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A Low Cost Method to Measure Finger Flexion in Individuals with Reduced Hand and Finger Range of Motion

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Abstract—**The goal of this research is to evaluate a custom sensor glove that will be used to measure real-time finger flexion in individuals having a wide range of hand and finger function. A feasibility study of a low-cost prototype sensor glove has been performed in order to explore several specific requirements, including glove donning (ease of donning in individuals with moderate to severe restriction in hand motion), and glove comfort and durability (for up to 24 hours of continuous data collection). Results show that commercially available passive-resistive flex sensors contained in Lycra®/Nylon sleeves can be used to collect real-time flexion data of each finger over extended periods of time. The individual sensor sleeves are securely attached to the back of each finger. This "sensor glove" demonstrates that data can be collected comfortably over an extended period of time while individuals perform daily activities away from the clinical site. Future work will investigate the repeatability of sensor glove measurements and the development of the wearable data recorder.**

Keywords— **Goniometry, hand function, wearable sensors**

I. Introduction

A recent emphasis in rehabilitation research has been to assess objective outcome measures that correspond to the functional improvements that an individual can expect from rehabilitation treatment or intervention [1]. Sensor gloves have been proposed as automatic goniometic devices, measuring a variety of parameters including finger flexion. These measurements can be used for planning rehabilitation therapies or for evaluating treatment efficacy, or to explore hand function with different disease or injury states. However, methods and devices to perform these measurements generally restrict the measurement process to the clinical or research site, rather than allowing the individual to interact with their daily environment during the data collection process.

In order to create a wearable sensor glove device that can meet these specific needs, the following requirements must be met.

1) *Donning and Removing*: The glove must be easy to don and remove for individuals having reduced range of motion in the hand and fingers.

2) *Comfort and Durability*: The glove must be lightweight and unobtrusive, and can be worn comfortably for up to 24 hours. It must not restrict range of motion or represent a snag hazard during use. In addition, low cost is an important consideration.

3) *Function*: The glove sensors must survive the 24 hour period and continue to function in a manner consistent with data collected at the start of the trial. The system must allow performance of common daily activities, although use of the glove in water is not required.

This sensor glove is part of a lightweight portable monitor that will be used to understand how individuals with compromised hand and finger function interact with their home and community environments. The quality and repeatability of the sensor glove will be evaluated in future work.

II. Methodology

Several methods exist to automatically measure finger flexion in real time; most are based on gloves containing sensors. Some gloves measure force and provide force feedback, although these are not appropriate for portable measurement because they are too heavy and often contain mechanical components on the palm that prevent wearers from performing everyday activities. Exoskeleton-based systems can provide a wealth of position and flexion information, although the glove components can become a snag hazard and can hinder the performance of many daily activities. Several other gloves have been proposed or are commercially available; some use bend sensors [5], fiber optics [6]-[8], Hall effect sensors [9], or potentiometers [10]. Most are either too expensive or require custom sizing, and none are designed to be easy to put on for individuals with moderate to severe range of motion restriction in the fingers.

A challenge for any sensor glove is to allow measurements of finger flexion without adversely influencing the measurement itself. The sensing system should not restrict flexion or extension. The challenge arises because the length of the dorsal surface of the finger increases with increased joint flexion. Since the sensor will be secured at the fingertip, it must be allowed to slide over the top of the finger as the joints bend.

Cost is a significant concern because these sensor gloves will be used in studies with many participants, and multiple gloves will be needed to complete studies in a timely manner. In addition, subjects will wear the glove while performing normal everyday activities; thus, the glove itself should be considered disposable so that behavior is not restricted in an attempt to protect an expensive device.

