Prototyping a Low-Cost Flexible Sensor Glove For Diagnostics and Rehabilitation

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Abstract: Individuals in developing regions who require hand therapy for rehabilitation face difficulties accessing local clinics. The objective of the current study was to create a cost-effective device capable of assessing finger range of motion (ROM) for diagnostic and potential rehabilitation purposes in these disadvantaged areas. The design employs flexible sensors and a soft glove that records the motion of key finger joints during a variety of daily activities performed by ten healthy participants. The results demonstrated the glove's effectiveness in measuring dynamic ROM for both hands of all participants. This promising outcome suggests that the flexible sensor holds great potential as a tool for hand rehabilitation and diagnosing hand impairment, offering a valuable solution to address accessibility issues in developing countries.

1 INTRODUCTION

Low-cost prosthetic devices are well-researched, while low-cost rehabilitative orthotic devices are less well-addressed. Specifically, low-cost rehabilitation of hand impairments using orthotic devices is not commonly addressed. Many diseases and disorders can lead to hand impairments that sees patients losing full use of their upper limbs. One of the more prevalent disorders is cerebrovascular accidents, commonly referred to as Stroke. Stroke is steadily increasing in developing countries (Yan et al., 2016) and is one of South Africa's leading causes of disability (Maredza and Chola, 2016). Stroke costs are at approximately 2-3% of the total health services expenditure in South Africa (Maredza and Chola, 2016).

Although stroke is prominent in developing countries like South Africa, it is still one out of many that affect the hand. Moodley (Moodley, 2018) highlights the significance of radial nerve palsy in South Africa. The radial nerve accounts for the extension of the wrist and fingers, thus damage to this nerve results in weakness and reduced mobility of the hand. The causes of radial nerve palsy can stem from physical injuries to infections, with the most common cause being related to overuse of the arm. This injury is more commonly seen in labourers where the radial nerve could be compromised due to the extent of their work.

Half of the Stroke patients in South Africa live in rural areas where the nearest clinic equipped for therapy is not easily accessed due to distance(Maredza et al., 2015). Statistics South Africa (StatsSA, 2015) found that lower-income households spend a higher proportion of their income on public transport than other expenses. Transport to clinics where rehabilitation can be accessed increases the expense of continual rehabilitation. In addition, due to the large turnovers observed by therapists (De Klerk et al., 2016), some patients may find themselves waiting for long periods of time which may result in them needing to return the next day to receive treatment. De Klerk et al. (2016) studied additional issues that South Africans face in terms of occupational hand therapy. One of the more pertinent issues is the high rates of cases and referrals. Each therapist is restricted to a set time for each patient. Therefore, with the rates of cases increasing, therapists are forced to minimize the time allocated for consultation and treatment. Limited academic resources and opportunities for hand occupational therapy in South Africa are a further barrier. Arguably, other developing countries may face similar difficulties. Methods of treatment that are accessible to all patients in South Africa and the developing world are thus required.

Given the number of medical diseases that can hinder or injure the hand, rehabilitation that can stim-

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ulate recovery is imperative. However, before attempting to produce methods that can provide effective therapy, consideration needs to be given to assessing the level of hand impairment. Methods of measuring the range of motion of the hand may result in a means of quantifying impairment, monitoring patient recovery and possibly diagnosing both neurological and hand-specific disorders. Hart and Tepper (2001) determined, through a questionnaire completed by patients with hand impairments, that patients who had undergone rehabilitative therapy perceived improvements in their functional abilities and health. By using a method of quantifying the range of motion of the hand, the data recorded can possibly validate any improvements observed in therapy.

Measuring the ROM of the hand has predominantly been achieved by using a goniometer. These methods have been used in several studies (Bain et al., 2015; Hayashi et al., 2014; Hume et al., 1990) to determine the static ROM of patients performing activities of daily living (ADL). The accuracy and reliability of the device are dependent on the patient's ability to hold a gesture, with minimal movements. In addition to this dependency, repeatedly measuring each joint of each finger during activities or gestures, is tedious and time-consuming. This can affect the patient's performance. Thus, a more efficient method of measuring the ROM that addressed these areas was developed.

