

Evaluation of a fiber optic glove for semi-automated goniometric measurements

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Abstract—Normal subjects were used to evaluate a fiber optic instrumented glove for semi-automated goniometric measurement. The glove electronically records and transmits hand and finger position to a host computer by measuring the amount of joint flexion. The glove was put through a series of range-of-motion (ROM) tests with five subjects. Metacarpal (MP) and proximal interphalangeal (PIP) joint angles of the five digits were compared during repetitive standardized motions to evaluate the glove's repeatability. The results showed an overall error of 5.6 degrees, as compared to an error of between 5 and 8 degrees with manual measurement. Additional tests were done to determine factors such as fit, grip force, and wrist motion that may contribute to the overall error. The glove should have applicability to some aspects of hand evaluation as a semi-automated goniometric measurement device.

Key words: *computers, DataGlove™, fiber optic glove, goniometric measurements, hand evaluation, range of motion.*

INTRODUCTION

Present methods for evaluating hand function are time-consuming and have limited accuracy (3). This presents a burden to both physician and therapist and takes time away from patient care. The measurement and recording of hand range of motion can take as long as 30 minutes, even when done by a trained therapist. A semi-automated computer based method for taking these measurements would demand less time and allow therapists more time

to work with the patients, while still achieving improved consistency and accuracy.

The DataGlove™ was developed by Visual Programming Languages, Inc., Redwood, CA (VPL) (4). The glove was used as a 6 degree-of-freedom interface device within a three-dimensional computer generated environment. Although the glove was used primarily as a gesture recognition device, it also has application as a goniometric device for hand evaluation.

Implementation of semi-automated goniometry will lessen intertester error by establishing an objective, standardized procedure for measurement of hand function and eliminate the subjective interpretation or influence by the tester (2). Previous tests of the DataGlove™ over the active range of motion of a single joint found it to be faster and more accurate than manual methods (4,13). The purpose of this study was to test for repeatability of multiple joints and to show whether or not the DataGlove™ could be used as a semi-automated goniometric measuring device for hand range-of-motion (ROM) evaluation.

MATERIALS AND METHODS

Glove description

The DataGlove™ is a fiber optic instrumented elastic fabric glove (**Figure 1**) designed to reproduce on a computer screen, the movements of a user's hand (8). The glove tracks movement of the skin surface, subject to local sliding where stretching of the fabric occurs; this is most apparent in finger abduction and adduction, which was controlled during these experiments by an external molded

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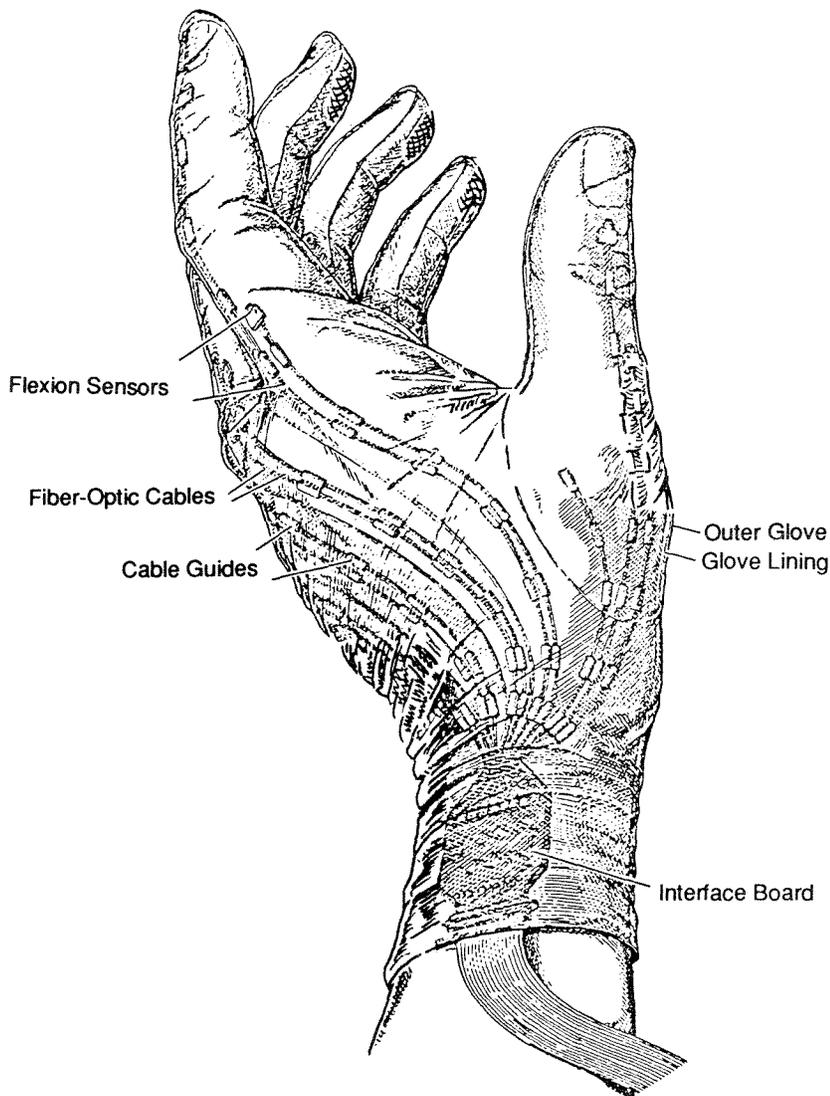


Figure 1.

DataGlove™ showing outer glove and glove lining with interposed flex sensors, fiber optic cables, and cable guides attached to interface board. Calibration is performed with the fingers in a single plane (zero angle), then with the MCP joints at 90 degrees, and finally with both MCP and PIP joints at 90 degrees. (Redrawn with permission from *Scientific American*, October 1987.)

restraint. The cotton/synthetic fabric does not appreciably impede motion in flexion-extension. The glove easily fits over a normal hand, but may not fit a hand having external fixators or severe contractures.

Sensing bending of the fingers is accomplished using loops of specially-treated optical fibers attached to the dorsal side of the fingers at the metacarpophalangeal (MP) and the proximal interphalangeal (PIP) joints of the fingers, and the interphalangeal (IP) and MP joint of the thumb. This version of the DataGlove™ does not record abduction, adduction nor does it characterize the thumb's carpo-metacarpal (CMC) or finger distal interphalangeal (DIP) joints. All the fiber optic loops originate and terminate in an optical adapter which plugs into the DataGlove™ control unit. The optical fibers from the hand to the adapter are loosely bundled and do not impede motion during the

relatively static activities tested here. The optical adapter contains the light-emitting diode (LED) sources that drive the fibers, phototransistor receivers, and analog amplifiers. Analog to digital (A/D) conversion of the signal and brightness adjustments are performed by the glove control unit.

The fiber optic bend sensors attenuate transmission through the fiber according to the angle of flexion experienced by the fiber in the treated region over the joint. The greater the angle of bend, the greater the loss of light. The sensors have a specified angular resolution of 1 degree. The specified static accuracy of the angular measurements is 5 degrees (14).

