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Evaluation of an instrumented glove for hand-movement acquisition

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Abstract—Quantitative assessment of digit range of motion (ROM) is often needed for monitoring effectiveness of rehabilitative treatments and assessing patients' functional impairment. The objective of this research was to investigate the feasibility of using the Humanware Humanglove, a 20-position sensors glove, to measure fingers' ROM, with particular regard to measurement repeatability. With this aim, we performed a series of tests on six normal subjects. Data analysis was based on statistical parameters and on the intraclass correlation coefficient (ICC). Sources of errors that could affect measurement repeatability were also analyzed. The results demonstrate that, in principle, the glove could be used as goniometric device. The main advantage yielded by its use is reduction in the time needed to perform the whole measurement process, while maintaining process repeatability comparable to that achieved by traditional means of assessment. It also allows for dynamic and simultaneous recording of hand-joint movements. Future work will investigate accuracy of measurements.

Key words: glove, goniometric measurements, hand-function assessment, range of motion, rehabilitation engineering.

INTRODUCTION

Hand-function assessment requires several kinds of measurements, including grip and pinch strength, sensitivity to temperature and vibrations, joint range of motion (ROM), and functional abilities. Acquiring these data can be useful for diagnosis, planning of the rehabilitative treatment (drug prescription, surgery, physical therapy), assessing treatment effectiveness and patient's progress, determining patient's readiness to return to work, and eventually compensating financially for her or his disability. Yet, measurements of joint ROM represent one of the primary quantitative methods of hand-function assessment [1]. Traditionally, a hand therapist performs these measurements via mechanical goniometers, which must be placed on each hand joint to measure flexion and extension angles [2]. Data recording is performed manually. However, several researches have shown that traditional goniometric measurements can be affected by several sources of errors; among them, the most important are the examiner, the instrument, and the subject [3]. Typical errors of inexperienced examiners can arise from

Abbreviations: DIP = distal interphalangeal, DOF = degree of freedom, GVH = Graphical Virtual Hand, ICC = intraclass correlation coefficient, IP = interphalangeal, MCP = metacarpophalangeal, PIP = proximal interphalangeal, ROM = range of motion, TMCP = trapeziometacarpal, VR = virtual reality.

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negligence in adhering to measurement standardized techniques, but even skilled hand therapists are susceptible to several measurement errors [4]. In addition, intratester and intertester variability is considerable [3]. Instrument errors usually are due to using goniometers of a size not appropriate to the joint being measured [4]. In contrast, the type of goniometer does not appear to be important when the procedures are standardized [5]. Subject errors are related to patient's physical characteristics or physiological deterioration and, because of the mechanical complexity of the hand structure, are more complex in hand goniometric measurements than in ROM measurements in larger joints [4].

Another limitation of measurements taken by traditional goniometers arises because acquiring ROM information simultaneously from all hand joints is not easy. Thus, the whole measurement process is tedious and time-demanding for the hand therapist and the patient.

Finally, goniometric measurements are most suited to static ROM measurements. In contrast, hands are mostly used in complex and dynamic tasks. Thus, any static test might not predict the patient's effective capacity to perform a functional task. This could lead, for example, to a premature, and then unsafe, return of the patient to the workplace or to over- or underestimated financial compensation of patient's disability.

To overcome the limitations of goniometric measurements just described, a few studies have suggested the use of glove-based devices, originally developed for gesture-based applications, for ROM acquisition, both for assessment and therapy enhancement [6–7]. In principle, glove devices should lessen intertester error by establishing an objective, standardized procedure for measurement of hand function and by eliminating the subjective interpretation or influence by the tester [8]. In addition, through contemporary acquisition of data from all hand joints, they are expected to speed up ROM measurement. Finally, since they allow for detailed and comprehensive analysis of hand performance while executing dynamic tasks, they may be a useful tool for assessing the patient's degree of impairment via investigation of her or his functional abilities.

Unfortunately, despite all these claims, works describing technical evaluations of sensorized gloves for investigating their suitability as goniometric devices have been lacking so far. A literature search produced only a few descriptions of testing protocols and experiments that evaluated glove devices' characteristics [8–12]. Consequently, to date, the potential of these devices in the field of rehabilitation seems not to be wholly exploited.

The objective of this work was to evaluate the performance of a commercial sensorized glove system, the Humanglove, version 1, to investigate its suitability as a computerized hand-capture motion system for goniometric applications. In this paper, we report the results of a study aimed at quantifying the repeatability of measurements taken by the Humanglove. An investigation to quantify accuracy of measurements will be described in the future. As a criterion for assessing the reproducibility of measurements, apart from their mean and variance, the intraclass correlation coefficient (ICC) was calculated.