2 MATERIALS AND METHODS

The current study was divided into three segments: (1) flexible sensor analysis, (2) development of the prototype, and (3) candidate testing.

2.1 Flexible Sensor Analysis

Before developing a prototype of the device, it was necessary to analyse the flexible sensor. The analysis entailed the configuration of the flexible sensors and multiple tests conducted to verify the application of the sensors. Apart from the sensor signal drift and the limitations, tests aimed to replicate the anatomical variations of the finger joints of a human hand, were included.

Flex sensors (Sparkfun Electronics, Colorado, USA), were chosen due to their availability and cost. Alternative sensors such as potentiometers, can be used as they can be configured in a similar manner. However, the difficulty arises when aligning the rotation of the sensor in conjunction to the rotation of a finger joint. Furthermore, designing and implementing this system brings further complications when considering the different hand sizes of patients.

The sensors are based on polymer ink and conductive particles. As the sensor is bent or flexed, the conductive particles move further away, increasing the path distance the applied current must travel through, thereby increasing the resistance. By recording the resistance at different angles of flexibility or bending, a correlation can be made against the range of motion.

Oess et al. (2012) had sampled multiple flexible sensors with respect to signal drift, comparing differences based on both type and sensor length. The results displayed a relation between signal drift and sensor length, with an increased length leading towards a decreased signal drift. In addition, the minimum signal deviations were observed from the sensors that had gone through a polyester over-lamination process. This suggests that a cover medium may result in lower variations of the signal. The current study is heavily influenced over the availability of resources and therefore confined to the use of locally sourced, single branded and sized flexible sensors.

Apart from the comments made by Oess et al. (2012), the sensor datasheet highlighted that the base of the sensor should be supported, and no bending should occur near the output pin of the sensors. In the current study a 3D printed base was used to secure the ends of the sensors.

The flexible sensors were used along the joints of the fingers. Before any prototype was developed, consideration had to be given to the anatomical variation in hand sizes and shapes. As discussed, the sensors output resistances based on the extent at which they are bent. The greater the bend, the higher the resistance. These resistances will be used to map angles that represent the rotation of the joint. It was thus necessary to determine the resistance fluctuations observed from these sensors.The basic configured circuit consisted of an Arduino Uno, one flexible sensor, a single bread board and a 100 kΩ resistor. Only the flexible sensor was changed within the circuit when testing for repeatability.

2.1.1 Signal Stability

The flexible sensors were configured with a resistor to replicate a voltage divider. This allowed the analog pins of the selected microcontroller to read a variable voltage. It was also necessary to determine whether the straight resistances of various flexible sensors were similar, had minimal signal fluctuations and are around 30 000 Ω, as indicated by the manufacturer. To ensure that the readings of the sensors remain undisturbed by any movements, a simple rig was created to keep the sensor in a straight posi-

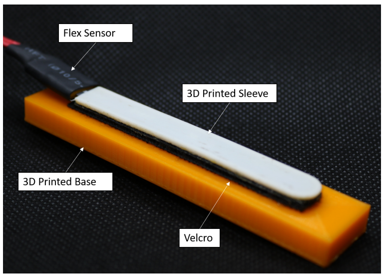


Figure 1: Flat Test Rig.

tion. This is shown in Figure 1. The straight test rig holds the sensor in place using a 3D printed flexible sleeve. The sleeve is attached to a solid 3D printed base using velcro.

Each flexible sensor had a consistent straight line with minor fluctuations, as shown in Figure 2. This was repeated 3 times across each sensor, resulting in a negligible, calculated coefficient of variance of less than 1%.

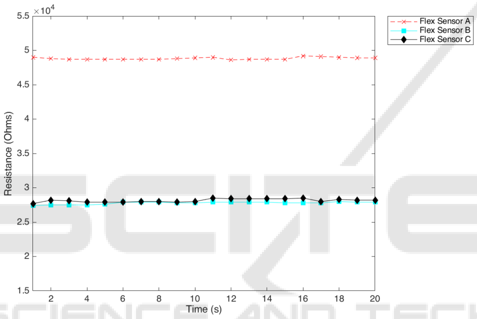


Figure 2: Flat Resistances.

