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Enhancement of Bend Sensor Properties as Applied in a Glove for Use in Neurorehabilitation Settings

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Abstract— **Following hand function impairment caused by a neurological disorder, the functional level of the upper extremities has to be assessed in the clinical and rehabilitation settings. Current hand function evaluation tests are somewhat imprecise. Instrumented gloves allow finger motion monitoring during the performance of skilled tasks, such as grasping objects. As a result, they provide an objective tool for evaluating slight changes in the fine motor skills of the hand. Numerous gloves are based on resistive bend sensors, given that this is an easy to handle, low-cost, and reliable sensing element. When bending is not applied homogeneously along such a sensor, as is the case with finger-joint bending, its output response varies with the sensor's longitudinal position. Our goal is to determine the optimal sensor position with respect to the finger-joint in order to enhance the resolution of the sensors embedded in a glove. The validity of the integrated sensors is evaluated and the accuracy values are given.**

I. INTRODUCTION

Hand function impairment resulting from neurological disorders such as quadriplegia and stroke has to be assessed in order to establish recovery over time as well as determine the efficiency of surgical interventions and rehabilitation treatments. Hand function assessment tests commonly carried out in the clinical field, such as the Sollerman [1] and Fugl-Meyer [2] tests, are subjective and somewhat imprecise, given that they evaluate hand function on an ordinal scale. Therefore, a tool that can objectively and precisely assess changes in hand function level is required.

Instrumented gloves make it possible to monitor hand motion. This technology has important advantages. First, it allows the simultaneous recording of dynamic finger movements during the performance of skilled tasks, such as grasping objects. Secondly, it offers an objective tool for evaluating slight changes in the fine motor skills of the hand. Finally, instrumented gloves make it possible to measure a patient's capacity during the execution of activities of daily living tasks. Commercialized instrumented gloves, such as the Nintendo Power Glove (Abrams/Gentile Entertainment Inc.), the Cyberglove II (Virtual Technologies Inc.), the P5 Glove (Essential Reality Inc.), the Data Glove (VPL Research Inc.), the 5DT Glove (5DT Inc.), and the Peregrine Glove (theperegrine.com), have mainly been developed to improve the human/machine interface in virtual reality environments and computer games as well as to facilitate sign language recognition [3]. By contrast, in academia, most gloves, such as the Wü-Glove [4], the Shadow Monitor Glove [5], and the Sigma Glove [6], have been developed to assess hand function in clinical and rehabilitation settings.

Among the different sensing technologies used to develop instrumented gloves, resistive bend sensors offer the most easy-to-handle, low-cost, and reliable alternative. For this reason, the main gloves are currently based on this sensing element. In this study, we demonstrate that when bending is not applied homogenously along a resistive bend sensor, as is the case with finger-joint bending, a change in the sensor's longitudinal placement affects the sensor output response. Our goal is to determine the optimal sensor position with respect to the finger joint to enhance the resolution of the sensors embedded in a glove that we have developed - the NeuroAssess Glove. The incorporated sensors are validated for accuracy, and the 95% confidence interval is given.

II. MATERIAL AND METHODS

A. NeuroAssess Glove

1) Glove Description: The NeuroAssess Glove is a stretchable polyamide/Lycra glove designed to monitor finger flexion as well as palmar and dorsal flexion of the wrist. The glove is equipped with six polyester over-laminated bend sensors (Flexpoint Sensor Systems, Inc., Draper, UT). These sensors contain a carbon-based ink whose resistance increases with bending. This sensor brand displays a stable signal over time. This stability is increased further with a polyester over-lamination process. As shown in Fig. 1, the glove has integrated sleeves into which the sensors are inserted. Four 50.8-mm (2-in) sensors cover the index metacarpophalangeal (MCP), proximal interphalangeal (PIP), distal interphalangeal (DIP), and thumb interphalangeal (IP) joints. These finger-joints are monitored, given that they present the greatest bending angle changes during grasping movements [7], [8]. Two 76.2-mm (3-in) sensors cover the radiocarpal (RC) joint to determine if patients make compensatory movements with the wrist. One sensor monitors palmar flexion, and the other one monitors dorsal flexion of the wrist. The glove exists in three different sizes: small, medium, and large.