METHOD

Glove Systems

Review

Several glove-based input systems have been developed so far. Sayre Glove, MIT LED Glove, and Digital Data Entry Glove were developed for real-time computer graphics animation and gesture recognition [6]. The Data Glove, based on fiber-optic technology, was developed by Visual Programming Language, Inc., initially as a gesture recognition tool. Wise et al. proposed its application in the rehabilitation field as a semiautomated goniometric device [8]. The lack of abduction and adduction (ABD/ADD) sensors was indicated as the main disadvantage of the Data Glove [13], although other researchers have reported that abduction sensors were sometimes used to measure angles between adjacent fingers [14]. The Cyber Glove, based on piezoresistive sensors and available in two versions (18 and 22 sensors), was developed by the Virtual Space Exploration Laboratory of Center for Design Research, Stanford University, in the framework of the Talking Glove project for sign-language recognition applications. It was then commercialized by Virtual Technology, Inc., for a range of applications spanning virtual reality (VR), telerobotics, and video games [14]. The Super Glove, commercialized by Nissho Electronics, and the Fifth Dimension Technologies 5th Glove were developed for entertainment applications as was the P5 Power Glove, an updated version of the Power Glove by Mattel Intellivision, developed by Essential Reality. Fakespace Pinch Glove, based on electrical contacts that meet to complete conductive paths, has been used recently in many VR applications [15–16]. The SIGMA Glove [13], with 30 degree of freedom (DOF), was developed by the University of Sheffield specifically for clinical hand goniometric assessment. One of the proposed applications was the evaluation of prosthetic joint implants in a VR-based system [13]. Sensor Glove, developed by the Technical University of Berlin, is used currently in robot control applications and recently has been proposed as a goniometric device [11]. In recent years, glove devices provided with haptic feedback (e.g., force) have been applied in virtual rehabilitation workstations [17–19].

Among commercial devices, aside from Cyber Glove and 5DT Data Glove 16 (the higher end version of the 5th Data Glove), most available gloves lack ABD/ADD sensors. The Humanglove has 20 sensors and 5 of them measure the ABD/ADD angles. Therefore, it meets an important requirement for a glove to be used as a goniometric device.

Figure 1.
The Humanglove (courtesy of Humanware).

The Humanglove

Glove Description. The Humanglove is a sensorized elastic fabric glove designed and commercialized by Humanware [20]. The Humanglove is equipped with 20 Hall effect sensors that are distributed as shown in **Figure 1**. Each sensor measures data related to a DOF of the hand. The nominal sensor characteristics are resolution, 0.4° over a range up to 90°; linearity, about 1 percent full-scale output; and accuracy, about 1°. However, no information about the sensors is available concerning their performance when they are mounted on the elastic fabric glove.

System Description. The glove control unit is connected to the host computer through a standard RS-232 at 38400 baud; the host computer can be any kind of workstation, PC, or Macintosh. Data acquisition is performed through a proprietary software package called Graphical Virtual Hand (GVH). This program calibrates the glove and displays an animated hand that mirrors movements of the user's hand, as shown in **Figure 2**. Data acquisition and storage in ASCII format can be performed both with and without the GVH interface (with a nongraphical version of the data acquisition software).

Figure 2.
Graphical Virtual Hand (GVH) interface (courtesy of Humanware).

The DOFs are as follows: DOF1 to DOF4 correspond to thumb joints movements, i.e., ABD/ADD of the thumb metacarpophalangeal (MCP) joint, flexion/extension of the trapeziometacarpal (TMCP) joint, flexion/extension of the MCP joint, and flexion/extension of the interphalangeal (IP) joint, respectively. DOF5 to DOF8 correspond to index finger movements, i.e., ABD/ADD of the index MCP joint, flexion/extension of the proximal interphalangeal (PIP) joint, and flexion/extension of the distal interphalangeal (DIP) joint, respectively. Similar to DOF5 to DOF8, DOF9 to DOF12, DOF13 to DOF16, and DOF17 to DOF20 correspond to middle, ring, and little finger movements, respectively. To simplify notation, in the following, we will refer to the glove sensors measuring:

- DOF1, DOF5, DOF9, DOF13, and DOF17 as ABD/ADD sensors.
- DOF2, DOF6, DOF10, DOF14, and DOF18 as MCP sensors.
- DOF3, DOF7, DOF11, DOF15, and DOF19 as PIP sensors.
- DOF4, DOF8, DOF12, DOF16, and DOF20 as DIP sensors.

The glove can be connected to a tracking system composed of a support base and hinged arms with Hall effect sensors. These sensors can measure position and orientation of a fixed anatomical point: the end point of the tracker is, in fact, rigidly connected to the user's wrist.

