Low-cost flexible sensor glove as a rehabilitation and diagnostic tool

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

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Declaration

I declare that this dissertation is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

Signed this 14th day of April 2020



Shival Indermun

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Abstract

Hand therapy for patients suffering with hand impairment, caused by physical injury or neurological disorders is often inaccessible to patients that live far away from local clinics. Apart from accessibility, developing countries face additional issues such as high patient referral rates and time limitations. Therefore, it is imperative that there are accessible and low-cost means for hand rehabilitation and impairment diagnosis. A low-cost flexible sensor was developed to measure the range of motion of the fingers for the application of rehabilitation in developing countries.. Flexible sensors were attached to the proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints of the fingers and the interphalangeal (IP) joint of the thumb. The gloves were validated through testing each joint at 30°, 45° and 60° degrees. Fluctuations had a maximum variation of +/- 5°. The glove measured the range of motion in 50 healthy subjects performing daily activities that were derived from the ICF (International Classification of Functioning, Disability and Health) guide. The testing was split into dynamic (10 participants) and static (40 participants) phases. There were no criteria for subject participation apart from the fit of the gloves. The gloves proved capable of measuring the range of motion of the finger joints. The IP joint of the thumb had the most variation throughout the dynamic tests. The static tests resulted in a ROM of 39.88°-69.42°, 18.92°-78.1° and 13.42°-60.15° for the MCP, PIP and IP joints, respectively. The data collected provided the range of motion required for an individual to perform activities of daily living and thus validating the gloves use as a finger motion measurement tool. Therefore, the glove can be applied to monitoring patient recovery, hand impairment diagnosis and providing rehabilitation therapy.

Published Work

Results of this dissertation have been submitted to the following journal:

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List of Symbols

Ω	Resistance	Ohms
θ	Angle	$^\circ$
r	radius	mm

List of Acronyms

COV	Coefficient of Variance
DIP	Distal Interphalangeal Joint
DoF	Degree of Freedom
ICF	International Classification of Functioning, Disability and Health
IP	Interphalangeal Joint
MCP	Metacarpophalangeal Joint
PIP	Proximal Interphalangeal Joint
ROM	Range of Motion
WHO	World Health Organization

Chapter 1

Introduction

Prosthetic development is vastly improving with such devices being inexpensively manufactured to restore basic human functionality to both amputees and those suffering birth defects. Additive manufacturing techniques have brought about multiple non-profit and community organizations that provide affordable yet functional prosthetic devices. In the case of orthotics, the study of treatment involved with external devices used to modify structural and functional muscular or skeletal systems [1], the prospect of minimizing costs while ensuring high therapeutic effectiveness has the potential to impact the lives of people who suffer with limb impairments. This can lead to advanced rehabilitation technologies being made available to patients unable to afford or access effective therapy.

1.1 Background and Motivation

People use their hands in every daily activity, from brushing their teeth to writing, typing or simply working in their respective professions. The hand is a human tool to provide a living and is arguably the limb that defines their independence. There are those who are less fortunate and are born with defects or have undergone amputation that have lost their primary hand function. However, global community organisations, like E-NABLE [2], make it possible for amputees to get custom prosthetics inexpensively manufactured through 3D printing.

Research has primarily focused on low-cost prosthetics, but the same cannot be said for rehabilitative orthotic devices for those suffering with hand impairment. Many patients do not have full use of their upper limbs due to a variety of medical disorders. There is an abundance of diseases and disorders that can lead to hand impairments. One of the more prevalent disorders is cerebrovascular accidents, commonly referred to as strokes. Stroke is steadily increasing in developing countries [3] and is one of South Africa's leading causes of disability [4]. Furthermore, with this neurological disorder comes high expenditure. Stroke costs are at approximately 2-3% of the total health services expenditure in South Africa [4].

Although stroke is prominent in developing countries, it is still one out of many that affect the hand. Moodley [5] highlights the significance of radial nerve palsy in South Africa. The radial nerve accounts for the extension of the wrist and fingers [6], 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. Thus, many labourers may find themselves in situations where their radial nerve could be compromised due to the extent of their work. In terms of treatment, a splint is often used that allows patients to extend their fingers and exercise simple motions under the supervision of a therapist.

Neurological disorders such as stroke, can lead to spasticity which is a condition that causes muscles to contract continuously [10]. In addition, nerve compression conditions like carpal tunnel syndrome, specifically lead to pain and loss of strength in the wrist and the fingers [11]. The condition is not based on physical ailments but rather stem from common diseases such as diabetes and arthritis [11]. Multiple sclerosis and Parkinson's disease are chronic conditions that cannot be cured and have a significant effect on the motion of a patient's limbs [12].The treatment and therapy provided are used to slow down the progressive affects of these chronic conditions.

With half the amount of stroke patients in South Africa occurring in rural areas [7], it may be difficult for them to seek therapy. In addition, practised therapists are limited, thus constraining the time for therapy. According to Statistics South Africa [8], lower income households spend a higher proportion of their income for public transport. Transport increases the expense of continual rehabilitation. In addition, due to the large turnovers observed by therapists [9], some patients may find themselves waiting for long periods of time that may result in them needing to return the next day. Therefore, an opportunity is available to create methods of treatment that can be accessible to all South Africans.

Therapy, in general, is often inaccessible to patients suffering with hand impairment, predominantly in developing countries. In 2015, South Africa had 35.2% [14] of citizens living in rural areas, with little or no access to medical clinics let alone rehabilitation centres. de Klerk [9] proposes 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 consult and treatment. Another restraining factor is the limited academic resources and opportunities of hand occupational therapy in South Africa. Arguably, other developing countries may face similar restrictions.

Given the amount of medical diseases that can hinder or injure the hand, it is of utmost importance that there are rehabilitative means that can stimulate recovery. 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 et al. [13] 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.

In summary, it is imperative that there are affordable and accessible means of providing treatment that can stimulate hand recovery and rehabilitation, in developing countries. Such treatment will involve a device capable of diagnosing hand impairment as well as monitoring patient recovery and rehabilitation. The proposed research will aim to minimize cost while ensuring a high level of effective therapy.

1.2 Range of Motion of the Hand

The human hand is one of the most complex parts of the human body, having up to 27 Degrees of Freedom (DoF) [15]. Given this high sense of flexibility, it is often difficult to apply robotics that can safely provide hand rehabilitation. Before developing a device that can replicate and measure the range of motion of the hand, it necessary to fully discuss and comprehend the DoF that the hand provides. The hand consists of 4 fingers, a single thumb and the wrist. Each of the 4 fingers can be broken down into 3 distinct joints, namely the distal interphalageal (DIP), proximal interphalageal (PIP) and the metacarpophalangeal (MCP) joint [15]. A model of the anatomy of the hand is shown in Figure 1.1 and has been adapted to represent the aforementioned finger joints.

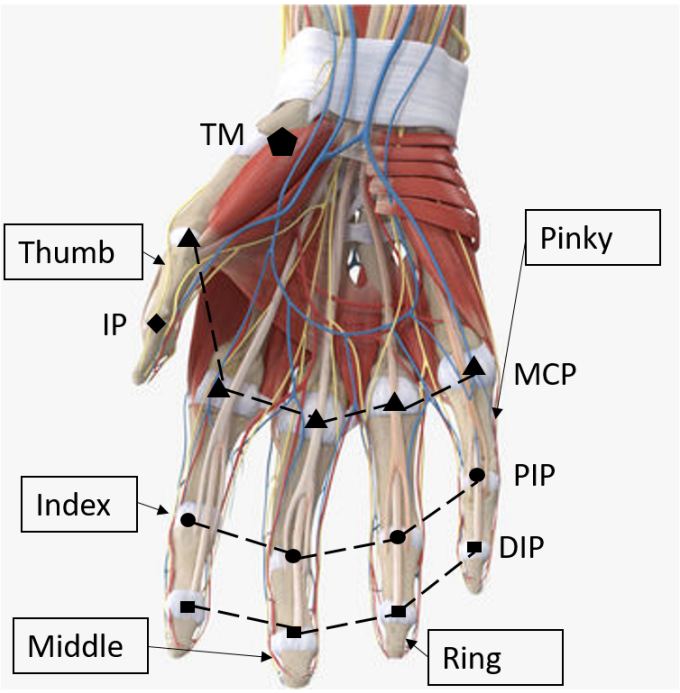
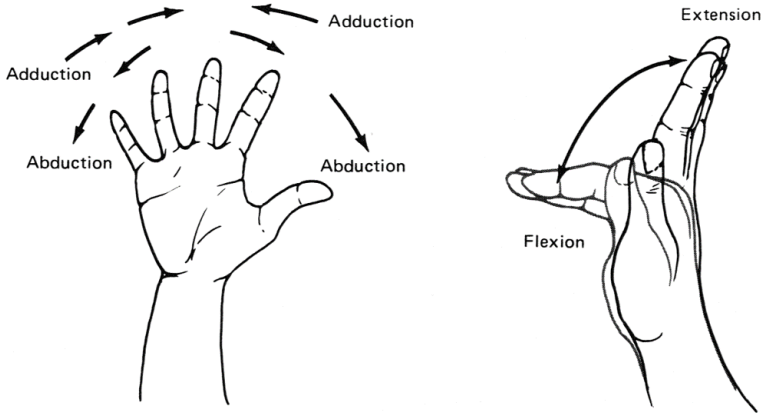


Figure 1.1: Hand Anatomy [16]

The DIP and PIP joints have 1 DoF, corresponding to both flexion and extension while the MCP joints have 2 DoF which include flexion-extension and abduction-adduction [15]. Therefore, the fingers have a total of 16 DoF. Figure 1.2a indicates the direction of the range of motion fingers can achieve. The thumb (Figure 1.2b) increases in complexity as it is able to provide 5 DoF. Similarly to the fingers, the interphalageal joint has 1 DoF (flexion and extension) while the trapeziometacarpal (TM) and MCP joints have 2 DoF each for flexion, extension and adduction and abduction. The remaining 6 DoF are for translation and rotation of the palm [15].



(a) Finger Motion [17]



(b) Thumb Motion [18]

Figure 1.2: Digit Motion

The range of motion for each of the joints, represented in the digits of the hand, can be expressed as inequalities which are defined as static constraints [15]. Equations 1.1-1.4 define the rotational limits of the digits with respect to each of the joints [15].

$$0^\circ \leq \theta_{DIP-FE} \leq 90^\circ \tag{1.1}$$

$$0^\circ \leq \theta_{PIP-FE} \leq 110^\circ \tag{1.2}$$

$$0^\circ \leq \theta_{MCP-FE} \leq 90^\circ \tag{1.3}$$

$$-15^\circ \leq \theta_{MCP-AA} \leq -15^\circ \tag{1.4}$$

FE represents flexion and extension and AA are adduction and abduction. An approximation was made for the MCP joint of the middle finger and the TM joint of the thumb due to the limited adduction and abduction motions [15]. These are represented in equation 1.5 and 1.6 [15].

$$\theta_{MCP_{Middle}-AA} = 0^\circ \tag{1.5}$$

$$\theta_{TM-AA} = 0^\circ \tag{1.6}$$

Apart from the static constraints, the digits are also restricted by both dynamic and natural constraints [15]. Dynamic constraints are defined as limits on the joints as a result of finger

motion. These constraints can either be intra-finger or inter-finger limitations. The intra-finger constraints are based on the joints of the same finger while inter-finger constraints are limits between fingers. One of the more significant intra-finger constraints is that in order to flex the DIP joint of the fingers, the PIP joint must also be flexed [15]. This is expressed in equation 1.7 [15].

$$\theta_{DIP} = \frac{2}{3}\theta_{PIP} \tag{1.7}$$

An example of inter-finger constraints is the action of bending the little finger, resulting in the MCP joint of the ring finger flexing. Such constraints are not significant with respect to the design of a robotic rehabilitation as they provide no beneficial function. However, these constraints still need to be considered as the device must not suppress the involuntary movements of a finger when performing various hand gestures. The final type of constraints are based on naturalness of the hand [15]. However, these constraints are difficult to quantify as natural hand gestures can be shared amongst a vast number of people or can be unique to an individual. Therefore, the current research will exclusively review both the static and dynamic constraints during the design of the device.

The wrist joint motions are shown in Figure 1.3 which corresponds to 2 DoF [19]. 1 DoF for flexion and extension, and 1 DoF for radioulnar deviation (radial flexion and ulnar flexion). The range of motion of each movement are expressed in equations 1.8-1.11 [20].

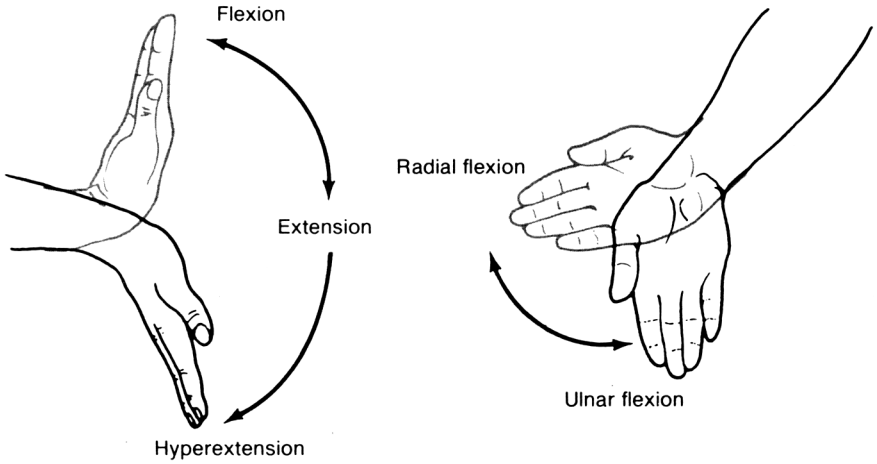


Figure 1.3: Wrist Motion [17]

$$80^\circ \leq \theta_{Wrist,F} \leq 90^\circ \tag{1.8}$$

$$80^\circ \leq \theta_{Wrist,E} \leq 110^\circ \tag{1.9}$$

$$\theta_{Wrist,RF} \leq 15^\circ \tag{1.10}$$

$$30^\circ \leq \theta_{Wrist,UE} \leq 45^\circ \tag{1.11}$$

1.3 Hand Rehabilitation Robotics

The hand has more than 20 DoF, making it one of the most complex parts in the human anatomy. This suggests the difficulty in developing robotic devices for rehabilitation due to the high flexibility of the hand. However, many devices have been developed for hand rehabilitation. Therefore, it is necessary to discuss the current progress and limitations of hand rehabilitation robotics before considering new developments.

Yue et al. [21] discusses hand rehabilitation robots for post-stroke recovery. One of the more significant parameters highlighted were the hefty costs that occur in stroke treatments and rehabilitation, which is seemingly concurrent with the argument made by Maredza et al. [4] regarding South Africa's high expenditure on the disorder. The main concern with creating devices for stroke rehabilitation is that stroke can uniquely affect an individual and occurs in various stages [21]. Thus, when designing a device intended for stroke rehabilitation therapy, the designer must specifically target the level and stage of the disorder. Majority of the current devices are intended for post-stroke motor recovery. Nevertheless, the parameters and characteristics of the designs still need to be discussed as they can be applied to alternate hand impairment disorders requiring rehabilitation.

A hand rehabilitation robot can be classified into two domains, namely the mechanical design or the rehabilitation treatment regime [21]. The mechanical design includes the physical hardware of the system while the rehabilitation treatments focus on the actual training paradigms for recovery [21]. These two classifications are dependent on one another, thus, both need to be regarded when developing a new robot. There needs to be a mutual relationship between the mechanical design and the expected training in order to produce a design that is both mechanically efficient and has high therapeutic capabilities.

1.3.1 Requirements

When developing any robotic device that requires human interaction, the primary concern during that process is safety. Given the premise of the design, it is apparent that the range of motion and capability of the hand should result in a greater emphasis on the user's safety and comfort. During rehabilitation, the user will be in a vulnerable state thus it is imperative that the proposed device does not intimidate the user and considers the patient's comfort. Yue et al. [21] further highlights the significance of mechanical failure as it can result in further injury or impairment to the user's hand.

Availability, which is a function of the cost and complexity of the device, is considered a requirement by Yue et al. [21]. The more complex the device is, the greater the skill requirements of the therapist which can arguably relate to increased treatment costs. The device is also limited by the manufacturing costs as it has a strong influence over its application across developing countries.

Additional requirements were reviewed by Veale et al. [22], however emphasis was placed on the relation between the requirements of an orthosis and the actuation system. It is apparent that the actuation of the device has a significant effect over the requirements of the corresponding orthosis. Table 1.1 shows some of the requirements presented by Veale et al. [22] which was considered during the design phase of the current research.

Table 1.1: Stakeholder Requirements [22]

Requirement	Description
Durability	Life time of orthosis
Ease of Maintenance	Ease of keeping orthosis operational
Effectiveness	Ability to improve user's quality of life
Operability	Ease of control and adaptability to each user
Comfort	Fit of the device and no physical harm to user
Portability	Ease of transport
Reliability	Consistency of orthosis performance

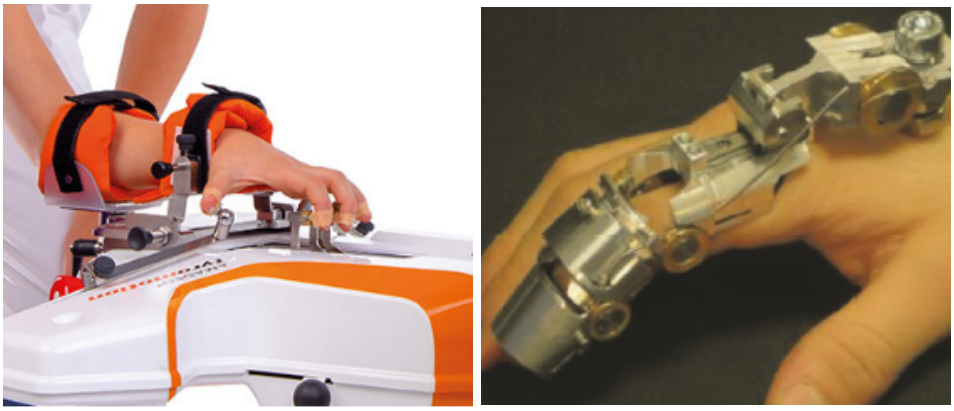
1.3.2 Design of Hardware

Yue et al. [21] breaks down the hardware system of a hand rehabilitation robot into four distinct categories that form the basic outline of a potential rehabilitation device. These categories include the type of robot, actuation, transmission and sensors. These fields will have to be distinctly assessed and reviewed when developing and prototyping the current research.

Robot Type

The robot type can either be an end-effector or an exoskeleton and is dependent on how the developer aims to provide hand motion and in turn rehabilitative exercises. The end-effector focuses on securing the hand of concern onto a fixed panel and applies a force to the end of the user's hand to provide rehabilitation. An example of an end-effector for hand rehabilitation is the AMADEO [23], which can be seen in Figure 1.4a.

The AMADEO is a high-end rehabilitation device that is based on phases of hand-finger rehabilitation [23]. This device is capable of providing continuous passive motion, active assisted therapy and interactive therapy through the use of virtual games. This is extremely beneficial especially on paediatric patients as the visual stimulus will encourage participation in therapy and can neurologically divert the patient from any discomfort. Another promising benefit is the ability of the device to integrate with the specific needs of the patient which include single finger motions. The drawback of the device is that the rehabilitation is not coherent with daily activities or primary functions which is something that hand rehabilitation devices should aim to achieve, in order to improve dexterity. Furthermore, this device is not a viable solution for developing countries due to the expected high cost, lack of portability and limited accessibility.



(a) AMADEO End-effector [23]

(b) Single Finger Exoskeleton [24]

Figure 1.4: Robot Types

The exoskeleton is worn by the user, externally mimics the joints of the hand and is generally portable. An example of a hand exoskeleton device is the HANDEXOS [24], which can be seen in Figure 1.4b. With the use of exoskeletons, such as the HANDEXOS patients are able to benefit from the portability of the device making treatment at home possible. However, some exoskeletons can be bulky and complex which is not a desirable feature when targeting rural communities. In addition to the complexity, the robot has to directly correlate to the joints of the hand as any differences can lead to detrimental effects on the hand.

In recent times, there is a trend in designing the exoskeleton as the primary robot type for hand rehabilitation [21]. In terms of measuring the range of motion of the hand, the exoskeleton design is more favourable as mimicking the joints will make it easier to relate the corresponding movements. Given that the current research is aimed at accessible and low-cost rehabilitation for developing countries, the exoskeleton robot design will be used in the study.

Signal

In terms of the sensor systems used in the manipulation of hand motion, many devices use either physical or bioelectrical signals [21]. Physical sensors include simple force or motion sensors to provide signals to the robot to manipulate the hand. Bioelectrical sensors deal with EMG (electromyogram) signals that are detected from the contraction or relaxation of the muscles [25]. One of the arguable advantages of using physical signal sensors is the cost is lower than bioelectrical sensors, however this is dependent on the quantity of sensors used.

Physical signals through flexible sensors (Figure 1.5) will be used in the current research due to availability and cost. The sensors are based on polymer ink and conductive particles [26]. As the sensor is bent the conductive particles move further away, increasing the resistance. Therefore, by manipulating the resistance output the motion of the device can be manipulated.

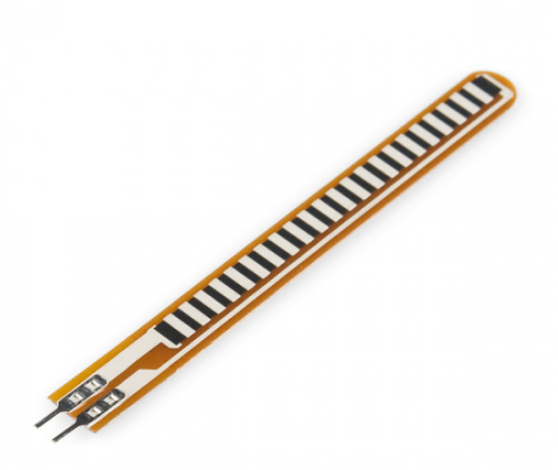


Figure 1.5: Flex Sensor [26]

Figure 1.6 represents the conductive ink particles moving further away as the sensor is flexed. The distance B is greater than A, which represents a longer path for the current to flow through. Using the recorded resistances at different bending angles, a correlation can be made against the range of motion.

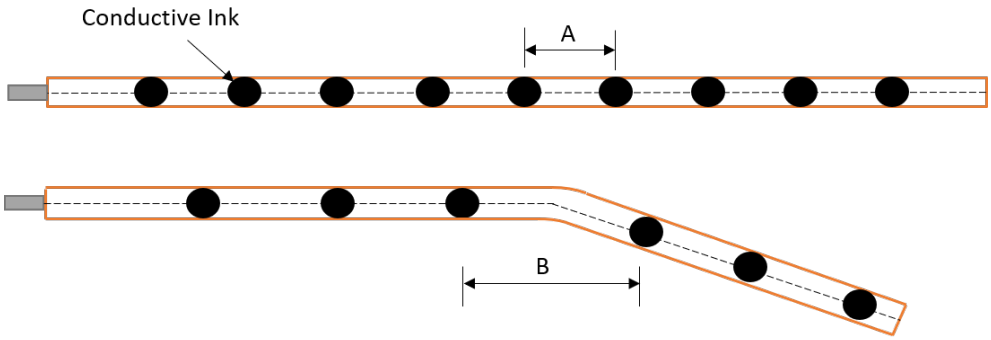


Figure 1.6: Conductive Ink through a Flex Sensor

1.3.3 Type of Robotic Therapy

The type of therapy that a robot can provide are listed as follows [21]:

- Resistive

  The robot applies a resistive force to the patient's hand movements to provide hand strengthening in the rehabilitation process. Based on the user's level of impairment, the resisting force can be modified. In this training regime, the patient is required to have some degree of motor recovery. Thus, this method is aimed towards patients in the later stage of rehabilitation.

- Active

  Active therapy is based on the user's ability to move and exercise their own impaired limb. The function of the robot is to act as a feedback system. This training can be used to quantify both the extent of the impairment and the rehabilitation progress.

- Assistive

  In assistive therapy, the patient voluntarily performs the rehabilitation movements with the aid of the robot. As in the active case, the user needs to provide voluntary motion thus the patient has to have some level of motor control.

- Active-Assistive

  This method combines both schemes of the active and assistance rehabiliation training. Here the user applies their own ability to perform the exercises and the robot only assists if the actions cannot be completed. However, the limitation of both the training regimes is also shared with the combination as some motor ability is required by the patient.

- Passive

  Passive treatment is where the robot provides the full motion of the patient's hand. This method is aimed to provide motion to the impaired hand without using the patient's ability in the hope of stimulating motor recovery. The treatment is beneficial as it may be implemented at the earliest stage of recovery, but this often depends on the cause of impairment and if the patient has undergone surgery.

The current research will focus on active therapy as the treatment pertains to measuring the patient's ability to use their limb. Active therapy can also be used to determine whether there is improvement in hand function. Furthermore, this type of therapy can be applied to all hand impairment disorders.

Conceptual Rehabilitation Therapy

There are many disorders that can lead to hand impairment but impairment can also be an earlier symptom to a neurological disorder. Therefore the prospective device can act as a tool to not only determine the levels of hand impairment to hand related injuries or disorders, but also diagnose early predictions of neurological diseases. Apart from diagnosis, the device can measure the ROM to quantify impairment. By determining the severity of the impairment, therapists and practitioners can establish the most optimal means for recovery and treatment.

In terms of rehabilitation, the device can act as a monitoring device that is capable of quantifying patient recovery. This will determine which methods of rehabilitation are more effective and whether the effects of therapy are recovering functionality within patients.

Bilateral therapy in hand rehabilitation is a therapeutic method of using paired movements of both the healthy and impaired hand. The premise behind it being that the mimicry movements will stimulate motor recovery. Motor recovery can be seen as the performance of voluntary movements and muscle control. Cauraugh et al. [27] reviewed the effect of neural plasticity and bilateral movements on rehabilitation for stroke patients. Neural plasticity refers to the change of neuron structure and function due to changes in their environment [28]. Therefore, plasticity can be seen as learning mechanism that can be applied to recovery treatments [29].

Cauraugh et al. [27] determined that using bilateral methods to promote neural plasticity and functional recovery of a paretic (partial paralysis) limb in stroke patients has yielded different results in various research cases. One of the more common examples often mentioned in connection to bilateral movements is that a study [30] showed that the non-dominant hand improved in performance when symmetrically executing circle-tracing tasks with the

dominant hand. Studies involving stroke patients have shown that bilateral movements can negatively affect the healthy hand by reducing its functional performance.

Lewis et al. [31] tested both post-stroke hemiparetic (one-sided paralysis) individuals (n=9) and healthy subjects (n=9) on unimanual and bimanual frequency-scaled circle drawing tasks. The results indicated no motor improvement in the impaired hand of the hemiplegic post stroke subjects. However, a decrease in task performances were observed in both hands of all the participants when engaged in bimanual motion. Other studies have also provided evidence of bilateral movements promoting motor recovery.

Cauraugh et al. [32] investigated the effects of EMG triggered neuromuscular stimulation and bilateral movements. The study was conducted on 25 cerebrovascular (brain and blood circulation) accident subjects who were separated into 3 distinct groups. 10 subjects each for unilateral and bilateral movements, while the remaining 5 served as a control. The rehabiliation tests were conducted over a 2 week period with a total duration of 6 hours. The results consisted of functional testing (number of blocks moved), chronometric reaction times and sustained muscle contraction. Across all three sets of results it was determined that bilateral movements increased voluntary motor control.

The above two cases are different with respect to the investigative approach and the tasks used for testing bilateral movements. Therefore, it is difficult to compare the research scenarios as the above research disparities may have led to discrepancies between the results, which is a similar argument that Caraugh et al. [27] makes when comparing the various research methods done in connection to bilateral movements.

The current research proposes a device that leads onto bilateral therapy as an initial stage of rehabilitation but is not not centred on neural plasticity. The therapy is aimed to initiate involuntary movements (passive) of the impaired hand as a progressive means of rehabilitation and recovery for non-functional movements. Therefore, the application serves to provide primary involuntary movements as preceding treatment before motor recovery and rehabilitation begin. Furthermore, the research hopes to extend to a variety of hand impairment disorders that may require surgeries, hence the device can be used as a passive motion tool for post operations. Opportunities will be available to further the scope of the current research to include effects of neural plasticity.

