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Measurements of Wrist and Finger Postures: A Comparison of Goniometric and Motion Capture Techniques

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A marker-based kinematic hand model to quantify finger postures was developed and compared to manual goniometric measurements. The model was implemented with data collected from static postures of five subjects. The metacarpal phalangeal (MCP) and proximal interphalangeal (PIP) joints were positioned in flexion of approximately 30, 60, and 90 degrees for 5 subjects. Wrist flexion/extension and ulnar/radial deviations were also examined. The model-based angles for the MCP and PIP joints were not statistically equivalent to the goniometric measurements, with differences of −1.8 degrees and +3.5 degrees, respectively. Differences between the two measurement methods for the MCP and PIP were found to be a function of the posture (i.e., 150, 120, or 90 degree blocks) used. Wrist measurements differed by −4.0 degrees for ulnar/radial deviation and +5.2 degrees for flexion/extension. Much of the difference between the model and goniometric measurements is believed due to inaccuracies in the goniometric measurements. The proposed model is useful for future investigations of finger-intensive activities by supplying accurate and unbiased measures of joint angles.

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The objective measurement of finger and wrist postures is of great importance to clinicians when assessing the outcomes of therapeutic interventions and surgical procedures. The manual goniometer is commonly employed in current clinical practice as a means to measure joint angles (Ellis & Bruton, 2002). While manual goniometers are used in the clinic setting, 3-D motion analysis systems are increasingly being used in research as a way of quantifying joint angles, velocities, and accelerations (Kuo et al., 2002; Li & Buckle, 1999; Rash et al., 1999). In addition to being used as a research tool, it is anticipated that 3-D motion analysis systems will also have clinical implications, such as in the prescription of ergonomic equipment, the documentation of abnormal motion in many pathological conditions, and the understanding of the effect of repetitive strain injuries (Rash et al., 1999). Thus, there is a need for a reliable model to estimate clinically relevant joint kinematics from recorded marker data.

Manual goniometers have well-described reliability and validity (Clarkson, 2000). Research suggests that trained therapists generally have adequate intrarater reliability of wrist and hand postures (LaStayo & Wheeler, 1994), although wrist flexion measurements tend to be more reliable than wrist extension measurements. Studies suggest that an error range of 3–5 degrees in repeated measurements is typical between therapists (Mayerson & Milano, 1984), which is considered a reasonable level of error for clinical measurements (Nitschke et al., 1999). Manual goniometers have routinely been used to calibrate electrogoniometers (Jonsson & Johnson, 2001), another method of measuring body angles during motion.

The reliability and validity of 3-D motion analyses tracking finger postures have also been demonstrated. Comparisons of finger measurements taken using external markers, such as 3-D motion analysis, and measurements taken using internal methods, such as fluoroscopy, suggest that these external systems are accurate representations of finger motion (Kuo et al., 2002; Rash et al., 1999). However, no published studies to date have compared goniometer measures to a 3-D motion analysis system, and only limited information exists about underlying biomechanical models of the hand and fingers used to derive joint angles (Rash et al., 1999; Zecevic et al., 2000). A comprehensive model to quantify hand, finger, and wrist kinematics is lacking, although models exist for individual digits (Kuo et al., 2002; Rash et al., 1999). We could find no studies that have examined the difference between the outputs of these models and standard clinical goniometry. This comparison is necessary in order to be able to translate the measurements obtained from motion analyses to the clinical settings.

The objective of this study was to twofold: to develop a marker-based model to determine joint angle measurements using data acquired with an optical measurement system (VICON) and to examine the differences between angle measurements obtained using clinical methods (manual goniometer) and those obtained using this marker based system.

Methods

The study was approved by the University of Pittsburgh Institutional Review Board. Five healthy college students, two females and three males, ranging in age from 20 to 34 years, participated in the study after informed consent was obtained.

Equipment Description

A VICON motion capture system (Vicon Peak, Lake Forest, CA) was used to collect 3-D position data from 4-mm reflective markers. Five VICON Mcam2 cameras on tripods were set up surrounding a desk. The cameras were connected to a VICON 612 DataStation and data was collected at 60 Hz. A standard clinical 17-cm hand-held transparent plastic manual goniometer with a scale reading 0 to 180 degrees (in 2-degree increments) was used. Triangular wooden blocks with approximately 150°, 120°, and 90° internal angles were fabricated and employed as a support for the joints of interest (Figure 1).

Figure 1 — Example of the use of wooden blocks to support the hand during testing. This particular block has an internal angle of 120°, and it is being used to support an MCP posture of 60° flexion. Note that the purpose of the blocks was not to ensure a particular deviation angle (i.e., 60° flexion) but simply to make it easier for the subject to hold his or her posture during the testing period.

