Evaluation of Hand Motion Capture Protocol Using Static Computed Tomography Images: Application to an Instrumented Glove

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There has been a marked increase in the use of hand motion capture protocols in the past 20 yr. However, their absolute accuracies and precisions remain unclear. The purpose of this technical brief was to present a method for evaluating the accuracy and precision of the joint angles determined by a hand motion capture protocol using simultaneously collected static computed tomography (CT) images. The method consists of: (i) recording seven functional postures using both the motion capture protocol and a CT scanner; (ii) obtaining principal axes of the bones in each method; (iii) calculating the flexion angle at each joint for each method as the roll angle of the composite, sequential, roll-pitch-yaw rotations relating the orientation of the distal bone to the proximal bone; and (iv) comparing corresponding joint angle measurements. For demonstration, we applied the method to a Cyberglove protocol. Accuracy and precision of the instrumented-glove protocol were calculated as the mean and standard deviation, respectively, of the differences between the angles determined from the Cyberglove output and the CT images across the seven postures. Implementation in one subject highlighted substantial errors, especially for the distal joints of the fingers. This technical note both clearly demonstrates the need for future work and introduces a solid, technical approach with the potential to improve the current state of such assessments in our field. [DOI: 10.1115/1.4028521]

Introduction

The human hand is used for over eighty percent of activities of daily living [1]. Consequently, the loss of hand function is very debilitating and often requires extensive rehabilitation. Hand motion capture protocols can be used to record hand kinematics that are useful for the functional evaluation of the pathological hand and the follow-up evaluation of its rehabilitation [2–4]. In addition, knowledge of hand kinematics obtained through motion capture can be used to understand human motor control strategies, to analyze sporting techniques, or in the ergonomic evaluation of handheld tool use [5–7].

The number of publications involving motion capture protocols for the hand has markedly increased in recent years as technology has improved. Performing a search for “hand motion capture” on Oct. 30, 2013 in Elsevier’s Engineering Village (Compendex and Referex) scientific database showed a sixfold increase in the number of publications between 2000 and 2012 (Fig. 1). Currently, there are two primary methods that allow for the simultaneous measurement of all hand joint angles in vivo. In the first method, cameras are used to optically track the motions of hand segments [8–15]. Many of the publications using this method require surface markers for tracking, but markerless techniques are also becoming increasingly popular. The second method consists of using a glove that is instrumented with bend sensors that are typically either resistive or fiber optic sensors [4,16].

Despite the increase in the number of publications, information quantifying the absolute accuracy and precision of these methodologies for recording hand motion are lacking. Most studies that include measures of optical-tracking performance mainly describe the repeatability and reproducibility of results [9,12,13,15]. When absolute accuracy is intended, the assessment generally focuses on the capabilities of the equipment as opposed to the performance of the protocol in capturing anatomical joint angles. For example, Metcalf et al. [10] instrumented the hand with 26 surface markers to capture movements of the wrist, metacarpal arch, fingers, and thumb. However, accuracy (reported to be less than 1 deg) was assessed by statically placing markers on flat surfaces and machined metallic frames, positioning these objects at 13 different set angles (meant to represent wrist postures only), and comparing marker outputs to these known reference configurations. Similarly, there is a paucity of data quantifying the performance of instrumented-glove motion capture protocols. In the past, instrumented gloves have been evaluated by comparing

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Fig. 1 The number of publications mentioning “hand motion capture,” plotted as a function of publication year. Results are from a literature search of the years 1985–2012 in Elsevier’s Engineering Village scientific database.

outputs with those from optical-tracking, motion capture protocols [e.g., Ref. 16]. This is not ideal because of the uncertainty in the accuracies of these reference marker protocols. Goniometers have also been used in the evaluation and calibration of instrumented gloves [4]; but it is not possible to register all 15 joint flexion angles of the hand simultaneously using handheld goniometers.

The purpose of this technical note was to present a method for evaluating the accuracy of the joint angles determined by a hand motion capture protocol using simultaneously collected static CT images. CT imaging was chosen as the reference technique because of the high resolution of the output and the capacity for registering the entire hand at one time. For demonstration, we applied our evaluation method to a specific instrumented-glove motion capture protocol developed from the current state of the art.