System description

The DataGlove™ control unit provides an intelligent interface to the host computer, in this case, a Macintosh

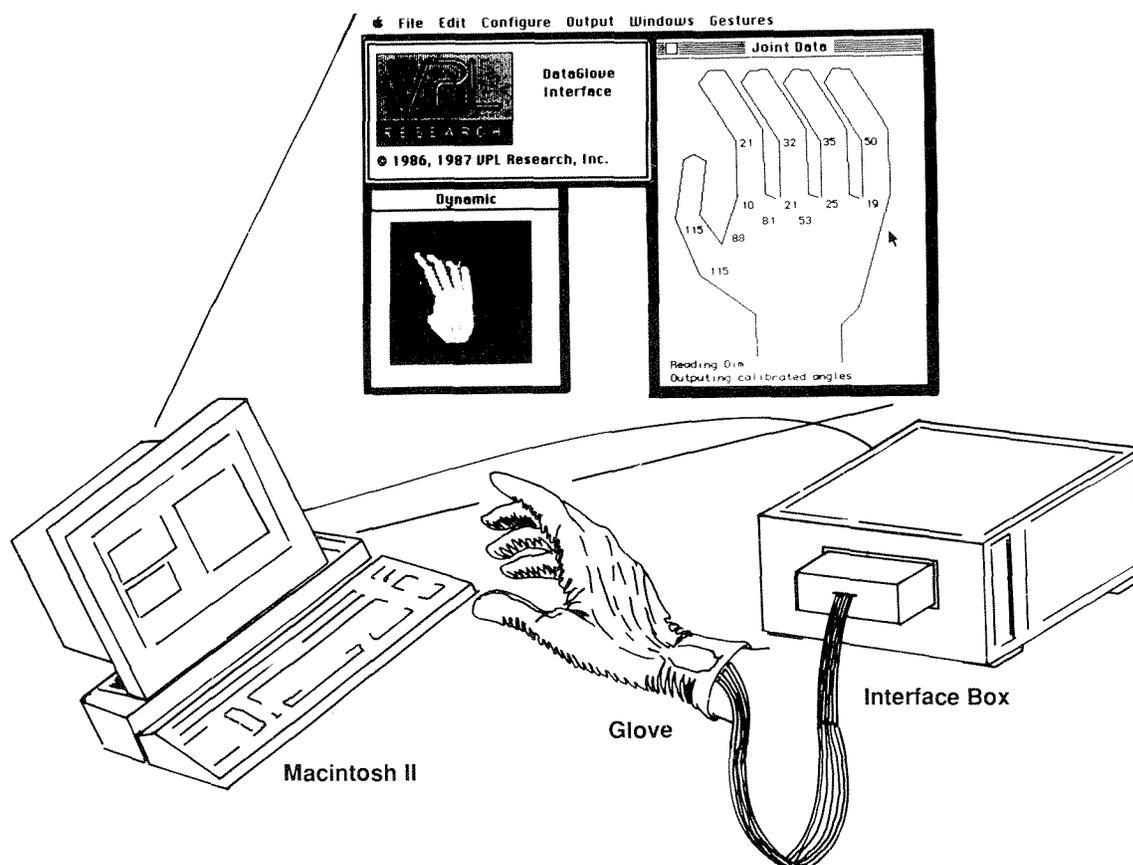


Figure 2.

System drawing showing the glove connected to interface box whose output is directed to the Macintosh II host computer. Also shown is the display of the computer graphics output as both dynamic and as numeric joint data.

II (Figure 2). It is capable of reading all the joint angles at a frame rate of 60 Hz, and can communicate with any host computer via an RS-232C serial interface at speeds up to 19,200 baud (15). Two programs are essential: 1) the Glove Interface program which displays an animated hand that mirrors the movements of the user's hand along with the numeric values of all the joint angles and creates a calibration file; and, 2) the data acquisition program, a modified version of the test software normally supplied with the system, a 26-command program that allows the user to choose the format of the results and collect the data desired into a computer spreadsheet for subsequent examination and analysis (15).

Special materials

Custom form-fitting molds of each subject's hand were constructed to assist the subject by providing a guideline

to place his hand in precisely the same position each time (Figure 3). One pound of plaster of paris and water was mixed in a 1:1 ratio by volume. As the mixture began to set, it was removed from its container and squeezed by the subject's right hand, while wearing a surgeon's glove, thumb opposing, in a partially clenched fist allowing for approximately a 1.5-inch central diameter and placing the MCP and PIP joints of 4 fingers into 30 to 80 degrees flexion. This grip was maintained until the plaster became stiff enough to handle without damage. Excess material that might interfere with establishing the proper grip was removed with a deburring tool.

Test description

Five normal subjects were tested, three males and two females. Each subject used his or her own plaster grip mold (Figure 3). The test procedure was as follows:

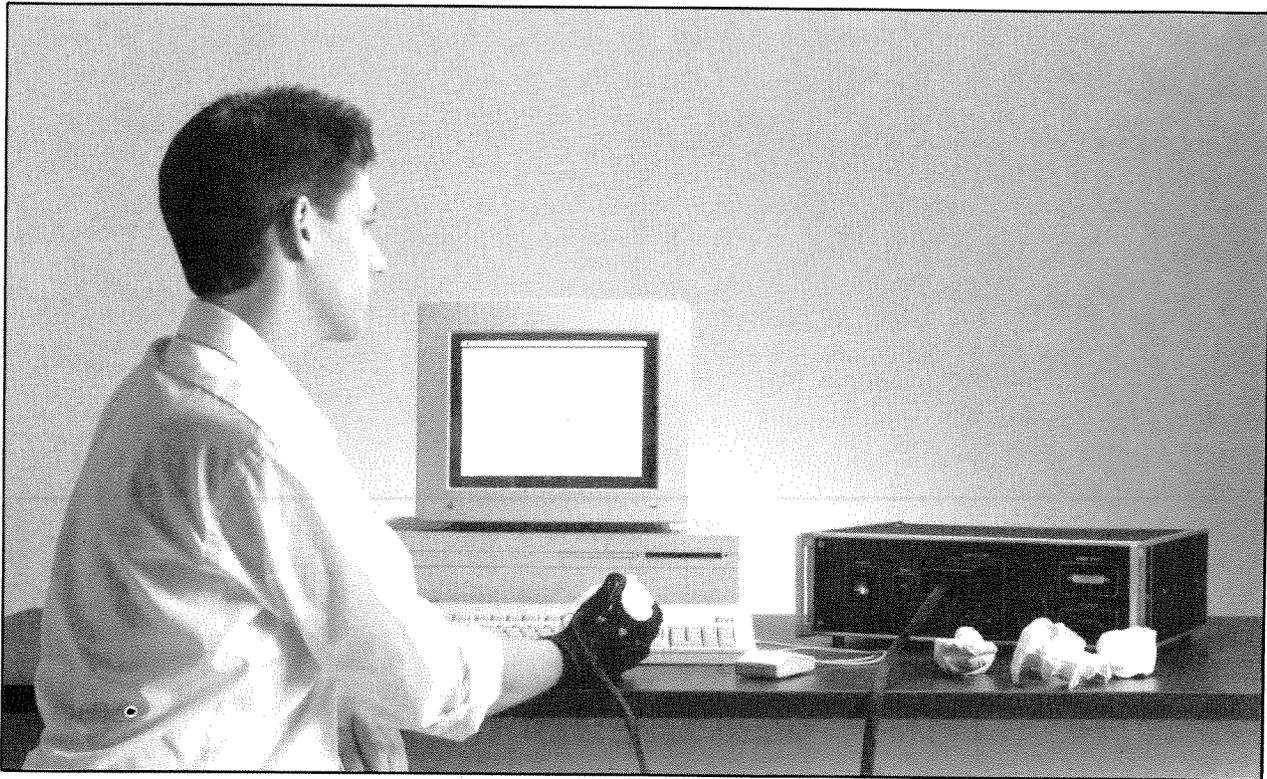


Figure 3a.
System including subject, interface box, additional plaster molds, and host computer.

