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Validation of the Leap Motion Controller using markered motion capture technology

Anna H. Smeragliuolo [a,b], N. Jeremy Hill [c], Luis Disla [d], David Putrino [a,b,*]

[a] Department of Telemedicine and Virtual Rehabilitation, Burke Medical Research Institute, White Plains, NY, USA
[b] Department of Rehabilitation Medicine, Weill-Cornell Medical College, New York, NY, USA
[c] Motor Recovery Laboratory, Burke Medical Research Institute, White Plains, NY, USA
[d] The City College of New York, School of Biomedical Engineering, New York, NY, USA

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ABSTRACT

The Leap Motion Controller (LMC) is a low-cost, markerless motion capture device that tracks hand, wrist and forearm position. Integration of this technology into healthcare applications has begun to occur rapidly, making validation of the LMC's data output an important research goal. Here, we perform a detailed evaluation of the kinematic data output from the LMC, and validate this output against gold-standard, markered motion capture technology. We instructed subjects to perform three clinically-relevant wrist (flexion/extension, radial/ulnar deviation) and forearm (pronation/supination) movements. The movements were simultaneously tracked using both the LMC and a marker-based motion capture system from Motion Analysis Corporation (MAC). Adjusting for known inconsistencies in the LMC sampling frequency, we compared simultaneously acquired LMC and MAC data by performing Pearson's correlation (r) and root mean square error (*RMSE*). Wrist flexion/extension and radial/ulnar deviation showed good overall agreement ($r=0.95$; $RMSE=11.6°$, and $r=0.92$; $RMSE=12.4°$, respectively) with the MAC system. However, when tracking forearm pronation/supination, there were serious inconsistencies in reported joint angles ($r=0.79$; $RMSE=38.4°$). Hand posture significantly influenced the quality of wrist deviation ($P<0.005$) and forearm supination/pronation ($P<0.001$), but not wrist flexion/extension ($P=0.29$). We conclude that the LMC is capable of providing data that are clinically meaningful for wrist flexion/extension, and perhaps wrist deviation. It cannot yet return clinically meaningful data for measuring forearm pronation/supination. Future studies should continue to validate the LMC as updated versions of their software are developed.

1. Introduction

In recent years, a number of low-cost, markerless motion-sensing systems have become commercially available for gamers and hobbyists; the Leap Motion Controller (LMC; Leap Motion Inc., San Francisco, CA) is one such system. This device has been designed to quantify hand movements and gestures. The LMC is portable, user-friendly, and can reliably track static objects within 0.2 mm accuracy (Weichert et al., 2013). Recently, it has been used successfully in combination with digital games as a tool for tele-rehabilitation (Khademi et al., 2014; Putrino, 2014). Telerehabilitation is an emerging method of remote clinical care delivery that has the potential to significantly decrease impairment and improve quality of life in individuals suffering from chronic disorders of motor control (Garrido et al., 2014; Taylor and Curran, 2015). Devices such as the LMC have already been established as useful tools for effective telerehabilitation, because they enable development of interactive systems that make therapy exercises fun and engaging, and allow therapists to remotely monitor compliance with ease (Putrino, 2014). It is still unclear, however, whether the LMC can capture accurate upper-limb kinematic data in a typical home or clinical environment. Until this question is addressed, the LMC cannot be used to perform in-home or in-clinic assessments of upper-limb function.

The raw sensor capabilities of the LMC have been validated as reliable. Work with robotic tools has determined that the LMC can relay static positional data with a standard deviation <0.5 mm (Guna et al., 2014). Furthermore, the distance between two moving fixed-distance points has been reported within 1.2 mm accuracy (Weichert et al., 2013). However, these studies focus exclusively on the LMC's ability to discriminate end-point motion under highly controlled, standardized circumstances – not its ability to accurately determine kinematic variables. There are currently no

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[*] Corresponding author at: Department of Telemedicine and Virtual Rehabilitation, Burke Medical Research Institute, 785 Mamaroneck Ave, White Plains 10605, NY, USA. Tel.: +1 914 368 3183; fax: +1 914 597 2225.
E-mail address: dap3002@med.cornell.edu (D. Putrino).

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studies that evaluate the LMC's ability to accurately track wrist and forearm motion in human subjects in a realistic clinical or home environment. If the LMC can provide accurate joint angle data in practical settings, it would allow clinicians to remotely perform assessments of upper-limb function. The implications are enormous for improving the delivery of care to individuals suffering from motor dysfunction of the wrist and forearm: clinicians could not only track compliance to home exercise programs, but also measure the effects of home exercises on joint range of motion with unprecedented accuracy and regularity. The ability to observe compliance to a home exercise program alongside measures of functional improvement will allow clinicians to rigorously evaluate the efficacy of home exercises for each patient.

In order to produce kinematic data, the LMC first acquires images of the environment, and uses object recognition to identify upper limbs in the field of view. The LMC official website provides a simple explanation of how it captures images (http://bit.ly/1A2UI7Q). Following image capture, the LMC software uses a proprietary variation of stereophotogrammetry for joint motion inference (Selvik, 1989). Stereophotogrammetry has become a well-adopted approach to markerless motion capture, but few devices focus exclusively on deriving upper-limb kinematic data (Cappozzo et al., 2005; Li et al., 2015). The specific details of how the LMC optimizes basic stereophotogrammetry algorithms to produce these data are not publicly available.

