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Development and evaluation of a sensor glove for hand function assessment and preliminary attempts at assessing hand coordination

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ABSTRACT

Quantitative measurement of hand kinematics can help us to better understand pathophysiological aspects of finger neural control and quantify hand impairments. A sensor glove was developed based on resistive bend sensors and resistive force sensors to monitor finger joint angles and forces exerted to objects by fingers. The validity and reliability of the glove were evaluated. A novel method was proposed to visualize and quantify the abnormality of the inter-joint coordination. The validity test indicated that the accuracy error of measuring joint angles was approximately ±6° and that of measuring forces was approximately ±8 g. The reliability test yielded an intraclass correlation coefficient of 0.9876 ± 0.0058 for the force sensors and 0.9561 ± 0.0431 for the bend sensors. The stability, accuracy and reliability of measuring joint angles were comparable with previous studies. The involvement of force sensors and the capacity of reflecting inter-joint coordination make the glove more comprehensive for hand function assessment.

1. Introduction

Hand function impairments caused by neurological disorders such as stroke affect a person's capacity of independent living and the quality of life. Studies have shown that training based on rehabilitation robots [1], functional electrical stimulation [2], non-invasive brain stimulation [3] and virtual reality systems [4] can effectively help patients restore their motor function of upper limbs. Function assessment should be conducted throughout the rehabilitation process to guide intervention treatments. The traditional clinical hand function assessment is based on ordinal scales, such as the Modified Ashworth Scale [5] and the Fugl-Meyer Scale [6] and focuses on the accomplishment of activities of daily living (ADL)-based tasks, such as the Action Research Arm Test [7]. Assessment tests based on ordinal scales have some defects. First, they are subjective and imprecise [8]. Second, they are incapable of reflecting hand kinematics during the performance of ADL-based tasks. Quantitative characterization of hand movements is of great significances, not only for understanding pathophysiological aspects of finger neural control but also for quantifying impairments of hands, guiding appropriate therapies and assessing the effectiveness of treatments. Therefore, an instrument that is objective, accurate and capable of recording hand kinematics is needed for clinical hand function assessment.

Various sensor gloves [9–12] have been developed by researchers for dynamic recordings of finger bending angles during the performance of skilled tasks, such as grasping objects. Commercial sensor gloves include the Cyberglove II (Virtual Technologies Inc., Palo Alto, CA), the 5DT Data Glove Ultra (Fifth Dimension Technologies, Irvine, CA), the P5 Glove (Essential Reality Inc., Mineola, NY) and the Humanglove™ (Humanware S.R.L., Pisa, Italy) [13]. These gloves present some drawbacks, such as sensor signal drift, high cost, incapability of monitoring metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints respectively and/or inability to fit different hand sizes. Some of the gloves have not been assessed for the validity and/or reliability. The researches of Oess et al. [9] and Gentner and Classen [10] are notable for they tested the validity and reliability of their gloves and proved that the gloves were competent for clinical use. High cost is another factor that sets back the clinical application of sensor gloves. Low-cost resistive bend sensors have been utilized in previous studies

Abbreviations: ADL, activities of daily living; MCP, metacarpophalangeal; PIP, proximal interphalangeal; IP, interphalangeal.

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[9–11]. However, as the bend sensors must be located exactly over the dorsal aspects of the MCP and PIP joints, gloves of different sizes have to be fabricated to fit different hand sizes, which will increase the cost. This is especially true when bend sensors are embedded and fixed in the gloves.

A common drawback of all gloves mentioned above is the inability to measure finger strength. The assessment of finger strength is of great significances for the later stage of recovery. In the Fugl-Meyer Scale [6,14], the strength is measured as the ability to grip a pen, a small can or a scrap of paper when others attempt to pull them out with a little tug. It can be determined by the magnitude of forces that are exerted to objects with fingers. As far as we know, all gloves mentioned above cannot monitor force magnitudes. Therefore, they are incapable of providing objective and quantitative measurements of the finger strength.

Hand function impairments caused by injures to the central nervous system result in not only a limited range of motion and feeble finger strengths, but also impaired hand coordination. Some researchers have conducted studies on the hand coordination of post-stroke patients [15,16]. Martin-Martin and Cuesta-Vargas tried to assess hand function by combining muscle activations and functional kinematics when subjects performed the Southampton Hand Assessment Procedure [17]. Limb coordination was often evaluated by studying the appropriateness of limb kinematic conditions. Gait coordination has been widely studied. A conventional method is to investigate the relationship between joint kinematics at some "critical moments", such as the moment when heels touch the ground [18]. However, there are numerous kinds of hand movements and none of them has such obvious "critical moments". Although sensor gloves can dynamically record joint angles, there is still no efficient way to reflect the angle relationship of different finger joints directly and assess the hand coordination.

In this study, a sensor glove, termed as the FuncAssess Glove, based on resistive bend sensors and resistive force sensors was developed. Bend sensors were placed on the dorsal sides of finger joints to monitor their bending angles. Force sensors were placed on the finger prominences to measure forces exerted to objects. The stability, validity and reliability of the glove were evaluated. Furthermore, a novel method was proposed to reflect the angle relationship of different joints for hand coordination assessments based on the FuncAssess Glove.