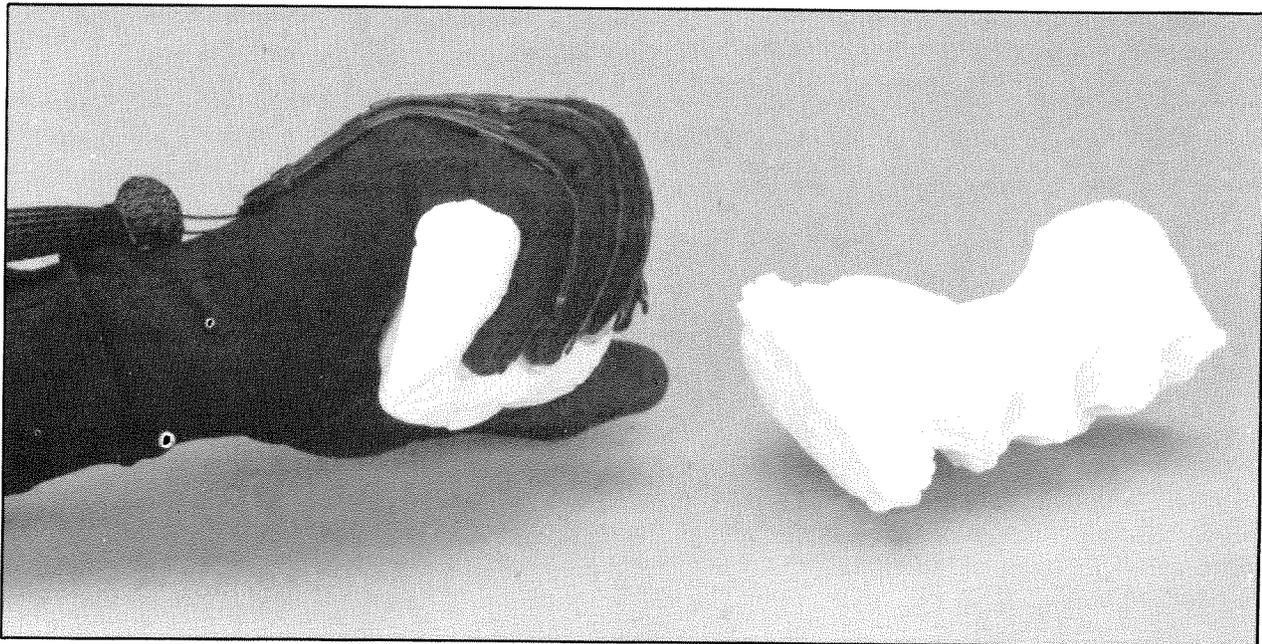


Figure 3b.
Hand inside DataGlove™ gripping a plaster mold and a plaster mold alone. The molded plaster fixture provided an individualized surface contour with fingers flexed to repeatable angles.

Calibration.

Because of difference in glove fit between subjects, the glove was calibrated for each subject (15). The subject placed his hand flat on a tabletop, with the wrist in a neutral position to define zero degrees for each joint angle. Next, the subject moved his thumb to define 45 degrees at the MP joint and 90 degrees, the IP joint. Then he placed his hand into a fist (with the wrist in a neutral position) to define 90 degrees at the finger joints. All subsequent measurements were normalized to these values.

Repeatability testing.

Test A. Plaster mold, glove on between measurements.

After the calibration, the subject clenched his hand onto the plaster mold for 6 seconds and then released his hand for 6 seconds. The cycle of clenching and releasing was repeated 10 times. Then without removing the glove between measurements, the tests were performed again. Each measurement consisted of 10 consecutive cycles of holding and releasing and each of these were performed 6 times.

Test B. Plaster mold, glove off between measurements.

Using the same calibration, the subject was once again asked to clench the mold in the same manner for ten 6-second cycles. However, between the measurements, the subject removed and replaced the glove. These tests were conducted on the same day. This was done to determine if any change in readings would occur if the glove was used in more than one wearing.

Test C. Hand flat, glove on between measurements.

The subject placed his arm on a flat tabletop so that his wrist was in a fixed, neutral position with the forearm pronated. The glove was then recalibrated with all of the joints in an active hyperextension in order to offset the angular readings from the zero degree limit established by the calibration software. Then the subject was asked to place his hand flat on the tabletop and in the same sequence of 6 seconds, clench his hand lightly, and then return it to the flat position, all without lifting his arm from the table. As in the first test, the glove was left on between measurements.

Test D. Hand flat, glove off between measurements.

The subject used the same hyperextended calibration and was instructed to continue to follow the same sequence as in C, but to remove the glove between each measurement.

Potential sources of error.

Two other tests were performed on one subject to discover whether grip force or wrist movement could affect the glove's reading. In one test the subject varied the

grip force cyclically against the plaster mold without moving any joints. In another experiment the subject held the mold, and without moving his fingers, flexed and extended his wrist.

RESULTS

The results of the repeatability tests for the MP and PIP joints of the fingers were as follows (see **Table 1** for a summary of these results):

1) Subject 1 was a male in his late teens. In the four different tests he achieved an average error of 4.2 degrees (**Figure 4**, Tests A-D). Of the individuals tested, he had the lowest error, 3.9 degrees on Test C. He achieved his lowest standard deviation on Test C as well, 1.5 degrees. His overall standard deviation for the four tests was 1.8 degrees.

2) Subject 2 was a male in his late twenties. His overall error was 4.3 degrees (**Figure 5**, Tests A-D). His lowest error was achieved on Test D, at 2.5 degrees, but his lowest standard deviation was achieved on Test C, 1.7 degrees.

3) Subject 3 was a female in her mid-twenties, having overall error of 7.9 degrees (**Figure 6**, Tests A-D). Her lowest error was also on Test C, with 4.1 degrees. As with Subject 2, her lowest standard deviation was on Test C, with 1.9 degrees.

4) Subject 4 was a male in his mid-teens. His error overall was 3.9 degrees (**Figure 7**, Tests A-D). His lowest error score was a 2.4 degree error on Test A. As with the others, his lowest standard deviation was on Test C, with 1.4 degrees.

5) Subject 5 was a female in her early forties. Her overall error was 7.6 degrees (**Figure 8**, Tests A-D). Her lowest scores for both error and standard deviation, were on Test C, with an error of 3.5 degrees and a deviation of 2.1 degrees.