In order to achieve bilateral therapy the device would need to be used in unison with another robotic tool capable of providing mechanical motion to the joints of the hand. However, the additional robot does not have to be unique as the existing devices can be adapted to incorporate the use of the device. The patient can manipulate the movement of their impaired hand through the use of either an end-effector or exoskeleton by using the glove to mimic the

movements observed in their healthy hand. Thus, the patient is able to control the amount and quality of therapy, limiting the need for a therapist. Ideally, the only person who is aware of how much ROM the impaired hand is able to achieve comfortably,is the patient. However, the therapist could also use the glove on their own hands to control the patient's mechanical movements of their impaired hand. This could benefit hand rehabilitation treatments involving children.

Ignoring the application of bilateral therapy, the device can be used to promote use of the impaired-hand. This can be done by using the glove to animate objects based on the level of ROM achieved with the glove. Therefore, encouraging the user to push past their limited ROM to manipulate the object. A similar result can be achieved by featuring games or virtual reality. These methods can also divert the patient's attention away from the strenuous therapy and possibly promote neural plasticity.

A device which can monitor improvements and and potentially facilitate rehabilitation would provide a huge benefit to hand-impaired patients in South Africa and the developing world. In order to determine the effectiveness of the device in the field of rehabilitation and diagnostics the research must aim to first test the developed device on healthy participants. The results can be used to verify the use of the glove as a measurement tool which can be used in future research aimed towards testing hand-impaired patients.

1.4 Problem Statement

The proposed research aims to develop a low-cost device that will monitor the movement of the hand for diagnosis and rehabilitation by measuring the range of motion of each digit. The underlying goal for the development of the device is targeted towards improving the treatment available for hand impairment patients in South Africa and developing countries. This will be centred on low-cost manufacturing as well as reducing the need for a practised physician by creating a device that is both simple and effective.

Developing a device, while minimizing cost and maintaining high levels of therapeutic capability, will benefit South Africa and other developing countries. To the author's knowledge, such a device has not been developed or utilized in South Africa while considering manufacturing, accessibility and cost.

The low-cost device can lead to new methods of therapy as well as a means of assessing standard hand rehabilitation. By quantifying physical improvements, therapists will be able to deduce the optimal treatments necessary for quick recovery and possibly diagnose hand impairment.

1.5 Research Objectives

The aim of the research is to advance hand rehabilitation therapy while ensuring quality treatment that is accessible to all in developing countries, specifically South Africa. The objectives of the current research are as follows:

1. To develop a low-cost flexible sensor glove that is capable of measuring the range of motion of the fingers, for patient diagnosis and potential application in rehabilitation, for use in developing countries.
2. Investigate the variations of the range of motion between the dominant and non-dominant hand.
3. Determine the range of motion of the hand for an individual to be functional throughout various of Activities of Daily Living (ADL).

1.6 Assumptions and Limitations

To achieve the set objectives, the current study needs to be restricted to the following assumptions and limitations:

- The materials and components used to manufacture the device must be locally supplied.
- The device will act as a proof of concept with minimal resources used.
- The cost analysis will be based on the prototype, exclusively on the cost of the materials used.

1.7 Chapter Overviews

Chapter 2 details the discussion of existing hand rehabilitative devices and measurement tools used to measure the range of motion of the fingers.

Chapter 3 pertains to the testing and calibration of the flexible sensors. The tests included varying the bend radii and bend locations. This was done to cater for the anatomical variations observed amongst all patients.

Chapter 4 discusses the development of the prototype from the physical glove to the completed circuit. The process of the final circuit has been outlined within this chapter. A validation was also completed to asses the level of accuracy of the prototype.

Chapter 5 is the first phase of patient testing. Tests were done on 10 healthy subjects performing dynamic tasks. Each candidate was tested on both the dominant and non-dominant hand. The results produced verified the gloves use as a measurement tool.

Chapter 6 is the second phase of patient testing. Forty candidates were tested, while performing static tasks only using their dominant hand. The results were comparable to previous literature, although different means of measurements were used.

Chapter 7 outlines the conclusions of the study with the main summary being that the glove is capable of measuring the range of motion of the fingers.

Chapter 8 describes the recommendations for future work, with the main parameter being to increase the level of comfort before progressing forward into testing hand-impaired patients.

Chapter 2

Literature Review

2.1 Current Hand Rehabilitation Robots

The following section presents some of the current exoskeleton devices that have been developed. Thus, the parameters defined in the previous section can be examined through existing models. By reviewing different designs of hand exoskeleton robots, a better understanding of robot-assisted therapy can be gained. The following designs were reviewed based on their relation to the current research.

2.1.1 Myoelectric Robotic Exoskeleton

Ben et al. [25] developed a 3D printed hand exoskeleton robot for rehabilitation. The design consisted of myoelectric sensors that produced EMG signals from muscle stimulation. These sensors send signals to a controller that manipulate 5 separate servo motors. Each motor corresponds to the digits of the hand. The motors apply the actuating force through a 3D printed cable-linkage system which is shown in Figure 2.1. The design of the linkages are done in such a way that the servo motor needs to simply pull the cable attached to a link on the exoskeleton in order to manipulate the whole finger. This is a prime example of how 3D printing and designing structured linkages can allow for simple yet effective motion of the fingers.

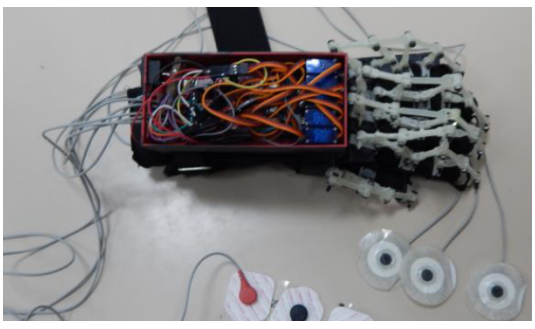


Figure 2.1: Myoelectric Robotic Exoskeleton [25]

- Robot Type : Exoskeleton
- Actuation : Servo motors
- Transmission : Cable driven - 3D printed linkages
- Signals : Myoelectric Sensors
- Target : Stroke Rehabilitation

The members and linkages designed can be seen as bulky, especially if it were to be applied as an assistance device for daily use. Additionally, the bioelectrical sensors may cause discomfort for users (primarily paediatric patients) due to the number of connecting cables. However, bioelectrical sensors allow the device to sense the user's intention through their muscles.

2.1.2 Under-actuated Jointless Exoskeleton

One of the desirable characteristics of hand rehabilitation devices is to be as compact as possible. This is essentially to reduce weight of the device but more importantly to extend the application passed rehabilitation and towards use as a daily assistance device. In et al. [33] investigated the possibility of developing a jointless device as a wearable exoskeleton. The design is analogous to the tendon structures observed in a finger and hence was mimicked to eliminate the need of external pin joint structures. By alleviating the need for pin joints, the issue of replicating the rotational axis of the finger is avoided. Thus, creating a safer approach in facilitating finger motion.

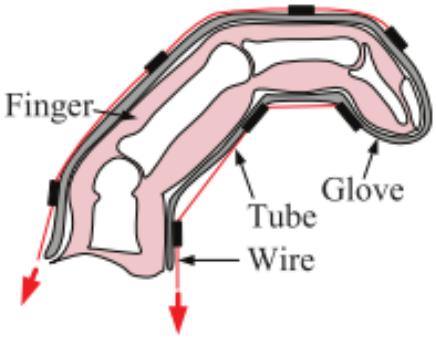


Figure 2.2: Jointless Exoskeleton [33]

- Robot Type : Exoskeleton
- Actuation : Electric Motor
- Transmission : Cable
- Signals : N/A
- Target : Achieve under-actuated system for compact hand exoskeleton

The design consists of a glove with guide tubes to case the extension and flexion wires. This is shown in Figure 2.2. By using a motor to pull the wires, extension and flexion can be achieved. However, the study goes on to determine the feasibility of under-actuation. This was tested by creating a connected system of tubes and wires to both the index and middle fingers and using a single motor to flex the joints. The results showed that the tubing and cable network are able to be used in a under-actuated configuration. However, this limits the device to collective motions. Difficulties may be present when trying to perform gestures using single fingers. Regardless, the use of such a compact design through cable networking has the potential for further development in hand rehabilitation and assistance devices.

2.1.3 Bilateral Therapeutic Device for Hand Rehabilitation

Rahman et al. [34] developed a hand exoskeleton for stroke rehabilitation through bilateral therapy. The design uses a flex sensor glove to manipulate the exoskeleton. Thus, bilateral training is achieved by the motions of the healthy hand through the glove, prompting the exoskeleton to mimic the identical movements onto the impaired hand. The design was primarily focused on being able to fit various hand sizes and be both lightweight and portable [34]. These requirements are essential and need to be considered when creating a hand rehabilitation robot that can be applied in developing countries.

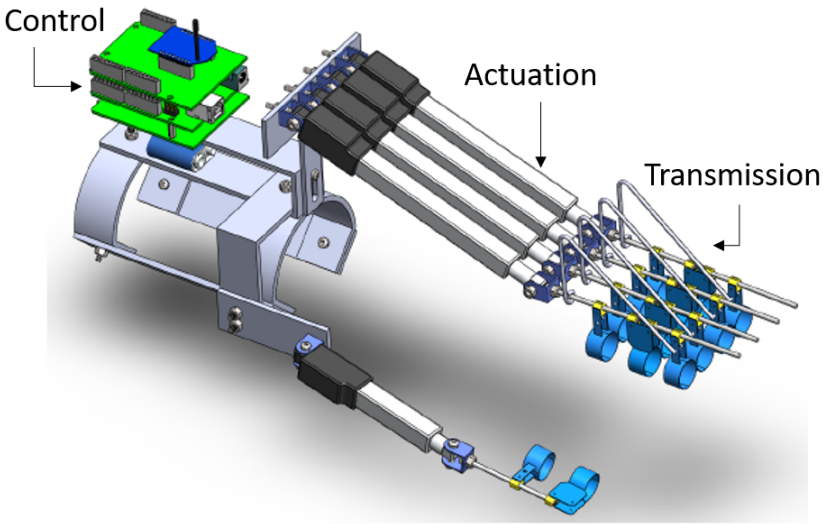


Figure 2.3: Bilateral Exoskeleton [34]

The exoskeleton design (Figure 2.3) consists of the control, actuation and transmission systems. The control of the device uses an At mega 328 micro-controller and 2.4Ghz XBee modules for radio transmission between the glove and the device [34]. The controller processes the signals received by the radio module and actuates the fingers through the use of linear actuators. From the actuation system, the force is transmitted to a system of rods that mimic the finger joints.

As previously mentioned, the glove (Figure 2.4) consists of flex sensors for each of the fingers. As the sensor bends, its resistance increases. Thus, by manipulating the resistance output, the exoskeleton motion can be controlled. The signals are processed through the glove control system and are sent to the receiver of the exoskeleton.

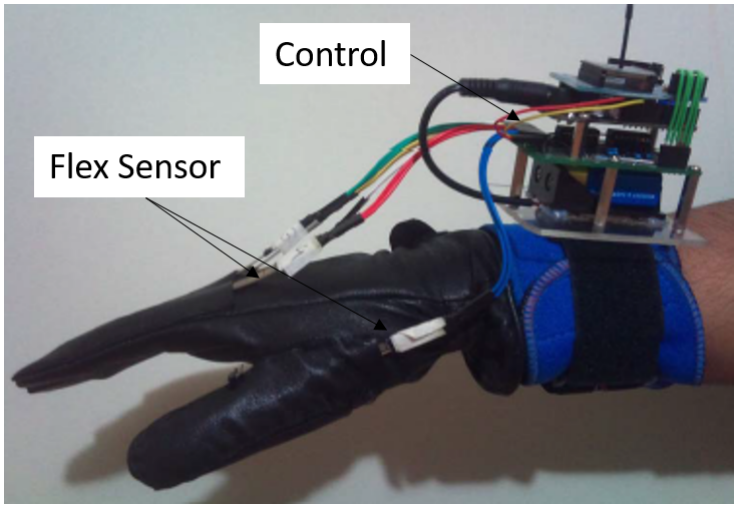


Figure 2.4: Flex Sensor Glove [34]

This device went through prototyping testing on a healthy subject. The results showed that the design was capable of complete flexion and extension of the fingers. However, the transmission had a minor slipping issue which was highlighted as something that can be easily improved. The design aptly met all of the requirements set within the study. Improvements can be made to the control, as it is an open loop system, and to its application towards testing impaired patients. Given that the system is able to perform mimicry movements between the glove and exoskeleton, opportunities are available for further testing and research on its application towards rehabilitation across all hand impairment disorders through bilateral therapy.

2.2 Measured Range of Motion of the Hand Joints

The current section discusses the types of devices used to measure the ROM throughout different studies. The results and methods used in previous studies, will not only be used as a comparison, but serve as a guideline in the testing of patients in performing activities of daily living. Furthermore, this section aims to provide insight on the alternative methods of hand joint measurement.

2.2.1 Functional range of motion of the joints of the hand - April 1990

Hume et al. [35] conducted a study on the functional range of motion of the hand with the aim to investigate said motion while performing 11 activities of daily living. Hume defined active range of motion as the participant's normal range of motion while functional motion was represented as movements required to perform the designated activity. These activities are listed in Table 2.1. All the activities were selected to allow the participants to fully flex and extend their hands by grasping objects of varying sizes. Therefore, the variation of sizes between objects must be considered when selecting the tasks for the current study. The current study may not mimic the exact activities shown below, but a comparison should be drawn on the average ROM achieved in each joint. The results can aid in determining an approximate ROM required for an individual to independently function throughout their day.

Table 2.1: Activities of Daily Living [35]

No.	Activity
1	Holding a telephone
2	Holding a can
3	Using a zipper
4	Holding a toothbrush
5	Turning a key
6	Using a comb
7	Writing with a pen (in print)
8	Holding a fork
9	Holding scissors
10	Unscrewing a jar
11	Holding a hammer

The candidates were 35 right-handed males that had no previous hand impairments and injuries. An electrogoniometer was used to measure the ROM of each participant. The results attained showed averages of 61°, 60° and 39° for the MCP, PIP and DIP joint, respectively [35]. These averages are the combined ROM for all the digits of the hand, excluding the thumb. The thumb averaged 21° and 18° for the MCP and IP joints, respectively [35].

2.2.2 The functional range of motion of the finger joints - May 2014

Similar to the above study, the purpose of the investigation by Bain et al. [36] was to determine the functional range of motion from 10 candidates performing activities of daily living. An analysis was done on the pre-grasp and grasp positions during each of the activities. The tasks were based of the Sollerman hand grip function test (a range of ADLs) and derived into 20 activities. This is shown in Table 2.2.

Table 2.2: Sollerman Test of Hand Grip Function [36]

No.	Activity
1	Turn a key in a lock
2	Turn a door handle in supination
3	Pick up a coin from a table surface
4	Open a zipper
5	Pick up a coin from a purse
6	Lift a wooden cube
7	Hold an iron
8	Hold a screw driver
9	Pick up a nut
10	Unscrew a jar lid
11	Do a button up
12	Use a knife
13	Pull tubigrip stocking over the other hand
14	Use a pen
15	Fold a piece of A4 paper
16	Put a paper clip on an envelope
17	Hold a telephone receiver
18	Hold a carton
19	Hold a jug
20	Hold a cup

The ROM of the finger joints were measured using an electric goniometer which is shown in Figure 2.5. The active and passive range of motion was measured to determine the range between the arc of full motion of each joint. Thus, creating boundaries for the functional range of motion tests. The current study will need to employ similar methods to limit the range of motion to pure flexion/extension and ignore the effects of hyperextension.



Figure 2.5: Electric Goniometer [36]

Bain et al. [36] defined the functional range of motion as the motion achieved to perform 90% of the activities. The results of the tests indicated a functional range of motion of 19°-71°, 23°-87°, and 10°-64° at the MCP, PIP and DIP joints, respectively. These results represent a range between the minimum and maximum motion.

2.2.3 Range of motion to maintain hand function - October 2014

Hayashi et al. [37] determined the required range of motion of the MCP joint for primary hand function. The tests were split into two experiments. The first entailed the effect of hand function without the use of an orthoses while the second was done by limiting the range of motion at various angles. The configuration of limiting the range of motion with an orthoses is shown in Figure 2.6, where A and B represent the limitation of flexion and extension, respectively.

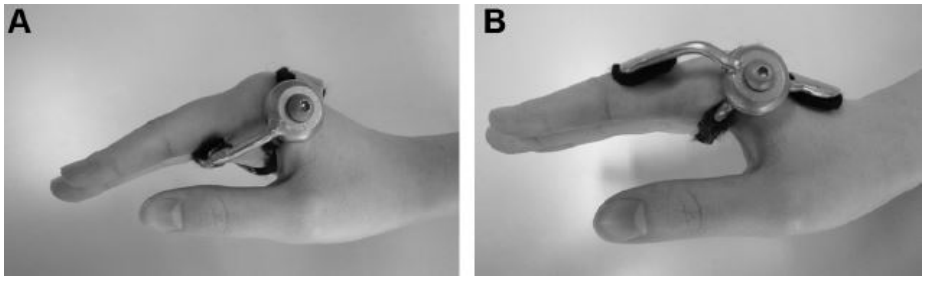


Figure 2.6: Limiting the Range of Motion using an Orthoses [37]

21 right-handed candidates were tested using the using the Jebsen-Taylor hand function test (a range of ADLs) and the O'Connor finger dexterity test (pegged board with pin placement). The results indicated that the MCP joints had a flexion $> 70°$.

2.2.4 Activities of Daily Living

To determine the range of motion required for an individual to be an independent and functional member of society, testing must include activities that encompass the expected daily routine of said individual. Gracia-Ibanez et el. [38] 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 were based on the International Classification of Functioning, Disability and Health [39] (ICF). The ICF is a basis for measuring level of health and disability for an individual or a population. Table 2.3 represents the categories selected by Gracia-Ibanez et al. and corresponding ICF areas, which can serve as a guide for the current investigation. By adhering to the ICF chapters in the activity selection process, the current study will be consistent with previous research.

Table 2.3: ICF Categories [38]

Communication		**Mobility**		**Self Care**		**Domestic Life**	
Code	Area	Code	Area	Code	Area	Code	Area
d325	Communicating with receiving-written messages	d430	Lifting and carrying	d520	Caring for body parts	d640	Doing housework
d345	Writing messages	d440	Fine hand use	d540	Dressing		
d360	Using communication devices and techniques	d445	Hand and arm use	d550	Eating		
				d560	Drinking		

2.3 Summary

With the above discussions pertaining to the past research on both hand rehabilitation and measuring devices, the current study can progress forward. Measuring the ROM of the hand has predominately been achieved by using a goniometer. The accuracy and reliability of the device is 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 effect the patient's performance. Thus, a newer and more efficient method of measuring the ROM of the hand will be developed and discussed in the current study.

In the current section, the measurement and rehabilitative methods produced in the previous studies will act as a guideline in the development of a working prototype. Additionally, comparisons will be made between the range of motion results achieved in the previous research with the results produced from the prototype of the current investigation. The next

chapter will discuss the flexible sensor and the required testing performed, to validate the use of the sensor as a prospective finger range of motion feedback device.

Chapter 3

Analysis of the Flex Sensor

3.1 Introduction

As mentioned in Section 1.3.2, flex sensors 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 to the flex sensors. 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 following chapter entails the configuration of the flex sensors and the multiple tests conducted in order to verify the application of the sensors. These tests aimed to replicate the anatomical variations of the finger joints of a human hand. The sensors were then attached to a glove and had gone through a series of bending angles and locations to determine the accuracy of the system.

There are multiple types of flexible sensors, however the most common, with respect to the application in orthotics, has been the flex sensors. Section 1.3.2 details the fundamentals of how the flex sensor functions. Oess et al. [40] had sampled multiple flex 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 [40]. 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 a locally sourced, single branded and sized flex sensors. The parameters of the Sparkfun Flex Sensor [26] can be found within the data sheet, in Appendix A. Apart from the comments made by Oess, Sparkfun have 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, shown in Figure 3.1.

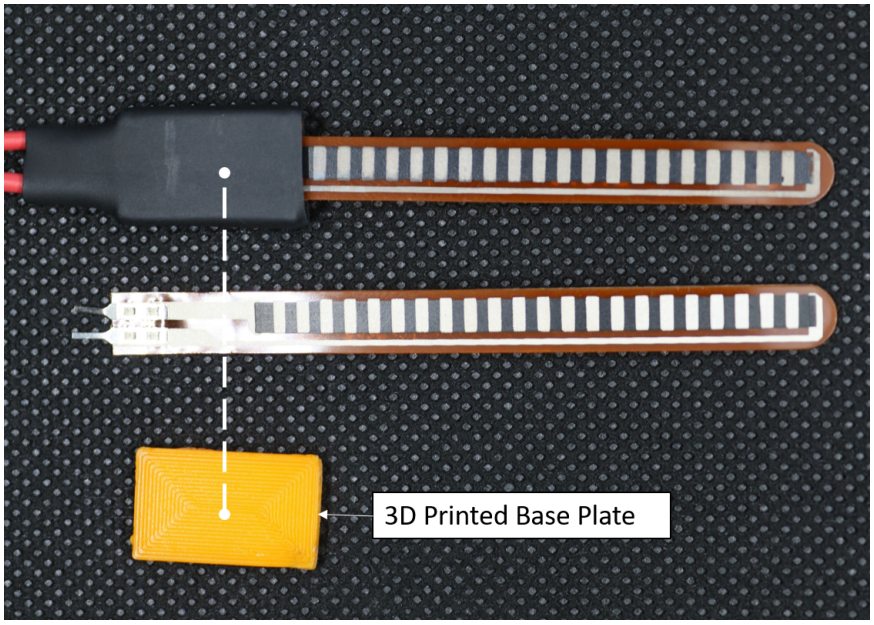


Figure 3.1: Securing Base of Flex Sensor

The flex sensors are aimed to be used along the joints of the fingers. Before any prototype is manufactured, consideration must be given to the anatomical variation in hand sizes and shapes.

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. Therefore, it is imperative to test and determine the resistance fluctuations observed from these sensors.

3.2 Flex Sensor Resistance Test

The flex sensors were configured with a resistor in order 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 flex sensors are similar and are around 30 000Ω as indicated by Sparkfun. Figure 3.2 represents a basic circuit that consists of: an Arduino Uno, one flex sensor, a single bread board and resistor. Using a multimeter the resistance of the single flex sensor was measured. By changing the resistor in the circuit below, a comparison was drawn between the output of microcontroller and the values attained through the multimeter.

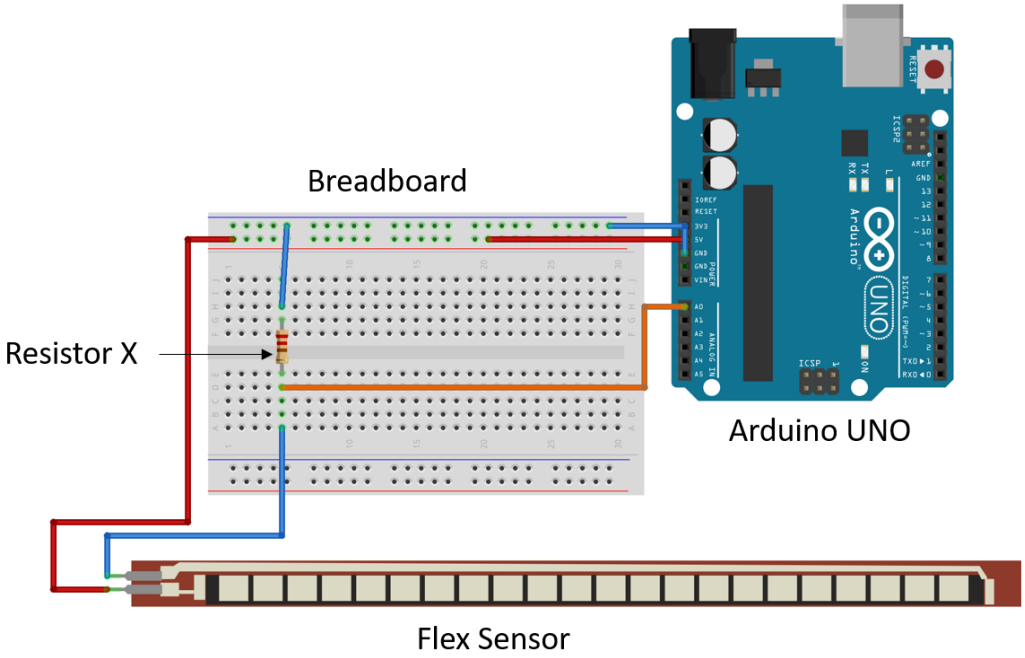


Figure 3.2: Basic Flex Sensor Circuit

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 position. This is shown in Figure 3.3. The straight test rig, holds the sensor in place using a 3D printed flexible sleeve. The sleeve is attached a solid 3D printed base using velcro.

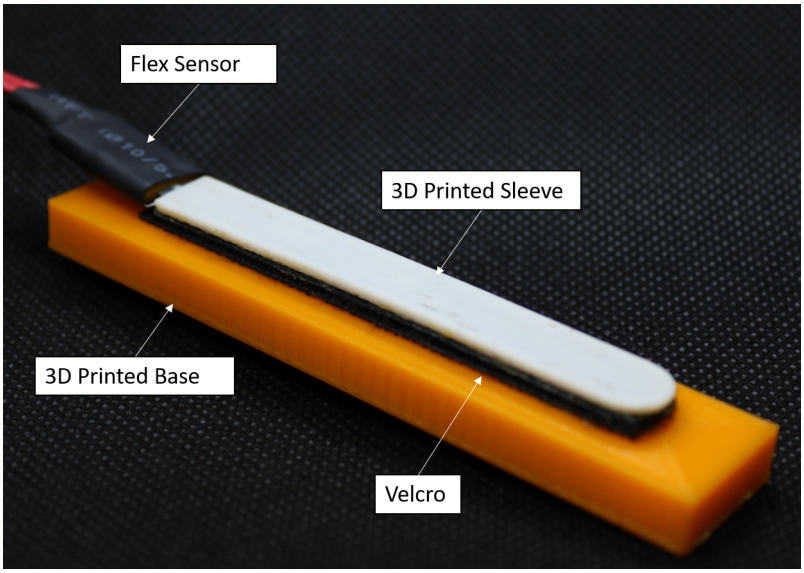


Figure 3.3: Straight Flex Sensor Rig

Figure 3.4 represents the straight resistances recorded for three flex sensors, using a digital multimeter. Evidently, there is variation between the magnitude of the resistances. The flat resistances of all the sensors should be similar and around 30 000Ω (Sparkfun). Flex Sensors B and C are aligned with the value suggested by Sparkfun while Flex Sensor A observed values significantly higher. Flex Sensor A, had an average resistance magnitude of 48 825Ω, while Flex Sensors B and C had lower values of 27 780Ω and 28 145Ω, respectively. These values can be seen as an approximation of the expected resistances for when the user's hand is in a flat (joints at 0°) position.

