Evaluation of the CyberGlove™ as a Whole Hand Input Device

G. Drew Kessler and Larry F. Hodges
College of Computing

Neff Walker
School of Psychology

Graphics, Visualization & Usability Center
Georgia Institute of Technology

Abstract

We present a careful evaluation of the sensor characteristics of the CyberGlove™ model CG1801 whole hand input device. In particular, we conducted an experimental study that investigated level of sensitivity of the sensors, their performance in recognizing angles, and factors that affect accuracy of recognition of flexion measurements. Among our results, we show that hand size differences between the subjects of the study did not have a statistical affect on the accuracy of the device. We also analyzed the effect of different software calibration approaches on accuracy of the sensors.

Categories and Subject Descriptors: B.4.2 [**Input/Output and Data Communications**]: Input/Output Devices; B.4.4 [**Input/Output and Data Communications**]: Performance Analysis and Design Aids; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces - *input devices and strategies*

General Terms: Experimentation, Human Factors, Measurement

Key Words and Phrases: Hand input, input devices, CyberGlove™, device evaluation

INTRODUCTION

The human hand is perhaps the most useful and diverse tool we use to interact with the environment around us. The hand is capable of both a powerful grip to push, pull, or twist objects; and a precise grip to twist and turn small objects or handles (Napier, 1980). Along with speech and facial expression, hand gestures are used as one of the primary methods of communicating with the people and things of our world. Given that our hands are such a useful tool in interacting with the real world, many claims have been made as to the value of using the hands directly in a Virtual Environment as an interface to that environment (Sturman and Zeltzer, 1994; Zimmerman, et al., 1987)

Despite these claims, the use of whole hand input has been limited in almost every published report to recognition of a few commands associated with the hand's posture[1]. Most glove and other hand posture recognition devices are used for tasks that could be accomplished as well or better (and at a fraction of the cost) with a three-button mouse used in conjunction with a 3-D tracker.

One limitation on the actual use of whole hand input is the difficulty of gesture recognition. Gesture recognition software must take into account the context of gesture, the motion of the participant's hands and arms, and hand posture. Hand posture is reported by glove devices as a series of values related to the bend in each joint of the hand. Values reported may vary based on resolution of the sensors, hand size, pressure on the sensors, human variations, and noise in the system. Before versatile and useful gesture recognition software can be written, we must have reliable data concerning the resolution, linearity, variability and reliability of the sensor information collected by the hand input device.

General issues that must be addressed include the following. If the sensors of the device report that the hand is in a particular posture, how certain can the application be that the hand is actually in that posture? Is the user's hand size a factor in the answer to that question? How much “noise” can be expected?

How many different hand postures (which the hand is actually capable of mimicking) can the device recognize? Even if the sensors do not report the hand position accurately, perhaps the sensor values could be grouped, and the groups could be ordered to reflect a practical number of positions for a particular joint (flexed, half-flexed, and extended for example).

How much can the error in recognizing joint angles be reduced simply by observing a history of sensor values? This question relates to the issue of device calibration for each individual. To recognize the set of gestures desired, do we need to train the gesture recognizer for each gesture, or can we use a much smaller number of calibrating hand positions (open and closed, for example), and become more precise as we go?

Lastly, what is the practical resolution of a joint? An application might not care what angle the joint is physically in, but would like to know how many discrete steps the sensor would traverse if the joint went from one extreme to the other (flexed to extended, for example).

In this paper we present a careful evaluation of the sensor characteristics of the CyberGlove™ model CG1801 whole hand input device. The evaluation will first present an analysis of data collected from a three-part experiment. From the data analysis we will then discuss the general issues listed above.

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[1] The bend or flexion of each of the participant's fingers relative to their hand and body.

Previous Work

Since the introduction of the terms virtual environment and virtual reality, proponents have made the point that humans interact with the real world primarily with their hands. Therefore *whole hand* input to Virtual Environments would be the most natural method to interact with the virtual world. Zimmerman, et. al. (1987), in introducing glove devices that provide a computer application with information on the user's hand posture, claimed that the gloved hand provided a more natural interface to manipulate three-dimensional objects. More recently, Sturman and Zeltzer (1994) reiterated the value of a whole hand interface to computers, claiming that the widespread availability of glove input devices has led to an “explosion” of research and development projects using hand input to a variety of applications. In actuality, there have been few reports in the literature of applications using hand input beyond trivial graphical representations of the user’s hand. Takahashi and Kishino (1992) presented a method of hand gesture recognition using various states of certain joints (bent/not bent) and hand orientation, rotation, and movement, which could recognize a limited set of the Japanese kuna manual alphabet. Hand input devices are occasionally used in Virtual Environment applications to give commands to the computer and manipulate objects in the Virtual Environment [see Weimer and Ganapathy(1989) and Codella, et. al. (1992)]. A good discussion of the use of hand gestures to interact with a Virtual Environment is given in (Sturman, et. al., 1989). Often the use of the device is limited to a small set of commands, for which the user trains the computer to recognize a hand posture and/or gesture. In (Baudel and Beaudouin-Lafon, 1993), a more extensive hand gesture recognizing system is used to allow a presenter using a VPL DataGlove to control a computer generated slide projector. In (Chapin, et. al., 1992), a system was described which uses a hand input device to drive a computer generated display of the user’s hand on a screen at the other end of a phone line. Using such a system at either end of the phone connection allowed for the use of a manual language between distant participants. In (Speeter, 1992), hand input from an EXOS dextrous hand master^{TM} controlled a robot hand some distance away from the user.

Discussion of the appropriateness of hand input for particular computer applications has been limited, as well. In his doctoral thesis, Sturman (1992) discusses the criteria one should use to decide if a given application would benefit from hand input versus more conventional mouse, joystick, or dial input devices. An experimental comparison between hand gestures (visually recognized by the experimenter) and speech input for image manipulation can be found in (Hauptmann, 1989).

A literature search produced only two descriptions of experiments which evaluated a glove device's characteristics, both involving the VPL DataGlove^{TM}. Quam, et. al. (1989) describes an experiment designed to test the accuracy, repeatability, and linearity of the VPL DataGlove^{TM} Model 2. The experiment was done in three parts and involved eight subjects. The first part consisted of placing the hand in known positions and measuring the response of the glove sensors. From the collection of positions, they obtained data for the thumb inner joint at 0 and 45 degrees, and all other joints at 0 and 90 degrees. From this data, they reported that the mean error for the thumb sensors was 11 degrees with a standard deviation of 9 degrees, and the mean error of the finger sensors was 6 degrees with a standard deviation of 3 degrees. The second part of the experiment attempted to determine the linearity of the sensors by measuring the joint angles as each finger was slowly curled from open to closed and back to open. From the plot of the sensor data they obtained, they reported the sensors to be approximately linear generally within two degrees, and no more than 5 degrees off in the worst case. The third part of their experiment involved measuring the accuracy of the Polhemus magnetic tracker attached to the glove.[2]

In their experiment, Wise, et. al. (1990) studied the repeatability of the glove's metacarpal and proximal interphalangeal sensors for all five digits using two static positions of the hand and five subjects (three male, two female). The two positions were flat on a desktop and wrapped around a mold created before hand for each subject. Two trials of 10 measurements each were performed, one where the subjects kept the glove on, and one where the subject removed the glove between measurements. They obtained an average of 5.6 degrees of error, with the female subjects having substantially worse results. The errors for the thumb sensors were not included in that number, as the molds did not adequately stabilize the thumb. Further experiments showed that increasing the force of the hand grip and side to side movement of the wrist and fingers affected the glove measurements, reducing repeatability.

