Development and Testing of a Hand Rehabilitation Device for Continuous Passive Motion and Active Resistance

by

Benjamin John Birch
BEng, University of Victoria, 2008

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of the Requirements for the Degree of

MASTERS OF APPLIED SCIENCE

in the Department of Mechanical Engineering

Supervisory Committee

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Abstract

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This thesis presents a novel table top hand rehabilitation device. The purpose for creating this device is to assist therapists in treatment of hand after injury. Injuries to the hand are common and can be very debilitating since our hands are our primary means for interacting with our world. The device is capable of independently mobilizing the metacarpophalangeal joint (MCP) and proximal interphalangeal joint (PIP) in the fingers of the hand, and recording their motion. The device is capable of moving either joint through a range of 0° to 90°, and can be used for either the left or right hand. In the Continuous Passive Motion (CPM) mode, the device moves the MCP and PIP joints through a trajectory that approximates healthy hand motion, known as the minimum jerk model. This is done using a Proportional Integral Differential (PID) controller, which compares the actual position of the device to the desired minimum jerk trajectory. The trajectory following of the minimum jerk model was found to be successful with a maximum error of only 1.46° in the MCP joint and 2.10° in the PIP joint across all trials with injured participants with an average error of 0.11° and 0.14° for the MCP and PIP joints respectively. The device also incorporated various user-friendly features such as user-defined maximum permitted torque, range of motion limits, speed control, and visual feedback. A survey of the participant's perceived comfort, safety, smoothness and passivity produced positive results. The average responses of the injured hand participants to questions of perceived Comfort, safety and Smoothness were above 9 out of 10 for each question. The average increases in ROM for the active extension of the MCP joint and the PIP joint were 3.3° and 3.2° respectively. The average increases in ROM for the flexion of the MCP joint and the PIP joint were 8.9° and 7.2° respectively. This is a sign that the device has an effect on the participant even if this effect can not be shown to last beyond the one hour session. It will require further testing with a long term group of participants and a control group to determine if this is a lasting effect and if the device is ready for clinical use. The active resistance and haptic modes are both operational but require additional work to increase smoothness and stability before testing can begin.

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Glossary

Active Resistance – This technique requires the patient to move their joint through a set range of motion while being resisted by and external force. This force can be produced by a therapist, a robotic device or a simple mechanical device such as a ball or spring.

Computer Aided Design (CAD) – CAD is a technique where a software package such as SolidWorks is used to during the design of a project. In this project specifically the software was used to create a model in two or three dimension and produce part diagrams for machining.

Continuous Passive Motion (CPM) – This is when an external force (a device or therapist) moves the patients joint through a set range of motion while the patient inputs no force or effort.

Distal Interphalangeal (DIP) – This joint is the end joint in the human finger.

Haptics – Haptics is the study of touch interaction, in this case specifically between a user and a robotic device. Thus the haptic feedback of a system would be in terms of a force or pressure applied to the user.

Modified Intrinsic Minus – This is a hand position where only the PIP joint is flexed while the MCP remains straight. This position can be seen in Figure 3 c.

Intrinsic Plus – This hand position consists of flexing the MCP joint while keeping hte PIP joint straight. This hand position can be seen in Figure 3 b.

Light Emitting Diode (LED) – This electronic component is a semiconductor which when a voltage is applied glows. LEDs are small, require low power and are robust which

makes them ideal indicators. LEDs are able to produce light in a variety of wavelengths such as the visual, ultraviolet, and infrared wavelengths.

Metacarpophalangeal (MCP) – This is the first joint of the human fingers.

Minimum Jerk – This is a trajectory between a known starting point and ending point over a set duration which minimizes the value of the derivative of acceleration (the jerk).

Proportional, Integral, Differential (PID) – PID is a standard controller type where the constants of p, i, and d are multiplied by the error between the desired and actual position, the integral of the error and the differential of the error respectively and added together. The solution is then used to determine the signal sent to the motor such that the controller attempts to maintain the error as close to zero as possible.

Proximal Interphalangeal (PIP) – This is defined as the second joint of the finger.

Pulse Width Modulation (PWM) – This is a system of controlling the power sent to a motor. A set voltage is sent to the motor at a set frequency in the form of a square wave. The PWM number is a percentage of the a single period of the signal where the voltage is at the high value. Therefore, a 25% PWM signal would be set to high for the first ¼ of the period and set to zero for the rest of the period.

Range of Motion (ROM) – This is defined as the comfortable ends of the motion of a joint. If the knee is used as an example, the ROM of the knee may be between 0° and 90°. In this example the patient can comfortably move from 0° to 90° without pain or discomfort but no further.

Acknowledgements

I would like to thank Dr. Dechev and Dr. Park for their support and guidance over the course of this project. I have greatly appreciated the knowledge and experience they have shared with me. They have been invaluable in determining the direction and scope of this work. I am very grateful to have been given the chance to work on this project.

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I have had the pleasure to also work with Clare Faulkner over the course of this project. She has been very helpful through all stages of the project, offering advice from both a therapist's perspective, and that of a fellow researcher. Later in the project she was also responsible for locating and arranging for patients to be available for the testing of the device. I would like to thank her very much for all her assistance.

I would also like to thank the Machinists in the UVic machine shop for their time and effort in first building the parts for the device and then for the myriad of small updates they performed over the course of the project.

Finally I would like to thank my family and friends for their encouragement and understanding. Their support has been crucial.

Thank you to everyone who has helped and supported me along the way.

Dedication

I would like to dedicate this to my family and loved ones. Their support made it possible for me to pursue this goal.

I appreciate all your help.

Chapter 1 Introduction

1.1 Motivation

The hand is often prone to injury since it is one of the primary ways we interact with our environment. Feehan et al [1] found that in British Columbia there were 72,481 hand fractures reported between 1996 and 2001 with an average of 14,485 per year. Cooper et al. [2] reported that in 2004, 20% of bone fractures in Britain were in the hand. This was the second largest group, only exceeded by forearm fractures. Both hand and forearm fractures can cause stiffness and complications for the finger knuckles, primarily the metacarpophalangeal joint (MCP) and proximal interphalangeal joint (PIP). The MCP is the first knuckle in the fingers and the PIP is the second knuckle, as shown in Figure 1. The third and final knuckle is the distal interphalangeal joint (DIP); the DIP passively follows the PIP. Some common injuries leading to loss of hand function (including burns, extensor and flexor lacerations, intra-articular adhesions, extra-articular contractures, crush injuries, and strokes) can often be treated in part with Continuous Passive Motion (CPM) and/or active resistance.

This thesis describes the development of a device used for aiding the recovery of hand injuries through the use of CPM, active resistance and haptics. The device is intended for use within a clinic, to assist a therapist in the treatment of patients with various hand injuries. A picture of the device can be seen in Figure 2.

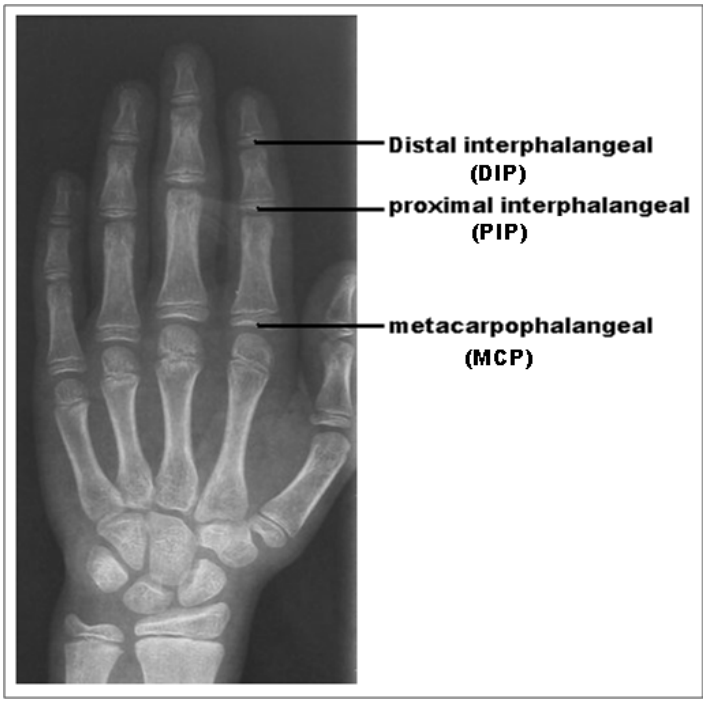


Figure 1: Joint definitions for the human hand.

Active resistance can be defined as having a patient move his/her limb through a range of motion (ROM) while an outside force resists that motion. This is traditionally done with rubber balls, force applied by a therapist, springs, or many other variations of these. CPM is a different technique, and is defined as moving a patient's joint through a ROM with no effort from the patient. The patient relaxes and an outside force (therapist or a device) guides the joint through a set motion. There is some debate over the effectiveness of CPM (see section 1.2). Despite this, it is commonly used by therapists as part of a rehabilitation regime.

There are currently a few different ways to implement CPM. Passive motion can be performed by direct manipulation by a rehabilitation therapist. The therapist will manually move the patient's hand through the ROM with no effort supplied by the patient. This is an easy and adaptable approach, but is very time consuming and does not produce repeatable ROM. One-on-one manipulation may be required for extended

periods, which requires a great deal of the therapist's time, decreasing the number of patients who can be treated and also increasing the cost of the therapy.

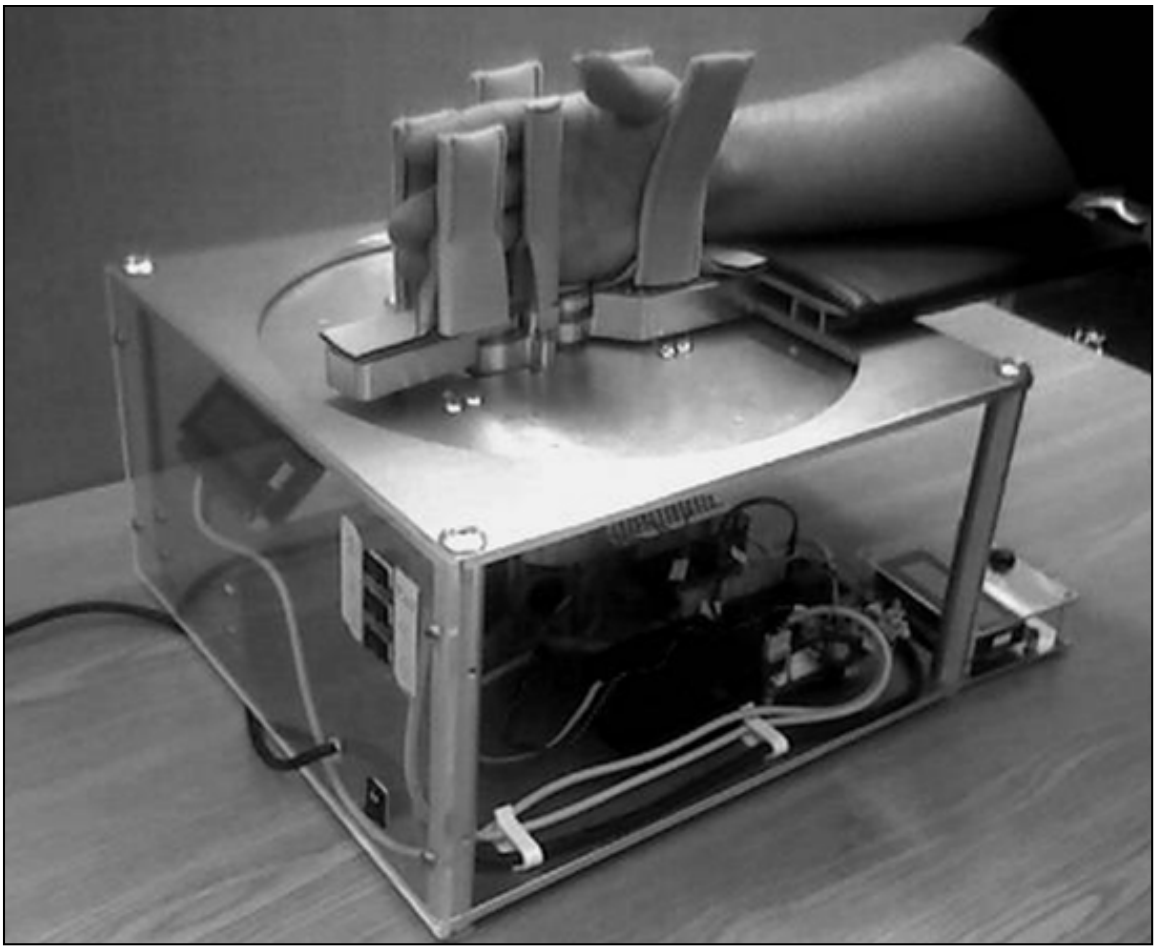


Figure 2: 3D view of complete device with padding in place and user hand present.

The concept of using a machine to perform CPM has been pursued in research and by companies. There are currently a number of different hand rehabilitation devices on the market or under research and development (R&D) [14-27]. These devices range from research tools to fully developed and marketed products. Section 1.2 will discuss the history of CPM in rehabilitation and hand rehabilitation devices.

1.2 Background

The treatment of hand injuries often involves a stage where the patient is attempting to overcome stiffness in the joints and a stage where the strength needs to be returned to the hand. These two stages can be prime candidates for CPM and active resistance respectively. Currently these techniques, or variations of them, are used. This section will provide the background and describe the current state of hand rehabilitation techniques, CPM and active resistance.

There is some debate over the effectiveness of CPM. Some researchers have found no statistical increase in injury recovery when using CPM. Most notably, Ring et al. [3] reported no benefit from CPM with MCP joint arthroplasty and Schwartz et al. [4] reported no statistically significant gains in a study of digital tenolysis with CPM. Other researchers have investigated the use of CPM very soon after a joint injury, and have reported positive results. O'Driscoll et al. [5] discuss how CPM is believed to improve the recovery of soft tissues and Dent et al. [6] outline a shift in general practices and research from the use of immobilization to the use of motion in treating injured joints. Feehan et al. [7], when comparing immobilization and early CPM as the treatment for a 3-point bending fracture to a rabbit forepaw, showed significantly better gains in the stiffness of the fracture site, failure load of the fracture site, energy absorbed per unit area before breaking at the fracture site and dorsal fracture angulation (most common pattern for malunion after this kind of fracture) with early CPM treatment. Rath et al. [8] showed that immediate active motion used after opposition tendon transfer (surgically transferring a tendon from the ring finger to regain thumb opposition) caused no increase in tendon pullout and the average rehabilitation time was reduced by 19 days (a 40%

reduction in rehabilitation time). Kim et al. [9] also showed that the use of CPM on a joint which has undergone nerve repair is feasible and does not harm the re-growth of the nerve. One question that is often asked is "what does CPM provide to aid in the recovery of hand injuries?" It is believed by some [10] that the extension and contraction of the joint causes a cyclical change in the pressure in the joint, which acts as a pump to remove edema and increase blood flow to the joint. Despite the debate about CPM, it is very commonly used by therapists as part of a rehabilitation regime.

Machine based CPM is often used with devices that vary in technique, but essentially allow for the patient's hand to be moved through some ROM while the patient supplies no input forces. In this way, early treatment of stiffness and other complications can be addressed to attempt to improve the recovery time and the amount of recovery. However, these devices are still relatively new, and most therapists still rely on manual methods. Manual manipulation is often used in place of a CPM device. The therapist will manually move the participant's hand through the ROM without any effort on the participant's part. This is an easy and very adaptable approach but is time consuming and does not provide repeatable ROM. Variations in the motion performed by the therapist may cause pain and nervousness to a patient. The therapist must perform one-on-one manipulation for extended periods, which requires much of the therapist's time, decreasing the number of patients who can be treated per day and also increasing the cost of the therapy.

There has been a great interest recently to use robotic devices to perform CPM and in some cases active resistance due to the inherent benefits of machines. Machines are ideal for tasks which require repetitive, accurate, monitored, and highly controlled motion.

Machines are able to perform the same motion as many times as desired without deviating from the desired trajectory. In this way a patient can be comfortable that the device will repeat the same motion and they need not worry that they will be moved farther on any given iteration. It also allows the patient to feel in control of the motion as they know what to expect and can stop the device at any time. With the ability to measure both position and in some cases torque, the safety of the device can be ensured by multiple safety checks. Finally the ability to record data allows the therapist to review past data and search for trends or inconsistencies which may be relevant to the patient's recovery and rehabilitation program.

There are currently a number of different hand rehabilitation devices on the market or under R&D [15-26]. One sub group of these devices are dorsal mounted devices. These devices are mounted on the back of the hand and fingers. One example is Yamura et al. [15] who developed a cable controlled device capable of manipulating the MCP and PIP independently and the DIP passively from the PIP. The system is currently only functioning for a single finger but may be extended to multiple fingers in the future. The device operates by utilizing sensors to measure the joint angles of the patient's good (healthy) hand, and to reproduce that motion by actuating the injured hand. Thus the patient can control the motion of their injured hand though movement of the healthy hand. This scheme allows the motion to mimic their own natural motion but requires the patient to provide their own constant motion and to be responsible for their ROM. This also does not address the issue of repeatability. Fu et al. [16] and later Fuxiang et al. [17] also developed a dorsal mounted design operated with cables. Their method is comprised of CPM with both position and torque sensing. They have undergone a number of

revisions and are looking to begin clinical testing. Both these devices however are large dorsal mounted linkages which may cause patient fatigue. The devices are able to move the MCP and PIP joints separately but only for CPM and not active resistance. Also, both systems are only capable of operating on one finger at a time.

Lambercy et al. [18, 19] have developed a haptic knob device. The device exercises the hand either passively or actively by opening and closing the hand. Passive opening motions are controlled by fitting the hand over a protrusion which spreads into two parts to open the hand. This method allows for the mobilization of very stiff hands. The fingers can also be attached within the center of the device's two parts and either pressed closed or the user can actively spread the device. The device is also capable of twisting motions. The limitation of this device is that it is a tool for functional recovery, and not motion for the individual joints. Only the bulk position of the grip is controlled, and thus not the specific joints. Also the device cannot achieve 0° to 90° ROM for the joints due to the knob limiting flexion and the use of a the knob to control extension.

There are also a number of marketed devices for hand CPM [20 - 24], one of the most notable being the Kinetic Maestra [20]. These devices all attach to the ends of the fingers and offer no independent control over the MCP and PIP joints without additional splinting. The devices simply move the finger from a 0 degree position (or slightly hyperextended) to approximately 270 degrees (90 degrees in the MCP, PIP, and DIP) but without separate control of the joints. Hence, the angle of each joint it is not known, only the sum angles of the three joints. Most of these devices come with a system to splint either the MCP or the PIP to isolate the other joint. This allows for separate control of one joint or the other, but not both simultaneously. The other marketed devices [21 - 24]

are of very similar design. They rely on attachments to the end of the fingers to control the total angle of the MCP, PIP and DIP joints without controlling the individual knuckles. Although these devices are very useful, they are unable to achieve certain configurations, such as those in Figure 3. These devices also often can not measure the torque at the joints.

A few groups are currently working at adapting haptic devices such as the dorsal-mounted CyberGrasp [25]. The CyberGrasp is designed specifically as a haptic interface for the hand. Combined with the Cyberglove it is capable of measuring position torque at each MCP and PIP joint independently. However, this device is bulky, expensive, and may be difficult to adapt to rehabilitation. Another haptic device adapted to rehabilitation is the palm-mounted Rutgers Master II-ND haptic glove [26]. It is capable of exercising the thumb and first three fingers separately. It has a limited ROM, and is not able to achieve 90° flexion in the finger joints, due to the placement of the actuators within the palm of the hand. The actuators also attach to the ends of the fingers and thus the haptic glove does not offer individual control of the joints in the finger, and hence lacks independent MCP and PIP control.

A wider range of rehabilitation devices are available for the larger joints such as the knee. For example, Ho et al. [27] developed a hybrid CPM/CAM knee device that was capable of supplying active resistance to a user by modifying an existing CPM device. The hand, however, due to its smaller size and myriad of joints, is still undergoing research to produce devices capable of this level of control. Presently, most active hand rehabilitation exercises are done manually with putty, resistance webs, squeeze balls, grip strengtheners, and other purely mechanical devices.

Therefore, there is currently a need for the development of a cost-effective device for hand rehabilitation clinics that can flex/extend the MCP and PIP joints independently without external attachments (to reduce cost and setup time) and that can perform both CPM and active resistance exercises.

1.3 Thesis Objectives

The goal of this project is to produce a table-top hand rehabilitation device capable of both CPM and active resistance. The objectives for the device include: (i) it must be able to manipulate the MCP and PIP joints independently, (ii) allow for quick patient setup between exercises (no need to add, remove or alter braces or other mechanical fixtures to change between different ROM or modes), (iii) allow for a quick change between the left and right hands (minor mechanical alteration), (iv) the CPM mode must follow a finger trajectory that closely mimics natural hand motion, and (v) the device should capture both torque and position data for further analysis.

During this thesis it was desired to produce the physical device, implement the electronics and software and perform a user trial to confirm the device functions as desired and determine the safety and comfort of the device. The goal was to produce a device which, after a few minor revisions outlined in the user study, would be able to undergo a full clinical trial with a comparison to standard rehabilitation techniques and then if successful be produced and marketed.

1.4 Scope of the Thesis

This thesis will discuss the progression of this thesis from initial design and project outline through to the user study involving both healthy and injured participants. Chapter

2 begins with an overview of the design objectives. Chapter 3 covers the concept and verification of the concept of using Minimum Jerk as the ideal trajectory for the device to follow over the ROM. The minimum jerk was compared to participants performing a normal motion of opening and closing of the hand. The mechanical design is covered in Chapter 4. The SolidWorks modeling, machining of the parts and building of the device is covered in detail. The design iterations required during the machining and assembly phase of the thesis is covered in Chapter 5. The design and implementation of the electronics are covered in Chapter 6 with circuit diagrams of the crucial components. Chapter 7 discusses the software design of the user interface menu, control loops and the interaction between the device and the PC used for the haptics mode. The flow of the code, code excerpts and design complications for the CPM, active resistance and haptic modes are covered. Chapter 8 discusses the Matlab model used for verification and to tune the PID controller used in the CPM mode. A user study designed to test the passivity, comfort, safety, and smoothness was performed with both healthy and injured participants. The setup of this study as well as the results and implications is covered in Chapter 9. The final chapters of this thesis contain a conclusion and an overview of the future work required to advance this project.

Chapter 2 Design Objectives

The design objectives for the project are based upon an analysis of the market, and input from hand rehabilitation therapists who would consider the device for their clinical practice. Some preliminary work in terms of a market analysis, and portable alpha-prototype work, was performed by a previous group at the Laboratory for Applied Control and Bionic Systems (LACOBS).