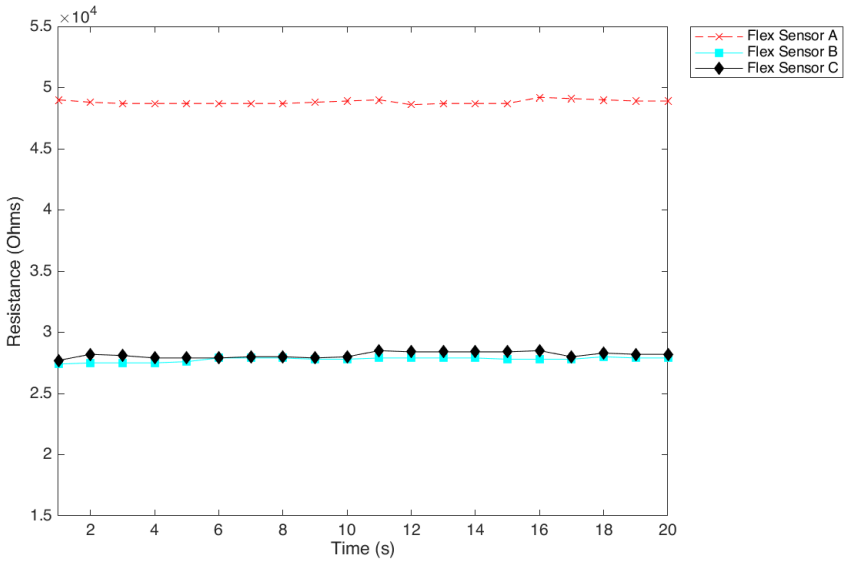


Figure 3.4: Digital Multimeter Readings for three Flex Sensors

Each flex sensor in Figure 3.4 has a consistent straight line with minor fluctuations. Each line had a calculated coefficient of variance of less than 1%. Flex Sensor A was used in the circuit shown in Figure 3.2 to determine the optimal resistance. Table 8.1 in Appendix B shows the results of the various resistors used.

As the resistor magnitude increases, the Arduino output slowly decreases towards the values attained using the digital multimeter. This is shown in Figure 3.5. Another visible observation, indicates the stablity of the sensor output as the resistance increases. Therefore, out of all the resistor options, the 100 kΩ was chosen in the current study as the values had negligible differences with the multimeter readings.

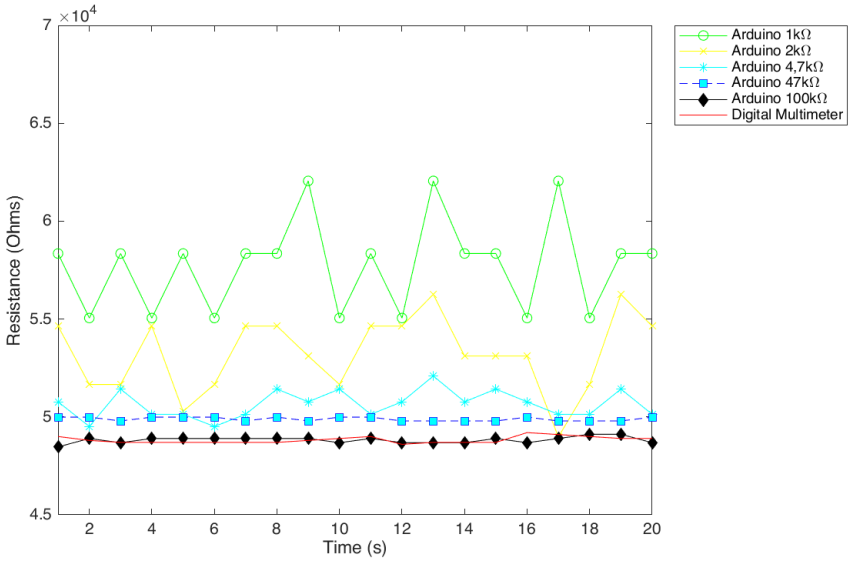


Figure 3.5: Comparison of Resistor Outputs for Flex Sensor A

A similar situation occurred using sensors B and C (Figure 3.6). Based on these results, the resistance of the sensors have a reasonable degree of stability but may differ in magnitude. However, this should not affect the use of the sensors as the change of resistance will be manipulated to output the range of motion.

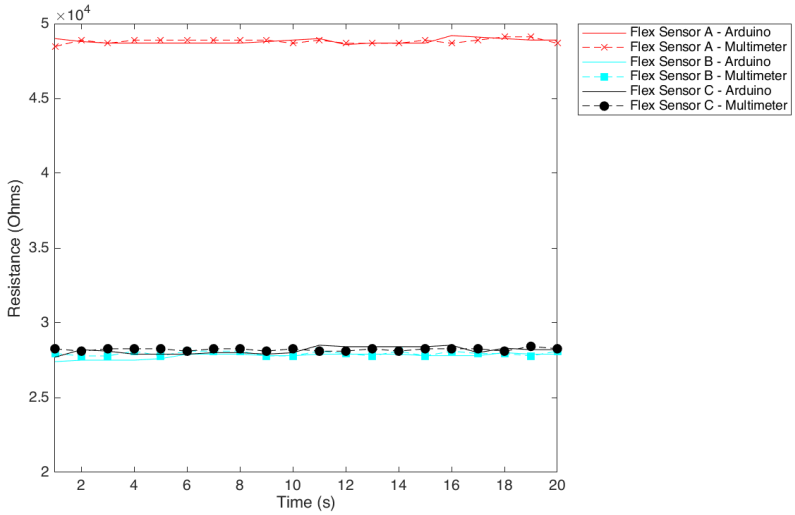
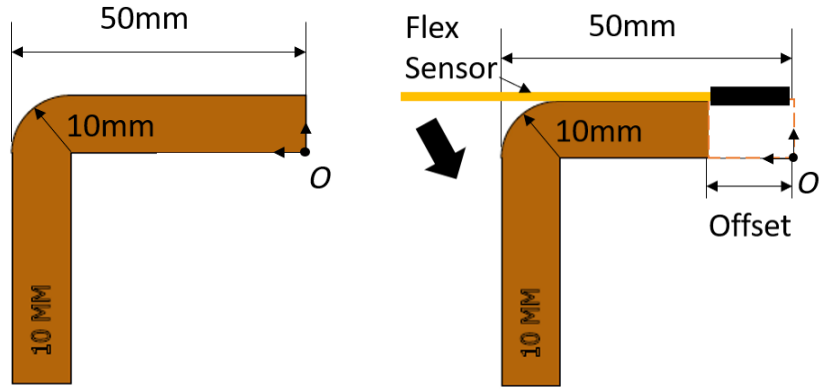


Figure 3.6: Comparison of the Resistances between the Arduino and Digital Multimeter

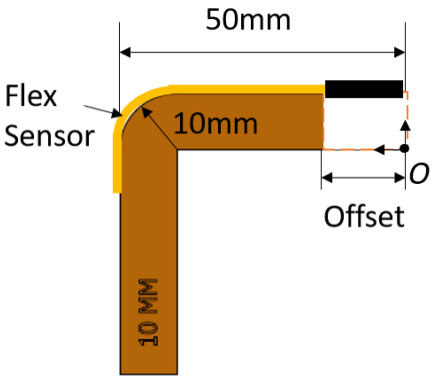
3.3 Flex Sensor Anatomical Variation Tests

3.3.1 Flex Sensor Bend Location Test

The bend location test indicates whether readings across the length of the sensor are consistent. This is significant as some patients may have hands of similar size, however the length and location of their joints may vary. In addition, the results will also determine the required positioning of the sensors in order to produce stable outputs. Multiple flex sensors were bent at several different locations. The locations were determined by three offsets, from the origin O, on a 3D printed piece with a radius of 10mm (Figure 3.7a.)



(a) 3D Printed 10mm Rig (b) 3D Printed 10mm Rig with Offset



(c) Positioning Flex Sensor

Figure 3.7: Bend Location Test Rig

Each offset, as indicated in Figure 3.8, was 20mm, 30mm and 40mm, respectively. In order for the attachment of the sensor base to have a secure level, the 40mm piece had an additional printed structure. Each sensor was positioned as shown in Figures 3.7b and 3.7c. The sensors were secured using insulation tape on either ends.

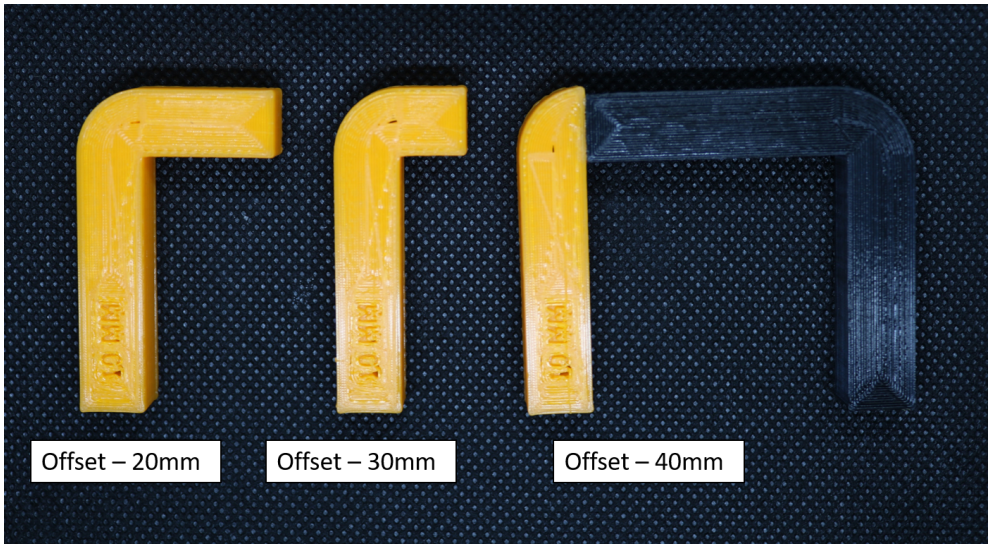


Figure 3.8: 3D Printed Offset Pieces

Figure 3.9 represents the resulting resistances for all offsets using Flex Sensor B. There was a significant difference in the magnitude between the bending locations. The 40 mm offset (bend location closest to the base of the sensor) represents the lower magnitude, while the 20mm and 30mm offsets experienced similar magnitudes. The following test was repeated three times on several sensors to determine whether a trend was achieved. Flex Sensor B has a resistance ranging from 70 000 - 80 000Ω, depending on the bend offset. These values can approximate the user's finger joint in a closed fist (joints at 90°) position.

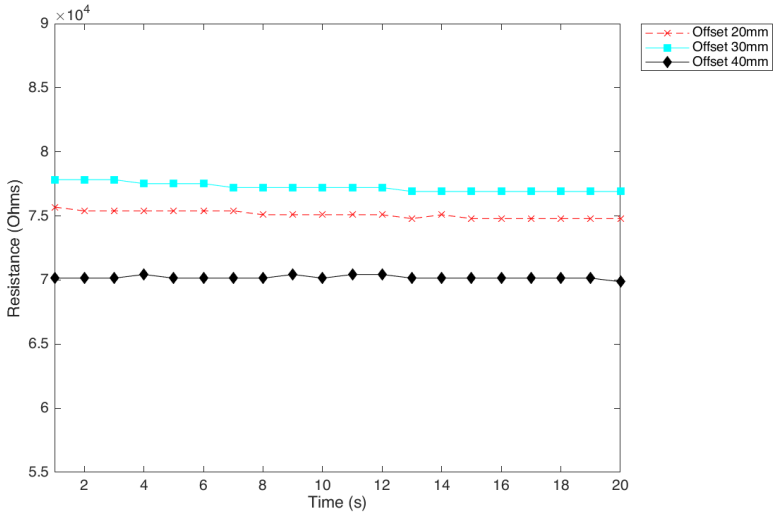
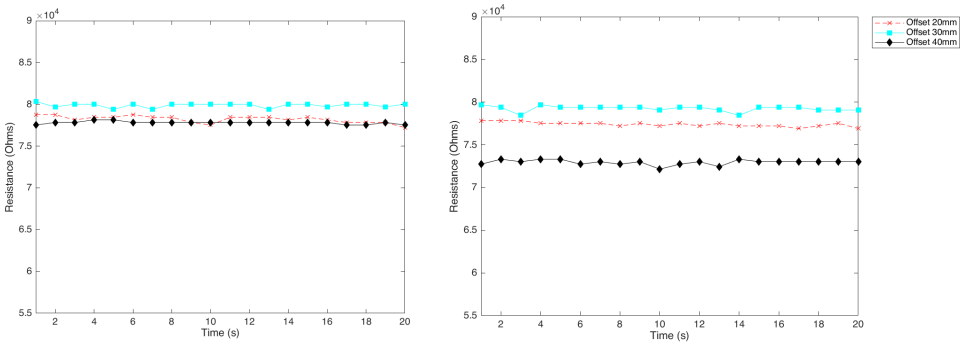


Figure 3.9: Resistance Output for Flex Sensor B

Figures 3.10a and 3.10b are the repeated tests for Sensor B. Both tests, shared the trend observed in Figure 3.9. Flex Sensors A and C, resulted in a similar behaviour, with the lower resistance averages occurring closer to the base of the sensor.



(a) Bend Location Test 2

(b) Bend Location Test 2

Figure 3.10: Flex Sensor B Bend Location Tests

There were cases, during the repeatability tests where the offsets did not follow the above trends. Therefore, no conclusion can be drawn in indicating an optimal position for bending the sensor at a specific location. Figure 3.11 represents the three bend locations tests at a 30mm offset for Flex Sensor A. All three tests resulted in a variation of magnitude. All test results were grouped as a single set of data in order to determine the extent of the variation. A coefficient of variance of less than 2.2% was calculated. Table 3.1 shows the resulting variation across all sensors with respect to repeating the offsets.

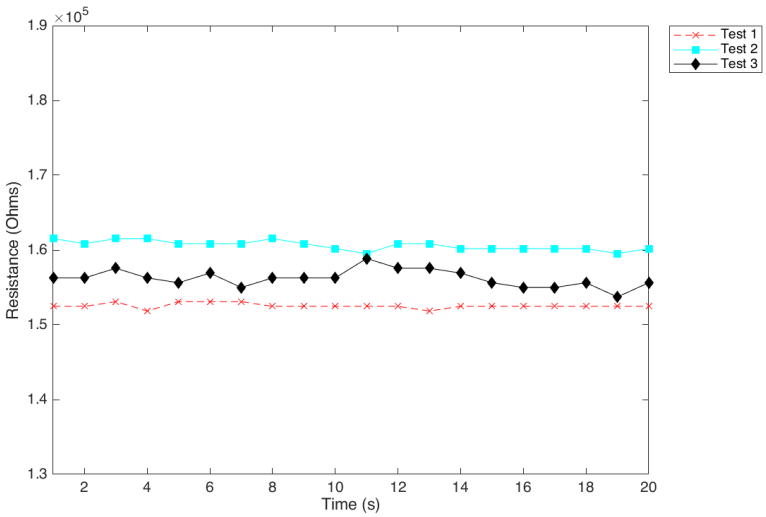


Figure 3.11: Repeatable Tests for Flex Sensor A at 30mm Offset

Flex Sensor A and B have similar magnitudes of variance when the sensor is bent towards the middle (Offset 20 and 30mm), with the highest value having a difference of 2.2%. The bending of the sensor closer to the end of base, resulted in a greater variation as shown in Table 3.1 with high values up to 4.6% (Flex Sensors A and B). Therefore, when positioning

the sensors, the location of bending should not be in close proximity to the base. In terms of variation in the repeatability of the results, 2.2% is acceptable as the variation is minimal.

Table 3.1: Coefficient of Variance for Flex Sensor Offsets

	Offset		
Flex Sensor	20mm	30mm	40mm
A	0.0217	0.0217	0.0456
B	0.0176	0.0148	0.0427
C	0.0162	0.0153	0.0114

3.3.2 Flex Sensor Variable Radius Bend Test

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 flex sensors at various radii. Figure 3.12 represents the setup which is quite similar to the previous bend test in Section 3.3.1.

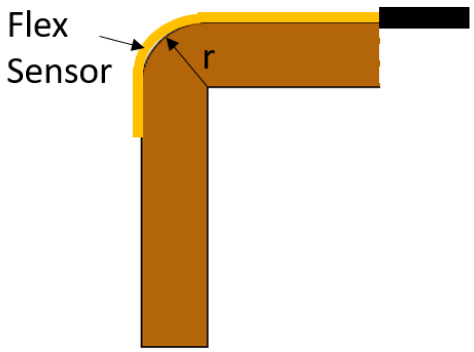


Figure 3.12: Radius Test Setup

Each sensor was taped down onto a 3D printed piece with different radii (5, 10 or 12mm). The 3D printed mounts are shown in Figure 3.13.

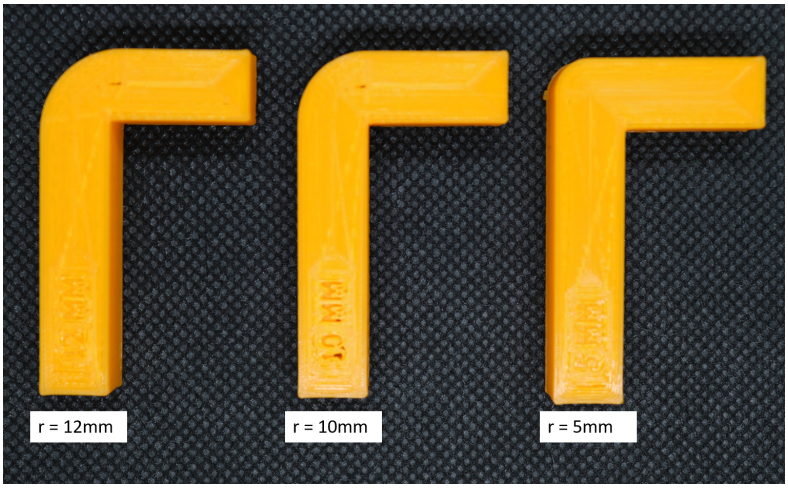


Figure 3.13: Radius Test Mounts

Figure 3.14 represents the resulting resistance obtained from Sensors C for all three radii. A radius of 5 and 10mm observed a similar behaviour, while the 12mm radius test deviated in magnitude from the previous tests.

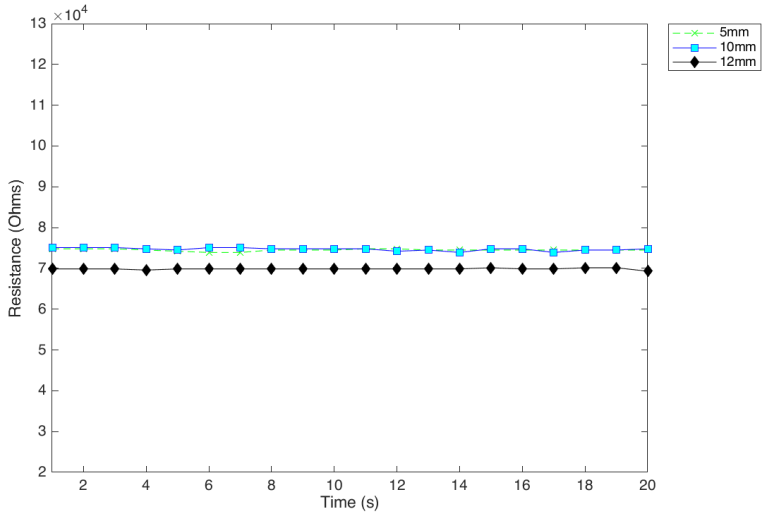


Figure 3.14: Radius Test for Flex Sensor C

The above observations differed for Sensors A (Figure 3.15) and B (Figure 3.16). Once again, similar to the bend location test, no conclusion can be drawn from the effects of the bend radii. However, considering the variation in the resistances across the multiple sensors a maximum coefficient of variance was calculated as 3.7%. Therefore, the variations were minimal. 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.

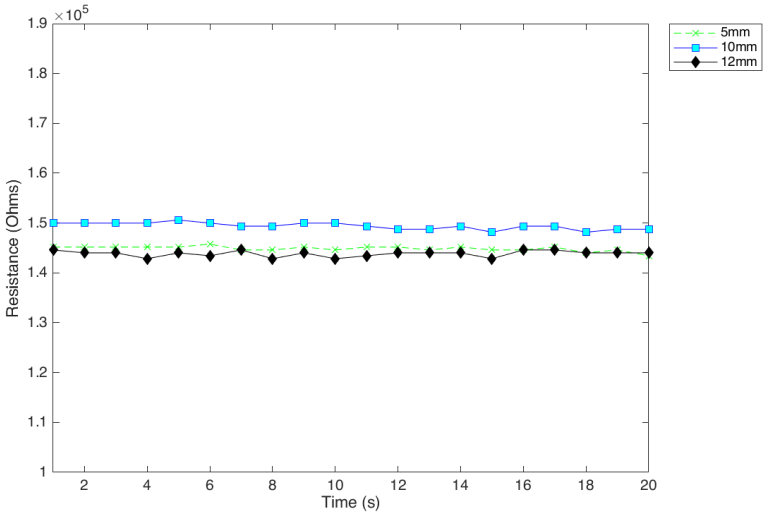


Figure 3.15: Radius Test for Flex Sensor A

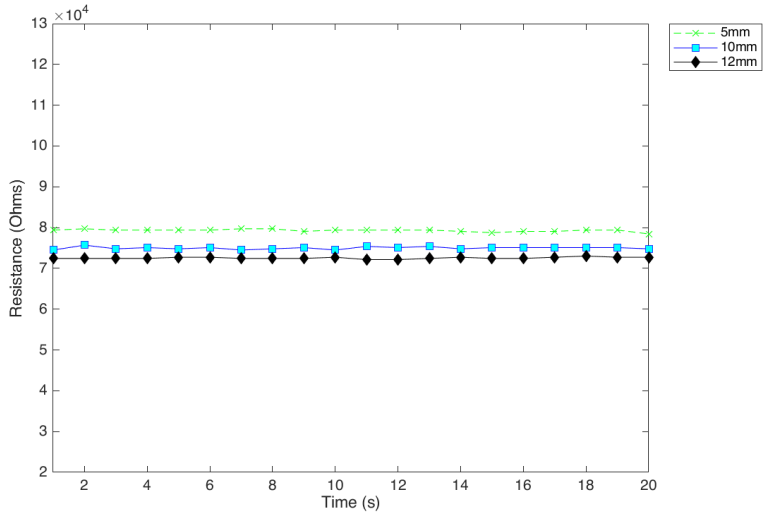


Figure 3.16: Radius Test for Flex Sensor B

3.4 Conclusions

During the straight resistance test, the 100kΩ resistor produced values that were the most similar and consistent when compared to the readings attained using the digital multimeter. The bend location and radius test was used to determine whether anatomical variation between humans, would effect the results. The bend location tests indicated that a flex sensor bent further away from the base of the sensor exhibited repeatable results. The sensors were then bent at different radii and again produced minor fluctuations. However, the results show that the curvature is more likely to affect the resistance of the sensors and not bend location. Based on all tests it was evident that the sensors are capable of producing repeatable results

with deviations being limited under 4%. Therefore, the results are promising with respect to application of the sensors to measure the range of motion of the finger joints. Considering the resistance variations observed, a calibration phase was required to minimize the fluctuations. This calibration will be discussed in the Chapter 4, where the next step will be to create a system of the sensors and use them in a working prototype.

Chapter 4

Development of the Prototype

4.1 Introduction

In the previous chapter, the results indicated minimal variations in sensor readings, which led towards creating a prototype capable of measuring the range of motion of the hand. This chapter will include the design and development of said prototype. Once the prototype was developed, a test validation was done to determine the accuracy of replicating measured motion of the hand.

The design of the device can be broken down into two sections, namely, the design of the glove/method of attachment and the design of the circuit used. Referring back to Sections 1.3.1 and 1.3.3, the requirements that need to be considered can be summarized into 2 parameters:

- Comfort/Safety
- Ease of Use

Apart from the above factors, consideration must also be given to the aim of research - to be a low-cost and accessible device, as well as the intended application - to serve as a prototype.

4.2 Glove Design

To simplify the research, golfing gloves were used as they were easily attainable and omitted the need for manufacturing. Furthermore, the gloves provided a simpler method of size selection. The brand used for both right-handed and left-handed gloves was Callaway, with both sizes being large. Therefore, the selection of participants was confined to these hand dimensions. Multiple methods were used to attach the sensors onto the glove. A sample test was done on the glove seen in Figure 4.2. A velcro strip was glued onto the index finger, a flexible 3D printed sleeve was sown onto the ring finger and glued onto the middle



Figure 4.1: Callaway Golf Glove [16]

finger. The velcro method introduced the possibility of making the prototype modular. The sensors could be attached and re-attached with ease, therefore creating a method allowing for modifications. However, constantly bending the index finger resulted in the slow separation between the velcro attachment and the flex sensor. This would alter the resistance in the sensors and effect the results. The 3D printed flexible sleeves worked well in securing the sensors, regardless of the method of connection with the leather glove. Velcro was used on the base of the sensor to keep it from moving in and out of the sleeve.



Figure 4.2: Methods of Attachment

A second glove was made using the flexible sleeves on the PIP joints of the hand (Figure 4.3). This glove had a reasonable degree of comfort and thus a third glove was made with the sleeves placed at both the PIP and MCP Joints. This is shown in Figure 4.4.



Figure 4.3: Flexible Sleeves across PIP Joints



Figure 4.4: Flexible Sleeves across PIP and MCP Joints

Once the sleeves were attached to all the joint locations, there was a significant increase in the resistance to motion while using the glove. Apart from impeding motion, the discomfort of the glove prototype could cause harm to a hand-impaired patient. Therefore the flexible sleeve attachment is not a viable solution. To reduce the introduction of resistance across the joints of the hand and to minimize costs in manufacturing the prototype, material medical tape was used to secure the flex sensors. Figure 4.5 represents the prototype for the right-handed glove using material tape. Material spacers were placed in between the material tape, to allow the sensors to slide in and out of position. Additional tape was used around the base of the sensors so that relative motion along the surface of the glove was minimal.



Figure 4.5: Medical Tape Prototype

4.3 Circuit Design and Process

Figure 4.6 represents the final circuit that was designed for the prototype. The full electronic circuit can be seen in Appendix C. The Arduino Uno was replaced with a different microcontroller that is similar to the Arduino MEGA but is more compact. This is due to the amount of analogue pins required to connect all 10 sensors. However, the circuit in Figure 4.6 acts as an example of how a single sensor is connected, but still incorporates the main components of the circuit used within the prototype. The following components were used to assemble the final circuit:

- Compact Mega Mini Pro 2560 - Microcontroller
- Veroboard - Connects all components
- 2 x Push Buttons
- 3 x LEDs (Red, Blue, Yellow)
- 10 x 100kΩ Resistors
- 5 x 47kΩ Resistors
- SD card module (Optional for data capturing)

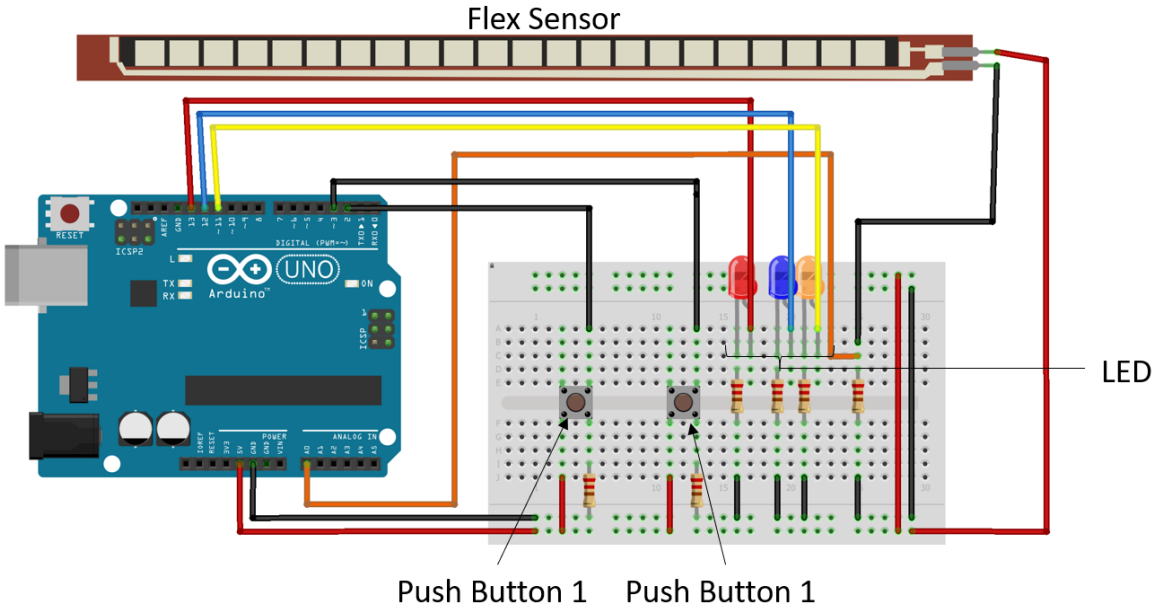


Figure 4.6: Main Circuit Design

4.3.1 Technical Procedure

With reference to Figure 4.7, the following procedure summarizes the technical process of testing a candidate:

- User wears the glove and lays the hand in a flat position. The first calibration phase begins. The sensor readings recorded during this phase are used as reference for 0°.
- After 30s the user changes the gesture from a flat to a fisted position. The second calibration phase begins. The sensor readings recorded during this phase are used as reference for 90°.
- As indicated in the flow diagram, the calibration phases end when all LEDs are off. This signals that activity testing can commence.
- Now the user simplify performs the directed tasks, while the glove records the ROM of the hand.