METHOD

Hand Input Device

The hand input device used for this study was the CyberGlove™ model CG1801, produced by Virtual Technologies, Palo Alto, CA (CyberGlove™ User's Manual, 1992), shown in Figure 1 (also described in Kalawsky, 1993). The glove has 18 sensors placed at critical points to measure the posture of the hand. The sensors are long, thin strips sewn into the glove fabric that measure the change in resistance to an electric current as the sensor is bent. The sensor measures the angle of bending between the two ends of the strip, as two bends in opposite directions on the same sensor will cancel out. (Patent no. 5,047,952, Sept. 10, 1991.)

This study examines 15 of the sensors (Figure 2), all of which are positioned on the side of the hand opposite the palm (the dorsal side). The thumb has two sensors to measure the

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[2] The CyberGlove™ does not provide a 3D positioning mechanism for the hand as a whole. We did not use a positioning device in conjunction with the CyberGlove™ device for the study described here, therefore the use of a positioning device is not discussed.

bend of the metacarpophalangeal and interphalangeal joints (the outer two joints) and a sensor to measure the rotations of the thumb across the palm towards the pinkie finger. The remaining four fingers have two sensors to measure the bend of the metacarpophalangeal and proximal interphalangeal joints (the two joints of the finger closest to and connecting to the palm). In addition, between each finger, there is an abduction sensor which measures the spread of the fingers laterally in relation to its neighboring finger. The three sensors not considered in this study are two sensors at the wrist which measure pitch and yaw of the palm in relation to the wrist, and a sensor which measures how much the pinkie rotates across the palm toward the thumb, which is the arch of the palm near the pinkie finger when the hand is cupped.

The CyberGlove™ interface unit translates the voltage output of each sensor to a digitized output of the range 0-255. The translation is calibrated so that a “typical” hand produces a minimum output of approximately 40 and a maximum of approximately 220. These values were chosen to allow for “headroom” for a hand that flexes or extends beyond that of a “typical' hand. The offset and gain values for this translation are adjustable by software, although they were not adjusted during this study so that comparisons could be made between subjects. Software provided will convert the digital value of the joint bend provided by the interface unit into an angle value using the equation (from the User’s Manual):

$$\text{Angle} = \text{Gain} * (\text{Digital\_Value} - \text{Offset}). \qquad (1)$$

The gain and offset values can be set by the application, and they represent the slope and y-intercept of a linear equation.

For this study, the CyberGlove™ interface unit was connected to a serial port of a SGI™ graphics workstation. The device was set at 9600 baud, although it is capable of higher transmission rates. Each time the computer application sampled the device, the device returned 24 bytes of data, which included the digital value of each of the 15 sensors considered in this study.

Noise Measurement

To address the issue of device noise, we conducted a preliminary evaluation, looking at the response of the 15 sensors of the glove when the hand was held still in each of two positions: flat on the table with the fingers completely spread out, and closed in a fist so that all of the finger joints (including the thumb joints) were bent and the thumb was rotated to be across the palm. These two positions placed each joint at one of two extremes, flexed or extended. This was done with one subject. The raw digital output of each sensor was sampled 100 times over a 4 second period. We found that the maximum change in any sensor was 3 (range = 256), and the mean change over 4 seconds was 1.1. A graph of the samples taken for the four “noisiest” joints is given as Figure 3. Each jump in a line in the figure represents a change of 1 unit. From this evaluation we concluded that noise was not a significant problem for the CyberGlove™.

Subject Selection

After the noise evaluation, a three-part experiment was conducted on 16 subjects. The subjects were selected to achieve a variation of hand sizes. To do this we used the four primary measurements of hand size. The measures of hand size were: hand thickness, the maximum distance between dorsal and palmar surface of the knuckle of the middle finger where it joins the palm; hand length, the distance from the base of the thumb to the middle fingertip; hand breadth at thumb, maximum breadth across the palm from the knuckle of the thumb; and hand breadth at metacarpal, the maximum distance across the knuckles joining the palm from pinkie to index finger. Subjects were selected for inclusion in the study to produce a range (Figure 4) of each measurement of hand size that extended from the lower 5% to the 95% range for men for all measures and from the lower 5% to the 95% range for women in all measurements except hand length and hand breadth. (Hertzberg, 1972).

Experimental Design

The experiment was done in three steps, each step using a different apparatus to constrain different sensors to particular angles. For each step, the sensor was calibrated by constraining the corresponding joint to two angles, either 0 and 90 degrees for the finger bend, thumb rotation and thumb abduction; to 0 and 60 degrees for the bend of the thumb joints; or to 0 and 30 degrees for the abduction sensors between the four fingers. The 0 degree angle represents the sensor's bend with the hand is laying flat, or with the fingers against each other when measuring abduction. The values measured at these two points were used to obtain an Offset and Gain for the equation(1) to determine an angle from the digital value given by the sensor. The angles used for this study result from this calculation which was performed by the experiment software, rather than the angles given by the CyberGlove™ interface unit. Excluding the abduction sensors, which are treated as a special case by the CyberGlove™ software, these two angle measurements are calculated using the same formula and parameters, and give the same results. The CyberGlove™ software calculates the abduction angle for each finger as degrees from an axis parallel to the hand length, rather than simply the angle between adjacent fingers[3]. As the apparatus constrained the fingers to a particular angle between adjacent fingers, the simpler offset-gain equation was used instead. For all sensors, the two calibration measurements were also used to obtain the resolution (number of discrete values between degrees) of the sensor.

The first step involved two bend sensors of each finger which measure the metacarpophalangeal and proximal interphalangeal (MCP and PIP) joints for each finger except the thumb, where the sensors measure the metacarpophalangeal and interphalangeal (MCP and

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[3] The CyberGlove™ software calculates the angle from the axis parallel to the hand length as that is what is required for a graphical representation of the hand. In this case, there are 3 sensors to determine four angles. Three offset and gain values are used to determine the angle between each pair of fingers, and one gain value is used to determine the angle between the middle finger and the axis parallel to the hand length.

