Original Article

Validity and reliability of Leap Motion Controller for assessing grasping and releasing finger movements

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Abstract

Objective: The leap motion controller (LMC) is a motion sensor that has recently become available and has advantages in terms of cost, size, and accuracy. However, it has not been fully investigated whether the LMC has sufficient accuracy for clinical assessments, particularly finger flexion and extension, which are important for diagnosis and prognosis in stroke or cerebral palsy patients. Herein, we have tested the validity and reliability of the LMC for measuring the grasp and release of finger movements.

Materials and methods: A healthy participant repeated finger flexion and extension movements, and his fingertip position was measured using an LMC from the palmar, ulnar, and dorsal sides of the hand. The fingertip position was also measured using an electromagnetic motion tracker and a video. The finger movement detected by the LMC was compared with those detected by the other instruments.

Conclusions: The LMC had a higher reliability in detecting the fingertip position by sensing it from the palmar or dorsal side of the hand, compared with the ulnar side. In the palmar/dorsal side measurements, an underestimation in the amplitude of the finger movement was shown in the middle range of its excursion compared to video-detected movement. However, the underestimation resulted in a highly correlated, proportional bias, especially in the palmar-side measurement, and could be calibrated by a nonlinear regression analysis. The palmar side measurement was thus the most suitable for evaluating the finger flexion and extension. We concluded that by taking into consideration the range of excursion and appropriate calibration, the validity and reliability of the LMC is sufficient for the quantitative evaluation of finger flexion and extension in laboratory experiments and also in clinical settings.

Keywords: Motion capture; Spasticity; Grasping; Bland–Altman plot

Introduction

In recent years, a variety of low-cost, markerless motion sensors have become commercially available. Among such sensors, the leap motion controller (LMC) has advantages in handiness and cost, even though its measuring target is limited to the movement of forearms, hands, and fingers (Hondori, 2014; Kim, 2015). In previous studies, verification of the accuracy of the LMC was emphasized, and its relatively high accuracy was reported (Kim 2015; Alagha, 2017; Guna, 2014; Smeragliuolo, 2016; Weichert, 2013; Bachmann, 2015). Thus, the LMC was used in basic investigations for motor control of hands and fingers, and is expected to be used in clinical applications, such as in a gamification tool for the rehabilitation of the upper extremities (Charles,

2014; Gieser, 2013; Iosa, 2015; Putrino, 2014). However, whether the LMC has sufficient accuracy for quantitative assessments in clinical situations remains unclear.

Patients with hemiplegia after stroke, or patients with median nerve palsy, often have severe motor and sensory paralysis in the distal limbs, resulting in limitations in executing activities of daily living (ADL). The simple test for evaluating hand function (STEF) (Kaneko, 1996) and the Purdue Pegboard test (Buddenberg, 2000) have been extensively used for clinical evaluation of the function of the upper extremities. However, these tests measure the time during which the patients pick up small objects and put them in a box as quickly as possible. Thus, these tests do not quantitatively assess the grasp and release of finger movements. Although grip force (McDonnell, 2006) and pinch force (Burtner, 2008) are also possible indices of the finger dexterity, they mainly focus on the ability of finger flexion based on the muscular strength. Consequently, they do not fully evaluate the finger extension and its excursion. In severe hemiplegic patients, difficulty in quickly releasing the hand grip was shown to occur owing to impaired finger extension and delayed termination of finger flexion (Selzer, 2014; Seo, 2009). This means that one of the critical aspects of the upper extremity dysfunction is associated with releasing as well as grasping hands. Thus, the quantitative measurement of both grasping and releasing finger movements is important for the evaluation of the level of the upper extremity disorder after stroke, particularly for patients with severe conditions. In addition, previous reports have indicated that the visually inspected voluntary finger extension (VFE) is an important early predictor of recovery of upper limb capacity at six months following a stroke (Winters, 2016). Continuous quantitative assessment of the VFE

using the LMC will improve the prognosis prediction.

Although few studies have applied the LMC to clinical situations, there has been a previous study to verify the accuracy in detecting the frequency of grip and release tasks using the LMC for the quantitative assessment of cervical myelopathy (Alagha, 2017). Smeragliuolo and colleagues (2016) have also investigated the accuracy of the LMC detection of hand and forearm movements with the intention to apply it in a clinical environment. However, these studies have not considered the accuracy of the LMC for detecting flexion/extension finger movements. The present study thus aims to apply the LMC for the clinical assessment of grasping and releasing finger movements, and the reliability and validity of the LMC were tested. For this purpose, here we addressed two sub-issues.

