assistant helped the subject hold the hand perpendicular to the surface of the water and immerse it in the water, and the water overflowed into the measurement cup. **(b)** When the water stopped overflowing, the mass of the spilled water was weighed to calculate the volume of the hand.

TABLE 1
Interrater reliability of the 3D scanning method between two operators

	Volume (mL)			
	Operator A	Operator B		
	Mean±SD	Mean±SD	ICC	*p*
Non-affected side	352.13±65.21	355.88±67.13	0.923	<0.001
Affected side	364.79±68.61	363.71±80.57	0.945	<0.001

3D: Three-dimensional; ICC: Intraclass correlation coefficient; SD: Standard deviation.

TABLE 2
Correlation analysis of the 3D scanning volume method and drainage method

	3D	WD		
	Mean±SD	Mean±SD	ICC	*p*
Non-affected side	352.13±65.21	352.02±65.16	0.938	<0.001
Affected side	364.79±68.61	366.63±81.25	0.927	<0.001

3D: Three-dimensional; WD: water displacement method; SD: Standard deviation.

high interrater consistency, suggesting that the 3D scanning method has good interrater reliability (non-affected side, ICC=0.923, p<0.001; affected side, ICC=0.945, p<0.001; Table 1).

Water displacement was used as the criterion standard. The volume of the non-affected hand measured by the 3D scanning method highly correlated with the volume measured by the WD (r=0.938, p<0.001), and the volume of the affected hand measured by the 3D scanning method highly correlated with the volume measured by the WD (r=0.927, p<0.001), suggesting that the 3D scanning method had good criterion validity (Table 2).

The differences between hand volumes measured by the WD method and the 3D method for the affected and non-affected hands conformed to a normal distribution according to the Shapiro-Wilk test. Thus, the Bland-Altman plot was also used to visualize the differences between the two methods (Figure 3). Figure 3a shows that 90% (18 of 20) of the data points were within ±1.96 standard deviation (SD) of the mean difference on the affected side, with a bias of 11.69 mL, and an agreement ranging from −61.67 to 85.05 mL. Figure 3b shows that 95% (19 of 20) of the data points were within ±1.96 SD of the mean difference on non-affected side, with a bias of −1.831 mL, and an agreement range from −62.97 to 59.31 mL.

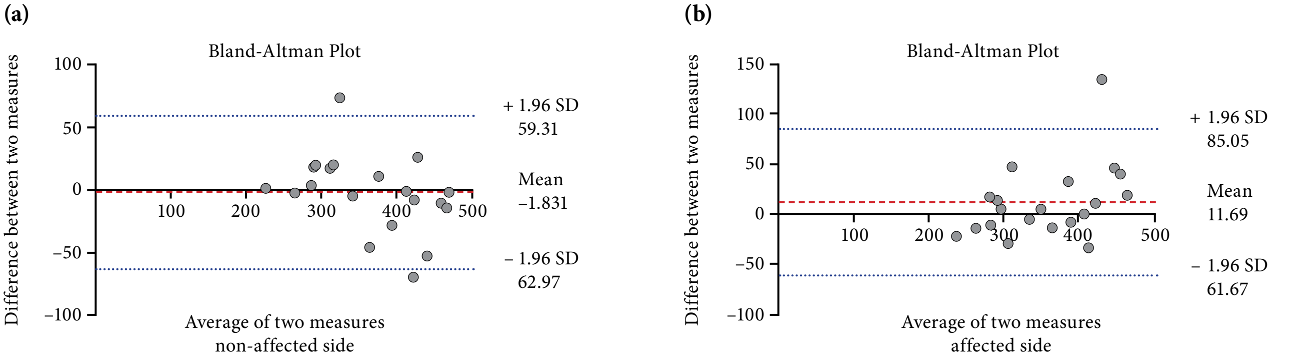

Figure 3. The X-axis shows the average of two measurements, and the Y-axis represents the difference between the two measurements. **(a)** shows that 90% (18 of 20) of the data points were within ±1.96 SD of the mean difference on the affected side. **(b)** shows that 95% (19 of 20) of the data points were within ±1.96 SD of the mean difference on non-affected side.

SD: Standard deviation.

DISCUSSION

Within two weeks of admission to the rehabilitation center, 72.7% of stroke patients were likely to experience hand swelling, 33.0% were likely to develop edema, and Frenchay upper extremity mobility test and nine-hole column test scores were significantly worse in patients with hand edema.[9] Measuring the volume of the affected hand is effective for assessing the degree of swelling compared to that of the non-affected hand. In addition, the treatment effect can be assessed by comparing the hand volume before and after treatment. The WD is the gold standard for measuring limb volume.[2] However, stroke patients often have accompanying functional impairments such as limb motor function and sensory deficits, which makes it difficult to measure limb volume using the WD.

There is currently no optimal method for assessing hand volume in poststroke edema, the use of more refined rating methods can provide stronger evidence to demonstrate the effectiveness of treatment. To our knowledge, Mestre et al.[10] were the first to compare the 3D scanning method and WD for lower limb volume measurement and confirmed that the 3D scanning method was accurate and suitable for the evaluation of limb volume. The 3D scanning method allows measurements to be taken at multiple levels to compare edema in all segments of the upper extremity completely. Scanning a limb with a 3D scanner allows the data to be stored as a 3D model, rather than just a numerical value. This 3D model reveals the distinct location of the swelling and quantifies the extent of the swelling more visually, allowing for a more responsive measure of treatment effectiveness.

The 3D scanning method can be used to measure different body structures quickly and easily,[11] mitigating issues such as difficulty in positioning and abnormal sensations. In addition, it has the advantage that it does not require contact and can reduce the risk of transmission of some infectious diseases. This method can also be used to measure patients with wounds.

In this study, we found that the 3D scanning method had high interoperator agreement in the measurement of hand volume on the non-affected and affected sides of stroke patients, suggesting good interrater reliability. In addition, the correlation between the 3D scanning method and the WD was high, suggesting good criterion validity.

In addition, a 3D model of the limb can be obtained after data acquisition through the 3D scanning method. The model enables the measurement of the volume, surface area, and circumference of the limb, which further completes the production of personalized rehabilitation aids. Compared to traditional orthoses, 3D-printed wrist and hand orthoses demonstrated greater changes in reducing spasticity and swelling and improving wrist motor function and the range of passive wrist extension in stroke patients.[12] Furthermore, 3D-printed wrist and hand orthoses resulted in a more significant improvement in pain.

However, some disadvantages of the 3D scanning method were also identified during testing, such as tremor and spasticity, which may interfere with scanning. The Bland-Altman plots of our study showed that 10% of the data points exceeded ±1.96 SD of the mean difference on the affected side, and 5% exceeded ±1.96 SD of the mean difference on the non-affected side. This condition may be relevant to patients with hemiplegia with tremor and spasticity. Future studies are needed to validate new methods for assessing hand volume using 3D scanning methods.

In conclusion, the 3D scanning method has good interrater reliability and criterion validity for hand volumetric measurements in stroke patients. The 3D scanning method can be used as an alternative to the WD method for hand volumetric measurements in stroke patients.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Idea/concept, design, analysis and/or interpretation, critical review, references and fundings: X.Q.; Control/Supervision: Y.B.; Data collection and/or processing: J.L., Y.C.; Literature review, materials: G.Z.; Writing the article: J.L., X.Q.

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