The goal of this work is to produce a table top hand rehabilitation device for clinical use, capable of independent control of the MCP and PIP joints, and also with the ability to offer both passive and active motion. To achieve this goal, a number of design objectives were developed, which include: (i) independent motion of the MCP and PIP joints over the range of 0° to 90° each, (ii) ability to provide both CPM and active motion, (iii) provide treatment for either the left hand or right hand, (iv) implement natural finger motion (minimum jerk trajectory), (v) implement redundancy in safety features, (iv) record torque and position during use, (vii) implement user-defined maximum permitted torque during use, (viii) be a ‘stand-alone’ and desktop mounted device, (ix) adaptable for various sized hands with a quick setup time (x) and minimise the device cost.

Independent motion of the MCP and PIP is an important feature, since preliminary investigations showed that the hand therapists expressed an interest in a device capable of moving between four key positions smoothly. The four positions are shown in Figure 3.

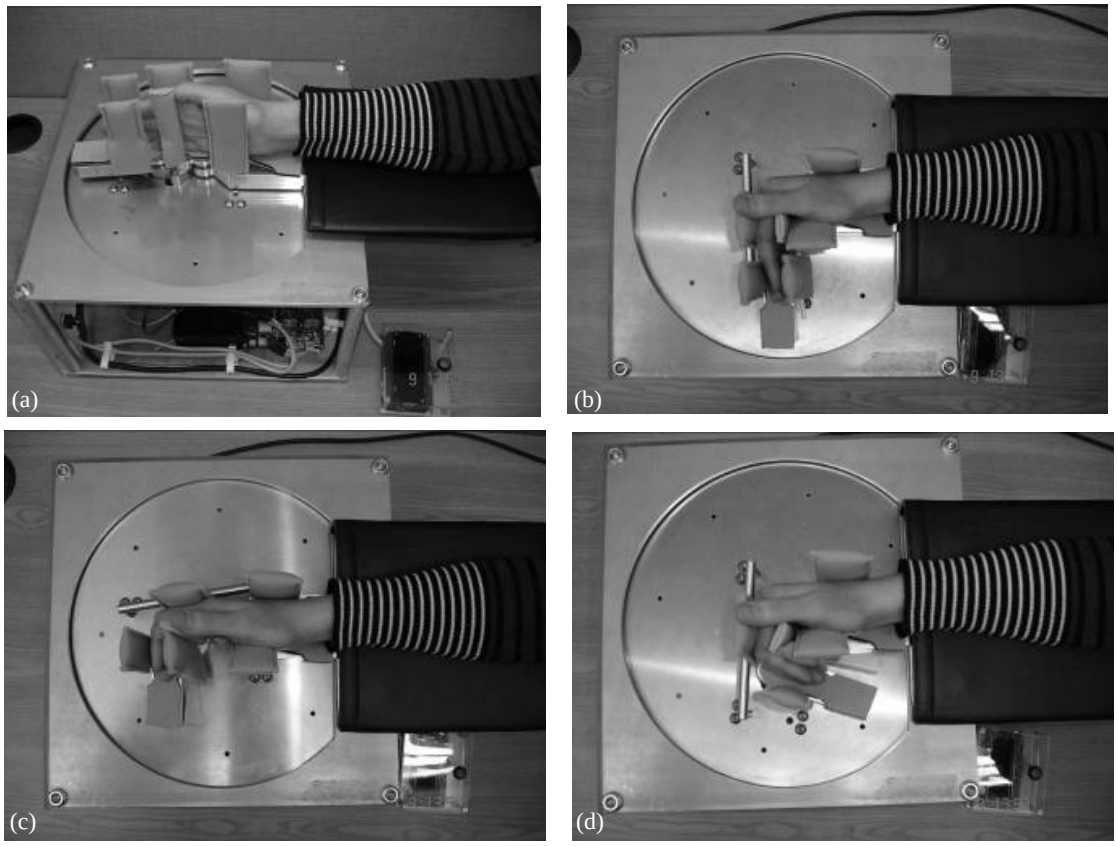


Figure 3: Hand rehabilitation device: (a) initial position, (b) intrinsic plus (MCP flexion only), (c) modified intrinsic minus (PIP flexion only), (d) modified fist (90° flexion of MCP and PIP joints).

A mathematical equation for human motion during opening and closing the fingers was needed to perform the trajectory following operation needed in CPM. The trajectory would need to be easily calculated during each time step, be smooth to ensure the hand was safe, and be as close to normal motion as possible.

It was desired for the device to be a stand-alone model with no need for a computer to operate in either the CPM or active mode, yet with the ability to save data to a computer during operation if so desired. In clinical use there is no guarantee that a computer will be available and requiring a computer to setup the device would both limit the convenience of such a device, as well as increase the cost of operating it.

Safety is a critical and essential requirement, and a number of safety features were implemented. The device was designed to have a physical stop to limit motion (a physical block limits the motion of both the MCP and PIP joints to 0° to 90°), and a user-controlled kill switch. Additionally, the device was designed to monitor position, torque, and electrical current (in the motor) at both joints. This allows for the implementation of a 'user-defined maximum permitted torque' setting, which will deactivate the device should the torque limit be exceeded during use. The user-defined maximum permitted torque is set by the therapist in consultation with the patient, prior to use.

The device must be both comfortable to use and adjustable to multiple hand sizes. Participants will have very different hand sizes and shapes due both to inherent variability as well as differences in the nature of the participant's injuries, such as swelling. The comfort and ease of use is paramount when dealing with injured hands as the user's acceptance of the device will often dictate the success or failure of its use. These design objectives were used to produce the mechanical and software design explained in the following sections.

The final criteria, to produce a device with a minimized cost is an important underlying objective which effects design decisions over the course of this project. In order to produce a device which will hopefully be accepted and purchased for clinical use the cost of the device must be minimized. The necessity for an inexpensive design was a factor in the decision to manipulate the MCP and PIP joints of all fingers in the hand simultaneously as well as the necessity for designing a torque sensor.

The design of the device was completed in a number of progressive stages. First, a mathematical model was developed to model natural human hand motion. Next the mechanical design of the device was performed SolidWorks, a 3D CAD (computer assisted design) software. This involved extensive modeling, to incorporate off-the shelf elements, with custom designed components, while trying to minimise the size, cost and complexity of the overall system. The design process also included the analysis for the speed and torque achieved through the combination of motor and gear train. Next, engineering drawings were made, parts were ordered, and the physical device was constructed in the Dept. machine shop. The electronics were designed and implemented with the help of Ed Haslam to allow for the desired functionality. This involved choosing appropriate components (sensors, microprocessor, displays and inputs) and designing in advance for the requirements of the software written for this task. The design of the software was crucial in order to produce the desired modes of operation. The software was written in C and Visual Basic and with minimal available packages to reduce code size. The majority of the work on the software concerned three aspects. The first was the design of the user interface which allows the therapist to setup the device while inputting percentages, durations and positions. The second was running the control loops at the desired rate (250 Hz) while continuously checking the sensors and for the haptic mode, interfacing with a PC. The final aspect was performing the calculations required without the use of negative numbers and with very limited RAM and ROM space. The microcontroller used for this device is does not inherently support the use of negative numbers in mathematical operations. There was also a very tight limit imposed on the RAM and ROM space due to the microcontroller.

Chapter 3 Minimum Jerk Model

One of the important design objectives for this project was to ensure that the CPM mode mimicked natural human hand motion as closely as possible. To achieve this, a mathematical formula was developed that would capture the 'essence' of human hand motion, and model the smoothest, most human-like trajectory. This mathematical formula is used by the CPM mode, which follows the mathematical trajectory using a Proportional Integral Derivative (PID) controller. This provides the ideal trajectory for the MCP and PIP joints over the complete ROM. Since different patients have different rehabilitation needs, the model must allow for variable start and end positions, as well as a variable duration or speed of the motion.

To develop our mathematical model for the CPM mode to follow, a reference motion from a healthy hand must first be captured. Specifically, a series of measurements were made to determine the joint angles of a human finger during normal motion using the Visualeyez optical motion tracking system (Pheonix Technologies Inc., Burnaby, BC) [28]. Three student volunteers (average age 24), one female and two males, had their middle fingers of their dominant hand outfitted with six light emitting diode (LED) markers. The markers were placed on the back of the volunteer's middle finger as follows: two on the back of the hand, two on the finger segment (proximal phalanx) between the MCP and PIP (distal phalanx), and two on the finger segment between the PIP and DIP, as shown in Figure 4. The data captured by the Visualeyez system was saved in an Excel file format. This data allowed for the vector between the two sensors on any given finger segment to be calculated and normalized. Next, the vectors on either side of the MCP, and PIP joint were used to calculate the joint angle through the dot

product. This way each pair of sensors could be used to determine the vector corresponding to the finger segment or part of the hand and thus the MCP and PIP angles could be calculated throughout the motion.

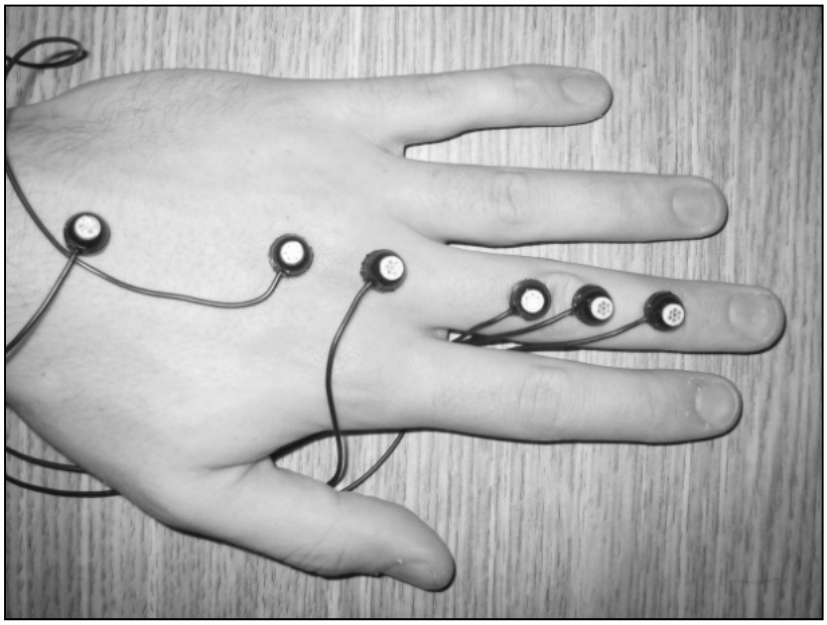


Figure 4: LED placement for VisualEyez

To create an average healthy finger joint motion profile, the student volunteers were then asked to perform a series of four hand motions typically used during rehabilitation - five repetitions for each motion. The four motions were movement from a straightened finger (full extension) to: a tight fist, a loose fist, flexion of just the MCP (intrinsic plus), and Flexion of just the PIP (modified intrinsic Minus). The intrinsic plus and modified intrinsic minus motions can be seen in Figure 3. The data from these tests was compiled and the joint angles of the PIP and MCP were then calculated for each time step. This produced the angles for the MCP and the PIP, as a function of time. Data for five consecutive time steps was then averaged to account for minor fluctuations in the data.

Next, the test data was compared to the minimum Jerk model in order to determine if the model can approximate human finger motion accurately. The minimum jerk model

was initially considered due to the smoothness of the motion and as it has been used previously as a model for human motion. It has been shown that the trajectory with the minimum jerk can be calculated as shown below [29]. Jerk is the time derivative of acceleration and is often used in the evaluation of the smoothness of a motion. It can be said that the smoothest trajectory between two points over a set duration is the trajectory with minimum jerk. Thus this trajectory is likely the closest to normal human motion and will also produce the smoothest motion for a user. This smooth motion is crucial when dealing with injured hands. The jerk value of any trajectory, x, is found by the following equation:

$$H(x(t)) = \frac{1}{2}\int_{t_i}^{t_f} \dddot{x}^2 dt$$

Equation 1: Base equation for evaluating Jerk.

If the calculation is carried out to find the function with the minimum value of jerk (e.g., for joint movement, $x = \theta$, between a set start and end point in a set time), it can be shown that the 6th derivative of the function must be equal to zero [29]. Constraints are placed on the formula such that the initial (at the time t_i) and final positions (at the time t_f) are set to θ_i and θ_f, respectively. The initial and final velocity and accelerations are set to zero. These constraints produce the following generic equation for moving from θ_i to θ_f in t seconds where θ is the joint angle at time t:

$$\theta = \theta_i + (\theta_f - \theta_i)\left(10\left(\frac{t}{t_f}\right)^3 - 15\left(\frac{t}{t_f}\right)^4 + 6\left(\frac{t}{t_f}\right)^5\right)$$

Equation 2: Minimum jerk trajectory from a known start angle to a known end angle over a given duration.

The duration of the motion as well as the initial and final angles of the joints are specified for different patients just prior to use. Based on these values, a trajectory is planned that has the minimum possible jerk. This formula was then compared to the

Visualeyez data by calculating the average duration and average maximum joint angle from the users and utilizing these values in the minimum jerk equation. The results of the plots were then compared to the user data recorded. Figure 5 shows a graph of the calculated minimum jerk trajectory (black) in comparison to the actual data collected from volunteers (grey) using the Visualeyez system for the PIP joint. It can be seen that minimum jerk trajectory follows a very similar trajectory as the data collected from the Visualeyez system.

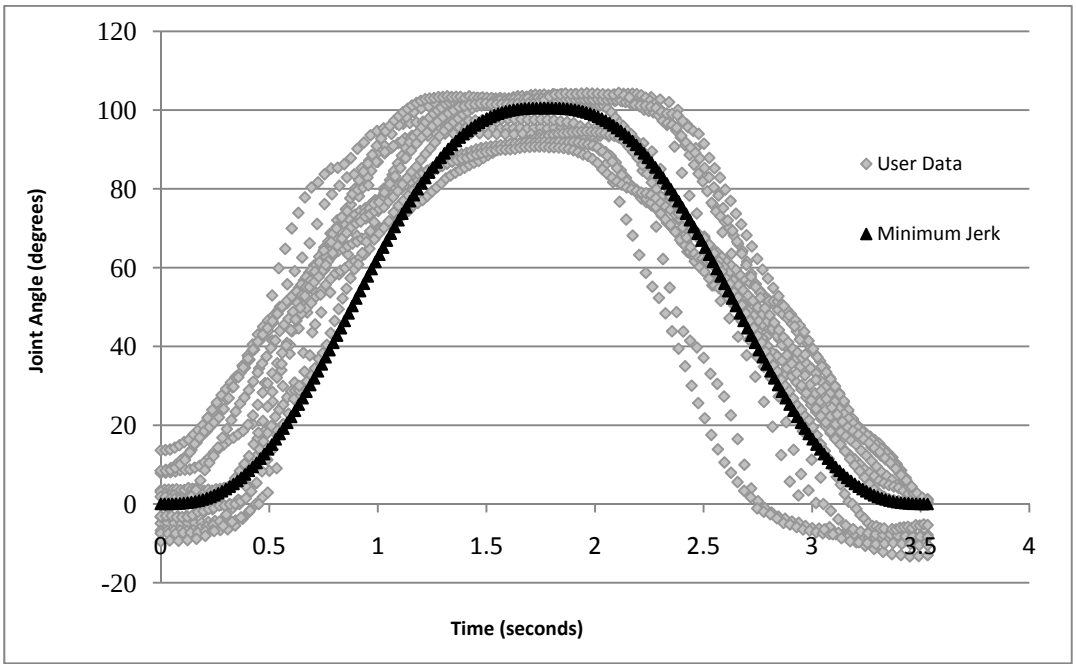


Figure 5.Minimum jerk trajectory model compared to user data for the MCP.

The Visualeyez results showed that the minimum jerk model is a good representation of normal human motion. The model is easily adaptable as it can be tailored to match the needs of different patients by adjusting the range of motion and the speed (duration) of the motion. Therefore, since the model closely matched natural motion, and was adaptable, it was incorporated into the CPM device to plan joint motion trajectory.

Chapter 4 Mechanical Design

The final mechanical design was based loosely off the previous prototype created during the summer of 2007 by the previous group as part of the market research into the feasibility of a hand rehabilitation device. The previous prototype shown in Figure 6 was a hand mounted CPM device with the potential for independent motion of the MCP and PIP joints.

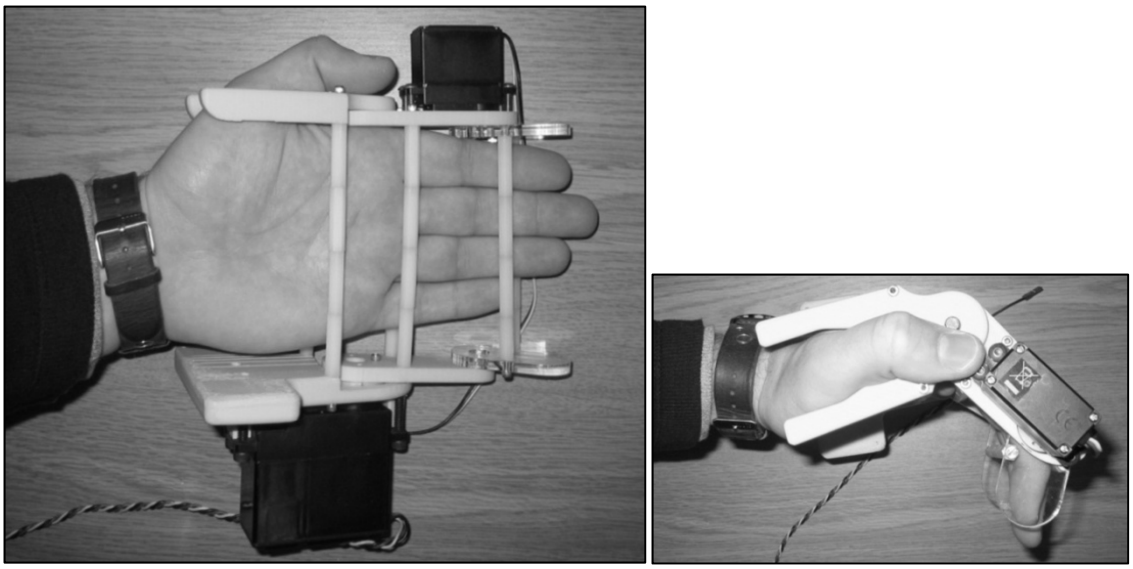


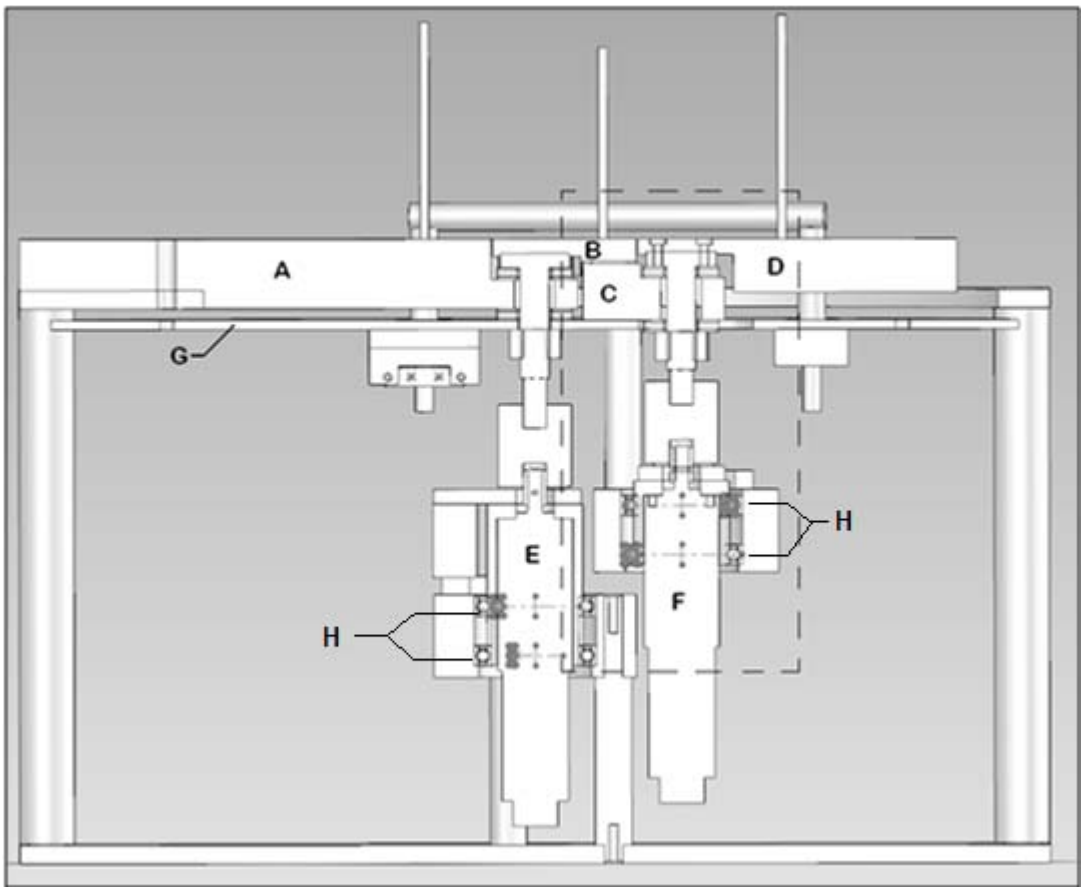
Figure 6: Prototype hand rehabilitation device: a) Side view, b) Top view.

Unlike the previous prototype, it was decided that the new device would be a table top machine. A table top machine can be used for extended periods, and will not place strain on the patient by making them support the weight of a portable CPM device. Further, a table top machine can support more functionality by allowing for more room for various components. The new device still provides the function of independent control of the MCP and PIP joints, and also monitors the position, torque and current at each time step. In designing the new device, some of the challenging mechanical design aspects included mounting the motors to allow for independent 0° to 90° motion for each finger segment,

creating custom torque sensors, securing the hand comfortably within the device, and ensuring the safety of the patient.

The design of the device was created using SolidWorks 3D CAD (computer aided design) software. The design included modeling of the custom designed components and also the off-the-shelf parts. All these parts were then combined into a single virtual 3D model. This 3D model was constrained using "mates" such that it could simulate the same motions and physical limits as those of the proposed physical device. The SolidWorks files were then used to create the engineering drawings that were used by the Mechanical Engineering machine shop to fabricate the parts. Samples of the engineering drawings for the "Frame", the "First Rotating Part", the "Extension", the "Bearing Mount" for the 2nd motor, and the "Second Rotating Part" are shown in Appendix A. These diagrams can also be saved directly as DXF files using SolidWorks. These DXF files were then used in a CNC milling machine to produce the desired parts. Most parts were constructed in this manner with only a few being made by hand. This allowed for very accurate quickly produced parts which could also be remounted and altered if necessary.