2.1.2 Anatomical Variations

The current investigation represented the anatomical variations observed across patients, through a bend location and radius test. These tests were used to determine the effect of anatomical variation on the output of a flexible sensor.

The bend location test indicated whether readings across the length of the sensor were consistent. This was significant as some patients may have hands of similar size, however the length and location of their joints may vary. In addition, the results also determined the required positioning of the sensors in order to produce stable outputs. Multiple flexible sensors were bent at several different locations. The locations were determined by three offsets (20, 30 and 40 mm), from the origin O , as seen in Figure 3.

The bend location test was repeated three times on several sensors, to determine whether a trend was observed. However, all of the sensors produced results of varying magnitude irrespective of the offset. Figure 4 represents the three bend locations tests at a 30 mm offset for a sample flexible sensor. All three tests resulted in a variation of magnitude. A coefficient of variance of less than 2.2% was calculated.

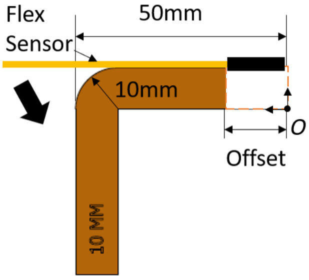


Figure 3: Radius and Bend Location Test.

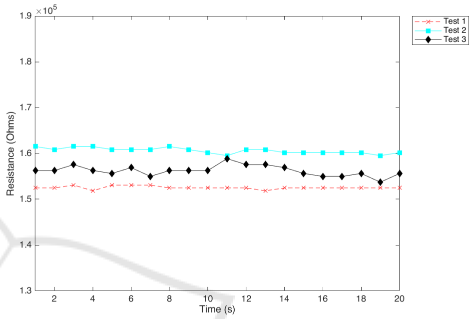


Figure 4: Repeatable Tests for Flex Sensor A (30mm Offset).

For the 40 mm offset (bending occurring close to the base of the sensor) higher variations occurred, up to 4.6%. Thus, the sensors in the current research were positioned away from the base, towards the centre of the sensor.

Considering the structure of the hand, physical variations may be present along the joints of the fingers. Some people may have bony knuckles and joints while others may have rounded and smoother joints. Nevertheless, it is necessary to replicate such scenarios by bending the flexible sensors at various radii (r = 5, 10 and 12 mm). The test setup was similar to that of the bend location test, shown in Figure 3, by keeping a zero offset and using different radi rigs. The results showed no significant trends, apart from fluctuations in magnitude, with no definitive correlation with the radii. However, considering the variation in the resistances across the multiple sensors a maximum coefficient of variance was calculated as 3.7%. This difference is greater than the difference evaluated in the bend location test, suggesting that the curvature of bending the sensors has a greater effect than the location at which the sensors are bent.

Based on the two tests, it was evident that the sensors can produce repeatable results with deviations being limited to under 4%. However, a calibration phase was introduced to the study to minimize the deviation as well as cater for signal drift, which will be discussed in the next section.

2.2 Development of the Prototype

2.2.1 Design

The device design involves two main aspects: the glove attachment and the circuit design. Golf gloves were chosen for simplicity and availability, eliminating the need for manufacturing. They also facilitated easy size selection for both right and left-handed individuals. Various attachment methods were evaluated, including velcro and 3D printed sleeves, which were either glued or sewn onto the glove.

While the velcro method offered modularity for sensor attachment, it posed issues with separation during repeated finger bending, potentially affecting sensor readings. On the other hand, the 3D printed sleeves effectively secured the sensors regardless of attachment method.

Initially, flexible sleeves were placed only on the proximal interphalangeal (PIP) joints, providing reasonable comfort. However, when extended to both PIP and metacarpophalangeal (MCP) joints, it resulted in increased resistance to motion, potentially causing discomfort or harm to hand-impaired users. The PIP joint is situated in the middle section of the finger, while the MCP joint is located at the knuckle. Due to the discomfort the flexible sleeve attachment was deemed impractical. To address this, medical tape was used to secure the flexible sensors, reducing joint resistance and minimizing manufacturing costs (see Figure 5).