Experimental Procedures

The experimental procedure used in this paper was proposed by Wise et al. for the evaluation of the Data Glove [8]. A similar procedure was also adopted by Williams et al. for SIGMA Glove evaluation [12].

Special Materials

Custom plaster molds were fabricated for each subject so that the same grip characteristics were obtained for repeatability testing. That is, whenever gripping the mold, all subjects' hand joints could be placed each time in the same position, with the joints forming the same angles obtained in the previous gripping actions. A mixture of water and plaster was prepared in a container. When the mixture started setting, each subject was asked to create a ball-shaped plaster "object" composed of an adequate amount of solidifying mixture and to squeeze it by placing the joints of four fingers into 30° to 80° flexion, with thumb opposing and the hand joints mimicking a cylindrical grasp posture. The grip was released when the mold became adequately stiff to retain the impressed volumetric shape.

Subjects

Data were collected from six able-bodied right-handed adult subjects, two females and four males. The female and the male group had comparable hand size ("small" and "medium" corresponded to hand size 7 to 7 1/2 and 7 1/2 to 8, respectively; the sizes are defined as the length of a hand, from the distal wrist flexion crease to the tip of the middle finger and are measured in inches). Subjects, aged 28 to 35, had no known history of orthopedic hand disfunction.

Calibration and Test Description

The calibration procedure was performed for each subject. Before repeatability testing, each subject was asked to place her or his hand flat on a tabletop, with the wrist in a neutral position to define the reference position for each joint at 0°. The subject was asked to move her or his hand until the maximum extension and flexion were achieved for all DOFs. A therapist helped the subject to passively perform the same movement. It is known that active and passive movements are characterized by different ROMs. Measurements in the interval between zero and maximum values reached during the procedure just described were then normalized.

Different tests were performed on the glove to evaluate repeatability on measurements taken from sensors and to discover additional sources of error.

Repeatability Testing Protocols

Test A: Mold Grip and Glove on Between Data Acquisition. The subject was asked to grip the mold for 6 s and then to release her or his hand for 6 s. During the release, the subject was asked to place her or his hand flat on the tabletop. The forearm was in a prone-supine position and the wrist in a neutral position. To achieve repeatability of the subject's wrist position when she or he gripped the mold (because of a custom mold, hand joints could be placed in the same position each time), we marked position landmarks, consisting of profiles of the subject's forearm and hand while gripping the mold, on the tabletop where the experiments would be performed. Landmarks for each subject were drawn before starting experiments; therefore, during the grip phase, the subject was asked to place the forearm inside the drawn profile. A single data block was composed of data from 10 grip and release actions. The experiment was repeated 10 times, without removing the glove between successive data blocks.

Test B: Mold Grip and Glove Off Between Data Acquisition. Test B was conducted in the same way as test A; the only difference was that between consecutive data blocks, the subject was asked to take the glove off. This was done to evaluate whether donning and doffing had an effect on the measurement process [8].

Test C: Hand Flat and Glove On Between Data Acquisition. The subject was asked to put her or his hand flat on the tabletop for 6 s, with the wrist fixed in a neutral position and the forearm pronated. Then the subject was asked to clench the hand lightly in maximum flexion for 6 s and to return it to the flat position. To achieve repeatability of the subject's wrist and hand-joint positions in the "flat phase," we drew the subject's hand (maximum extension of the hand, all hand joints and elbow touching the table, and thumb abducted at 37°) and forearm (in pronated position) profiles on the tabletop where the experiments were performed. The drawing for each subject was done before starting experiments. During the "flat phase," the subject was asked to place the forearm and the hand inside the drawn profile. The flat and clench phases were repeated 10 times to form a data block. The experiment was repeated 10 times, without removing the glove between successive data blocks.

Test D: Hand Flat and Glove Off Between Data Acquisition. Test D was conducted in the same way as test C, with one exception. Between consecutive data blocks, the subject was asked to take the glove off.

Potential Sources of Error Testing Protocols

Two additional tests were performed on each subject to discover potential sources of error. These tests are described in the paragraphs that follow.

Test T1: Force Test. The subject was asked to clench the mold with the maximum possible grip force for 6 s and then to release the force for 6 s, holding the mold without moving any hand joint and without moving the wrist. Strong and light grip actions were repeated 10 times.

Test T2: Wrist Flexion/Extension Test. The subject was asked to hold the mold and to flex the wrist without moving the fingers for 6 s and then to extend the wrist without moving the fingers for 6 s. Flexion and extension were repeated 10 times.

Data Processing

Figure 3(a) shows a typical acquisition data block during test A.

