A novel clinical test of pointing acuity 
with open and closed eyes– a validity study

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Abstract

Hand proprioception is crucial for daily activities and may be compromised by diseases or injuries, impacting patients' independence. The lack of feasible, accurate, and affordable clinical tools for hand proprioception assessment poses a significant challenge, essential for identifying dysfunction and evaluating treatment effects.

The purpose of this study was to evaluate the concurrent validity of the LeapMotion controller (LMC) for assessing hand proprioception. We compared the LMC with a 3D camera system for motion analysis (Qualisys Motion Capture, QTM), known for its high measurement accuracy as the gold standard. Twenty participants (10 men, 10 women), 15 without, and 5 with hand injury or pain, took part in this cross-sectional study. Assessments included pointing acuity with open and closed eyes using the right and left hand. There were moderate to good correlations between LMC and QTM performed with closed eyes, with intraclass correlation coefficient (ICC) values of 0.6 and 0.89. Contrary, tests with open eyes showed a poor overall correlation with ICC between 0.003 and 0.3. Bland-Altman analysis showed median biases of \( \leq 1.5 \text{ mm} \) between LMC and QTM with eyes open, and \( \leq 5.1 \text{ mm} \) with eyes closed. Limits of agreement ranged from \(-0.4 \text{ to } 3.5 \text{ mm} \) with eyes open and \(-31.6 \text{ to } 21.5 \text{ mm} \) with eyes closed.

The results indicate that the LMC could be a cost-effective and feasible tool for quantifying hand proprioception with a clinically acceptable bias. Although the median biases were small for measurements with eyes open, the ICCs were poor. This may be due to a high pointing acuity within the group combined with limited variability between the participants in the eyes open tests.

**Keywords:** proprioception; hand; validity; Qualisys Motion Capture (QTC); Leap Motion Controller (LMC)
Introduction

Good function of the hand enables powerful grips during lifting and moving heavy loads, fast dynamic movements such as throwing or catching objects, and precision grips such as snapping a button or typing on a smartphone (1, 2, 3). To perform these tasks with precision, optimal sensorimotor function of the hand is vital which requires mobility; muscle strength, endurance, and coordination; and sensory input and processing, with and without visual assistance, i.e., proprioception (4).

Proprioception is according to Röijezon et al. defined as the conscious and unconscious perception of the body's and body parts' position, movement, and perception of weight, force, and effort (5). This sensory information is crucial for movement behaviors to be well adapted, coordinated, and precise, but is also important for the learning of new skills (5). Proprioceptive information originates from mechanoreceptors, e.g., muscle spindles and Golgi tendon organs, which are located within the muscles, tendons, ligaments, joint capsules, and skin (6). The brain processes input from these receptors to produce well adapted motor actions (6).

Altered sensorimotor functions, including proprioception, that can have a negative impact on the activity and abilities of the hand are described in various musculoskeletal disorders, with or without traumatic origin, and in neurological disorders (7, 8, 9, 10, 11, 12).

The importance of proprioception in musculoskeletal disorders has received increasing attention in recent years in research and clinical work, including hand rehabilitation (13, 14). Therefore the interest in measuring proprioception of the hand has increased and has been used in studies to identify disturbances and for evaluation of the effectiveness of different interventions to treat injuries or diseases affecting the hand and fingers (4, 7, 9, 13, 15).

There is a wide variety of methods developed to measure the different aspects of proprioception of the hand (16, 17, 18). However, feasible, affordable, accurate, and objective methods are relatively scarce in the clinical setting. The assessment methods that are used today by clinicians are often subjective with low sensitivity and specificity (19, 20).
Objective and accurate measures of kinematics, function, and impairments usually take place in movement science laboratories, with technically advanced and costly motion capture systems. One example is optoelectronic systems with multiple video cameras to track motions in three dimensions (3D) by utilizing reflective markers attached to the body enabling the visualization of multiple body segments (21). The technology has a very high measurement accuracy and is used as the gold standard when comparing the measurement results of kinematic analysis. The technique is however time-consuming, expensive, and technically complicated and consequently, the method is rarely used in clinical settings (22, 23).