For decades, marker-based motion capture systems have been held as the gold-standard in motion capture technology (Ceseracciu et al., 2014). They are used across disciplines to obtain the most reliable, non-invasive measurements describing human motion (Cook et al., 2007). Data from these systems, combined with joint center estimations established by the use of validated kinematic algorithms, allow for the calculation of joint motion to a high degree of accuracy (Metcalf et al., 2008; Todorov, 2007; Zhang et al., 2011). However, the lengthy setup times and specific technical knowledge needed not only to operate such a system, but also to acquire and process the data, renders its use as a rehabilitation tool unfeasible.

Here, we use gold-standard motion capture technology to quantify the accuracy with which the LMC records joint angles of the wrist and forearm, under conditions that were designed to be reproducible in a supervised clinical environment.

2. Methods

Subjects were recruited from the general population. Inclusion criteria stipulated that subjects must be neurologically healthy, with no history of significant injury to either upper limb. Informed written consent was obtained for each subject that was recruited into the study. All experimental practices were conducted with full approval of the Burke Rehabilitation Hospital Committee for Human Rights in Research.

2.1. Subject information

We recruited 16 subjects into the study, allowing us to examine 32 hands in total: 16 right and 16 left. Average hand size was 18.3 cm × 9.0 cm (Table 1). There were six female participants, and ten male participants, with ages ranging from 23 to 55 (mean: 31; standard deviation: 10.1). All subjects completed the assigned protocol without incident, and no subjects were excluded.

2.2. Markered motion capture system

Eight motion capture cameras from MotionAnalysis Corporation (MAC; MotionAnalysis Corp., Santa Rosa, CA) were strategically placed in our laboratory to create a capture volume of approximately 2.2 m × 2.3 m × 2.3 m. We utilized the “Kestrel” camera line for data acquisition, which is capable of a 300 hertz (Hz) acquisition rate, with 2048 × 1088 (2.2 million) pixel resolution. The MAC system allows for highly accurate motion capture data to be collected, which can subsequently be converted to joint angle estimations (Zhang et al., 2011). Using standard calibration practices outlined by the MAC user's manual, we completed system calibration prior to data acquisition. Calibration was accepted if average 3D residuals were estimated at under 0.8 mm, and data acquisition was only attempted after an adequate calibration was achieved. Each subject wore a set of 21 retro-reflective, spherical (5 mm diameter) markers on their upper body. Marker placement was determined according to private consultations with the MotionAnalysis Corporation as well as prior published recommendations (Rab et al., 2002; Schmidt et al., 1999). Final placement decisions were made in order to facilitate ease and accuracy of joint center calculations. The markers were applied to each anatomical landmark as determined by palpation (Fig. 1).

2.3. The Leap Motion Controller

The LMC is a low-cost, patternless infrared and stereo vision motion capture device that specializes in markerless motion capture of the forearm, wrist and hand. It contains two cameras and three infrared lights. It is a small, rectangular device (13 mm × 13 mm × 76 mm) that weighs 45 g. It performs live-feedback motion capture of both hands when it is placed underneath the hands of the user (Fig. 2). The LMC streams data at a variable acquisition rate of up to 120 Hz. It is dual platform (Macintosh/Windows), connects to a computer via a USB 3.0 connection, and has a full-functioning Software Developer Kit (SDK). Using the SDK (v2.3.0), we programmed a piece of data acquisition software that allowed us to stream and save data from the device.

2.4. Data acquisition

We acquired simultaneous recordings from the LMC and the MAC systems, while subjects performed a series of one-dimensional rotations of the hand around axes passing through the wrist: radial/ulnar deviation (rotation about the global x-axis, Fig. 4a), flexion/extension (rotation about the global z-axis, Fig. 4b), and pronation/supination (rotation about the global y-axis, Fig. 4c). Each subject was instructed to sit in a chair with their arm at their side and elbow flexed to 90°. A wooden dowel was placed at the height of each subject's elbow to ensure that they kept their forearm stationary throughout the protocol. The LMC sat atop a height-adjustable platform, positioned approximately 1.5 hand-lengths below the subject's hand (Fig. 3). We chose a metric that was customized to each subject so that subjects with larger hands did not come too close to the sensor, and those with smaller hands were not too far from the sensor at any point during the protocol. Hand length, breadth, circumference, and palm length were all measured according to the US Army guidelines (White, 1980). In order to approximate tracking problems that could arise due to fixed, pathological hand postures, each subject repeated the three motions with their hands in three different positions: open hand (Fig. 4d), loose fist (Fig. 4e), and tight fist (Fig. 4f). The subjects completed each movement pair five times for the recording. To ensure that movement speed was consistent across subjects, they were instructed to move to the beat of a metronome set at 60 beats per minute.

2.5. Kinematic analysis

We used a specialized motion capture software called Cortex (MotionAnalysis Corp., Santa Rosa, CA) to acquire and process the MAC data. The Skeleton Builder software package within Cortex allows for calculation of joint centers and a segmental skeleton from the positional marker data. The joint angles presented here were obtained from a simple three-segment model representing the humerus, forearm, and metacarpals. This skeleton's local axes were assigned in accordance with the International Society of Biomechanics' (ISB) recommendations for joint coordinate systems (Wu et al., 2005). For the right wrist joint, these guidelines

Table 1
Average (±standard deviation), maximum and minimum hand size metrics (cm).

	RH length	RH breadth	RH circ.	RH palm length	LH length	LH breadth	LH circ.	LH palm length
Average	18.3 (±1.3)	9.1 (±0.9)	20.7 (±1.5)	10.0 (±0.8)	18.2 (±1.5)	9.0 (±0.9)	20.4 (±1.6)	9.9 (±1.0)
Maximum	21.3	10.8	24.1	11.9	22	11.1	23.5	11.8
Minimum	16.2	8	8.2	8.4	15.6	7.7	17.8	8.2

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