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 by calculating the difference between the two sets of data for each joint. Therefore, the first recorded activity (Activity

1 - Correction Factor) has been set as holding the fist position. A description of how the circuit works and the main functions used, can be found in Appendix D. The full code can be found in Appendix E.

The necessity of the calibration phase is to further minimize the variations observed in the anatomical variation tests (Section 3.3). Apart from different hand sizes, patients will have different gestural behaviours. Therefore, the calibration serves to uniquely record and map the data according to the distinctiveness of the user's hand movements.

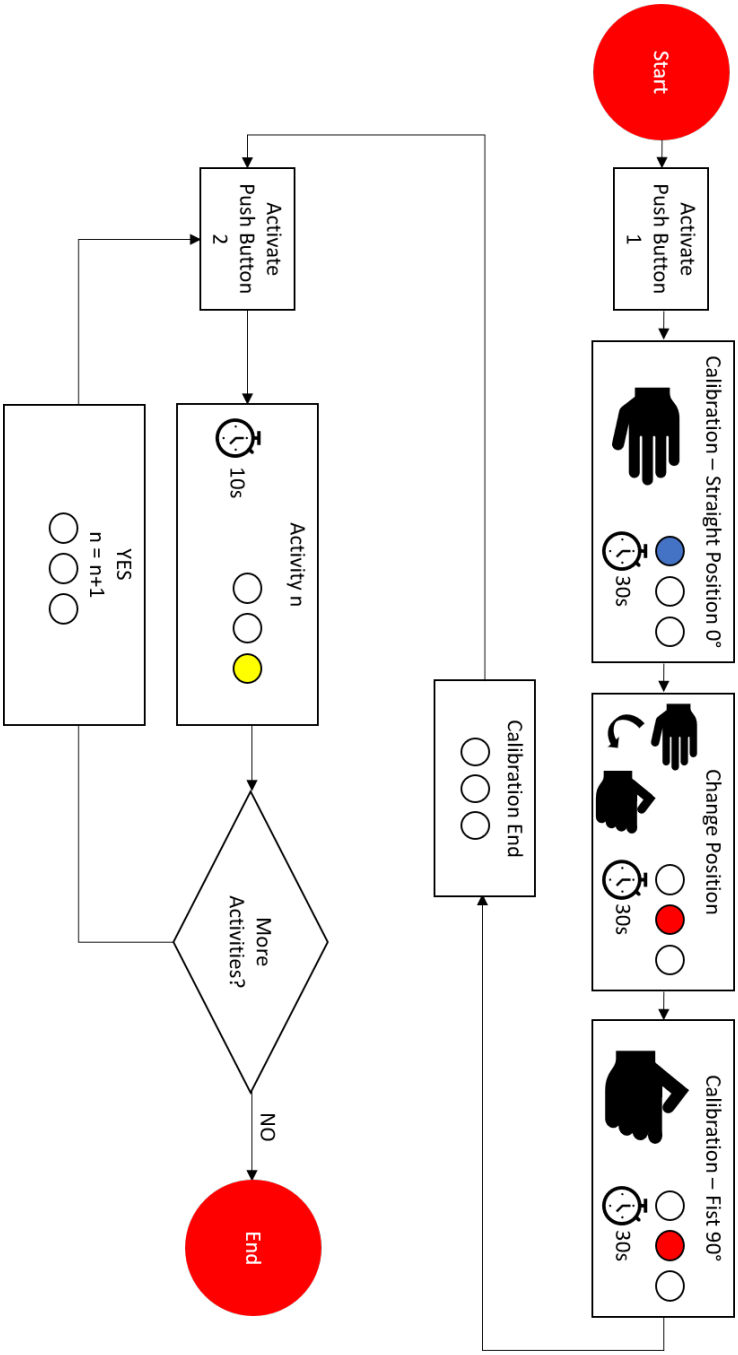


Figure 4.7: Control Flowchart

4.4 Cost Analysis

Table 4.1 represents the total cost of the working prototype. The evaluation is purely based on material costs and manufacturing methods were not considered. Leading on to one of the objectives of the study, the current cost analysis was done to serve as a benchmark and determine where costs can and should be minimized.

Table 4.1: Cost of Prototype

Item	**Amount**	**Cost (R)**	**Availabilty**
Materials			
Glove	2	470	Amazon*
Material Tape	1	60	Dischem
Electronics			
Mega Mini Pro	1	228	MicroRobotics
LEDs	3	3	MicroRobotics
Push Buttons	2	3	MicroRobotics
100kΩ Resistor	10	5	MicroRobotics
47kΩ Resistor	5	2.5	MicroRobotics
SD Card Module	1	45	MicroRobotics
VeroBoard	1	35	MicroRobotics
Ribbon Cable	2m	25	MicroRobotics
Flex Sensors	10	1400	MicroRobotics
TOTAL		**R2276.5**	

*At the time of the study, right-handed golf gloves were not locally available (but usually are) and therefore were bought from Amazon for the convenience of the research.

Apart from the golf gloves, all of the above components were sourced locally. Based on the analysis, it is evident that the materials that were the most costly were the flex sensors, followed by the golf gloves and the microcontroller. The flex sensors, form 61% of the total costs. This is dependent on the number of sensors used which in the case of this study was 10. Therefore, to reduced the costs, attention must be directed elsewhere.

The cost of the gloves can easily be reduced by purchasing them locally, even veering away from golf gloves but other types that may be better suited, such as nylon or nitrile gloves. These gloves are favourable as they are non-stretch and will therefore result in an easier means of attaching the sensors to the gloves. The microcontroller can also be replaced by another board so long as the analogue pins are sufficient enough for 10 sensors. The components

indicated by italics, are not needed for the prototype to function so long as a computer is available. However, they do not greatly affect the cost of the prototype. However, by combining these differences with the above mentioned changes the prototype will be able to fall under a budget of R2000.

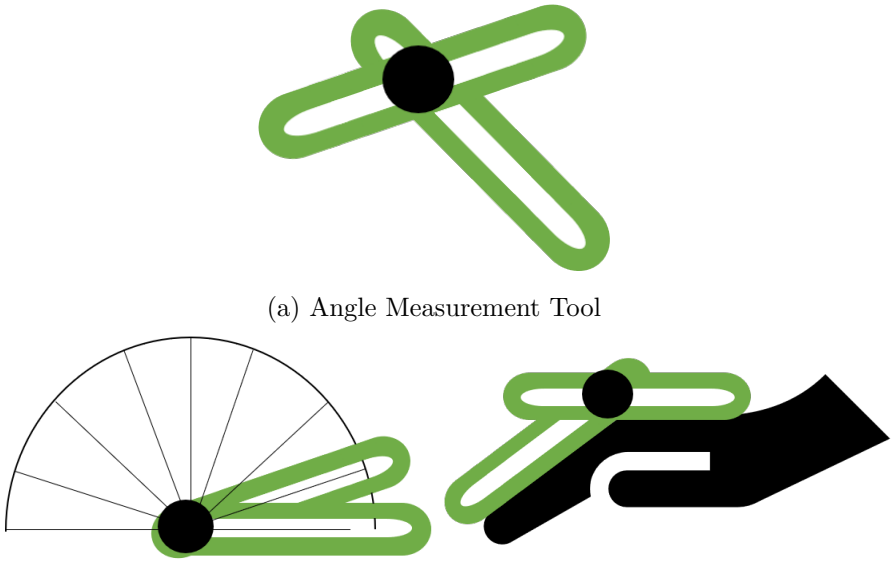
It must be emphasised that this cost relates to a prototype and that the device can be taken further into a working product. During this phase costs can be significantly reduced. Many of the components can be manufactured from base materials, whether it be the gloves or the electrical components.

The prototype measures the ROM of the hand, therefore when comparing the price to existing devices, the comparisons should be made with a device that has the same function. Many previous studies measured the ROM of the hand using a finger goniometer. A simple device that is used alongside the joints of the finger. A standard goniometer ranges between R95 - R800 [41], which is dependent on whether it is a digital or standard model.

Although the goniometer is a simple device, the procedure of measuring all joints during tests may be tedious and time constraining for both the therapist and patient. The therapist would need to take multiple readings of each joint of each finger for a single gesture that a patient holds. This may be difficult for a hand-impaired patient. In Section 1.1, it was mentioned that therapy in South Africa is affected by high referral rates and time constraints, therefore this method may not be the most applicable to developing countries. Although the cost is more for the current device, the effectiveness of measuring the ROM of the hand, with respect to time and practicality, is greater with the use of the glove. In addition, the glove is a robotic device, encouraging the introduction of new technology into developing countries - a fundamental objective of the current research. The main aim can be seen as a low-cost yet effective flexible sensor glove, capable of measuring the ROM of the hand, for use in developing countries.

4.5 Validation

The validation of the glove consisted of testing each joint at 30°, 45° and 60°. This was done by using a 3D printed angle measurement tool shown in Figure 4.8a. The angle was determined using a protractor and thereafter aligned with the finger across the selected joint (Figure 4.8). The participant for the validation tests was the principle investigator of the current study.



(a) Angle Measurement Tool

(b) Protractor

(c) Angle Measurement Tool on Joint

Figure 4.8: Angle Measurement Process

The results for the validation tests are shown in Table 4.2. Each set of tests were repeated in a similar manner to the resistance testing done in Section 3.2, across 3 different sensors. As mentioned in Section 4.3, the procedure of testing included an approximate correction factor due to the physical slack within the glove. For the validation, the correction factor was applied to determine upper and lower bounds as seen in Table 4.2. The deviations represented, consider the correction factor and thus the calculations include the lower and upper bounds.

Table 4.2: Validation Results

Left Hand	Test Angles									Deviation	Max RMSE
	30°			45°			60°				
	Lower	Average	Upper	Lower	Average	Upper	Lower	Average	Upper		
Thumb IP	27.23	27.85	28.47	44.29	45.3	46.31	58.18	59.5	60.82	1.53	2.44
Thumb MCP	33.59	35.55	37.51	41.53	43.95	46.37	58.26	61.65	65.04	3.59	5.63
Index PIP	28.49	29.2	29.91	48.29	49.5	50.71	55.75	57.15	58.55	3.29	3.19
Index MCP	35.87	36.75	37.63	44.27	45.35	46.43	58.27	59.7	61.13	**5.89**	7.61
Middle PIP	27.39	27.85	28.31	44.2	44.95	45.7	51.77	52.65	53.53	**6.47**	7.41
Middle MCP	33.91	35.55	37.19	41.92	43.95	45.98	58.81	61.65	64.49	3.91	5.61
Ring PIP	30.44	30.85	31.26	46.42	47.05	47.68	59.2	60	60.8	1.42	2.13
Ring MCP	27.54	28.9	30.26	43.88	46.05	48.22	51.97	54.55	57.13	2.87	5.5
Pinky PIP	33.26	33.8	34.34	41.86	42.55	43.24	53.47	54.35	55.23	4.77	5.71
Pinky MCP	32.49	34.65	36.81	44.87	47.85	50.83	59.78	63.75	67.72	2.49	4.72
Right Hand	Test Angles									Deviation	Max RMSE
	30°			45°			60°				
	Lower	Average	Upper	Lower	Average	Upper	Lower	Average	Upper		
Thumb IP	31.2	32.65	34.1	36.79	38.5	40.21	54.42	56.95	59.48	4.79	3.2
Thumb MCP	26.07	27.95	29.83	33.86	36.3	38.74	48.36	51.85	55.34	**6.26**	8.43
Index PIP	26.51	27.6	28.69	41.35	43.05	44.75	55.76	58.05	60.34	1.31	2.52
Index MCP	28.07	28.95	29.83	38.68	39.9	41.12	58.94	60.8	62.66	3.88	5.21
Middle PIP	32.05	34.1	36.15	43.1	45.85	48.6	52.17	55.5	58.83	2.05	4.62
Middle MCP	28.41	29.15	29.89	45.17	46.35	47.53	55.64	57.1	58.56	1.44	3.15
Ring PIP	32.64	33.75	34.86	43.57	45.05	46.53	51.89	53.65	55.41	4.59	6.62
Ring MCP	28.09	29.5	30.91	45.28	47.55	49.82	63.89	67.1	70.31	3.89	7.26
Pinky PIP	25.75	26.35	26.95	48.71	49.85	50.99	58.93	60.3	61.67	3.71	4.92
Pinky MCP	30.33	31.5	32.67	52.42	54.45	56.48	64.99	67.5	70.01	**7.42**	9.52

The RMSE (Root Mean Square Error) is a measure of the average of the differences between values predicted and the values observed. The column on the far right represents the maximum RMSE error across each finger. The average error across the left and right hand is 4.8° and 5.2°, respectively. These errors do not consider the correction factor and thus ignores the slack of the glove.

The deviations on the right hand side of Table 4.2 were calculated by determining the highest difference between the actual angle required and the angle (upper or lower bound) achieved during the tests. Both the left and right hand results had minimal variations with only two joints showing differences higher than 5°. However, the differences were not across similar joints. These occurrences can be due to the instability of the wearer's hand during the validation phase as it may be difficult to hold gestures for a set period of time. This observation, must also be considered when testing other healthy participants. Additionally,

the MCP joint of the thumb (right and left) was inconsistent in the second calibration phase. Keeping the joint at 90° proved to be a difficult and uncomfortable gesture to hold and will invalidate the calibration method. Therefore, for the testing of healthy subjects, the measurement of that joint was dismissed.

By averaging the variation across the whole hand, the results indicated that the differences were below 5°, with 3.6° and 3.9°, for the left and right hand, respectively. In comparison with the RMSE error, it is evident that the slack of the glove produces additional error and therefore the correction factor must be applied. The results indicated that the glove is capable of achieving an accuracy of +/- 5° which is congruent with the research conducted by Oess et al.[40]. The accuracy of the glove is within an acceptable range for its applications; namely measurement of of large changes in the ROM of patients, and determining the state of impairment or recovery.

4.6 Observations and Conclusions

The circuit and process design included a calibration phase to cater for anatomical and gestural variations across all users. The process incorporated the use of LEDs to indicate the various phases of the glove while measuring the range of motion of the hand. The cost analysis showed promise of achieving a material price lower than R2000, however this analysis was based on a prototype. Therefore, further reductions can be made when producing a final product. The validation phase indicated a variation of +/- 5°. The MCP joints of the thumbs produced inconsistencies as it was difficult and uncomfortable to hold the second calibration position and thus was omitted in the testing analysis. Based on these observations, holding gestures for a set period of time may be difficult for candidates and therefore must be considered in the next phase of patient testing.

Chapter 5

Subject Testing - Dynamic Motion

5.1 Introduction

The glove was validated and is capable of measuring the range of motion of the finger joints. This has led to the following section which includes the dynamic testing of 10 candidates on both the dominant and non-dominant hand. Figure 5.1 represents the finished prototype that was used in the current testing.

By determining the dynamic ROM of the patients, observations can be made about how functional each joint is within the hand. Therapists can investigate whether the observed range of motion of the joints has deteriorated over time or how effective the method of therapy is. Dynamic results will show therapists and physicians, the level of functionality that the hand-impaired patient has, as opposed to static tests where holding gestures does not fully describe and represent the use of the hand.

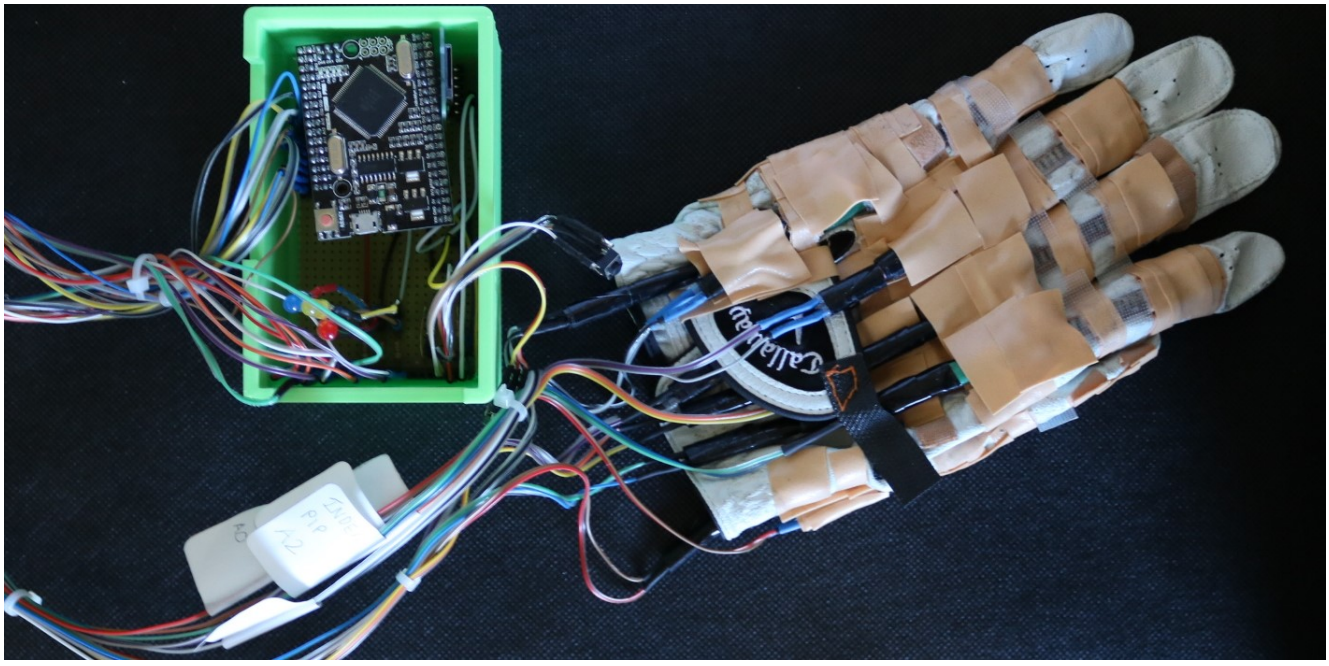


Figure 5.1: Final Prototype for Dynamic Testing

5.2 Selection of Activities

The flowchart in Figure 5.2, represents the activities selected for the dynamic range of motion tests. Each activity was based of the ICF categories similar to those found in Table 2.3. These activities serve to replicate the tasks that may occur during the daily lifestyle of an independent individual.

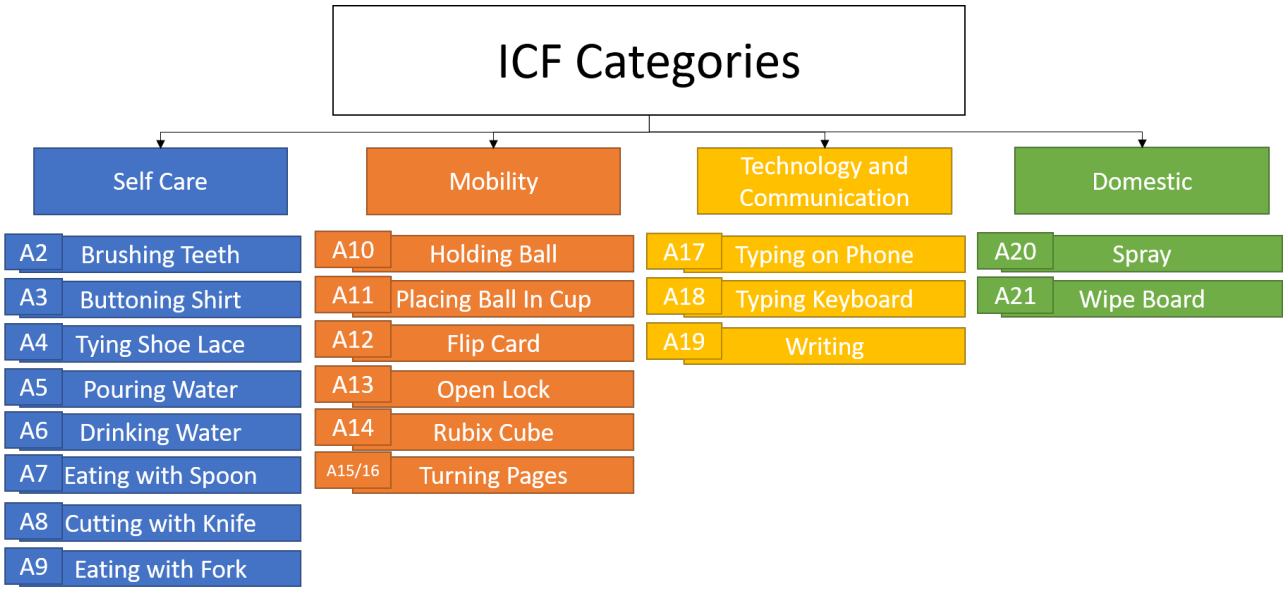


Figure 5.2: Selected Activities for Dynamic Tests

5.2.1 Summary of Selected Activities

The following details the task descriptions that was given to the participants in order to perform the above activities:

- **Activity 1 - Fist** - This gesture was kept from the second calibration phase and was recorded as Activity 1. This enabled a correction factor to be calculated. See Section 4.3.1 for more details.

Self Care

- **Activity 2 - Brushing Teeth** - Single hand to simulate the action of brushing teeth with a toothbrush.

- **Activity 3 - Button Shirt*** - Both hands to button up a shirt.
- **Activity 4 - Tying Shoe Lace*** - Both hands to tie the laces of a given shoe.
- **Activity 5 - Pouring Water** - Single hand to pour water from a jug into a cup.
- **Activity 6 - Drinking Water** - Single hand to pick cup up and take a sip of water.
- **Activity 7 - Eating with Spoon** - Single hand to scoop some water out of a cup and sip the contents using a spoon.
- **Activity 8 - Cutting with Knife** - Single hand to cut a piece of an apple.
- **Activity 9 - Eating with Fork** - Single hand to eat piece of apple that was just cut in the previous activity.

Mobility

- **Activity 10 - Holding Ball** - Single hand to grasp ball into palm of hand with the fingers encasing the tennis ball.
- **Activity 11 - Placing Ball in Cup** - Single hand grabbing ball and placing it into a cup.
- **Activity 12 - Flip Card** - Single hand used to flip playing card on a flat surface.
- **Activity 13 - Open Lock** - Single hand to turn key and open padlock.
- **Activity 14 - Rubix Cube** - Single hand manipulated rubix cube based off instruction. Here, the user will hold the cube with hand not being tested and manipulated the rubix cube with the hand wearing the glove by rotating the right/left column clockwise. This was dependent on which hand was currently being monitored.
- **Activity 15 - Turning Pages** - Single hand to skim across pages of a book.
- **Activity 16 - Turning Pages** - Single hand to turn single page of a book.

Technology and Communication

- **Activity 17 - Typing on Phone** - Single hand to type a number (Randomly generated - 082 565 9374) using a Samsung S7 smartphone.
- **Activity 18 - Typing Key Board*** - Both hands to type the words 'Wits University' onto a keyboard.

- **Activity 19 - Writing** - Single hand to write, using a black marker, the words 'Wits University' onto a white board.

Domestic

- **Activity 20 - Spraying** - Single hand to spray alcohol onto white board where writing is located.
- **Activity 21 - Wiping Board** - Single hand to wipe board clean.

Activities marked with an * represent a task requiring both hands. The dynamic tests included the separate testing of both the dominant and non-dominant hand. Therefore, the combined data will be able to represent activities that required usage of both hands. All activities were carefully instructed to the user before the test commenced. Each activity was labelled, so that an orderly manner will be followed throughout the duration of the tests.

5.3 Dynamic Testing Procedure

1. **Introduction to Study**
   The contents of the study was explained to the potential candidate.
2. **Questionnaire**
   The candidates completed a questionnaire (Appendix H).
3. **Fitting of Glove**
   The principle investigator ensured that the glove comfortably fits the user.
4. **Calibration**
   Data was recorded while the user held a flat and fisted hand. These two streams of data were averaged and mapped to 0° and 90°, respectively. Please see Section 4.3.1 for a more detailed explanation.
5. **Performance of Activities**
   The participant was directed to perform a certain activity. Once the motion was observed, the candidate repeated the activity while the device recorded the data. During the current phase, a checklist was marked to verify that the set activity has been done. The checklist is shown in Table 5.1.
6. **Evaluation**
   Once steps 1-5 were completed on both the right and left hand of the user, an evaluation

(Appendix H) was completed by the participant, indicating the level of comfort of the glove.

A detailed description of the full dynamic testing procedure can be seen in Appendix F.

5.3.1 Precautions and Participant Considerations

- If the user felt any harm or discomfort during any of the activities, testing was immediately halted. The continuation was completely up to the participant.
- Subjects were allowed to leave the study at any time.
- Activities involved with eating or drinking, could be ignored and replaced with a simulation of said tasks.
- Participation was voluntary, however candidates could be dismissed if said participation was not conducted in a respectful manner, in violation to the study and ethical clearance of the university.

Table 5.1: Checklist for Dynamic Testing

Activity No.	Activity	ICF Reference	Activity Reference Right	Left
1	Fist	Calibration		
2	Brushing Teeth	Self Care		
3	Buttoning Shirt			
4	Tying Shoe Lace			
5	Pouring Water			
6	Drinking Water			
7	Eating with Spoon			
8	Cutting with Knife			
9	Fork Eat			
10	Holding Ball	Mobility		
11	Place Ball Into Container			
12	Flip Card			
13	Open Lock			
14	Rubix Cube Manipulation			
15/16	Turning Pages of Book	Technology and Communication		
17	Typing (Phone)			
18	Typing			
19	Writing			
20	Spray White Board	Domestic		
21	Wipe White Board			

5.4 Results and Discussion

5.4.1 Range of Motion

The dynamic tests were successfully conducted on 10 candidates. The test took approximately 40 minutes for each participant. Both the dominant and non-dominant hands were used across a set of 21 activities. Figure 5.3 represents the ROM for the left hand of Candidate 1, during Activity 11 (placing the ball into the cup).

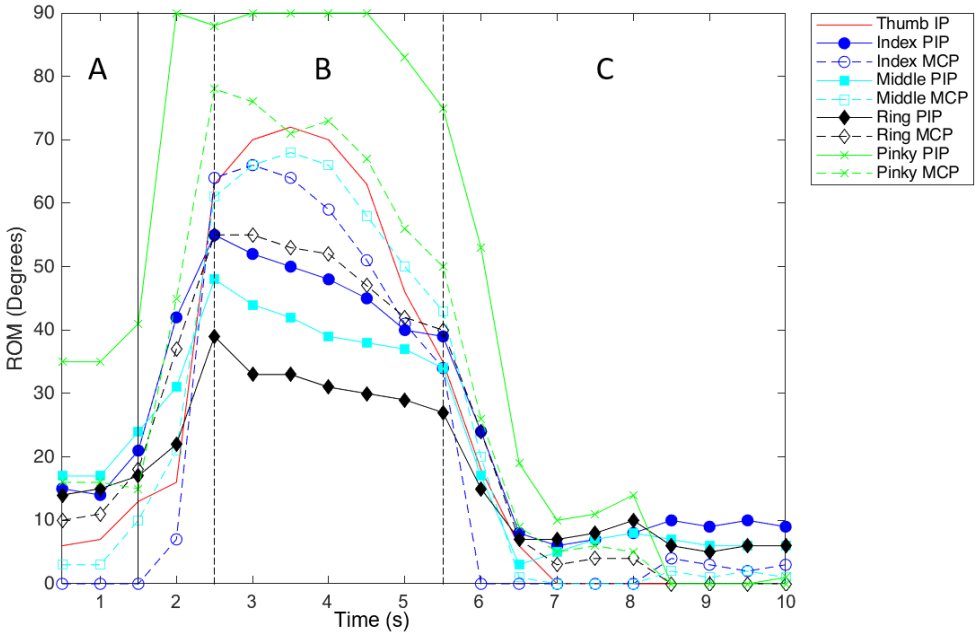


Figure 5.3: Candidate 1 - [A11] Placing Ball into Cup

Based off Figure 5.3, all 9 joints began to increase in ROM from time t = 1.5-2.5s. Thereafter a slow decrease was observed until time t = 5.5s, followed by a rapid reduction in ROM. This behaviour described the candidate's physical movements. For example, from times t = 0-1.5s (A) the candidate was reaching for the ball. From times t = 2.5-5.5s (B) the ball was then picked up and placed into the cup. Finally, from time t = 5.5s (C) onwards the user had released the ball and their hand was back in a neutral position.