Methods

We evaluated the accuracy of a motion capture protocol for the hand by comparing joint flexion angles determined using the protocol to corresponding joint angles computed from simultaneously collected CT images. The evaluation was performed in a single subject (male; 200 mm from the base of the palm to the tip of third digit; 85 mm across the palm; age 51; no history of hand impairments) in seven different static hand postures (Fig. 2). As hand motion capture protocols are typically used to examine functional tasks, the postures were designed to span functional ranges of motion for the fingers while minimizing exposure to radiation. The motion-capture protocol, we evaluated for demonstration, was an instrumented-glove protocol in which data were collected with the Cyberglove II (Cyberglove Systems LLC; San Jose, CA). The Cyberglove II is designed to be one size fits all and includes 22 proprietary, resistive, bend sensors that each output an eight bit digital signal proportional to the underlying joint angle. The signals are output at 90 Hz to capture hand motion over time. We used a GE Lightspeed 16 CT Scanner (Milwaukee, WI) with an in plane resolution of $0.3 \times 0.3 \text{ mm}^2$ and a slice thickness of 0.625 mm. The radiation dose for seven scans of the distal upper extremity is approximately 1.03 mSv, which is equivalent to the background dose due to natural radiation in a four month period. The imaging protocol was approved by the Institutional Review Board of Rhode island hospital, the site of data collection. The CT images were manually segmented using 3D Doctor Software (Lexington, MA) and further image processing and data analyses

Fig. 2 The seven postures used to evaluate the accuracy of the Cyberglove motion capture protocol

were completed using MATLAB (Natick, MA). The same CT image data were used previously in a method for calculating kinematics for the CMC joints of the fourth and fifth digits of the hand [17].

Experimental Protocol. The subject donned the glove and first completed a set of calibration tasks (described below) that were used to define the mapping from glove sensor outputs to joint angles. The subject then put his hand (wearing the glove) in the CT scanner and assumed the first hand posture. The posture was held for several minutes as the scan was completed and Cyberglove sensor output was simultaneously recorded. This was repeated until all seven postures were captured by both the glove and the scanner.

Instrumented Glove Protocol. To quantify finger and thumb joint flexion angles from the Cyberglove output, we used custom, subject-specific, sensor gains to transform sensor output from the glove to anatomical, joint-angle values. The Cyberglove sensor gains were calculated using a calibration process in which the subject completed four, distinct, calibration tasks (one for each of the four fingers). This process was adapted from an existing procedure in a study on robot telemanipulation [18]. The existing procedure was used as the basis for our approach because of its ease of implementation, as it requires no external hardware other than the glove and only several minutes for completion. Sensor output was imported to MATLAB where the calibration process was then completed. We used a custom calibration approach because it has been reported that the manufacturer’s automatic approach provides poor results [19].

In each calibration task, the glove was worn by the subject and a closed loop was made between the current finger and the thumb (Fig. 3). The two digits were then repeatedly flexed and extended for 10 s while maintaining digit tip contact. After completing the four calibration tasks, the glove output from each task was input separately into an optimization routine that used a kinematic hand model (described below) to compute a set of sensor gains for the appropriate finger and thumb. The gains were optimized such that they transformed sensor output for the calibration task to anatomical joint angles in the model that best maintained digit tip contact throughout the task. Because the thumb was involved in all four calibration tasks, four sets of thumb gains were generated by the calibration process. For each thumb joint, the median of the four possible gains was used.

The optimization routine also required explicitly recording the subject’s posture when all joint angles were zero. To do so, we recorded sensor outputs from the glove when the subject’s palm

Fig. 3 An example of a closed loop made between the current finger and thumb while the Cyberglove was calibrated to the subject

was on a flat surface and thumb was fully extended. The positions of the bones in this neutral posture were defined to correspond to their zero positions in the underlying kinematic model.

Once the sensor gains were computed, they were used to transform the glove output recorded in each of the seven postures. We computed flexion joint angles at the carpometacarpal (CMC), metacarpophalangeal (MCP), and interphalangeal (IP) joints of the thumb, as well as the MCP, proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints of all four fingers. Because it took several minutes for the CT scanner to record a posture, the Cyberglove recorded a joint angle profile for each joint over the time course of data collection for each posture. The joint angles chosen to represent a specific posture were the set of joint angles at the approximate midpoint of data collection when no fluctuations in the angle values were occurring.