The range and standard deviation measures were highly correlated, and so are roughly comparable estimates of measurement repeatability.

There were significant differences in repeatability among the subjects ($p=0.017$, two-way analysis of variance). Investigation of the data showed that repeatability was substantially worse for the two female subjects (± 2.3 degrees) than for the male subjects (± 1 degree). This presumably reflects the fact that the glove fit was poorer for the female subjects due to their small hand size. In all cases the repeatability was within the ± 5 -degree range prescribed in the DataGlove™ operations manual.

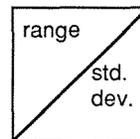
The difference in repeatability among the four tests

Table 1. Summary of results

Test	Test Subject					average across subjects
	1	2	3	4	5	
A. Plaster mold leaving the glove on between readings	3.9	6.0	9.5	2.4	10.6	6.5
	1.8	2.1	3.1	1.9	4.0	2.6
B. Plaster mold removing the glove between readings	4.6	4.8	10.4	4.6	9.4	6.8
	2.1	1.9	3.2	2.4	3.3	2.6
C. Flat tabletop with the glove off between readings	3.9	3.7	7.4	4.0	3.5	4.5
	1.5	1.2	1.9	1.4	2.1	1.6
D. Flat tabletop with the glove on between readings	4.3	2.5	4.1	4.6	6.7	4.4
	1.8	1.4	2.4	2.3	2.9	2.2
average across all four tests	4.2	4.3	7.9	3.9	7.6	5.6
	1.8	1.7	2.7	2.0	3.1	2.3

Range Refers to the difference between highest and lowest measured values, in degrees.

Std. Dev. The standard deviation of measurements, in degrees.



Each entry represents an average across 10 points.

was not significant ($p=0.128$, two-way analysis of variance) for this small group of subjects. However, investigation of the data showed that repeatability was better in the flat-hand tests (± 4.4 degrees) than in the plaster mold test (± 6.6 degrees) for all subjects. This implies that the hand can be positioned more accurately by laying it flat on the table than by clenching a mold. There was little difference in overall error between tests A and B and between tests C and D, indicating that removing or keeping the glove on between measurements made very little difference in repeatability.

The squeeze strength test showed that the force of the grasp does influence joint measurements, causing measurements of MP to vary by up to 11 degrees, and of PIP to vary up to 6 degrees. (Figure 9, joints a-d).

In wrist movement tests as in the flex tests, the MP joints responded much more than did the PIP joints. The

PIP joints showed angular movement up to 6 degrees while the MPs moved 7 to 8 degrees (Figure 10).

During testing it became apparent that the reading taken from the thumb MP and IP joints were not repeatable. Because the molds did not adequately stabilize the thumb, the results have been plotted in the graphs but have not been included in Table 1. Future tests will need to be performed to control thumb movements more adequately.

DISCUSSION

Loss of hand movement is a serious problem that costs on an average of 10 billion dollars a year (7). Injuries such as these can result from fractures, spinal damage, tendon injuries, or arthritis. Dealing with this problem demands that the patient be carefully evaluated with respect to 1) the

DataGlove Repeatability

SUBJECT 1

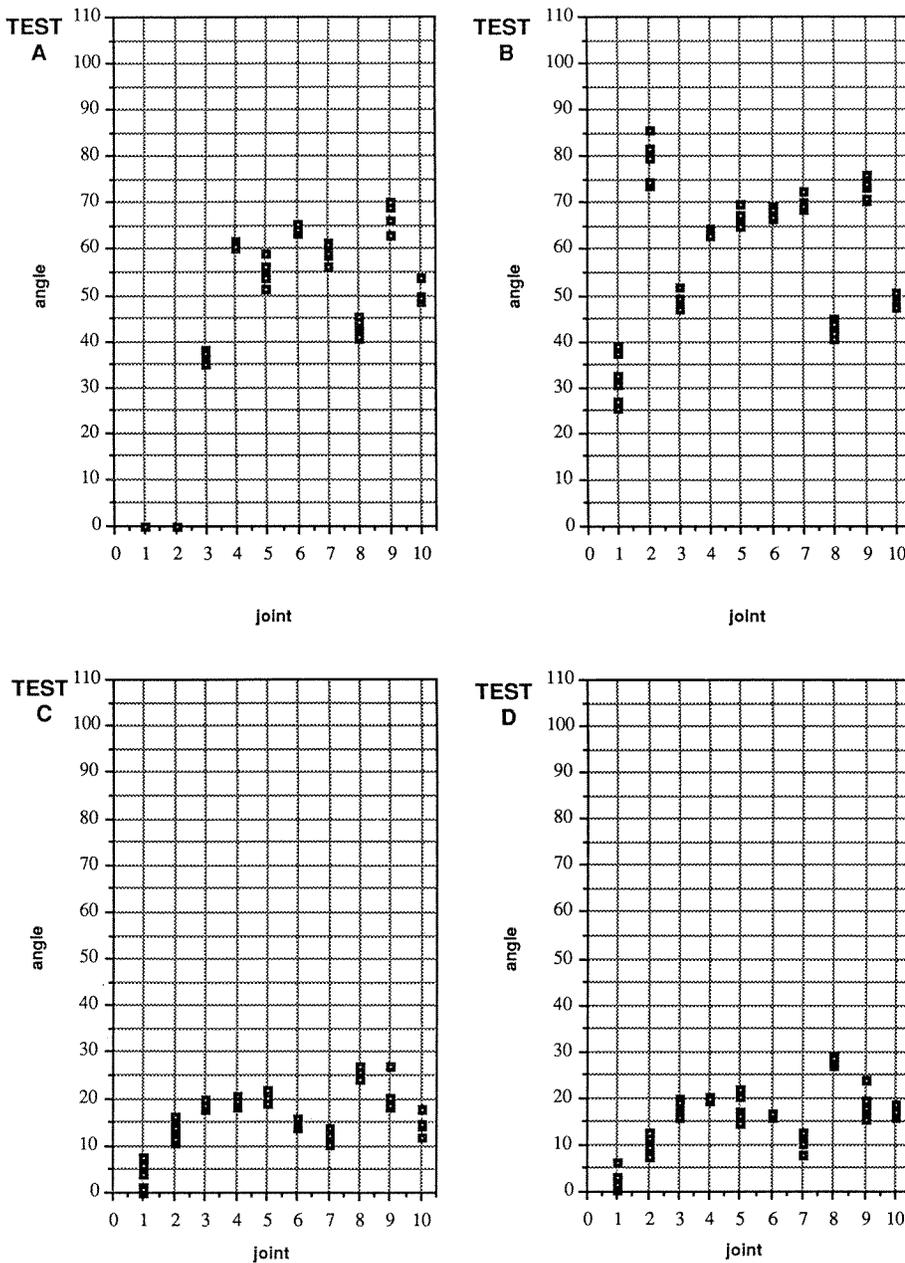


Figure 4.

Graphs of DataGlove™ repeatability. Subject 1, tests A-D. (Y axis indicates angle of flexion, x axis shows various joints, where joint 1 is thumb MP, joint 2 thumb IP, joint 3 is index MP, joint 4 is index PIP, joint 5 is middle MP, joint 6 is middle PIP, joint 7 ring MP, joint 8 is ring PIP, joint 9 little MP, and joint 10 is little PIP).

exact extent of the damage; 2) the best method for dealing with the problem; and, 3) the progress during and after therapy and the end result of the treatment (12).