Procedure

Before recording the data, VICON 4-mm markers were attached with adhesive to predetermined anatomical points of the right wrist, hand, and fingers (Figure 2 and Table 1). In the first trial, the subject's right hand was placed flat on the desk with the third metacarpal aligned with the length of the forearm, and the VICON system was used to capture 10 s of 3-D data to be used as the "zero" angle for wrist-angle normalization. Then three trials of each test posture were collected using VICON and the goniometer. The postures tested were as follows: 30°, 60°, and 90° of finger MCP and PIP flexion (all except thumb); 20° of radial deviation; 20° of ulnar deviation; 30° and 60° of wrist extension; and 30° and 60° of wrist flexion. The finger flexion angles of 30°, 60°, and 90° were obtained by placing the hands on the appropriate triangular blocks of 150°, 120° and 90°, respectively. All flexion and extension angles were measured from the horizontal. The wooden block was used to support the joint of interest for all postures except ulnar/radial deviation, for which a sheet of paper with a 20° reference

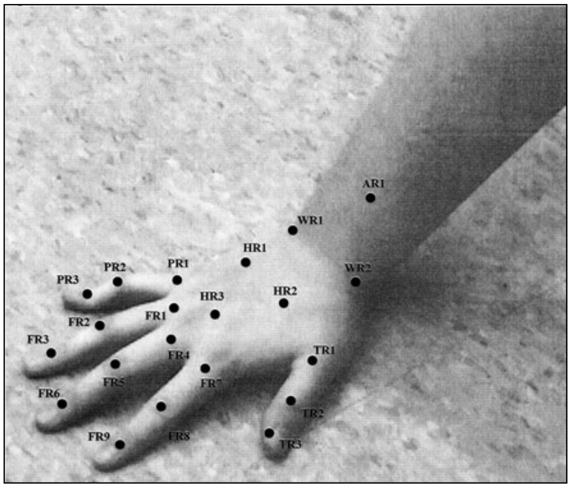

Figure 2 — Placement of markers on right hand for VICON measurements. Marker name and description of marker position are as follows: AR1—right distal forearm (between radius and ulna); WR1—right ulnar styloid; WR2—right radial styloid; HR1—right hand marker (proximal 4th MCP); HR2—right hand marker (proximal 1st MCP); HR3—right hand marker (distal 2nd MCP); PR1—right 5th digit, distal side MCP; PR2—right 5th digit, PIP joint; PR—right 5th digit, distal DIP; FR1—right 4th digit, distal side MCP; FR2—right 4th digit, PIP joint; FR3—right 4th digit, distal DIP; FR4—right 3rd digit, distal side MCP; FR5—right 3rd digit, PIP joint; FR6—right 3rd digit, distal DIP; FR7—right 2nd digit, distal side MCP; FR8—right 2nd digit, PIP joint; FR9—right 2nd digit, distal DIP; TR1—right 1st digit, medial aspect of MP; TR2—right 1st digit, medial aspect of IP; TR3—right 1st digit, medial aspect of nail.

line was used to line up the third metacarpal. The positioning blocks were used to assist the subject in maintaining his or her joints in the same position during the goniometric and VICON measurements. For each trial, subjects positioned their wrist and/or fingers on one of the positioning blocks and the joint angle was obtained with a manual goniometer. After the goniometric measurement was completed, the subject continued to hold the position and 10 s of VICON data was obtained.

The MCP and PIP goniometric measurements were obtained by placing the axis of the goniometer on the dorsal aspect of the joint (Clarkson, 2000). Wrist flexion was obtained by placing the axis of the goniometer on the dorsal aspect of the wrist over the point where the scaphoid, lunate, radius join. Wrist extension was obtained by placing the axis on the medial aspect of the hand over the ulnar styloid. Radial and ulnar deviations were measured by placing the axis on the dorsal aspect of the hand over the capitate. The subject removed and repositioned his or her hand for each joint measurement.