Kinematic Hand Model. The kinematic hand model used in the calibration process was adapted from an existing musculoskeletal model of the upper limb [20]. The existing model includes digitized surface representations of the bones of the hand scaled to reflect the size of a 50th percentile male. In particular, the hand kinematics of the existing model were augmented to allow flexion degrees of freedom at the MCP, PIP, and DIP joints of the third, fourth, and fifth digits of the hand [11]. In addition, CMC joints were added to the fourth and fifth digits, as described previously [17]. Flexion of the CMC joint of the fifth digit was coupled to flexion of the CMC joint of the fourth digit to form one palmar degree of freedom known as the metacarpal arch [17], which is measured by the Cyberglove with only one sensor. We did not analyze CMC motion in this technical brief because CT images from the subject of this evaluation were the same data previously used to define kinematic functions for the metacarpal arch [17]. In order to visualize the kinematic model and recorded hand motions, we structured the joint axes and kinematic constraints such that the model and any recorded motions could be input into the Software for Interactive Musculoskeletal Modeling (SIMM; Musculographics, Inc.; Santa Rosa, CA).

CT Image Processing. Each of the seven CT hand-posture images was segmented in order to generate digital surface representations of all the bones in the posture. The segmentation was completed by manually selecting the pixels representing the bone surfaces in each slice of each image after initially applying global thresholding [21]. The collection of digital bone surfaces for each posture was then used to determine joint flexion angles for the

same finger and thumb joints we examined with the Cyberglove. In a specific posture at a specific joint, the joint flexion angle was defined as the roll angle of the composite, sequential, roll-pitch-yaw rotations relating the orientation of the distal bone to the orientation of the proximal bone.

The roll, pitch, and yaw rotations relating the orientations of adjacent bones were computed from the homogeneous transformation relating the three orthogonal principal axes of the distal bone to the corresponding principal axes of the proximal bone. The roll axis (i.e., the positive flexion axis) of a bone was defined by the principal axis that was oriented primarily in the ulnar to radial direction. The yaw axis corresponded to the longitudinal principal axis of the bone (positive directed distally) and the remaining axis defined pitch, with positive directed dorsally. Principal axes for the bones were calculated as orthonormal bases of the digitized, bone surfaces. This was done via singular value decomposition in MATLAB under the assumption that the vertices were evenly spaced about the bone surface. Because the roll axes were approximately aligned with the anatomical flexion axes, rotations about the pitch and yaw axes were small and ignored in this study. We have previously demonstrated that this methodology quantified angles about the roll axis with an accuracy of approximately 1 deg [17].

Joint Angle Comparison. To facilitate an exact comparison between Cyberglove and CT output, we transformed the Cyberglove angles resulting from the protocol described above into measurements that were analogous to the roll angles computed in the CT images. To do this, we used the digital bone representations in the augmented, upper-limb, kinematic model. For each of the seven postures, we input the Cyberglove angles from the protocol into the model and then calculated the composite roll-pitch-yaw angles between adjacent digitized bones. The joint flexion angles were determined from the rotations about the appropriate roll axes using the same process we developed for analyzing the CT images.

Once the Cyberglove joint angles were transformed at each joint for all seven functional postures, we calculated the absolute errors between each of these angles and the angles from the CT images. Considering the CT values as the gold standards, the errors ($\Delta\theta_{ij}$) were defined as

$$\Delta\theta_{ij} = \left| \theta_{ij}^{\text{CT}} - \theta_{ij}^{\text{G}} \right| \quad (1)$$

where θ_{ij}^{CT} is the flexion angle calculated from the CT data for the i th joint ($i = 1$ to 15) in the j th posture ($j = 1$ to 7) and θ_{ij}^{G} is the corresponding, transformed value resulting from the instrumented-glove motion-capture protocol. The accuracy and precision of the Cyberglove protocol were then quantified for each of the 15 joints evaluated as the mean and standard deviation of the errors at that specific joint across the seven postures, respectively. We then summarized the overall accuracy and precision by the mean and standard deviation of the errors across all joints and postures. To examine the agreement between the measurement methods, we also completed Bland and Altman assessments of limits of agreement comparing the Cyberglove and CT measurements [22,23]. In these assessments, the differences between pairs of corresponding Cyberglove and CT measurements were plotted versus the means of the corresponding pairs of measurements.