Advances in technology have given us new cheaper and more user-friendly sensors that can be applied in clinical settings for measuring movements of the hand. The Leap Motion controller (LMC) is a small markerless 3D sensor with optics for tracking the 3D coordinates of the hand, wrist, and fingers in horizontal (x), vertical (y), and depth (z) plane (Figure 1) (24, 25). The LMC connects to a computer through a USB port and with software it can measure the movement and position of the hand and fingers with a sampling rate of approximately 100 Hz (Figure 2). The LMC system has been shown to be a valid and reliable device to measure movement in general of the hand, wrist, and fingers (26, 27, 28, 29, 30).

Studies that analyze the feasibility of using cheaper sensors that are applied without direct contact with the skin, to obtain clinically objective values of the hand's proprioception have to the best of our knowledge not been presented.

Figure 1. LMC records motion and position of the hand in three planes X, Y and Z.

Figure 2 a) Leap motion controller (LMC) connected to a computer. b) The software creates a model of the hand that is shown on the screen.
The LMC could be a user-friendly tool for measures of proprioception of the hand in clinical practice. To do this the first step is to evaluate the validity of the LMC capacity to accurately measure the proprioception of the hand.

The aim of this study was to evaluate the concurrent validity of the LMC and a custom made software, using the Qualisys Motor Capture system as reference, to determine whether it is an accurate measurement tool for measurement in a pointing acuity test.

**Materials and Method**

**Study design**

This was a quantitative cross-sectional study in which pointing movements were simultaneously recorded with LMC by UltraLeapTM and QTM (Qualisys TM AB, Sweden). The study was conducted at the Human Health and Performance Lab - Movement Science at Luleå University of Technology, by a physiotherapist with experience in hand rehabilitation. The QTM system was managed by an experienced lab engineer. The test was conducted according to the Declaration of Helsinki and with the approval of Swedish Ethics Review Authority, (ref. No. 022-03946-01).

**Participants**

Twenty participants 10 men and 10 women were recruited from Luleå University of Technology (LTU) through advertising on message boards, the university's social media, and mail.

Inclusion criteria were people over 18 years of age with or without musculoskeletal pain or impairments from the neck, back, or upper limb. Exclusion criteria were people with a considerably reduced range of motion or neuromuscular dysfunction of the hand or arm, that would hinder the participant's ability to complete the task. Individuals with visual impairment that was not corrected with glasses or contact lenses were also excluded due to the reduced ability to visualize the target during the visual task.
All the participants meet the inclusion criteria. A questionnaire with ten background questions regarding gender, age, dexterity, pain, and general function related to the hands and fingers, as well as a questionnaire with six questions regarding discomfort from the upper musculoskeletal quadrant was distributed to the participants (Table 1). Before participation, all participants read and signed informed consent.

**Equipment**

The LMC used in the study was manufactured and sold by Ultraleap TM. A custom-made 45-centimeter wide and 14-centimeter deep platform made by a 3d printer with standardized target and starting positions was used for optimal tracking for the LMC – system and standardization of the tests (Figure 3). A software was custom-made for data collection and calculation of outcome variables from the LMC.

The Qualisys Motion Capture system with 8 cameras was used for simultaneous measurements for comparison with the LMC. Qualisys track manager (QTM) software was used for data collection. Qualisys is regarded as a gold-standard system for standard system for three-dimensional motion capture and has shown consistent accuracy in the measurement of human motion (22, 23). A retro-reflective tape was placed around the tip of the participant's index fingers as a reference point for the QTM system to track the hand movements (Figure 4).

![Figure 3. Experimental setup for recording targeted pointing movement with right and left hand with Leap Motion Controller. a) prefabricated platform. b) Leap Motion Controller. c) Starting position right hand (red arrow). d) Computer with the custom-made software that collects and processes the data. Frames with motion and position data](image-url)
Testing procedure

The participants were seated in a standardized chair in an upright body position in front of a table. They were asked to keep in contact with the backrest and have their feet on the floor during the test. The custom-made platform with a hole for the LMC was placed in front of the participant on the table.