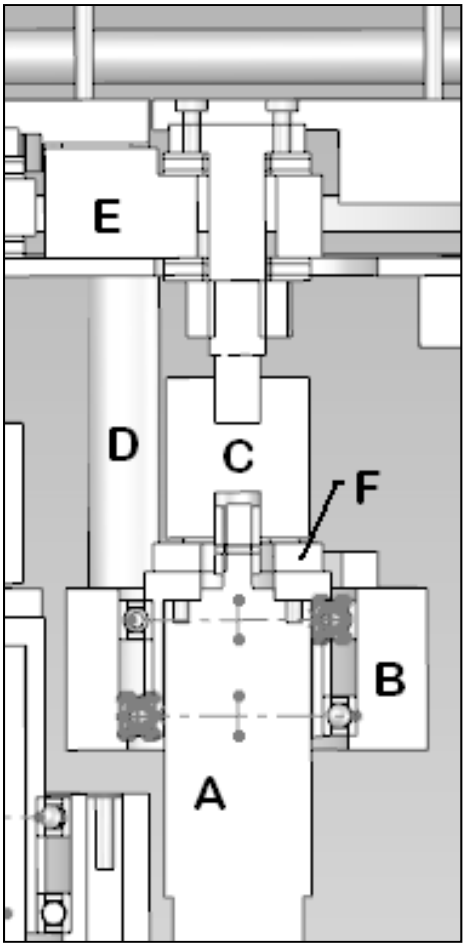
The motors needed to be mounted in such a way as to: (i) enable measurement of torque, (ii) maintain a low profile, (iii) compensate for minor misalignment between the motors and rotating parts, (iv) separate the user from the moving parts, (v) allow for variable separation between the two motors and (vi) allow the center of rotation of the second motor to move with the rotation of the first joint.



A)	Frame	B)	First rotating part
C)	Extension	D)	Second rotating part
E)	First motor	F)	Second motor
G)	Guard	H)	Double ball bearing

Figure 7: A cut away side view of the device, showing the motor and linkage assemblies.

A 3D view of the device has been shown in Figure 2 and a schematic diagram (side view) of the device is illustrated in Figure 7. The components of the device are named as labelled in Figure 7. A close-up side-view of one of the motors and torque sensors is illustrated in Figure 8. The overall shape of the device is a square ended box, consisting of square top and bottom aluminum plates, attached by four posts in the corners. The posts are designed to snugly fit into the plates on both top and bottom to accurately align the two plates. This creates a rigid and accurate structure for aligning further components.



A) Motor casing
B) Double ball bearing assembly
C) Coupler
D) Support post
E) Extension
F) Brace

Figure 8: Close-up side-view of motor mount.

The “Frame” is attached to this structure through screws and two press fit pins for alignment. This “Frame” supports the edge of the patient’s hand from the wrist to the MCP of the pinky finger. The “First Motor” is fixed to the base plate with the shaft protruding through the “Frame” and attached to the “First Rotating Link”. Both motors are MicroMo motors with integrated magnetic encoders and built-in 246:1 planetary gear heads. The method used to mount the “First Motor” was chosen to meet the requirements (i-iii) of measuring torque, keeping a low profile, and handling minor misalignment. The major design complication was designing the torque measurement feature. Originally off-the-shelf torque sensors were considered for use. However, those torque sensors were

found to be either too bulky to fit within the design space, or far too expensive. Thus an innovative and custom sensor design was created. This was done by attaching the motor to three posts via a “Double Ball Bearing” assembly. The three posts were in turn attached to the base plate. This way the “First Motor” is constrained in all directions of translation and rotation except rotation about the output shaft. The rotation about the shaft is constrained by a “Brace” attached to the motor casing and flanges on “Double Ball Bearing” assembly as shown in the top-down view of Figure 9. Two tabs on the “Brace” are blocked by the tabs on the “Double Ball Bearing” assembly by means of two pairs of rubber “bumpers” sandwiching two separate Tekscan pressure sensors. Each pair of “bumpers” and sensors constrains the rotation of the motor in one direction of rotation about its shaft. In this way, when the motor exerts a torque on the shaft the reaction force is applied to the “pressure sensors”. Since the radial distance of the sensor from the rotational axis is known, the torque can be calculated from the voltage reading on the sensor.

The design offered an inexpensive and accurate system for measuring the torque produced by the motor while maintaining the required low profile. The shaft of the “First Motor” then enters a “Coupler” to handle a small amount of misalignment between the motor assembly and the “First Rotating Part”. Next the shaft is attached to the “Guard”. After this the shaft is supported by the “Frame” by means of a needle roller bearing and a needle thrust bearing and then directly attached to the “First Rotating Part”. When the shaft rotates the entire “Guard” and the “First Rotating Part” rotate with it while being supported by the “Frame”. It is this “Guard” which separates the patient from the

majority of the moving parts and ensures the patient's safety from the electronics and motor assemblies (iv).

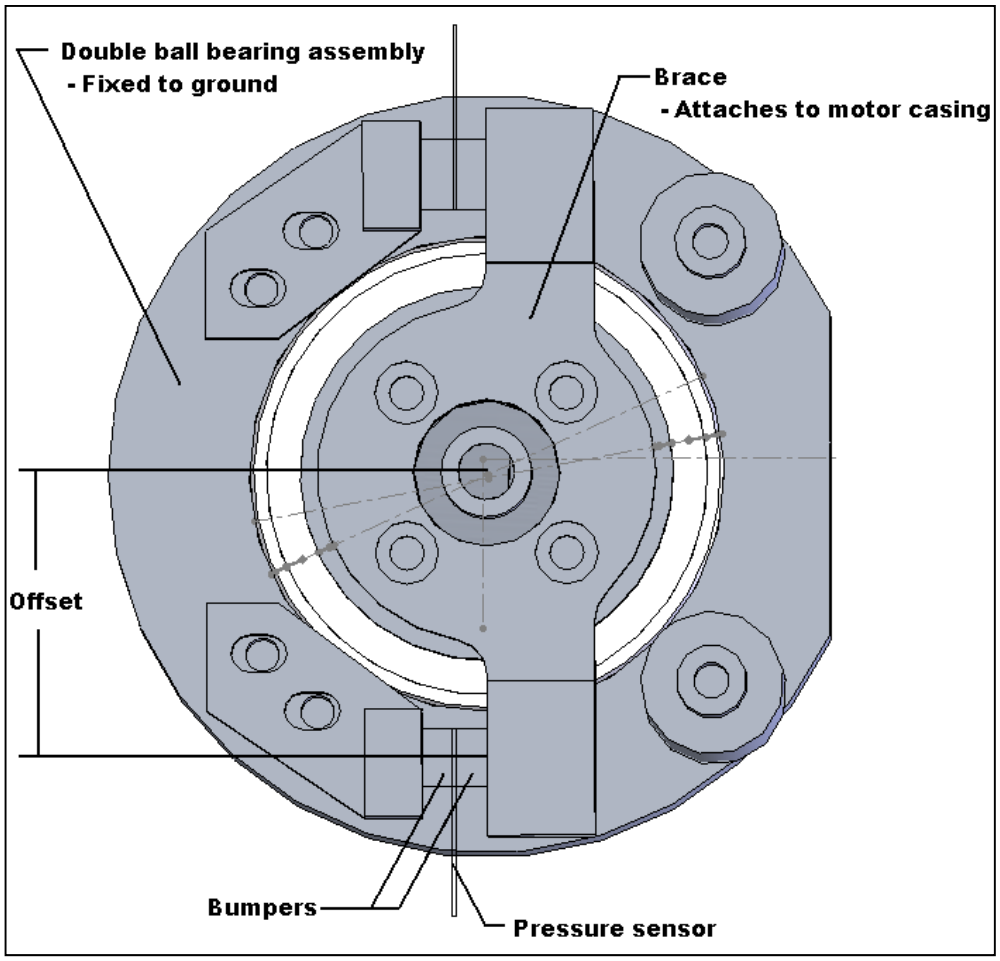


Figure 9: Top-down view of torque sensor used to monitor the torque produced by the motors.

The next stage of the assembly is the sliding fit of the "First Rotating Part" with the "Extension". The sliding fit allows the "Extension" to slide in and out increasing or decreasing the distance between the first and second motors (v) while maintaining a safe structure for the patient's hand to rest on. This is done to allow the device to accommodate a variety of hand sizes. The separation of the first and second motors is related to the distance from the patient MCP joint to their PIP joint. The array of holes in the two parts allows a pin to be used to lock the two parts in place once the desired separation is achieved. The "Extension" is attached by posts to the second motor's

“Double Ball Bearing” assembly and the same system is used to mount the “Second Motor” as was used for the “First Motor”. The only exception being that the “Second Motor” is affixed to the Extension instead of the base plate. When the “First Motor” is activated it rotates the “First Rotating Part”, “Guard”, “Extension” and the “Second motor” as all these parts are connected. This allows the axis of the “Second Motor” to follow the trajectory of the “First Motor” (vi). The output shaft of the “Second Motor” enters a “Coupler” to handle minor misalignments and then passes through the “Guard” by means of double thrust bearings. Next the shaft passes through the “Extension” with a thrust bearing and a needle roller bearing and then attached directly to the “Second Rotating Part”. This section of the motor linkage is shown in Figure 8.

The entire assembly is designed to allow for an inexpensive means of measuring torque while keeping the size of the device relatively small. The linkages are isolated to ensure forces from the patient’s hand are not transmitted to the motor gearbox (except for rotation). The couplers are used to ensure alignment since both the end effectors and the motors are constrained in all axes except rotation about the shaft.

During use, the patient places the palm of his/her hand on the “frame” of the device so that the MCP of their hand is lined up with the axes of rotation of the first motor. The proximal segment of the fingers between the MCP and the PIP joints rests on the “first rotating link”. The “extension” is slid until the PIP joint is aligned with the axes of rotation of the second motor and the remaining segments of the finger rest on the “second rotating link”. The extension is then locked in place with two pins. There is an array of holes for placing the pins such that multiple lengths can be achieved as shown in Figure 10.

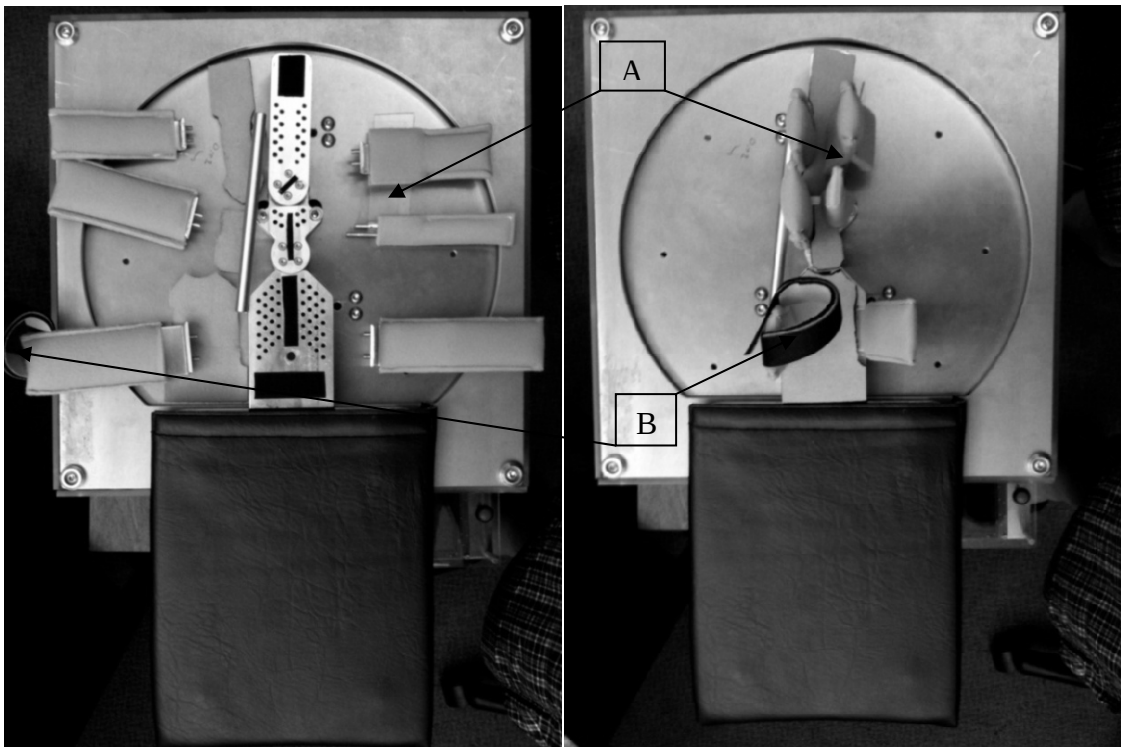


Figure 10: Top view of the device set for the left hand: a) supports disassembled, b) supports in place. A indicates the clear plastic finger guard and B indicates the thumb strap.

Once the hand is in position, the five padded plates are slotted into position to secure the hand from moving side to side. These plates have two ground steel pins extruding from the base to allow a drop in interface with the device. Two plates secure the front and back of the main structure of the hand, one secures the back of the proximal bones between the MCP and PIP joints, and two secure the end of the fingers. The inside of the proximal section of the hand is secured with the two pins locking the extension in place. There is built-in variability to allow the device to accommodate different sizes of hands which is achieved by an array of holes to allow for multiple positions for the padded plates to be inserted. There is also a thin flexible plastic guard which is looped around one of the pins in the extension to support the end of the finger. This thin guard serves to keep the pinky or ring finger from slipping out of position.

This design allows the device to operate the MCP and the PIP independently, enabling modified intrinsic minus (PIP only), intrinsic plus (MCP only) and modified fist (90° flexion of the MCP and PIP joints) motions without attachments, as shown in Figure 3. The design has a range of -90° to +90° (to accommodate either hand) for both MCP and PIP. The maximum torque for the device is 4.5 Nm, which is the maximum torque rating on the motor's gearhead. Standard rehabilitation grip mechanisms (such as Digi-grip) offer a maximum of 9 lbs for rehabilitation. When this is converted to an equivalent torque on the MCP, it is approximately 2 Nm. Therefore the range and torque offered by the proposed device should be sufficient for both the active and passive exercises.

The complete device is enclosed in a Plexiglas case, and equipped with two output screens. One output screen is mobile to allow for easy visibility, and is equipped with a kill switch (safety shut-off switch) which is accessible to the patient. The other output screen is on the side of the device itself, facing the therapist along with the on/off switch and 3 bi-direction toggles for input. A bi-directional toggle is a switch which is able to be pressed in two different directions and always resets to a middle, neutral position. There is also an elbow brace attached to the main frame to support the user's forearm for comfort and arm alignment during use.

Chapter 5 Design Iterations

A number of design decisions were changed upon building and interacting with the first device constructed from the SolidWorks models. These alterations were made based on physically examining the device, interacting with it and from showing the device to Clare Faulkner, the owner of Island Hand Therapy Clinic. The major alterations concerned: (i) the attachment of the coupler to the motor shaft, (ii) the replacement of the pins bracing the hand with plates, (iii) the inclusion of an elbow brace, (iv) the positioning of the thumb and pinky, and (v) changing the patients LCD display and kill switch to a tethered format.

The attachment of the coupler to the motor shaft was designed as an aluminum sheath press fit to the motors output shaft. This sheath was designed to increase the shaft diameter to fit into the standard Oldham coupler which was readily available. The original shaft diameter on the motor was too small to fit the off-the-shelf coupler. The press fit of the sheath onto the shaft was deemed to be potentially damaging to the motor as there was no means of clamping the shaft to allow press fitting. Without clamping the shaft, any force used to press the sheath onto the shaft would be applied to the planetary gear head and may cause damage to the gearhead or to the motor itself. The solution presented by the Mechanical Engineering machine shop was to drill a through hole in the sheath and the motor shaft and use a spring pin to connect the two parts. The spring pin was found to be not strong enough and broke during use. A solid hardened pin was used after this point. Upon further use the pin was found to have deformed the aluminum sheath and thus a larger pin was used to spread out the applied torque across the larger pins surface area. The larger solid pin was found to be sufficient.

The method for constraining the hand within the device was designed as a series of stainless steel pins which were inserted into an array of holes to allow for variances in hand size. A total of twelve pins were used in groupings of four. Each section of the hand (before the MCP, between the MCP and PIP and after the PIP) was constrained by two pins on the palmar and two pins on the dorsal side. Pairs of pins were used and with wrapped padding to increase comfort. Upon showing the device to a hand therapist (Clare Faulkner) it was commented that the pins were uncomfortable especially on the dorsal side of the hand. It was also found that the pins when in the widest positions were still not wide enough to accommodate a very large or swollen hand. Aluminum plates were then designed to replace the pins. These braces are shown in Figure 10. For ease of adjustment and to avoid re-machining more of the device than was necessary the new plates were designed to interface with the original array of holes. The aluminum plates are bent near one end at approximately 90° and two pins are press fit into two reamed holes in the bent section. The pins can then be slotted into two adjacent holes in the array. These plates are fitted with padded sheaths made of foam to increase comfort. The bent plate design also allowed the vertical portion of the plate to be offset from the pins. Therefore, when the widest holes in the array were used the vertical portions of the plates (which braces the hand) were set wider than was previously possible. This design of bent plates allows for more comfort and also increases the allowable hand width to accommodate larger hands. The use of plates allowed the brace for the palm of the hand to be bent at an outward angle to accommodate the thumb and the natural curve of the palm of the hand. The padding on the plates was harder to sanitize. Therefore, a roll of thin cloth tubing (similar to the top section of a sock) is used to cover the patient's hand.

This is a technique currently used in some clinics as the material can be labelled with the patient's name and reused as necessary.

When the device was shown to a hand therapist (Clare Faulkner), the other key comment made was that since the device did not support the elbow, the patient may experience fatigue during long sessions. This was solved by the addition of a large padded elbow brace connected to the top plate of the device. The elbow brace needed to be strong enough to support the weight of the patients forearm and able to withstand a person leaning on it. It also needed to be comfortable and easily sanitized. The design of the elbow brace consist of two U-beam shaped bars covered by a thin aluminum plate (shown in Figure 10). The U-beams are used for support and are bolted to the plate at the free end and four bolts are placed through the brace, beams and top plate of the device to mount the assembly. This creates a light weight brace with the sufficient strength to withstand the patient's weight. Velcro is glued around the edges of the underside of the elbow brace and a vinyl material backed with neoprene padding is strapped to the device using the Velcro. This creates a surface that comfortably supports the elbow and forearm and is easily sanitized with cleaners.

The positioning of the pinky and thumb of the patient was found to be a potential hazard when the device was first assembled and tested. It was found that the thumb could slip down and get wedged inside the closing hand and the pinky could slip between the last two braces on the palmar side to get wedged in a similar position. The torque sensors are designed to stop the device from harming a patient if this occurred but a mechanical safety feature was also used. The thumb is restrained by a length of Velcro with neoprene padding on the middle portion (providing padding separating the user from the

Velcro). The strap is comprised of approximately three inches of padding with an inch of exposed Velcro at each end. This strap is attached to the dorsal side plate before the MCP joint and is looped around the thumb then reattached to the same plate. This is a very simple design that supports the thumb and limits it from dropping into the closing fist. The strap can be seen in Figure 10. The pinky is braced by a thin clear plastic sheet of plexiglass which is looped around the pin for the palmar side of the hand between the MCP and PIP joints and is threaded through the final plate on the palmar side. As the device moves the sheet slides through the final plate and separates the pinky from getting wedged between the braces. This sheet of plexiglass can be seen in the top right corner of both Figure 10 (a) and 10 (b).

The last of the major design alterations was the modification of the LCD display and kill switch on the patient's side of the device. These interface devices were mounted in the patient's side of the plexiglass wall of the device. The addition of the elbow brace blocked line of sight to the display and made access to the kill switch difficult. Therefore the LCD display and the kill switch were mounded in a separate mobile configuration with one thick cable tethering it to the main device (shown in Figure 17 in Chapter 7). This way the mobile unit could be positioned where easily visible and where the kill switch was accessible. This was crucial when dealing with participants who had been injured both arms and thus had less mobility and flexibility with their other hand which was operating the kill switch.

Chapter 6 Electronic Design

The electronic design, layout, and integration were performed by Ed Haslam, an electronic technician in our research group. He was responsible for choosing the electrical components and creating the circuits required to perform the intended tasks. A basic overview of the electronics used and the major design decisions will be covered in this section.

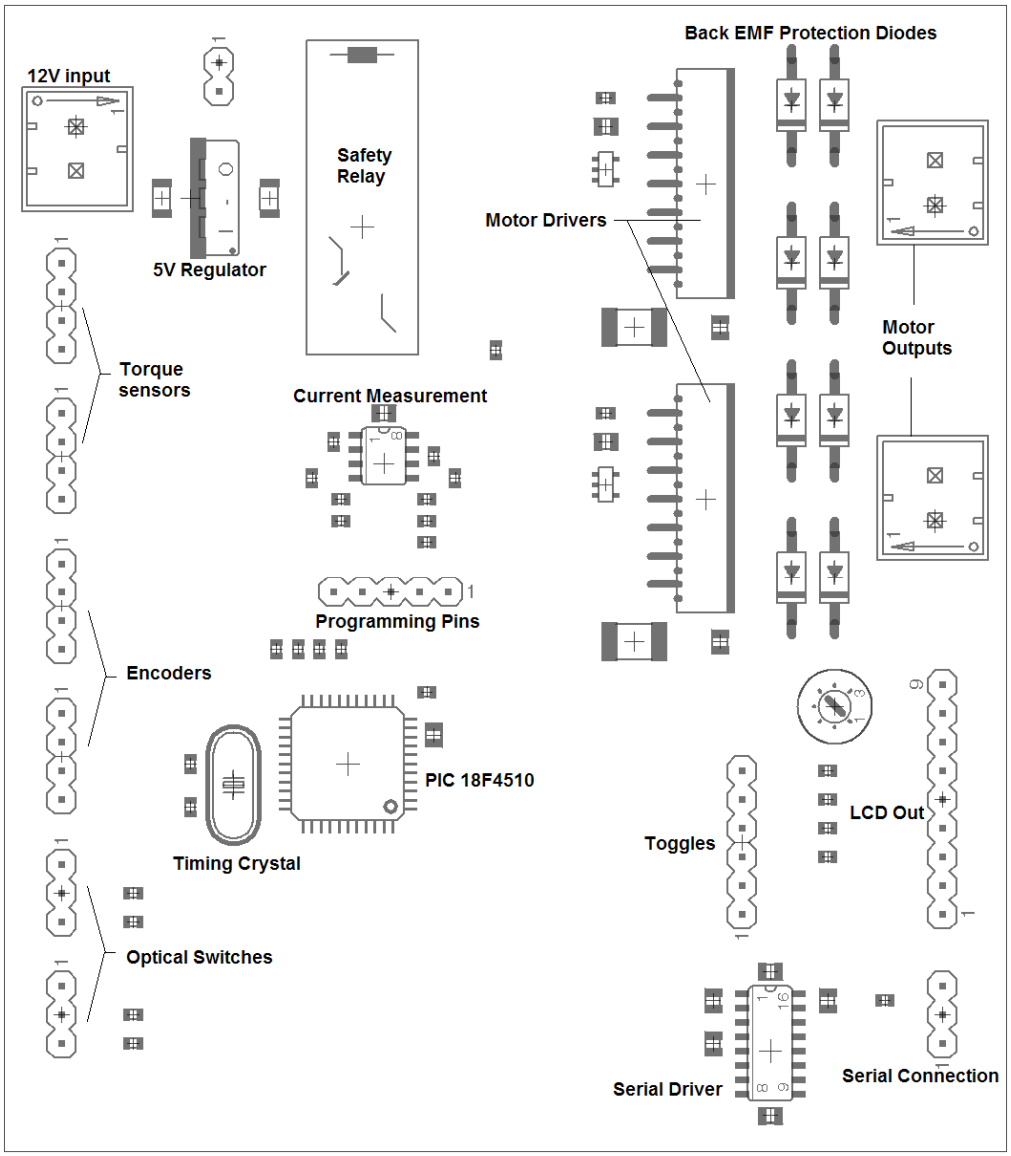


Figure 11: Main board layout.