Over the last 80 years, goniometric measurement has changed very little (10). Measurements are done with a

mechanical device, either plastic or metal, and resembles a geometry protractor. Problems with goniometric techniques limit their reliability and accuracy (11). The device is manually placed on the patient's hand with the protractor hinge above or alongside the desired joint (10). Then

DataGlove Repeatability

SUBJECT 2

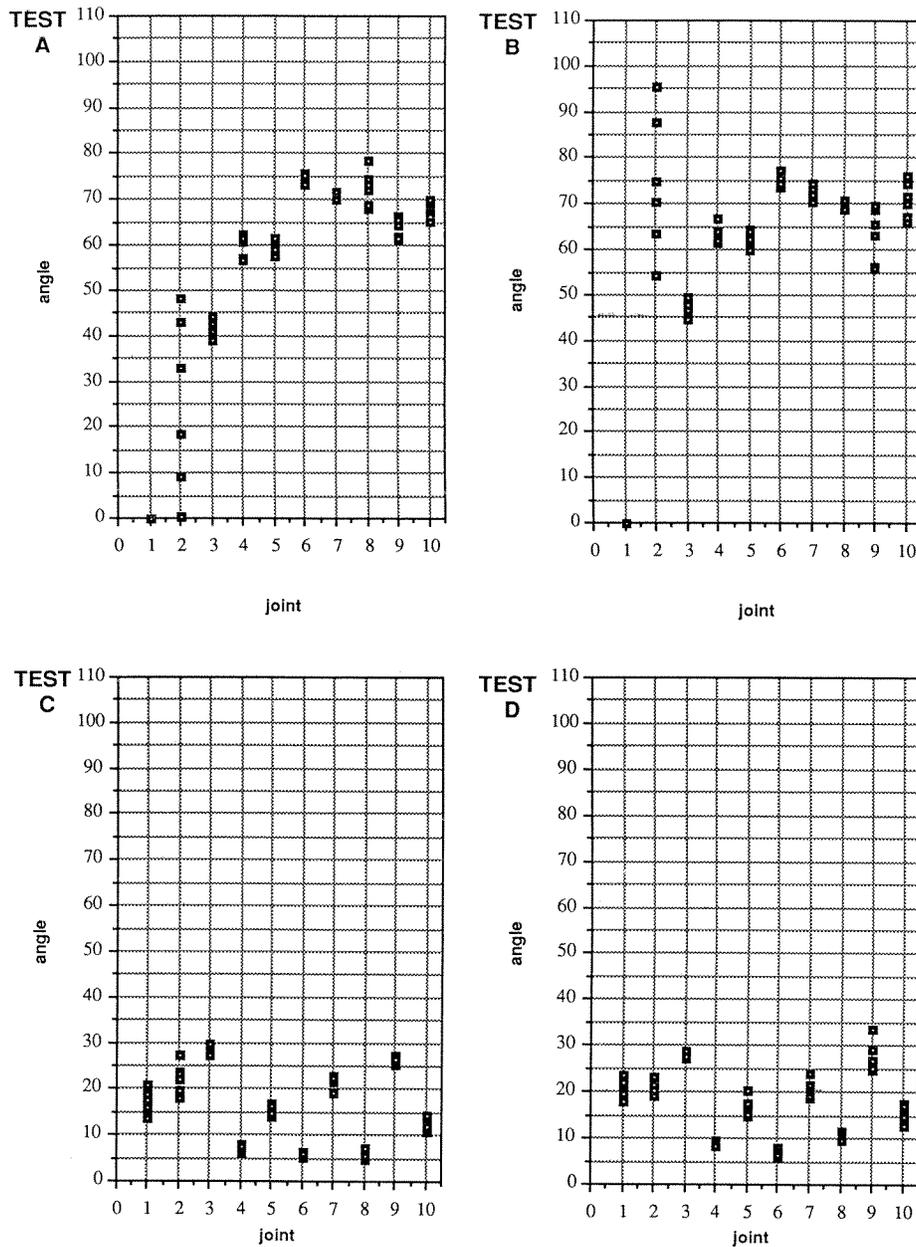


Figure 5.

Graphs of DataGlove™ repeatability. Subject 2, tests A-D, where Test A used the plaster mold with glove on between measurements, Test B used the plaster mold glove off between measurements, Test C used the hand flat with the glove on between measurements, and Test D used the hand flat with the glove off between measurements.

the angular results are recorded manually. Goniometric measurements are either active, when the fingers are moved by the patient's muscle contraction, and passive, when moved by the therapist. The reliability of a skilled therapist was 7 degrees or less in 95 percent of the repeated

trials with measurements on two different goniometers; average physical therapists were within 7 degrees in 62 to 72 percent of trials (6).

In a study of intratester and intertester reliability, a change of 3 or 4 degrees of goniometric range of motion