As the starting position, the participant's hand was placed on a marked position on the platform 30 centimeters from the target, with the right hand on the right side and the left hand on the left side of the target. The target was placed 20 cm above the sensor (28) (Figure 3).

The task was to reach the target position with the index finger as accurately as possible. This was repeated 10 times at a pre-determined pace of two seconds between the start and stop of each hand movement. The pace was set by a metronome within the custom-made software, giving a beep sound with two second intervals. This was used to standardize the pace and speed of the movement for each trial and between test conditions and participants. The task was performed with the right and left hand, respectively, in two different visual conditions: eyes opened, and eyes closed.

Each of the four test conditions started with an initial calibration of the target position of the index finger, which was repeated during the 10 trials. The calibration was done by the participant holding the index finger at the target and memorizing this exact position for 3 seconds, meanwhile, an initial measure was taken at this position. For each of the 10 trials, a measure of the position of the index finger was taken automatically with the LMC when the beep sounded and the hand was at the target, but not when the beep sounded, and the hand was at the starting position. The deviation, i.e., the errors, of the 10 test trials were then calculated by comparing the position of each trial with the target position. During the visual conditions, the target remained in the same position during the whole test, while the target was removed after the calibration measure during the non-visual conditions. The target was removed to avoid any tactile input when performing the test with eyes closed.
A familiarization and warm-up procedure were performed consisting of guided trials with both visual and verbal instructions and feedback applied until the participant understood and felt familiar with the task and the pace of the movement. The test took altogether 15-20 minutes to carry through with both hands, eyes open and closed. The QTM system simultaneously recorded the participant trails.

Outcome measures

The outcome variables are based on the distances between the participants individual target position point and repeated measurement points of 10 trials and is calculated by absolute error (AE) in millimeters (mm). Absolute error is commonly used when calculating positions (28). The absolute error AE is defined as the mean value of the distances between the target position, and all considered measured positions, that is

\[ AE = \frac{1}{n} \sum_{i=1}^{n} \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2} \]

where \((x_0, y_0, z_0)\) is the target position and \((x_i, y_i, z_i)\) is the measurement position for measurement number \(i\), and \(n\) is the number of considered measurements (10 in this case). This gives an absolute difference from the reference point regardless of direction and gives an indication of the accuracy without consideration of error direction (directional bias) values (the measurements) and the true value (the target position) (31). The data collection and calculation were made automatically by the custom-made software for the LMC. Data from Qualisys Motion Capture system was exported from QTM to MatLab for calculation of the outcome variables.

Figure 4. a) Right hand above the sensor in a open position of the hand and a straight index finger. b) Left hand above the sensor in a open position of the hand and a straight index finger.
Statistical analysis

All data variables were imported to the software program Statistical Package of Social Sciences (SPSS), IBM, version 29). The data was described descriptively with median values, percentiles, mean, and Standard Deviations (SD). Shapiro–Wilk test was used for the assessment of the normality of data, combined with a visual analysis of histogram, skewness, and kurtosis. Paired samples t-test was performed to analyze the difference between LCM and QTM-data, for data that was normally distributed with a significance level of p<0.05. A non-parametric Wilcoxon Signed rank test was performed to analyze the difference between LCM and QTM-data, for data that was not normally distributed. These tests were done to analyze if there were statistically significant differences in the measurement values between the two methods. A statistically significant difference between measurement values suggests a lack of agreement or systematic bias between the two methods. Conversely, a non-significant difference enhances confidence that the methods produce similar and consistent results.

The Intraclass Correlation Coefficient (ICC) 2.1, two-way random effects, absolute agreement, was used to analyze the correlation and agreement between the two measurements. Values less than 0.5, indicate poor correlation and agreement, 0.5 - 0.75 moderate, 0.75 - 0.9, good, and values greater than 0.90 indicate excellent correlation and agreement (32).