Data Reduction: Segmentation

A segmentation procedure was performed to separate the data pertaining to the grip and release phases for tests A and B and to the flat and clench phases for tests C and D, respectively. Segmentation was done manually from data computed as the sum of all acquisition channels, as shown in **Figure 3(b)**. Hence, for each subject and each test, 10 intervals for each of the 10 available data blocks were identified. The measures in each identified interval were then averaged. An array $\{X_{ijk}\}$, $i = 1,...,10$, $j = 1,...,10$, $k = 1,...,20$ was finally obtained to specify the data for the ith trial in the jth data block and related to the kth sensor.

Data Reduction: Extraction of Significant Parameters

For each subject and each test, we defined: (1) The range $R_k = (\max_j(\bar{X}_{jk}) - \min_j(\bar{X}_{jk}))$ where $\bar{X}_{jk} = \frac{1}{10}\sum_{i=1}^{10} X_{ijk}$; (2) its average value; (3) the standard deviation (SD) of the $\bar{X}_{jk}$ values; and (4) the average of the SD across the sensors. For each sensor, range and SD were found to be correlated. Together, these values give an approximate measure of repeatability [8]. Another statistical procedure that we adopted was based on the intraclass correlation coefficient (ICC) of reliability analysis [21]. Among a series of measurements performed on different subjects, two components of variability exist, the variability among their average values computed over each repeated measure σ_t^2 and the variability of the random errors σ_e^2. ICC is a single quantity that describes the relative magnitude of the two components of the variability. As σ_e^2/σ_t^2 decreases, the measurement error explains a decreasing percentage of the variance in the data, reliability increases, and ICC approaches its maximum value of one. As σ_e^2/σ_t^2 increases, the measurement error explains an increasing percentage of the variance in the data, reliability therefore decreases, and ICC approaches its minimum value of zero.

RESULTS

Table 1 shows an average range and SD obtained for each subject in each test. Subjects 1 to 4 were male with comparable hand size. Subjects 5 and 6 were female with comparable hand size. Actually, the size of the Humanglove was medium and suited subjects 1 to 4 quite well, while its fitting to the female subjects 5 and 6 was quite poor because of their small hand size. For this reason, additional analysis was performed only on male subjects' data. Also, since comparisons between male subjects' data and female subjects' data would not be correct because of their anthropometric differences, results that concerned the "male" cluster (subjects 1 to 4) and the

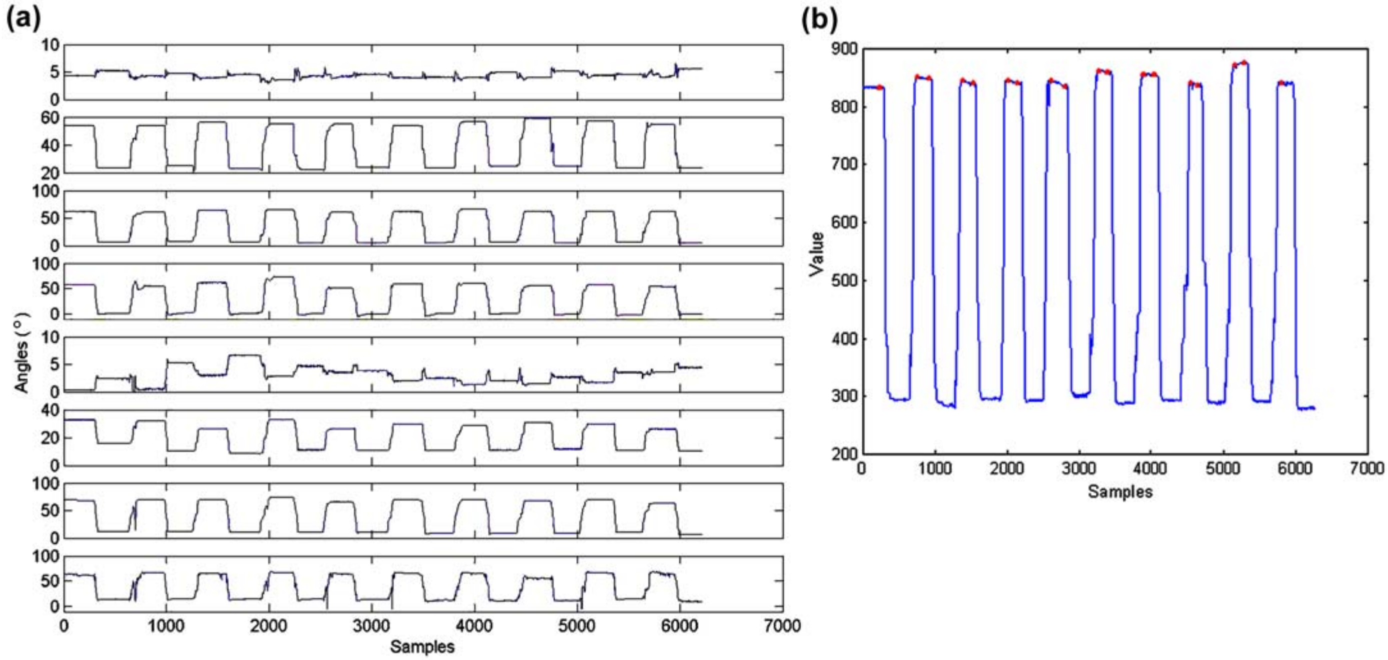

Figure 3.
Typical data: **(a)** Typical sensors acquisition by Humanglove (starting from top, data related to DOF5 to DOF8, DOF13 to DOF16 are shown) and **(b)** typical results of data segmentation.