A. Materials

The sensor used in this application is the Abrams Gentile Entertainment, Inc. patented flex sensor, which is ¼ inch wide and almost 5 inches long [2]. The use of these commercial sensors in measuring finger flexion in gaming and virtual reality applications has already been reported [3]-[5], and analysis of the actual signals measured during this test is not included here. A prototype was developed using a Lycra®/Nylon material as a sleeve for the bend sensor. The sleeve was constructed using a 93% Lycra® and 7% Nylon blend, a common material for swimsuits and active wear. A long, thin pocket was created for the sensor. The sleeves were 1/2 inch wide and 6 inches long, with the internal sensor pocket slightly wider than the sensor. Two methods of sleeve construction were evaluated: hand stitching and "no-sew" fusible fabric adhesives. The sleeve is attached to the back of each finger with tape in order to locate the sensor directly over the joints. Three types of tape were evaluated: two-sided foam tape, two-sided toupee tape, and loops of medical tape. The adhesive type and location for each finger is shown in Fig. 1, leaving the joints free of adhesive that would restrict movement. The sleeves extend to the wrist and all are secured with toupee tape as shown in order to allow sensor movement along the entire sleeve with finger flexion.

B. System Description

To collect data for this prototype, a host computer with an 8 channel 16-bit A/D card was used. The flex sensors are passive resistive devices that range from approximately 13 KΩ when extended flat to 60 KΩ when flexed beyond 180 degrees. The sensors were connected to an interface box and data on all 5 sensors was collected at 100 Hz using Labview. Each sensor was placed in series with a 28.7KΩ resistor in a resistor divider configuration, with an input voltage of 5V. The output voltage was taken as the voltage across the sensor. No additional signal processing was performed, although an analog filtering circuit has been developed for future tests that will occur in less controlled environments.

C. Test Description

One subject was tested to evaluate ease of donning, comfort and durability, and functionality of the sensor sleeves. A sensor with sleeve was affixed to each of the five digits, with the tip of the sensor aligned to the end of the fingertip. Both the proximal and distal interphalangeal joints are covered by the sensor. The metacarpophalangeal joint is partially covered depending on finger length. Two donning methods were tested: the sensor was applied after it was pre-inserted into the sleeve (digits 2, 3, and 4), and the sleeve was applied to the finger first and the sensor inserted after application (digits 1 and 5). (The thumb is digit 1.) Both methods were attempted with the finger fully extended (digits 2 and 5) and fully flexed (digits 1, 3 and 4). As shown in Fig. 1, foam tape was used on digits 1 and 5, toupee tape on digits 2 and 4, and medical tape on digit 3. After all sensors were placed, the sensor wires were attached to the interface box using a 4 foot cable, allowing freedom of movement during the trial.

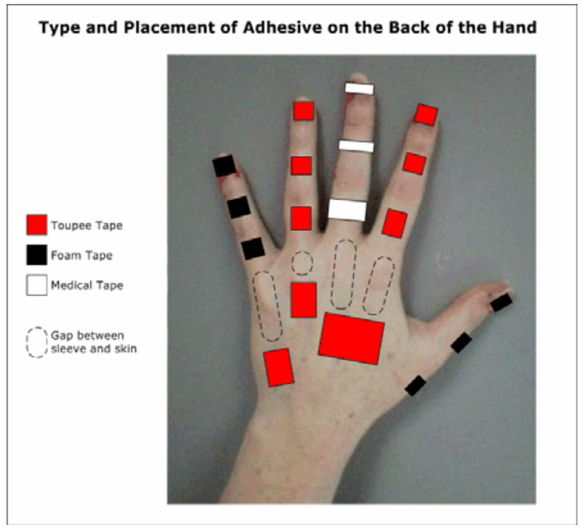

Fig. 1. Location of adhesive to attach sensor sleeves to the back of the fingers and hand.

The test was divided into two parts: a 2 hour data collection session and a 22 hour comfort and durability session, for a total of 24 hours. During the first part, data was collected continuously while the wearer performed several daily activities including touch typing, grasping a pen, writing with a pen, flipping through a book, holding onto the edge of the table, picking up a trash can, wiggling fingers as quickly as possible, and holding a cup. Because the subject was attached to the computer by the data collection cable, all activities occurred while the subject sat at the computer. For the remainder of the 2 hour data collection session, the subject (who is a member of the lab) was instructed to remain at the computer and to complete some normal work tasks while data was collected.