Figure 5: Medical Tape Prototype.

Figure 6 represents the final circuit that was designed for the prototype. The Arduino Uno was replaced with a different microcontroller (Microrobotics, Johannesburg, SA) that is similar to the Arduino MEGA but is more compact. This is due to the number of analogue pins required to connect all 10 sensors. However, the circuit in Figure 6 acts as an example of how a single sensor is connected, but still incorporates the main components of the circuit used within the prototype.

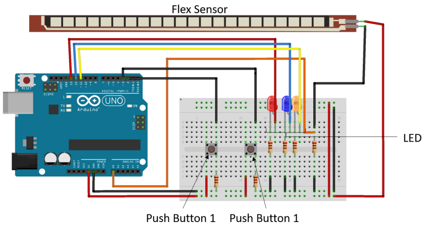


Figure 6: Final Circuit.

For the testing procedure, the user wears the glove and lays the hand on a flat surface in a flat position. The first calibration phase begins, with Push Button 1 pressed. The sensor readings are recorded and are used as the 0° reference.

After 30s has elapsed the user changes the gesture into a fisted position for the second calibration. The sensor readings recorded during this are used as a reference for 90°. The user is expected to hold the fisted position after the second calibration phase. This step is used to record a set of data and compare these values with the calibration results. This procedure aims to quantify the physical slack in the glove, signal drift and possible anatomical variations by calculating the difference between the two sets of data for each joint. Thus, the difference will be used as a unique correction factor for each candidate.

LEDs acted as visual cues for each phase. All LEDs remained off after calibration 2, signalling the commencement of activity testing in which the user performed the directed tasks, while the glove records the ROM of the hand.

2.2.2 Validation

The validation of the glove consisted of testing each joint at 30°, 45° and 60°. This was done by using a finger goniometer. The results of the validation are shown in Table 1. Each set of tests were repeated three times across 3 different sensors, similar to that of Section 2.1.

The RMSE (Root Mean Square Error) is a measure of the average of the differences between values predicted and the values observed. The average error across the left and right hands is 4.8 and 5.2, respectively. These errors do not consider the correction factor and thus the signal drift and physical slack of the glove.

The average deviations shown in Table 1 were calculated including the correction factor as discussed in the previous section. In comparison with the RMSE error, it was evident that the signal drift and slack of the glove produced additional error and thus the correction factor had to be applied. The results indicate an accuracy of ± 5° which was congruent with re-

Table 1: Validation Results.

Average Drift	Right(°)	Left(°)
RMSE	5.2	4.8
Deviations	3.9	3.6

search conducted by Oess et al. (2012). The accuracy of the glove is within an acceptable range for its application, namely the measurement of large changes in the ROM of the patients.

2.3 Candidate Testing

2.3.1 Study Participants

A total of 10 healthy participants were recruited. Participation was completely voluntary with the recorded data to remain disclosed through the use of number profiling. All participants were right-handed and male, however this was not due to a selection criterion, as the only requirement was the fit of the glove. Both hands were tested across the same set of activities. This study was authorized and approved from the Human Research Ethics Committee (Medical) at the University of Witwatersrand. Both the principle investigator and each participant signed a declaration of consent before each test session.

2.3.2 Performing ADLs

To determine the dynamic range of motion of an individual participant as an active member of society, testing must include activities that encompass the expected daily routine of said individual. Gracia et al. (2017) investigated the suitability between the active range of motion and the functional range of motion of the dominant hand, during various activities of daily living. The selection of the activities was based on the International Classification of Functioning, Disability and Health (ICF). The ICF is a basis for measuring the level of health and disability for an individual or a population. The ICF categories selected by Gracia et al. (2017) were as follows: communication, mobility, self-care, and domestic life. By adhering to the ICF chapters in the activity selection process, the current study will be consistent with previous research. Each candidate was required to perform a set of activities derived from ICF categories using each hand. The categories and corresponding activities selected can be seen in Table 2.