"female" cluster (subjects 5 and 6) are presented separately in **Table 1**. However, average values across subjects 1 to 6 were reported to provide an overall picture of the performance of the Humanglove. As summarized in **Table 1**, performance related to the "male" (σ_m) cluster are better than those related to the "female" (σ_f) cluster (σ_m = 1.98, σ_f = 2.46).

During testing, the readings related to DOF2 were found to be unreliable, perhaps because of damage in the sensor. They have not been included in the following analysis, although they are shown in **Figures 4** and **5**. Moreover, the overall repeatability is better in flat-hand tests than in mold tests (σ_m = 2.33 in tests A and B, σ_m = 1.62 in tests C and D). The reason may be that the hand

Table 1.
Average range and average standard deviation (SD) (°) obtained for each subject and each repeatability test. Subjects 1 to 4 are male and 5 to 6 are female.

Subject	Test A		Test B		Test C		Test D		All Tests	
	Range	SD	Range	SD	Range	SD	Range	SD	Range	SD
1	7.44	2.34	12.37	4.04	3.37	1.05	5.18	1.71	7.09	2.28
2	3.13	1.07	5.00	1.55	2.37	0.80	6.64	2.25	4.28	1.42
3	6.92	2.31	9.02	2.77	5.49	1.77	6.51	1.99	7.03	2.21
4	5.20	1.63	9.50	3.01	3.16	1.04	7.34	2.38	6.30	2.01
Mean Male	5.67	1.83	8.97	2.84	3.59	1.16	6.41	2.08	6.17	1.98
5	10.07	3.29	12.12	3.80	3.90	1.26	5.44	1.82	7.88	2.54
6	12.07	4.01	8.31	2.64	4.75	1.47	4.21	1.39	7.34	2.38
Mean Female	11.07	3.65	10.21	3.22	4.32	1.36	4.82	1.60	7.61	2.46
Overall Mean	7.47	2.44	9.38	2.96	3.84	1.23	5.88	1.92	6.65	2.14

is positioned more accurately by placing it flat on the table than by clenching the mold.

Figure 4 shows the histogram distribution of the SDs of each sensor averaged across tests A to D and across subjects 1 to 4. At first approximation, the histogram summarizes the performance of each sensor. The DIP sensors have the poorest performance, while the ABD/ADD sensors have the best performance. However, the analysis of the DIP and ABD/ADD sensors performance across the four tests shows that this is true for tests A and B, but not for tests C and D. This finding may suggest that gripping the mold does not stabilize the fingers joints as does placing the hand flat.

ICC analysis was conducted separately for each of the four repeatability tests. The ICC calculation was performed as follows: 2 out of the 10 data blocks were randomly selected; then for each data block, a trial out of the 10 trials available in the data block was randomly selected. The ICC for the two selected measurements was calculated. To evaluate the consistency of the estimated ICC, the preceding procedure was repeated 20 times and the average and SDs of the ICC were computed. The

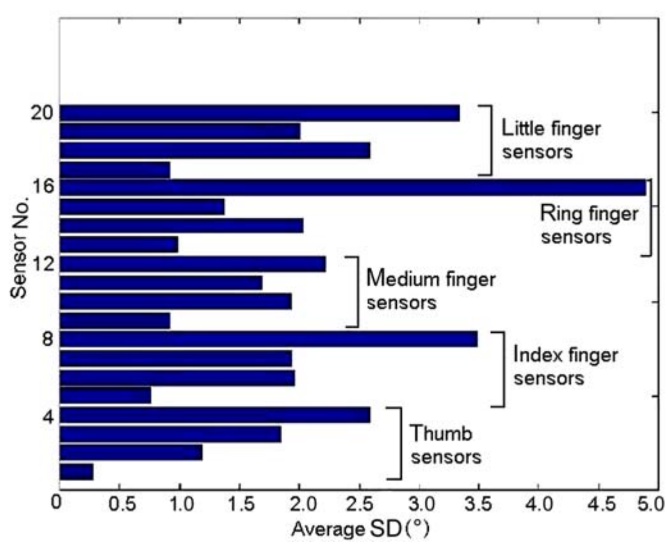

Figure 4.
Histogram of average standard deviation (SD) (average across four male subjects and across four tests) for measurements taken from each sensor. Sensors measure following movements: thumb ABD/ADD (sensor 1), flexion/extension of TMCP (sensor 2), MCP (sensor 3) and IP (sensor 4) thumb joints, index ABD/ADD (sensor 5), flexion/extension of MCP (sensor 6), PIP (sensor 7), and DIP (sensor 8) index joints. Similarly to sensors 5 to 8, sensors 9 to 12, sensors 13 to 16, and sensors 17 to 20 measure middle finger, ring finger, and little finger joint movements, respectively.