To investigate the concurrent validity, Bland-Altman plots were used. The traditional Bland Altman method gives information about agreement between measures and gives an idea if the LMC and QTM assign similar position values within the same participant. The method uses the differences between the two systems (LMC minus QTM) plotted against the mean of both measures. The mean difference is presented together with 95% Limits of agreement (LOA) which describes the mean difference ±1,96 x SD and provides an estimate of the interval including 95% of the differences between LMC and QTM (33, 34).

When the difference variables were not normally distributed a modified non-parametric Bland Altman approach was used, using median bias and 10th and 90th percentile as LOA. This provides an estimate of the interval including 80% of the differences between both LMC and QTM (35).
Results

All 20 participants (10 women and 10 men) performed the entire test protocol. No adverse effects, such as discomfort, pain, or fatigue were reported during or after the tests. All participants answered the questionnaire regarding background information. Five of the participants reported pain in one or both of their hand/hands (mean pain score 2.8 on the numerical pain scale), of which four reported reduced hand function (Table 1).

<table>
<thead>
<tr>
<th>Table 1. Background information.</th>
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<tbody>
<tr>
<td>Participants (Men/women)</td>
</tr>
<tr>
<td>Mean Age/SD (years)</td>
</tr>
<tr>
<td>Mean Wight/SD (Kg)</td>
</tr>
<tr>
<td>Mean Length/SD (cm)</td>
</tr>
<tr>
<td>Dominant hand (Right/Left)</td>
</tr>
<tr>
<td>Demands on the hand (Normal/High)</td>
</tr>
<tr>
<td>Hand injury or pain one or both hands (n)</td>
</tr>
<tr>
<td>Reduced hand function (n)</td>
</tr>
</tbody>
</table>

In the following, data are presented as the average AE measurements in the combined horizontal, vertical, and depth planes of the ten trials in mm for each test condition, i.e., right, and left hand, with eyes open and closed, respectively.

Data from the tests performed with eyes open (right and left hand) were not normally distributed. A non-parametric Wilcoxon Signed rank test showed a statistically significant difference between LMC and QTM for tests performed with eyes open (Table 2).
Data from the test performed with eyes closed (right and left hand, respectively) were normally distributed. The paired samples t-test showed no statistically significant difference between LMC and QTM for tests performed with eyes closed (Table 3).

Table 2. Absolute error for measurements with eyes open measured with QTM and LMC and comparison with Wilcoxon Signed rank test.

<table>
<thead>
<tr>
<th></th>
<th>QTM Median (*IQR) mm</th>
<th>LMC Median (*IQR) mm</th>
<th>Median difference mm</th>
<th>Percentile mm 10th</th>
<th>Percentile mm 90th</th>
<th>z-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right hand</td>
<td>2.7 (1.8 - 4.2)</td>
<td>4.1 (3.2 - 5.2)</td>
<td>1.4</td>
<td>-0.43</td>
<td>3.52</td>
<td>-3.1</td>
<td>.002</td>
</tr>
<tr>
<td>eyes open</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left hand</td>
<td>3.2 (2.0 - 3.6)</td>
<td>4.5 (3.7 - 6.2)</td>
<td>1.3</td>
<td>0.1</td>
<td>17.53</td>
<td>-3.51</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>eyes open</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results are presented in median, interquartile range (IQR) and median difference between QTM and LMC AE values. p: significance two-sided p-value. QTM= Qualisys track manager, LMC=LeapMotion Controller.

Table 3. Absolute error for measurements with eyes closed measured with QTM and LMC and comparison with paired t-test.