Results

Figure 4 shows a comparison of one of the postures simultaneously captured by the CT scanner and by the Cyberglove. The overall, gold-standard accuracy of the implemented protocol for predicting the flexion joint angles adopted by this single subject across seven static postures was 16 deg. The overall precision of the protocol was 14 deg (Table 1). The joint angles calculated for

Fig. 4 A comparison of the Cylinder grasp posture captured by the CT image (left) and the Cyberglove (right). The CT posture is shown using the digitized bone surfaces visualized in MATLAB. The Cyberglove posture is shown using our adapted hand model in the Software for Interactive Musculoskeletal Modeling (SIMM; Musculographics, Inc.; Santa Rosa, CA).

the fifth digit of the hand were the least accurate, with a mean error of 23 deg. The mean joint angle errors for the first through fourth digits were 17, 16, 12, and 12 deg, respectively. In all five digits, the most distal joint was the least accurate, with a mean error of 26 deg.

When we examined all corresponding pairs of Cyberglove and CT joint angle measurements using a Bland and Altman assessment of limits of agreement, we found a poor agreement between the two measurement methods (Fig. 5). The lower and upper limits of agreement, between which 95% of differences between measurements are expected, were -44 deg and 41 deg, respectively. Removing the measurements from the most distal joint of each digit from the analysis improved the agreement between the measurement methods considerably (Fig. 6). The lower and upper limits of agreement were improved to -19 deg and 31 deg, respectively.

Discussion

In this technical brief, we have described a method for evaluating the accuracy of a hand motion capture protocol using simultaneously collected static CT images. We applied the method to a Cyberglove II motion capture protocol and evaluated the accuracy and precision of the glove in quantifying fifteen joint angles, when a single subject adopted seven different hand postures. The data suggest that the Cyberglove sensors designed to record from the DIP joints, in particular, were highly inaccurate. This led to poor agreement between the Cyberglove and CT joint angle measurements. When DIP joint angle measurements were not considered in the analysis, the agreement between the glove and CT measurements improved but considerable differences remained. Propagation of errors from the distal Cyberglove sensors likely contributed substantially to the remaining differences.

We believe the distal sensor inaccuracy was the result of a poor fit between the glove and the subject. It appeared that the subject's fingers did not reach far enough into the tips of the glove and therefore the sensors recording the DIP joints did not bend the appropriate amount when the fingers were flexed. This likely introduced large errors into the DIP sensor outputs. Because the manufacturer states that the glove is one size fits all, poor fit is potentially a critical limitation of any Cyberglove II motion capture protocol in which recording DIP joint angles is a focus. Our results suggest that the Cyberglove II is not appropriate for this type of analysis if a subset of the subjects have smaller hands. Future studies using similar methodology could be used for the validation of an improved calibration protocol for the Cyberglove that solves this shortcoming; incorporating more subjects to achieve statistically meaningful results. Solving the distal sensor inaccuracy would likely improve the performance of the Cyberglove protocol at all joints by reducing propagation of the distal joint error.

Despite the high distal joint errors, we still believe the evaluated Cyberglove protocol can be an effective method for hand motion capture if this shortcoming is taken into consideration during data collection, analysis, and interpretation. In particular, the motion capture protocol we describe is extremely useful in that it is easy to implement, requiring minimal expertise for setup and less than 5 min for completion of all calibration tasks. For the appropriate applications, this is preferable to assembling markers for optical tracking because markers often take a substantial amount of time to setup and can become occluded during the recording of tasks [16]. Furthermore, when compared to other instrumented-glove protocols described in the literature that are calibrated with markers or goniometers, the gold-standard errors we observed for this subject are comparable to the relative errors reported by others. Specifically, an existing study compared

Table 1 The accuracy and precision of the evaluated Cyberglove motion-capture protocol in degrees. Accuracy was defined as the mean of the joint angle errors and precision was defined as the standard deviation of the errors.