IP) joints. The sensors are sewn into the glove so that they lie flat on the back of the fingers (as the fingers bend forward). The sensor, therefore, measures the angle of the joint bend at the back of the finger. The sensors were constrained to 0, 30, 60, and 90 degree angles by blocks of wood with the desired angle cut out of the block, which were placed snugly on top of the joint being measured (Figure 5). The center of the block's side which fit against the glove was raised so that the abduction sensors, which stand out from the glove on either side of the knuckles, would not prevent the block from touching the joint at all points. This part of the experiment consisted of 200 trials, where each of the ten joints were constrained to one of four angles values five times. The order of trials was randomly generated.

The second step of the experiment involved measuring the abduction sensors whose value relates to the spread of adjacent fingers. The hand was placed on a wooden board with metal nails sticking out of the board to guide the spread of two fingers to achieve a particular angle (Figure 6). The subjects were told to insure that the fingers came in contact with all of the three nails adjacent to that finger, unless the finger was too short, so that the finger ran parallel to a particular line. For the abduction sensors between the four fingers, the angles 0, 10, 20, and 30 degrees were used. For the abduction sensor of the thumb, the angles 0, 30, 60, and 90 were used. This step used 80 trials, consisting of four abduction sensors placed at four different angles five times. The order of these trials was also randomly generated.

The final step of the experiment measured the rotation of the thumb across the palm towards the pinky. The sensor is sewn into the glove so that it is perpendicular to the middle finger if the finger is held pointing straight out. The subject was told to imagine a line going down the center of the middle finger and passing through the grove at the base of the hand. The subject was then told to place the hand on the block of wood so that the edge of the block coincided with that line (Figure 7). The thumb was to be pointed straight out so that it was perpendicular to the middle finger. The wood block was constructed so that, with the middle finger on the edge, the thumb could rotate a given number of degrees toward the pinky. Metal nails sticking out of the block insured that the middle finger and thumb were perpendicular for each measurement. The thumb rotation was measured for block angles of 0 (flat), 30, 60 and 90 degrees, five trials each. The order of the 20 trials was randomly generated.

ANALYSIS AND RESULTS

From our data we were able to address four broad questions specific to the performance of the CyberGlove™. These questions were: 1) what level of sensitivity can be obtained from the CyberGlove™ with no pre-test calibrations being made; 2) what is the performance of the CyberGlove™ once these simple calibrations were made; 3) what factors affect the accuracy of the flexion measurements from the CyberGlove™, and 4) what would be the best data that could be obtained with improved calibration. A series of analyses were performed on mean absolute error and hit rate to answer these questions. These analyses are presented below.

Question 1: What level of sensitivity can be obtained from the CyberGlove™ with no pre-test calibrations being made?

For each of the 15 flexion measurements, the initial test was to have a single reading made using the two extreme flexion values (either 0 and 90 or 0 and 30). The range of these values serve as a quick measure of the absolute sensitivity of the CyberGlove™ sensors for each of these measurements. The averages of these ranges over all subject are reported in Table 1. The range of values obtained from all subjects during the experiment are shown in Figure 8.

As can be seen in the table, the ranges for different joints and fingers varied considerably. One item to note is that the three abduction measures were large for the 0 to 30 degree range they represented compared to the other measures which represented a 0 to 90 degree range. In addition, the low ranges for the two flexion joints for the thumb were unexpected, and as will be shown below, this limited range resulted in lower overall accuracy in measuring flexion for these joints. Figure 8 shows that one explanation for the smaller range and poor results for the thumb's metacarpophalangeal joint (labeled "T-M" in the figure) is saturation at the higher angle values.

Question 2: What is the performance of the CyberGlove™ once these simple calibrations were made?

The means and standard deviations for absolute error were calculated for finger, joint, and measured degree. These values are presented in Table 2. In addition to the mean and standard deviations, a hit rate was calculated for each of these conditions. A hit was defined as any reported angle that was closer in value to the measured angle than the next highest angle. For example, if the measured angle was 30 degrees, any angle between 15.00 and 44.99 degrees was classified as a hit. Values above and below this cut off were classified as misses.

As can be seen in Table 2, accuracy and hit rate varied across fingers, joints, and measured angle. To determine if this variation was significantly related to these factors, a series of Chi-squared analyses were performed on hit rate. These analyses were performed for joints 1 and 2 for all five fingers, for the three abduction measures, and for the two measures of thumb rotation.

The analyses of hit rate for joints one and two revealed that there were significant differences related to finger, angle, and joint. In general, the hit rate was lower for the flexion measures for the thumb than for the other four fingers ($\chi^2 = 49.48$, 4 df., $p < .001$). The hit rate was also lower for the second joint than for the first joint ($\chi^2 = 73.29$, 1 df., $P < .001$).

Finally, hit rate was higher for the lowest three angle values (0^o = 96.6%, 30^o = 94.3%, 60^o = 90.9%) than for the highest (χ^2 = 145.88, 3 df., P < .001)value (90^o = 80.3%).

The analysis on hit rate for the three abduction values revealed that there was significantly lower hit rate (χ^2 = 145.87, 3 df., p<.001) for the three highest angle values (10^o = 88.8%, 20^o = 58%, 30^o = 86.7%) than for the lowest angle value (0^o = 97.1%). There was also a significant difference in hit rate due to which abduction joint was measured. There was a higher hit (χ^2 =20.28, 2 df., p<.001) rate for abduction 3 (mean = 89.7%) than for either abduction 1 (mean = 81.9%) or abduction 2 (mean = 76.3%).

Finally, the chi-squared analyses on the two measures of thumb rotation showed that both angle and type of rotation had significant effects on hit rate. The hit rate was higher (χ^2 = 18.26, 1df., p<.001)for spread between thumb and index finger (mean = 68.1%) than for rotation towards the palm (mean = 51.6%). Hit rate was also higher (χ^2 = 244.75, 3 df., p<.001) for angles of 0^o and 90^o (means = 85.6% and 94.3%, respectively) than for angle 30^o and 60^o (means = 30.0% and 29.4% respectively).

Question 3: <u>What factors affect the accuracy of the flexion measurements from the CyberGlove™?</u>

As the first step in determining what factors affect accuracy of angle measurements from the CyberGlove™ we performed a series of correlations between the four measures of hand size and absolute error. These correlations revealed a pattern of low correlation between hand size and absolute error. The coefficients for the hand size measurements of hand length, hand thickness, hand breadth at thumb, and hand breadth at metacarpal were -0.047, 0.021, -0.007, and -0.080, respectively. The correlations between hand length, hand breadth at metacarpal, and absolute error were significant (p<.05), but the amount of variance explained was very small. Therefore hand size does not appear to be a significant factor in causing error.

In order to investigate the possibility that hand size has a non-linear relationship to error we plotted error by the four measures of hand size and looked for curvilinear functions. Our inspections yielded no patterns so these measures were not used in further analyses.