First, from which side of the hand does the LMC reliably detect the grasp and release movements? Although the specific details of how the LMC detects the kinematic data are not publicly available, according to the document on the LMC official website (Colgan, 2014), the detection procedure seems to consist of stereophotogrammetry (Cappozzo, 2005) and tracking algorithms that interpret and infer the hand and finger positions, even if they are occluded. This implies that some fingers occluded behind the palm can be detected. Previous studies using the LMC generally detect hands and fingers from the palmar or ulnar side of the hand (Alagha, 2017; Guna, 2014; Bachmann, 2015; Charles, 2014; Iosa, 2015). It should be considered whether the other sides of the hand (dorsal and radial sides) are available for detecting finger motion.

Second, how do we define the actual finger positions to validate the accuracy of the LMC? A previous study adopted the gold-standard optical motion tracking

technology for validating the accuracy of the LMC. It also pointed out the instability of the LMC detection owing to the contamination of infrared light between the instruments (Smeragliuolo, 2016). Motion tracking methods without infrared light, such as electromagnetic motion tracking and simple video tracking, are thus alternative candidates.

Materials and Methods

1. Apparatus

An arm stand was attached on an acrylic desk, and its height was set to approximately 20 cm from the desk to hold an elbow and a forearm. An LMC (Version 2.3.1+31549, Firmware revision 1.7.0, Orion, Leap Motion Inc., CA, USA) was placed on the desk, and its center was adjusted just below the tip of the recorded finger (horizontally extended). The anterior-posterior and left-right axes of the participant corresponded to the Z and X axes of the LMC, respectively. A laptop computer (MacBook Air, Apple, CA, USA) was also placed on the side of the LMC for recording finger movements with the LMC, and for displaying the visual cue. The laptop monitor was set parallel to the Z axis to capture the moving visual cues, and finger movement was simultaneously recorded by the video camera. This also allowed the participant to match the finger flexion/extension to the visual cue intuitively. A video camera (Everio GZ-L330, JVC KENWOOD Corporation, Kanagawa, Japan) was set beside the desk using a tripod (along the X-axis of the LMC (at the origin of the Z-axis) at approximately 40 cm from the LMC center, so that it could record the hand movements and the visual cue simultaneously (Figure 1). This setting was flipped in the left-right axis to recode the (digit) fingertip when the dorsal side of the hand was directed to the LMC.

The visual cue presentation and the detection of the finger movement by the LMC was conducted using the computer language Processing (Processing, 2017), and its software development kit (GitHub, 2017). For validation of the video-detected finger movement, we used a three-dimensional magnetic field digitizer (MFD) (Model 3SF0002, Polhemus, Navigation Science Division, Kaiser Aerospace, VT, USA). The manufacturer reported the root mean square accuracy of this system as 0.3–0.8 mm when the source (transmitter) to sensor (receiver) separation is up to 76 cm. In this validation, the arm stand, the LMC, and the laptop were removed from the desk.
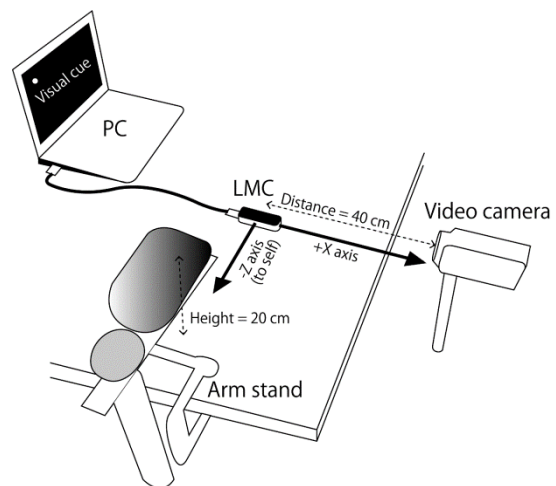

Figure 1: Schematic of the experimental setup

2. Experimental procedure

One of the authors of this paper, unaffected by any neuromuscular diseases, conducted the experiments. In all the experiments, the participant sat in a chair and moved the fingers of his right hand in a bright room without any direct sunlight.