After two hours of data was collected, the data collection cable was removed and the subject was asked to wear the sensors and sensor sleeves until the next day, for a total of 24 hours. Sensor wires were wrapped around the subject's wrist and secured with a sweat band. All activities were allowed except those that might cause the sensors or sleeves to get wet. The subject was asked to note any activities that were limited by the sensors, any time the sensors were snagged, or any time a sleeve detached from a finger. At the completion of the 24 hour period, sensor function was validated by repeating several activities and verifying that the sensor signals were in the range of those reported for activities performed at the beginning of the trial.

III. RESULTS

A. Donning and Removing Gloves

For all configurations tested, the easiest donning method was to pre-insert the sensors into the sleeves and to apply the sleeves to slightly bent fingers. However, placement was only slightly more difficult when the digit was fully flexed; this is mostly due to assuring proper alignment of the sensor directly over the flexed joints. The time required to apply all five sensors was less than 10 minutes. To remove, each sensor sleeve was pulled from the skin and total removal time was less than 1 minute. On removal, the toupee tape stays attached to the sleeve.

B. Comfort and Durability

At the completion of the test, the subject was asked to evaluate wearing the sensors while participating in daily activities. The activities were grouped into three categories: those that were difficult or impossible to perform, those that caused moderate concern (the sensor sleeves became snagged or damaged, or the task caused the subject to consciously think (or "worry") about the sensors), and all other activities. The subject reported that most fell into the third group; most activities could be performed without giving a conscious thought to the sensors being present.

1) *Difficult to Impossible*: Impossible activities included washing dishes and washing hair in the shower. Difficult activities included taking a shower, brushing the teeth, removing change from a pocket, and washing only the palmar surface of the hands without getting the sensors wet.

2) Moderate: The subject reported that the pinkie finger (digit 5) sensor sleeve was slightly dislodged from the fingertip after tucking a shirt into pants after "forgetting that the sensors were on." Other tasks causing a hesitation included putting on a coat, writing with a pen, and filling a glass with water.

3) *No thought needed*: Some specifically mentioned tasks included typing, sleeping, eating, driving, talking on the phone, and carrying baskets and objects around the house.

Evaluating the sensors and sensor sleeves at the completion of the 24 hour period showed that of the three tapes used to attach the sensor sleeves to the fingers, the toupee tape was clearly the most effective. Neither the foam tape nor the medical tape was able to hold the sensor sleeves securely throughout the entire 24 hour period. Two sided foam tape was thicker and lifted the sensor slightly off the fingertips, making it easier to rub and stick to other objects. For example, the sleeve of the pinkie finger showed lifting as described above. However, the toupee tape was by far the best adhesive for the sensor sleeves, even when the sleeve (without the sensor) was held under running water for a few seconds at the very end of the test. The tape is very thin which gives the glove a lower profile, and the tape is difficult to remove from the sleeve.

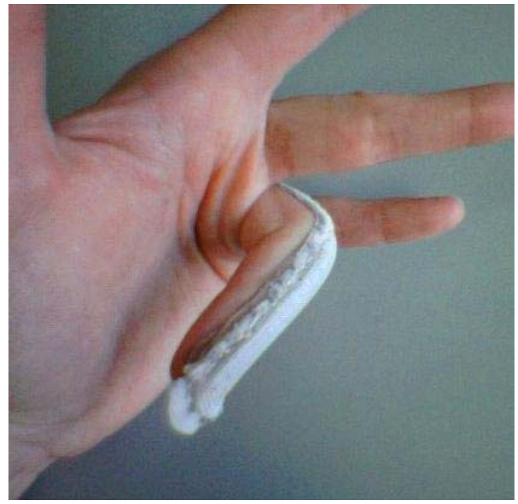

Fig. 2. Sensor within sensor sleeve attached to the finger using toupee tape. This configuration was the most successful in satisfying the requirements, and it is shown after 24 hours of use.