To better describe Figure 5.3, a wooden hand model was used and is shown in Figure 5.4. However the model is left-handed and is limited in ROM, particularly in the thumb. Therefore, the model is specifically used as an approximation to visually depict the ROM. Each joint of the hand model was roughly positioned according to each reference point (A,B and C).

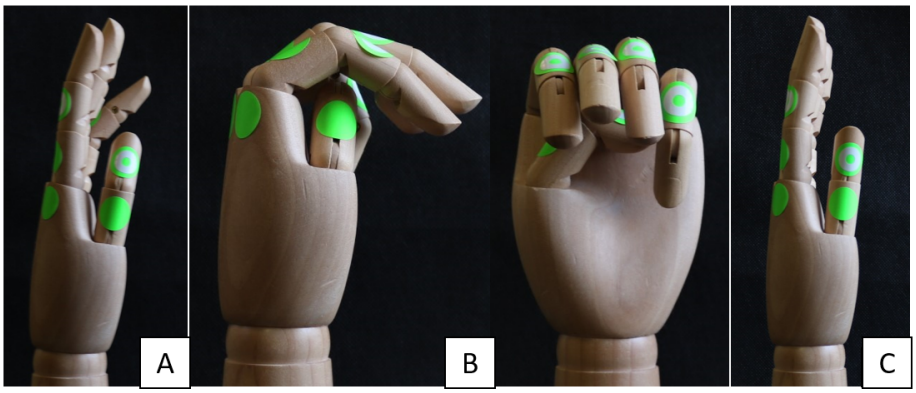


Figure 5.4: Candidate 1 - Activity 11 Reference Gestures

Figure 5.5 shows the ROM for the left hand of Candidate 7, during Activity 5 (pouring water from a jug into a cup). The graph indicates a consistent ROM with an instant drop occurring at around time t = 5.5s. After the drop, the ROM appears to stabilize under 20°. Once again the graph is depicting the actions of the user during the specified activity, with the current task being pouring water from a jug into a cup. This was shown using the hand model in in Figure 5.6. It is apparent that the results attained from the dynamic tests can be correlated back into the key gestures used to complete each activity.

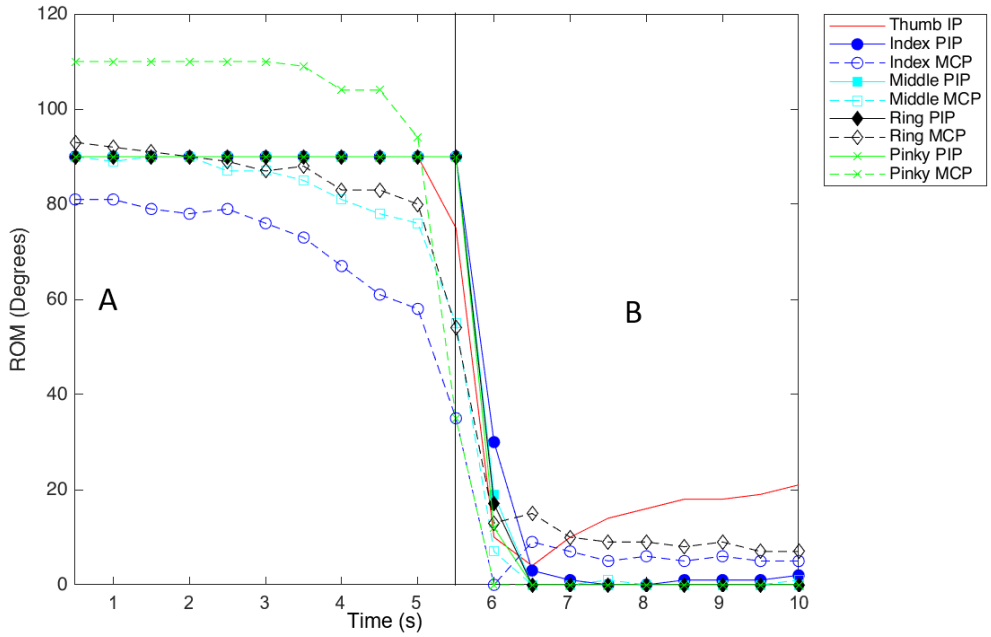


Figure 5.5: Candidate 7 - [A5] Pouring Water into Cup

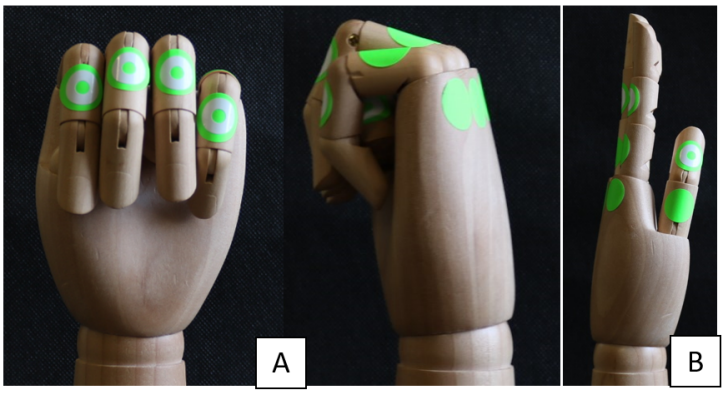


Figure 5.6: Candidate 7 - Activity 5 Reference Gestures

Activity 13 was the action of unlocking a padlock with a key and is described by Figure 5.8. The activity was completed by Candidate 4 using their right hand. The pinching of the key can be related to time t = 2s on the graph (A), with the lower ROM from time t = 4.5s (B) onwards indicating that the action was completed. Figure 5.8 correlates with the graph above.

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. Each activity was performed in 10s with a recording every 0.5s. By manipulating the recording times, a smoother representation of the hand motion can be attained. Therefore, replacing the instantaneous drops observed in the various plots with a more detailed reduction in ROM.

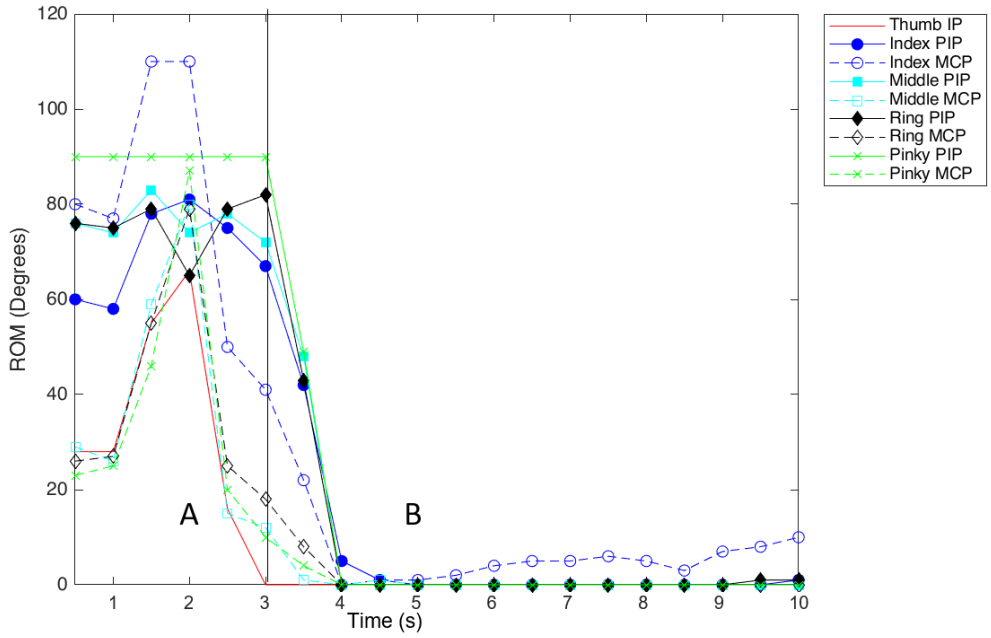


Figure 5.7: Candidate 4 - [A13] Opening Padlock with Key

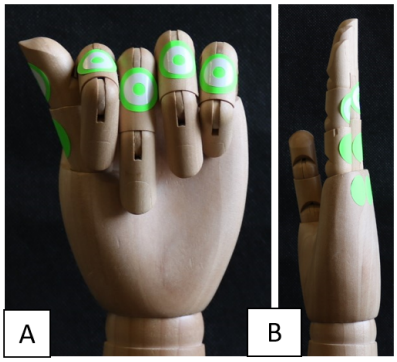


Figure 5.8: Candidate 4 - Activity 13 Reference Gestures

The above activities were related to a general motion of the hand as a whole, when completing a task. Figure 5.9 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 = 1.5-3s (A), t = 3-4.5s (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 = 5s onwards. The hand model was positioned as shown in Figure 5.10.

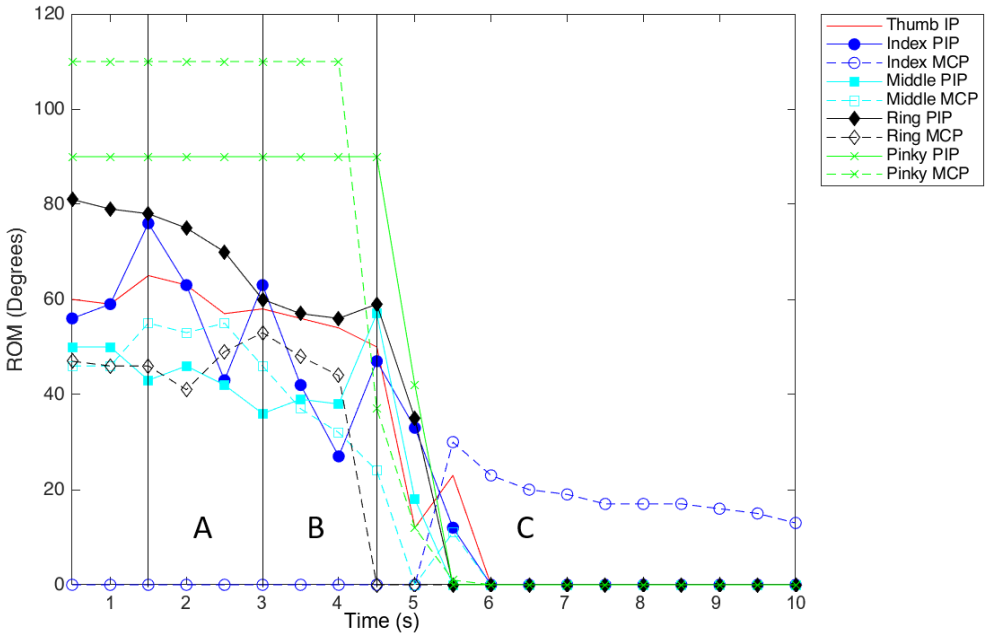


Figure 5.9: Candidate 10 - [A20] Spraying White Board

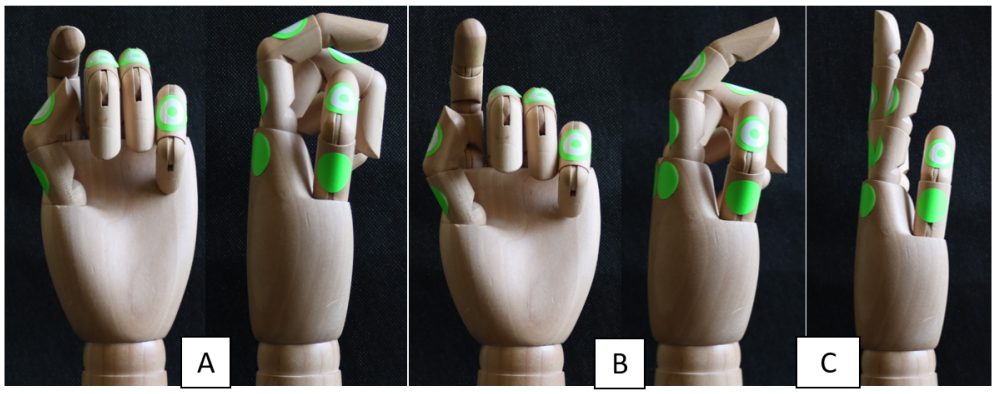
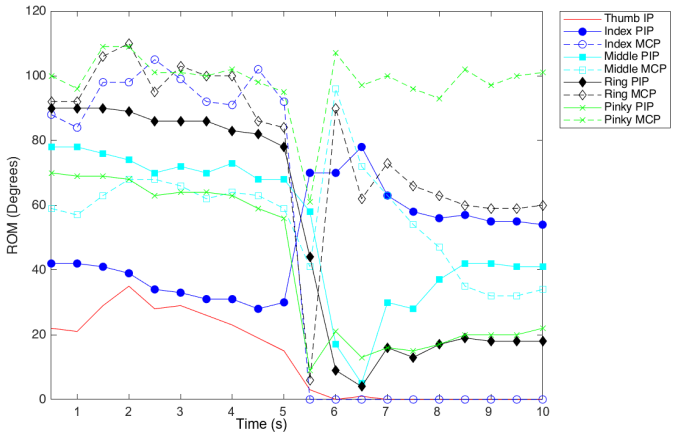


Figure 5.10: Candidate 10 - Activity 20 Reference Gestures

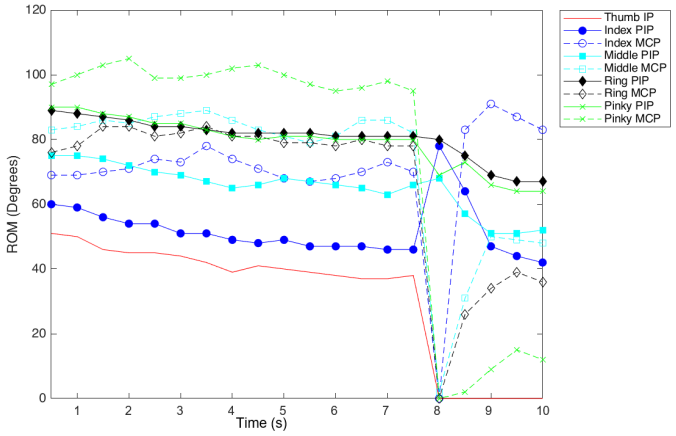
5.4.2 Comparison of Dominant and Non-dominant Hand

In the previous section, it was shown that the results obtained from dynamic data, can describe and validate the activities the participants were requested to perform. A comparison was made regarding the differences between the ROM of the dominant and non-dominant hand. Participation was voluntary which resulted in all 10 candidates being right-handed.

Participants were encouraged to perform each activity in a motion natural to their specific behaviour. Figure 5.11a and 5.11b represents the ROM for Candidate 9 performing the activity of simulating brushing their teeth. The graphs represent a unique movement based off the candidate's preference and thus is difficult to compare the differences throughout the duration of the activity. However, the graphs depict the different gestural behaviour between the dominant and non-dominant hand.



(a) Left Hand



(b) Right Hand

Figure 5.11: Candidate 9 - [A2] Brushing Teeth

Using the same candidate and activity as above, Figure 5.12 represents the maximum range of motion achieved in both hands. As mentioned, all candidates were right-handed but 6 out of the 9 joints in Figure 5.12 appear to have a greater ROM in the case of the left hand. This did not motivate the participant's dominant hand, but rather suggested the behaviour.

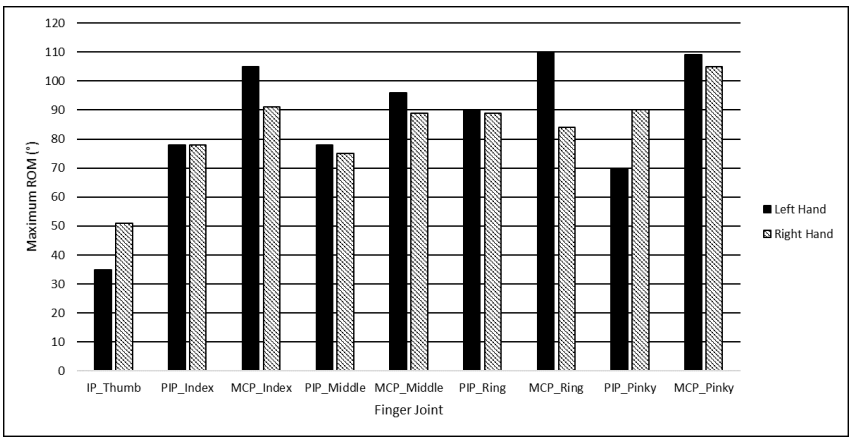


Figure 5.12: Candidate 9 - [A2] Maximum ROM

Figure 5.13 shows the maximum ROM for Candidate 9 performing Activity 8 (cutting with a knife). The maximum ROM appears to be evenly separated amongst the joints. Both graphs are expected to produce different magnitudes across the joints, for both hands, as the study was focused on obtaining a collection of data that was based on the uniqueness of multiple candidates.

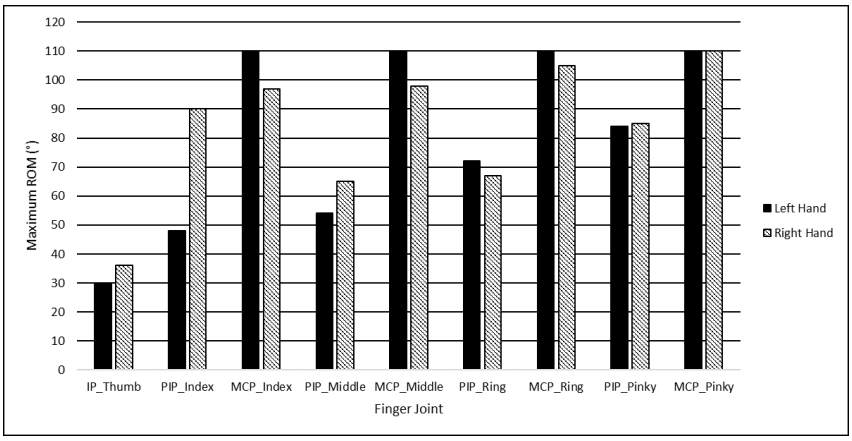


Figure 5.13: Candidate 9 - [A8] Maximum ROM

Candidate 7 produced a similar result with respect to Activity 2, showing greater maximum ROM for the left hand (Figure 5.14). This behaviour can relate to an observation made during the testing procedures. A few of the candidates would grip the various objects tighter in their left hand due to their lack of control of their non-dominant hand. Thus, it may explain the greater magnitude in ROM for some of the candidates' left hands.

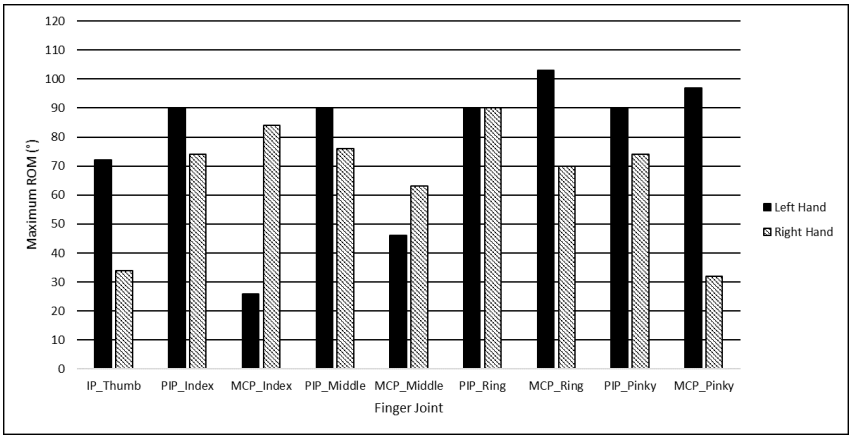


Figure 5.14: Candidate 7 - [A2] Maximum ROM

Candidate 3 was an interesting case as participant was ambidextrous. According to the questionnaire the candidate was able to write and perform sporting activities using either hands. Activity 10 was the task of holding a tennis ball and the range of that action for Candidate 3 is shown in Figure 5.15. The range within each joint is not dominated by the left or right hand. This could indicate the ambidexterity of Candidate 3.

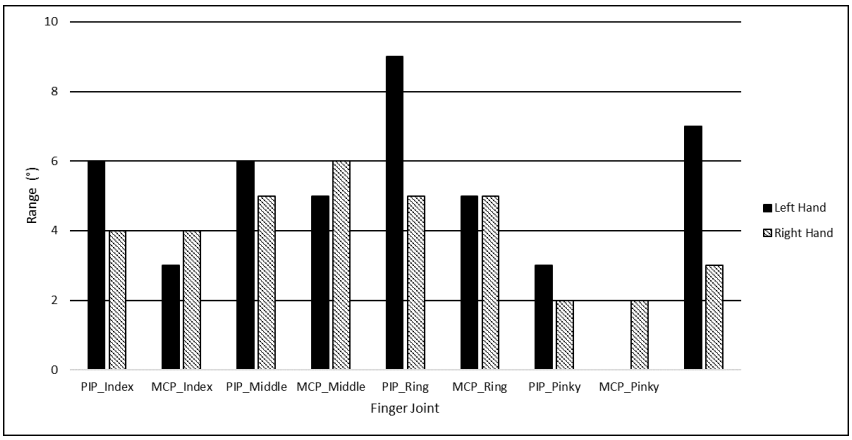


Figure 5.15: Candidate 3 - [A10] Range

Figure 5.16 shows the differences between the range of the movements while Candidate 3 was requested to write on a white board. As in the case of the ball, there is no distinct behaviour that can determine which hand performed the movements with greater ease. However, it showed that the participant experiences a different variation in ROM for either hand. Thus, suggesting the user may be capable of performing these activities with a degree of control over their ROM for each hand.

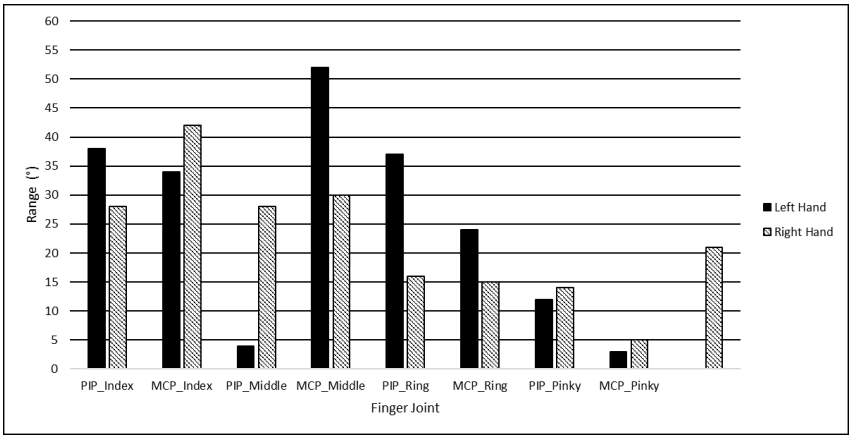


Figure 5.16: Candidate 3 - [A19] Range

Candidate 5 and 10 had injured their right hand in the past. Candidate 5 had broken the ring finger during a sporting injury which resulted in titanium screws being inserted within the joint. Candidate 10 had broke their index finger during an accident. However, both candidates fully recovered with full function of their joints. Figure 5.17 represents the PIP joint of Candidate 5's ring finger. Activities 7, 15, 16 and 21 show the left hand having a greater range of motion. In these activities the ring finger plays a limited role as the actions relate to gripping gestures. However, this can indicate that right ring PIP joint could not fully achieve the natural gripping positions due to the injury. These results could possibly relate to a behavioural preference of the participant.

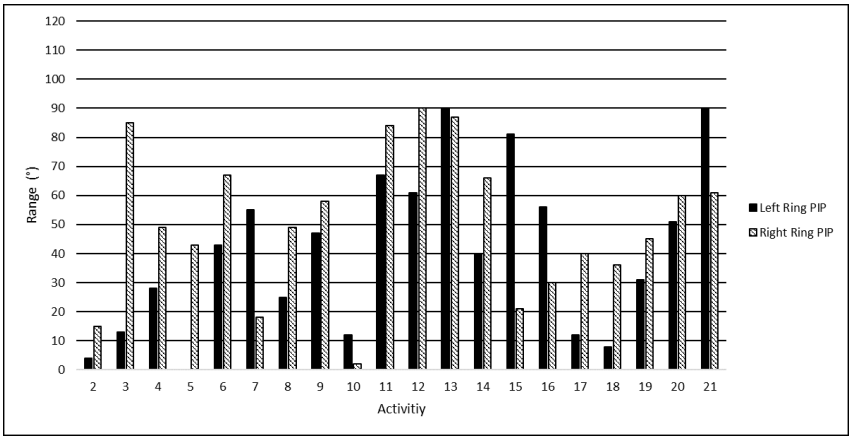


Figure 5.17: Candidate 5 - ROM of Ring PIP Joint

Figure 5.18 indicates the MCP joint of Candidate 5's ring finger. Compared to Figure 5.17, majority of the joints have a greater ROM in the right hand. This may suggest that the injury of the participant occurred at the PIP joint. The candidate may have completed all activities with ease but the affect of the injury may have adjusted the way the candidate uses the ring finger of his right hand.

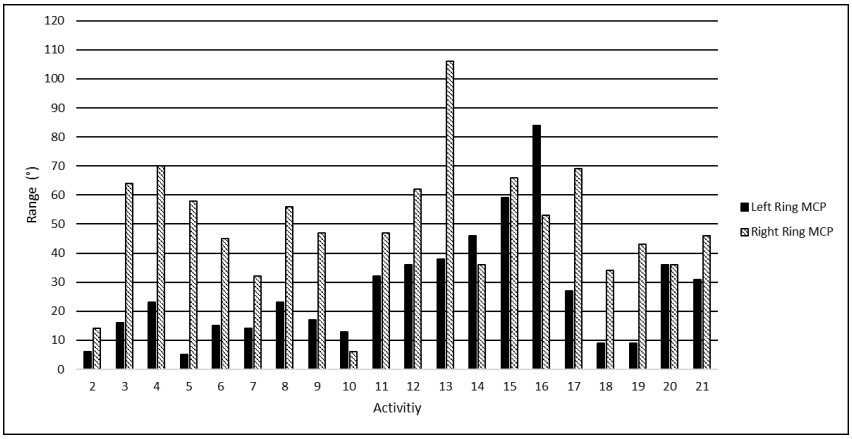


Figure 5.18: Candidate 5 - ROM of Ring MCP Joint

The index finger joints of Candidate 10 are represented in Figure 5.19 and 5.20. There is a greater ROM within the MCP joint as compared to the PIP joint with respect to the left hand. This may suggest an injury in the MCP joint of the right hand. This observation is limited as the graphs also indicated high ROMS for both joints in various activities. The uniqueness of a candidate's movements played a very important role when trying to determine whether an injury is affecting the function of the hand.

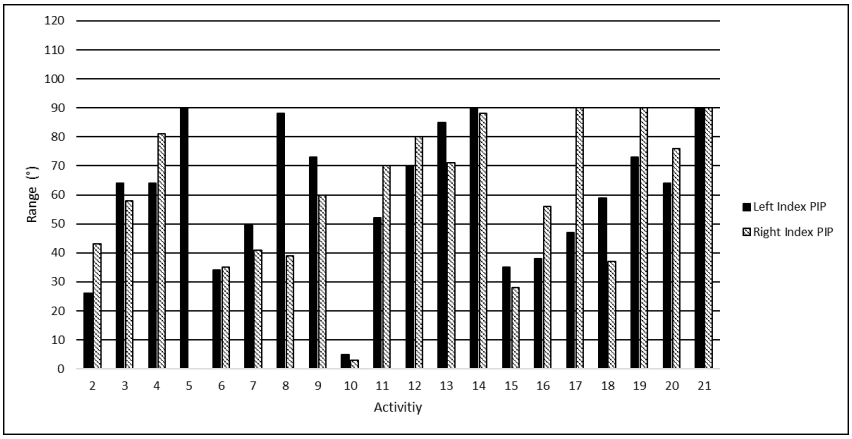


Figure 5.19: Candidate 10 - ROM of Index PIP Joint

If the current device was used on the candidates hands during the recovery phase of their injuries, a more significant difference in the ROM may have been observed in the specific injury locations. Ideally, if the patients' ROM was captured before injury, a deduction could have been made regarding the effect said injury made to their ROM and functionality of their joints, which was one of the key aims of the current research.