Table 1 Placement of VICON Markers (Right Side Only)

Marker name	Description of marker position
AR1	Right distal forearm (between radius and ulna)
WR1	Right lateral wrist (ulnar side)
WR2	Right medial wrist (radial side)
HR1	Right hand marker (proximal 4th MCP)
HR2	Right hand marker (proximal; 1st MCP)
HR3	Right hand marker (distal 2nd MCP)
PR1	Right 5th digit, distal side MCP
PR2	Right 5th digit, PIP joint
PR3	Right 5th digit, distal DIP
FR1	Right 4th digit, distal side MCP
FR2	Right 4th digit, PIP joint
FR3	Right 4th digit, distal DIP
FR4	Right 3rd digit, distal side MCP
FR5	Right 3rd digit, PIP joint
FR6	Right 3rd digit, distal DIP
FR7	Right 2nd digit, distal side MCP
FR8	Right 2nd digit, PIP joint
FR9	Right 2nd digit, distal DIP
TR1	Right 1st digit, medial aspect of MP
TR2	Right 1st digit, medial aspect of IP
TR3	Right 1st digit, medial aspect of nail

Biomechanical Model

The hand was modeled as a rigid body segment. Three markers placed on the dorsal side of the hand (HR1, HR2, HR3) defined its local reference frame as follows (see Figures 2 and 3 and Table 1 for marker definitions):

- The origin of the frame is located at the midpoint between markers HR1 and HR2.
- The first local axis, z-axis, is defined from HR2 to HR1.
- The second local axis, y-axis, is perpendicular to the plane (HR1, HR2, HR3).
- The third axis, x-axis, is formed by the cross product of the y- and z-axes.

Thus, the local sagittal and coronal planes of the hand segment are defined by the (x, y) and (x, z) axes, respectively. These planes are used as the projection planes for the finger MCP and wrist angles.

Six vectors representing the five proximal phalanges (PR1-PR2, FR1-FR2, FR4-FR5, FR7-FR8 and TR1-TR2 in Figure 2) and the forearm (AR1-midpoint of WR1 & WR2 in Figure 2) were projected onto the local sagittal plane of the hand to calculate the flexion-extension angle of the MCP joints and wrist, respectively (Φ_m in Figure 3). Similarly, these vectors were projected onto the hand's local coronal plane to calculate the abduction-adduction angle of the MCP joints and wrist.

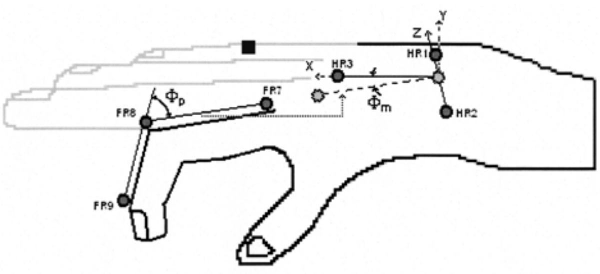

Figure 3 — Example of projection and dot product angles used by the model. The PIP angle is found using the dot product, which calculates the angle between segments FR8-FR9 and FR8-FR7 resulting in angle, Φ_p. MCP angles are found using the projection angle method, which projects segment FR8-FR7 onto the local coordinate system defined by HR1, HR2, and HR3. The flexion angle is the angle between the segment and the *z*-axis (marked as Φ_m). Similarly, the ab/adduction angle is the angle between the segment and the *x*-axis.

All finger PIP joints were assumed to be 1-*df* hinge joints, and thus they were computed using the dot product of the appropriate distal and proximal phalange vectors. For example, the dot product between vectors FR8-FR7 and FR8-FR9 was used to derive the second PIP joint angle as shown by Φ_p in Figure 3.

The subject's neutral wrist position did not necessarily correspond to a zero angle output from the model unless the output was normalized by subtracting the neutral angle. This was not necessary with the MCP and PIP angles, since the neutral angles of these joints lined up with a zero angle output from the model. Normalizing the wrist also eliminated any error caused by misplaced markers.

Data Processing and Analysis

The model was implemented in BodyBuilder (Vicon, Inc.) to calculate joint angles from the marker data. The wrist angle was normalized by subtracting the "zero" angle from the measured angle for both flexion-extension and abduction-adduction.

Within-condition differences in angle measurements between the manual goniometer and model were calculated separately for each joint/trial by subtracting the model angles from the goniometer angles (thus, positive angles indicate the goniometer angle was the larger angle and negative angles indicate that the marker-based angle was the larger angle). Mean angle differences and standard deviations were then obtained. To test the hypothesis that the goniometric and 3-D measurements were not significantly different from each other, equivalence tests were run on the data. An equivalence test contains an additional parameter, delta (δ), that defines the maximum clinical difference allowed between the two outcomes for them to be considered equivalent. The testing examines the differential between the two outcomes, and if that differential is less than δ the two outcomes are considered equivalent (Atherton Skaff & Sloan, 1998). Thus, the null hypothesis in equivalency testing is that the two sources are different when the differential exceeds the δ selected for analysis, whereas the alternative hypothesis in equivalency testing is that the two sources are equivalent when they are smaller than that δ. In this study, a p value $\leq .05$ indicates that the two measurement sources are equivalent to each other.