DataGlove Repeatability

SUBJECT 3

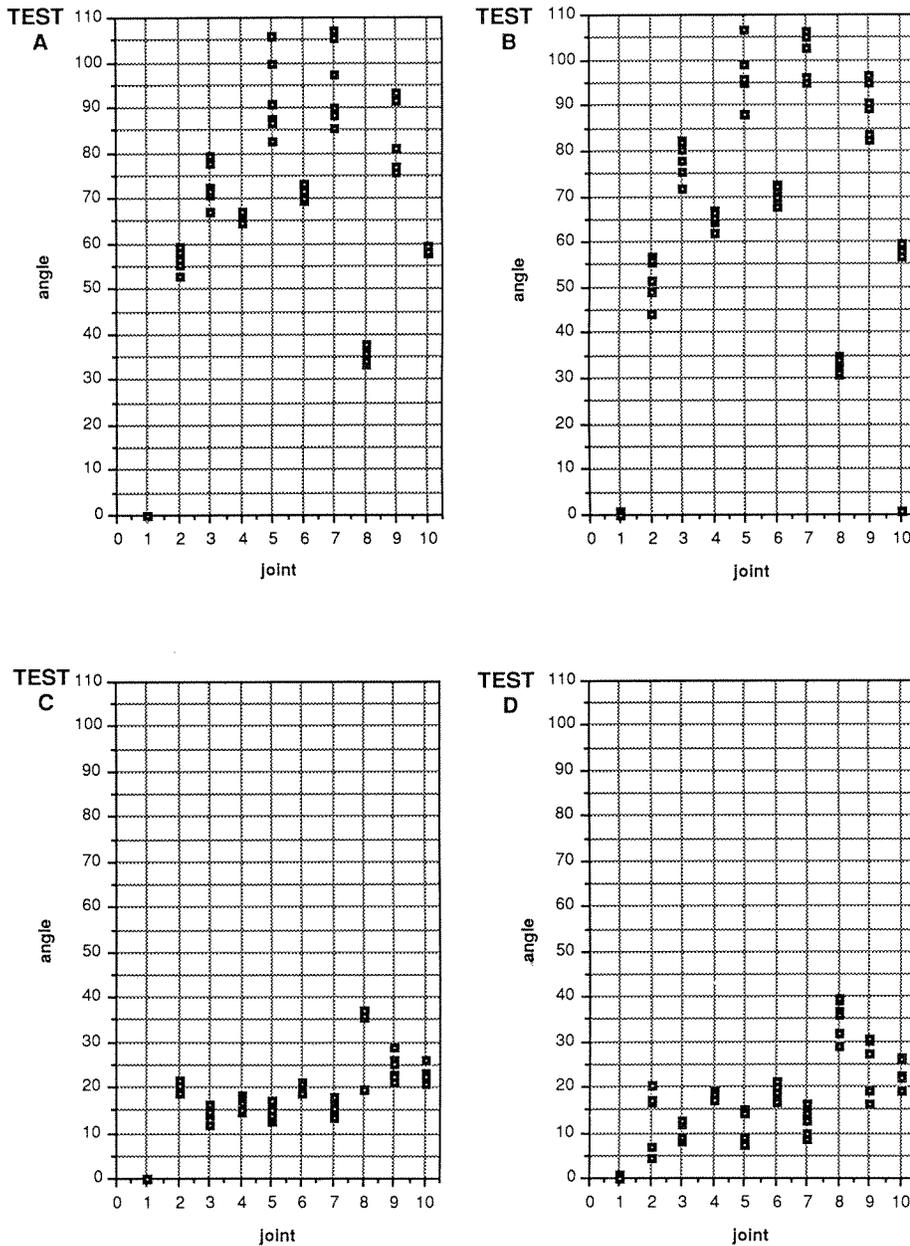


Figure 6. Graphs of DataGlove™ repeatability. Subject 3, Tests A-D.

was required to determine improvement for intratester reliability for upper extremities. For intertester reliability an increase in joint motion should exceed 5 degrees for the upper extremity before determining improvement (1).

A series of tests of the DataGlove's™ accuracy were conducted at NASA for the index finger PIP joint only (4). Using a Polhemus 3Space™ Isotrack™ magnetic position

and orientation tracking system, the movement measured by the glove in the index PIP joints was compared to the amount of movement registered by the Polhemus. The Polhemus sensing coil was attached to the tip of the index finger over the DataGlove™ using a small plastic splint that fit over the distal interphalangeal joint (DIP), which held the reference sensor in place and effectively immobilized

DataGlove Repeatability

SUBJECT 4

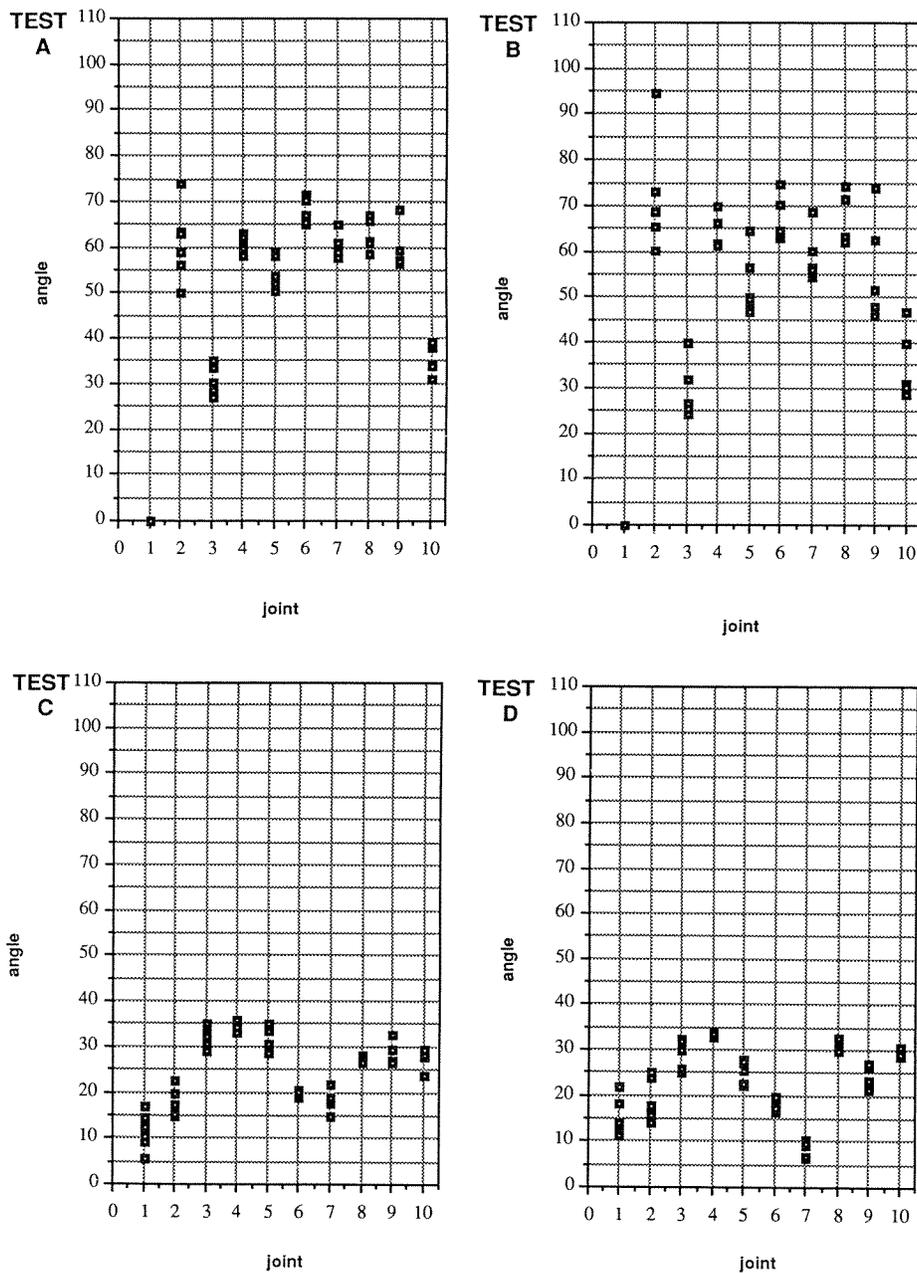


Figure 7.
Graphs of DataGlove™ repeatability. Subject 4, Tests A-D.

that joint. The subject flexed his PIP joint while results were recorded from both devices (the glove and the Polhemus) during every increment of the movement. The MP joint and the rest of the hand were kept stationary with respect to the Polhemus source coil (4).