A second area investigated as a source of error was non-linearity between the angles measured and the output of the CyberGlove™. In order to test for possible non-linearity between the signal produced from the CyberGlove™ and the actual angles that the joints were in, we performed a series of regression analyses. In these 15 analyses the actual angle value was regressed on the actual output from the CyberGlove™. The regressions all revealed significant linear relationships, with R^2 values ranging from 0.732 to 0.984. While this shows an overall good linear fit between values reported by the CyberGlove™ and actual angle, a closer inspection of the data revealed several interesting points.

First, while there was a strong linear association between angle and glove output for all 15 measures, the data for spread between thumb and index finger was better fit with a power function. None of the other output to measured angle data revealed a curvilinear pattern.

In order to investigate other possible problems with the linear relationship between glove output and measured angle, scatter diagrams were plotted for all fifteen regression equations. These plots revealed heteroscedacity for 7 of the 15 regression equations[4]. For all of these regressions, the errors around the predicted value increased with angle size. This suggests that more angle distinctions could be made at the lower angle values, while fewer distinction could be made at the larger angle values.

Question 4: Can the hit rate be improved by further calibration?

As was shown above, there was considerable bias in the means of the reported angle. A calibration procedure which took this bias into consideration could increase the hit rate. There are two ways to make this adjustment, to adjust based on group mean performance (GHR) or to base the adjustment on each individual subject's performance (IHR). The first approach would approximate adjusting hit rates based on previous information collected on the CyberGlove™, while the second approach would approximate the effectiveness of having a much larger initial calibration procedure for each subject.

In our initial procedure to determine hit rate, we used an equal split between the actual angle values. To compute GHR we use the actual means from all of the subjects for each finger joint and angle to determine the split points. For the IHR we used the mean from each subject for each finger, joint, and angle. We still used equal splits between angle values, but the size of the range between angles was based on the reported means. Then each angle measurement was re-evaluated into hits and misses according to these ranges and splits. The adjusted hit rates, GHR and IHR, as well as the initial, unadjusted hit rates (UHR) are presented in Table 3.

As is clearly shown in the table, adjusting cutoff values based on group means and individual means increased the overall hit rate of the glove data. The overall increase from UHR by adjusting with group means was 6.9%, raising the overall hit rate to 91.5%. Adjusting based on each subject's means raised the overall hit rate to 95.8% Also as can be seen, most of the improvement in hit rate performance occurred because of increased accuracy in the two measures related to the intermediate angle values for thumb spread and thumb rotation. In addition, the adjustment also increased somewhat the hit rate for the intermediate angle values for the three measures of abduction, although these hit rates were still much lower than for any other measures.

The results of adjusting hit rate based on both group and subject means suggest that the data reported from the CyberGlove™ could be greatly improved with either adjustments

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[4]. Thumb MCP, Index MCP, Middle MCP, Ring MCP, Middle PIP, Pinkie PIP, and TA

made from prior data collection or an extensive calibration procedure. As a reminder, the normal calibration procedure is to simply use two extreme values of flexion for each finger and joint to determine the linear relationship. The results from both of these adjustment techniques suggest that there would be a considerable increase in hit rate accuracy with a calibration procedure that used more than the two extreme values.

DISCUSSION

We now relate our specific results back to the general issues introduced in the INTRODUCTION. The first issue was with how well the device represented the user's hand to the computer application. There are two sub-issues involved in the answer to this question: noise and repeatability. Noise in the CyberGlove™ was not a significant factor in determining hand posture (Table 1 shows that this would be less than plus or minus one degree in most cases). The other sub-issue involved the repeatability of a particular joint angle bend (independent of the user's ability to repeat a joint angle bend). The “Mean Error” and “Standard Deviation Error” values in Table 2 demonstrate that the repeatability of the device is dependent on both the joint being measured and the angle being measured. Scatter plots of the data values measured and the statistical analysis demonstrate that the sensors have a linear response in most cases. In addition, the analysis indicates that the size of the user's hand does not affect the angle calculated from the two calibration points.

Besides the index, middle, ring, and pinkie sensors at low angles (finger extended), there were notable oddities in the data we collected. In particular, the joints associated with the saddle joint of the thumb (the abduction between the thumb and the index, and the rotation of the thumb towards the palm) gave poor results. The range of digital values obtained from the CyberGlove™ interface unit for the thumb's abduction sensor over the experiment shown in Figure 8 provides an explanation for the poor results obtained for that sensor. The sensor’s range (labeled “T-A” in the figure) shows that the values provided saturated at the high values (low angles), which would suggest that the calibration extrema used were invalid, and would explain the non-linearity observed in the sensor’s response. Poor results from the rotation sensor could be attributed to the difficultly in calibrating it correctly, as the device's user manual points out that the axis of rotation of the saddle joint may vary as a function of rotation angle. The axis chosen for this experiment was perpendicular to the sensor used to measure the rotation, running across the middle of the palm length wise. This axis was chosen mainly to allow for a constraint block to be used.

Having observed the higher resolution of the abduction sensors between the index, middle, ring, and pinkie fingers, we had hoped to obtain a better response from them. We discovered, however, that the response in degrees was similar to the other joints.

Our second general issue involved hand posture recognition. If there is no guarantee that a joint can repeat a particular angle, how much error should be allowed? To address this problem, we divided each range of angle measures into four divisions, centered at the expected angle, and calculated the "hit rate", or the percentage of measured angles in the expected angle range. The increased standard deviation error for higher angles produced a smaller hit rate. This suggests that equal divisions do not make most efficient use of the device's response. Using smaller divisions for smaller angles, and larger divisions for larger angles might lessen the errors in the hit rate. This method would also match well to how we use our hands, as precise finger motions (small angles) tend to be done with the fingers mostly extended, while more crude (but more powerful) finger motions (large angles) are done with the fingers mostly flexed.[5]

The real resolution of the abduction sensors between the index and pinkie fingers produced poor hit rates for the middle angle measurements (10 and 20 degrees). To improve the response, we used two divisions (greater or less than 15 degrees), and achieved an almost perfect hit rate. Once again, this matches how we usually use our hands, where we are usually only concerned with fingers being spread out, or adjacent.

A third general concern was whether we could get better results if we invested a large amount of time calibrating the device to a particular user, or used a history of use over time for a particular user. To address this question, we assumed that we had collected the 300 measurements for each person already, and created four divisions using the means of the actual measurements (rather than the expected value). Using these adjusted divisions, we obtained a better hit rate and the response for the thumb abduction was greatly improved, but the problems with the abduction for the other fingers, and the decaying hit rate with the increase of the angle used, remained.

As can be seen in Figure 8, the resolution in degrees of the sensors could be increased by changing the offset and gain values the CyberGlove™ unit uses to translate the analog voltage output to the digital value used in equation (1). In particular, the values should be changed for the thumb's metacarpophalangeal ("T-M") sensor, the abduction sensor between the thumb and the index finger ("T-A"), and the abduction sensor between the index and middle fingers ("IM-A") to avoid saturation at the extremes. Besides those sensors, however, changes in resolution of the sensors would not result in a significant improvement of the hit rates we obtained, as the change in the angle calculated for the sensor would be small (as much as 0.167 degrees for a 33.3% increase in resolution) compared to the errors shown in Table 2.