average ICC was in the range 0.70 to 1.0 for almost each channel and each test. Moreover, the ICC values were quite stable with regard to selection of data blocks. DOF16 reported low ICC values across the four tests A to D; this was not surprising (see also **Figure 4**). Low ICC values were also reported for DOF12 in test B and for DOF6 in tests C and D. As for the bad behavior of DOF6 sensor, a likely explanation is that when performing tests C and D, the palm of the hand did not keep consistent contact with the table. As shown in **Figure 4**, measurements taken by the DIP sensors were more erratic than those taken by the other sensors. This might account for the results related to DOF12, although it is not clear why only the sensor related to this DOF suffered from poor performance and just in test B.

Figure 5 shows typical results of test T1 (**Figure 5(a)** and **(b)**) and test T2 (**Figure 5(c)** and **(d)**). For each of the four male subjects, maximum and minimum values across test T1 and across test T2 have been identified. Data on **Table 2** show the average range (difference between maximum and minimum values) obtained across the four subjects for each sensor, both for test T1 and test T2. Grip force had an effect on measurements, and the measurements taken from DIP joints sensors were the most affected. This is due to inadequate stabilization of the DIP joints by the mold, so it may be that the glove does not fit adequately to the terminal part of the fingers. Wrist flexion/extension affects measurements as well, and as shown by results from test T1, the measurements taken from DIP joints are the most affected. We propose a similar explanation of this behavior to that reported as for the results of test T1. In our tests, we controlled the effect of grip force by asking the subjects to apply a grip force as low as possible. We controlled the wrist flexion/extension effect by asking the subjects to keep the wrist in a neutral position.

DISCUSSION

The experimental procedure in this paper was first proposed by Wise et al. [8]. It could be argued that the experimental protocol is not very precise. For example, the measurement error that was investigated may be, in fact, a combined result from different factors, such as movement variation, glove instability, or glove inaccuracy. However, it would be quite complicated to identify the weight of these factors on the total measured error. In