Any δ can be chosen, and it is frequently a percentage of one of the outcomes. For this study, a fixed δ of 5 degrees was chosen based upon the accuracy of the manual goniometer shown to be around 5 degrees (Clarkson, 2000). Equivalency testing was run on several groups of data: overall data, overall MCP, overall PIP, overall wrist, MCP 30, MCP 60, MCP 90, PIP 30, PIP 60, and PIP 90 for each finger, wrist flexion 30, wrist flexion 60, wrist extension 30, wrist extension 60, radial deviation 20, and ulnar deviation 20.

Linear regressions of groups of flexion-extension data (MCP flexion of 30°, 60°, and 90°; PIP flexion of 30°, 60°, and 90°; and wrist flexion of 30° and 60°, and extension of 30° and 60°) were calculated after trends within the groups were noted.

Results

Angles calculated from the model were generally not similar to goniometric measurements for all joints under the various conditions (Table 2). Individual joint measurements varied, sometimes in systematic ways. The two measurement systems for the MCP and PIP joints were not statistically

Table 2 Mean Angle Estimates From Model-Based and Goniometric Sources and the Average, Minimum, and Maximum Differences and *p* Value, *M (SD)*

Condition		Joint	*N*	Model		Goniometric		Mean difference		Minimum difference	Maximum difference	*p*
30° block	MCP	2nd digit	13	21.5	(7.5)	17.5	(3.4)	−4.1	(4.6)	−8.7	5.4	.34
		3rd digit	11	21.2	(8.7)	16.5	(2.8)	−4.6	(4.8)	−9.2	6.1	.44
		4th digit	14	18.7	(5.6)	17.7	(2.7)	−1.0	(3.9)	−6.9	6.4	.01
		5th digit	13	15.8	(3.1)	21.7	(6.1)	5.9	(7.8)	−5.6	16.1	.69
	PIP	2nd digit	14	24.3	(1.4)	24.0	(1.6)	−0.3	(2.8)	−5.9	4.3	<.01
		3rd digit	14	23.0	(2.5)	25.1	(2.0)	2.1	(2.5)	−0.7	4.9	<.01
		4th digit	14	22.3	(2.9)	22.1	(4.5)	−0.2	(2.9)	−4.0	6.9	<.01
		5th digit	15	21.1	(2.3)	21.5	(4.0)	0.3	(3.2)	−7.3	5.9	<.01
60° block	MCP	2nd digit	15	46.0	(6.1)	40.3	(4.2)	−5.7	(5.1)	−10.0	7.3	.64
		3rd digit	15	46.1	(6.2)	42.5	(4.7)	−3.6	(5.7)	−9.2	7.4	.26
		4th digit	15	41.5	(6.8)	41.1	(4.4)	−0.5	(6.9)	−7.0	18.3	.04
		5th digit	15	37.6	(5.3)	41.1	(7.0)	3.6	(7.7)	−5.6	18.8	.30
	PIP	2nd digit	15	42.1	(2.9)	46.1	(4.2)	4.0	(4.2)	−1.6	11.4	.27
		3rd digit	15	43.4	(4.0)	48.6	(4.9)	5.2	(3.3)	0.3	10.2	.55
		4th digit	15	42.7	(2.9)	47.6	(4.3)	4.9	(6.5)	−17.3	11.6	.48
		5th digit	15	40.3	(5.2)	44.9	(5.0)	4.6	(3.5)	0.8	8.3	.40
90° block	MCP	2nd digit	15	71.5	(5.8)	64.0	(6.5)	−7.4	(7.1)	−15.0	5.9	.87
		3rd digit	15	69.6	(7.1)	63.7	(7.9)	−5.9	(7.7)	−20.5	5.3	.63
		4th digit	16	65.4	(6.6)	59.7	(11.4)	−5.7	(8.5)	−17.5	8.7	.58
		5th digit	14	63.4	(16.9)	60.3	(15.7)	−3.2	(11.3)	−20.8	16.4	.35
	PIP	2nd digit	14	63.5	(4.7)	73.2	(3.0)	9.7	(5.5)	2.6	17.0	.99
		3rd digit	15	65.0	(3.9)	71.7	(4.1)	6.7	(3.1)	0.2	10.3	.84
		4th digit	15	61.3	(3.9)	68.6	(4.5)	7.3	(5.8)	−1.1	18.6	.91
		5th digit	12	55.8	(1.7)	64.5	(2.5)	8.8	(6.4)	−1.1	13.2	.86
20°	wrist	ulnar dev.	15	−17.4	(3.8)	−23.3	(6.8)	−5.9	(7.32)	0.2	−17.0	< 01
		radial dev.	15	17.5	(3.0)	15.5	(2.5)	−2.0	(3.74)	0.4	−10.7	<.01
30°	wrist	flexion	15	15.5	(5.4)	19.9	(6.8)	4.3	(5.97)	0.9	15.9	0.38
		extension	14	−21.5	(5.2)	−13.4	(4.0)	7.8	(3.83)	0.8	15.0	<.01
60°	wrist	flexion	13	37.9	(6.4)	38.6	(6.7)	0.3	(7.35)	1.3	−16.9	0.04

