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Design and Implementation of an Instrumented Data Glove that measures Kinematics and Dynamics of Human Hand

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Abstract— **Human hands are versatile biomechanical architectures that can perform simple movements such as grasping to complicated movements such as playing a musical instrument. Such extremely dependable and useful parts of the human body can be debilitated due to movement disorders such as Parkinson's disease, stroke, spinal cord injury, multiple sclerosis and cerebral palsy. In such cases, precisely measuring the residual or abnormal hand function becomes a critical assessment to help clinicians and physical therapists in diagnosis, treatment and in prescribing appropriate prosthetics or rehabilitation therapies. The current methodologies used to measure abnormal or residual hand function are either paper-based scales that are prone to human error or expensive motion tracking systems. The cost and complexity restrict the usability of these methods in clinical environments. In this paper we present a low-cost instrumented glove that can measure kinematics and dynamics of human hand, by leveraging the recent advances in 3D printing technologies and flexible sensors.**

I. INTRODUCTION

The human hand has a wide range of abilities to perform simple grasp movements to complex typing movements and playing musical instruments [1][2]. However, these abilities are too frequently disrupted by movement disorders such as Parkinson's disease (PD) [3] [4], and, paralysis caused by many other debilitating disorders like stroke [5] and spinal cord injury. Reliably measuring abnormal and/or residual hand function (by using instrumented gloves [6][7]) in such individuals is an important metric in clinical assessment that can help in diagnosis, therapy and rehabilitation.

Within individuals with stroke, about 70% of stroke incidences result in upper-extremity impairments for survivors [8]. Upper Extremity rehabilitation robotic devices are receiving more attention and development as the field of technology expands and becomes infused across various fields of work. The hand, a complex structure used in everyday activities such as eating, writing, grasping onto objects, etc., requires a multitude of sensors in a limited space. Comprised of 27 bones and over 30 muscles, there is much to take into account for when constructing robotic devices for hands [9].

Various forms of developed finger motion measuring systems can be used in post-stroke rehabilitation. The SmartGlove [10] consists of five multi-optical linear encoder (OLE) strips, each with two OLEs and a microcontroller mounted onto an off-the-self glove. The large sizes of the encoders and cables might hinder the natural movement of the fingers. The SmartGlove may also not accommodate various hand sizes in its design and lacks the abduction and adduction measurements.

The CyberGlove [11], a commercial hand movement tracking system has about 22 sensors to accommodate flexions and abductions, however, it does not accommodate all hand sizes as it is a one-size fits all. The CyberGlove has a minimum and maximum finger dimensions that limits the usage. If the subject’s hand size is outside of the suggested range, the sensors would not be in the correct position to measure the finger flexions. Additionally, the non-stretchable property constrains the sensors in a fixed location, which may cause skewed joint angle recording during the finger flexion and extension. Additionally, the high price of CyberGlove in fabrication method and materials chosen, pose a serious limitation for measurement and tracking of activities of daily living. Furthermore, current data gloves embed sensors into the fabric gloves and directly attach the sensors to a data acquisition (DAQ) module. Through repeated usage if the glove is damaged, the DAQ module will also be rendered useless.

The proposed data glove, SensoriGlove, aims to overcome these limitations by exploring a new design and fabrication method. By using a variety of thin, flexible sensors embedded in a passive tendon-like custom-designed 3D printed glove, the SensoriGlove maintains a low-profile, is cost-efficient, can be designed to fit custom hand sizes, and thus the design allows for more accurate readings. The SensoriGlove is designed to measure the degree of finger flexion and fingertip forces. This additional sensor adds the measurement of grip strength thus combining metrics of kinematics and dynamics.

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II. METHODS

Major aspects that influenced the final product design were the selected sensors, the fabrication method, and customizability. The design is comprised of low-profile flexible sensors that measure both finger flexion/extension and fingertip force. The SensoriGlove is a tendon-like design with 3D flexible print, which ensures accurate sensor placement over the desired location throughout all hand motions.

A. Model design

The SensoriGlove design is biomimetically inspired by the finger tendons. To mimic the tendon, the design included a thin layer of flexible plastic with embedded sensors resting on the top of the finger with the capability to extend as the finger flexions. In order to anchor the design to the finger and incorporate a force sensor on the pad of the finger, the material wraps around the tip of the finger creating a finger cap as shown in Fig. 1. The finger cap is folded during the gloves fabrication and secured via the wings (Fig.1 (a)). There is an embedded force sensor on the palm facing side of the finger cap that can be seen in the cross-sectional view of the finger design in Fig.1 (b). In the design, a cavity was made to house the force sensor along with a raised puck. The puck is a small, extruded area that concentrates the force applied to the finger to the sensor's active region. The wires from the force sensor are also embedded and extend to the base of the finger through a channel to the back of the hand.