2) System Description: The NeuroAssess Glove is connected to an 8-channel, 12-bit, 10kS/s NI-6008 analog digital converter (National Instruments Corp., Austin, TX). The converter is wired to a portable computer via a USB cable. The raw data are sampled continuously at 100 Hz using LabVIEW (NI Corp., Austin, TX). The resistance of a polyester over-laminated 50.8-mm bend sensor varies from

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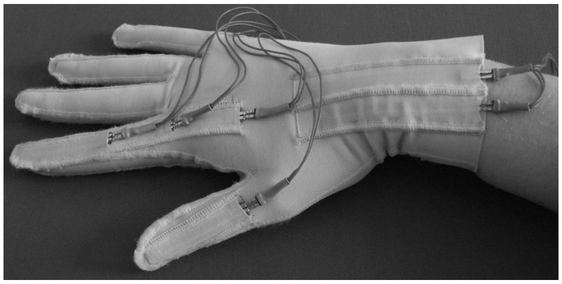

Fig. 1. Medium hand size of a subject wearing the NeuroAssess Glove. The glove has integrated sleeves into which bend sensors are introduced. Four 50.8-mm (2-in) sensors are used for finger flexion monitoring and two 76.2-mm (3-in) sensors for palmar and dorsal wrist flexion monitoring.

about 11 kΩ, when put in a flat position, to 130 kΩ, when bent beyond 180°.

3) Calibration: A common way to convert the sensor output voltages into angles in degree is to perform a calibration procedure before each measurement session. In this procedure, a traditional goniometer is used to measure a few finger bending angles, and the corresponding sensor output voltages are determined. From these voltage-angle pairs, a linear or nonlinear relationship is established from which output voltages can be converted into angles. Such a calibration procedure is tedious, time-consuming, and a source of inaccuracy [3]. In the case of the NeuroAssess Glove, a program converts the sensor output voltages into angles in degree by reading lookup tables. Each sensor lookup table is based on the average of three voltage-versus-angle curves. These reference curves are pre-measured by means of an automated instrument. This instrument comprises a dummy finger part whose joint is covered by the sensor. The finger part executes 0.5° steps in a 0°-135° range. The sensor is first bent from 0° to 135° and then opened out from 135° to 0°. To take into account the sensor hysteresis, only the curve measured when the sensor is opened out is considered. The sensor hysteresis measured after one joint closing and opening cycle is, however, very low (between 0% and 1.3%). The advantage of this pre-measurement system is that the lookup tables are based on real measurements and not on regression lines or interpolation curves. Moreover, this method saves a significant amount of time.

B. Sensor Characterization

The output signal of a 50.8-mm bend sensor is nonlinear overall. Though, it contains a partly linear region and a saturation region. Each sensor of the glove is connected in series with a resistor. The constant voltage input received by the circuit is 5 V and the output voltage is measured from the sensor. In order to determine the optimal amount of series resistor, a simulation program is implemented with LabVIEW. This program approximates the sensor output response by a polynomial function and simulates a resistor connected in series with the sensor. The polynomial function is obtained with a Newton interpolation using MATLAB (The Mathworks Inc., Natick, MA). The simulation program shows that a 33-kΩ series resistor maximally increases the sensor measurement region. To validate this simulation, the output responses of the sensor are measured as a function of the bending angle with series resistors of 10, 22, 33, and 68 kΩ. For each series resistor, three voltage-versus-angle curves are measured and their average is taken into account.

During palmar and dorsal flexion of the wrist, bending is applied homogenously along the 76.2-mm sensors that cover the radiocarpal joint. Indeed, the RC joint, like the MCP joint, is ellipsoid, whereas the DIP, PIP, and IP joints are hinge joints. During finger-joint flexion (except for the MCP joint), bending is not applied homogenously along the 50.8-mm sensor. As a consequence, the following questions arise: Does the longitudinal placement of the sensor with respect to the finger joint affect the sensor curve? And if so, to what degree? To answer these questions, the sensor output response is measured as a function of the bending angle for different sensor locations. The sensor is placed at distances of 15, 20, 25, 30, 35, and 40 mm from its proximal end on the dummy finger joint of the automated instrument. Fig. 2 shows the different sensor bending locations. Here also, the curve measured when the sensor is opened out from 135° to 0° is taken into account. For each location, three voltage-versus-angle curves are measured, and their average is considered.

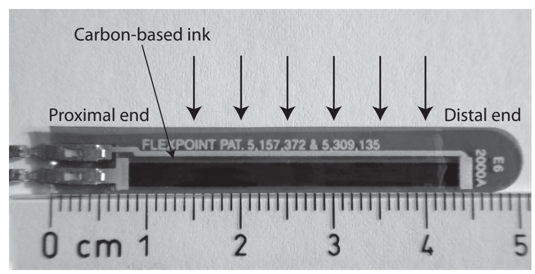

Fig. 2. Different bending locations of a 50.8-mm resistive bend sensor used to monitor finger joint motion.