Note. Positive signs indicate either flexion or adduction of the joint; positive differences indicate that the manual goniometer angle was larger than model-based angle. The *p* values result from equivalency testing. In this case, *p* values ≥.05 support the null hypotheses that there is a difference between the two measurement sources, whereas *p* values ≤.05 support the alternative hypotheses that the two measurement sources are equivalent.

equivalent with differences of −1.8 degrees ($p = .07$) and +3.4 degrees ($p = .26$), respectively (Figure 4). Table 2 shows which measurements were statistically equivalent.

Within the finger angular measures, there was a progression of difference between the measurements as the flexion angle increased (Figure 5). For the MCP joints, the position with the greatest flexion (90° position) created a difference of 4 degrees, with the model estimating a greater angle. For the PIP joint, the position of greatest flexion showed a difference of just over 6 degrees overall, with the goniometer estimates being greater than the model.

There was a progression of difference between the measurements of wrist flexion angle (Figure 6). The goniometer measurement was increasingly

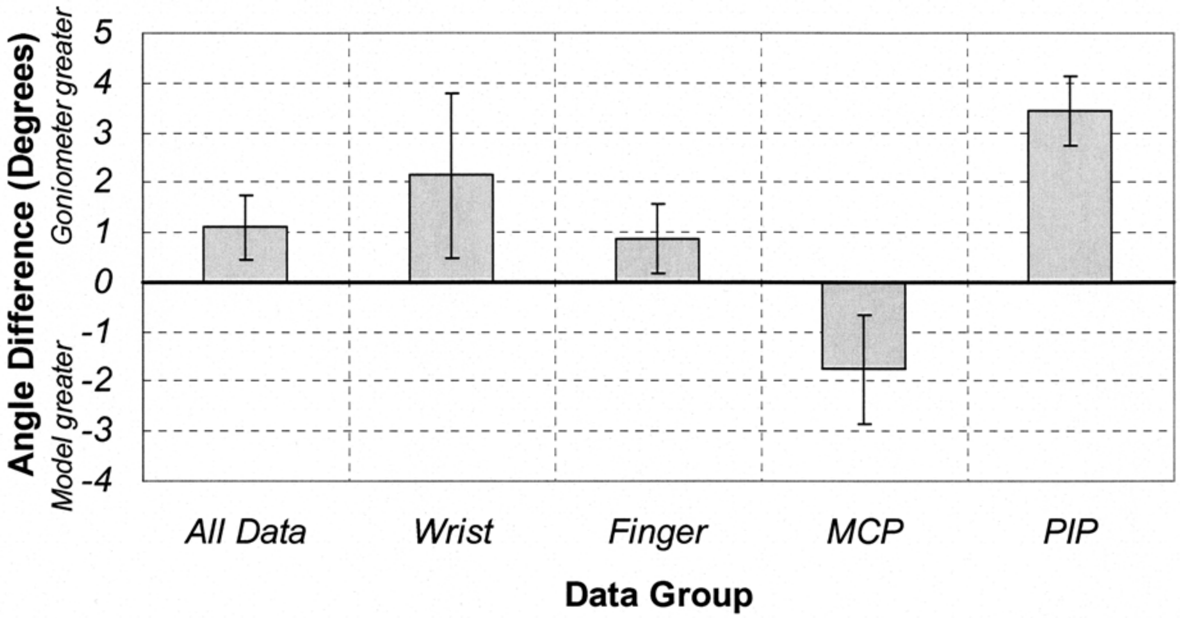

Figure 4 — Expected values of the differences between goniometric and 3-D model–based measurements of various data groups. Error bars show 95% confidence interval for the paired *t* test.