Another feature in the finger cap is a thin plastic neck, which ensures that the SensoriGlove conforms to the fingertip by eliminating bowing caused by excess plastic along the width of the wire track. Along the dorsal side of the finger, a long tendon-like section of NinjaFlex (Adafruit Industries, NY, USA) extends from the fingertip to the wrist. Embedded in this section are two flex sensors. A 1-inch Tactilus (Sensor Products Inc., USA) flex sensor measures the angle of the proximal interphalangeal (PIP) joint, while a 2-inch sensor measures the metacarpophalangeal (MCP) angle. Distal Interphalangeal (DIP) is not considered due to the biomechanical joint angle correlation between DIP and PIP. The flex sensors are placed into cavities made in the design while the printer is paused. The wires are merged with the force sensor and continue in the proximal direction of the dorsal side of the hand. The entire finger piece is then connected to a wrist strap using a spring-like geometry. The inclusion of springs makes the glove stretchable, flexible, and adds to the tension in the SensoriGlove. The spring expands and contracts in conjunction with the fingers. The wires from the force and two flex sensors travel through a cavity down the center of the spring-like structure.

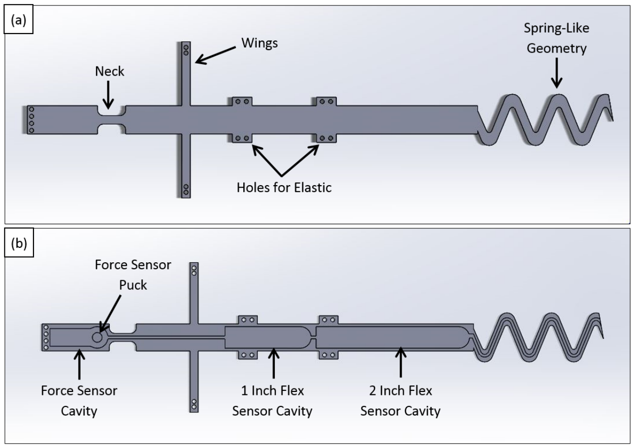

Figure 1. (a) The full view of the pointer finger designed. (b) A cross-sectional view of the pointer finger showing the sensor cavities and the puck location.

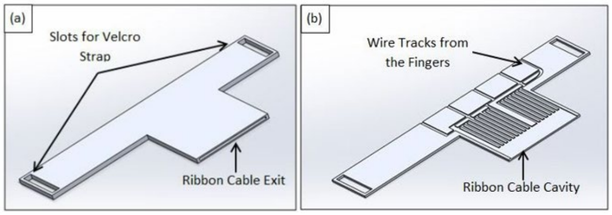

Figure 2. (a) The wrist strap section isometric view that contains slots for a Velcro strap. (b) A cross-sectional view of the wrist strap depicting wire tracks from the individual fingers to the ribbon cable.

The bottom of the SensoriGlove is a wrist strap structure that houses and organizes the sensing wires shown in Figure 2 (a). Each finger has three sensing units, making six wires per finger and 30 wires per hand. Half of the wires are for ground/reference, and the other half corresponds to sensors. The 15 sensing wires are organized in the wrist strap, Figure 2(b), and attached to a 20-pin ribbon cable wire. The ribbon cable is half embedded in the brace, and the exposed half is attached to a 20-pin connector. The 20-pin connector attaches directly to the ribbon cable and has the capability to connect the glove to a data acquisition (DAQ) module.

B. Fabrication

SensoriGlove embeds the sensors in a 3D flexible print. Of the various sensors researched, flexible sensors similar to those used in the CyberGlove were used based on sensing accuracy, cost, and overall size. The chosen sensor is available in two sizes, 1 inch and 2 inches, which can be used for the smaller and larger hand sizes. For these reasons, these sensors were chosen to be implemented in the proposed system. Additionally, sensors used to measure the fingertip forces were chosen based on the same criteria. A flexible, low-profile force sensor, FlexiForce A101 (from Tekscan, Inc., Boston, MA, USA), was selected. Both the FlexiForce A101 and the flex sensors are of the same thickness of 1 mm and a width no larger than 8 mm. The consistency of the different sensors' profiles makes it easier to implement in the proposed design.