The main board layout can be seen in

Figure 11. The board consists of a few main elements: a microcontroller, optical switches, LCD drivers, toggle inputs, safety relay, 12V input, motor controller, current sensor, torque sensors, and encoders. The motor controller, torque sensors and encoders have separate external circuits to change the signals into the format required by the microcontroller while the rest of the circuitry is contained on this main board. These external circuits will be discussed later in this section. A circuit diagram of the main board can be seen in Figure 12.

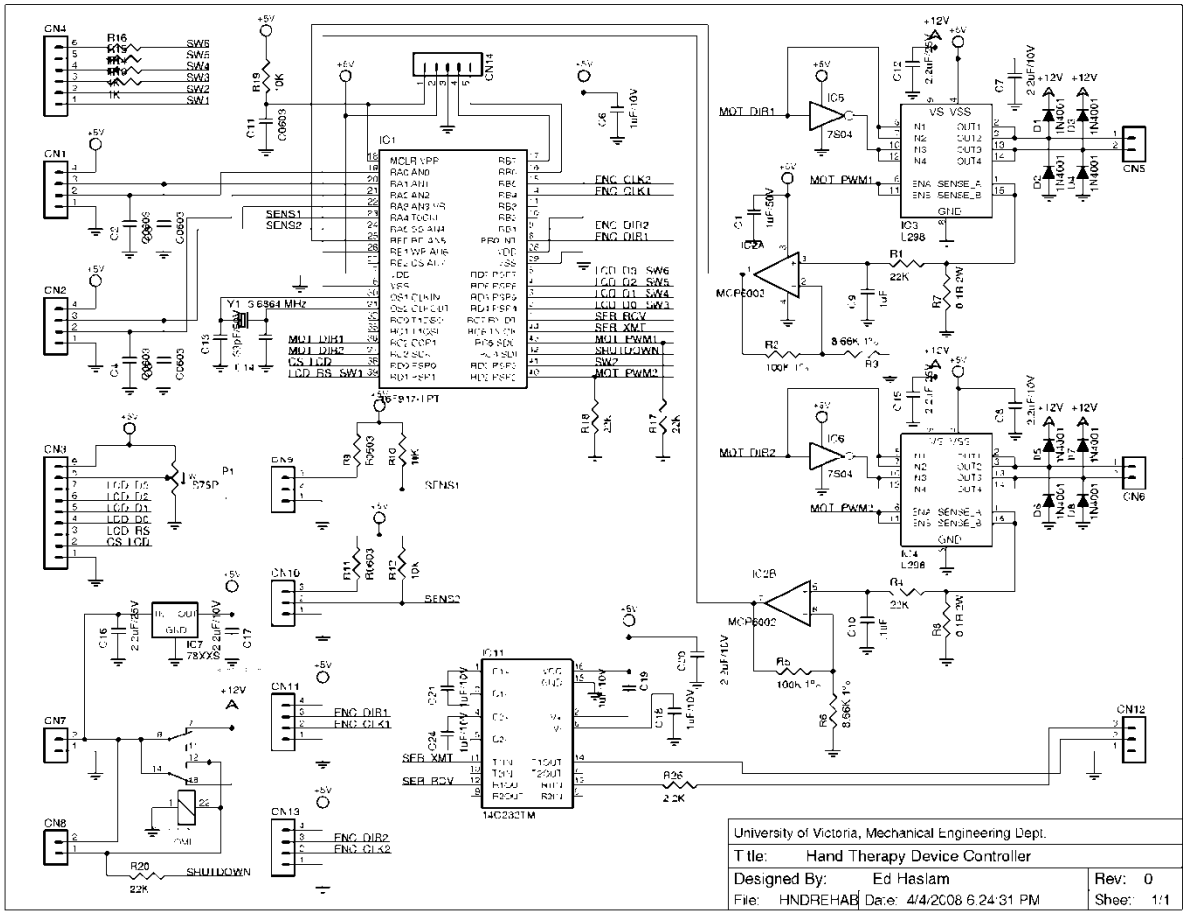


Figure 12: Circuit diagram of main board.

The main component on this board is the microcontroller. The microcontroller was changed to the PIC 18F4510 late in the development of the device from a similar PIC

microcontroller due to its ability to handle very high clock rates. In order to get the 250 Hz update speeds required, the clock frequency was changed from 3.6864MHz to 40MHz. This was done by replacing the old timing crystal with a 10MHz crystal and using the PIC PI18F4510's built in four times multiplier. This clock rate was found to be necessary to achieve the desired accuracy of less than 5° error in the CPM trajectory following mode. The microcontroller handles all calculations both for the CPM and for the active resistance modes while the haptic mode is handled both by the microcontroller and by a PC by means of the serial port.

The optical switches are directly fed to input ports on the microcontroller to determine if the safety handle is in use and which side it is presently placed on. The LCD output is run to the therapist's LCD screen and then to the patient's LCD screen in parallel. There is a potentiometer located on the board for adjusting the contrast. The toggles' connectors are wired to the three bi directional toggle inputs used to setup the device. They are connected to the microcontroller's input ports. The safety relay is attached to the kill switch on the patient's tethered display. When the kill switch is pressed the relay triggers and interrupts the power delivered to the motors. In this way the power to the motors is cut and held off until the device is powered down. Only when the device is powered down will the relay reset. This also allows the rest of the circuit to continue to function but without allowing any motion of the device. The 12V input comes directly from a power supply encased within the device. During testing the input was lowered to approximately 10V for a better torque range from the motors. This produces an actual peak voltage of approximately 8V at the motors due to losses in the motor controllers. The motor controllers take the low voltage PWM signal form the microcontroller and put

out a high power signal to the motors. A simple external circuit was added to the motor outputs to integrate the signal. With the high frequency of the PWM there was a problem with the motors not receiving enough torque at some PWM values. There was also a problem with the microcontroller resetting with a quick change in motor direction and speed. This was solved with the circuit shown in Figure 13. The inductor, capacitor circuit integrates the signal from a very high frequency and noisy signal to a much more constant signal which is more easily handled by the motors.

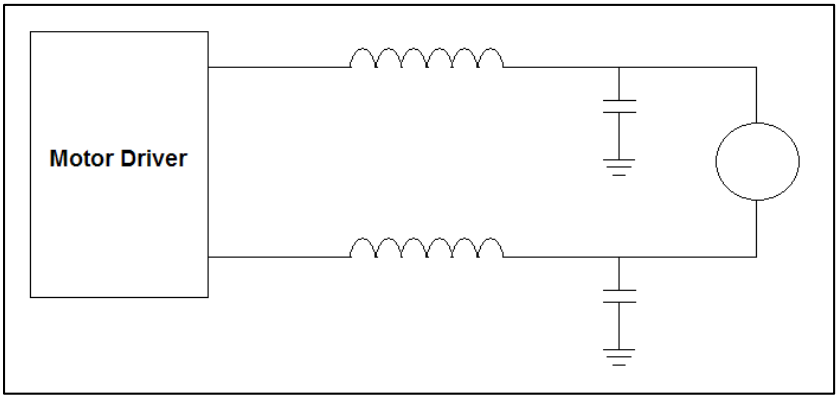


Figure 13: Motor circuit diagram.

The torque sensing is handled by a set of four pressure sensors (two per motor). The voltage across the pressure sensor changes as the resistance changes. Since this change in resistance is linked to the change in pressure, the voltage can be used to calculate the pressure on the sensor. The voltage recorded at the sensor is too low for the microcontroller to easily read and thus an amplifier circuit, seen in Figure 14, is used to amplify the voltage to 0-5V. The circuit is an amplifier consisting of an operational amplifier and is located on a small board mounted near the pressure sensors.

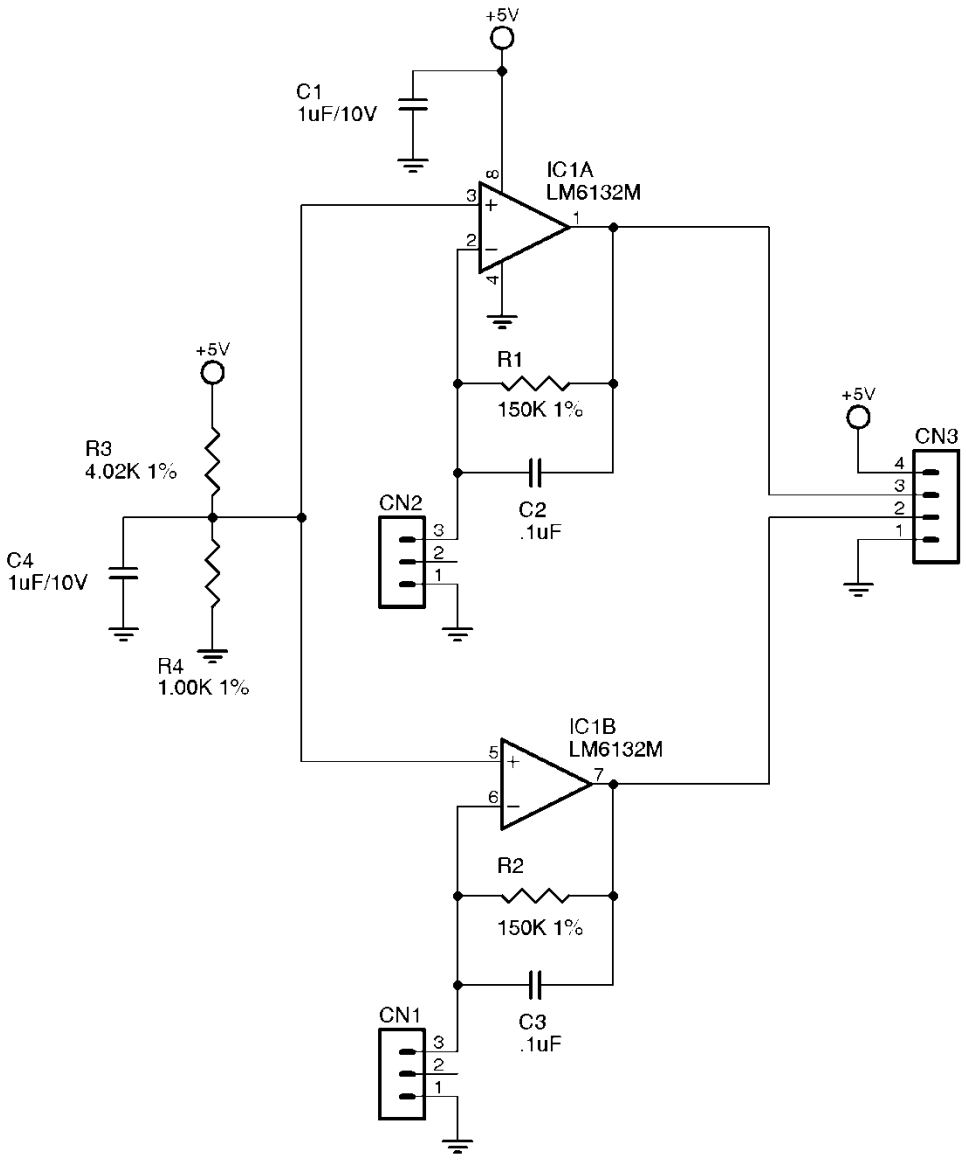
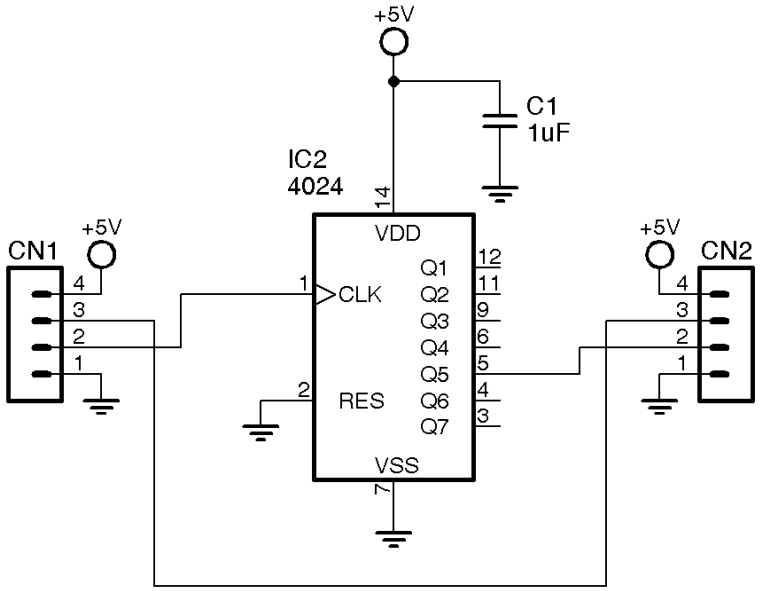


Figure 14: Torque sensor circuit diagram.

The encoder used to measure the position of the joints is an integrated magnetic encorder. The magnetic encoder, however, counts at much too high a rate for the microcontroller to interrupt off each falling edge. For this reason a divider circuit is included between the encoder and the main board. This divider circuit can be seen in

Figure 15 which divides the incoming number of pulses by 64. This allows the microcontoller to interrupt off each falling edge while still running the main controll loop within the required time.



University of Victoria, Mechanical Engineering Dept.		
Title: Hand Rehabilitation Optical Encoder Pulse Divider		
Designed By: Ed Haslam		Rev: 0
File: ENCDIV	Date: 7/16/2010 11:00:18 AM	Sheet: 1/1

Figure 15: Encoder divider circuit diagram.

The device is fully stand-alone for both the CPM and active modes. The serial connection is used to output data but is not required for these modes. The haptic mode utilizes the serial connection to communicate with the PC during every time-step.

Chapter 7 Software Design

The device operates in three main modes: CPM, active resistance, and haptics. These modes were chosen both based on an assessment of current established rehabilitation techniques and based on the advice of hand therapists concerning what they deem most important for such products. The CPM mode is fully functional and has undergone the preliminary phase of user testing. The active resistance and haptic modes are functional but not ready for human testing. These modes are hampered by instability and a lack of smooth operation. It is believed that this is due to the torque measurements being updated too slowly, and maybe the need for a more sophisticated feedback controller. The update speed of the torque sensors is currently too slow to offer the type of response time needed to adjust the motor PWM signal from the torque reading directly. An update speed of 250Hz is desired. This section will cover initial setup of the device (common to all modes) and then the user interface and main control loop for the CPM, active resistance, and haptic modes.

The initial setup of the device is common to all modes and is performed through the microcontroller. The CPM and active resistance modes are handled by the microcontroller independently, while the haptic mode also includes code on a PC linked by the serial connection. The basis for the C code used for the microcontroller is from a previous project by Ed Haslam. The code contained the methods for initializing and interfacing with many of the components as well as the code for simple timers and PWM operations. This code was the basis for the project and greatly sped up the software process.

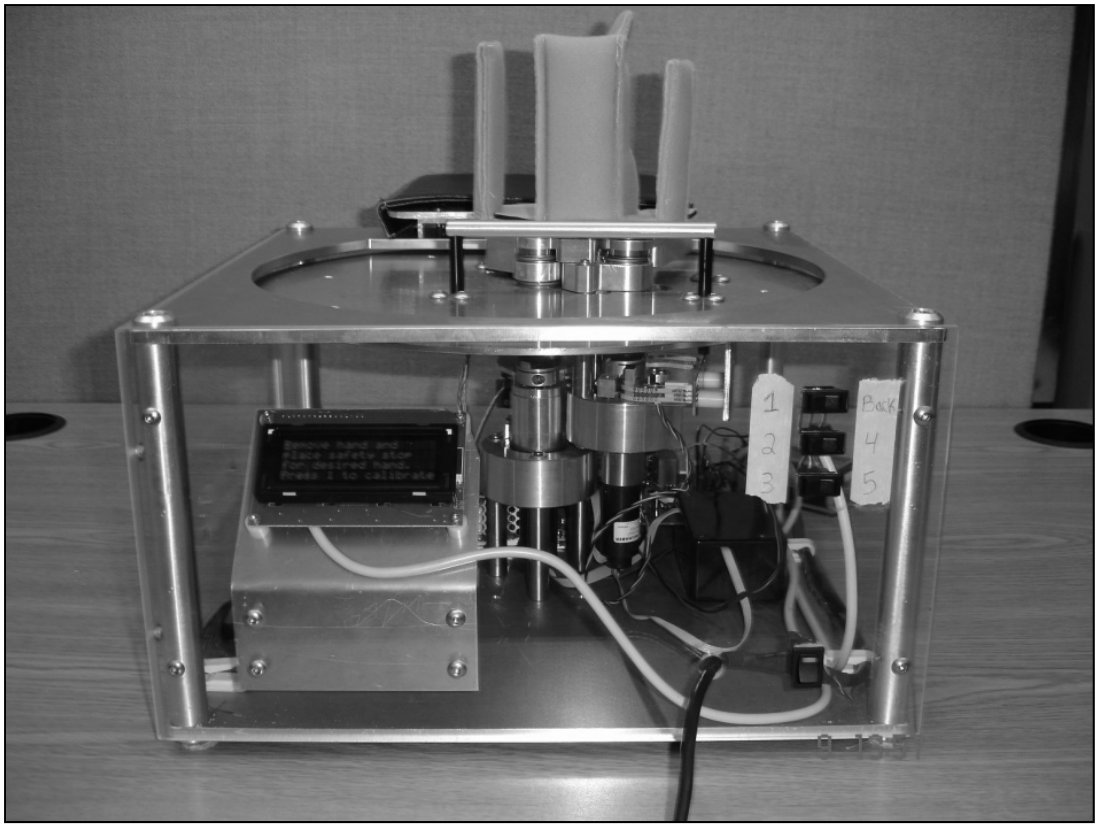


Figure 16: Display and inputs for therapist.

The initial setup of the device is identical across all modes and is handled internally on the microcontroller. The input from the therapist is handled through a series of three bi-direction toggles and the output is displayed on a four line LCD display seen in Figure 16. The power switch is also located on this side of the device for the therapist's use. The toggles are arranged such that they are numbered 1, 2, and 3 down the left hand side and "back", 4 and 5 down the right hand side. The patient is given a tethered display with an identical LCD display and a kill switch as seen in Figure 17. The display allows the patient to see the setup and any notifications during use. The kill switch controls the safety relay which will interrupt all power to the motors until the device is powered off and then back on. In this way the user is given a safety switch which when triggered will ensure the device is unpowered.

Figure 17: Tethered display and kill switch for patient.

The initial menu flow chart can be seen in Figure 18. The initial message is to press one to calibrate the device. When button one is pressed the device engages first the MCP then the PIP motors to drive the device to the fully closed position. The direction of motion is determined by the placement of the safety handle. The position of the safety handle is determined by the handle interrupting an optical switch in one of the two positions. The device will only begin calibration if the safety handle is in place.

Next the user is asked to input a safety limit as a percentage. The safety limit is used to set both the torque and current based shutoffs. These values calculated from the input percentage will be compared to the actual torque and current at each time step. If the current values exceed the limits, the device will shut off the motors and exit the control loop. At this time a message will display the cause for the stop. The percentage is input

by using buttons 2 and 4 to handle adding or subtracting one respectively, while buttons 3 and 5 are used to add or subtract ten respectively. This method is used in all instances where a number needs to be entered. For most steps, 1 is used to advance and back is used to return to the previous step. The next display offers the choice between CPM, active resistance, and haptics. The C code for the entire menu can be seen in Appendix B. This code controls the initialization of the device, menu setup for all three modes, and safety conditions checks (torque and current) for each of the loops.

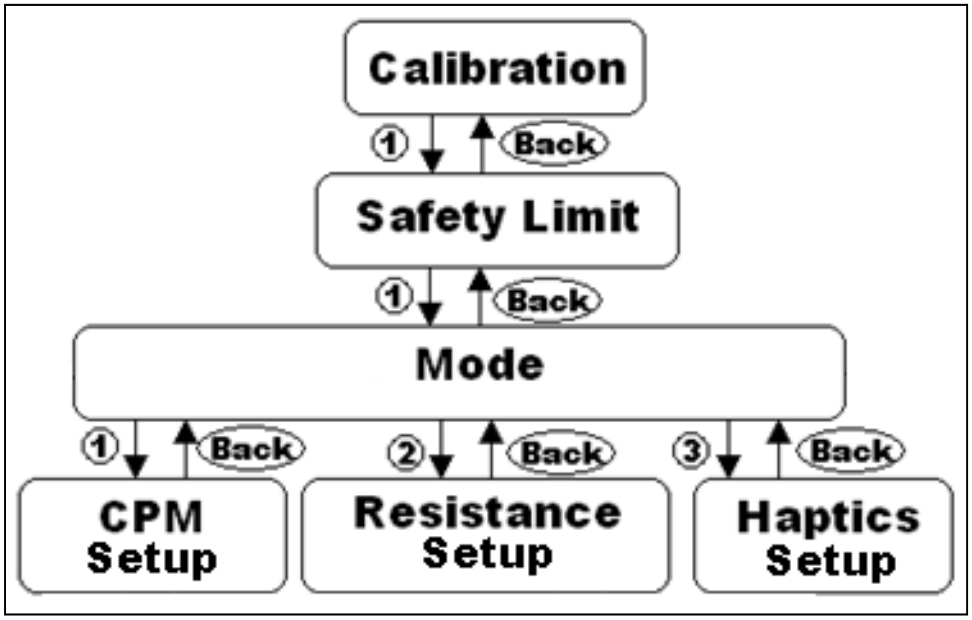


Figure 18: User interface

The control loops presented in the following sections are complicated by a number of factors. The major factor is that there is no inherent support for negative numbers. This means that with almost every mathematical operation the two inputs and the output need to be checked to see if they are negative and if so handled appropriately. This adds a lot of complexity to the code. The code must also be able to function for both the left and right hand as well as in both directions. The solution used was to have a “hand in use” variable that tracks which hand is being used (set by the optical switch) and then check if

the end position is a higher encoder value then the start position. The modulus 2 of the direction decided by both the relative encoded values and the sign of the PWM signal is then calculated with the “hand in use” variable to determine the direction to drive the motor. This value was used for the motor direction variable.