Joint	First digit			Second digit			Third digit			Fourth digit			Fifth digit			Overall
	CMC	MP	IP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP	
Accuracy	6	23	22	15	10	22	4	7	24	6	6	24	19	9	39	16
Precision	5	6	19	3	7	12	2	2	13	4	4	14	8	7	21	14

Fig. 5 A plot depicting a Bland and Altman assessment of limits of agreement for all corresponding pairs of Cyberglove and CT joint angle measurements. The differences between corresponding measurements were plotted on the vertical axis and the mean of the corresponding measurements were plotted on the horizontal axis. The solid black line represents the mean difference between corresponding measurements. The dashed black lines represent the lower and upper limits of agreement between which 95% of differences between measurements are expected.

instrumented-glove output to marker output for the second and third digits and reports an overall accuracy of less than 7 deg for these digits [16]. Importantly, these authors calculated signed error values (rather than absolute values) and did not assess joint angle errors for the distal joints in the two digits they tracked with the instrumented glove. When we recalculated our results using this methodology and included only the finger joints that corresponded across studies, our overall accuracy was 2 deg. This is especially noteworthy considering that our study used CT data for comparison rather than optical tracking data.

Fig. 6 A plot depicting a Bland and Altman assessment of limits of agreement for corresponding pairs of Cyberglove and CT joint angle measurements excluding the measurements taken from the most distal joint of each digit. The differences between corresponding measurements were plotted on the vertical axis and the mean of the corresponding measurements were plotted on the horizontal axis. The solid black line represents the mean difference between corresponding measurements. The dashed black lines represent the lower and upper limits of agreement between which 95% of differences between measurements are expected.

Overall, the CT-based evaluation method we have proposed allows for clear and systematic evaluations of new and existing instrumented-glove tracking protocols. Using CT images as the gold standard, scientists will know the exact resolution of the reference method to which they are comparing. This is in contrast to protocol evaluations that compare output joint angles to values determined using goniometers or markers [4,16]. The inherent resolutions of these reference methods are unclear and dependent on operator expertise. Moreover, CT images allow comparison to the actual, biological, joint structure. This is an improvement over evaluation methods that only use reference objects with known angles as the gold standard for comparison [10]. Given that when tracking multiple degrees of freedom simultaneously, variability in accuracy will always exist [e.g., Ref. 24]; detailed knowledge of accuracy values at specific joints can improve interpretation of the data. For example, such information can be used to assign higher weights to more accurate joints when performing further analyses of motion-capture data, such as principle component analyses [e.g., Ref. 25] or residual reduction analyses [e.g., Ref. 26].

The primary limitation of our evaluation methodology is the radiation emitted by the CT scanner. This restricted the number of images we were able to take from the subject to seven and likely limits broad implementation of such studies. Another important limitation is that a typical CT scanner only allows the evaluation of a motion capture protocol in static postures. To compensate, we performed our evaluation in several static postures across the functional ranges of motion of interest. Importantly, it is not clear how accuracy and precision data from static trials apply to dynamic trials. Our method would be improved through the use of dynamic CT imaging, but this technology is not widely available and has not yet been successfully used to capture hand kinematics. A third limitation is that marker tracking protocols cannot be implemented simultaneously in a CT scanner. However, the proposed technique could still be used to assess the accuracy of such protocols by comparing very repeatable hand postures performed consecutively (i.e., data collection first with the scanner and then using markers). Finally, we ignored rotations about the pitch and yaw axes in this evaluation. Although these rotations have been reported to be much smaller than those about the roll axis by Degeorges et al. [11], this methodology could easily be expanded to include evaluations about these axes as well.

In general, we believe there is a need for more rigorous evaluation of motion-capture protocols for the hand. There has been a sharp increase in the use of hand motion-capture methodologies over the past 20 yr; however the absolute accuracies of these techniques are still unclear. Motion-capture is essential to advancing many areas of study, including motor control, rehabilitation, and ergonomics. Therefore, we advocate increased use of high-resolution imaging and tracking, such as described here, to optimize the use of this important technology to study the complex hand motions we are capable of performing.

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Nomenclature

CT = computed tomography
CMC = carpometacarpal
DIP = distal interphalangeal
IP = interphalangeal
MCP = metacarpophalangeal
PIP = proximal interphalangeal

$\Delta\theta_{ij}$ = the joint angle error at a specific joint in a specific posture
 θ_{ij}^{CT} = the joint angle of the CT image from a specific joint and posture
 θ_{ij}^{G} = the joint angle of the Cyberglove from a specific joint and posture

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