The content of the study was explained to each potential participant and an assessment of the fit of the glove was made to determine whether a participant was suitable. Participants then completed a questionnaire to determine hand dominance and whether the participant had any relevant medical history.

Table 2: Activities measured in each ICF category.

ICF Category	Action
Self-care	Brushing teeth Buttoning a shirt Tying a shoelace Pouring liquid Drinking water Eating with a spoon Cutting with a knife Eating with a fork
Mobility	Holding a ball Placing a ball in a cup Flip a card Open a lock
Technology and Communication	Turning pages of a book Typing numbers on a phone Typing Writing
Domestic	Spray a white board Wipe a white board

The principal investigator ensured the flexible sensors were correctly positioned and secured before beginning calibration. During calibration, the participant was required to keep their hand in a flat position on top of a desk. This represents the 0° position, which was recorded by the device. Thereafter, the participant gestured a specific fist, while ensuring that all joints were as close to 90° as possible. The principal investigator closely investigated and corrected the required hand positions. Once more, the data was recorded. These two streams of data were averaged and mapped to 0° and 90°, respectively.

The participant was directed to perform a certain activity. Once observed, the candidate repeated the activity while the device recorded the data. Following data recording on both hands, an evaluation was completed by the participant, indicating the level of comfort while using the glove and any overall comments that they may have had about the study.

3 COST

Components were sourced locally. The flexible sensors were the highest-cost component (61% of the total cost), followed by the golf gloves and the microcontroller. This is dependent on the number of sensors used which was 10 in this study. Since this is a critical component, cost reduction must be directed elsewhere.

Nylon or nitrile gloves are non-stretch and will thus simplify attaching the sensors to the gloves. These therefore present a lower-cost alternative.

The resulting material cost of the prototype was approximated to $121. Comparing the costs of the goniometer and the glove is not straightforward solely based on their price. The goniometer, while more affordable, involves a labor-intensive process for therapists and may be particularly challenging for hand-impaired patients. This could potentially lead to extended therapy sessions and higher overall costs in terms of time and resources.

In contrast, the glove offers a more efficient and technologically advanced approach. It not only streamlines the measurement process, making it less burdensome for both therapists and patients, but it also introduces mechatronics into the rehabilitation process, aligning with the broader goal of integrating technology into local and rural healthcare practices.

4 RESULTS

The dynamic tests were successfully conducted on 10 participants. Both the dominant and non-dominant hands were measured across a set of 20 activities.

In Figure 7 (a) and (b), the ROM measured is depicted for two activities: (a) placing the ball into the cup (Candidate 1 - left hand) and (b) pressing a spray bottle (Candidate 10 - right hand). A wooden hand model visually depicts the ROM by taking a few reference points from the graphs to position the hand model.