There was also a problem with abruptly switching the motor direction causing the microprocessor to reset. This was handled both with the electrical circuit in Figure 13 and by imposing a delay between switching motor directions of five milliseconds. This avoids quick motor direction switching that causes electrical spikes. There is also some complexity remaining in the code from the initial iteration with the old microcontroller. The original setup had a clock speed of 3.6864MHz which was upgraded to 40MHz with a new microcontroller and a new timing crystal. This was done to increase the speed of the control loop to smooth out the response in the CPM and active modes. It also had the effect of greatly increasing the ROM and RAM size of the microprocessor. The original code was required to be very thrifty with the use of ROM and RAM as with the addition of new modes, old sections had to be paired down to remain under the limit of the device. The new microcontroller removed this restriction but much of the code still maintains the style adopted to combat the lack of storage space.

7.1 CPM

The CPM mode passively moves the user’s hand (no force from the user) through a preset ROM following a minimum jerk trajectory, as discussed in Chapter 3. The ROM used in this mode is defined by the user (therapist), as they can choose a start position and a single end position or a series of end positions that the machine will cycle through sequentially. If the user picks multiple end points, for example three points, then the

device will move from the start to end_1 and back, then the start to end_2 and back, and finally from the start to end_3 and back. In this way the different motions can be incorporated into one fluid motion. The user could move from a neutral position back and forth to a modified intrinsic minus position (PIP flexion only), a modified fist (90° flexion of the MCP and PIP joints), and then an intrinsic plus position (shown in Figure 3). This allows for utilizing the full capabilities of the two-motor design. If the CPM mode is selected then the following steps can be seen in Figure 19. The code for these steps can be seen in Appendix B.

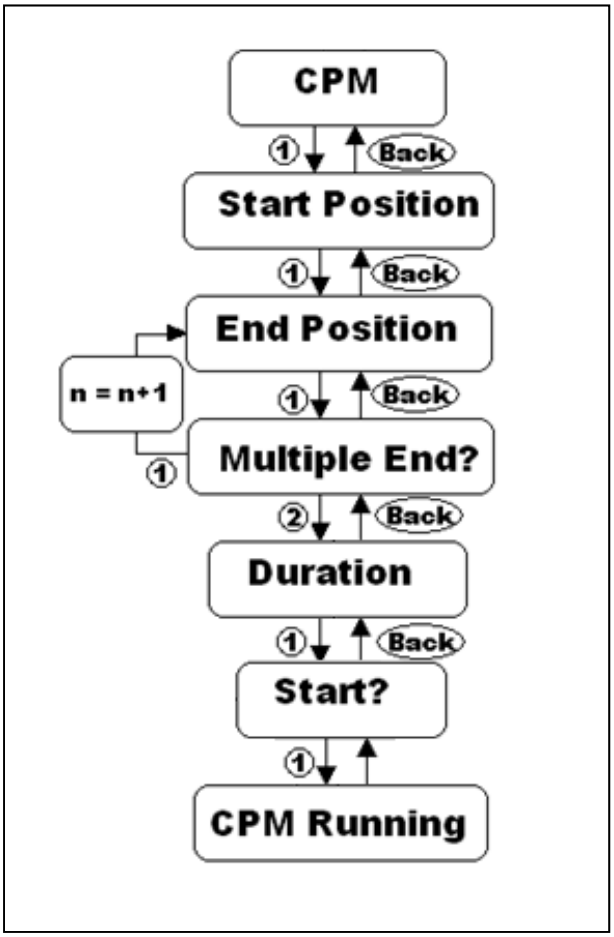


Figure 19: CPM user interface

At this point the participant is able to place their hand in the device while the therapist adjusts the position for the 2nd motor as well as the placement of the support pads. The

thumb strap is also attached at this time. The start position is then input for the CPM by commanding (moving) the mechanism to the start position. This is done using buttons 2 and 4 to control the MCP joint in flexion and contraction, and buttons 3 and 5 to control the PIP joint in flexion and contraction. It is also possible (although not recommended) to manually move the device to the desired location by back driving the motor. Backdriving the motor is defined as forcing the motor to rotate by applying a torque to the shaft of the motor and is not recommended as the motors were not intended for this function and may be damaged. This scheme is used for all device positioning tasks. Since the device is driven to the desired position, it is assured that the position will be the exact position desired. The participant's hand was moved to this position directly and thus it is not possible there was not an error such as entering 90° when 9° was intended. This method avoids error in inputting the desired position which may cause the device to exceed the user's comfort range.

Next, the end position is input using the same position scheme outlined in the previous paragraph. When the device is in the end position the user may select this as the only end position or enter multiple end positions. Up to three end positions can be set with the device driving from the start to $end_1$and back, then start to end_2 and back, and finally start to end_3 and back.

After entering at least one end position, the user/therapist is prompted to input the desired duration of the exercise. This duration is input in seconds and is the duration of one direction of travel (such as from the start position to the first end position). The duration can be set between 2 and 20 seconds. This number is input in the same manner as all numerical inputs; by using the 2 and 4 keys to add and subtract one and the 3 and 5

keys to add and subtract ten. The device is now setup for use and with the press of the 1 button it will drive to the start position and begin the CPM motion by way of a PID control loop.

The CPM loop C code can be seen in Appendix C and is run by looping case 16 in the code from Appendix B. Case 16 of the menu starts by reading the torque, current, and position sensors and the torque and current values are compared to the cut off values calculated from the safety limit input. If they exceed the limits then the device is stopped and an error message is sent describing the conditions for stopping the loop. If the limits are not exceeded then the code in Appendix C will be run. This code uses the elapsed time and the minimum jerk model to determine where the device should be and compare this to where it is (position sensor). The desired position is calculated directly from the elapsed time, start position, and end position using the minimum jerk model. The difference between the ideal and actual position is input to a PID controller which determines the PWM signal to send to the motor. This allows the device to use trajectory following to approximate the minimum jerk trajectory (and thus natural human motion) over the desired duration and ROM specified by the user. This will continue until the patient or therapist stops the device.

7.2 Active Resistance

The active motion mode of the device maintains a predetermined resistance against the user's hand. The therapist sets the start and end points of the exercise and the desired resistance as a torque. Then the user attempts to flex or extend his/her hand from the start to the end point with the device displaying a count of the number of repetitions achieved. During the motion, the torque sensors measure the torque produced by the user and

compare it to the desired torque, thereby controlling the resistance with a closed-loop control scheme. This enables the device to produce a steady torque to resist the movement of the user from the start to the end positions. The torque is scaled up from zero to the full value over the first 5° from the start position so as not to force the user back further than the starting point, and to ensure that a large jerk is not applied when the user first crosses the starting point. This mode is a new approach and uses a technique which usually requires a human therapist to apply resistance, or a more limited mechanical ball, grip strengtheners, or the Powerweb. The device is capable of resisting the closing or opening of the hand. The device is capable of providing both concentric and eccentric resistance.

The setup for the active resistance mode is very similar to the setup for the CPM mode. Initially the start and single end positions are input as in the CPM mode. Next the resistance is input as a percentage. This resistance value is used to set the desired torque for both the MCP and PIP joints. This value can be adjusted to scale the resistance that the device supplies to the user between the least and most force that the device is safely capable of.

After inputting the resistance the device drives to the start position and then runs the control loop. This loop starts by case 21 of the Appendix B code reading the torque, current, and position sensors. The torque and current values are compared to the cut off values calculated from the input safety limit. If they exceed the limits then the device is stopped and an error message is sent describing the reason for stopping the loop. If the limits are not exceeded then the active resistance code in Appendix D is run to determine the desired torque by using the full desired resistance torque or a fraction of it if the

device is within 5° of the start. In this way the supplied torque will scale up from zero to the full amount over the first 5° deviation from the starting position. This will ensure that the device does not jump from zero to full resistance as soon as the device passes the starting point. The actual torque measured by the sensors is compared to the desired input torque and the difference is used in a PID loop to determine the value of the PWM required. This allows the user to feel the desired torque regardless of the position or stiffness of the device. If the device is very stiff the motor will even assist the user to maintain the desired torque. In this way stiffness in back driving can be overcome and the device is capable of producing very low resistance torques.

7.3 Haptics

The haptics mode is designed to simulate the forces that would naturally be applied to the user in the situation depicted in the virtual environment. A display is used to show the patient a virtual environment consisting of a hand and a spring connecting the end of the fingers to the palm. As the user moves their hand within the device, the virtual hand on the monitor moves accordingly. The position of their hand in the device dictates the position of the virtual hand while the forces which would be imparted to the virtual hand by the spring are calculated and imparted on the patient's hand. In this way the device is able to simulate simple tasks such as squeezing a spring or other interactions. In this simple setup the position and torques for both joints are read from the device every time step and sent to the PC. The PC calculates the desired torque from the position given and sends it back to the microcontroller. The microcontroller then uses a PID loop to determine the proper PWM signal to send given the desired torque from the PC and the actual torque from the sensors. The PC side of the code is run on Visual Basic and the

microcontroller side is run on C code. The interactions are handled using a serial connection and simplified handshaking.

The setup of the device is handled through the same user interface as both the CPM and active resistance modes and can be seen in Appendix B. The code does the same initial setup of encoders and safety limits and then when the mode is selected the therapist is prompted to enter the spring constant. This constant is entered as a percentage where 0% is roughly the lowest torque which can be applied steadily by the motors, and 100% is the highest value as dictated by using 100% safety limit.

Next the start and end points of the motion are entered using the standard technique of using the toggles or physically moving the device to the desired positions. At this time the therapist selects to begin the loop and the device sends a signal character of 200 ASCII to the PC and then sends: (i) which hand is being used, (ii) MCP starting position, (iii) PIP starting position, (iv) MCP ending position, (v) PIP ending position, and (vi) the spring constant. These values are used to setup the model of the virtual environment on the PC.

Next the main loop of the Haptic mode is run. First the current and torque at both motors is measured and compared to the safety limits. If either is over the limit the device is stopped and a warning of the error is displayed. If the limits are not exceeded then the Haptic_loop()code in Appendix E – C Code on Microprocessor is run.

The loop begins by checking for a 201 or a 202 on the serial line. A 201 initiates the report_joint_angles() code in Appendix E and the value of the encoder for the MCP and PIP joints is sent via the serial line to the PC. A 202 code at the start of the haptic loop

initiates the get_desired_torque() code in Appendix B and a 203 ascii character is sent to the PC on the serial line to signify that the Microprocessor is ready to receive the new desired torque values. The values are then sent via the serial connection and stored on the microcontroller. If a 201, 202 or no code is sent the next section of the haptic loop is still executed. This section takes the stored desired torque value and compares it to the actual torque from the sensors. The difference is used in a PD loop to determine the correct PWM signal to send to the motors. In this way the PD loop can be executed as fast as possible while the 201 and 202 codes act as simple handshaking protocols to control the timing for sending encoder positions to the PC and of the updated torques being sent from the PC.

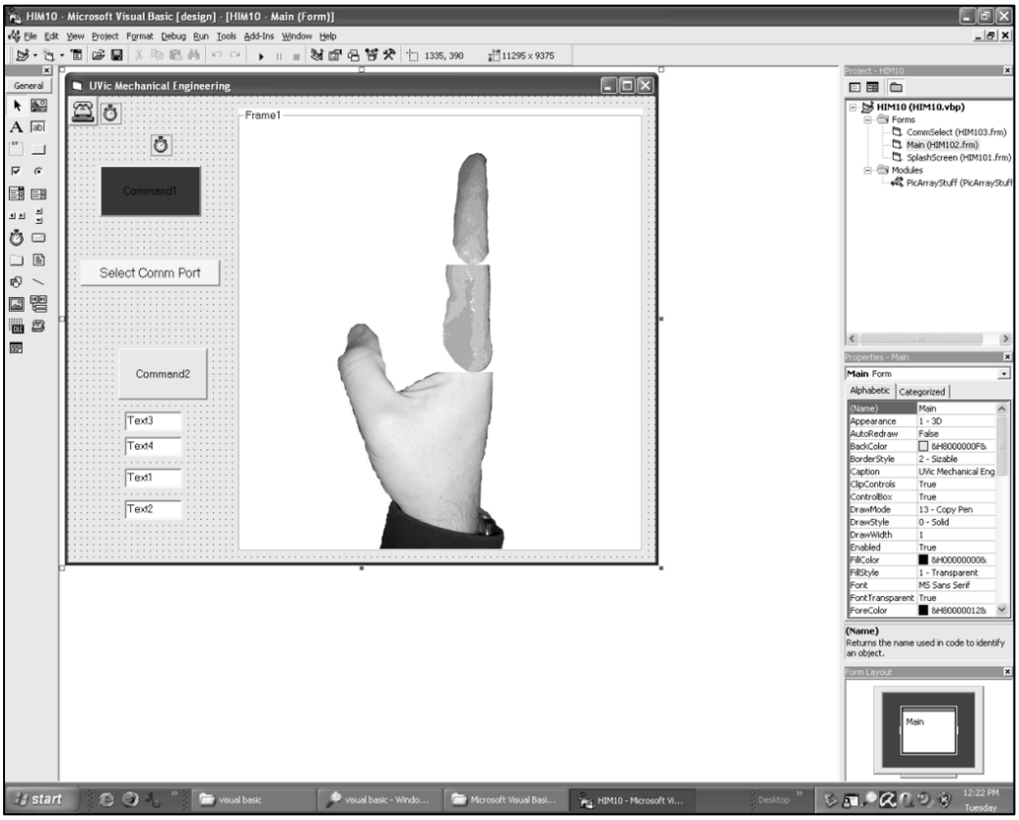


Figure 20: Visual Bacis GUI.

The code on the PC was originally written in Matlab and Simulink but there were a number of problems with the execution. The major issue stemmed from having a

feedback loop in the control block. The code was later translated to Visual Basic at the suggestion of Ed Haslam. An earlier code from a previous project of Ed Haslam's was used as a template for utilizing the serial connection and the basic menu interface. The GUI for Visual Basic is shown in Figure 20 and an excerpt of the code can be seen in Appendix E – Visual Basic Code on PC.

The code begins by initializing the GUI and drawing the hand in its initial position. Next the code waits for a 200 ASCII character to be sent form the microcontroller and then reads the six initialization variables sent from the microprocessor (values i– vi listed previously in this Chapter). These values are then used to calculate the initial position of the hand and the un-stretched spring length. The hand is then redrawn in the position indicated by the MCP and PIP start positions. The graphical boxes are offset to keep the picture looking accurate and rotated to the proper angle.

Next the code loops waiting for the device to be within 2 degrees of the start position indicated. This is done by sending a 201 ASCII character to the microprocessor to ask for the current position and looping until it is within 2 degrees of the start position sent for both the MCP and PIP. When the device is in position, the main loop is initiated. This loop sends a 201 to the device and receives the position of the device. At this time the compressed spring length is calculated and the force associated with this compression is also calculated. The torque at both the MCP and PIP joints is then calculated from the spring force and the known link angles. These MCP and PIP desired torques are then sent back to the Microprocessor by first sending the 202 ascii character for handshaking and then the values as a high and low section. Finally every tenth iteration the visuals are updated by rotating the graphic box for the proximal phalanx and distal phalanx and

translating them to maintain the visuals. This code is then looped until the device is stopped or the Visual Basic code is stopped.

The haptics mode was successful in running through all components of the code and producing the torques dictated by the virtual environment. The basic operation was successful but it was a very jerky application of torque and was not stable. It is believed this is due to the update speed of both the control loop and the torque sensors. The adjustment to the 40MHz processor was made after work on the haptics mode was stopped and would be very beneficial to the stability of the system. Also the replacement of the pressure sensors with faster updating sensors, as suggested for the active resistance mode, should also act to speed up the control loop and increase the smoothness and stability. Changing to a fixed time step will ease the process of ensuring stability.

Chapter 8 Mathematical Model

The mathematical modeling of the system was done with the aid of Matlab and Simulink. The purpose of this modeling was to determine the suitable PID gain values to use for the CPM controller and to simulate the system performance. The initial step was to perform the basic motor calculations by hand and then convert them to a Simulink diagram. The initial calculations can be broken into two groups: (i) electrical equations and (ii) mechanical equations.

The electrical calculations are based on a simple circuit containing a power source at a set voltage (e_a) and an electric motor with a known armature resistance (R_a) and a known armature inductance (L_a). The armature current (i_a) and the derivative of the current (di/dt) are unknowns. The initial formula for the voltage around the circuit loop is as follows in Equation 3.

$$\mathrm{e_a} = R_a i_a + L_a \frac{di}{dt} + e_m$$

Equation 3: Voltage loop equation for a simple motor.

The back EMF (e_m) is not a known quantity but can be calculated from the motor velocity ($\dot{\theta}_m$) and known back EMF constant (k_e) as shown in Equation 4.

$$e_m = k_e \dot{\theta}_m$$

Equation 4: Back EMF.

The last electrical equation is the formula for the torque produced by the motor (τ_m)as a function of the current in the armature (i_a) and the torque constant (k_m) as shown in

Equation 5.

$$\tau_m = k_m i_a$$

Equation 5: Torque produced.

The mechanical equations calculate the torque of the motor in terms of the inertia (J), damping (B) and static friction torque (τ_f). The subscripts m and L signify that the parameter is referenced at the motor and the load respectively. Specifically the inertia and damping terms are specified to be internal to the motor or from the linkages and bearings following the motor assembly. Static friction was used to compensate for conditions when very low voltage was sent to the motor and the model showed motion when the physical system did not. The following two equations show the process of taking the original equation (Equation 6), and simplifying using equivalent inertia and damping (Equation 7).

$$\tau_m = \left(J_m + \frac{J_L}{\mu N^2}\right)\ddot{\theta}_m + \left(B_m + \frac{B_L}{\mu N^2}\right)\dot{\theta}_m + \tau_f$$

Equation 6: Torque equation with load transferred across gear train.

$$\tau_m = (J_{eq})\ddot{\theta}_m + (B_{eq})\dot{\theta}_m + \tau_L$$

Equation 7: Simplified torque equation with equivalent inertia and damping.

These formulae were then transferred to the s domain using Laplace transforms and input into the Simulink graphical form shown in Figure 21. The static friction was not directly transformed to the S domain but was implemented in the Simulink model. Static friction was implemented by applying a resistive friction force opposing the net motor force, limited to a maximum of the experimentally determined static friction. In this way static friction does not exceed the applied torque and cause motion in the opposite direction. The initial setup used solely the MCP joint while the PIP joint was fixed in place.

The constants in the model were taken from the MicroMo specifications sheet or from physical calculations of the system (such as inertia) and are shown in Table 1. For example, the values for the torque constant, resistance, and inductance were taken

directly from the MicroMo specifications of the motor. The damping and inertia were found experimentally by comparing the model to the physical system over simple trial cases. The static friction torque (τ_f) was found by determining the lowest torque required to produce motion in the physical system and comparing that to the model.

	value	Units
L_a	6.50E-05	H
R_a	1.90E+00	ohms
K_e	2.33E-04	V·s/degree
K_m	1.34E-02	N·m/A
J_{eq}	1.07E-06	kg·m²
B_{eq}	3.92E-05	kg·m²/s
τ_F	7.45E-04	N·m

Table 1: Physical values used in the Simulink model. The values were taken from specification sheet or solved for by comparing the model to the physical system.

The model was tuned using a constant voltage input. The above process was performed for the MCP joint and then repeated with minor modifications for the PIP joint. These modifications were concerned with the inertia and damping primarily. The resulting model is capable of matching the actual positions and velocities.

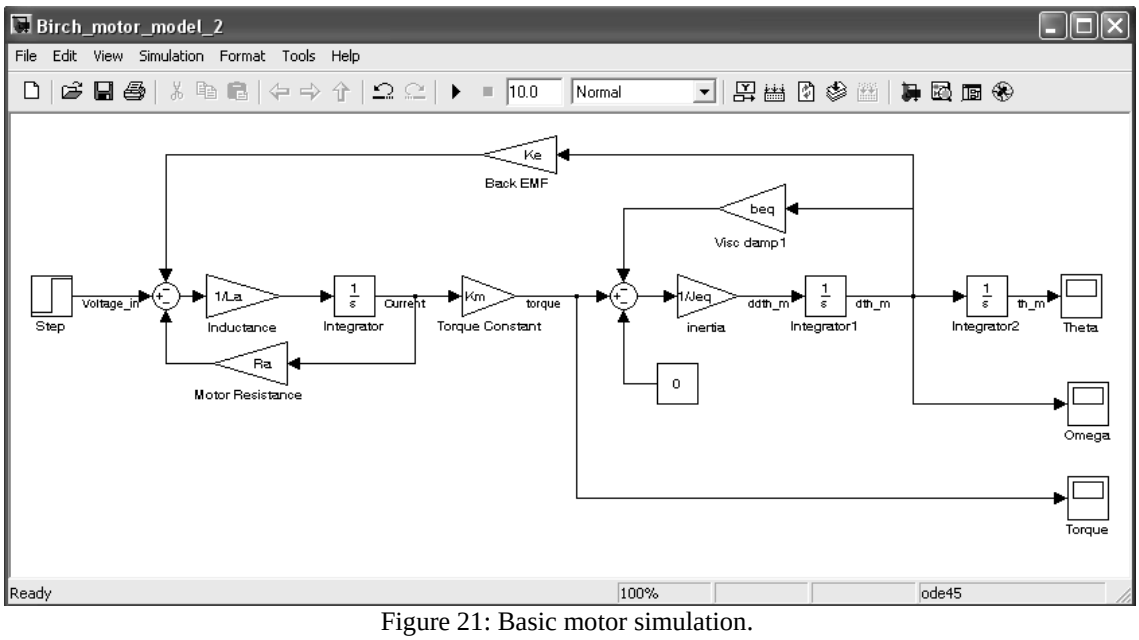


Figure 21: Basic motor simulation.