<table>
<thead>
<tr>
<th></th>
<th>QTM Mean (SD) mm</th>
<th>LMC Mean (SD) mm</th>
<th>Mean difference (mm)</th>
<th>Std. Error of Mean</th>
<th>95% Confidence Interval of the difference</th>
<th>t-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>Right hand</td>
<td>39.5 ±17.0</td>
<td>35.4 ±17.5</td>
<td>-4.41 ±10.9</td>
<td>2.3</td>
<td>-9.2 - 1</td>
<td>-1.7</td>
<td>.108</td>
</tr>
<tr>
<td>eyes closed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Left hand</td>
<td>36.7 ±15.5</td>
<td>31.6 ±17.4</td>
<td>-5.1 ±13.6</td>
<td>3.0</td>
<td>-11.4 - 1.3</td>
<td>-1.7</td>
<td>.111</td>
</tr>
<tr>
<td>eyes closed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results are presented in mean, standard deviation (SD) and mean difference between QTM and LMC AE values. p: significance two-sided p-value. Negative values represent lower values for LMC, positive values represent higher values for LMC. QTM= Qualisys track manager, LMC=Leap Motion Controller.
The ICC analyses indicate a poor correlation between the LMC and QTM measurement values with eyes open, but a moderate to good correlation with eyes closed (Table 4).

Table 4. Intra class Correlation (ICC 2.1) between QTM and LMC absolute error measurement with 95% CI

<table>
<thead>
<tr>
<th></th>
<th>ICC (2.1)</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right hand eyes open</td>
<td>.248</td>
<td>-.112 to .590</td>
</tr>
<tr>
<td>Left hand eyes open</td>
<td>.003</td>
<td>-.321 to .385</td>
</tr>
<tr>
<td>Right hand eyes closed</td>
<td>.789</td>
<td>.542 to .914</td>
</tr>
<tr>
<td>Left hand closed</td>
<td>.645</td>
<td>3.06 to .814</td>
</tr>
</tbody>
</table>

ICC - Intraclass Correlation Coefficient, (2.1) two-way random effects model, absolute agreement, single measures between Qualisys (QTM) and Leap motion controller (LMC) average absolute error (AE) measurements.

Bland-Altman plots were conducted separately for the right and left hand and for eyes open and eyes closed. The difference variables between LMC and QTM for right- and left-hand eyes open was not normally distributed, hence presented with a median difference and 10th to 90th percentiles LOA in the Bland Altman plots. The difference variables between LMC and QTM for right- and left-hand eyes closed were normally distributed, hence presented with mean difference and 95% LOA in the Bland Altman plots (Table 5, and Figure 1a-b and 2a-b).

Table 5. Target accuracy of QTM (Qualisys) compared to LMC (Leap motion controller)

<table>
<thead>
<tr>
<th></th>
<th>Mean bias mm</th>
<th>Median bias mm</th>
<th>95% LOA mm</th>
<th>LOA Percentiles mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10th</td>
<td>90th</td>
</tr>
<tr>
<td>Right hand eyes open</td>
<td>1.96</td>
<td>1.3</td>
<td>-.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Left hand eyes open</td>
<td>4.41</td>
<td>1.5</td>
<td>-25.4</td>
<td>17.2</td>
</tr>
<tr>
<td>Right hand eyes closed</td>
<td>-4.1</td>
<td>-5.1</td>
<td>-21.6</td>
<td>21.5</td>
</tr>
<tr>
<td>Left hand eyes closed</td>
<td>-5.1</td>
<td>-3.5</td>
<td>-21.6</td>
<td>21.5</td>
</tr>
</tbody>
</table>

Mean and median bias 95% LOA and 5th and 95th LOA for Bland Altman. Values are based on Leap motion controller (LMC) average and Qualisys (QTM) average AE values.
Bland Altman plots (Figures 4a-b) illustrate the agreement between the LMC and QTM for the tests performed with eyes open. Median differences are 1.3 mm (LOA -0.4 – 3.5 mm) and 1.5 mm (LOA 0.1 – 17.5 mm) for right and left.

**Figure 4a - b.** Bland Altman plots comparing Leap motion controller (LMC) and Qualisys (QTM) for tests with eyes open. The y-axis represent the differences between the two methods, and the x-axis the mean values of the two methods. The marked line represents the median difference (bias) between QTM and LM). Dotted lines represent the Limits of agreement (LOA). The upper dotted line is 90th percentiles, and the lower dotted line is the 10th percentiles.
Bland Altman plots (Figures 5a-b) illustrate the agreement between average AE measurements between LMC and QTM for the tests with eyes closed. Bland Altman plots showed relatively large measurement values of the LMC and QTM with a range of LOA between with one value outside the LOA in both tests. Measurement values are spread around the mean difference line -4.41 and -5.07.