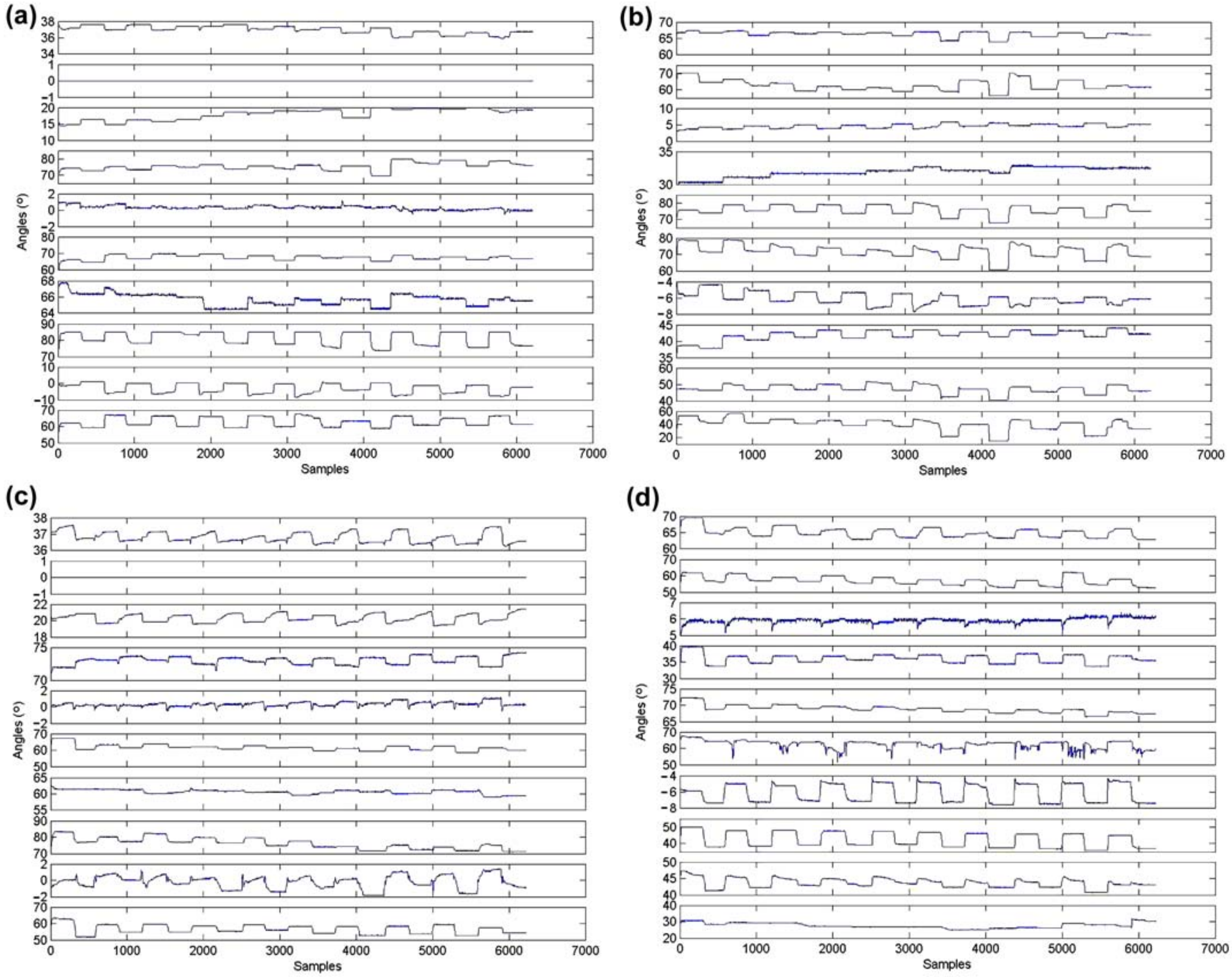

Figure 5.
Grip force test results and wrist flexion/extension test results for subject 4: **(a)** Grip force test results (test T1); starting from top, data related to DOF1 to DOF10 and **(b)** to DOF11 to DOF20. **(c)** Wrist flexion/extension test results (test T2); starting from the top, data related to DOF1 to DOF10 and **(d)** to DOF11 to DOF20.

addition, at this stage of our work, our target was to investigate the overall repeatability performance of the system. Moreover, it must be pointed out that only a few descriptions of testing protocols and experiments that evaluated glove device's characteristics are available in literature [8–12]. The significant parameters chosen for

Table 2.
Average values (°) of differences between maximum and minimum values of measurements across four male subjects during test T1 and test T2 for DOF1, 3, 5–7, 9–11, 13–15, and 17–19. Values related to DIP sensors and sensor 2 have not been reported here.

Test	1	3	5	6	7	9	10	11	13	14	15	17	18	19
T1	1.33	8.01	2.43	10.55	16.13	5.20	10.86	8.31	0.95	5.43	9.16	2.89	11.91	14.27
T2	1.05	3.79	1.97	10.78	12.05	5.06	13.67	6.37	0.92	11.19	4.18	5.30	13.65	13.69

data analysis in this paper are similar to those proposed by Wise et al. In addition, an ICC analysis, particularly suitable to repeatability investigation, was completed. Humanglove repeatability testing on four male subjects showed an overall error of 6.17° (average across the four tests and the four male subjects). Data were also acquired from two female subjects. As expected, range was higher than that related to male subjects because of inadequate fitting of the glove to hand size of the female subjects. Importance of adequate fitting of the glove to the hand size was also shown by results related to DIP sensors that had, overall, the poorest performance.

The ICC analysis showed, in general, high ICC values for almost every channel (0.70 to 1.0). The primary motivation of this study was to evaluate the repeatability of measurements taken from the Humanglove sensors to discern the suitability of the Humanglove for applications in the rehabilitation field. In addition, this evaluation would allow comparisons with the performance of other gloves, both commercial and not commercial. With regard to repeatability, the results presented here show that the Humanglove could be suitable for semiautomated goniometric measurements in rehabilitation. We believe the suitability for rehabilitative applications to be an important issue, because in this field, a general lack of instruments for hand-function assessment exists.

Results presented here show that the Humanglove has improved performance compared to manual measurements. The reliability of a skilled therapist was 7° or less in 95 percent of repeated trials with measurements on two different goniometers. Average physical therapists were within 7° in 62 to 72 percent of trials [3,8]. In a study of intertester and intratester reliability, a change of 3° or 4° of goniometric ROM was required to improve the intratester reliability for upper limbs [8]. As for the intertester reliability, an increase in joint motion should exceed 5° for the upper limbs before improvement is determined [8]. Results of the Humanglove testing show an overall error of 6.17°; this error is comparable to that incurred in the case of manual goniometric measurements. However, the glove has important advantages.