In order to establish if the reproducibility of the sensor varies with the bending location, the three repeated voltage-versus-angle curves are assessed separately for each bending location. Two sensor signals measured at two different times are compared using Lin's concordance correlation coefficient (LCCC). LCCC is a reproducibility index that evaluates the agreement between two readings by measuring the closeness of the data about the 45° line through the origin. According to Lin, this index has a better accuracy than other reproducibility indexes such as the intraclass correlation coefficient [9]. For each bending location, the average of three LCCCs obtained between three sensor curves is considered.

C. In Vivo Measurements

Once the optimal sensor region that needs to be placed on the dummy finger joint is determined, lookup tables are created. To guarantee a maximal accuracy of the glove, the same sensor region is placed on the real joints during finger flexion monitoring. The sensors' proximal ends are fixed to the glove cloth with medical tape to avoid sensor displacement during finger motion recording. The accuracy of the sensors embedded in the glove is evaluated in one subject by asking the person to bend each finger joint 30°, 60°, and 90°. The angles measured with the sensor are compared with the angles measured using a traditional goniometer (Type F35 operating with a K100 Amplifier, Biometrics Ltd., Gwent, UK). For each joint and each bending angle, five measurements are carried out.

III. RESULTS AND DISCUSSION

A. Sensor Characterization

The output responses of the sensor are measured as a function of the bending angle with a series resistor of 10, 22, 33, and 68 kΩ and are displayed in Fig. 3. These results validate the simulation program and confirm that a 33-kΩ series resistor maximally increases the sensor measurement region.

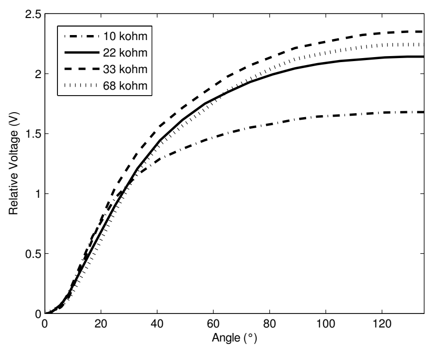

Fig. 3. Output responses of a 50.8-mm sensor as a function of the bending angle with a series resistor of 10, 22, 33, and 68 kΩ.

The sensor output responses are measured as a function of the bending angle with different sensor positions, and the results are displayed in Fig. 4 (with a 2° interval to make the graphic more readable). For small angles, when the sensor bending site is at the distal end, the sensor response tends to have a lower amplitude than when the bending site is at the proximal end. Inversely, for larger angles, when the bending site is at the sensor's distal end, the sensor curve tends to have a higher amplitude than when the bending site is at the proximal end. Furthermore, when the sensor is bent at a distance between 30 mm and 40 mm from its proximal end, the resolution is 0.5° over the whole 0°-135° range. In this study, however, the resolution is limited to 0.5°, given that the sensor responses are measured at an equivalent interval. By contrast, when the sensor bending location is below this distance, the overall resolution is poorer. The resolution of each curve is extracted from the average of the three repeated measurements and therefore corresponds to the resolution of the lookup tables. The 35-mm and 40-mm sensor-distance curves show an important discrepancy. If the sensor, disregarding the fact that it is fixed, slightly moves from its initial position, its output response will be strongly affected by the displacement. In contrast, if the sensor is bent at a distance between 15 mm and 30 mm from its proximal end and slightly moves, the sensor curve will not be modified much. The 30-mm bending location from the sensor's proximal end offers the best compromise between a high resolution and a low discrepancy. Accordingly, we decide to place the sensors at this distance on the finger joints. Thus, the sensors embedded in the glove have a 0.5° resolution in the 0°-135° range. If they move slightly from their initial positions, their output responses are not modified much by the displacement.

TABLE I
SENSOR REPRODUCIBILITY EVALUATION

Distance (mm)	ρ_c
15	0.9961
20	0.9959
25	0.9960
30	0.9961
35	0.9960
40	0.9960

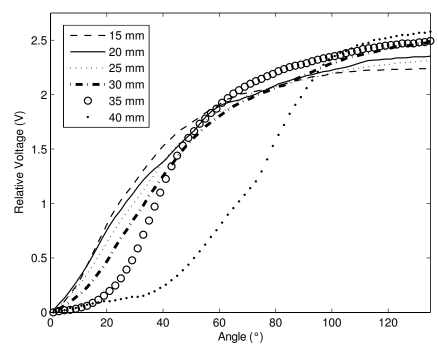

Fig. 4. Output responses of a 50.8-mm sensor as a function of the bending angle with bending locations of 15, 20, 25, 30, 35, and 40 mm from the sensor proximal end.

The bend sensor consists of a proprietary carbon/polymer-based ink, which is printed on a thin and flexible polyimide substrate, and the whole is over-laminated with polyester. The ink is very hard and brittle. When the sensor is bent, the ink separates into many microcracks, thereby increasing the resistance [10]. We observed that when bending is not applied homogenously along the longitudinal axis of the sensor, the location where the microcracks appear affects the sensor response.