**Figure 5a - b.** Bland Altman plots comparing Leap motion controller (LMC) and Qualisys (QTM) for tests with eyes closed. The y-axis represent the differences between the two methods, and the x-axis the mean values of the two methods. The marked line represents the mean difference(bias) between QTM and LMC. Dotted lines represent the upper and lower 95% Limits of agreement (LOA) with 1.96 standard deviations from the mean.
Discussion

The purpose was to investigate the concurrent validity of the LMC compared to a ‘gold-standard’ motion capture system for the assessment of hand proprioception. The measures included were pointing acuity with eyes open and eyes closed, respectively in a cohort of people with and without pain or injuries in the hand. Absolute error in 3D was calculated for each measurement system and compared using ICC, and agreement using Bland-Altman plots. The ICC between the measurement systems was poor for eyes open but moderate to good for eyes closed. On the other hand, the agreement was better with a small bias for the eyes open tasks, median bias ≤ 1.5 mm and LOA -0.4 to 3.5 mm, but somewhat larger for eyes closed tasks, with mean bias ≤ 5.1 mm and -31.6 to 21.5 mm. These results indicate questionable concurrent validity of the LMC, but it could still hold value in clinical settings, given the limited resources available for objective measurements of hand proprioception. This type of measurement can guide specific, individualized intervention plans with targeted treatments.

The non-parametric Wilcoxon Signed rank test was significant for tests performed with eyes open. This implies that there was a systematic bias between the LMC and QTC, which indicates that one system tends to consistently produce higher or lower values compared to the other (Table 2). We could not find any explanation for this systematic bias in our data or algorithms, but the fact that the measurement errors were very small between measurement systems and between individuals could contribute to these results.

Tracking of hand and finger movements with the LMC has in several studies reported the accuracy to be between 0.1 mm and 2.5 mm (27, 36, 37, 38). These values are similar to the data that was collected for the test performed with eyes open in our study (right and left) which had a median difference of 1.3 and 1.5 mm. The difference and LOA were lower with both eyes open and closed for measurements of the right hand, than the mean differences for tests performed with eyes open and closed with the left hand, This may be explained by the fact that the participants had a higher precision in tests conducted with open eyes and the right (dominant) hand. (Table 5 and Figures 1-2).
Previous comparing of kinematic accuracy of the hand and finger between LMC and a standard goniometry or between 3D-based camera systems have shown various levels of agreement and correlation. Nizamis K. et al concluded from their study comparing LMC to goniometer measurement of wrist and finger range of motion a mean bias of 1.5° - 2.9°, with a wide range of LOA from 19° to -15°. The authors assess results as a lack of agreement between LMC and goniometer (39). Arman N. et al compared LMC to a goniometer for measuring hand and finger mobility with a mean difference of 0.21° - 5.5° between the two methods (40). These results are difficult to compare with the present study as they used angles (degrees) as the outcome measure.

Niechwiej-Szwedo, E et al concluded from their study that the LMC cannot reliably provide accuracy, precision, or maximum grip aperture. Accuracy had a wide LOA (67 to -54 mm) with a mean bias of 4 mm. Precision had a mean bias of 10 mm and a standard deviation of ±5.55 (24). Tung J. Y. et al studied participants performing a pointing movement at a target. The test was measured in millimeters and the outcome was calculated by root mean square error for each participant in horizontal and vertical axis. For the horizontal axis, the mean difference was 2.4 mm and for the vertical axis 0.4 mm, 95% LOA ranged between −29 and +30 mm. The results were considered unsatisfactory due to the large LOA (41). Ganguly A. et al compared LMC with QTM for static and dynamic kinematics of fingers. They also presented varied results in Bland-Altman plots both regarding mean bias and LOA (41). One reason for the wide LOA compared to LOA in the present study could be the extreme values and number of missing data points that both Niechwiej-Szwedo, E. et al and Tung J. Y. et al accused in their studies. These were more present than in the current study (23, 40).