The Polhemus tracker has a specified angular accuracy of 1.5 root mean square (RMS). Measurements taken from

the Polhemus were used as a reference standard to compare the values obtained from the glove interface. The paired readings were within 2 degrees at each flex sensor value. When successive measurements were compared, the angular spread, measured from the highest result number to the lowest result number for each person, was approximately 6 degrees. At extreme angles of flexion (>54

DataGlove Repeatability

SUBJECT 5

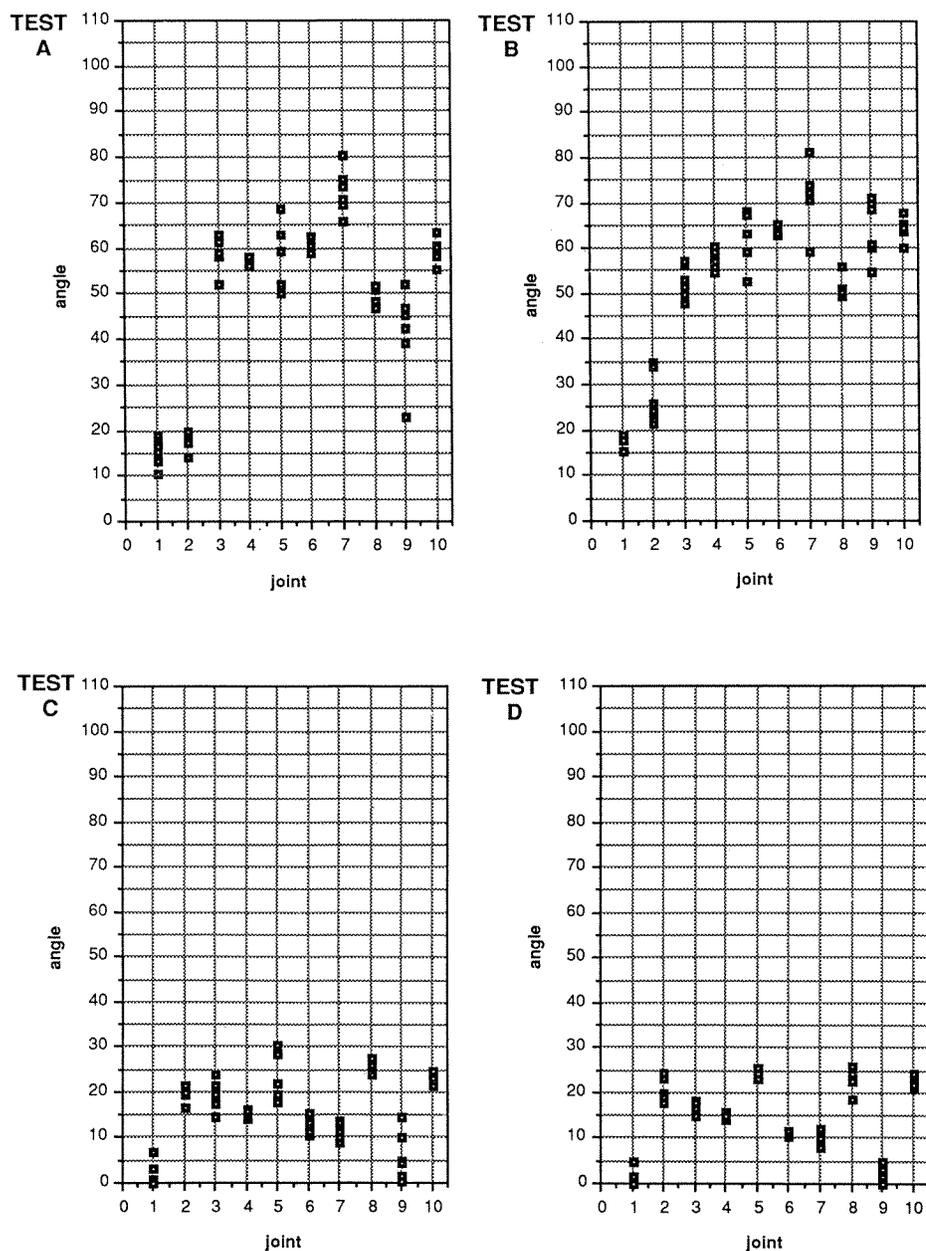


Figure 8.
Graphs of DataGlove™ repeatability. Subject 5, Tests A-D.

degrees), resolution decreased from approximately 1 to 2.5 degrees (4).

The objective of this study was to use the DataGlove™ as a device for relative measurement of the PIP and MP joints of all five fingers so as to establish whether or not VPL's DataGlove™ would be a reliable and effective clinical tool for semi-automated goniometric measurements.

We studied the repeatability of the glove for measuring multiple joint angles simultaneously. We also tested the reproducibility of these measurements while changing the glove by taking it off and putting it back on again. In addition, we also tested possible situations which would decrease the accuracy of the glove. These included squeezing the hand against the plaster mold and changing the

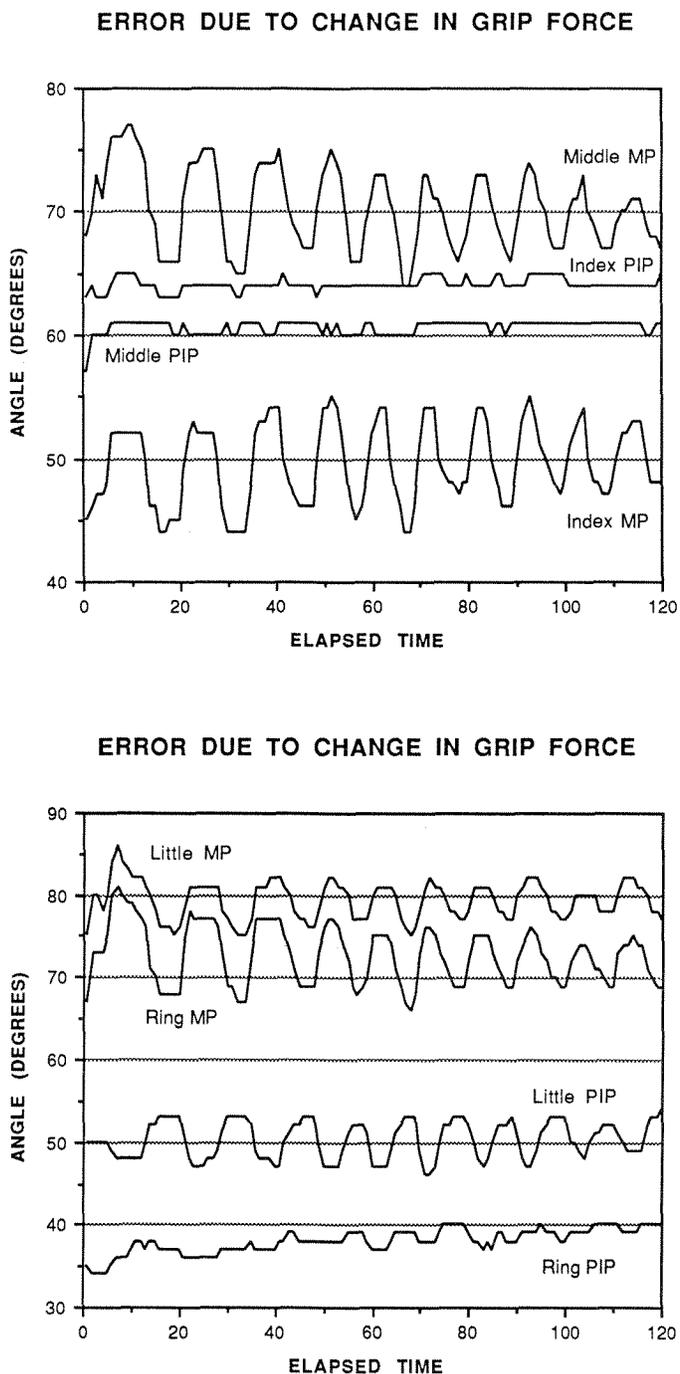


Figure 9. Angle error due to change in grip force. Finger flexors were contracted then relaxed 10 times while holding molded fixture. Upper graph: index and middle fingers; lower graph: ring and little finger.

position of the wrist.