Using the data we obtained for four divisions over the range of 0 to 90, or 0 to 30 degrees, we were able to make a conjecture as to the average hit rate for a larger number of divisions by calculating the hit rate of the 0 degree section for smaller divisions of the range. For four divisions of a 90 degree range, any measurement (for a 0 degree trial) that fell within -15.00 to 14.99 was considered a "hit". For 9 divisions, any measurement that

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[5] The classification of "precision grips" and "power grips" was first done by Napier, and has since been extended. Interested readers are referred to (Mackenzie and Iberall, 1994), pp. 22- 30.

fell within -10.00 to 9.99 would be considered a “hit”. Since the hit rate for 0 degree trials tended to be higher than the trials at other angles, the hit rate calculated for different numbers of divisions could be considered a bast case. We calculated the average hit rate for the MCP and PIP joints of the index, middle, ring and pinkie fingers, the average hit rate for the abduction sensors between the index and pinkie fingers, and the average hit rate for the thumb sensors. The predicted accuracy versus number of angles recognized (which is the number of divisions in the range) are presented in Figure 9 for unadjusted hit rates and Figure 10 for individual adjusted hit rates. As can be seen in the figures, expected hit rate drops quickly as the number of angles to be recognized increases.

FUTURE WORK

In future work we plan to apply what we have learned about the glove's characteristics to the problem of posture recognition. Our current plan is to use a probabilistic approach in which each joint will contribute a probability as to whether the hand is in a particular posture. The probabilities will be multiplied together to obtain an overall probability. The defined posture with the largest probability over a specified threshold is the one recognized by the algorithm. Note that if a joint says “zero probability”, there is no need to determine the probabilities of any other joints, as the overall probability will be zero regardless.

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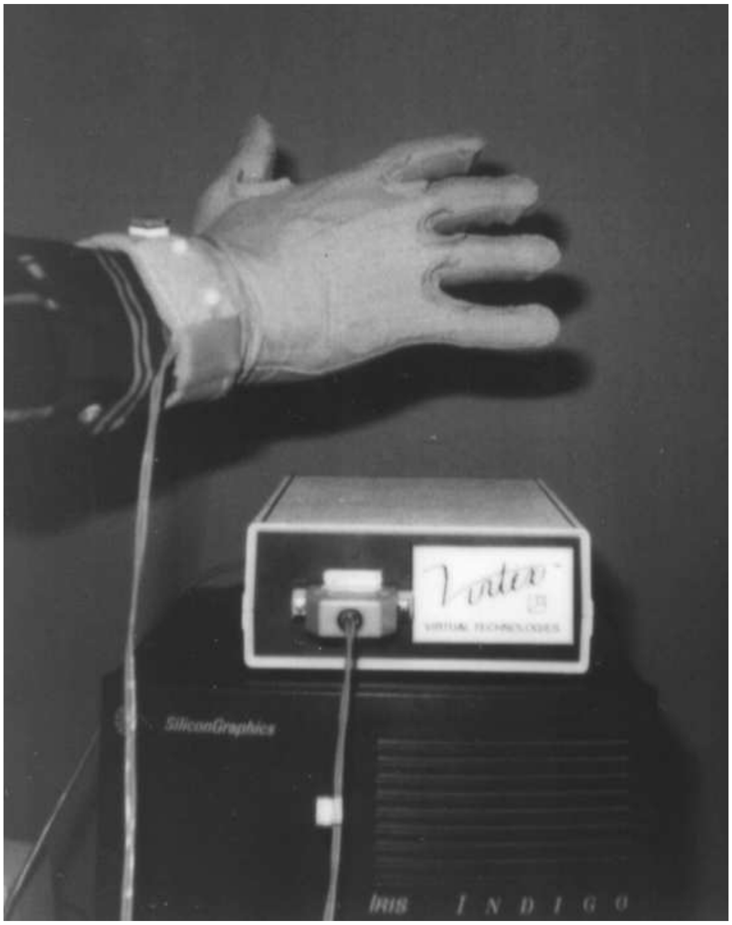