In the pre-experiment, we validated the video-detected finger movement and compared it with that detected by an MFD. The transmitter of the magnetic field was attached on the back surface of the acrylic desk, and the receiver of the magnetic field was attached to the ulnar side of the right fifth digit's tip. A

small circle was drawn on the receiver for tracing its position in the video (Figure 2a). The right arm was placed on the desk directly, palm facedown, and fingers were grasped and released on the desk according to the sinusoidally moving visual cue at a frequency of 0.5 Hz. We measured the center position of the MFD sensor (sampling rate: 60 Hz) and video camera (sampling rate: 30 Hz) simultaneously. The MFD-detected sensor position was downsampled to 30 Hz and compared with the video-detected one to calibrate the small distortion in video-detection. After the recording, a 10-cm black wooden stick was placed along the path of the moving receiver. It was recorded by the video camera that was used to calibrate the sensor position from the recorded pixels to centimeters (Figure 2b). Note that we attempted to simultaneously record the digit fingertip position using the LMC and MFD, but the LMC could not detect the fingertip position with the MFD attached.
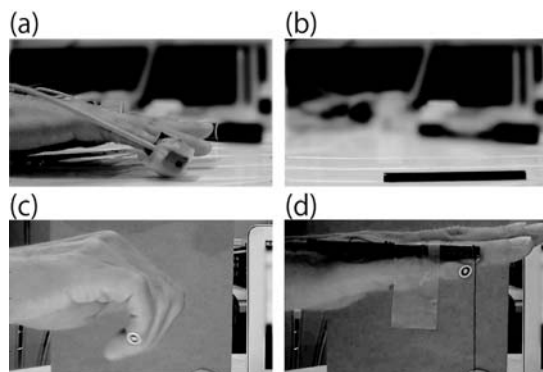

Figure 2: Photographs of the recorded video: (a) fingers and a magnetic field receiver attached on the fifth digit, (b) wooden stick for calibration, (c) fingers showing a sticker placed on the fifth digit, and (d) wooden stick for calibration attached on the fifth digit.

In the first experiment, the participant held his right forearms horizontally on the arm stand. The palmar (Figure 3a), ulnar (Figure 3b), or dorsal (Figure 3c), sides of the forearm and hand were directed to the LMC sensor, and the hand repeatedly performed grasping and releasing motions (four fingers—except for the thumb—were rhythmically flexed and extended from tight grasping to horizontally extended fingers), according to the sinusoidally moving visual cue at a frequency of 0.25 Hz. The position of right fifth digit fingertip was recorded with a sampling rate of 50 Hz and downsampled to 30 Hz for further analysis. The recording from the radial side of the hand was not recorded because it was often impossible for the LMC to detect the fifth digit in this position. For each recording direction (palmar, ulnar, or dorsal), the grasping and releasing fingertip positions were recorded 10 times (consecutive five-time recordings × 2) using the LMC.
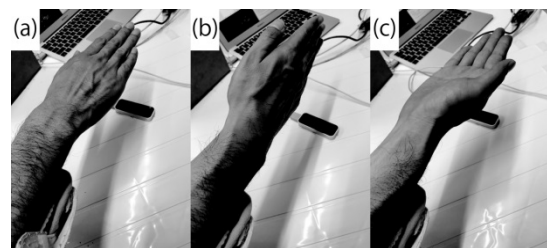

Figure 3: Photographs of hand postures for testing the reliability of the LMC: (a) recording from palmar, (b) ulnar, and (c) dorsal sides

In the second experiment, the flexing and extending finger movements were simultaneously recorded by the LMC (sampling rate: 50 Hz) and the video camera (sampling rate: 30 Hz). The recording directions were from the dorsal and palmar sides of the hand, because these directions showed higher reliability for recording finger movement compared to the ulnar side in the first experiment. The procedure of moving fingers was the same as the first experiment. The finger movement was tracked by a small sticker that was attached on the ulnar side of the right fifth

digit fingertip (Figure 2c). After the recording, a 10-cm black wooden stick was attached on the right fifth digit and was recorded by the video camera to calibrate the finger position from video pixels to centimeters (Figure 2d).

3. Data analysis

In the pre-experiment, the finger movement captured on the video was transformed to a Z-axis finger position, based on the written marker, using a custom-written MATLAB (MATLAB R2016a, Natick, MA, USA) program. The video-detected finger position was compared to the finger position at the same axis, as detected by the MFD. These data were compared using a Bland–Altman plot after temporally aligning them using cross-correlation. The calibration ratio between the video-detected and the MFD-detected finger positions were then calculated. In the second experiment, video-detected finger positions were calibrated using this calibration ratio.