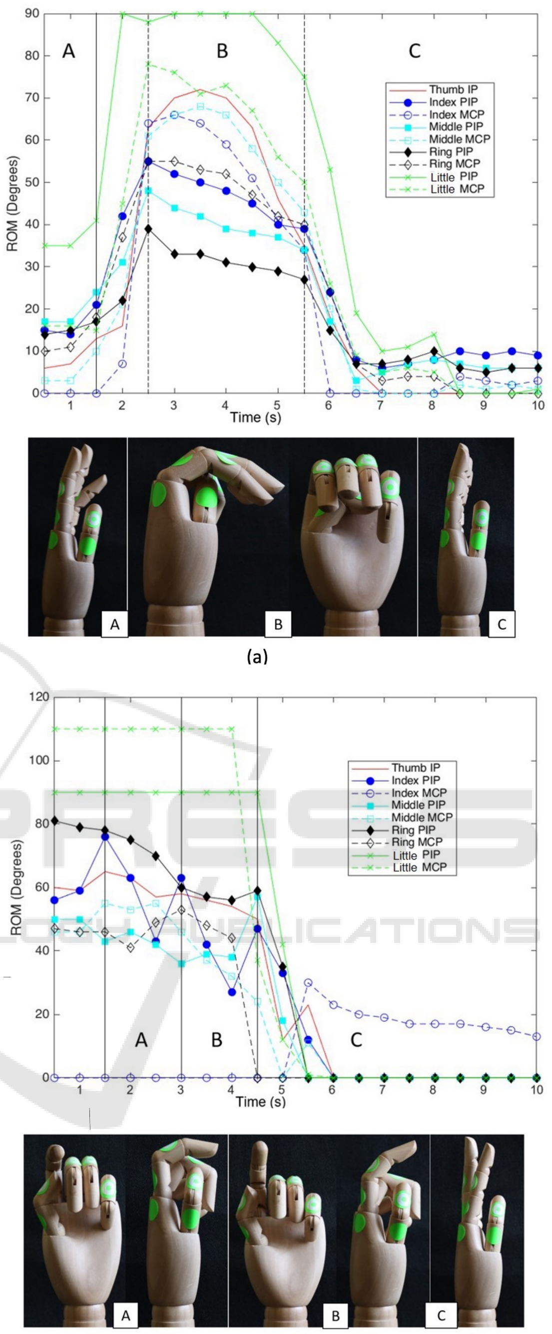
4.1 Dynamic ROM

Figure 7(a) represents a collected motion of all the finger joints while Figure 7(b) describes an action that can be explained by the movements of a single joint (PIP joint of the index finger).

4.2 Dominant vs. Non-Dominant Hand and Joint Variation

An approximate of the amount of change observed between the joints can determine which joint or hand has a greater degree of controlled motion. Based on this premise, the coefficient of variance was calculated for each hand and each joint for every participant, across all activities. These values were then summed for each participant to represent the total variation for each hand. The total variation of both hands can be seen in Figure 8.

Considering all participants as a whole, the variation amongst the joints were summed and are shown in Figure 9.



(a)

(b)

Figure 7: (a) Candidate 1: Placing Ball Into a Cup, (b) Candidate 10: Using a Spray Bottle.

5 DISCUSSION

All 10 candidates performed all of the required activities with ease. The results produced from the study were successful in recording the dynamic range of motion. From Figure 7(a), all 9 joints began to in-

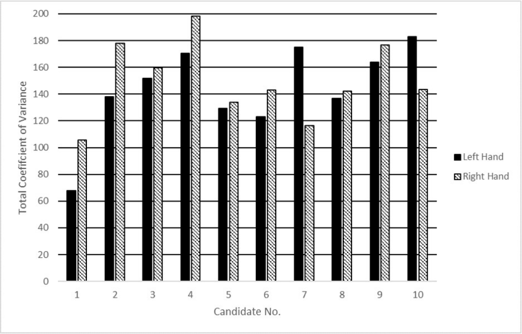


Figure 8: Total Hand Variation of all Candidates.

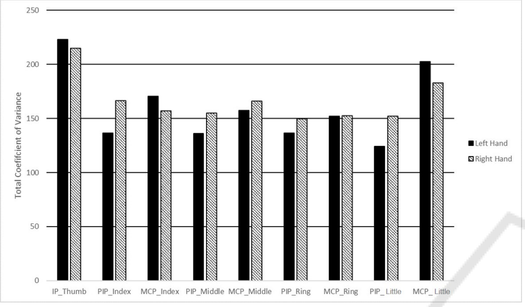


Figure 9: Total Variation across each Joint.

crease in ROM from time t = 1.5-2.5s. Thereafter a slow decrease was observed until time t = 5.5 s, followed by a rapid reduction in ROM. This behaviour described the participants physical movements. For example, from times t = 0 - 1.5 s (A) the candidate was reaching for the ball. From times t = 2.5 - 5.5 s (B) the ball was then picked up and placed into the cup. Finally, from time t = 5.5 s (C) onwards the participant had released the ball and their hand was back in a neutral position.

Figure 7(b) describes an action that can be explained by the movements of a single joint. The task was the action of pressing a spray bottle. The graph shows two stages, times t = 1.5 -3 s (A), t = 3 - 4.5 s (B) corresponding to a dip and rise in the ROM of the PIP joint in the index finger. These stages can be seen as the pressing of the head on the spray bottle. According to the ROM of all the joints, the spray bottle is released from time t = 5 s onwards. The hand model represents the changes of the PIP Joint.