Next, the model was expanded to include PWM inputs and again the model was matched to the physical system. This section was less reliable with matching the physical

system. It was later discovered that the PWM signal produced by the device electronics was not indicative of the expected PWM signal. The signal produced by the physical device is not an ideal square wave as it has a DC offset and a large amount of oscilation. This is believed to be due, in part, to the electronics added to protect the device from the back EMF of the motors. This is believed to be the direct cause of the discrepancies. The next step was to expand the model to incorporate the PID controlled with the minimum jerk trajectory tracking. An optimization subblock which can be found in the Simulink toolbox was then run to minimize the error in the model's θ versus the ideal θ. This optimization produced the PID gain values used in the device, shown in Table 2.

K_p	12.27
K_i	18.83
K_d	0.94

Table 2: PID constants solved for using an optimization routine to minimize the error between the model and the desired trajectory.

Despite the non-perfect matching between the device and the model for the PWM signal the PID gain values produced were found to be very stable and produced the tight accuracy desired for the CPM (less than 5° maximum error). Manual tuning of the PID controller was also performed. The values produced by the model for the PID constants were found to produce a smoother motion with less angular position error between the desired and actual joint angles. The final model can be seen in Figure 22 and Figure 23. Figure 22 is the main Simulink model used. This model takes as inputs the same initial position, final position, and duration values as the physical system. Figure 23 is the subsystem of the model which represents the physical linkage, including the motor, bearing, rotating parts and potential perturbations from the user's hand.

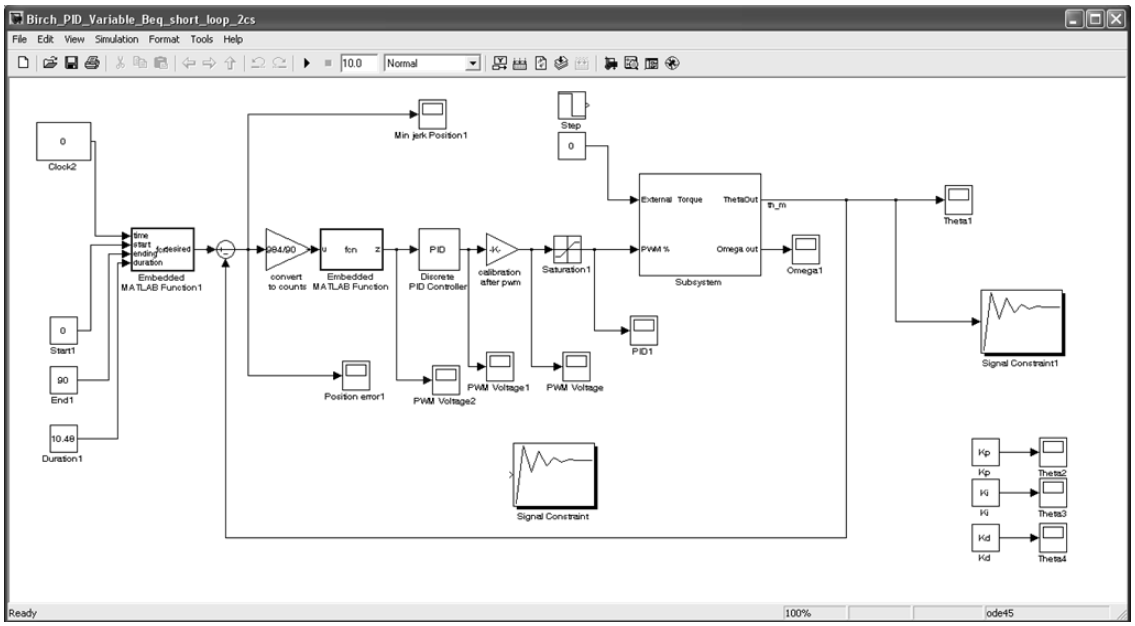


Figure 22: Simulink model of the first level of the device. The plots the minimum jerk trajectory between the input start and end points over the input duration. All steps of the process are output to scopes. The subsystem is shown in Figure 23.

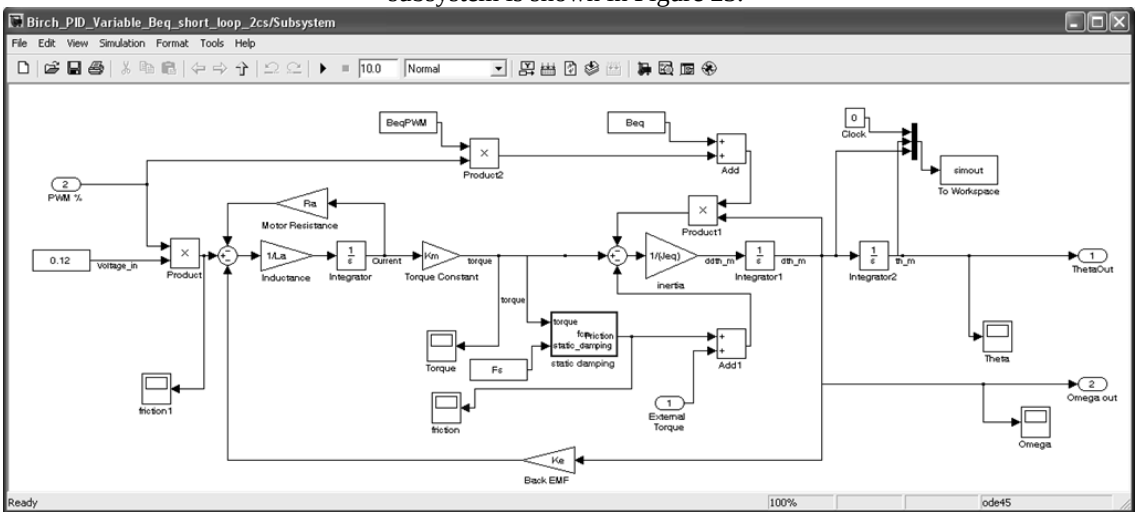


Figure 23: Simulink model subsystem of the physical system. The subsystem intakes a PWM number and output the angular position and velocity.

Scopes in the models (Figure 22 and Figure 23) were used in testing and verification.

The optimization subsystems were used to determine the PID gain values to be used on the physical system by optimizing the output theta or the error between the output theta and the calculated minimum jerk trajectory. The motor model subsystem used is shown in Figure 23. This model takes in the same values of initial position, final position, and duration as the physical system.

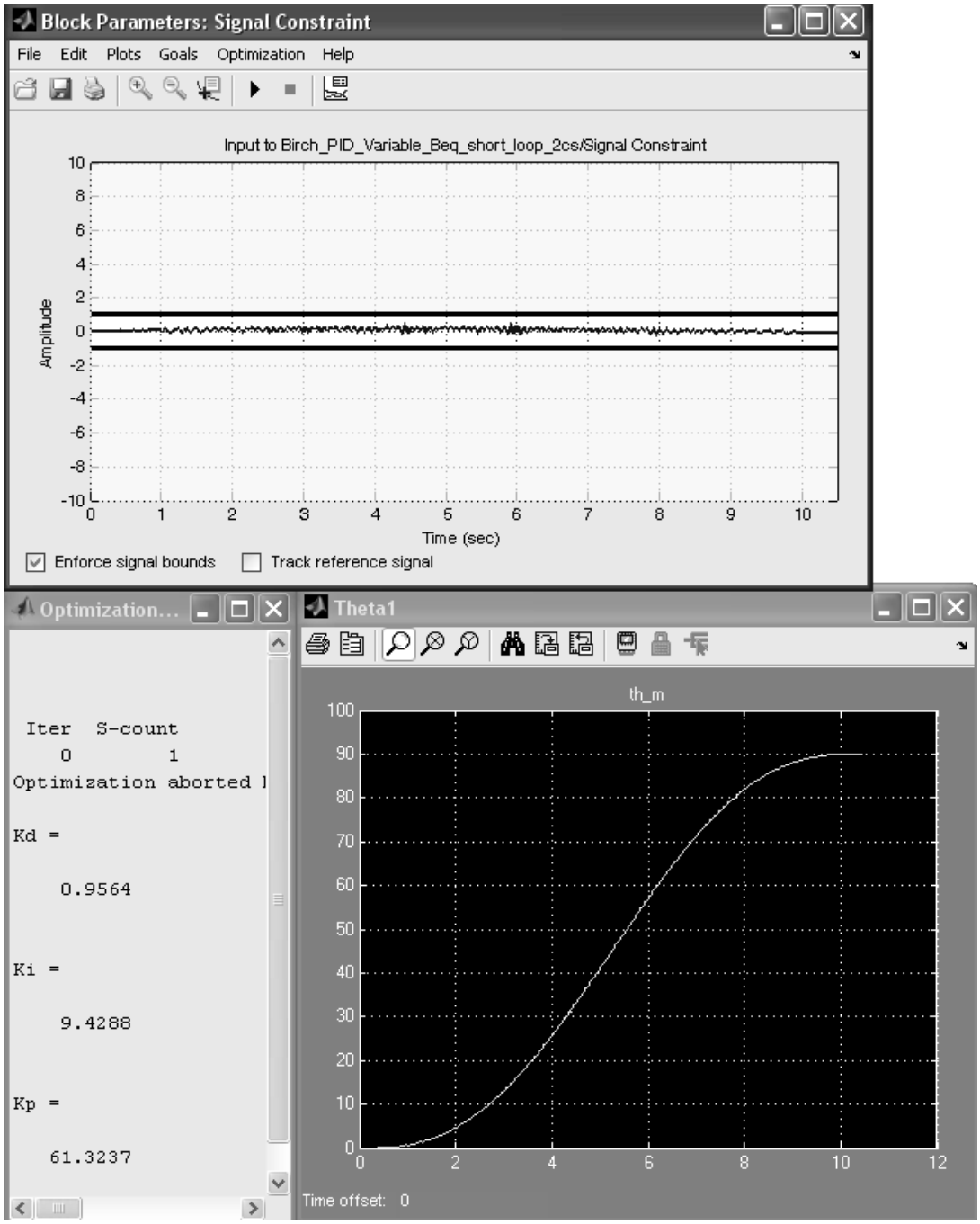


Figure 24: Optimization output for minimizing the MCP error (between the desired and models actual angular position) over a minimum jerk trajectory from 0° to 90°. Top center window is a graph of the error in degrees, bottom left is the output produced for the PID values and bottom right is the graph of the angular position over time produced by the simulated device.

Figure 24 shows the output from a sample optimization routine. This particular routine minimizes the error between the desired and actual (simulated) MCP joint angles. The

optimization tunes the K_P, K_I, and K_d values over a complete motion from 0 to 90 following the minimum jerk trajectory.

It is believed that the model could be made to match the physical system even more accurately by digitizing the actual PWM signal from the device and using it in place of the ideal PWM signal currently utilized. This would allow a much tighter matching between the model and the device.

Chapter 9 Experimental Testing

The testing of the hand rehabilitation device was done in three stages. The first stage was an analysis of the positional accuracy of the device performed with and without external forces applied to the device. The second stage of testing was performed on nine healthy volunteers who performed the CPM motion in a controlled environment. This phase of testing included pre and post measurements of the participant's active range of motion (ROM), evaluation of their current hand function, shoulder and arm health, measurements of torque and position during motion, as well as a questionnaire. The third stage of testing was performed on eight participants with various hand injuries, which were deemed to be suitable for treatment with CPM. This group of eight participants underwent a similar analysis as the healthy group. The purpose of these two user studies was to determine: (a) if the device was safe, (b) if the device was comfortable and easy to use, and (c) to bring to light any issues that need to be addressed before the device could be used in a full study. The human subject tests that were performed in this work were approved by UVic's Human Research Ethics board (see Appendix G). In future work, a full study would be needed to determine the effectiveness of the device as part of a standard treatment regime.

9.1 Evaluation of Positional Accuracy

The device was evaluated to determine the positional accuracy prior to being tested with human subjects. The accuracy of the device was determined by evaluating the error at each time step. The error was calculated as the difference between the desired position, calculated from the minimum jerk equation at each time step, and the actual position, measured by the magnetic encoders. Since the minimum jerk profile was used as the

ideal motion of the device, this error value directly measures how far the device has deviated from the intended trajectory. The error was calculated in degrees at each time step (at approximately 250 Hz). A maximum error of les then 3° was desired.

These tests were performed in three stages. First the tests were performed with no external forces applied. Next, they were done with external forces applied that would exceed the maximum permitted torque (user defined limit) and hence cause the device to shut off. Finally, with external forces which were near the maximum permitted torque and then suddenly released.

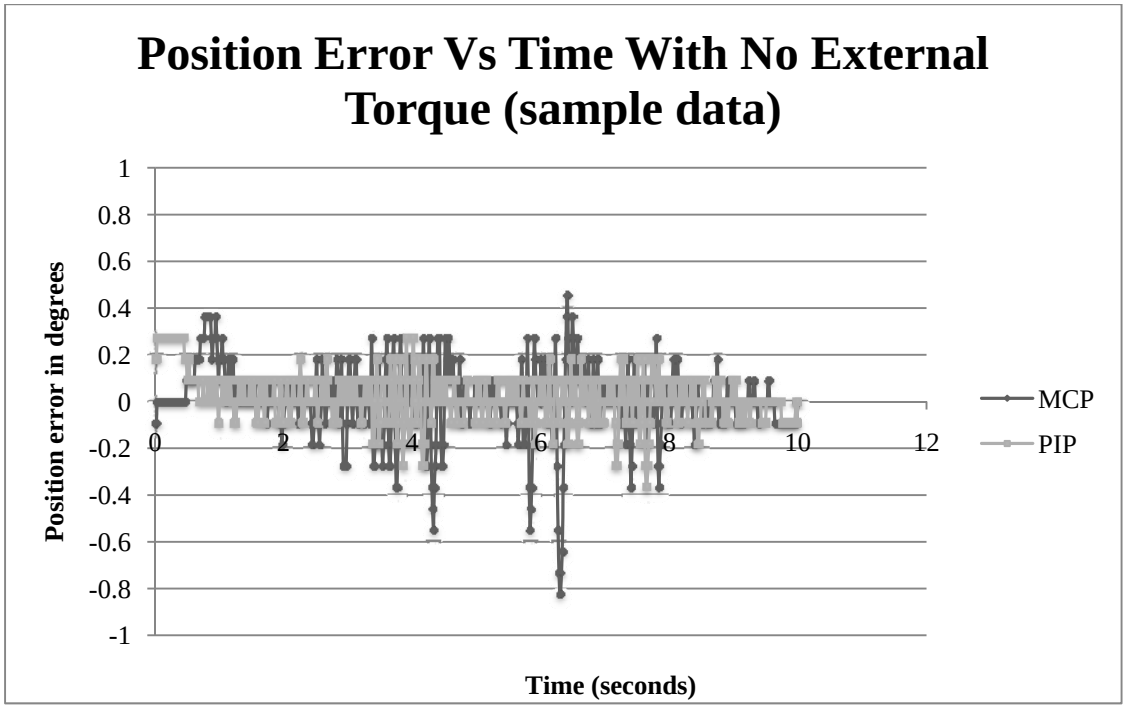


Figure 25: Position error with no external torque applied

The first test consisted of running the device over its full range of motion within a ten second duration, with no externally applied forces (i.e. by the device itself with no subjects). Thirty opening and closing repetitions were monitored, with a sample of these shown in Figure 25. Over these motions the average absolute error was 0.1° for the MCP

and 0.3° for the PIP. The maximum error was 1.2° for the MCP and 1.46° for the PIP. This is a very small error for a device of this nature and thus was considered acceptable.

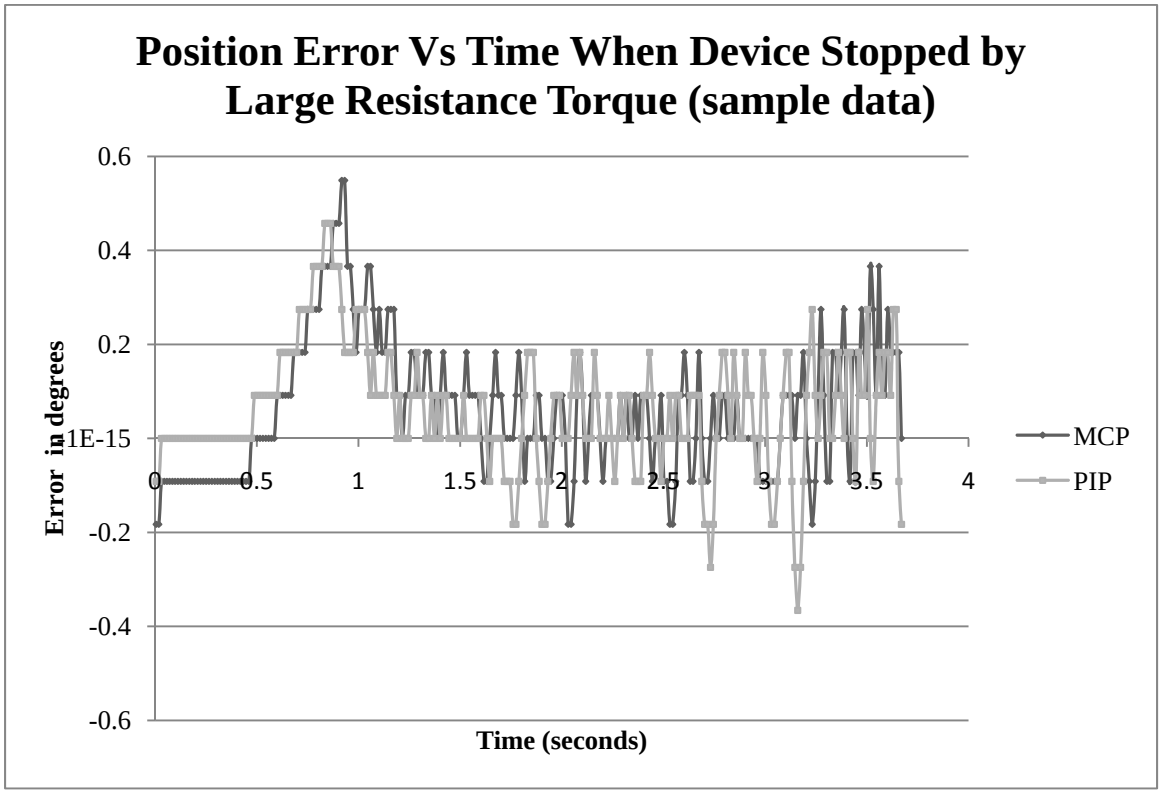


Figure 26: Position error with the device physically blocked during motion.

The next test was to determine the maximum error when the device was subjected to external resistance to the point where the user-defined maximum permitted torque was exceeded. This was done by placing an obstructing aluminum block in the motion trajectory of the device and then commanding the device to run through a full range of motion with a ten second duration. The motion of the device would cause the "Second Rotating part" to collide with the aluminum block, which would lead to a sudden increase in the torque measured, until the user-defined maximum permitted torque safety limit is exceeded. The maximum error between the actual joint angle and the desired joint angle (from the minimum jerk model) was recorded. This test was performed 10 times and the maximum error was1.4° and 0.6°for the MCP and PIP respectively. Figure 26 shows a

sample of the data over a single test, where the test reached the user-defined maximum permitted torque just after 3.5 seconds into the motion. Again, this is considered to be a small error for a device of this nature, and hence was deemed as acceptable. Therefore, if the device was used with a human subject and encountered rigid resistance due to their hand that exceeded the maximum permitted torque, the device would shutoff within 1.4° for the MCP and 0.6°for the PIP joint.

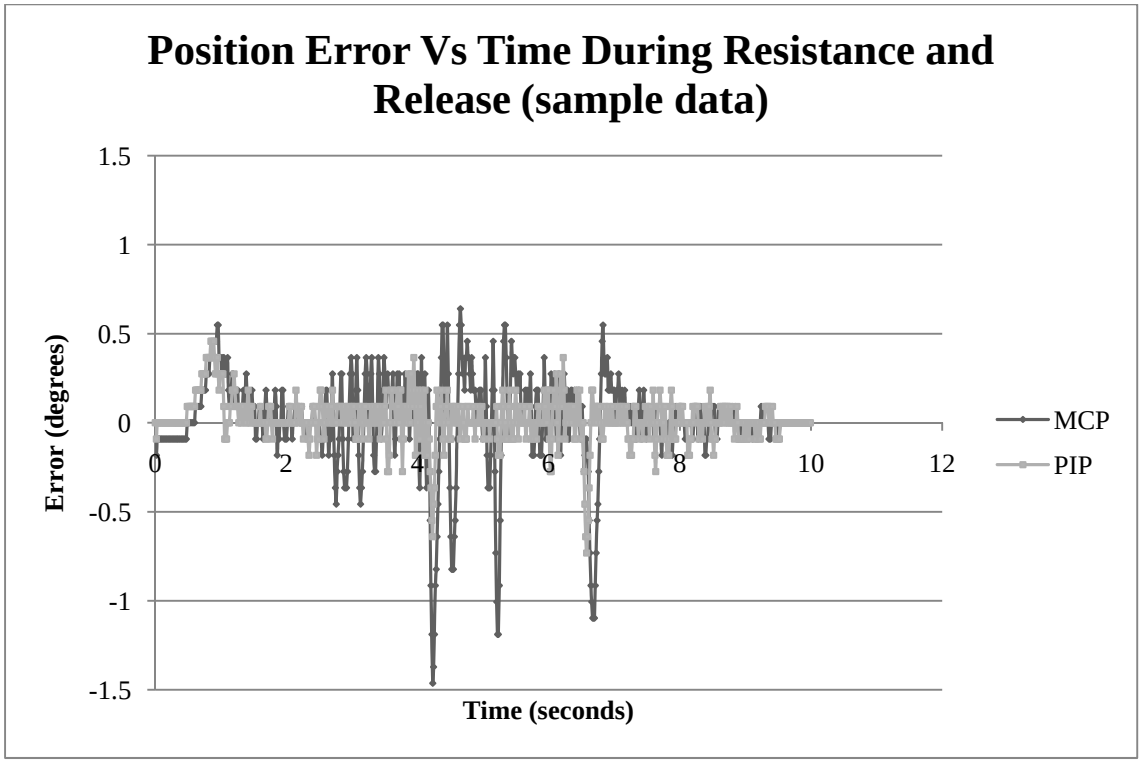


Figure 27: Position error with the device motion resisted and then the resistance suddenly removed.

The final test determines the response of the device when it is incorrectly used. During CPM mode, a participant is required to relax their hand, and let the device drive the relaxed hand through the desired ROM. This test aimed to determine the device response if the participant actively tries to use their hand to resist the CPM, or actively tries to assist the CPM. This situation was simulated by applying an external torque (resisting the direction of motion) for 1-2 seconds, and then suddenly removing that external

torque. The resisting torque is produced by first blocking the device with an aluminum block and then quickly removing that block before the torque limit is reached. This sudden change in external torque caused the device to slightly overshoot the desired trajectory as seen in Figure 27. The maximum error during ten tests was found to be 1.6° and 2.1° for the MCP and PIP respectively. As with the previous two results, this was deemed to be an acceptable level of error, well below the 3° error desired.