2. Method

2.1. Sensor selection and glove design

Sensor stability has been assessed for bend sensors from Flexpoint Sensor Systems (Draper, UT), Abrams Gentile Entertainment, Inc. (New York, NY) and Spectra Symbol (Salt Lake City, UT) in previous studies [9–11,19]. Bend sensors from Flexpoint Sensor Systems present the greatest sensor stability among them. Flexpoint bend sensors of three sizes are available and they are 4.5-in, 3-in and 2-in sensors respectively. For each size, Flexpoint typically supplies three kinds of configurations. They are sensors with a polyimide over-laminate, a polyester over-laminate and bare sensors without an over-laminate. It has been demonstrated by Oess et al. [9] that the bare 4.5-in sensors have the smallest drift of approximately 0.9% and the bare 3-in and 2-in sensors have 8.25% and 18.2% drifts respectively. In spite of the smallest drift, the 4.5-in sensor was not selected in the FuncAssess glove, because it is so long that it will cover both MCP and PIP joints. Gentner and Classen [10] were able to decrease the drift of the bare 2-in sensors to approximately 1% by fixing a thin unplasticised polyvinyl chloride foil over the carbon layer on the front side of the sensor. Oess et al. [9] first demonstrated that the 2-in sensors with a polyester over-laminate also showed a high sensor stability with a drift less than 1%. In previous studies, force sensors were rarely used in sensor gloves for hand function assessment. O'Flym et al. [20] designed a novel smart sensor glove for the arthritis rehabilitation which utilized Force Sensing Resistor (FSR) sensors from Interlink Electronics, Inc. (Los Angeles, CA), but the sensor stability was not evaluated. Tekscan (Tekscan, Inc. South Boston, MA) supplies a series of force sensors named Flexiforce that have been widely used for force measuring.

According to the results mentioned above, the 2-in (50.8 mm) bend sensors with a polyester over-laminate from Flexpoint were selected for the FuncAssess glove because the modification to the bare sensors was not needed, thereby decreasing the complexity for fabricating the glove. Its width and thickness is 7.1 mm and 0.125 mm respectively. The length of the sensing area is approximately 35.3 mm. The resistance changes approximately from 10 kΩ to 80 kΩ when the sensor is bent from a position of 0–90°. Two kinds of force sensors were analyzed in this study in view of their appropriate sizes. They were Type A301 from Tekscan and type FSR402 from Interlink Electronics. The thickness, length, width and diameter of the sensing area of A301 are 0.208 mm, 25.4 mm, 14 mm and 9.53 mm respectively. The thickness and diameter of FSR402 are 0.46 mm and 18.29 mm respectively. The diameter of its active area is 12.70 mm. The resistances of both A301 and FSR402 are at the level of megohm when no load is applied. When a load is applied, it changes to the level of kilohm. Sensor stability was evaluated, which will be described in part 2.2. And the force sensor with a high stability was used in the FuncAssess glove.

The FuncAssess glove was fabricated out of stretchable cloth (Fig. 1(a)). Sleeves were integrated to the glove over the dorsal aspects of the MCP and PIP joints of the index finger (I), the middle finger (M), the ring finger (R) and the little finger (L). For the thumb (T), sleeves were placed over the MCP and interphalangeal (IP) joint. Ten bend sensors were inserted into the sleeves respectively and marked as 'T-MCP', 'T-IP', 'I-MCP', 'I-PIP', 'M-MCP', 'M-PIP', 'R-MCP', 'R-PIP', 'L-MCP' and 'L-PIP'. Snap-fasteners were used to fix the bend sensors, thus avoiding the slide of sensors when fingers flex and extend. As shown in the subfigure in Fig. 1(a), sleeves were also placed over the prominences of five fingers to insert force sensors. Force sensors were located there because finger prominences would always contact with objects in daily hand motions. Five force (FRC) sensors were marked as 'T-FRC', 'I-FRC', 'M-FRC', 'R-FRC' and 'L-FRC' respectively. Force sensors were not fixed within the palm area because sensors there may hinder the movement of hand and motions such as grasp can induce unexpected deformation of sensors thereby decreasing the accuracy of measurement. Unlike commercial gloves and the Wü-Glove [10], all sensors can be taken out of and put into the sleeves conveniently. Therefore, gloves of different sizes can share the same sensor system, which decreases the cost consequently.

Modifications were conducted to the force sensors in the current study. The sensing area is flexible and the deformation can change the resistance unexpectedly. For example, curved surfaces of finger prominences can cause deformations and then influence the resistance-load relationship of force sensors. In addition, the load should be applied the same way each time and distributed evenly across the sensing area to ensure accurate and repeatable force readings. To prevent sensor deformations and guarantee even load distributions, rigid circle slices were adhered to both sides of force sensors as shown in Fig. 1(b), (c) and (d). A 3-D printer with a machining accuracy of 0.1 mm was used to fabricate rigid slices. They were both 1 mm thick but with different diameters, i.e. 12.5 mm and 8 mm respectively. The slice with a 12.5-mm diameter was adhered to one side (termed as the reverse side) of the