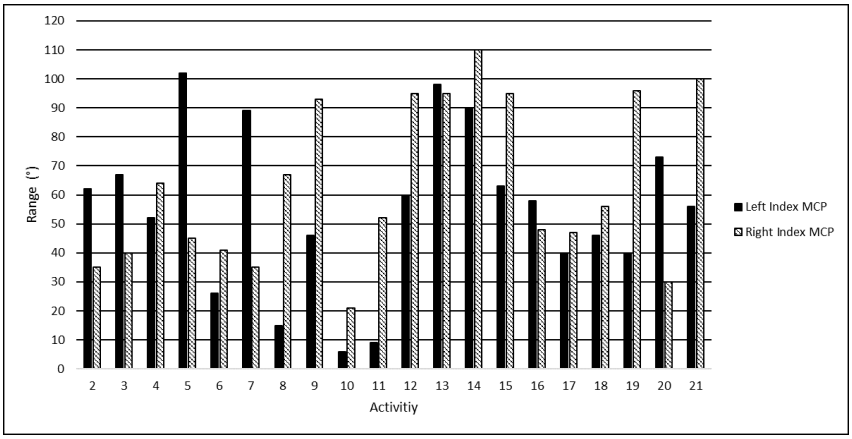


Figure 5.20: Candidate 10 - ROM of Index MCP Joint

5.4.3 Variation Amongst the Joints of the Hand

The maximum or range of the joint motion did not fully represent the functionality of the hand. An approximate amount of change observed between the joints can determine which joint or hand has a greater degree of controlled motion. Based off this premise, the coefficient of variance was calculated for each hand and each joint of every candidate, summed across all activities. The coefficient of variance is a measure of variability within a dataset. Therefore, it acts as a statistical representation to the amount of movement that has occurred over a specific joint, given the captured ROM data for said joint. These values were then summed for each candidate to represent the total variation within each hand. The total variation of both hands can be seen in Figure 5.21.

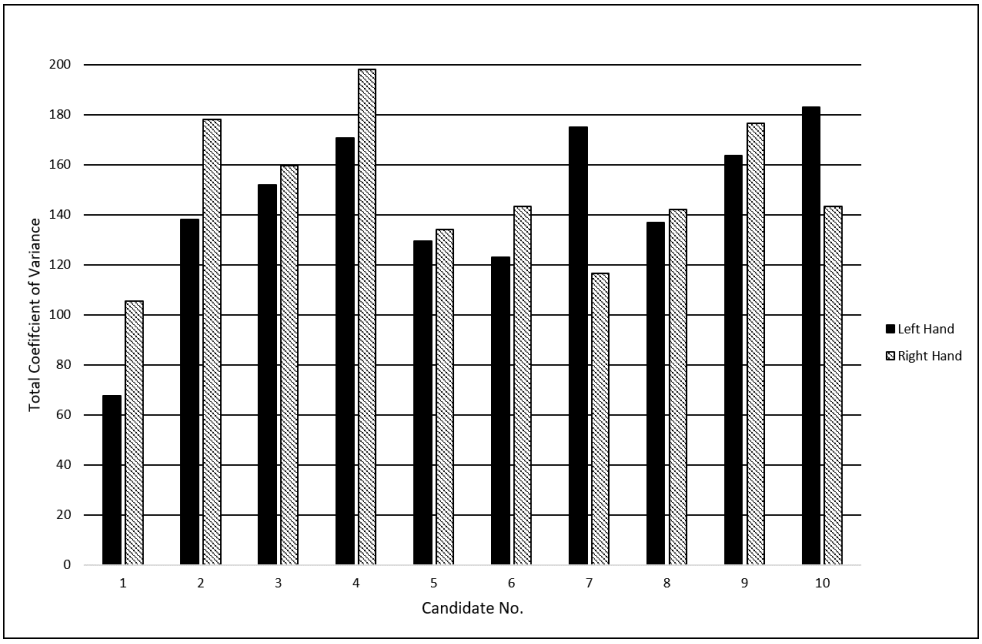


Figure 5.21: Total Variation for each Participant

As expected, most candidates (80%) appear to have a greater variation in their right hands, apart from Candidate 7 and 10. This can be due to over-gripping gesture of the non-dominant hand when attempting the various activities as a result of lack of control. Candidate 3 had a similar magnitude of variation across both hands which may motivate the ambidexterity. Considering all candidates as a whole, the variation amongst the joints were summed and are shown in Figure 5.22.

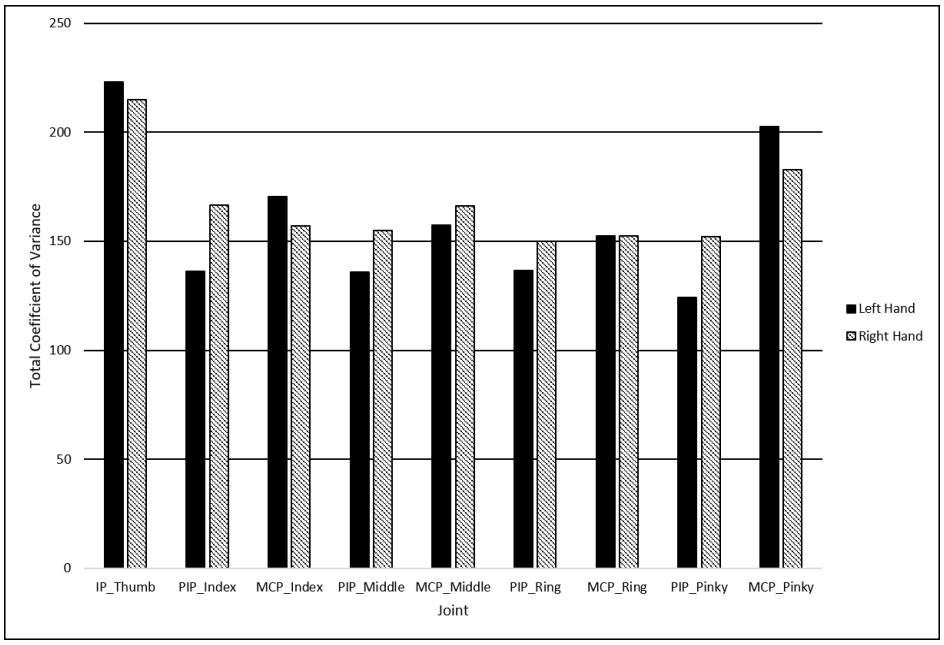


Figure 5.22: Total Variation for each Joint

The IP joint of the thumb experienced the most variation in both the left (COV = 222) and right (COV = 214) hands of all candidates. This was 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 be correlated to majority of the tasks within the current study.

Figure 5.23 represents the total variation across each finger, excluding the thumb. The right and left hands experienced a similar trend. The maximum variation occurs in the pinky, index, middle and ring, in order of highest to lowest. The pinky 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 pinky 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.

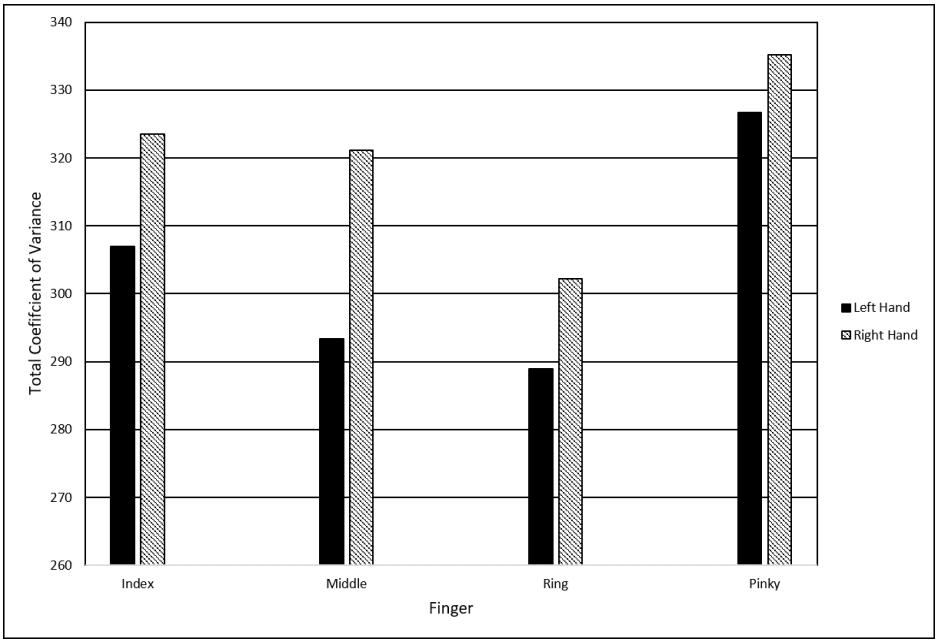


Figure 5.23: Total Variation for each Finger

5.5 Conclusions

The flexible sensor glove proved capable of measuring the dynamic range of motion for each hand of all 10 candidates. 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, confirmed the capability of gloves in measuring the dynamic range of motion. Thus, in the application of therapy, physicians will be able to use the glove to determine patient performance and functionality throughout any stage of treatment.

Comparisons were made between the dominant and non-dominant hand of a few candidates. The results showed a greater ROM in the dominant hand for 80% of all the candidates. However, 2 candidates experienced a higher ROM in their non-dominant. Based on these results and observations made during the testing procedure, it was evident that some candidates would emphasize 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 (COV = 222) and right (COV = 214) hand. The thumb is a significant joint with respect to hand functionality and thus would observe a higher ROM throughout the activities.

Chapter 6

Subject Testing - Static Holds

6.1 Introduction

With the completion of the dynamic testing, the static experiments can begin. The procedure of the experiment was analogous to the dynamic testing shown in Section 5.3. The parameters that were changed include the involvement of 40 participants. These participants were only tested on their performances of their dominant hand.

The results of the dynamic tests validated the use of the glove as a measurement tool. Furthermore, these results can be used to quantify hand functionality. However, static tests need to be conducted in order to compare with previous studies. As mentioned earlier, finger goniometers (static process) were mostly used to measure the ROM of the fingers, thus in order to determine the effectiveness of the glove, comparisons need to be drawn between the two methods. However, the fundamental reasoning for the static tests were to replicate the process of measuring the ROM of the fingers. This will provide quantifiable reference points that can represent the patient's ability in performing gestures that are required during activities of daily living. By recording the static ROM of abled candidates performing the activities, a statistical range and mean can be calculated, which determines the required ROM for an individual to be functionally independent.

6.2 Selection of Activities

Given the amount of test subjects for the current phase, the activities were reduced to 11 but under the same ICF categories shown in Figure 5.2. The reduced activity list is shown in Figure 6.1. Reducing the number of activities was done to decrease the duration of testing for convenience of the prospective participants, given the lengthy testing that occurred during the dynamic phase.

The corresponding checklist for the static test procedure is shown in Table 6.1.

Table 6.1: Checklist for Static Testing

Activity No.	Activity	ICF Reference	Activity Reference Right	Left
1	Fist	Calibration		
2	Brushing Teeth	Self Care		
3	Holding Cup			
4	Holding Fork			
5	Holding Knife			
6	Holding Ball	Mobility		
7	Hold Key			
8	Hold Phone	Technology and Communication		
9	Hold Pen			
10	Hold Spray	Domestic		
11	Hold Cloth			

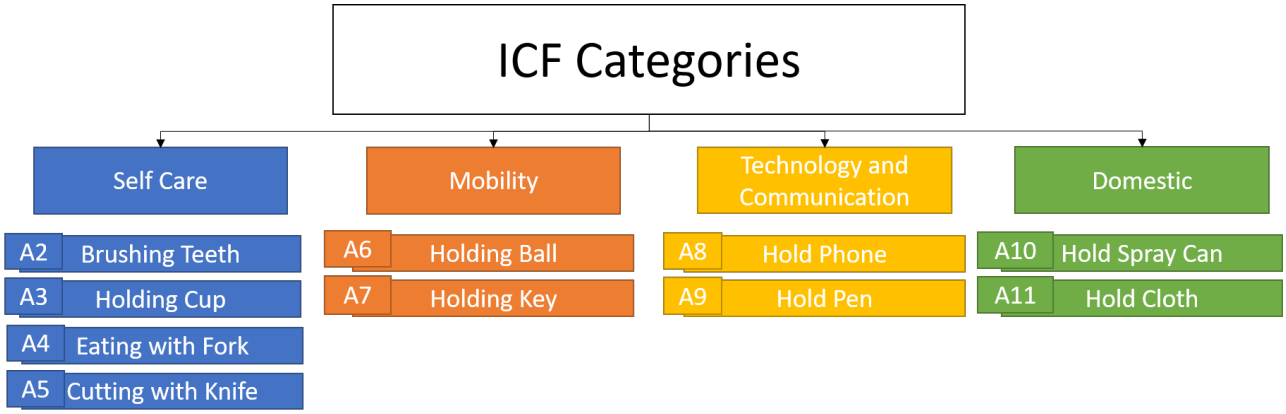


Figure 6.1: Reduced Activities for Static Tests

6.3 Results and Discussion

6.3.1 ROM for Static Holds across all Participants

All 40 candidates were successfully tested on 11 activities of daily living. Unlike the dynamic results, left handed candidates were present. As mentioned earlier in Section 6.2, the activities were shortened to reduce the duration of subject testing for the convenience of the participant. Figure 6.2 represents the the average, minimum and maximum ROM for all of the joints, across all 40 participants. Refer to Figure 1.1 for a description of the joints.

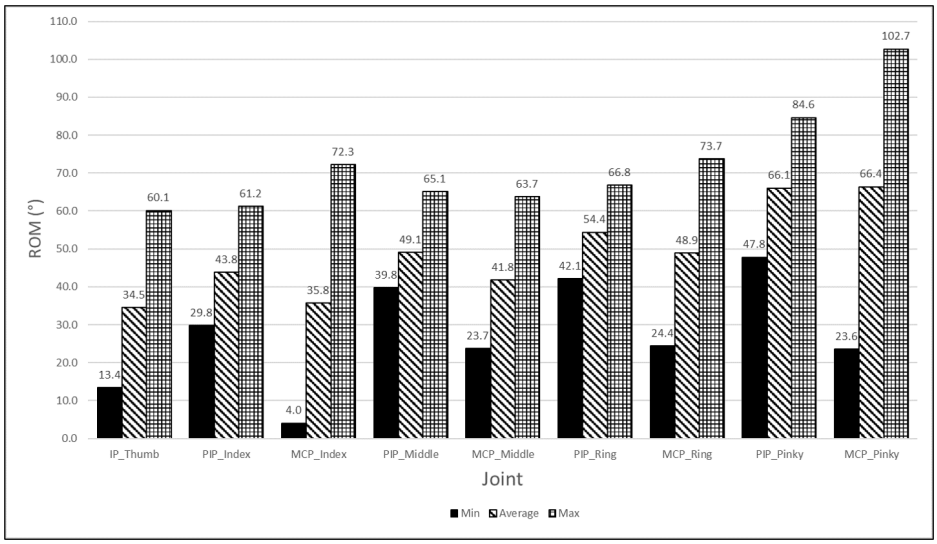


Figure 6.2: Average, Maximum and Minimum ROM for all Joints

The pinky finger had the highest ROM for the static tests. When gripping smaller objects the pinky finger was be completely flexed as it did not fully partake in the static hold (for example, gripping a pen). Since the tests include holding objects of various sizes, the pinky finger would therefore be the finger that has the most variation.

The IP joint of the thumb showed large fluctuations within some of the candidates. This could be due to a physical problem with the prototype or more likely a connection issue within the circuit. The fluctuations only occurred with 4 candidates. Therefore, the results did not include the thumb ROM from these participants. In terms of reliability, the glove still produced consistent results with 46 other candidates (including dynamic testing) and thus has a success rate of 92% as a prototype. The results of the single activities are not significant as the static phase of the study was focused on a collective range of data that indicates the required ROM to perform all the given activities.

6.3.2 Comparison with Previous Studies

Table 6.2 indicates the required ROM to perform a collection of specific activities of daily living. All of the previous studies used electric or standard goniometer as the device for measuring the ROM throughout the activities.

Table 6.2: Comparison of Static Test Results

Previous Studies	**MCP (°)**	**PIP (°)**	**IP (°)**
Hume et al. [35]	61	60	18
Bain et al. [36]	23-87	10-64	-
Hayashi et al. [37]	>70	-	-
Current Study			
Average	53.34	48.21	34.51
Max	69.42	78.10	60.15
Min	39.88	18.92	13.42

As mentioned earlier, in Section 2.2, Hume [35] determined the functional ROM for 35 candidates performing 11 activities of daily living. The results of the study are shown in Table 6.2 and in Figure 6.3. These results were the average ROM for each joint. In comparison to the average results of the current study, the MCP and PIP joints attained values that were lower in magnitude. The differences were evaluated as 20.9% and 11.1% for the MCP and PIP joint, respectively. The activities performed by the different studies may also affect the variation amongst the results. The object sizes played a significant role in the amount of ROM a participant could use. The larger the object the less flexion within the joints and vice versa. Another factor to consider is that the flexible sensor glove had an accuracy of +/- 5°, which can therefore relate closer to the previous work done by Hume [35]. Figure 6.3 shows the similar behaviour observed between the two studies with respect to the decreasing magnitude from the MCP joint to the IP joint.

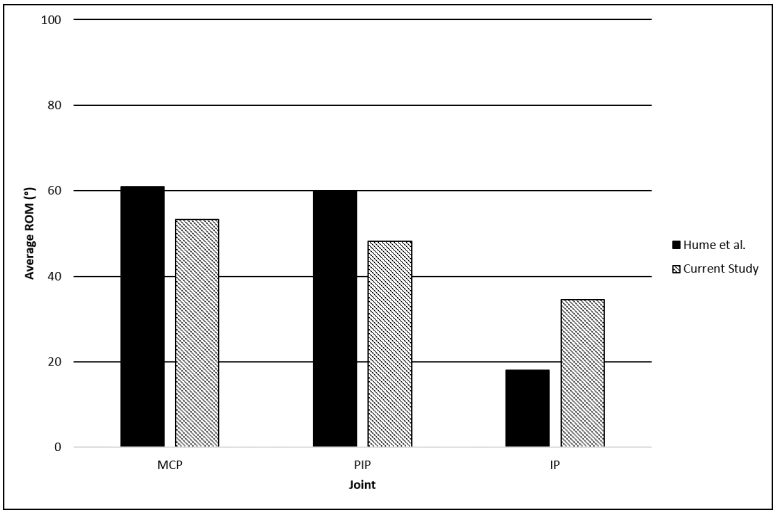


Figure 6.3: Average ROM Comparison

The results obtained from the investigation by Bain [36], are a range between the minimum and maximum degrees of motion. Comparing the MCP joints (Figure 6.4), the minimum ROM is higher in the current study, however the maximum is higher with respect to Bain's results. For the PIP joint (Figure 6.5), both boundaries were higher in the current study. As in the case of Hume [**?**], these results are heavily influenced over the selection of activities. Bain had a larger span of activities (20) which may better represent the full use of the hand. The statistical range for the MCP joints for Bain and the current investigation are 64° and 29.54°, respectively. Therefore, both the amount and types of activities can affect the ROM. However, in the case of the PIP joint, the statistical range was greater in the current study. This can also relate to the amount of candidates tested, as the current study had 40 participants as compared to the 10 tested in Bain's investigation.

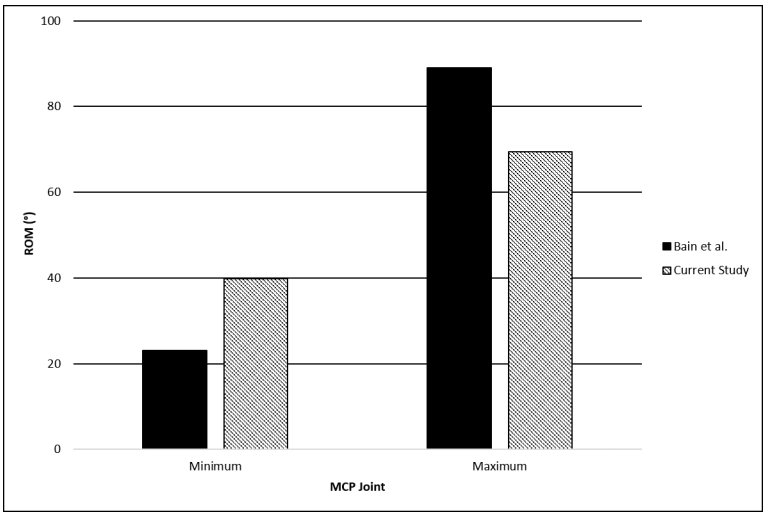


Figure 6.4: Comparison between MCP Joints

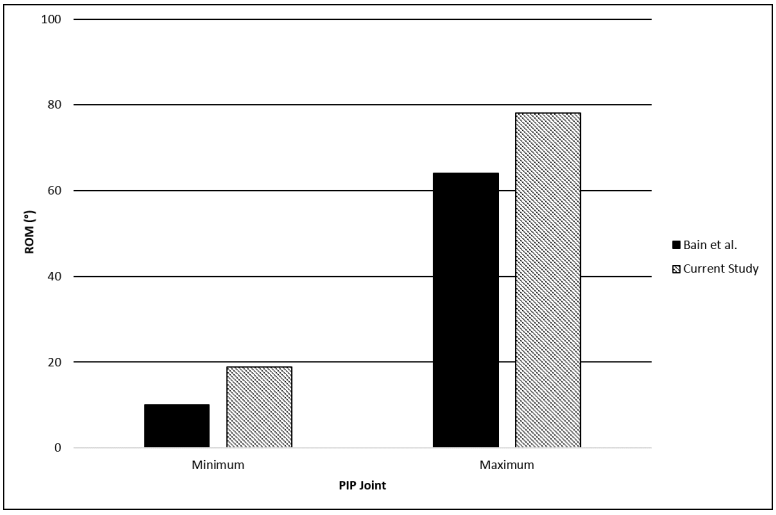


Figure 6.5: Comparison between PIP Joints

The accuracy of the goniometer used was +/- 1° as compared to the +/- 5° of the glove. Using the goniometer the candidate must keep there gestures rigid during measurements, whereas the glove allows for a more natural positioning. There is no assurance that the candidates do not move their joints in between physical measuring with a goniometer. In the case of the glove, measurements can be taken instantly, with time of each measurement being a preference to the therapist or investigator.

Hayashi's [37] results are specific to the MCP joints of the hand. In order to be functional, the required ROM of the MCP joints had to be greater than 70°. The tests were done by limiting the ROM of the participants using an orthoses at various angles. Thus, these experiments were based on restrictions and resulted in 70° being the minimum required ROM to functionally perform the Jebsen Taylor and O'Connor dexterity tests. The maximum ROM for the MCP joint of the current study was 69.42°. This did not coincide with Hayashi's resulting limit. However, Hayashi's experiments were dependent on restricting the ROM while performing activities as opposed to the current study measuring the required ROM for performing the activities. Another key difference is that the current study was focused on measuring the ROM for activities of daily living and not against specific hand dexterity tests. Therefore, you may not need a ROM greater than 70° to be functional in performing activities of daily living.

6.3.3 Comfort of Device

To further the study by applying the flexible sensor glove to hand-impaired patients, it was necessary to evaluate the glove's level of comfort. This is pertinent as any discomfort that arises from using the glove can hinder those suffering with impairment. Thus the current

study included an evaluation by each participant involved in the research. The candidates were asked to evaluate the comfort of the glove by indicating a value between 1-5, where 5 indicated the most discomfort.

The average result was 2.02. Therefore, the prototype was mostly comfortable, throughout the procedure, with respect to healthy hand test subjects. However, there were some candidates that gave the glove a score of 4. Although the average indicates an adequate level of comfort, any indication of high discomfort must be considered. These scores are represented by candidates with full use of their hands. Any level of discomfort for a healthy candidate could be magnified in the case of a subject suffering with hand impairment.

The participants who evaluated the glove with a score of 4, suggested that the sizing of the glove resulted in the discomfort. As a prototype a single sized glove was used, however if the study were to expand, multiple glove sizes would be used. Additionally, the glove stands as a working prototype and for application in hand impairment patients, a new design must be developed as to cater for hand sizing but more importantly the comfort of the patient.

6.4 Conclusions

As in the case of the dynamic tests, the glove was capable of recording the ROM of the hand while candidates performed 11 static holds relating the activities of daily living. The results were averaged according to each joint of the hand where the maximum and minimum limits were determined. The maximum, minimum and average range of motion for the MCP, PIP and IP joint to complete the 11 activities were successfully determined. Thus, the required ROM for a person to be functionally independent was quantified with respect to the selected activities of daily living. In conjunction with the previous studies, the glove did represent a ROM that was comparable, although different measurement methods were used. According to the 50 participants the glove was moderately comfortable, however a new design must be developed for the application on hand-impaired patients as to achieved a maximum level of comfort and safety.

Chapter 7

Conclusions

7.1 Summary of Findings

The current research has successfully developed a low-cost flexible sensor glove that can be implemented as a rehabilitation and diagnostic tool. The glove was tested in two phases that represented both a dynamic and static ROM.

The glove was capable of measuring the dynamic range of motion of the hand as the data could be replicated back into gestures using a wooden hand model. The comparisons between the dominant and non-dominant hand suggest that no conclusive differences in motion can be determined as the results were highly influenced by behavioural gesturing, specific to each candidate. Comparisons were also made between both hands of candidates who were previously injured but the effect of the injuries were negligible as the candidates seemed to have fully recovered. However, a better comparison could have been made if quantifiable data on the ROM before the injuries and during the recovery phases was available.

The total variation amongst the right and left hand, showed that most of the dynamic candidates experienced a greater variation in their right hands. Coincidently, all 10 of the candidates in the dynamic tests were right handed. The IP joint of the thumb had the most variation throughout the dynamic tests.

The static tests produced the statistical range and average ROM for each joint performing activities of daily living. These results were comparable with previous research, although different methods were used. The differences observed can be related to multiple parameters that include the amount and type of activities selected for the investigations.

The comfort of the device was evaluated by all 50 candidates through an evaluation and questionnaire. The results of the evaluation indicated that the glove was moderately comfortable. However, a redesign is necessary for the implementation of testing hand impaired patients as the slightest discomfort can hinder the ROM of the impaired patients.

7.2 Conclusions

The current research successfully developed a low-cost flexible sensor glove that is capable of measuring the ROM of the hand. The material cost is evaluated to be under R2000.

The variation between the dominant and non-dominant for each candidate across specific activities, show no distinctive differences that can verify the dominance of the hand. However, the total variation across both hands amongst most of the 10 candidates hands had shown a greater variation in the right hand, suggesting right-handedness dominance which correlates with the participants.

The static tests resulted in a ROM of 39.88°-69.42°, 18.92°-78.1° and 13.42°-60.15° for the MCP, PIP and IP joints, respectively. These ranges of motion represent the required ROM of the hand for an individual to be functionally independent, based on the selected activities of daily living.

The glove is capable of measuring the ROM of the hand and can potentially be applied to rehabilitation therapy, either as a monitoring device or a rehabilitation tool for bilateral therapy when coupled with an actuated exoskeleton device.