3D printing is a layer-by-layer manufacturing technique where plastic is melted through a hot nozzle and deposited onto a build substrate. By using this method, the chosen sensors can be placed into cavities between layers of the print. The 3D printer has the capability to be paused at a certain layer height, making this process possible. Once it is paused, the force and flex sensors can be placed into the designed cavities, and the print can resume. The result is an embedded sensor glove. The embedded sensors limit outside noise from interfering with the sensors. Additionally, as a fabrication method, 3D printing not only the reduces the time consumption but also the cost of material. The material used in the printing the SensoriGlove is NinjaFlex (Adafruit Industries, NY, USA), which is a thermoplastic polyurethane (TPU) based material that offers flexibility, elasticity and high strength properties. The material is cost-effective and highly durable in comparison to the fabric-based materials.

For customizability, a measuring technique was implemented to customize glove to a particular person's hand. The SensoriGlove has 36 measurements to ensure a perfect fit, including each finger that has seven measurements (thumb has six measurements). The parameters include the distances in between the MCP, PIP, DIP, and fingertips (top and bottom), along with the width of the finger. The remaining measurements are the length and width of the wrist that are utilized in the wrist wrap section of the design. Measurement landmarks for the SensoriGlove are made with elastic bands. A thin elastic loop is worn at each joint of the hand and around the wrist. This loop ensures the glove is conformed to the subject's hand comfortably. Measurements between the elastic bands are repeated twice, and the average of the three measurements is determined. The finger width is measured using a caliper and is taken at the fingertip. The angle from the wrist to the individual finger is measured using a string and a protractor/ goniometer. All the measurements are recorded and automated into the design process. In the near future we aim to replace this process by 3D scanning the user's hand to obtain the measurements.

C. *Data Acquisition Module (DAQ)*

The data acquisition module (DAQ) module contains analog circuits which convert the varying resistances of the sensors into varying voltages. The force sensor circuit uses a single op-amp circuit similar to that recommended by the sensor manufacturer. The flex sensor circuit uses one op-amp circuit to convert the varying resistance of the sensor to a varying voltage, and a noninverting amplifier circuit to increase the amplitude of the signal for the 0-5V range of the microprocessor's analog inputs. The sensor glove is connected to the PCB through the ribbon connector on the left side of the board. The force and flex sensor circuits are grouped in the middle area of the board, and the microprocessor and the serial-to-USB converter chip are positioned to the right. The microprocessor digitizes the analog signals from the sensor circuits and outputs the digital measurements to its serial communication terminals. The USB communication chip reads the serial messages and communicates them over the micro-USB port on the right edge of the board. The board plugs into a PC, allowing any software capable of USB communication to record data from the device. For this prototype, the DAQ module communicates with a laptop or desktop computer over a wired USB connection into LabVIEW. However, our future DAQ modules may be capable of communicating wirelessly using Bluetooth or wifi. They may also interface with other devices than a laptop or desktop computer, such as a phone/tablet/mobile device, cloud server, purpose-built data logger, or standalone systems such as assistive or rehabilitative robotic devices, or other human-machine interfaces.

The resulting glove after fabrication is shown in Fig. 3. The glove did not have visible manufacturing defects (e.g., holes) and all sensors and wiring were fully embedded. The weight of the sensor glove for this subject was 32 grams. The final glove was then tested. During testing, the glove was able to be donned and doffed with one hand. The overall fit of the glove was contoured to the subject's hand in both the resting and flexing positions showing minimal slippage over the joints. The subjects were able to wear the glove for