9.2 User Study

After the initial testing described in Section 9.1, a user study was designed and an application for ethical approval was submitted. The ethical approval application was a rigorous process where each step of the proposed study was described in full detail. The application proposed a study of approximately ten healthy participants, and ten injured participants, with collaboration from Clare Faulkner and the Vancouver Island Hand Therapy Clinic. The main sections of the application were: (a) the purpose for the tests and why human trials were required, (b) the level of risk to the participants, (c) an outline of the recruitment process (including the selection criteria and possible conflicts with a researcher being in a position of “power-over” a possible participant), (d) the data acquisition, storage and disposal process, (e) the compensation offered, (f) the issues of informed consent and right to withdrawal and (g) the researchers qualifications. An excerpt from the full ethics application can be seen in Appendix F. After the initial application a series of revisions, specifications and alteration were required by the ethics review board. The ethics approval was given with the condition that a number of concerns and specifications were addressed. The decision to perform the tests in two stages (first with healthy participants and then with injured participants) was a made to

due to a suggestion by the Ethics Review Board. Another notable revision was the inclusion of an introductory period where the injured hand group would familiarize themselves with the device by using their healthy hand in the device first.

Confirmation of ethical approval was received for a 1 year testing period involving two groups of participants. The ethical approval form can be seen in Appendix G. As outlined previously, the purpose of the two user studies was to determine: (i) if the device was comfortable and easy to use, (ii) if the motion felt smooth to the user, (iii) if the user felt safe while using the device, (iv) if the device felt passive to the participant (ie. if the user felt like the device moved them through the motion while they needed to supply no force or effort), and (iv) to bring to light any issues with the device that need to be addressed. The first stage consisted of testing nine healthy participants, to determine if the device was safe and comfortable enough to proceed with the injured user group. In terms of determining if the device was "safe", we wanted to determine if the healthy user's hands had any ill effects while using the device or in the subsequent days after the tests. The second stage consisted of testing eight injured participants with various hand injuries, who were deemed to be suitable candidates for CPM during their recovery. Hand therapist Clare Faulkner determined which candidates would be suitable for the second stage tests. The testing of the injured group would then determine the comfort, safety, ease of use, and level of acceptance of the device.

9.2.1 Test Setup

The purpose of testing the device with the healthy hand group was to determine if the device was safe to use and felt comfortable to users, prior to attempting to use it on participants with an injured hand. The healthy hand tests were also a requirement for the

ethical approval process, described in the previous section. Finally, the healthy hand tests served as a 'reference' for the device performance, which could later be compared to the performance with injured users. Hence, it was important that the testing protocol, from start to finish was identical for the healthy hand participants and for the injured users.

The process began by first giving each participant (healthy or injured) a consent form outlining all aspects of the study. A copy of the consent form is shown in Appendix H. After this they were asked to complete a form describing the current functional level of their shoulder, arm and hand, called the "Disability of the Arm, Shoulder and Hand" (DASH) survey. The DASH survey is a tool for assessing the functional level of a participant's hand, shoulder, and arm before the tests. A copy of the DASH is shown in Appendix I.

Next, the existing active range of motion (ROM) of the participant was established. For the purpose of these results ROM measurements will always be active ROM measurements. Generally, an injured hand that would benefit from CPM exhibits a limited ROM. Hence, one of the objectives of performing CPM is to help the injured hand to recover to its normal ROM. Note that for injured hands, the ROM of each finger will vary. Some fingers will exhibit a large ROM, while others will be quite limited due to the specific nature of the injury. The proposed device moves all the fingers in unison through the ROM, hence the concept of "limiting finger" is now described. The limiting finger is the finger in the hand which exhibits the smallest angle of passive flexion or extension, in comparison to the rest. Therefore, it is very important to identify this finger prior to testing, and to record its active ROM to establish safe and comfortable levels for ROM for CPM. Additionally, the limiting finger's active ROM is recorded after testing

to establish a metric to gauge the success of the CPM treatment. For the healthy group, limiting finger flexion was used as this metric, since all healthy participants were able to achieve full extension. In the case of the injured group, the ROM of all injured fingers was recorded in both flexion and extension. The finger ROM was measured using a goniometer, which is a tool designed to measure joint angles. It has small sections before the pivot and after the pivot that are placed adjacent to the bones on either side of the joint. Thus the angle at the pivot corresponds to the angle of the user's joint.

The physical testing of the device was done next. The test procedure for the healthy subjects was slightly different than that for the injured subjects. For the healthy subjects, the test consisted of a five minute CPM session, repeated 3 times. For each session, the device was configured to use the maximum ROM, using durations of 15 seconds per cycle for the first, 10 seconds per cycle for the second, and 5 seconds per cycle for the third. For the injured group, the test also consisted of three sessions of five minutes each. However, the ROM for each test was based upon the individual participant's injury level, and their maximum comfortable ROM. The participant was asked to select a ROM where the joint felt tight but did not cause any pain. This range was updated for each of the three sessions in the hopes of increasing the ROM. Additionally, the CPM cycle speed was set on a case-by-case basis to ensure the participant's comfort as measured by the follow-up questionnaire. After the tests with healthy or injured participants, the ROM of the same limiting fingers was measured again. Finally, a short questionnaire was filled out by the participant to evaluate their experience with the device.

The questionnaire contained a variety of questions pertaining to the comfort, safety, and functionality of the device. These questions included:

(Q1) How comfortable was the device in general use? 1 = Uncomfortable, 10 = Comfortable.

(Q2) Did this mode feel passive? I.e. did you feel like you did not have to do any work while the device moved your fingers?

(Q3) How safe did the device make you feel? 1 = Very Nervous, 10 = Completely Safe

(Q4) How smooth was the CPM motion? 1 = Very Jerky, 10 = Very Smooth

Question 2 was a “yes or no” question while the others were done on a sliding scale from 1 to 10, with the ends of the scale labelled as seen above. There was also a comment section for each question to allow the participant to elaborate on their answers to any question.

Another method used to determine the safety of the device was to monitor the accuracy of the CPM motion while in use with the participants. This was found by calculating the difference in degrees between the desired position and actual position at each time step. Equation 2 was used to determine the desired position by inputting the time, desired duration, start point and end point of the desired motion. The actual position was measured from the magnetic encoders. The difference between these two numbers is a measure of how accurately the device is positioned. This was calculated for each time step, with the average and maximum values calculated.

Finally the torque exerted by both motors was recorded directly from the torque sensors for each time step. This value was compared to the user-defined maximum permitted torque, at each time step. If the measured torque value exceeded the user-defined limit, then the CPM mode should have stopped. Therefore, subsequent evaluation of this data could determine if the torque was being maintained at acceptable values.

9.2.2 Results

The device and its CPM performance were evaluated based upon four criteria. These four criteria were: (i) the ROM measurements of the participants before and after the CPM, (ii) the answers given to the survey, (iii) the error between the minimum jerk model and the actual position of the device, and (iv) the ability of the device to operate below the user-defined torque limit.

9.2.2.1 Results with Healthy Participants

The healthy group consisted of nine volunteers. The participants were not of any specific demographic and the only stipulation was that they had a hand without any major current injuries. Arthritis was present in two cases but was not considered to be a concern.

For criteria (i), the limiting finger of each user was identified, and its ROM was measured before and after CPM, using a goniometer. Based upon these measurements, the change in ROM could be computed, and is summarized in Table 3.

As can be seen in Table 3, there was an average loss of 0° in the ROM of the MCP joint and an average increase of 2° in the PIP joint. These are very small changes in ROM and this is can be interpreted as no change given the inherent inaccuracy in the measurement of ROM using a goniometer. It should be noted that only the limiting finger of the participant was measured. This means that only the finger with the lowest ROM for the MCP and PIP was measured. Note that the original ROM data for the healthy participants can be seen in Appendix J.

Healthy Hands		
Participant #	Change in MCP	Change in PIP
1	1°	1°
2	4°	-5°
3	0°	2°
4	-4°	4°
5	0°	0°
6	-1°	1°
7	6°	10°
8	-4°	0°
9	-3°	2°
AVG	0°	2°
STDEV	3.4°	4.0°

Table 3: Change in the ROM measurements for the healthy hands group between before and after using the device. A positive change represents an increase in ROM.

To establish criteria (ii), the questionnaire that was administered to all participants (as outlined in section 10.2.1) was evaluated. The summary of the data from these questions is shown in Figure 28. For question (Q1), regarding the comfort of the device, the average response was 9.8 with all participants selecting either 9 or 10.

For question (Q2) regarding passivity, the user was given a choice between yes and no to indicate whether the mode felt passive on not. Seven of the nine participants selected it felt passive, one did not circle either choice, and one selected not passive. The comments accompanying the answers to this question were all positive. The one participant who selected that it was not passive commented, “It was quite passive, but not totally passive”. This demonstrates the difficulty of “yes or no” questions when asking about the participant’s perception of the motion. Also, this question may not have been fully understood by participants.

For question (Q3) regarding how safe the user felt, the average response was 9.9 with eight of the participants selecting 10 and the ninth selecting a 9. There was an option for

participants to write down a comment. Three participants chose to do this, and their comments regarding their perception of safe feeling were" "well monitored", "the emergency stop button was reassuring", and "pretty safe, especially with the little guard bar at the backs of my fingers". These comments refer to the safety features of the device. Based on the numeric response and the user comments, it is reasonable to conclude that the participants' feeling of safety was very high.

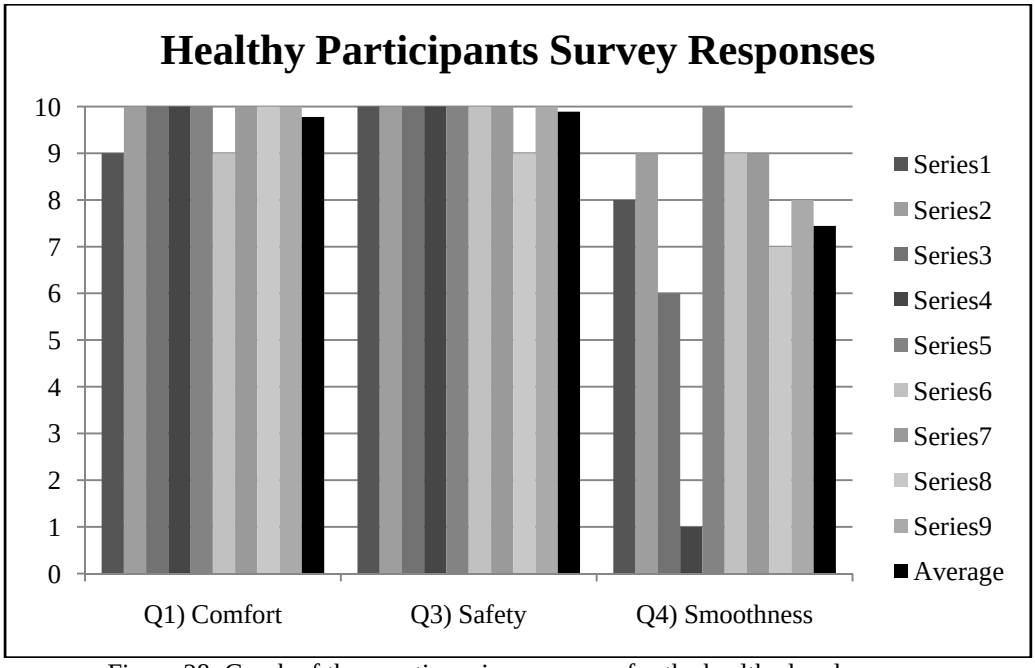


Figure 28: Graph of the questionnaire responses for the healthy hands group.

For question (Q4), regarding the smoothness perceived by the participant, the average response was 7.4. One participant responded with a score of 1, while the other eight participants selected 6 or higher. These tests were run at cycle durations of 15 seconds, 10 seconds, and 5 seconds for full flexion. The 5 second cycle time is fairly fast, and may have been the reason some users perceived "jerkiness" or a "choppy" feeling. Due to the responses to this question and the verbal comments during use, it was deemed that the five-second duration was too fast and was not used for the subsequent trials with injured hand participants.

The participant's response to if the device was passive was positive with only one participant stating that it did not feel passive. The answers to the survey were very positive for the comfort and safety of the device with averages of 9.8 and 9.9 respectively. These are crucial criteria as any safety or comfort concerns would be magnified when working with injured participants. The final question of the survey was concerned with the smoothness of the motion. The average response was 7.4. This was remedied by utilizing slower speeds in injured group trial (no faster than 10 seconds duration). The fastest speed used (5 second duration) was deemed too fast as it was far less smooth and had larger errors when following the minimum jerk model. With a strong positive response to the safety and comfort questions and with the adjustment to the speed, progressing with the injured group was deemed safe.

To establish criteria (iii), the accuracy of the CPM motion was recorded. The accuracy of the trajectory following can be seen by looking at the data recorded from the trials, and the maximum and average errors, as listed in Table 4. The device follows the minimum jerk trajectory discussed in Chapter 2 by means of a PID controller. The value for intended position (calculated from the time at each step and the minimum jerk mathematical model directly) and the actual position (taken from the integrated encoders) are compared to determine the error in the MCP and PIP at every time step (approximately every four milliseconds). The maximum error in both the MCP and PIP was calculated for the healthy participants and was used to determine the maximum deviation from the intended trajectory. The duration of the tests from open to close were fifteen seconds, ten seconds, and five seconds. The five-second duration was found to be too fast for the full range of motion due to being too quick of a motion for an injured

participant. Therefore the five-second duration tests were not considered and this speed was not used in the injured trials. Over the fifteen and ten second durations the maximum error was 1.28° in the MCP and 2.84° in the PIP. The average error over the trials was between 0.12° and 0.14° for the MCP and PIP joints respectively. This shows that the device is very accurate at following the minimum jerk profile and within the 3° maximum desired position error.

		Maximum Angular Error		Average Angular Error	
Participant #	Duration (s)	MCP	PIP	MCP	PIP
1	15	1.19°	1.37°	0.11°	0.14°
	10	1.10°	1.19°	0.12°	0.15°
2	15	0.91°	1.46°	0.11°	0.14°
	10	1.10°	1.37°	0.13°	0.14°
3	13	1.01°	1.55°	0.11°	0.14°
	10	1.10°	1.37°	0.13°	0.14°
	10	1.10°	1.55°	0.11°	0.14°
4	15	0.91°	1.46°	0.11°	0.14°
	10	1.10°	1.55°	0.13°	0.15°
5	*15	1.10°	1.37°	0.11°	0.14°
	10	1.10°	2.84°	0.13°	0.15°
6	15	1.28°	2.20°	0.11°	0.15°
	10	1.19°	1.37°	0.13°	0.15°
7	15	1.01°	1.46°	0.11°	0.14°
	10	1.19°	1.46°	0.13°	0.15°
8	15	0.91°	1.55°	0.11°	0.14°
	10	1.19°	1.65°	0.14°	0.15°
9	15	1.01°	1.46°	0.11°	0.14°
	*10	1.10°	1.65°	0.14°	0.15°
Maximum		1.28°	2.84°	0.14°	0.15°
Average		1.08°	1.57°	0.12°	0.14°
STDEV		0.10°	0.37°	0.01°	0.00°
* Intentionally stopped by user.					

Table 4: Error between minimum jerk model and actual position for healthy hand group (in degrees). Maximum and average recorded for each participant and each joint. Also averaged and the maximum value calculated for each criteria (participants maximum error or participants average error) and joint.

It should be noted that in two cases the user intentionally stopped the device and the maximum error values at these times are still 1.37° and 1.65° (Table 5). This shows how tightly the device can follow the trajectory even with a larger external force.

To establish criteria (iv), the torque was used to determine if the device was operating at a level below the user-defined torque limit. Hence, this would establish whether the user was experiencing undue torque due to stiffness in their hand or if the device was obstructed. The torque readings throughout the tests were observed to be within the allotted range, and were only exceeded on two occasions. On both occasions the participant intentionally resisted the device to determine the ease of stopping it for their own curiosity. This served to reassure them that it could be stopped if they so desired, by forcibly resisting the CPM motion with their hand.

9.2.2.2 Results with Injured Participants

The group of injured hand participants consisted of eight volunteers. The participants were not of a specific demographic, and had various hand injuries. They were deemed to be suitable candidates for trials with the proposed CPM device, based on the professional assessment of hand therapist Clare Faulkner. The test results were evaluated using the same four criteria as that used for the healthy subjects.

For criteria (i), the ROM was measured for each of the injured fingers before and after the CPM. For the injured users, the CPM consisted of three sessions, of five minutes duration each. Due to the nature of the device, all the fingers are moved through the same ROM at the same time. Hence, the limiting finger in either extension or flexion will get the greatest stretch to its ROM. The limiting finger is the finger with the lowest maximum active flexion measured in degrees. “Active flexion” refers to the user flexing their fingers without external forces applied. If two or more fingers are considered limiting then those fingers are all listed and the change in ROM is averaged. The average is taken since multiple limiting fingers should experience the same amount of exercise

and thus the results should be comparable. There is no guarantee that the limiting finger will be the joint with the greatest improvement. The limiting finger was used as this is the joint which should receive the greatest stretch and thus the most direct effect from the device. The complete set of data for the ROM measurements of the injured hand group can be seen in Appendix K. The ROM data was collected before and after the trials. The data is separated by which joint was measured (MCP or PIP) and by the direction of measurement (extension or flexion). The following tables display theROM before and after the trials and the difference for the limiting finger. The results are then averaged over all the users to achieve and average change in ROM for the limiting finger, grouped by joint and direction of measurement. This value should show the average change in ROM of the particular joint in the particular direction regardless of which finger is injured. It is important to note that for all the change in ROM measurements a positive number is considered to be in increase in ROM.

Injured Group MCP Extension				
Participant #	Limiting Finger(s)	Pre Test	Post Test	Change in MCP angle
1	Middle	5°	-2°	7°
2	Pointer	10°	10°	0°
3	Pointer	-2°	-5°	3°
4	Pointer	45°	30°	15°
5	Middle	0°	0°	0°
6	Pointer	-2°	-2°	0°
7	Pointer	5°	-5°	10°
8	Pointer	15°	10°	5°
Average				5°

Table 5: Change in ROM (measured before and after trial) of the injured hand groups limiting finger for MCP extension. A positive number indicates an increase in ROM.

The changes in ROM for the injured group, measured as the maximum active extension of the MCP, are shown in Table 5. The changes in ROM for the limiting finger range from 0° to 15° with an average of 5°. This average is the mean increase in active

extension for the limiting finger. If the finger with the greatest increase was used instead of the limiting finger the average would be 6°.

Injured Group MCP Flexion				
Participant #	Limiting Finger(s)	Pre Test	Post Test	Change in MCP angle
1	Pointer	50°	65°	15°
2	Ring	55°	70°	15
3	Ring	75°	75°	0°
4	Ring / Pinky	15° / 15°	40° / 35°	23°
5	Middle	95°	95°	0°
6	Pointer	70°	80°	10°
7	Ring / Pinky	65° / 65°	82° / 82°	17°
8	Ring / Pinky	75° / 75°	80° / 80	5°
Average				11°

Table 6: Change in ROM (measured before and after trial) of the injured hand groups limiting finger for MCP flexion. A positive number indicates an increase in ROM.

Table 6 shows the change in ROM of the limiting finger of each participant for flexion of the MCP joint. Participants showed between 0° and 23° of increased ROM. The average change in ROM of the MCP in flexion was an 11° increase. If the finger with the greatest increase in ROM was used instead of the limiting finger the average increase in ROM would be 12°.

Injured Group PIP Extension				
Participant #	Limiting Finger(s)	Pre Test	Post Test	Change in PIP angle
1	Pointer / Middle	25° / 25°	20° / 20°	5°
2	Middle	20°	10°	10°
3	Pinky	5°	0°	5°
4	Ring	47°	47°	0°
5	Middle	15°	15°	0°
6	Pointer	12°	10°	2°
7	Middle	7°	0°	7°
8	Ring	20°	5°	15°
Average				6°

Table 7: Changes in ROM (measured before and after trial) of the injured hand groups limiting finger for PIP extension. A positive number indicates an increase in ROM.

The change in ROM as measure before and after the user trial for the extension of the limiting PIP joint is shown in Table 7. The changes in ROM range from 0° to an increase of 15°. The average change in the active extension of the PIP in the limiting finger is 6°.

In the case of extension in the PIP the limiting fingers for each participant was also the finger with the greatest increase in ROM.

Injured Group PIP Flexion				
Participant #	Limiting Finger(s)	Pre Test	Post Test	Change in PIP angle
1	Middle	30°	45°	15°
2	Pointer	52°	52°	0
3	Pinky	85°	90°	5°
4	Pointer	20°	25°	5°
5	Middle	72°	72°	0°
6	Pointer	72°	82°	10°
7	Pinky	70°	90°	20°
8	Pinky	60°	70°	10°
Average				8°

Table 8: Change in ROM (measured before and after trial) of the injured hand groups limiting finger for PIP flexion. A positive number indicates an increase in ROM.

Table 8shows the changes in ROM for the flexion of the PIP joint in the limiting finger. The values range from 0° to 20° with an average of 8°. If the PIP joint with the greatest increase in extension ROM were used instead of the limiting finger the average change in ROM would be an increase of 11°.

The collective data for the change in ROM of the two joints in flexion and extension show good values for the increases in ROM. In no cases did the limiting finger decrease in ROM and the averages changes in ROM were between 5° and 11°. This shows that the participants increased in ROM on average for their limiting finger. The similarity between the limiting finger and the finger with the greatest increase in ROM suggests that the limiting finger, on average, has a greater increase in ROM, as expected.

The averages of the changes in ROM for each joint (MCP and PIP) and for each direction of motion (extension and flexion) are shown in Table 9. The averages are taken over all the measured joints and not just limiting joints. These averages show the mean change in an injured joints ROM directly after using the device. The averages for

extension of the MCP and PIP are 3.3° and 3.2° respectively. The averages for the change MCP and PIP flexion are 8.9° and 7.2° respectively. These average increases in ROM show that the participants gained a greater increase in flexion then extension. This also shows that on average, the participants gained 12.2° and 10.4° to the total ROM of their MCP and PIP respectively. This is an excellent short term increase in ROM.

Joint	Direction	Average Change in angular ROM
MCP	Extension	3.3°
	Flexion	8.9°
PIP	Extension	3.2°
	Flexion	7.2°

Table 9: Average change in angular ROM measured before and after the trial and averaged over all injured joints of all participants.

The change in ROM as a percentage between the measurements before and after the tests is presented in Table 10. This table shows the participants complete ROM (angular distance from maximum active flexion to maximum active extension) for each of their fingers measured. The percent change is the ROM after tests divided by the Rom before the tests as a percentage. The average percent increase in ROM was 138%. This shows that, on average, the participants increased their ROM by 38% of their original ROM.