ICC analyses in this study indicate poor correlation for measurements with open eyes and a moderate to good ICC for tests with closed eyes (Table 4). The correlation values in studies that have compared range of motion measurements between the LMC and a goniometer for forearm, wrist, and fingers have achieved ICC values of 0.68 to 0.88 and r values 0.92 to 0.95 for wrist motion and 0.79 for rotation of the forearm. The lowest correlations were found in middle and ring finger MCP flexion, with ICCs of 0.09 and 0.12. (34, 35). The discrepancy in the current study may be due to the small variability in AE between participants observed in tests with open eyes, while this variability was larger in the test with eyes closed.
Results were presented separately for open and closed eyes, and for the right and left hands. While segregating dominant and non-dominant sides might have been more optimal, considering that 18 out of 20 participants were right-handed, differences observed between the right and left hands can be assumed to be influenced by dominance. Few participants reported higher degrees of pain and disability. The data from these individuals was not significantly different from the rest of the data and therefore no further analysis was done.

A strength of this study was the inclusion of participants, of both sexes, with a wide age span and both with and without pain or disabilities of the hands. This allowed the concurrent validity to be evaluated with a variety of movement strategies. This is important as, in a clinical setting, movements of the arm and hand will vary between and within patients. The sample is considered representative of a larger Swedish population aged between 18 and 65 years. The results should not be generalized to children, young adults, the elderly, or patient groups with high pain and disability ratings. This needs to be investigated in future studies.

**Limitation**

We chose to examine 20 individuals, a number based on estimations from similar studies (42). The small sample size of 20 participants contributed to non-normally distributed data, increasing result uncertainty. Tests were conducted in a controlled and standardized laboratory environment. The procedure was administered uniformly by the same person for all participants. Despite efforts to capture procedures that could represent a clinical environment the protocol for this study is constrained, with aspects that do not mimic the clinical situation, which has an impact on the generalizing of study results to a clinical environment.

Previous studies report LMC sensitivity to lighting conditions and difficulty accurately tracking fingertip trajectories, particularly if hands rotate or are outside the device's field of view (43). QTM measurement was manually timed with a custom software metronome and then adjusted to match LMC measurement by a half-second ratio, potentially contributing to synchronization issues between LMC and QTM. The timing of movement also posed challenges for a majority of participants in this study, which potentially affected the results. Further analysis is relevant to determine if the outliers could be explained by missed timing between LMC and QTM.
Smeragliuolo A. H. et al. demonstrated LMC's lower accuracy in capturing forearm rotational movements and optimal arm and hand positions (27). These factors were considered in selecting hand position and arm movement for this study. However, movement in this study offered greater freedom than previous LMC-evaluated movements, which could have influenced the results. LMC accuracy error increases as hand movement strays further from the sensor, as in this study, where motion was executed by participants from the LMC center to the periphery and back repeatedly (40, 44). Using multiple Leap motion controllers has been proposed to compensate for difficult angles to detect and assess by one LMC (25, 45).

**Clinical implications**
LMC has advantages as it is a marker-less equipment, that does not require any contact with the patient’s skin that partly could influence proprioception due to sensory feedback. It is also a low-cost, portable system, which could facilitate the collection of kinematic data outside of the traditional laboratory settings and can generate continuous data as the hands are moved in space. The technology can also enable self-monitoring and collection of objective data for assessment and remote rehabilitation.

Proprioception is a sensory system component. LMC aims to examine this system. Specific proprioception tests in clinical settings should eliminate reliance on other sensory systems, such as vision. In this regard, results from this study are promising, showing more favorable correlation and agreement for tests with closed eyes than those with open eyes.

Tests conducted with eyes open could be seen as assessments of hand-eye coordination. Conducting these tests on a population with more pronounced motor difficulties, like patients with neurological diseases, might yield more promising data, where a wider range of results would be expected. Future research should investigate the discriminant validity of LMC for pointing acuity in a larger cohort.