In the first experiment, the fifth digit's Z-axis position detected by the LMC was temporally aligned across trials (10 trials), based on the visual cue and the calculated variance of the finger positions at each time point. The variances were compared across the recording direction by a paired t-test with Bonferroni correction.

In the second experiment, we compared the fifth digit fingertip position recorded by the LMC with that recorded by the video camera. The finger position on the video was detected based on the written marker, as in the pre-experiment. The temporal difference between the LMC-detected and video-detected finger positions was computed using cross-correlation. The video-detected and temporally aligned LMC-detected finger positions were compared on a Bland–Altman plot.

To predict the video-detected finger position using the LMC data, we applied a nonlinear support vector machine (SVM) regression to the LMC data using MATLAB. To construct the regression model, the half-width of the epsilon-insensitive band was set to 0.3 and the Gaussian function was used as the kernel for computing the elements of the Gram matrix. A seven-hold cross-validation was adopted to evaluate the model prediction, because the LMC data included 7 cycles of 4-s finger flexion and extension, i.e., the 6-cycle finger flexion and extension was used as the training data, whereas the remaining 1-cycle was tested. For each validation, we calculated the correlation coefficient between the video-detected and predicted finger positions from the LMC data using the trained model.

Results

1. Validity of the video detection of grasping and releasing finger movement (pre-experiment)

The validity of the video-detected finger movement was tested by comparing it with the finger movement detected by a three-dimensional MFD using a Bland–Altman plot (Figure 4). The error in the Bland–Altman plot was 3.00 ± 4.04 mm (mean $\pm$ 2SD). The result showed that there was a small proportional bias between them, and the video-detected finger displacement was overestimated by approximately 8% against the MFD-detected movement. Therefore, the video-detected finger movement was calibrated for further analyses by integrating the corresponding calibration ratio (0.926). The calibrated video-detected finger movement was compared with the MFD-detected movement. As a result, the difference between the video-detected and MFD-detected finger movements was within two standard deviations (2SD), i.e., within ± 2.3 mm. There was neither

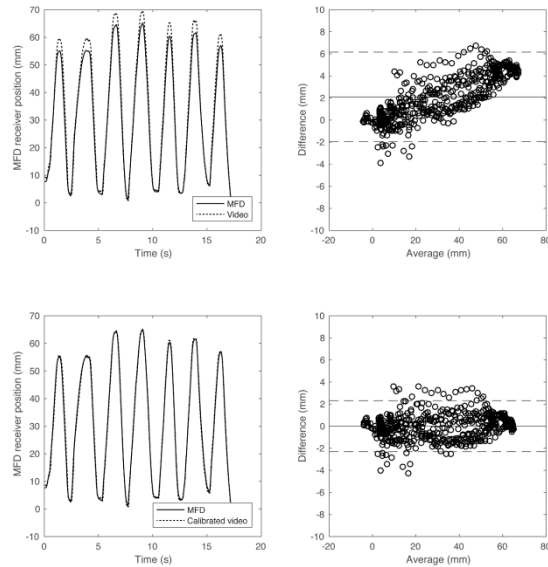a proportional bias nor a fixed bias between them.

Figure 4: Time series and a Bland–Altman plot for finger position measured with an MFD and a video camera. Top and bottom panels indicate the comparisons of their original signals and calibrated (only video) signals, respectively.

1. Intertrial reliability for recording directions of the LMC (first experiment)

We have examined the direction from which the LMC reliably detects finger movements. The trial variability values were compared at each time point among the right fifth digit's tip positions recorded from the palmar, ulnar, and dorsal sides of the hand (Figure 5). The results showed that the variances in the palmar and dorsal-side measurements were significantly smaller than those in the ulnar-side measurements, and there was no significant difference between them (Table 1).
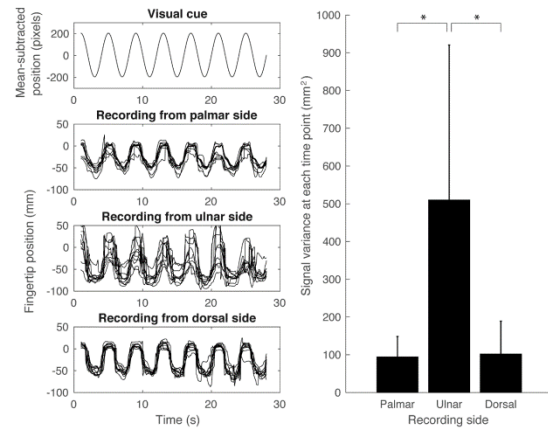

Figure 5: Reliability for recording directions of the LMC. The left panels indicate the visual cue signals for each recording direction. The right panel indicates the temporal variation of the motion traces.