Finger range of motion was not restricted as long as the toupee tape was localized to specific points on the back of the hand and fingers, and not placed directly over joints. However, a small gap must be left on the back of the hand proximal to the metacarpophalangeal joint to allow flexing of the sensor sleeve over the joint. Referring to Fig. 1, the ring finger (digit 4) shows the optimal tape placement and gap location to allow free movement without creating a snag hazard. The subject's hand is shown in Fig. 2 with the sensor and sensor sleeve after the 24 hour trial was completed. The sleeve is still securely attached.

No difference in ease of use was found between the two sensor sleeve construction methods. The only advantage may be ease and speed of sleeve construction, which is slightly better for the no-sew adhesive method.

C. Function

A continuous stream of data from each of the five flexion sensors was collected while the subject performed a variety of activities. Collected data shows that the sensors are able to capture signals that correspond to a wide range of activities, including those requiring fine control. Before and after each activity, the subject placed the hand flat on the table to establish a resting (fully extended) finger position. The measured resistance value for each digit ranged from 10KΩ to 18KΩ, with standard deviations for each finger less than 500Ω (although most averaged 50Ω). The swing in resistance values for all activities occurred in the range of 35KΩ to 45KΩ. Activities requiring fine motor control such as writing still showed a 4K-8KΩ swing in resistance, which is well above the noise. It is clear that the sensors must be calibrated to compensate for the large differences in the resting position (full extension) before the individual digit values can be compared with one another.

Comparing sensor readings between the start and end of the 24 hour period shows resistance values within 250Ω for each sensor, indicating that the sensors were able to withstand 24 hours of continuous use. Mechanically, the sensors must be firmly attached to the end of the sensor sleeves or they have a tendency to work themselves backwards out of the sleeves with repeated flexion/extension of the finger.

IV. Discussion

The goal of this experiment was to test the feasibility of a novel method to place flex sensors on the fingers. This is one step in the development of a portable measurement system that has a unique set of requirements for future research. Because the flex sensor is a commercially available sensor that has been incorporated into gloves for other purposes, our primary focus has been on the method of application rather than on the sensors themselves.

The sensor sleeve configuration has several significant advantages over existing sensor glove methods. Using this method, the glove is attached rather than donned, which provides an advantage when range of motion is significantly restricted and when a glove-based system would be difficult to put on. This glove does not represent a snag hazard because there are no components that protrude, and the toupee tape allows a very low profile for the sensors over the fingers.

Another significant advantage of existing systems is that the fingertips and the entire palmar surface of the hand are uncovered and free of obstruction. Through the evaluation of other prototypes in our lab, we have found that when the fingertips are unobstructed, it is much easier for the subject to forget that the sensors exist because normal sensory function is not masked. This is important because we wish to capture individuals performing activities as they would normally, without modifications in behavior because the sensor system is in place.

The configuration and application method of the sensor glove are unique. The sleeve fabric is low cost but highly suited for the application. Nylon provides strength and resistance to damage, and Lycra® provides lightweight form-fitting stretch needed when the finger is flexed and extended. The adhesive used to attach the sensor sleeves to the fingers is critical. Of the three adhesive methods explored, toupee tape provided much better performance than foam tape or medical tape; it sticks extremely well to skin and to the sensor sleeves, and it is inexpensive. The resulting glove has a materials cost of $1.20 without the sensors (which are $10 each), which allows researchers to throw away the glove after each use if needed or desired.

V. Conclusion

The feasibility of this sensor system has been established although much additional work needs to be done to create a portable measurement system. Tests of measurement repeatability will be performed on the glove as described in [11], and the feasibility testing will be extended to include more healthy controls and individuals with reduced finger function caused by brain injury or stroke. The data collection hardware and software must be made portable and wearable. With further development, this method can become a valuable low-cost tool for measuring long term finger flexion while individuals perform daily activities in their homes and communities.

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