Figure 1: Virtual Technologies CyberGlove^{TM}

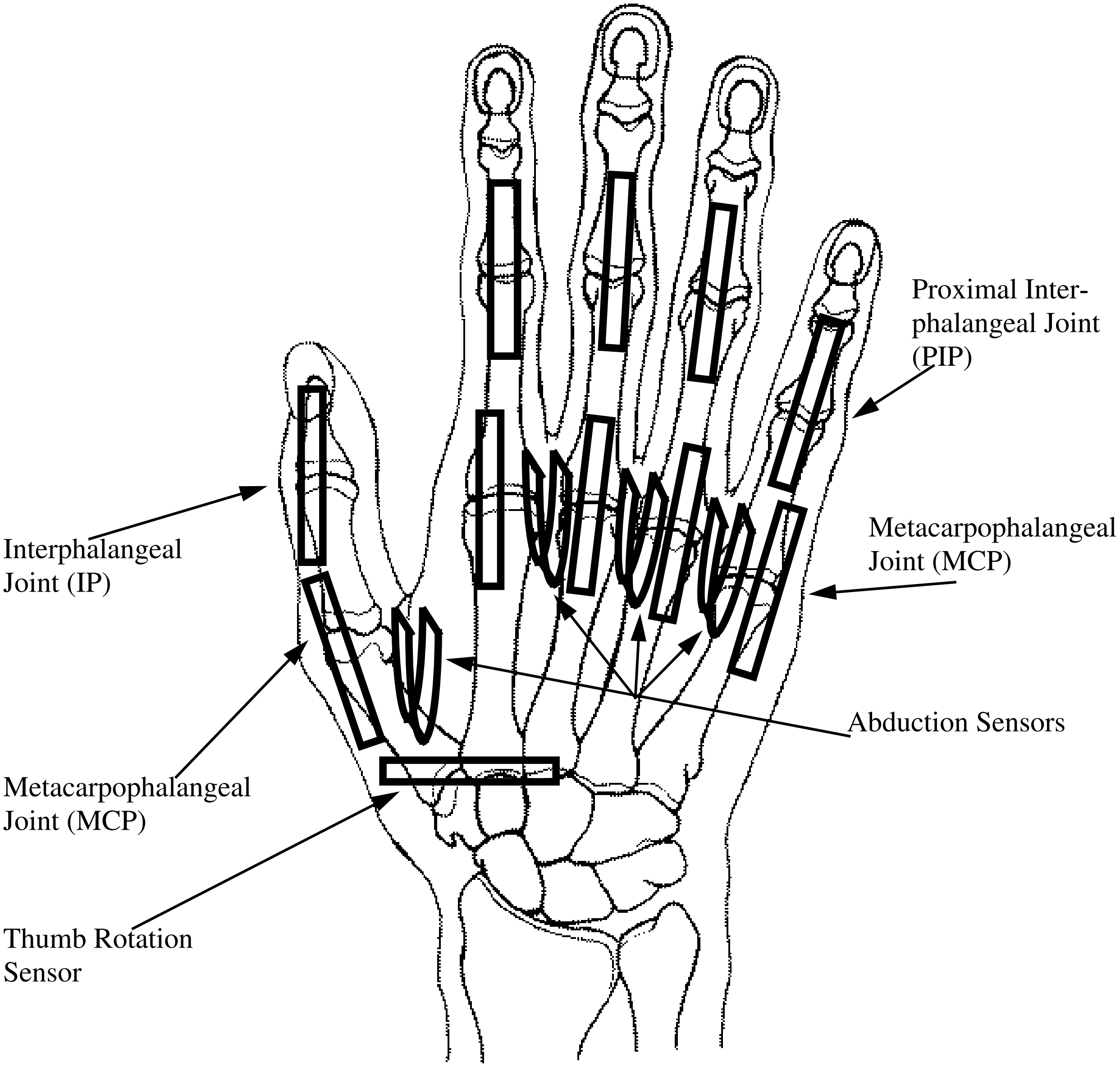

Figure 2: Sensors and Joints

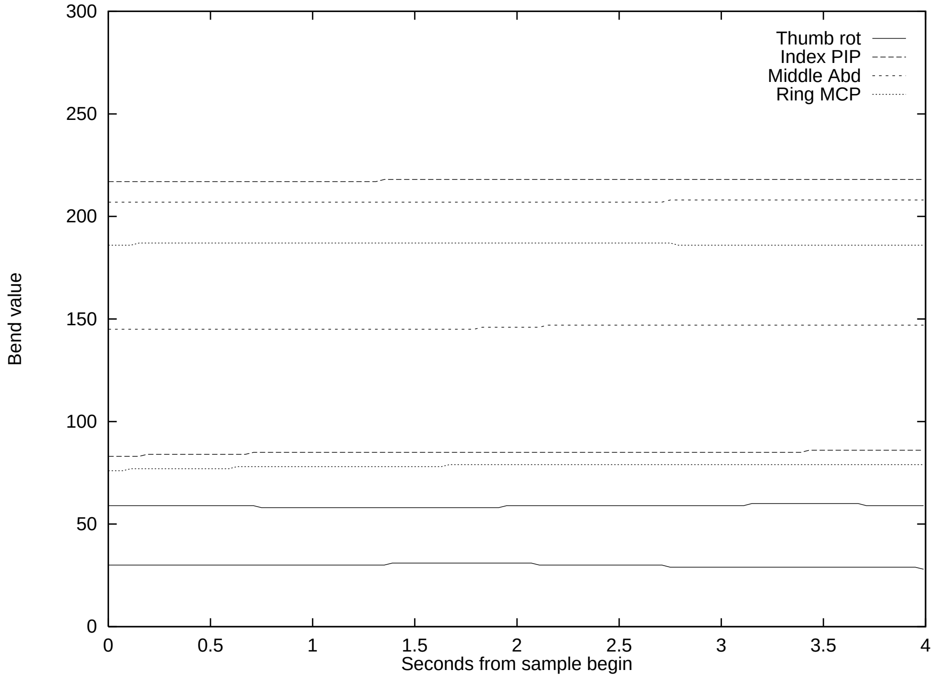

Figure 3: Response of Noisiest Sensors for Hand Held Still at Two Poses

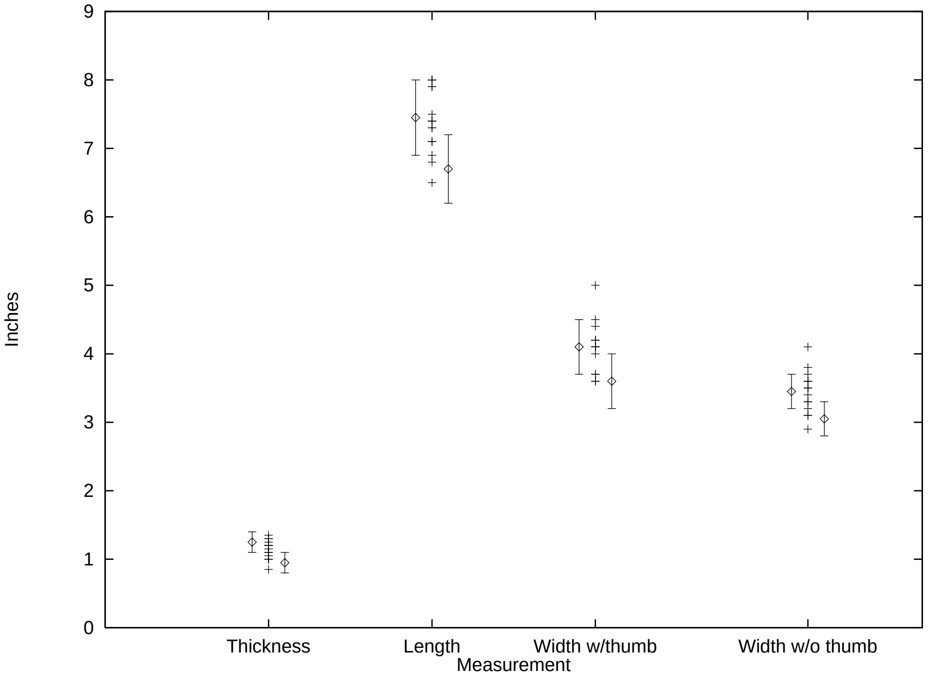

Figure 4: Hand measurements plot for the four measurements taken of the subject's hand. The bar to the left of the measurements represent the 5th to 95th percentiles of the male population. The bar to the right of the measurements represent the 5th to 95th percentiles of the female population.