Being able to correlate the results to a hand model that resembles the requested activities can validate the application of the glove as a device to monitor the ROM of the hand. Previous studies have used finger goniometers (Bain et al., 2015; Hume et al., 1990; Hayashi et al., 2014) as they are reliable devices for joint measurements. However, they will require a patient to hold the requested gestures for longer periods as the therapist needs to measure each joint of each finger. This may be difficult for hand-impaired patients. Irrespective of the duration of the measurements, the finger goniometer is targeted towards static hand gestures while the current study is focused on dynamic motions. Each activity was performed in 10 s with a recording every 0.5 s. By manipulating the recording times, a smoother representation of the hand motion can be attained. Thus, replacing the instantaneous drops observed in the various plots with a more detailed reduction in ROM.

It was expected that most participants would have a greater variation in their right hands due to their right-hand dominance. This can be seen in Figure 8. However, this was not the case for Candidate 7 and 10. This can be due to over-gripping gesture, observed during the testing phase, of the non-dominant hand when attempting the various activities as a result of lack of control.

The IP joint of the thumb experiences the most variation in both the left and right hands of all participants (Figure 9). This is expected, as the thumb is what separates humans from most animals because it allows for complicated hand gestures. The thumb promotes functionality in the forms of gripping and pinching, which can correlate to the majority of the tasks within the current study. Excluding the thumb and summing the variation across each finger showed that the maximum variation occurred in the little, index, middle and ring finger, in order of highest to lowest. This trend was present in both the right- and left-hand results. The little finger does not dominate motion with respect to functionality however it does achieve a full ROM due to its closed positioning throughout the fundamental movements. For example, when gripping or pinching a pencil from a neutral position, the little finger would move from an opened to a completely fisted position. This is due to the thumb, index and middle finger dominating the action. The index and middle finger support the thumb in functional movements of the hand and thus exhibit the next highest variation.

For the evaluation of the glove, the average rating (between 1-5, 5 being the most discomfort) was 2.02. Therefore, the prototype was mostly comfortable, throughout the procedure. However, this rating is with respect to healthy candidates. Any level of discomfort indicated by healthy participants could be magnified in the case of a patient suffering with hand impairment.

The reasoning of the slight discomfort had to do with the sizing of the glove. Expanding the study will require gloves of varying sizes. While the current device acts as a prototype, newer designs must be developed to cater for variation in hand size, but most importantly patient comfort.

6 CONCLUSIONS

The flexible sensor glove proved capable of measuring the dynamic range of motion for each hand of all 10 participants. A hand model was positioned according to the dynamic plots and resulted in replicated hand gestures that would have occurred during the specific activities. Being able to correlate the data to the specific activity, confirms the capability of gloves in measuring the dynamic ROM.

Comparisons were made between the dominant and non-dominant hand of some participants. The results showed a greater ROM in the dominant hand for most candidates. However, a few participants experienced a higher ROM in their non-dominant hand. Based on these results and observations made during the testing procedure, it was evident that some participants would exaggerate their grip onto objects due to lack of control with their non-dominant hand.

The variation of the motion between joints was calculated using the coefficient of variance. The variation was more prominent amongst the right hand and therefore could suggest dominance. The IP joint of the thumb had a maximum variation of ROM for both the left and right hand. The thumb is a significant joint with respect to hand functionality and thus would observe a higher ROM throughout the activities.

According to the participants, the glove was moderately comfortable, however new designs must be implemented for the application on hand-impaired patients to achieve a maximum level of comfort and safety. Apart from the design aspect, future work should include a larger test scale, while introducing static gestures for comparisons with previous work.

The prospective applications of the glove include diagnostics, patient monitoring and rehabilitation. In the case of diagnostics and patient monitoring the glove can act as an aid to quantify the level of impairment. Rehabilitation methods can incorporate the glove with virtual reality systems or exoskeletons in the form of bilateral therapy. Specifically, the glove holds promise in aiding individuals facing challenges associated with stroke, radial nerve palsy, tendinopathies and similar pathologies. However, for the glove to act as an effective tool clinically, the study needs to implement the above recommendations as well as further testing.

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