2. Validity and intercycle reliability of the LMC for detecting grasping and releasing finger movements (second experiment)

To verify the accuracy of the LMC for detecting finger movement, the fingertip positions of the right fifth digit recorded from the palmar and dorsal sides of the hand were compared with the actual fifth digit positions detected by the video (after calibration). At the first step, a cross-correlation analysis was conducted to evaluate the similarity and time delay between the LMC-detected and the video-detected finger movements. For both the dorsal-side (Figure 6, top panels) and palmar-side (Figure 7, top panels) measurements, the correlation coefficient at the cross-correlation peak was very high (dorsal: $r = 0.97$, $p < 0.001$; palmar: $r = 0.98$, $p < 0.001$),

Table 1: Comparison of the signal variance of the fingertip position recorded from palmar, ulnar, and dorsal sides of the hand.

Comparisons	t-value	df	Corrected p-value	Effect size (d)
Palmar vs. Ulnar	30.61	810	< 0.001	1.07
Palmar vs. Dorsal	2.02	810	0.13	0.94
Ulnar vs. Dorsal	26.86	810	< 0.001	0.07

although there was a time delay of approximately 200 ms in the LMC detection. After the temporal alignment with this time delay, the Bland–Altman plot showed that the error in the dorsal-side measurement was 4.32 ± 13.50 mm (bottom panels in Figure 6), and that in the palmar-side measurement was 7.43 ± 19.15 mm (bottom panels in Figure 7). The former was slightly smaller than the latter. For both measurements, the amplitude of the LMC-detected finger movements was smaller than the actual movement based on video detection, particularly as the fingers were flexed and approached the palm. In this range, the reliability across flexion/extension cycles was apparently higher in the palmar-side measurement than that in the dorsal-side measurement. We found the proportional bias in the Bland–Altman plot for the finger excursion from the position at which the fifth digit horizontally pointed to the palm (Figure 8a) to the position at which the fifth digit pointed below the palm (Figure 8b). This proportional bias was apparent in the palmar-side measurement, and its correlation coefficient was significantly high (r = −0.96, p < 0.001, Figure 8c). The proportional bias (or sign-reversed bias) was small, but there was a fixed bias at the finger excursion as the fifth digit was more flexed compared to a loosely grasped position (the fifth digit horizontally pointed to the palm, as described above, Figure 8a).

3.   Predicted finger movements from the LMC data using a non-linear SVM regression (second-experiment)

Using a non-linear SVM regression, we successfully predicted the video-detected finger flexion and extension from the LMC data, despite its non-linear decrease in the middle range of the finger excursion described above. The predicted finger flexion and extension were
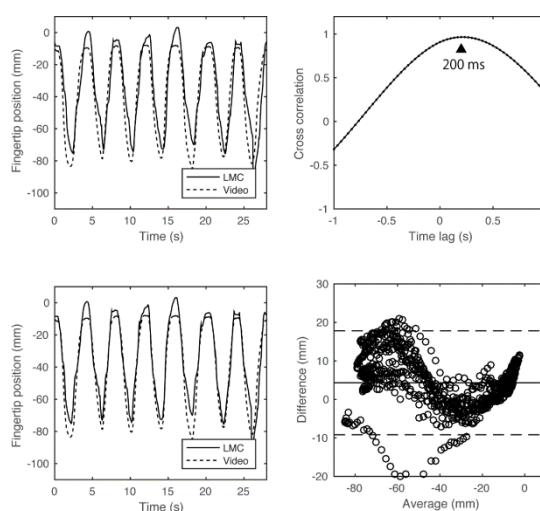

Figure 6: Time series and a Bland–Altman plot for fingertip positions measured from the dorsal side of the hand using the LMC and a video camera. The top and bottom left panels depict the original and temporally adjusted signals, respectively. The top right panel illustrates a cross-correlation function of the top left signals. The bottom right panel illustrates a Bland–Altman plot of the bottom left signals.
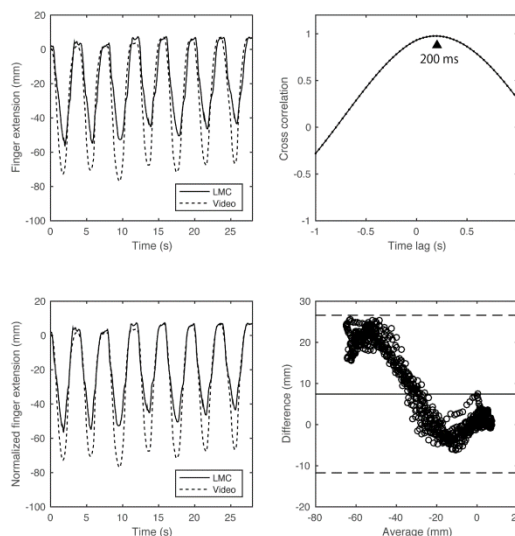