The LCCC values, resulting from the reproducibility evaluation, and the corresponding bending distances from the sensor's proximal end are given in Table I. The LCCC values obtained for each position are very similar. These results show that the sensor is highly reliable, whatever its bending location.

B. In Vivo Measurements

The 50.8-mm sensors are introduced inside the sleeves of the glove with the sensors covering the finger joints at a 30-mm distance from their proximal ends in order to obtain both a high resolution and a low discrepancy. The sensors' proximal ends are fixed to the glove cloth using

TABLE II

SENSORS EMBEDDED IN THE GLOVE ACCURACY EVALUATION

Finger joint	Angle measured (°)	Mean difference (°)	SD of difference (°)	95% confidence interval (°)
DIP	30	-2.1	1.2	-4.5 to 0.3
DIP	60	1.0	1.5	-1.9 to 3.9
DIP	90	-1.9	1.3	-4.5 to 0.7
PIP	30	-1.6	1.1	-3.7 to 0.5
PIP	60	-2.0	1.7	-5.3 to 1.3
PIP	90	0.8	0.4	-0.1 to 1.7
MCP	30	-1.6	0.9	-3.4 to 0.2
MCP	60	1.9	1.3	-0.6 to 4.4
MCP	90	0.1	1.3	-2.4 to 2.6
IP	30	2.3	1.6	-0.9 to 5.5
IP	60	1.0	1.3	-1.5 to 3.5
IP	90	-1.1	1.9	-4.8 to 2.6
Mean		**-0.3**	**1.3**	**-2.8 to 2.3**

medical tape to avoid sensor displacement during finger motion monitoring. The accuracy of the sensors embedded in the glove is evaluated. The angles measured with the sensor are compared with the angles measured using a goniometer. The mean difference between the angles measured with both methods, the standard deviation (SD) of the difference, and the 95% confidence interval are calculated and are given in Table II. The results show that, across sensors and angles, the average difference between the angles measured with each method is small (-0.3°). Thus, a systematic error can be neglected. Furthermore, the average 95% confidence interval of the NeuroAssess Glove is within $\pm 3°$. In comparison, this interval is within $\pm 5°$ for the Sigma Glove, the Cyberglove, and the Data Glove [6]. In contrast to the NeuroAssess Glove, these gloves require an ordinary calibration procedure.

A Bland-Altman graphic (Fig. 5) illustrates the agreement between sensors embedded in the glove and traditional goniometry. The horizontal dotted line indicates the average difference between the angles measured with each method (the bias), whereas the two solid lines are the 95% confidence interval boundaries. The graphic shows that the agreement gets slightly higher as the average angle increases. Consequently, the accuracy of the integrated sensors depends somewhat on the magnitude of measurement. Given that the sensor resolution is 0.5° over the entire 0°-135° range and that the most scattered points around the bias line do no correspond to specific finger joints, we assume that the incorporated sensors are not the cause of this trend. An explanation could be that the subject reported a slight difficulty to keep the finger completely still when bending it with a 30° angle.

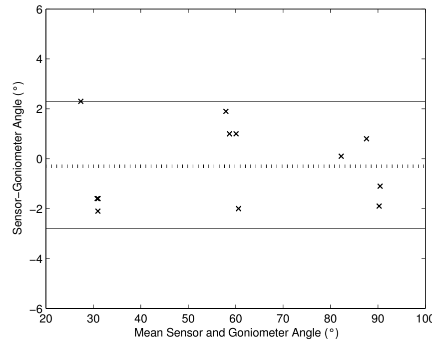

Fig. 5. Bland-Altman graphic illustrating the agreement between the sensors embedded in the glove and traditional goniometry.

IV. CONCLUSION

New instrumented gloves are regularly developed in fields as different as virtual reality, computer gaming, sign language understanding, and clinical and rehabilitative hand function assessment. Most of the current gloves are based on resistive bend sensors, given that this sensing element is easy to handle, low-cost, and very reliable. We emphasize the importance of the sensor positioning when bending is not applied homogenously along the sensor, as is the case with finger bending. Indeed, a longitudinal displacement of a few millimeters with respect to the finger joint changes the shape of the sensor's voltage-versus-bending angle curve. This can be a drawback when trying to obtain repeatable measurements, depending on the initial sensor position. In this study, the sensor bending location that provides both a high resolution and a low discrepancy for a bend sensor glove is determined. This position is located 30 mm from the sensors' proximal ends. Finally, the accuracy validation of the sensors embedded in the glove shows that its 95% confidence interval is largely within the interval established for other validated gloves.

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