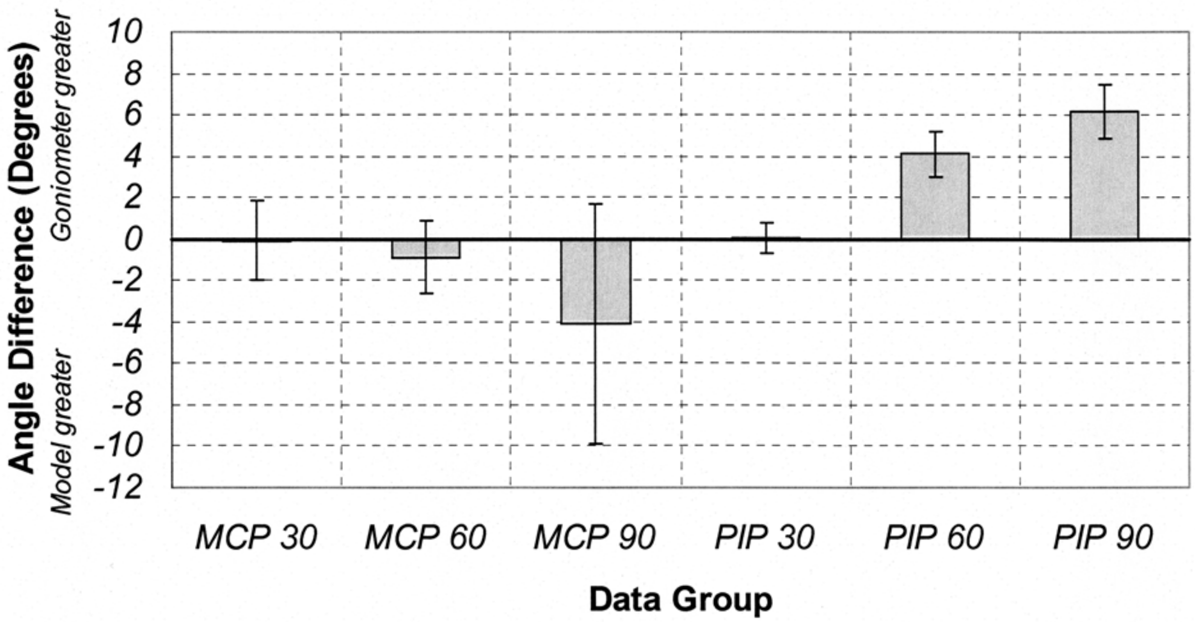

Figure 5 — Expected values of the differences between goniometric and 3-D model–based measurements of finger postures. Error bars show 95% confidence interval for the paired *t* test.

larger than the model angles with increased wrist extension. Ulnar deviation showed the goniometer measurements smaller than the model angles.

Linear regression analyses performed on the data groups (EV_{diff} vs. MCP, PIP, and wrist flexion angles) are shown in Figures 5 and 6. These regressions showed that the difference in the goniometric data and model data could be represented as a linear function of the flexion angle, with the following results:

$$\Delta = 2.35° - .07*(FA_{MCP}), \quad R^2 = .89 \quad (1)$$

$$\Delta = -2.70° + .10*(FA_{PIP}), \quad R^2 = .97 \quad (2)$$

$$\Delta = 5.19° - .07*(FA_{wrist}), \quad R^2 = .93 \quad (3)$$

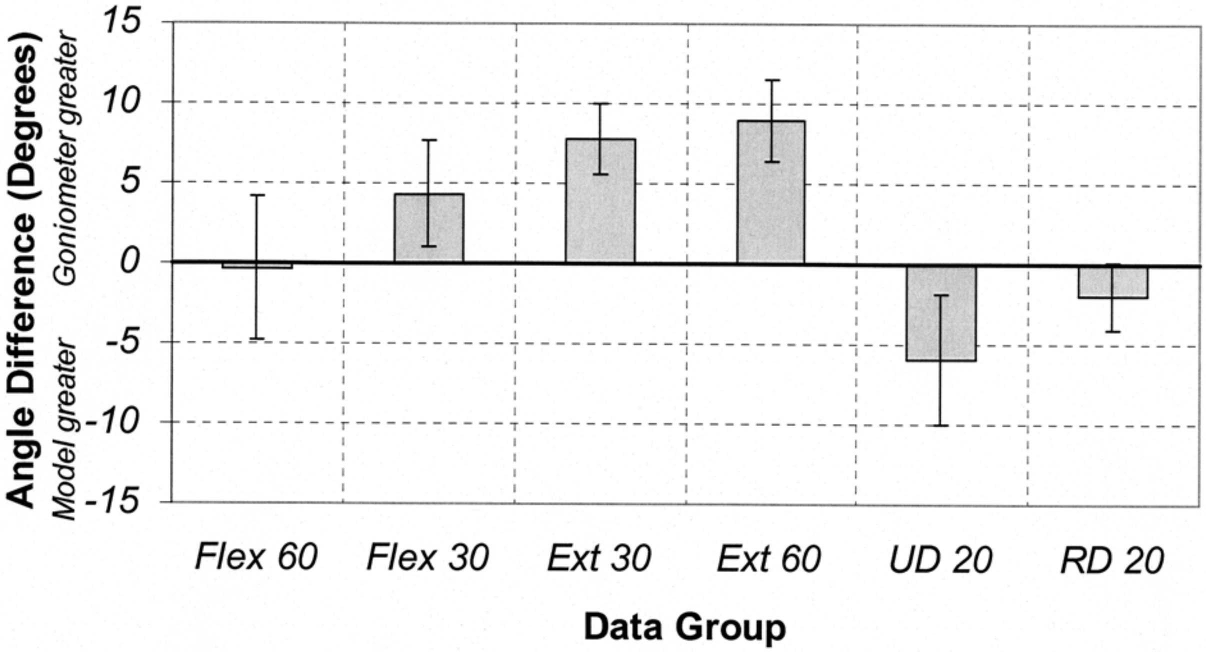

Figure 6 — Expected values of the differences between goniometric and 3-D model–based measurements of wrist postures. Error bars show 95% confidence interval for the paired *t* test.

where, Δ is the difference between goniometer and model-based measurements and FA is the flexion angle of the specified joint.

Discussion

This study presents a model used to describe angle measurements obtained through motion analysis systems and describes the differences obtained using a standard clinical measurement compared to a motion analysis system. Goniometric measurements are most often used clinically to evaluate finger/hand postures; they are difficult to use for studies of complex finger motions. Previous studies of hand use during work tasks (such as computer use) have generally used relatively bulky motion monitors, such as electronic goniometers attached to the skin or a glove, to gather kinematic data (Clarkson, 2000; Nelson et al., 2000; Simoneau et al., 1999; Sommerich et al., 1996). These goniometers are accurate, but they must be carefully calibrated for each person, can shift on the subject's hand, and are often very bulky, which undoubtedly alters the subject's normal motions while performing a task (Chaffin et al., 1999). This marker-based model can provide a basis for future use of optical motion capture systems for measuring hand motions.

In this study, although individual comparisons were not generally equivalent, the overall combined marker-based angles and the manual goniometer angles were equivalent to within the 5-degree difference that we selected as clinically relevant and that formed the basis of comparison for the equivalency test. This degree of error is less than the reported variation in intrarater measurements of goniometer measurements reported in the literature (Ellis & Bruton, 2002). This corresponded with results from Rash et al. that suggested that the tracking of joint angles in the hand using 3-D motion capture systems have excellent correspondence with tracking the same joint angles via fluoroscopic imaging (mean adjusted coefficient of multiple determination equal to 0.96, 0.98, 0.94 for MCP, PIP, and DIP joints, respectively) (Rash et al., 1999). The mean difference between the two measurements has ranged from 0 to 9.7 degrees, which is comparable to the differences in comparisons to the internal systems. The proposed marker model showed estimates of finger flexion that were on average 1.1° different from measurements obtained with manual goniometer. Although the mean differences between the goniometer measurements and the normalized marker-model estimates for individual wrist motions varied between 0.3 to 9 degrees, the combined mean differences between the wrist goniometer measurements and the normalized marker-model estimates were fairly low as well (average of 2.1°) (see Table 2). However, considerable variation occurred between the two methods of measurement for each individual finger measurement. This difference is believed to be due to variability in manual goniometric measurements of the fingers.

In evaluating both methods of joint measurement, the marker-based system is generally a more accurate method of measuring joint angles based upon the measurement error inherent in both systems. Optical systems have been shown to be accurate to less than 1 millimeter for focused hand movements. The error for the VICON system used in this study was examined by computing the error associated with relative marker location during static trials. Marker identification error (i.e., the variability in marker location during 30 s of data collection for a static marker) was found to an RMS of less than 0.1 mm and a range of 0.245 mm. Given the intermarker distances during data collection, the estimated maximum error in angle estimation using the range of VICON digitization error is 1.4 degrees, and the error associated with the RMS digitization error is less than 1 degree. Whereas the manual goniometer has been reported to be accurate to within 4–5 degrees, the percentage of exact agreement between observers is 64% (Mayerson & Milano, 1984). The variation in goniometer measurement reflects the difficulty of reading an exact angle on an instrument where two angles are separated by a space of less than a millimeter on the manual goniometer. Problems with manual goniometers are also evident for the fingers when the long axis of the segments are relatively short, resulting in difficulty in accurate placement of the device. Thus, the use of a marker-based system would be more accurate than the goniometric method. In addition, the marker-based system can look at dynamic motion, whereas the manual goniometer can examine only static motion and is usually used clinically to document the extremes of joint motion. The manual goniometer has the advantage of being quick and easy to use, requires little set up, and is very inexpensive.