Figure 7: Time series and a Bland–Altman plot for fingertip positions measured from the palmar side of the hand using the LMC and a video camera. The top and bottom panels depict the original signals and temporally adjusted signals, respectively. The top right panel illustrates a cross-correlation function of the top left signals. The bottom right panel illustrates a Bland–Altman plot of the bottom left signals.

highly correlated with the video-detected ones (Figure 9), and the mean and SD of the correlation coefficient were 0.996 and 0.003, respectively.
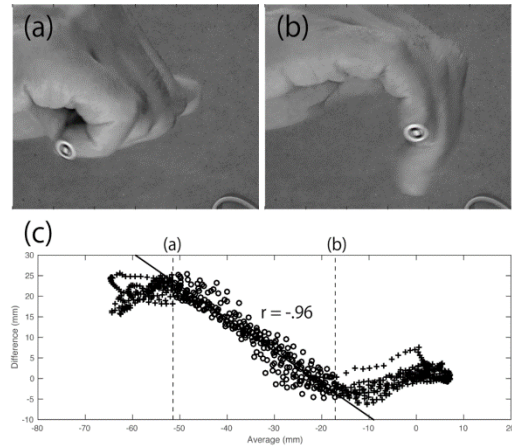

Figure 8: The relation between finger excursion and detected bias of the LMC for the palmar-side measurements: (a) photograph of the finger position where the peripheral part of the fifth digit was positioned horizontally and directed to the palm, (b) photograph of the finger position where the peripheral part of the fifth digit was positioned vertically and pointed downwards, (c) Bland–Altman plot of the fifth digit's tip position detected by the LMC and a video camera. Proportional bias was shown in the middle range of finger excursion from position (a) to position (b).

Discussion

In the current study, we verified the accuracy of the LMC for detecting the finger movements and the excursions when the hand was grasping and releasing. For this purpose, the LMC-detected finger movement was compared to the actual movement detected using the video camera. We adopted consecutive procedures for verification of the video-detected finger movement with the MFD-detected movement, and verification of the LMC-detected finger movement with the video-detected movement. When the finger movement was detected by the LMC and MFD
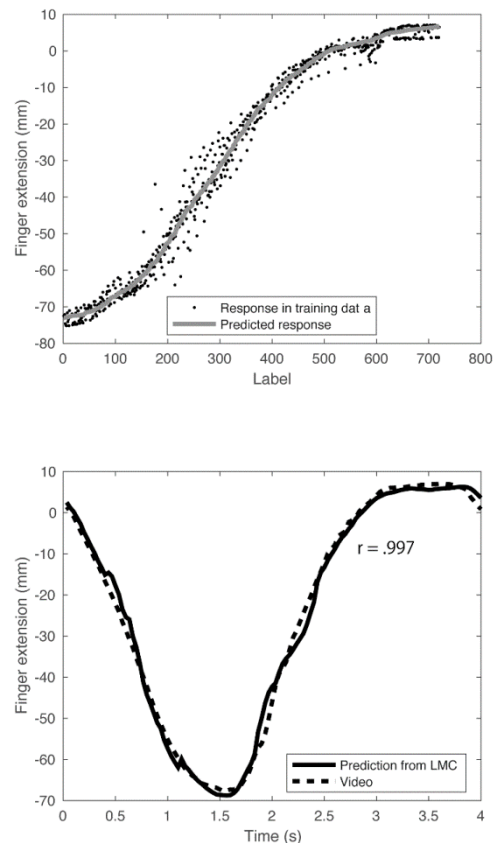

Figure 9: An example of SVM regression and 7-hold cross validation between the LMC-detected finger movement (predictor) and the video-detected one (response). The top panel depicts the training data of the 6-cycle finger extension/flexion (black dots) and the predicted response (gray solid line). The bottom panel depicts the corresponding test result of the validation. A solid line indicates the fingertip position predicted from the LMC data, and a dashed line indicates the video-detected fingertip position. A correlation coefficient value is superimposed.

simultaneously, the LMC could not detect the hand model, probably owing to the magnetic field receiver and connection cables attached around the fingertip.