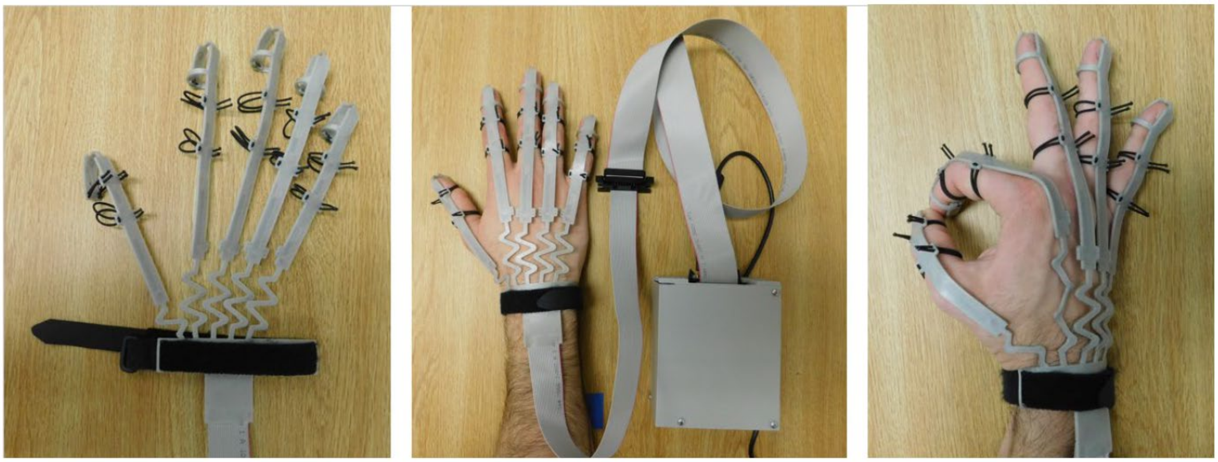

Figure 3. The design of SensoriGlove (Left). Glove connected to DAQ module via ribbon cable and a USB cable that connects it to computer (Center). An American Sign Language (ASL) posture showing the flexions of thumb and index finger and enslaving observed in other fingers (Right).

extended periods of time. The glove also did not irritate the skin and allowed the user to move freely. The low profile of the glove and sensors allowed the hand of the subject to operate naturally.

C. *Testing and Validation*

Ten heathy individuals (6F, 4M, mean (SD) age: 19.9 (1.4), handedness: 9R, 1L) were enrolled in this study after signing informed consent form. The protocol was approved by the Stevens Institute of Technology Institutional Review Board. Participants engaged in various object grasping and manipulation tasks using their hands while wearing CyberGlove (CyberGloveSystems, Inc.) and the Data Glove designed under this project. The CyberGlove was one-size-fits-all, but the Data Glove was designed in 3 sizes. The best fitting one was used and secured into place by us. The participants were asked to complete various tasks with each glove. Participants moved their hand into two calibration postures: placed flat on the table and in a tight fist close to the body. Then, a researcher would place a guide with a predetermined angle against each joint to have the joint mimic that angle. These set angles were 0, 45, and 90 degrees.

III. RESULTS AND DISCUSSION

The error analysis results used to determine the root mean squared error (RMSE) between the two gloves are shown in Figure 4. The data set used in this comparison is the set angle data, where the angles were 0, 45, and 90 degrees. The red and blue bars represent the RMSE of the SensoriGlove (in red) and CyberGlove (in blue), respectively, and the error bar display ± standard deviation. At 0 degrees of joint flexion, the SensoriGlove displayed an RMSE of 40.8 ± 39.6 degrees, and the CyberGlove displayed an RMSE of 67.5 ± 61.9 degrees. At 45 degrees of joint flexion, the SensoriGlove displayed an RMSE of 50.6 ± 37.4 degrees, and the CyberGlove displayed an RMSE of 40.0 ± 38.3 degrees. At 90 degrees of joint flexion, the SensoriGlove displayed an RMSE of 36.1 ± 35.5 degrees, and the CyberGlove displayed an RMSE of 63.9 ± 50.4 degrees. Overall, our glove's recordings are comparable to the commercially available instrumented glove.

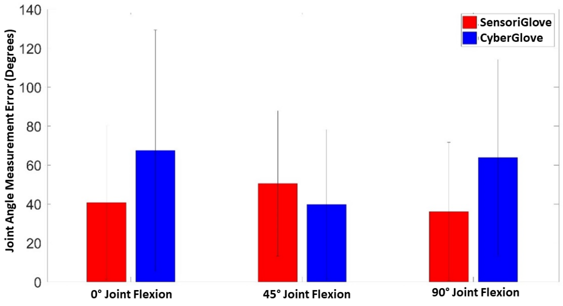

Figure 4. The comparison of SensoriGlove developed under this study and CyberGlove (as a standard commercial glove) through root mean squared error of standard set joint angular flexions.

The SensoriGlove has unique model generation and design allowing for custom-fit data gloves. This is accomplished by designing and implementing the product out of 3D printed flexible plastic. The 3D printed glove's manufacturing process permits sensors to be directly embedded into the product which may lead to more durable instruments for harsher environments. The production process underlying this product can also be readily adapted for other applications that current technology is not robust enough to address. A soft, wearable hand exoskeleton with embedded sensors can be produced to allow accurate grasping control without obtrusive, bulky hardware. Furthermore, offshoots of this product can be created for other body parts such as the arm, leg, back, neck or head. This could lead to new applications in tracking energy expenditure for the general population as well as those in physically demanding situations. Such wearables can also be integrated into consumer smart-health applications [3][6][8] and could even be used in producing smart fashion.

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