In graphing the results of the differences, it was found that as the angle of the joint increased, the mean differences between the two methods of measurement also increased, and the equivalency testing indicated that these angles were not equivalent, even though the overall difference was relatively small. These increasing differences could be due to regular marker shift as the skin was stretched over the flexing joint or regular misestimates of flexion angles with the goniometer. The trends suggest that these increases can be modeled mathematically, and the high R^2 values of the regression models (Equations 1–3) support this hypothesis, as the regression fits well with the data points. However, in some cases (as with MCP and PIP) there are only three data points being fit, so tests acquiring more data points must be completed to further validate this model. If the regression models calculated are valid, then this will provide a solid transformation of goniometric measures into marker-based measures and vice versa.

The marker-based model can be used for measuring finger and wrist motions in a laboratory environment. The results suggest that the overall model estimates are similar to manual goniometer measurements, with differences under specific conditions. It is believed that the model results are more accurate than the goniometric measurements, owing to potential sources of error for the goniometer. The results suggest that there are certain biases in particular postures with the goniometers for specific finger joints. However, despite these errors, goniometric measurements still provide a powerful and reasonably accurate method to document joint angles, particularly in clinical settings. The marker-based model provides a more accurate and unbiased method to measure joint angles of the fingers in the research of finger-intensive activities such as typing or small parts manufacturing.

Studies using motion capture methods are frequently used to describe the kinematics of the body during tasks. Researchers have assumed that these methods reflect clinical measures of performance. This study provides new information on the ability to compare measures taken by clinicians using hand-held devices to measures taken using motion analysis. This study suggests that even though overall comparisons are useful, there are variants between the two measuring methods that should be considered when interpreting data from any study.

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References

Atherton Skaff, P.J., & Sloan, J.A. (1998). *Design and analysis of equivalence clinical trials*. SAS Users Group International. Retrieved September 6, 2005, from the World Wide Web: http://www2.sas.com/proceedings/sugi23/Stats/p218.pdf

Chaffin, D.B., Andersson, G.B.J., & Martin, B.J. (1999). *Occupational biomechanics* (3rd ed.). New York: John Wiley & Sons, Inc.

Clarkson, H. (2000). *Musculoskeletal assessment* (2nd ed.). Philadelphia, PA: Lippincott, Williams & Wilkins.

Ellis, B., & Bruton, A. (2002). A study to compare the reliability of composite finger flexion with goniometry for measurement of range of motion in the hand. *Clinical Rehabilitation, 16,* 562-570.

Jonsson, P., & Johnson, P.W. (2001). Comparison of measurement accuracy between two types of wrist goniometer systems. *Applied Ergonomics, 32,* 599-607.

Kuo, L.-C., Su, F.-C., Chiu, H.-Y., & Yu, C.-Y. (2002). Feasibility of using a video-based motion analysis system for measuring thumb kinematics. *Journal of Biomechanics, 35*, 1499-1506.

LaStayo, P.C., & Wheeler, D.L. (1994). Reliability of passive wrist flexion and extension goniometric measurments: A mulitcenter study. *Physcial Therapy, 74*, 162-176.

Li, G., & Buckle, P. (1999). Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. *Ergonomics, 42*, 674-695.

Mayerson, N.H., & Milano, R.A. (1984). Gonimetric measurement reliability in physical medicine. *Archives of Physical Medicine & Rehabilitation, 65,* 92-94.

Nelson, J.E., Treaster, D.E., & Marras, W.S. (2000). Finger motion, wrist motion and tendon travel as a function of keyboard angles. *Clinical Biomechanics, 15,* 489-498.

Nitschke, J.E., Nattrass, C.L., Disler, P.B., Chou, M.J., & Ooi, K.T. (1999). Reliability of the American Medical Association Guides' model for measuring spinal range of motion: Its implication for whole-person impairment rating. *Spine, 24,* 262-268.

Rash, G.S., Belliappa, P.P., Wachowiak, M.P., Somia, N.N., & Gupta, A. (1999). A demonstration of validity of 3-D video motion analysis method for measuring finger flexion and extension. *Journal of Biomechanics, 32,* 1337-1341.

Simoneau, G.G., Marklin, R.W., & Monroe, J.F. (1999). Wrist and forearm postures of users of conventional computer keyboards. *Human Factors, 41,* 413-424.

Sommerich, C.M., Marras, W.S., & Parnianpour, M. (1996). A quantitative description of typing biomechanics. *Journal of Occupational Rehabilitation, 6,* 33-55.

Zecevic, A., Miller, D.I., & Harburn, K. (2000). An evaluation of the ergonomics of three computer keyboards. *Ergonomics, 43,* 55-72.