Previous studies have reported the relatively high accuracy of the LMC for detecting the positions and movements of the hands and fingers (Kim 2015; Alagha, 2017; Guna, 2014; Smeragliuolo, 2016; Weichert, 2013; Bachmann, 2015). However, these

studies did not focus on the validity of the LMC for detecting the finger movement during hand grasping and releasing. In addition, to our knowledge, there exist no prior studies investigating the direction from which the LMC detects the finger flexion and extension of the hand more accurately. We found that the finger movement was detected from the dorsal and palmar sides of the hand more accurately than from the ulnar side. A previous study pointed out that LMC-detected forearm supination/pronation was unstable, especially when the hand was grasping into a fist (Weichert, 2013). The authors of this study argued that this problem was caused by an error in discriminating the palmar from the dorsal sides of the hand. The unstable detection of finger movements in this study (recorded from the ulnar sides of the hand) might cause similar detection errors, although the unstable range of the forearm supination/pronation in the previous study was not consistent with our findings. Our results suggested that the clinical assessment of the finger flexion/extension should be recorded from the palmar and dorsal sides of the hand. Surprisingly, the dorsal-side measurements were as stable as the palmar-side measurements, despite the fact that the fingertips were not projected to the LMC when the hand was grasped into a fist. Although the detailed procedure to detect finger positions was not publicly available, the LMC's tracking algorithm would somehow infer them despite occlusion behind the palm (Colgan, 2014). Thus, if the patients have difficulty in forearm extension and supination due to spasticity, dorsal-side measurements can be substituted for the palmar-side measurement. However, if the palmar-side measurement is necessary, the LMC must be located in the vicinity of the trunk, such as the chest or upper arm.

We also found that the finger movement was underestimated when the fingers were close to the palm, even in the dorsal- and palmar-side measurements. In the dorsal-side measurements, the underestimation can be explained by the fact that the fingertips in a fist were not projected to the LMC. In the palmar-side measurements, the image contrast around the fingertips was lowered when the fingertips were flexed and approached the palm. Both phenomena might distort the inferred tracking of the finger positions (Colgan, 2014), resulting in its underestimation. We found that the intercycle reliability of the finger movement in the dorsal-side measurement seemed to be worse than that in the palmar-side measurement, and the proportional bias for the palmar-side measurement was highly correlated (Figure 8c). These results also support the different mechanisms leading to the underestimation of the dorsal- and palmar-side measurements (the fingers were occluded from the dorsal side but visible from the palmer side when the hand was grasped). Furthermore, the proportional bias disappeared or reversed at the limited range of finger excursions in cases where the fingers were tightly grasping (the finger excursion of the fifth digit was more flexed than the loosely grasping position, Figure 8a). This suggested that, in this range, the position of the proximal interphalangeal joint started moving and contributed to improve the inferred detection of the overall fingers, including the fingertips. The implication of this finding is that the clinical assessment of the small finger extension of the spastic "clenched" hand in patients is rather accurate.

As described above, the intercycle reliability of the finger movement was apparently higher in the palmar-side measurements than in the dorsal-side measurements. This indicates that the LMC-detected finger movement in the palmar-side measurement was underestimated but still sensitive to change in the movement.

We also demonstrated that the model constructed using nonlinear SVM regression could predict the video-detected finger movement from the LMC-detected one. Correspondingly, an appropriate calibration based on nonlinear regression was effective for the absolute evaluation of the finger movement and excursion. In these regards, we concluded that the palmar-side measurement was suitable for detecting the flexion/extension finger movement and excursion.

A major limitation of this study is that there was only one participant to verify the LMC performance. Evaluation of the tolerance of the LMC validity for individual differences, including the case of patients, will be conducted in our future study. Another limitation is that the specific finger (a right fifth digit) and its movement in one dimension (Anterior-posterior axis, Z axis of the LMC, Figure 1) were validated. Simple finger flexion/extension might allow us to extend the current findings for a fifth digit to those for the other fingers. However, for detecting complex postures and movements of all fingers, three-dimensional information on the fingers' position was necessary. The LMC can provide three-dimensional information of each finger. This information is useful for clinical assessments of various types of patients with hand and finger disorders, although further investigation will be needed.