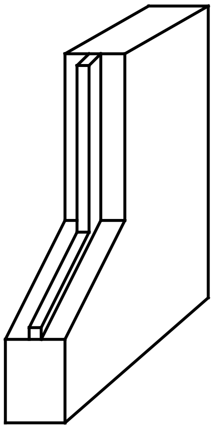

Figure 5: Finger Bend Constraint

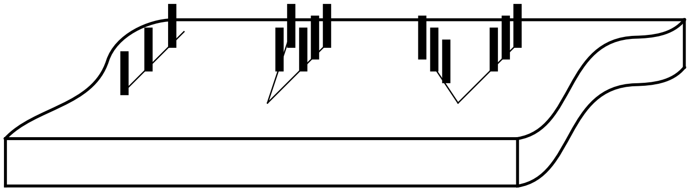

Figure 6: Finger Abduction Constraint

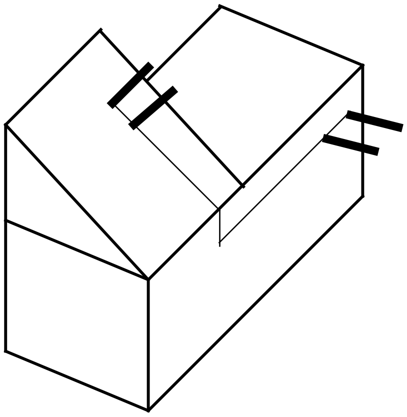

Figure 7: Thumb Rotation Constraint

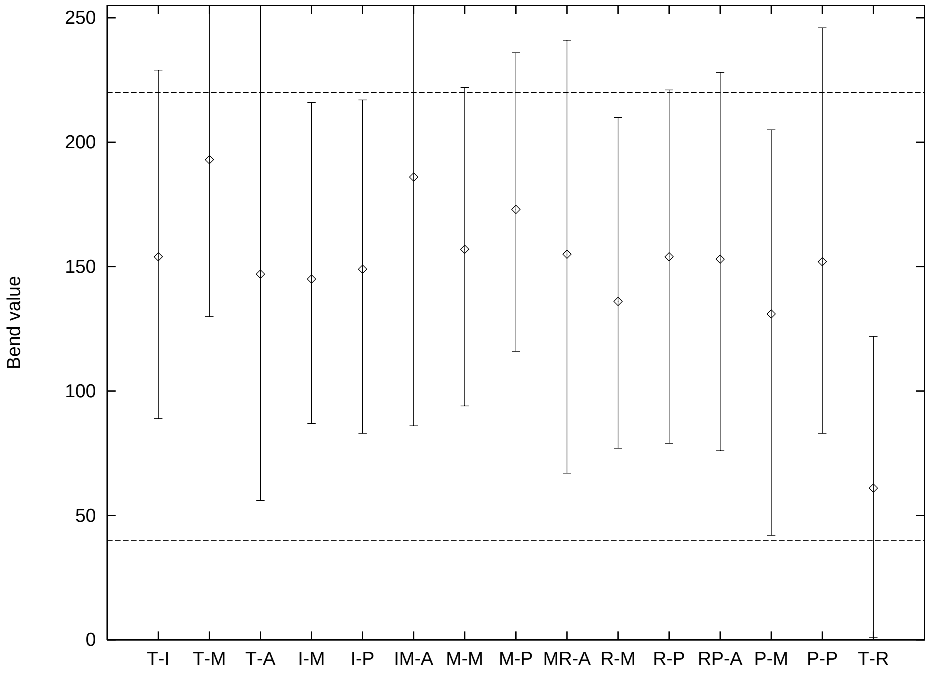

Figure 8: Response range of the CyberGlove^{TM} sensors over all of the trials of the experiment. The sensors are indicated by a 'finger-joint' classification. The fingers are: the thumb ('T'), index ('I'), middle ('M'), ring ('R'), and pinky ('P'). The joints are: interphalangeal ('I'), metacorpophalangeal ('M'), abduction ('A'), proximal interphalangeal ('P'), and rotation ('R'). 'IM-A' indicates the abduction between the index and middle fingers. Note that for all sensors except the abduction sensors, high values represent flexed joints and low values represent extended joints. High values for the abduction sensors represent larger spread angles between fingers.

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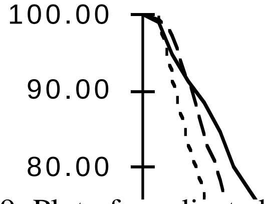

Figure 9: Plot of unadjusted hit rate versus number of angles recognized for the MCP and PIP joints of the index, middle, ring and pinkie fingers; the abduction sensors between the index and pinkie fingers; and the thumb sensors.

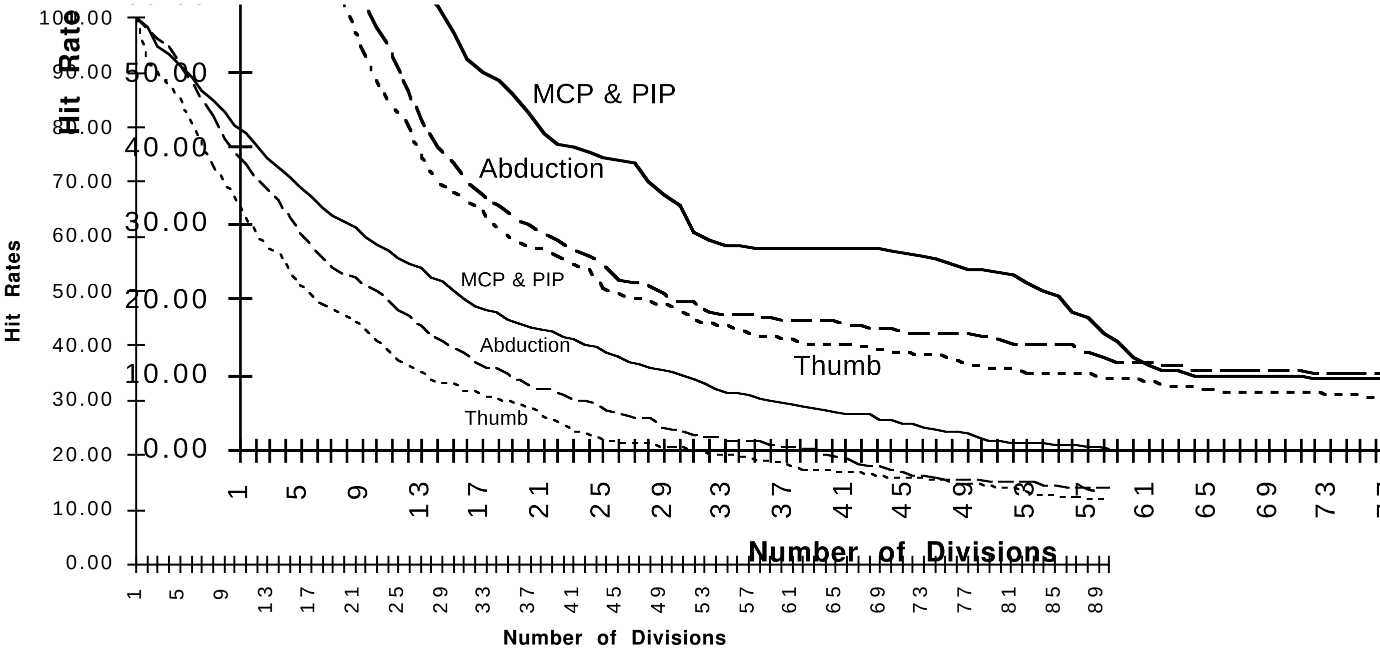

Figure 10: Plot of adjusted hit rate versus number of angles recognized for the MCP and PIP joints of the index, middle, ring and pinkie fingers; the abduction sensors between the index and pinkie fingers; and the thumb sensors.

Table 1: Mean range for each finger and joint combination at the largest and smallest angle values.