Chapter 8

Recommendations for Future Work

A prototype of the flexible sensor glove has been successfully developed to measure the ROM of the hand. However, to improve the performance and reliability of the device the following measures can be taken:

- The device can be redesigned to improve the comfort of the glove and consequently tested on hand-impaired patient.
- To improve the accuracy of the device, the implementation of a control system or signal processing can be applied.
- To test the capability of the device to monitor recovery, clinical tests can be done where a candidate is undergoing rehabilitative therapy.
- The device can incorporate additional sensors to provide data on the MCP joint of the thumb and the adduction-abduction motions.
- The device can be applied to bilateral therapy through designing an actuated hand exoskeleton.

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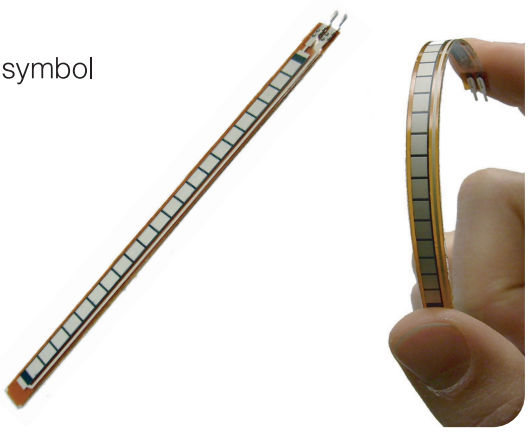
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Glossary

Abduction	Stretching your fingers away from each other.
Adduction	Closing your fingers adjacent to one another.
Bilateral Therapy	Therapeutic method of using paired movements of both the healthy and impaired hand.
Extension	Extending your fingers away from your palm.
Diagnostic	Relation to diagnosis of illness.
Flexion	Flexing your fingers towards palm.
Impairment	State of being physically impaired.
Occupational Therapy	The use of specific activities to assist recovery from a physical /mental illness.
Orthotic	External devices used to modify structural and functional muscular or skeletal systems.
Plasticity	Neural changes due to the effect of enviromental influences.
Rehabilitation	Process of restoring health to patient through training and therapy after illness or impairment.

Appendix A - Flex Sensor Data Sheet

Flex Sensor FS



Features

- Angle Displacement Measurement
- Bends and Flexes physically with motion device
- Possible Uses
  - Robotics
  - Gaming (Virtual Motion)
  - Medical Devices
  - Computer Peripherals
  - Musical Instruments
  - Physical Therapy
- Simple Construction
- Low Profile

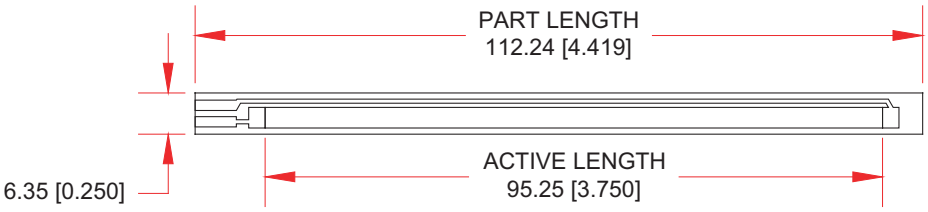
Mechanical Specifications

-Life Cycle: >1 million
-Height: ≤0.43mm (0.017")
-Temperature Range: -35°C to +80°C

Electrical Specifications

-Flat Resistance: 10K Ohms ±30%
-Bend Resistance: minimum 2 times greater than the flat resistance at 180° pinch bend *(see "How it Works" below)*
-Power Rating : 0.5 Watts continuous; 1 Watt Peak

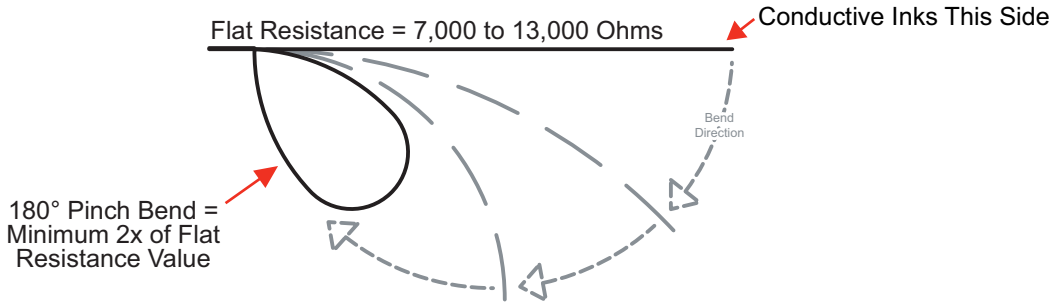
Dimensional Diagram - Stock Flex Sensor



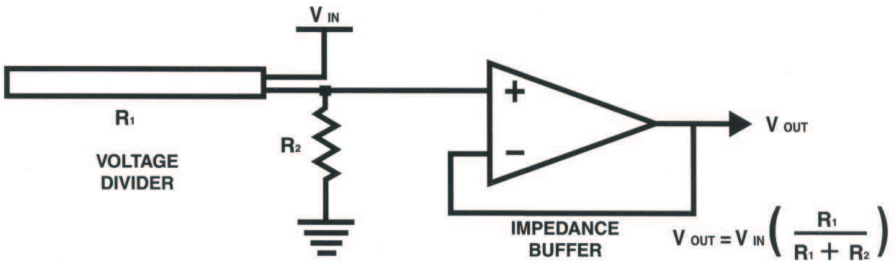
How to Order - Stock Flex Sensor

FS	–	L	–	0095	–	103	–	ST
Series		Model		Active Length		Resistance		Connectors
FS = Flex Sensor		L = Linear		0095 = 95.25mm		103 = 10 KOhms		ST = Solder Tab

How It Works



BASIC FLEX SENSOR CIRCUIT:

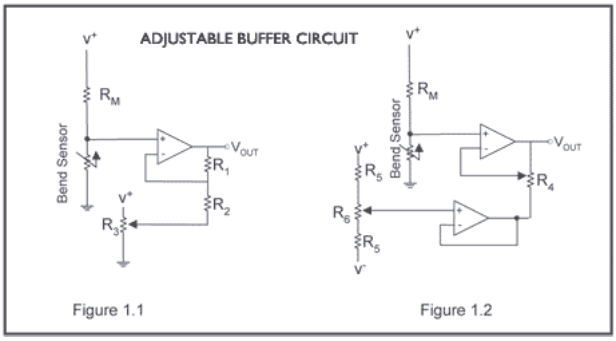


Following are notes from the ITP Flex Sensor Workshop

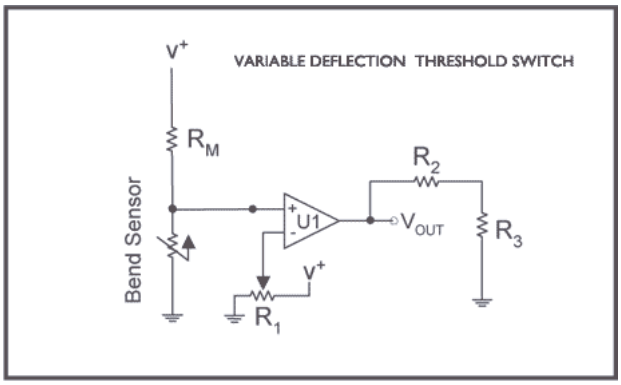
"The impedance buffer in the [Basic Flex Sensor Circuit] (above) is a single sided operational amplifier, used with these sensors because the low bias current of the op amp reduces errer due to source impedance of the flex sensor as voltage divider. Suggested op amps are the LM358 or LM324."

"You can also test your flex sensor using the simplest circut, and skip the op amp."

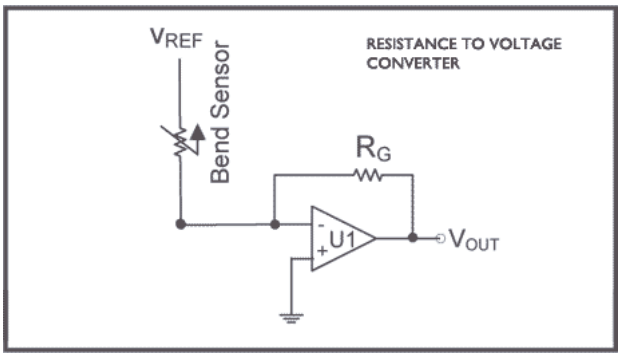
"Adjustable Buffer - a potentiometer can be added to the circuit to adjust the sensitivity range."



"Variable Deflection Threshold Switch - an op amp is used and outputs either high or low depending on the voltage of the inverting input. In this way you can use the flex sensor as a switch without going through a microcontroller."



"Resistance to Voltage Converter - use the sensor as the input of a resistance to voltage converter using a dual sided supply op-amp. A negative reference voltage will give a positive output. Should be used in situations when you want output at a low degree of bending."



Appendix B - Resistor Data

Table 8.1: Variable Resistor Results

	Arduino 1kΩ	**Arduino 2kΩ**	**Arduino 4,7kΩ**	**Arduino 47kΩ**	**Arduino 100kΩ**	**Digital Ω**
	58348	54641.42	50772.33	49989.85	48468.13	49000
	55051.67	51660.66	49512.5	49989.85	48898.98	48800
	58348	51660.66	51424.47	49794.53	48683.25	48700
	55051.67	54641.42	50135.17	49989.85	48898.98	48700
	58348	50284.93	50135.17	49989.85	48898.98	48700
	55051.67	51660.66	49512.5	49989.85	48898.98	48700
	58348	54641.42	50135.17	49794.53	48898.98	48700
	58348	54641.42	51424.47	49989.85	48898.98	48700
	62056.38	53110.75	50772.33	49794.53	48898.98	48800
	55051.67	51660.66	51424.47	49989.85	48683.25	48900
	58348	54641.42	50135.17	49989.85	48898.98	49000
	55051.67	54641.42	50772.33	49794.53	48683.25	48600
	62056.38	56259.54	52092.33	49794.53	48683.25	48700
	58348	53110.75	50772.33	49794.53	48683.25	48700
	58348	53110.75	51424.47	49794.53	48898.98	48700
	55051.67	53110.75	50772.33	49989.85	48683.25	49200
	62056.38	48977.97	50135.17	49794.53	48898.98	49100
	55051.67	51660.66	50135.17	49794.53	49115.35	49000
	58348	56259.54	51424.47	49794.53	49115.35	48900
	58348	54641.42	50135.17	49989.85	48683.25	48900
Average	57750.54	53250.91	50652.37	49892.19	48823.56	48825

Appendix C - Full Circuit Diagram

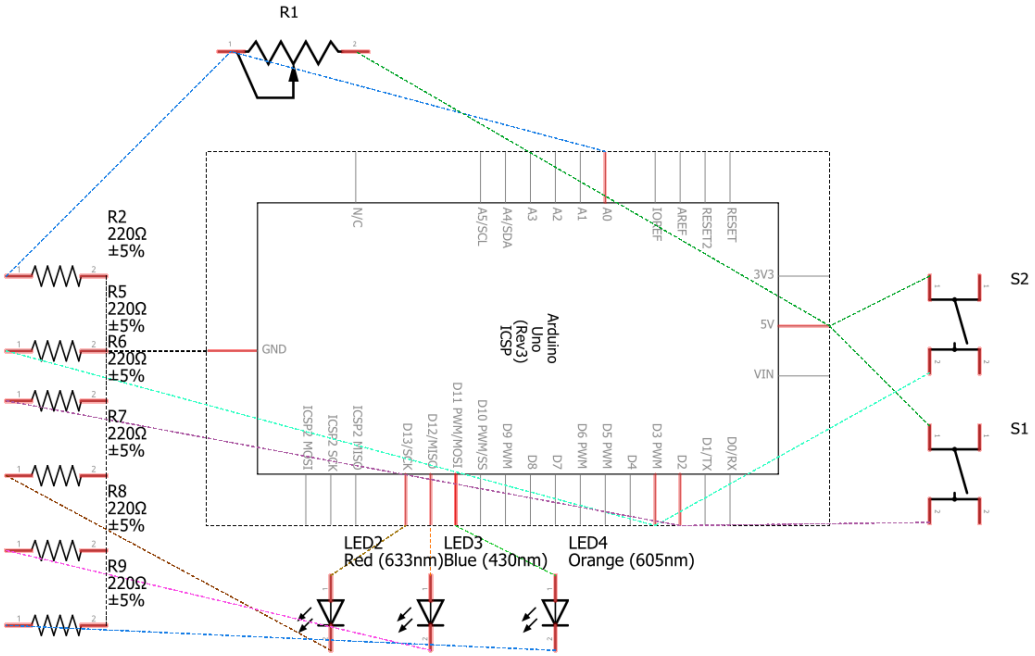


Figure 8.1: Circuit Diagram

Appendix D - Process and Logic Guide

The following process describes the process and logic behind the code and technical procedure:

1. Push Button One is Pressed - This step activates the calibration code which is represented by the blue LED. Here the user keeps their hand flat on the desk to act as reference position for 0°.
    - 30 data points over a period of 30s were averaged to determine the zero position for all 10 flex sensors. Main function in Code - **Calibration One**. Data is recorded on an SD card using the module.
    - After the 30s has elapsed, the blue LED will switch OFF and the red LED will start to blink over a duration of 30s. This will indicate to the user to change the hand gesture. Main function in Code - **Calibration Two**.
    - During this phase, the user changes the flat hand position to a fist, while ensuring that each joint is as close to 90° as possible.
    - After 30s the red LED will stop blinking and remain ON until 30 data points over a period of 30s are averaged to determine the fist position for all 10 flex sensors. Data is recorded on an SD card using the module.
    - The end of the calibration phase is indicated by all LEDs being switched OFF. However, the user keeps their hand in the fisted position.
2. Push Button Two is Pressed - Activates the code to record the data for which the user performs the requested activity. This phase is indicated by the yellow LED switching ON.
    - The duration of the data capture for each activity is 10s (20 data points). Thereafter the yellow LED will switch OFF. Data is recorded on an SD card using the module. Main function in Code - **Angle**.
    - This function maps the resistances from the flex sensors into angles based on the calibration data. However, both the resistances and converted angles were written to the SD card.
    - Each time the push button is pressed the value of 'n' (Figure 4.7) changes to represent the corresponding activity number and the data capture for the activity begins.

As mentioned in point 1, 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 by calculating the difference between the two sets of data for each joint. Therefore, the first recorded activity (Activity 1 - Correction Factor) has been set as holding the fist position. The board is powered by a USB type B cable connected to a laptop which was also used to observe the serial monitor during the execution of the code.

Appendix E - Main Arduino Code

```
1 // FLEX SENSOR VARIABLES
2
3 const int FLEX_IP_THUMB_PIN = A0;
4 const int FLEX_PIP_INDEX_PIN = A2;
5 const int FLEX_PIP_MID_PIN = A4;
6 const int FLEX_PIP_RIN_PIN = A6;
7 const int FLEX_PIP_PIN_PIN = A8;
8
9 const int FLEX_MCP_THUMB_PIN = A1;
10 const int FLEX_MCP_INDEX_PIN = A3;
11 const int FLEX_MCP_MID_PIN = A5;
12 const int FLEX_MCP_RIN_PIN = A7;
13 const int FLEX_MCP_PIN_PIN = A9;
14
15
16
17 const float VCC = 5.00; // Measured voltage of Ardunio 5V line
18 const float R_DIV = 99100; // Measured resistance of  resistor
19
20 ////////////////////////////
21
22 //CALIBRATION INITIAL VARIABLES
23
24 int sensorValue = 0;
25 int sensorMax = 0;
26 float sensorMin = 48250.00;
27
28 int LED_BLUE = 14;//Blue
29 int LED_RED = 12;
30 int LED_YELLOW = 10;
31 int BUTTON_BLUE = 9;
32 int BUTTON_ACT = 3;
33 volatile int button_change;
34 int STATE = 0;
35 int PREV_STATE =0;
```

```
36
37 ////////////////////////////
38
39 //SD Card Variables
40
41 #include <SPI.h>
42 #include <SD.h>
43 int pinSS = 53;
44 int ID = 1;
45
46 ////////////////////////////
47
48 // Intial Variables
49
50 int Cal_State = 0;
51 int Cal2_State = 0;
52 int check;
53 int check2;
54
55
56 float IP_THUMB_CAL_0;
57 float PIP_INDEX_CAL_0;
58 float PIP_MID_CAL_0;
59 float PIP_RIN_CAL_0;
60 float PIP_PIN_CAL_0;
61
62 float MCP_THUMB_CAL_0;
63 float MCP_INDEX_CAL_0;
64 float MCP_MID_CAL_0;
65 float MCP_RIN_CAL_0;
66 float MCP_PIN_CAL_0;
67
68
69 float IP_THUMB_CAL_90;
70 float PIP_INDEX_CAL_90;
71 float PIP_MID_CAL_90;
72 float PIP_RIN_CAL_90;
73 float PIP_PIN_CAL_90;
74
```

```
75 float MCP_THUMB_CAL_90;
76 float MCP_INDEX_CAL_90;
77 float MCP_MID_CAL_90;
78 float MCP_RIN_CAL_90;
79 float MCP_PIN_CAL_90;
80
81 float Cal_Two;
82 int counter;
83
84 ////////////////////////////////
85 ////////////////////////////////
86 ////////////////////////////////
87
88
89 void setup ()
90 {
91 //Pin Definition
92 Serial.begin(9600);
93
94 pinMode(LED_BLUE,OUTPUT);
95 pinMode(LED_RED,OUTPUT);
96 pinMode(BUTTON_BLUE,INPUT);
97
98
99 pinMode(FLEX_IP_THUMB_PIN, INPUT);
100 pinMode(FLEX_PIP_INDEX_PIN, INPUT);
101 pinMode(FLEX_PIP_MID_PIN, INPUT);
102 pinMode(FLEX_PIP_RIN_PIN, INPUT);
103 pinMode(FLEX_PIP_PIN_PIN, INPUT);
104
105 pinMode(FLEX_MCP_THUMB_PIN, INPUT);
106 pinMode(FLEX_MCP_INDEX_PIN, INPUT);
107 pinMode(FLEX_MCP_MID_PIN, INPUT);
108 pinMode(FLEX_MCP_RIN_PIN, INPUT);
109 pinMode(FLEX_MCP_PIN_PIN, INPUT);
110
111 pinMode(pinSS, OUTPUT);
112
```

```
113 attachInterrupt(digitalPinToInterrupt(BUTTON_ACT), ISR_Activity,
      CHANGE);
114
115 // SD Card Initialization
116 if (SD.begin())
117 {
118 Serial.println("SD␣card␣is␣ready");
119 } else
120 {
121 Serial.println("SD␣card␣not␣detected");
122 return;
123 }
124
125 // Creating File and Headers (CSV)
126 File Data = SD.open("Data.csv", FILE_WRITE);
127 if (Data)
128 {
129 Data.println(",␣,␣,␣,␣,"); // Blank line incase there was previous
      data
130 Data.println("NEW␣CANDIDATE");
131 String Header = "CALIBRATION,␣THUMB␣IP,␣THUMB␣MCP,␣INDEX␣PIP,␣INDEX
      ␣MCP,␣MIDDLE␣PIP,␣MIDDLE␣MCP,␣RING␣PIP,␣RING␣MCP,␣PINKY␣PIP,␣
      PINKY␣MCP";
132 Data.println(Header);
133 Data.close();
134 }
135 else
136 {
137 Serial.println("Error");
138 }
139 }
140 ////////////////////////////////
141 ////////////////////////////////
142 ////////////////////////////////
143 void loop()
144 {
145
146 Calibration_Button();
```

```
147 Calibration_One(FLEX_IP_THUMB_PIN, FLEX_MCP_THUMB_PIN,
      FLEX_PIP_INDEX_PIN, FLEX_MCP_INDEX_PIN, FLEX_PIP_MID_PIN,
      FLEX_MCP_MID_PIN, FLEX_PIP_RIN_PIN, FLEX_MCP_RIN_PIN ,
      FLEX_PIP_PIN_PIN, FLEX_MCP_PIN_PIN);
148 Calibration_Two(FLEX_IP_THUMB_PIN, FLEX_MCP_THUMB_PIN,
      FLEX_PIP_INDEX_PIN, FLEX_MCP_INDEX_PIN, FLEX_PIP_MID_PIN,
      FLEX_MCP_MID_PIN, FLEX_PIP_RIN_PIN, FLEX_MCP_RIN_PIN ,
      FLEX_PIP_PIN_PIN, FLEX_MCP_PIN_PIN);
149
150 Angle (FLEX_IP_THUMB_PIN, FLEX_MCP_THUMB_PIN, FLEX_PIP_INDEX_PIN,
      FLEX_MCP_INDEX_PIN, FLEX_PIP_MID_PIN, FLEX_MCP_MID_PIN,
      FLEX_PIP_RIN_PIN, FLEX_MCP_RIN_PIN ,  FLEX_PIP_PIN_PIN,
      FLEX_MCP_PIN_PIN, IP_THUMB_CAL_0, MCP_THUMB_CAL_0,
      PIP_INDEX_CAL_0, MCP_INDEX_CAL_0, PIP_MID_CAL_0, MCP_MID_CAL_0,
      PIP_RIN_CAL_0, MCP_RIN_CAL_0, PIP_PIN_CAL_0, MCP_PIN_CAL_0,
      IP_THUMB_CAL_90, MCP_THUMB_CAL_90, PIP_INDEX_CAL_90,
      MCP_INDEX_CAL_90, PIP_MID_CAL_90, MCP_MID_CAL_90, PIP_RIN_CAL_90
      , MCP_RIN_CAL_90, PIP_PIN_CAL_90, MCP_PIN_CAL_90 );
151
152
153
154 }
155 ////////////////////////////////////////////FUNCTIONS
      ////////////////////////////////////////////////
156
157
158 ////////////////////////////////////////////BUTTONS
      ////////////////////////////////////////////////
159
160
161
162 void Calibration_Button()
163 {
164 float Cal_One;
165 if(digitalRead(BUTTON_BLUE)==HIGH && PREV_STATE ==0) // same as if(
      BUTTON_BLUE == high && oldBUTTON_BLUE == low)
166 {
167 //we have a new BUTTON_BLUE press
168 if(STATE == 0) // if the STATE is off, turn it on
```

```
169 {
170 digitalWrite(LED_BLUE,HIGH);
171 STATE = 1;
172 }
173 else // if the STATE is on, turn it off
174 {
175 digitalWrite(LED_BLUE,LOW);
176 STATE = 0;
177 }
178 PREV_STATE = 1;
179 }
180 else if(digitalRead(BUTTON_BLUE)==LOW && PREV_STATE ==1) // same as
       if(BUTTON_BLUE == low && oldBUTTON_BLUE == high)
181 {
182 // the BUTTON_BLUE was released
183 PREV_STATE = 0;
184 }
185 }
186
187 \\CALIBRATION ONE FUNCTION
188 float Calibration_One (int FLEX_IP_THUMB_PIN, int
      FLEX_MCP_THUMB_PIN, int FLEX_PIP_INDEX_PIN, int
      FLEX_MCP_INDEX_PIN,  int FLEX_PIP_MID_PIN, int FLEX_MCP_MID_PIN,
       int FLEX_PIP_RIN_PIN, int FLEX_MCP_RIN_PIN , int
      FLEX_PIP_PIN_PIN, int FLEX_MCP_PIN_PIN)
189
190 {
191
192 if (digitalRead(LED_BLUE) == HIGH && digitalRead(LED_RED)== LOW){
193 Serial.println("Calibration␣0␣Degree␣:␣ON");
194 Cal_State = 1;
195
196 int av1_IP_THUMB = 0;
197 int av1_PIP_INDEX = 0;
198 int av1_PIP_MID = 0;
199 int av1_PIP_RIN = 0;
200 int av1_PIP_PIN = 0;
201
202 int av1_MCP_THUMB = 0;
```

```
int av1_MCP_INDEX = 0;
int av1_MCP_MID = 0;
int av1_MCP_RIN = 0;
int av1_MCP_PIN = 0;

for (int i=0; i < 30; i++)
{
av1_IP_THUMB = av1_IP_THUMB + analogRead(FLEX_IP_THUMB_PIN);
av1_PIP_INDEX = av1_PIP_INDEX + analogRead(FLEX_PIP_INDEX_PIN);
av1_PIP_MID = av1_PIP_MID + analogRead(FLEX_PIP_MID_PIN);
av1_PIP_RIN = av1_PIP_RIN + analogRead(FLEX_PIP_RIN_PIN);
av1_PIP_PIN = av1_PIP_PIN + analogRead(FLEX_PIP_PIN_PIN);

av1_MCP_THUMB = av1_MCP_THUMB + analogRead(FLEX_MCP_THUMB_PIN);
av1_MCP_INDEX = av1_MCP_INDEX + analogRead(FLEX_MCP_INDEX_PIN);
av1_MCP_MID = av1_MCP_MID + analogRead(FLEX_MCP_MID_PIN);
av1_MCP_RIN = av1_MCP_RIN + analogRead(FLEX_MCP_RIN_PIN);
av1_MCP_PIN = av1_MCP_PIN + analogRead(FLEX_MCP_PIN_PIN);

Serial.println(i);
delay(500);
}
av1_IP_THUMB = av1_IP_THUMB/30;
av1_PIP_INDEX = av1_PIP_INDEX/30;
av1_PIP_MID = av1_PIP_MID/30;
av1_PIP_RIN = av1_PIP_RIN/30;
av1_PIP_PIN = av1_PIP_PIN/30;

av1_MCP_THUMB = av1_MCP_THUMB/30;
av1_MCP_INDEX = av1_MCP_INDEX/30;
av1_MCP_MID = av1_MCP_MID/30;
av1_MCP_RIN = av1_MCP_RIN/30;
av1_MCP_PIN = av1_MCP_PIN/30;



//THUMB IP
float flexV_IP_THUMB = av1_IP_THUMB * VCC / 1023.0;
float flexR_IP_THUMB = R_DIV * (VCC / flexV_IP_THUMB - 1.0);
```

```
242 float flexT_IP_THUMB = round(flexR_IP_THUMB/1000);
243 IP_THUMB_CAL_0 = flexR_IP_THUMB;
244 //THUMB MCP
245 float flexV_MCP_THUMB = av1_MCP_THUMB * VCC / 1023.0;
246 float flexR_MCP_THUMB = R_DIV * (VCC / flexV_MCP_THUMB - 1.0);
247 float flexT_MCP_THUMB = round(flexR_MCP_THUMB/1000);
248 MCP_THUMB_CAL_0 = flexR_MCP_THUMB;
249
250
251 //INDEX PIP
252 float flexV_PIP_INDEX = av1_PIP_INDEX * VCC / 1023.0;
253 float flexR_PIP_INDEX = R_DIV * (VCC / flexV_PIP_INDEX - 1.0);
254 float flexT_PIP_INDEX = round(flexR_PIP_INDEX/1000);
255 PIP_INDEX_CAL_0 = flexR_PIP_INDEX;
256
257 //INDEX MCP
258 float flexV_MCP_INDEX = av1_MCP_INDEX * VCC / 1023.0;
259 float flexR_MCP_INDEX = R_DIV * (VCC / flexV_MCP_INDEX - 1.0);
260 float flexT_MCP_INDEX = round(flexR_MCP_INDEX/1000);
261 MCP_INDEX_CAL_0 = flexR_MCP_INDEX;
262
263
264
265 //MIDDLE PIP
266 float flexV_PIP_MID = av1_PIP_MID * VCC / 1023.0;
267 float flexR_PIP_MID = R_DIV * (VCC / flexV_PIP_MID - 1.0);
268 float flexT_PIP_MID = round(flexR_PIP_MID/1000);
269 PIP_MID_CAL_0 = flexR_PIP_MID;
270
271 //MIDDLE MCP
272 float flexV_MCP_MID = av1_MCP_MID * VCC / 1023.0;
273 float flexR_MCP_MID = R_DIV * (VCC / flexV_MCP_MID - 1.0);
274 float flexT_MCP_MID = round(flexR_MCP_MID/1000);
275 MCP_MID_CAL_0 = flexR_MCP_MID;
276
277
278 //RING PIP
279 float flexV_PIP_RIN = av1_PIP_RIN * VCC / 1023.0;
280 float flexR_PIP_RIN = R_DIV * (VCC / flexV_PIP_RIN - 1.0);
```

```
281 float flexT_PIP_RIN = round(flexR_PIP_RIN/1000);
282 PIP_RIN_CAL_0 = flexR_PIP_RIN;
283
284 //RING MCP
285 float flexV_MCP_RIN = av1_MCP_RIN * VCC / 1023.0;
286 float flexR_MCP_RIN = R_DIV * (VCC / flexV_MCP_RIN - 1.0);
287 float flexT_MCP_RIN = round(flexR_MCP_RIN/1000);
288 MCP_RIN_CAL_0 = flexR_MCP_RIN;
289
290 //PINKY PIP
291 float flexV_PIP_PIN = av1_PIP_PIN * VCC / 1023.0;
292 float flexR_PIP_PIN = R_DIV * (VCC / flexV_PIP_PIN - 1.0);
293 float flexT_PIP_PIN = round(flexR_PIP_PIN/1000);
294 PIP_PIN_CAL_0 = flexR_PIP_PIN;
295
296 //PINKY MCP
297 float flexV_MCP_PIN = av1_MCP_PIN * VCC / 1023.0;
298 float flexR_MCP_PIN = R_DIV * (VCC / flexV_MCP_PIN - 1.0);
299 float flexT_MCP_PIN = round(flexR_MCP_PIN/1000);
300 MCP_PIN_CAL_0 = flexR_MCP_PIN;
301
302 String dataString = String(1) + "," + String(flexR_IP_THUMB)+ "," +
       String(flexR_MCP_THUMB) + "," + String(flexR_PIP_INDEX)+ "," +
      String(flexR_MCP_INDEX) + "," + String(flexR_PIP_MID)+ "," +
      String(flexR_MCP_MID) + "," + String(flexR_PIP_RIN)+ "," +
      String(flexR_MCP_RIN)+ "," + String(flexR_PIP_PIN)+ "," + String
      (flexR_MCP_PIN);
303 File Data = SD.open("Data.csv", FILE_WRITE);
304 if (Data)
305 {
306 Data.println(dataString);
307 Data.close();
308 }
309 else
310 {
311 Data.println("Error");
312 }
313
314 delay(1000);
```

```
315 Serial.println("Calibration Zero Complete");
316 check=1;
317 digitalWrite(LED_BLUE,LOW);
318 }
319
320 else
321 {
322 //Do nothing
323 }
324 //return;
325 }
326
327 //CALIBRATION TWO FUNCTION
328 float Calibration_Two (int FLEX_IP_THUMB_PIN, int
      FLEX_MCP_THUMB_PIN, int FLEX_PIP_INDEX_PIN, int
      FLEX_MCP_INDEX_PIN,  int FLEX_PIP_MID_PIN, int FLEX_MCP_MID_PIN,
       int FLEX_PIP_RIN_PIN, int FLEX_MCP_RIN_PIN , int
      FLEX_PIP_PIN_PIN, int FLEX_MCP_PIN_PIN)
329 {
330
331 if (Cal_State == 1 && digitalRead(LED_BLUE) == LOW)
332 {
333 Serial.println("Calibration Two Commencing");
334 digitalWrite(LED_RED, HIGH);
335 delay(1000);
336 digitalWrite(LED_RED, LOW);
337 delay(1000);
338 digitalWrite(LED_RED, HIGH);
339 delay(1000);
340 digitalWrite(LED_RED, LOW);
341 delay(1000);
342 digitalWrite(LED_RED, HIGH);
343 delay(1000);
344 digitalWrite(LED_RED, LOW);
345 delay(1000);
346 digitalWrite(LED_RED, HIGH);
347 delay(1000);
348 digitalWrite(LED_RED, LOW);
349 delay(1000);
```

```
350 digitalWrite(LED_RED, HIGH);
351 delay(1000);
352 digitalWrite(LED_RED, LOW);
353 delay(1000);
354 digitalWrite(LED_RED, HIGH);
355 delay(1000);
356 digitalWrite(LED_RED, LOW);
357 delay(1000);
358 digitalWrite(LED_RED, HIGH);
359 delay(1000);
360 digitalWrite(LED_RED, LOW);
361 delay(1000);
362 digitalWrite(LED_RED, HIGH);
363 delay(1000);
364 digitalWrite(LED_RED, LOW);
365 delay(1000);
366 digitalWrite(LED_RED, HIGH);
367 delay(1000);
368 digitalWrite(LED_RED, LOW);
369 delay(1000);
370 digitalWrite(LED_RED, HIGH);
371 delay(1000);
372 digitalWrite(LED_RED, LOW);
373 delay(1000);
374 digitalWrite(LED_RED, HIGH);
375 delay(1000);
376 digitalWrite(LED_RED, LOW);
377 delay(1000);
378 digitalWrite(LED_RED, HIGH);
379 delay(1000);
380 digitalWrite(LED_RED, LOW);
381 delay(1000);
382 digitalWrite(LED_RED, HIGH);
383 delay(1000);
384 digitalWrite(LED_RED, LOW);
385 delay(1000);
386 digitalWrite(LED_RED, HIGH);
387 delay(1000);
388 digitalWrite(LED_RED, LOW);
```

```
389 delay(1000);
390 digitalWrite(LED_RED, HIGH);
391 delay(1000);
392 digitalWrite(LED_RED, LOW);
393 delay(1000);
394 digitalWrite(LED_RED, HIGH);
395 delay(1000);
396 digitalWrite(LED_RED, LOW);
397 delay(1000);
398 digitalWrite(LED_RED, HIGH);
399 delay(1000);
400 digitalWrite(LED_RED, LOW);
401 delay(1000);
402 digitalWrite(LED_RED, HIGH);
403 delay(1000);
404 digitalWrite(LED_RED, LOW);
405 delay(1000);
406 digitalWrite(LED_RED, HIGH);
407 delay(1000);
408 digitalWrite(LED_RED, LOW);
409 delay(1000);
410 digitalWrite(LED_RED, HIGH);
411 delay(1000);
412 digitalWrite(LED_RED, LOW);
413 delay(1000);
414 digitalWrite(LED_RED, HIGH);
415 delay(1000);
416 //digitalWrite(LED_RED, LOW);
417 Cal_State = 0;
418
419 int av1_IP_THUMB = 0;
420 int av1_PIP_INDEX = 0;
421 int av1_PIP_MID = 0;
422 int av1_PIP_RIN = 0;
423 int av1_PIP_PIN = 0;
424
425 int av1_MCP_THUMB = 0;
426 int av1_MCP_INDEX = 0;
427 int av1_MCP_MID = 0;
```

```
int av1_MCP_RIN = 0;
int av1_MCP_PIN = 0;

for (int i=0; i < 30; i++)
{
av1_IP_THUMB = av1_IP_THUMB + analogRead(FLEX_IP_THUMB_PIN);
av1_PIP_INDEX = av1_PIP_INDEX + analogRead(FLEX_PIP_INDEX_PIN);
av1_PIP_MID = av1_PIP_MID + analogRead(FLEX_PIP_MID_PIN);
av1_PIP_RIN = av1_PIP_RIN + analogRead(FLEX_PIP_RIN_PIN);
av1_PIP_PIN = av1_PIP_PIN + analogRead(FLEX_PIP_PIN_PIN);

av1_MCP_THUMB = av1_MCP_THUMB + analogRead(FLEX_MCP_THUMB_PIN);
av1_MCP_INDEX = av1_MCP_INDEX + analogRead(FLEX_MCP_INDEX_PIN);
av1_MCP_MID = av1_MCP_MID + analogRead(FLEX_MCP_MID_PIN);
av1_MCP_RIN = av1_MCP_RIN + analogRead(FLEX_MCP_RIN_PIN);
av1_MCP_PIN = av1_MCP_PIN + analogRead(FLEX_MCP_PIN_PIN);

Serial.println(i);
delay(500);
}
av1_IP_THUMB = av1_IP_THUMB/30;
av1_PIP_INDEX = av1_PIP_INDEX/30;
av1_PIP_MID = av1_PIP_MID/30;
av1_PIP_RIN = av1_PIP_RIN/30;
av1_PIP_PIN = av1_PIP_PIN/30;

av1_MCP_THUMB = av1_MCP_THUMB/30;
av1_MCP_INDEX = av1_MCP_INDEX/30;
av1_MCP_MID = av1_MCP_MID/30;
av1_MCP_RIN = av1_MCP_RIN/30;
av1_MCP_PIN = av1_MCP_PIN/30;


//THUMB IP
float flexV_IP_THUMB = av1_IP_THUMB * VCC / 1023.0;
float flexR_IP_THUMB = R_DIV * (VCC / flexV_IP_THUMB - 1.0);
float flexT_IP_THUMB = round(flexR_IP_THUMB/1000);
IP_THUMB_CAL_90 = flexR_IP_THUMB;