The present finding that the dorsal-side measurements are as stable as the palmar-side measurements also provides important insights for the clinical use of the LMC, because it widens its application range for patients whose possible postures are limited owing to their upper limb spasticity. Thus, the LMC is a strong candidate for an easy but quantitative evaluation of the upper extremity functions in hemiplegic patients or patients with median nerve paralysis.

References

Alagha MA, Alagha MA, Dunstan E, et al, 2017. Development of a new assessment tool for cervical myelopathy using hand-tracking sensor: Part 1: validity and reliability. Eur. Spine J. 26(4), 1291-1297.

Bachmann D, Weichert F, Rinkenauer G, 2015. Evaluation of the leap motion controller as a new contact-free pointing device. Sensors 15(1), 214-233.

Buddenberg LA, Davis C, 2000. Test–retest reliability of the Purdue pegboard test. Am. J. Occup. Ther. 54(5), 555-558.

Burtner PA, Poole JL, Torres T, et al, 2008. Effect of wrist hand splints on grip, pinch, manual dexterity, and muscle activation in children with spastic hemiplegia: a preliminary study. J. Hand Ther. 21(1), 36-43.

Cappozzo A, Della Croce U, Leardini A, Chiari L, 2005. Human movement analysis using stereophotogrammetry: Part 1: theoretical background. Gait Posture, 21(2), 186-196.

Charles D, Pedlow K, McDonough S, et al, 2014. Close range depth sensing cameras for virtual reality based hand rehabilitation. J. Assist. Technol. 8(3), 138-149.

Colgan A, 2014. How does the Leap Motion Controller work? http://blog.leapmotion.com/hardware-to-software-how-does-the-leap-motion-controller-work/ (accessed Sep. 25, 2017).

Gieser SN, Gentry C, LePage J, Makedon F, 2013. Comparing objective and subjective metrics between physical and virtual tasks. In 5th International Conference, VAMR 2013, Held as Part of HCI International 2013, Lackey S., Shumaker R., Eds., 3-13.

GitHub, 2017, https://github.com/nok/leap-motion-proces sing (accessed May 10, 2017).

Guna J, Jakus G, Pogačnik M, et al, 2014. An analysis of the precision and reliability of the leap motion sensor and its suitability for static and dynamic tracking. Sensors 14(2), 3702-3720.

Hondori HM, Khademi MA, 2014. Review on technical and clinical impact of Microsoft Kinect on physical therapy and rehabilitation. J. Med. Eng. 1-16.

Iosa M, Morone G, Fusco A, et al, 2015. Leap motion controlled videogame-based therapy for rehabilitation of elderly patients with subacute stroke: a feasibility pilot study. Top. Stroke Rehabil. 22(4), 306-316.

Kaneko T, Murai T, 1996. Development and standardization of the hand function test. Bull. Allied Med. Sci. Kobe 6, 49-54.

Kim JJ, Gonzalez DA, Mintz A, et al, 2015. Motor control assessment using leap motion: filtering methods and performance in indoor and outdoor environments. In IFMBE Proceedings; Jaffray D. A., Ed., Toronto, Canada, 51, 1150-1154.

McDonnell MN, Hillier SL, Ridding MC, Miles TS, 2006. Impairments in precision grip correlate with functional measures in adult hemiplegia. Clin. Neurophysiol. 117(7), 1474-1480.

Processing, 2017, https://processing.org (accessed May 10, 2017).

Putrino D, 2014 Telerehabilitation and emerging virtual reality approaches to stroke rehabilitation. Curr. Opin. Neurol. 27(6), 631-636.

Selzer M, Clarke S, Cohen L, et al, Eds., 2014. Textbook of Neural Repair and Rehabilitation: Volume 2, Medical Neurorehabilitation; Cambridge University Press, Cambridge, UK.

Seo NJ, Rymer WZ, Kamper DG, 2009. Delays in grip initiation and termination in persons with stroke: effects of arm support and active muscle stretch exercise. J. Neurophysiol. 101(6), 3108-3115.

Smeragliuolo AH, Hill NJ, Disla L, Putrino D, 2016. Validation of the leap motion controller using markered motion capture technology. J. Biomech. 49(9), 1742-1750.

Weichert F, Bachmann D, Rudak B, Fisseler D, 2013. Analysis of the accuracy and robustness of the leap motion controller. Sensors 13(5), 6380-6393.

Winters C, Kwakkel G, Nijland R, Van Wegen E, 2016. When does return of voluntary finger extension occur post-stroke? A prospective cohort study. PLoS One 11(8), e0160528.