Finger	Joint	Range
Index	MCP	99.5
Index	PIP	118.2
Middle	MCP	97.9
Middle	PIP	96.8
Ring	MCP	102.8
Ring	PIP	109.4
Pinkie	MCP	104.6
Pinkie	PIP	117.1
Thumb	MCP	72.4
Thumb	IP	64.9
Thumb	TA	136.7
Thumb	TP	70.2
Abduction 1		122.2
Abduction 2		126.3
Abduction 3		101.2

MCP = metacorpophalangeal joint
PIP = proximal interphalangeal joint
IP = interphallangeal joint
TA = abduction between thumb and index
TP = rotation of thumb towards the palm
Abd 1 = abduction between pinkie and ring
Abd 2 = abduction between ring and middle
Abd 3 = abduction between middle and index.

Table 2: Mean and standard deviation of error and hit rate broken down by finger, joint and angle.

		ANGLE											
		0			30			60			90		
Finger	Joint	Mean Error	s.d. Error	Hit Rate	Mean Error	s.d. Error	Hit Rate	Mean Error	s.d. Error	Hit Rate	Mean Error	s.d. Error	Hit Rate
Index	MCP	3.59	(22.10)	88.7	0.81	(8.65)	92.5	5.51	(11.96)	92.5	2.82	(13.88)	76.3
Index	PIP	1.43	(2.79)	98.7	0.49	(1.97)	100.0	1.55	(2.54)	100.0	-0.13	(4.87)	100.0
Middle	MCP	-4.03	(9.56)	88.7	-3.55	(5.71)	93.7	0.27	(6.70)	96.2	-1.28	(12.20)	83.7
Middle	PIP	1.11	(5.07)	98.7	2.73	(6.69)	93.7	5.27	(12.96)	86.3	1.06	(10.83)	88.7
Ring	MCP	0.48	(4.09)	100.0	-0.79	(9.44)	85.0	5.03	(11.75)	80.0	5.80	(12.33)	77.5
Ring	PIP	1.31	(2.62)	100.0	2.28	(5.04)	98.7	2.42	(6.73)	86.3	0.40	(7.73)	90.0
Pinkie	MCP	1.61	(5.73)	98.7	0.31	(7.95)	93.7	4.46	(13.21)	87.5	3.33	(10.36)	87.5
Pinkie	PIP	2.16	(13.77)	97.5	-0.83	(4.22)	98.7	1.55	(9.07)	95.0	1.36	(14.77)	88.7
Thumb	MCP	2.41	(6.07)	96.2	7.15	(8.54)	86.2	4.65	(8.36)	83.7	-19.53	(11.08)	32.5
Thumb	IP	0.76	(5.18)	98.7	1.79	(3.94)	98.7	3.08	(6.43)	95.0	-2.61	(13.15)	77.5
Thumb	TA	2.78	(9.86)	88.7	23.13	(6.70)	10.0	21.32	(4.59)	7.5	0.80	(4.11)	100.0
Thumb	TP	5.83	(11.05)	82.5	11.69	(12.44)	50.0	10.73	(14.80)	51.2	-2.47	(12.18	88.7

		ANGLE											
		0			10			20			30		
Abduction 1		0.70	(1.45)	100.0	1.45	(2.55)	90.0	2.04	(6.11)	58.7	0.45	(3.83)	78.7
Abduction 2		0.64	(1.95)	100.0	3.11	(3.06)	77.5	5.53	(4.90)	41.2	1.26	(4.54)	86.2
Abduction 3		-0.31	(3.20)	91.2	1.50	(1.96)	98.7	2.67	(3.56)	73.7	-0.15	(3.75)	95.0

MCP = metacorpophalangeal joint, PIP = proximal interphalangeal joint, IP = interphallangeal joint, TA = abduction between thumb and index, TP = rotation of thumb towards the palm, Abd 1 = abduction between pinkie and ring, Abd 2 = abduction between ring and middle, Abd 3 = abduction between middle and index.

Table 3: Adjusted hit rate when calculated using subject mean (IHR), group mean (GHR), and unadjusted hit rate (UHR) for finger, joint and angle.

		ANGLE											
		0			30			60			90		
Finger	Joint	IHR	GHR	(UHR)	IHR	GHR	(UHR)	IHR	GHR	(UHR)	IHR	AHR	(UHR)
Index	MCP	93.7	93.7	(88.7)	98.7	92.5	(92.5)	96.2	92.5	(92.5)	97.5	90.0	(76.3)
Index	PIP	98.7	98.7	(98.7)	100.0	100.0	(100)	100.0	100.0	(100)	100.0	97.5	(100)
Middle	MCP	100.0	98.7	(88.7)	100.0	98.7	(100)	98.7	97.5	(96.2)	95.0	90.0	(83.7)
Middle	PIP	98.7	98.7	(98.7)	100.0	95.0	(93.7)	96.2	87.5	(86.3)	93.7	93.8	(88.7)
Ring	MCP	100	100.0	(100)	96.2	85.0	(85.0)	100.0	86.3	(80.0)	95.0	96.3	(77.5)
Ring	PIP	100	100.0	(100)	100.0	98.7	(98.7)	98.7	95.0	(86.3)	100.0	93.7	(90.0)
Pinkie	MCP	100	100	(98.7)	97.5	93.7	(93.7)	96.2	87.5	(87.5)	95.0	96.3	(87.5)
Pinkie	PIP	97.5	97.5	(97.5)	100.0	98.7	(98.7)	98.7	95.0	(95.0)	95.0	95.0	(88.7)
Thumb	MCP	100.0	100.0	(96.2)	95.0	95.0	(86.2)	63.7	72.5	(83.7)	66.6	56.3	(32.5)
Thumb	IP	100.0	100.0	(98.7)	100.0	100.0	(98.7)	100.0	93.7	(95.0)	98.7	83.8	(77.5)
Thumb	TA	98.7	98.7	(88.7)	100.0	100.0	(10.0)	98.7	82.5	(07.5)	93.7	90.0	(100)
Thumb	TP	97.5	92.5	(82.5)	92.5	78.8	(50.0)	71.2	61.3	(51.2)	87.5	86.3	(88.7)

	ANGLE											
	0			10			20			30		
Abduction 1	100.0	100.0	(100)	98.2	96.3	(90.0)	86.2	56.3	(58.7)	96.2	86.3	(78.7)
Abduction 2	100.0	100.0	(100)	98.7	98.7	(77.5)	86.2	66.3	(41.2)	95.0	75.0	(86.2)
Abduction 3	97.5	97.5	(91.2)	100.0	98.7	(98.7)	92.5	87.5	(73.7)	97.5	91.3	(95.0)

MCP = metacorpophalangeal joint, PIP = proximal interphalangeal joint, IP = interphallangeal joint, TA = abduction between thumb and index, TP = rotation of thumb towards the palm, Abd 1 = abduction between pinkie and ring, Abd 2 = abduction between ring and middle, Abd 3 = abduction between middle and index.