The results show an overall error of 5.6 degrees (average of 4 tests and 5 subjects). This error rate is comparable to the presently acceptable error rate for manual goniometric measurements. The computer glove system has the added advantage of semiautomation, thus providing a significant saving in time required to perform routine goniometric measurements. This occurs both because the glove measures multiple joints simultaneously and because the data is automatically loaded into a computer spreadsheet.

It is likely that with further modifications in the glove design and testing that the results can be improved. We noted a significant ($p=0.017$) variability between subjects tested. The best subject showed an error of 3.9, whereas the worst case subject achieved 7.9 degrees error. There are probably many reasons for this variability. These include glove fit, force applied by the subject, and position of other joints such as the wrist.

The glove comes in three sizes: small, medium, and large. In this study we evaluated the medium size glove in a population of subjects with small- to large-size hands. Better results were obtained when the glove presented a snug fit (medium to large hands in our study). Greater variability is evident in the two subjects with smaller hands. Errors due to wrist motion may be dependent on fit because the longer fingers had space between the fingertip and glove so that the fabric did not have to stretch to fit (**Figure 10**).

We also studied the effect of force applied by the hand on the plaster molds. We found that increasing forces produced errors in the glove measurements especially in the MP joints. This may be due to changes in the profile of the muscle and soft tissue or to lateral motions of the biaxial MP joints, causing greater apparent flexion than actually occurs. In repeatability tests we attempted to minimize this effect by having the subject apply the minimal amount of force required to hold the plaster mold; however, it is possible that minor alterations in this force affected our results. In future tests force sensors could be placed in either the glove or the plaster molds to accurately control the force applied.

We also found that flexion-extension of the wrist affected the glove measurements. In our repeatability experiments this was controlled by keeping the wrist in a neutral position. The glove itself, rather than the sensors, is the most likely cause of error when the wrist is flexed or the fingers and thumb abducted or adducted; the fabric is forced to slide over the skin when performing these movements and is prevented by friction from returning exactly to its starting position.

Although our testing of the glove shows it to be promis-

ing, these tests were not applied to clinical subjects with hand impairments, a more difficult test of the glove's repeatability. If used in a clinical setting, the complications that could affect measurement, as with an ordinary goniometer, include: swollen, hypersensitive, infected, wounded (trauma or surgery), or misshapen hands (contracted, amputated digits, rheumatoid deformities, tumors and nodules) (5), calibration of the glove for each individual, and maintenance of the glove in a hygienic state. The glove needs further study on subjects having disabled hands to address questions such as the accuracy and reliability of the glove with patients having contractures and digit amputations. Since the movements of the proximal joints (wrist) affect the readings of the distal joints (MP and PIP) while holding the plaster mold, movement at a proximal joint would affect the digit measurement even if the digit was absent. Although the measurements by the glove of the PIP joints were very good, repeatability of the MP joint measurements needs to be improved. According to Low some joints are more accurately measured than others by conventional ROM tests (9). The range of the MP joint and the changes in the readings during isometric contraction and subtle movement that occur during proximal joint movement may actually indicate movement which we are unable to measure manually. The complexity of the human body with respect to multijoint movements, may make it difficult to reliably measure muscle and soft tissue. The variation of skin tension and muscle tension with joint position can affect measurement (9). The type of joint measured can also affect reliability of joint measurement; uniaxial joints being easier to measure than those which are biaxial or multiaxial (6).

Future versions of the glove will have the ability to measure an extended set of flexure characteristics of the joints of the hand with improved accuracy. Clinical trials now underway will determine what modifications will need to be made to accommodate patients with hand impairments.

SUMMARY

The glove is comparable in repeatability to manual goniometry in normal subjects. The advantages of the glove are in its ability to measure multiple joints at one time and to record that data directly into a spreadsheet or report. Disadvantages of the glove include lack of abduction or adduction, wrist motion, and full characterization of thumb movement. With further development and testing the glove may become an effective clinical tool.

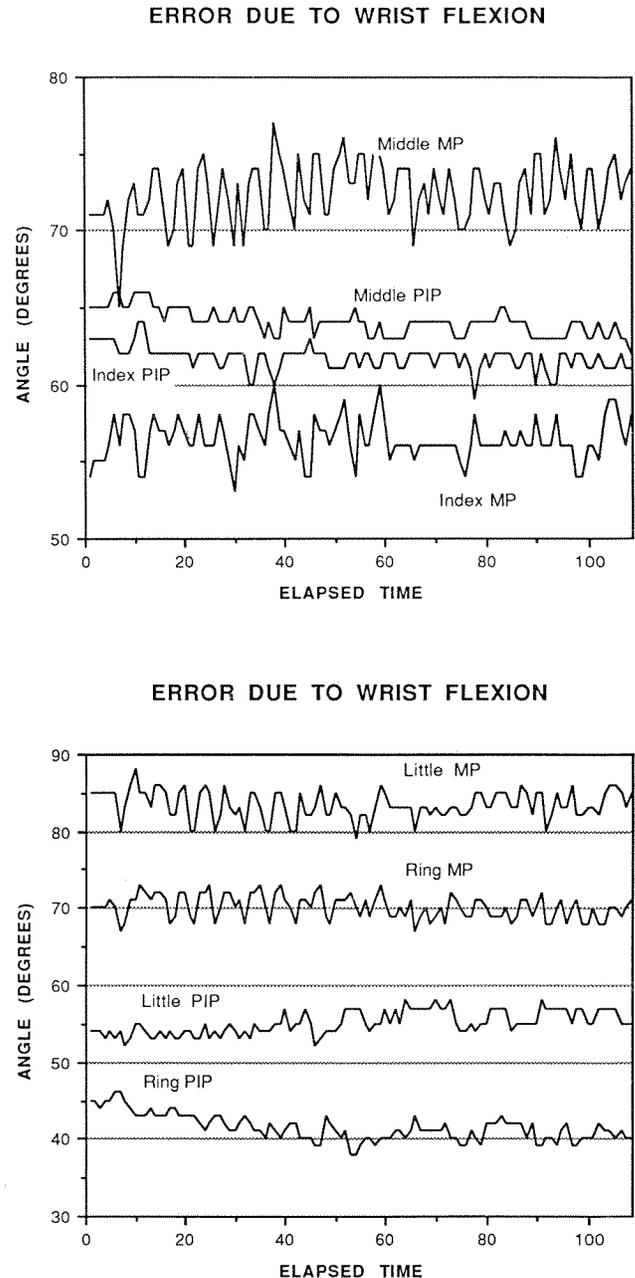


Figure 10.

Angle error due to wrist motion. Wrist was flexed and extended while holding molded fixture without changing grip force. Upper graph: index and middle fingers; lower graph: ring and little fingers. Note drift of middle and ring PIP angles due to slip of fabric over skin.

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