```

```
467 //THUMB MCP
468 float flexV_MCP_THUMB = av1_MCP_THUMB * VCC / 1023.0;
469 float flexR_MCP_THUMB = R_DIV * (VCC / flexV_MCP_THUMB - 1.0);
470 float flexT_MCP_THUMB = round(flexR_MCP_THUMB/1000);
471 MCP_THUMB_CAL_90 = flexR_MCP_THUMB;
472
473
474 //INDEX PIP
475 float flexV_PIP_INDEX = av1_PIP_INDEX * VCC / 1023.0;
476 float flexR_PIP_INDEX = R_DIV * (VCC / flexV_PIP_INDEX - 1.0);
477 float flexT_PIP_INDEX = round(flexR_PIP_INDEX/1000);
478 PIP_INDEX_CAL_90 = flexR_PIP_INDEX;
479
480 //INDEX MCP
481 float flexV_MCP_INDEX = av1_MCP_INDEX * VCC / 1023.0;
482 float flexR_MCP_INDEX = R_DIV * (VCC / flexV_MCP_INDEX - 1.0);
483 float flexT_MCP_INDEX = round(flexR_MCP_INDEX/1000);
484 MCP_INDEX_CAL_90 = flexR_MCP_INDEX;
485
486
487
488 //MIDDLE PIP
489 float flexV_PIP_MID = av1_PIP_MID * VCC / 1023.0;
490 float flexR_PIP_MID = R_DIV * (VCC / flexV_PIP_MID - 1.0);
491 float flexT_PIP_MID = round(flexR_PIP_MID/1000);
492 PIP_MID_CAL_90 = flexR_PIP_MID;
493
494 //MIDDLE MCP
495 float flexV_MCP_MID = av1_MCP_MID * VCC / 1023.0;
496 float flexR_MCP_MID = R_DIV * (VCC / flexV_MCP_MID - 1.0);
497 float flexT_MCP_MID = round(flexR_MCP_MID/1000);
498 MCP_MID_CAL_90 = flexR_MCP_MID;
499
500
501 //RING PIP
502 float flexV_PIP_RIN = av1_PIP_RIN * VCC / 1023.0;
503 float flexR_PIP_RIN = R_DIV * (VCC / flexV_PIP_RIN - 1.0);
504 float flexT_PIP_RIN = round(flexR_PIP_RIN/1000);
505 PIP_RIN_CAL_90 = flexR_PIP_RIN;
```

```
506
507 //RING MCP
508 float flexV_MCP_RIN = av1_MCP_RIN * VCC / 1023.0;
509 float flexR_MCP_RIN = R_DIV * (VCC / flexV_MCP_RIN - 1.0);
510 float flexT_MCP_RIN = round(flexR_MCP_RIN/1000);
511 MCP_RIN_CAL_90 = flexR_MCP_RIN;
512
513 //PINKY PIP
514 float flexV_PIP_PIN = av1_PIP_PIN * VCC / 1023.0;
515 float flexR_PIP_PIN = R_DIV * (VCC / flexV_PIP_PIN - 1.0);
516 float flexT_PIP_PIN = round(flexR_PIP_PIN/1000);
517 PIP_PIN_CAL_90 = flexR_PIP_PIN;
518
519 //PINKY MCP
520 float flexV_MCP_PIN = av1_MCP_PIN * VCC / 1023.0;
521 float flexR_MCP_PIN = R_DIV * (VCC / flexV_MCP_PIN - 1.0);
522 float flexT_MCP_PIN = round(flexR_MCP_PIN/1000);
523 MCP_PIN_CAL_90 = flexR_MCP_PIN;
524
525
526
527 String dataString = String(2) + "," + String(flexR_IP_THUMB)+ "," +
       String(flexR_MCP_THUMB) + "," + String(flexR_PIP_INDEX)+ "," +
      String(flexR_MCP_INDEX) + "," + String(flexR_PIP_MID)+ "," +
      String(flexR_MCP_MID) + "," + String(flexR_PIP_RIN)+ "," +
      String(flexR_MCP_RIN)+ "," + String(flexR_PIP_PIN)+ "," + String
      (flexR_MCP_PIN);
528 File Data = SD.open("Data.csv", FILE_WRITE);
529 if (Data)
530 {
531 Data.println(dataString);
532 Data.close();
533 }
534 else
535 {
536 Data.println("Error");
537 }
538
539 delay(1000);
```

```
Serial.println("Calibration Two Complete");
check2=1;
digitalWrite(LED_RED,LOW);
}

else
{
// Do nothing
}
//return;
}


float Angle (int FLEX_IP_THUMB_PIN, int FLEX_MCP_THUMB_PIN, int
    FLEX_PIP_INDEX_PIN, int FLEX_MCP_INDEX_PIN, int FLEX_PIP_MID_PIN
    , int FLEX_MCP_MID_PIN, int FLEX_PIP_RIN_PIN, int
    FLEX_MCP_RIN_PIN ,  int FLEX_PIP_PIN_PIN, int FLEX_MCP_PIN_PIN,
    float IP_THUMB_CAL_0, float MCP_THUMB_CAL_0,  float
    PIP_INDEX_CAL_0, float MCP_INDEX_CAL_0, float PIP_MID_CAL_0,
    float MCP_MID_CAL_0, float PIP_RIN_CAL_0, float MCP_RIN_CAL_0,
    float PIP_PIN_CAL_0, float MCP_PIN_CAL_0, float IP_THUMB_CAL_90,
     float MCP_THUMB_CAL_90, float PIP_INDEX_CAL_90, float
    MCP_INDEX_CAL_90, float PIP_MID_CAL_90, float MCP_MID_CAL_90,
    float PIP_RIN_CAL_90, float MCP_RIN_CAL_90, float PIP_PIN_CAL_90
    , float MCP_PIN_CAL_90)
{
if (button_change){
counter++;
File Data = SD.open("Data.csv", FILE_WRITE);
Data.println(",,,,,"); // Blank line incase there was previous
    data
Data.println("Activity " + String(counter) );
String Header = "No, THUMB IP, DEGREE, THUMB MCP, DEGREE, INDEX PIP
    , DEGREE, INDEX MCP, DEGREE, MIDDLE PIP, DEGREE, MIDDLE MCP,
    DEGREE, RING PIP, DEGREE, RING MCP, DEGREE, PINKY PIP, DEGREE,
    PINKY MCP, DEGREE";
Data.println(Header);
Data.close();
```

```
564
565 Serial.println("Activity Begin " + String(counter));
566 digitalWrite(LED_YELLOW,HIGH);
567 if (check == 1 && check2 == 1)
568 {
569 for (int i=0; i < 20; i++)
570 {
571 float av1_IP_THUMB = analogRead(FLEX_IP_THUMB_PIN);
572 float av1_PIP_INDEX = analogRead(FLEX_PIP_INDEX_PIN);
573 float av1_PIP_MID = analogRead(FLEX_PIP_MID_PIN);
574 float av1_PIP_RIN = analogRead(FLEX_PIP_RIN_PIN);
575 float av1_PIP_PIN = analogRead(FLEX_PIP_PIN_PIN);
576
577 float av1_MCP_THUMB = analogRead(FLEX_MCP_THUMB_PIN);
578 float av1_MCP_INDEX = analogRead(FLEX_MCP_INDEX_PIN);
579 float av1_MCP_MID =  analogRead(FLEX_MCP_MID_PIN);
580 float av1_MCP_RIN = analogRead(FLEX_MCP_RIN_PIN);
581 float av1_MCP_PIN = analogRead(FLEX_MCP_PIN_PIN);
582
583
584 //THUMB IP
585 float flexV_IP_THUMB = av1_IP_THUMB * VCC / 1023.0;
586 float flexR_IP_THUMB = R_DIV * (VCC / flexV_IP_THUMB - 1.0);
587 float flexT_IP_THUMB = round(flexR_IP_THUMB/1000);
588
589
590 //THUMB MCP
591 float flexV_MCP_THUMB = av1_MCP_THUMB * VCC / 1023.0;
592 float flexR_MCP_THUMB = R_DIV * (VCC / flexV_MCP_THUMB - 1.0);
593 float flexT_MCP_THUMB = round(flexR_MCP_THUMB/1000);
594
595
596
597 //INDEX PIP
598 float flexV_PIP_INDEX = av1_PIP_INDEX * VCC / 1023.0;
599 float flexR_PIP_INDEX = R_DIV * (VCC / flexV_PIP_INDEX - 1.0);
600 float flexT_PIP_INDEX = round(flexR_PIP_INDEX/1000);
601
602
```

```
603 //INDEX MCP
604 float flexV_MCP_INDEX = av1_MCP_INDEX * VCC / 1023.0;
605 float flexR_MCP_INDEX = R_DIV * (VCC / flexV_MCP_INDEX - 1.0);
606 float flexT_MCP_INDEX = round(flexR_MCP_INDEX/1000);
607
608
609
610 //MIDDLE PIP
611 float flexV_PIP_MID = av1_PIP_MID * VCC / 1023.0;
612 float flexR_PIP_MID = R_DIV * (VCC / flexV_PIP_MID - 1.0);
613 float flexT_PIP_MID = round(flexR_PIP_MID/1000);
614
615
616 //MIDDLE MCP
617 float flexV_MCP_MID = av1_MCP_MID * VCC / 1023.0;
618 float flexR_MCP_MID = R_DIV * (VCC / flexV_MCP_MID - 1.0);
619 float flexT_MCP_MID = round(flexR_MCP_MID/1000);
620
621
622
623 //RING PIP
624 float flexV_PIP_RIN = av1_PIP_RIN * VCC / 1023.0;
625 float flexR_PIP_RIN = R_DIV * (VCC / flexV_PIP_RIN - 1.0);
626 float flexT_PIP_RIN = round(flexR_PIP_RIN/1000);
627
628
629 //RING MCP
630 float flexV_MCP_RIN = av1_MCP_RIN * VCC / 1023.0;
631 float flexR_MCP_RIN = R_DIV * (VCC / flexV_MCP_RIN - 1.0);
632 float flexT_MCP_RIN = round(flexR_MCP_RIN/1000);
633
634
635 //PINKY PIP
636 float flexV_PIP_PIN = av1_PIP_PIN * VCC / 1023.0;
637 float flexR_PIP_PIN = R_DIV * (VCC / flexV_PIP_PIN - 1.0);
638 float flexT_PIP_PIN = round(flexR_PIP_PIN/1000);
639
640
641 //PINKY MCP
```

```
642 float flexV_MCP_PIN = av1_MCP_PIN * VCC / 1023.0;
643 float flexR_MCP_PIN = R_DIV * (VCC / flexV_MCP_PIN - 1.0);
644 float flexT_MCP_PIN = round(flexR_MCP_PIN/1000);
645
646
647
648
649 float angle_IP_THUMB = map(flexR_IP_THUMB, IP_THUMB_CAL_0,
       IP_THUMB_CAL_90, 0, 90.0);
650 float angle_PIP_INDEX = map(flexR_PIP_INDEX, PIP_INDEX_CAL_0,
       PIP_INDEX_CAL_90, 0, 90.0);
651 float angle_PIP_MID = map(flexR_PIP_MID, PIP_MID_CAL_0,
       PIP_MID_CAL_90, 0, 90.0);
652 float angle_PIP_RIN = map(flexR_PIP_RIN, PIP_RIN_CAL_0,
       PIP_RIN_CAL_90, 0, 90.0);
653 float angle_PIP_PIN = map(flexR_PIP_PIN, PIP_PIN_CAL_0,
       PIP_PIN_CAL_90, 0, 90.0);
654
655 float angle_MCP_THUMB = map(flexR_MCP_THUMB, MCP_THUMB_CAL_0,
       MCP_THUMB_CAL_90, 0, 90.0);
656 float angle_MCP_INDEX = map(flexR_MCP_INDEX, MCP_INDEX_CAL_0,
       MCP_INDEX_CAL_90, 0, 90.0);
657 float angle_MCP_MID = map(flexR_MCP_MID, MCP_MID_CAL_0,
       MCP_MID_CAL_90, 0, 90.0);
658 float angle_MCP_RIN = map(flexR_MCP_RIN, MCP_RIN_CAL_0,
       MCP_RIN_CAL_90, 0, 90.0);
659 float angle_MCP_PIN = map(flexR_MCP_PIN, MCP_PIN_CAL_0,
       MCP_PIN_CAL_90, 0, 90.0);
660 //Serial.println(IP_THUMB_CAL_0);
661 //delay(1000);
```

```
662 String dataString = String(i)+ "," + String(flexR_IP_THUMB)+ "," +
      String(angle_IP_THUMB) + "," + String(flexR_MCP_THUMB)+ "," +
      String(angle_MCP_THUMB) + "," + String(flexR_PIP_INDEX)+ "," +
      String(angle_PIP_INDEX)+ ","+ String(flexR_MCP_INDEX)+ "," +
      String(angle_MCP_INDEX)+ "," + String(flexR_PIP_MID)+ "," +
      String(angle_PIP_MID)+ ","+ String(flexR_MCP_MID)+ "," + String(
      angle_MCP_MID)+ "," + String(flexR_PIP_RIN)+ "," + String(
      angle_PIP_RIN)+ ","+ String(flexR_MCP_RIN)+ "," + String(
      angle_MCP_RIN)+ "," + String(flexR_PIP_PIN)+ "," + String(
      angle_PIP_PIN)+ ","+ String(flexR_MCP_PIN)+ "," + String(
      angle_MCP_PIN);
663 File Data = SD.open("Data.csv", FILE_WRITE);
664 if (Data)
665 {
666 Data.println(dataString);
667 Data.close();
668 }
669 else
670 {
671 Data.println("Error");
672 }
673 Serial.println(String(i));
674 delay(500);
675 }
676 digitalWrite(LED_YELLOW,LOW);
677 }
678 }
679 button_change = 0;
680 }
681 void ISR_Activity ()
682 {
683 button_change = 1;
684 }
```

Appendix F - Detailed Dynamic Testing Procedure

The following process details the full procedure of the dynamic testing phase:

1. **Introduction to Study**
   The contents of the study was explained to the potential candidate. An assessment of the fit of the glove was made to determine whether a participant was a suitable candidate. Participation was completely voluntary with the recorded data to remain disclosed through the use of number profiling. A declaration was signed by both the participant and principle investigator.

2. **Questionnaire**
   The candidates completed a questionnaire (Appendix D) to determine which hand was dominant and whether the candidate had any relevant medical history pertaining to the use of their hands.

3. **Fitting of Glove**
   The principle investigator ensured that the glove comfortably fits the user as well as whether the flex sensors were correctly positioned and secured.

4. **Calibration**
   The user was required to keep their hand in a flat position on top of a desk (Figure 8.2a). This represented the 0° position. Based on the code of the device, data was recorded accordingly. Thereafter the user gestured a specific fist (Figure 8.2b), while ensuring that all joints are as close to 90° as possible. The principle investigator closely investigated and corrected the required hand positions. Once again, the data was recorded. These two streams of data were averaged and mapped to 0° and 90°, respectively. Please see Section 4.3.1 for a more detailed explanation. The fist was held until the next step.

5. **Performance of Activities**
   The participant was directed to perform a certain activity. Once the motion was observed, the candidate repeated the activity while the device recorded the data. As mentioned, the first activity was represented by holding the fisted position from the previous step so that the slack in the glove was quantified.



(a) Neutral Position (b) Required Fist

Figure 8.2: Calibration Gestures

During the current phase, a checklist was marked to verify that the set activity had been done. The checklist is shown in Table 5.1. The column marked as 'Activity Reference' was used to indicate the activity number that the code outputs onto the computer screen. This had been done to cater for any error during an activity, where said activity could be repeated as the reference was marked on the checklist.

6. **Evaluation**

   Once steps 1-5 had been completed on both the right and left hand of the user, an evaluation (Appendix D) was completed by the participant, indicating the level of comfort when using the glove and any overall comments they may have had about the current study.

Appendix G - Variation Across All Dynamic Candidates

Table 8.2: Variation across all Dynamic Participants

Left									
Candidate	**IP_Thumb**	**PIP_Index**	**MCP_Index**	**PIP_Middle**	**MCP_Middle**	**PIP_Ring**	**MCP_Ring**	**PIP_Pinky**	**MCP_Pinky**
1	14.50	6.31	12.34	4.71	8.87	4.57	6.82	3.63	5.97
2	29.23	13.50	11.25	13.11	12.66	13.29	14.00	13.12	17.77
3	18.01	14.89	19.88	15.06	15.28	15.44	15.40	16.30	21.60
4	25.37	13.30	13.24	14.01	20.80	16.15	22.01	13.35	32.38
5	26.78	11.94	20.04	9.58	14.83	9.69	8.69	9.27	18.67
6	14.29	14.72	14.54	12.35	14.62	12.78	12.02	12.44	15.15
7	17.18	15.85	28.70	16.87	21.90	18.14	17.69	16.57	22.13
8	30.60	11.45	11.56	13.65	15.39	12.65	13.58	12.37	15.51
9	26.12	15.01	21.58	17.15	16.07	13.96	17.71	13.82	22.27
10	20.90	19.35	17.48	19.45	16.96	19.96	24.39	13.21	31.13
Right									
Candidate	**IP_Thumb**	**PIP_Index**	**MCP_Index**	**PIP_Middle**	**MCP_Middle**	**PIP_Ring**	**MCP_Ring**	**PIP_Pinky**	**MCP_Pinky**
1	11.08	13.63	16.78	10.27	12.20	10.07	10.27	9.46	11.82
2	24.80	19.32	25.07	19.22	16.69	18.55	17.67	17.97	18.83
3	22.80	16.32	17.01	15.70	14.43	17.50	14.40	21.81	19.57
4	27.96	22.02	15.48	19.64	29.56	19.38	23.01	20.98	20.16
5	25.17	20.54	13.55	10.92	12.82	10.42	12.08	8.54	19.97
6	22.45	13.89	12.71	16.54	14.86	16.26	12.59	15.93	17.95
7	9.39	11.82	11.93	13.18	14.71	12.54	11.47	11.42	20.05
8	24.03	14.48	17.45	13.74	16.46	11.79	14.35	13.49	16.27
9	27.63	17.21	17.30	19.93	16.88	17.99	19.66	18.21	21.75
10	19.62	17.19	9.85	15.90	17.53	15.32	16.91	14.40	16.58

Appendix H - Participant Questionnaire and Evaluation

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LOW-COST FLEXIBLE SENSOR ROBOT FOR HAND REHABILITATION AND ASSISTANCE

Questionnaire

Date:

Age:

Gender:

Question 1

Please tick dominant hand:

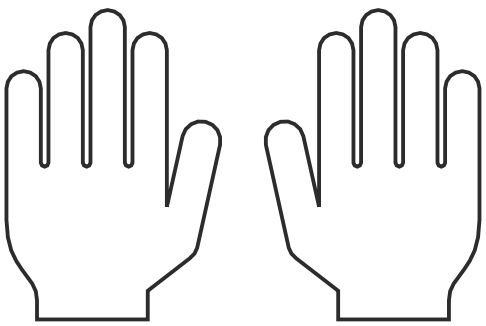
Left ☐

Right ☐

Question 2

Have you had any injuries or medical disorders that have previously hindered the functionality of your hand?

If so, please specify the type of ailment that lead to your temporary impairment and if the ailment was a physical injury please indicate (marking) on the diagrams below which hand/s or finger/s were damaged.



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Evaluation

Please could you evaluate the comfort of the data glove used so we can improve on the design further into the study. On a scale of 1 to 5 please **circle your level of discomfort**, with **1 being as comfortable as a regular glove** and **5 being the most uncomfortable.**

1 2 3 4 5

Comments:

_____

_____

_____

If you have any comments about the study and the procedures done, please feel free to do so in the space below. This will help us improve and better the study going further on into the research.

_____

_____

_____

Thank you for your participation and insight in the current investigation!