First of all, the measurement process can be automated. Implications of those advantages are that hand assessment performed with the Humanglove could be less time-demanding for the hand therapist and the patient as well. This, in principle, could reduce costs of rehabilitative treatments; however, in practical terms, it remains to be elucidated whether the added expense of the glove and software would make the overall system appealing for clinical use.

The second advantage is that the glove allows dynamic (and simultaneous) recording of all hand joints during execution of dynamic tasks, while presenting several advantages in comparison to instruments used at present for the same purpose. Dynamic digital ROM measurements can be obtained via systems, such as electrogoniometers and motion-analysis systems. With the former, simultaneous ROM acquisition from all hand joints is still a hard task. Motion-analysis systems that consist of cameras tracking trajectories of markers placed on patient's anatomical landmarks are presently used for research rather than for clinical assessments [22,23]. The systems' main disadvantages when used for hand-movement assessment are due to marker placement, which suffers from poor repeatability, besides being time-demanding. Another major disadvange is due to the need (for many systems) of an accurate setting of workspace for hand movements performed by the patient during assessment. For systems using passive markers, accurate camera placement is needed as well, because markers could be occluded during the execution of the hand assessment test.

A third advantage is that several studies have pointed out that disability evaluation should include measurements of the patient's ability to perform functional tasks, which, ideally, should be very similar to those required in their job setting. However, disability is assessed with the use of detailed tables, where each deficit is expressed quantitatively [1]. Time-based assessment tests are also used sometimes. In these tests, the patient is required to manipulate several items while time needed to accomplish the task is monitored [4]. Since the glove allows for detailed analysis of hand-movement data and is quite easy to use, it may be useful for augmenting the traditional approaches to hand-function assessment, e.g., to perform better evaluations of disability.

Finally, the glove could be an optimal solution for performing hand-data acquisition in all those environments where very simple and easy-to-use devices are needed, e.g., in zero gravity environments [24], where motion analysis systems could be unavailable and other systems (e.g., goniometric systems) could be too time-demanding.

Comparison of Humanglove performance versus other glove devices performance is difficult, because of the lack of standard glove testing protocols and technical parameters widely accepted as significant. Since the protocol proposed by Wise et al. was used in this work [8], a qualitative comparison can be made with the Data Glove tested in their paper. Repeatability performance of the Humanglove and Data Glove appears to be comparable. In fact, the overall error reported for Data Glove is 5.6°, but it must be considered that the Humanglove testing involved 19 sensors, while the Data Glove version tested by Wise et al. had 10 sensors and testing was done on 8 sensors only [8]. Errors of finger flexion sensors approximating ±5° were also reported for the SIGMA Glove, tested with a similar experimental procedure and for the Cyber Glove [12].

Finally, regarding the feasibility of using the Humanglove in different rehabilitation engineering frameworks, we believe the Humanglove measurement performance is suitable for most gesture-based applications [6]. Among them, in recent years, applications of glove devices as man-machine interface in aids for the disabled based on sign-language understanding have become quite popular. In such systems, a set of hand gestures is recorded through a glove device, recognized by a gesture recognition software, and used by motor-impaired people for machine control or by deaf and/or vocally impaired subjects for human communication. The former systems have been developed to allow even subjects with severe motor disabilities to remotely control devices through simple hand gestures. The latter systems usually translate sign languages into text or synthetic voices that allow deaf and/or vocally impaired subjects to communicate outside their community (e.g., to talk on the telephone or to people who do not speak sign languages). Usually, in these applications, glove devices are not required to have measurement performance as restrictive as in applications for goniometric devices. In fact, in this case, the problem is to know how many different hand postures can be recognized by the device. Even if measurements made by the sensors are not highly repeatable, their output values would be adequate for clustering, i.e., creating classes of angle measurements by dividing the whole angle range, such that a number of patterns would be determined for each joint (e.g., flexed, half-flexed, and extended) [10].

CONCLUSIONS

The repeatability of measurements taken from the Humanglove is adequate to recommend the system for several applications in the field of rehabilitation engineering. It is comparable to repeatability of manual goniometric measurements in normal subjects, so in principle, the Humanglove can function as goniometric device for digit ROM acquisition. Moreover, as an additional advantage, the glove dynamically acquires data simultaneously from 20 hand DOFs, including ABD/ADD of fingers and thumb. This latter feature is quite interesting, since most commercial gloves lack sensors to acquire those data. Potential sources of errors in measurements have been discussed as well. Finally, the Humanglove is also suitable, in principle, for a number of applications in rehabilitation engineering research, such as dynamic functional-hand assessment, motion analysis to assess hand-movement patterns, and in aids for motor or vocally impaired subjects. Future research will be aimed at investigating accuracy of Humanglove measurements.

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