From a clinical perspective, the values for tests performed with eyes open are considered small and interpreted as acceptable agreement. Regarding values for tests performed with eyes closed, the range for LOA (Limits of Agreement) is wider. However, most values had a range from 10 to -10 mm for both the right and left hand (see Table 5a-b), which should also
be regarded as an acceptable agreement from a clinical standpoint. There are few options for feasible and affordable objective measures. Based on this LMC could be a clinically valuable objective tool for measurements of hand proprioception despite the poor ICC. Further investigation regarding LMC psychometric properties is needed.

Conclusion

This study demonstrates that the LeapMotion controller (LMC) exhibits acceptable agreement compared to a 3D-based camera system (QTC) and the device should be viewed as a potential tool for use in clinical settings to quantify proprioceptive properties of the hand. However, the concurrent validity must be regarded as questionable due to the low correlation between the two methods, particularly with eyes open. The ability to instantly quantify proprioception facilitates pre- and post-intervention, providing clinicians with new possibilities for tailored rehabilitation and precise evaluation of movements.

Future Research

To provide the ability for improved objective assessment of motor dysfunction of hand and finger future studies should investigate the discriminative validity, test-retest reliability, and responsiveness of LMC regarding measurement of proprioception in different patient groups. For the LMC to become a clinically valid measurement tool, further research should focus on standardizing tests and procedures to better align with technical equipment. This could be the initial step to minimize the risk of outliers and optimize LMC's utility. The present study included subjects that were healthy or had minor pain and disabilities. Before more specific clinical recommendations can be made, further research is needed in populations with various disorders. Future studies should also compare the dominant and non-dominant hand. Finally, it would be interesting to investigate more types of hand and finger movements than those included in this study.
References


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Förväntad betydelse

Inom ramen för specialområdet OMT tillämpas en omfattande undersökning som syftar till att hitta dysfunktioner i kroppens muskuloskeletala system samt andra relevanta system och hur dessa dysfunktioner är relaterade till individens funktionsnedsättning eller funktionsbegränsning i enlighet med WHO’s International Classification of Functioning, Disability and Health (ICF). För att kunna uppfylla dessa kriterier behövs objektiva, valida och reliabla undersökningsmetoder.

Arbetet kan komma att tillföra nya specifika, objektiva och användarvänliga kliniska undersökningsmetoder för handens proprioception, vilket saknas idag. Utveckling och utvärdering av nya metoder är därför av stort värde för att skapa en effektivare rehabilitering för handen sensomotorisk.

Resultatet av denna studie möjliggör i sin tur mer precisa och skräddarsydda interventioner för den enskilda individen samt mer specifik utvärdering av behandlingseffekter, i enlighet med specialistområdet OMT samt personcenterad vård och precisionshälsa.
Etiska överväganden

Forskningsprojektet är inskickat och godkänt hos Etikprövningsmyndigheten, diarienummer: 022-03946-01

Deltagarna erhåller både muntlig och skriftlig information enligt informationskravet. Informationsbrevet är skrivet med ett enkelt och tydligt språk så personerna enkelt kan ta ställning till om de vill delta eller inte enligt autonomiprinципen (bilaga 3). Skriftligt samtycke inhämtas för varje enskild deltagare innan studien påbörjas enligt samtyckekravet (bilaga 4). Deltagare informeras om att deltagande i studien är helt frivilligt enligt autonomiprinципen. Deltagaren kan när som helst välja att avbryta sitt deltagande i studien, utan att behöva ange någon orsak.


Nyttan med projektet anses mycket stor då teknik och metod har betydande potential att öka kunskaperna om sensomotoriska funktionsstörningar och effektivisera rehabiliteringen av handbesvär. Ingen enskild individ kommer kunna identifieras då resultaten kommer presenteras på sådant sätt att ingen deltagare kan identifieras i kommande publikationer enligt konfidentialitetskravet.