Participant #	Finger	Joint	ROM before test	ROM after test	% change
1	Pointer	MCP	50°	67°	134.00%
		PIP	15°	27°	180.00%
	Middle	MCP	50°	67°	134.00%
		PIP	5°	25°	500.00%
2	Pointer	MCP	60°	67°	111.67%
		PIP	42°	42°	100.00%
	Middle	MCP	70°	65°	92.86%
		PIP	42°	57°	135.71%
	ring	MCP	55°	70°	127.27%
		PIP	58°	72°	124.14%
	pinkey	MCP	67°	65°	97.01%
		PIP	62°	75°	120.97%

Table 10: % change in ROM, measured from the complete ROM (flexion and extension) pre and post test.

Participant #	Finger	Joint	ROM before test	ROM after test	% change
3	Pointer	MCP	92°	95°	103.26%
		PIP	90°	100°	111.11%
	Middle	MCP	90°	100°	111.11%
		PIP	100°	107°	107.00%
	ring	MCP	80°	85°	106.25%
		PIP	95°	105°	110.53%
	pinkey	MCP	85°	92°	108.24%
		PIP	80°	90°	112.50%
4	Pointer	MCP	17°	45°	264.71%
		PIP	22°	27°	122.73%
	Middle	MCP	20°	45°	225.00%
		PIP	20°	30°	150.00%
	ring	MCP	15°	40°	266.67%
		PIP	18°	18°	100.00%
	pinkey	MCP	15°	35°	233.33%
		PIP	23°	28°	121.74%
	Middle	MCP	95°	95°	100.00%
		PIP	57°	57°	100.00%
6	Pointer	MCP	72°	82°	113.89%
		PIP	60°	72°	120.00%
7	Pointer	MCP	70°	90°	128.57%
		PIP	95°	97°	102.11%
	Middle	MCP	75°	90°	120.00%
		PIP	88°	102°	115.91%
	ring	MCP	65°	92°	141.54%
		PIP	95°	93°	97.89%
	pinkey	MCP	65°	94°	144.62%
		PIP	68°	88°	129.41%
8	Pointer	MCP	67°	72°	107.46%
		PIP	47°	65°	138.30%
	Middle	MCP	70°	75°	107.14%
		PIP	52°	60°	115.38%
	ring	MCP	70°	75°	107.14%
		PIP	42°	70°	166.67%
	pinkey	MCP	75°	80°	106.67%
		PIP	43°	60°	139.53%
	Average				137.79%

Table 10 continued: % change in ROM, measured from the complete ROM (flexion and extension) measured before and after the tests.

It is important to remember that the ROM results are simply preliminary data points, for the purpose of analysing the performance of the CPM device, within the four criteria described. Therefore, the increases in ROM for the injured users cannot be shown to be lasting, nor can they be shown to be indicative of a beneficial gain to the participant at this time. The data does seem to indicate that the device has an effect on the participant in the short term (a few hours), and there is no detrimental effect in the short term. In other words, the ROM seems to increase in the short term, and there was no pain or other ill effects reported by the participants. Therefore, the fingers are being affected and it suggests that there is merit in performing a further study to determine the functional gains possible with this device over the long term.

To establish criteria (ii), the questionnaire administered to the injured participants (as outlined in section 9.2.1) was evaluated. The summary of the data from these questionnaires is shown in Figure 29. The average response for question (Q1) (comfort) was 9.4. Most of the participants' comments confirmed that the device was comfortable. The only non positive comment was, "Initially I didn't really want it to do it, then after a couple of times [it] felt comfortable. Okay to do it every day".

For question (Q2), all participants but one selected that the device felt passive. The participant who selected "no" commented that "It was fine and hardly noticeable". This indicates that the device was perceived as passive by most participants.

For question (Q3), the participant was asked how safe the device made them feel on a sliding scale of 1 (very nervous) to 10 (completely safe). The average response was 9.3 with 6 users selecting 10, one user selecting 9, and one selecting 5. The user who

selected 5 commented, “A little nervous at first”. On average most participants felt safe using the device.

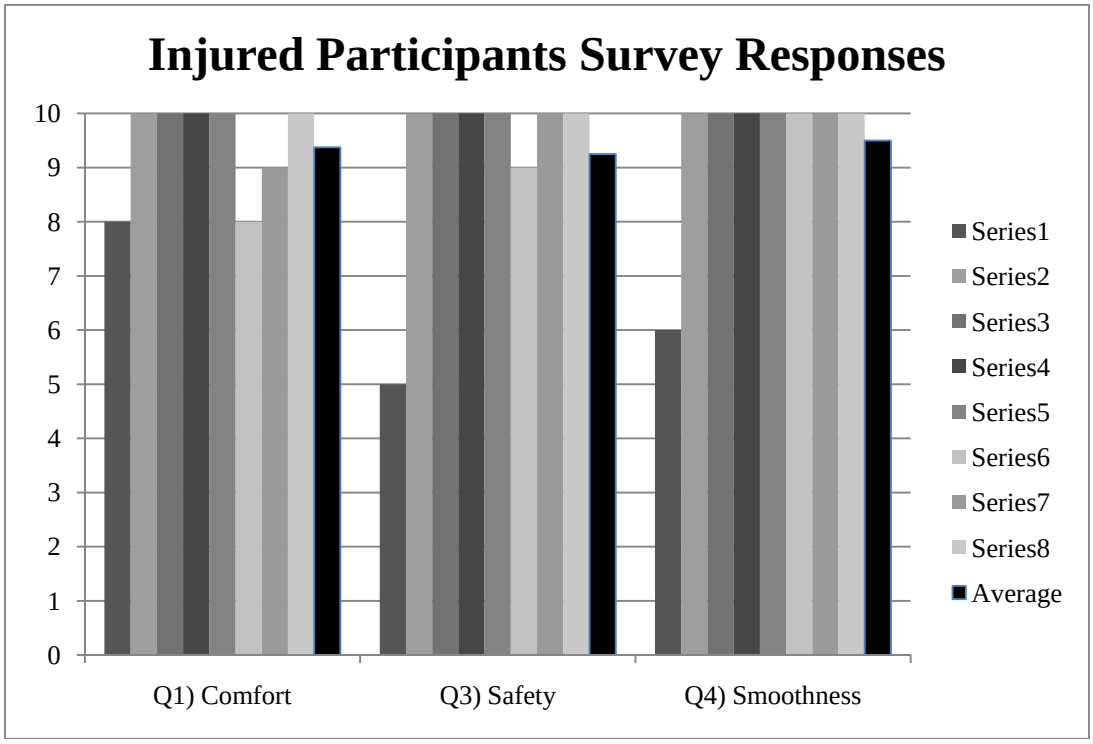


Figure 29: Graph of the Questionnaire responses for the injured hands group.

For question (Q4), the participant was asked how smooth the CPM motion was. The average response was 9.5 with one user selecting a 6 and the other 7 selecting 10. The participant who selected the 6 commented that it was “a little jerky – didn’t affect the feeling I got, but it looked jerky”. The effect of the device looking jerkier than it felt was also commented on by a number of other participants and will need to be examined further. On average the device was perceived to be smooth.

To establish criteria (iii), the error in the trajectory was evaluated. The error in degrees between the desired joint angles (calculated from the minimum jerk equation) and the actual joint angles (measured from the encoders) was recorded at each time step. The maximum error between the desired Minimum jerk trajectory and the actual position was

calculated for each participant for the two joints respectively (shown in Table 11). The average error for each participant was also calculated for each joint. The maximum errors during all the injured tests were 1.46° in the MCP joint and 2.10° in the PIP joint. The average error found during the testing of participants with injured hands was 0.11° for the MCP joint and 0.14° for the PIP joint. This shows that the device very closely followed the minimum jerk model.

		Max angular Error		Average Angular Error	
Participant #	Duration (s)	MCP	PIP	MCP	PIP
1	10	1.10°	1.55°	0.12°	0.15°
	10	1.19°	1.55°	0.11°	0.15°
	10	1.10°	1.55°	0.12°	0.15°
2	12	1.01°	1.46°	0.10°	0.14°
	12	0.91°	1.46°	0.10°	0.14°
	12	0.91°	1.46°	0.10°	0.14°
3	15	0.91°	1.46°	0.10°	0.13°
	15	0.91°	1.28°	0.10°	0.15°
	15	1.46°	1.37°	0.10°	0.14°
4	12	0.82°	N/A	0.09°	N/A
	12	0.82°	N/A	0.10°	N/A
	15	0.82°	N/A	0.09°	N/A
5	13	0.82°	1.37°	0.11°	0.14°
	13	0.82°	1.37°	0.11°	0.15°
	13	0.91°	2.10°	0.11°	0.15°
6	13	0.91°	1.46°	0.11°	0.14°
	13	0.91°	1.46°	0.10°	0.14°
	13	1.10°	1.37°	0.10°	0.14°
7	13	1.37°	1.65°	0.11°	0.15°
	13	0.91°	1.46°	0.11°	0.15°
	13	0.91°	1.46°	0.11°	0.14°
8	13	1.46°	1.46°	0.11°	0.14°
	13	1.01°	1.55°	0.12°	0.14°
	13	1.01°	1.55°	0.11°	0.13°
Maximum		1.46°	2.10°	0.12°	0.15°
Average		1.01°	1.50°	0.11°	0.14°
STDEV		0.19°	0.16°	0.01°	0.01°

Table 11: Error between minimum jerk model and actual position for injured hand group (in degrees). Maximum and average recorded for each participant and each joint. Also averaged and the maximum value calculated for each criteria (participants maximum error or participants average error) and joint.

To establish criteria (iv), the ability of the device to operate or stop based on the user-defined torque limit, was evaluated. During operation, it was found that the torque

measurements were within the acceptable ranges. In one case, the user-defined torque was exceeded, and the device 'shut off' as it is programmed to do. This also demonstrates the success of the device to obey the user's desires. In this one case the maximum permitted torque was set too low. The safety limit was set to 2% due to the participant expressing nervousness about the device. 2% safety limit is defined as 2% of the maximum software allowed user-defined maximum permitted torque. Hence, the device shut off multiple times in the participant's CPM session. To alleviate this, the user-defined maximum permitted torque was raised slightly (to 5%) and there were no further problems.

Chapter 10 Future Work

The rehabilitation device operates well and has been successful during the trials, but there are many possible areas for improvement and future work. There are a few mechanical alterations which should be performed both for comfort and functionality, the active and haptic modes need to be finalized and then undergo testing similar to the testing performed on the CPM mode, the model inputs should be altered to match the physical system more closely, and all three modes need to undergo a large trial where the device is used as part of a rehabilitation treatment plan and compared to current techniques over the full course of a participant's recovery.

A few mechanical alterations have been deemed useful for increasing comfort over the course of testing the device. The distance between the two motors and thus the MCP and PIP joints is adjustable but the range should be altered to accommodate smaller separations. It was found during use that some participants were at the very extreme small end of the acceptable MCP to PIP separation. It would also be ideal to increase the possible width of the device since with severe swelling there may be cases where participants are not able to comfortably fit their hand into the device. The angle of the wrist during the trials was also considered and needs to be looked at closely. It may be desirable for the forearm to be elevated slightly to reposition the wrist for comfort during prolonged use.

A number of mechanical changes have been considered for increased functionality and ease of use. The angle of the MCP and PIP joints during positioning should be displayed on the LCD screen or on a scale around the ring of the guard so that the therapist can easily determine the ROM during device setup. This would make setting up the device

for a second test far easier since it would be easily apparent if the second test was performed at a greater or decreased ROM. It would also be ideal if pressing the button to increase or decrease the desired ROM were directly mapped to an increase or decrease of a single degree for fine adjustment. At this time the duration the button is pressed for determines the amount of movement but it is believed that a set amount of motion would be easier and more repeatable.

The current system used for user input during menu navigation and device setup needs to be streamlined and made more accessible to therapists. This can be achieved through switching from a toggle and LCD display system to a touch screen. The touch screen would allow for a simplified menu system more easily learned and more intuitive.

For the active and haptic modes, a new pressure sensor should to be tested to determine if a faster response time will smooth out the active resistance motion to an acceptable level. A maximum error of 10% is desired during active motion and guaranteed stability is required. It is believed that moving to the piezoresistive Honeywell force sensor will offer the update speeds required to produce smooth active resistance and haptics motion. This modification has been planned and the parts acquired but it has not been fully implemented at this time. The active resistance and haptic modes also need to be altered to operate with a fixed time step. Finally, when the active resistance and haptic modes are fully operational they need to be tested first on healthy participants then again on injured participants in the same manner as the recent CPM tests.

The mathematical model does not match the physical system to the degree of accuracy desired when performing PID based trajectory following. Currently the model behaves in

a stable manner when given inputs which cause instability in the actual system. It is believed this is due to the noise and irregularity in the signal being sent to the motors. The PWM signal is not the expected output used in the theoretical model. The next step is to digitize the physical signal sent to the motors during operation and use this signal as the input to the model. This technique should allow for a better match between the theoretical and physical systems.

If these tests proposed for the haptic and active resistance modes are successful then a final clinical trial needs to be performed to determine the effectiveness of the device as a rehabilitation tool. This will be done by organizing trials where the device is used within a rehabilitation regime for a number of participants over the course of their treatment. Collaboration with a hand rehabilitation clinic, such as the Island Hand Therapy Clinic, should be arranged in order to allow for the participants to have as little deviation from standard treatment as possible. The hand therapist would be in charge of selecting a number of participants (between 5 and 10) who would be suitable for utilizing the device. A treatment plan would then be followed which mimicked a standard treatment with the exception that the rehabilitation device would be utilized to offer CPM, active resistance and haptic resistance over the course of the treatment. The timing, duration and type of exercises which the device was used for would be decided by the therapist using their medical judgment. The results from the prolonged study will be compared to standard rehabilitation times and effectiveness in order to determine if the device is able to produce results comparable with standard techniques. If the clinical trial was successful then the device could be produced and used as a clinical aid in hand recovery.

Chapter 11 Conclusion

CPM and active resistance have become more commonly used tools in hand rehabilitation recently. The trend towards early passive and active motion over the more traditional immobilization models has created a need for more sophisticated and versatile devices. The larger time and cost associated with manual manipulation in a one-on-one situation can be offset by the inclusion of a machine in the rehabilitation process. A number of devices are in research or market phases but the lack of a device capable of CPM and active resistance indicates there is still a need for a device capable of both these modes as applied to the MCP and PIP joints independently with torque and position feedback.

The device presented in this thesis was designed to fill this role. It is a table top device capable of independent activation of both the MCP and PIP joints. The device is capable of CPM and has been tested both with healthy and with injured participants. The results from the trials were very promising. The trials were not sufficient to declare that the device is capable of being used as part of a hand rehabilitation regime at this time. The trials did however show no sign of the device causing any pain or injury to the participants and short term increases in ROM were recorded. The data for changes in ROM measurements between measurements taken before and measurements taken after the trials show, on average, increase in the ROM for both flexion and extension for both the MCP and the PIP. The average increases in ROM for the active extension of the MCP joint and the PIP joint were 3.3° and 3.2° respectively. The average increases in ROM for the flexion of the MCP joint and the PIP joint were 8.9° and 7.2° respectively. This is a sign that the device has an effect on the patient even if this effect can not be

shown to be lasting at this time. It will require further testing with a long term group of participants and a control group to determine if this is a lasting effect and if the device is ready for clinical use. At this point, the results are very promising. The trajectory following of the minimum jerk model was also found to be successful with a maximum error of only 1.46° in the MCP joint and 2.10° in the PIP joint across all trials with an average error of 0.11° and 0.14° for the MCP and PIP joints respectively.

The active resistance and haptic modes still need to undergo adjustments before they are ready for clinical testing. It is believed that with the replacement of the pressure sensors and changing to fixed time steps these modes will be ready for this testing. Future work on these modes will need to start with these minor adjustments and then if it is successful, progress to the same testing process that was used for the CPM mode in this study.

The device has shown that it is capable of CPM motion with independent control of the MCP and PIP joints. The feedback of position and torque were both successful. The error in the trajectory following operation of the CPM mode was within acceptable limits and the clinical trials were very positive. The response of the therapists and participants to the device was also very positive. The responses to the questionnaire, ROM measurements, and accuracy of the device all showed that the tests were successful. The average responses of the injured hand participants to questions of perceived Comfort, safety and Smoothness were above 9 out of 10 for each question. Future work should enable the active resistance and haptic modes to be tested in a similar manner and then the device should undergo a full clinical trial with a long term comparison to standard techniques.

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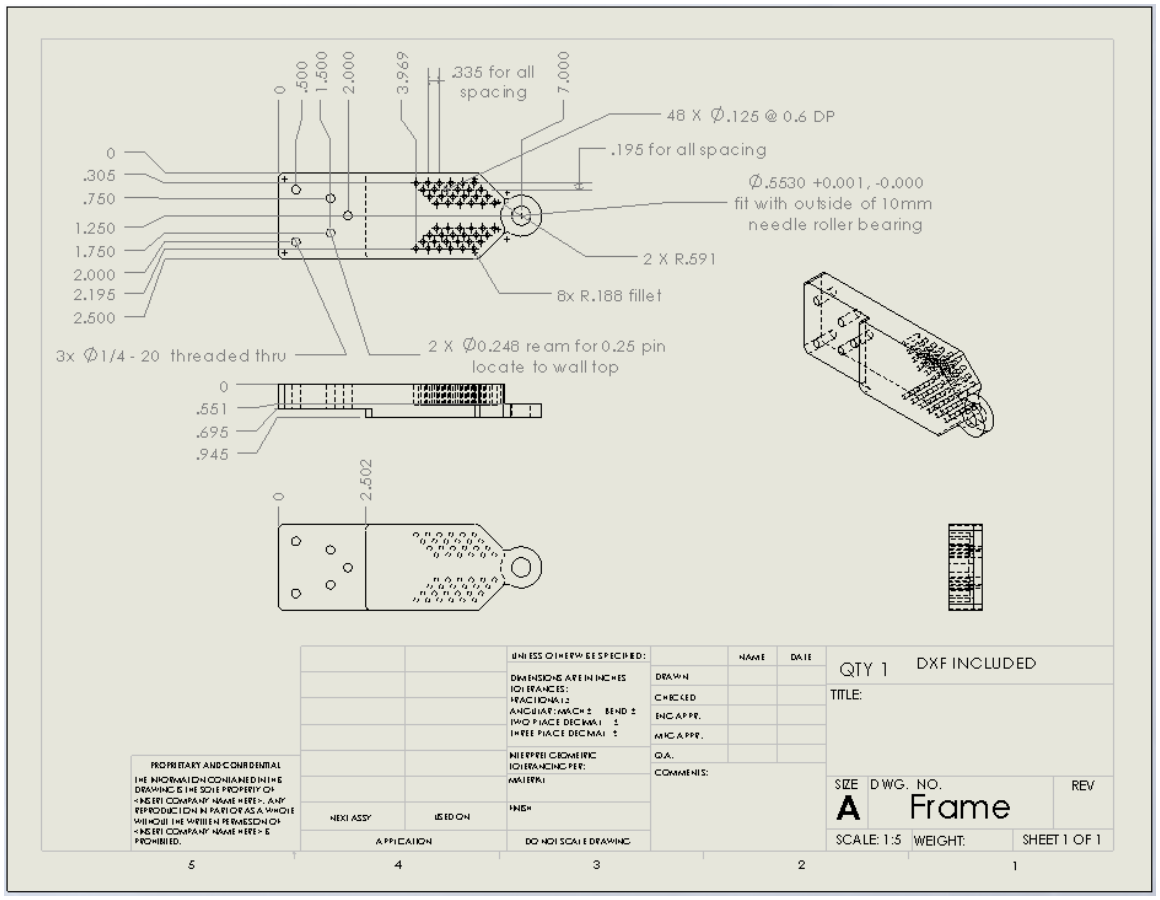
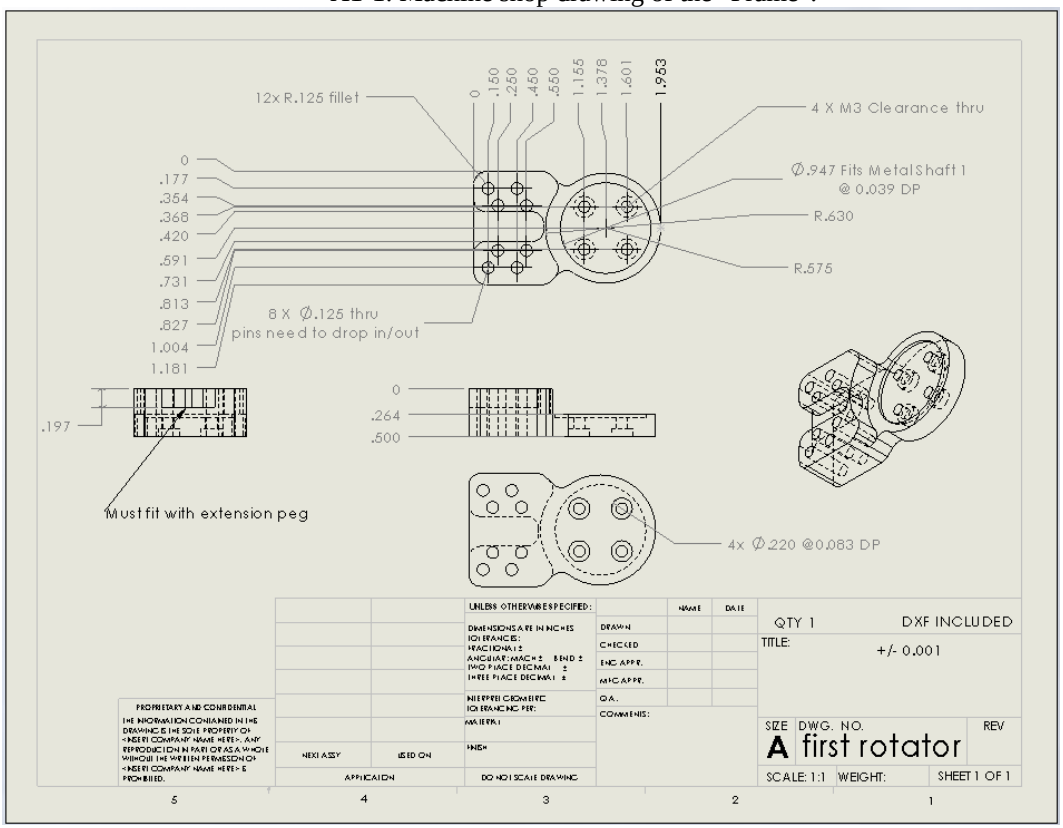
Appendix A – Sample Drawings of Parts

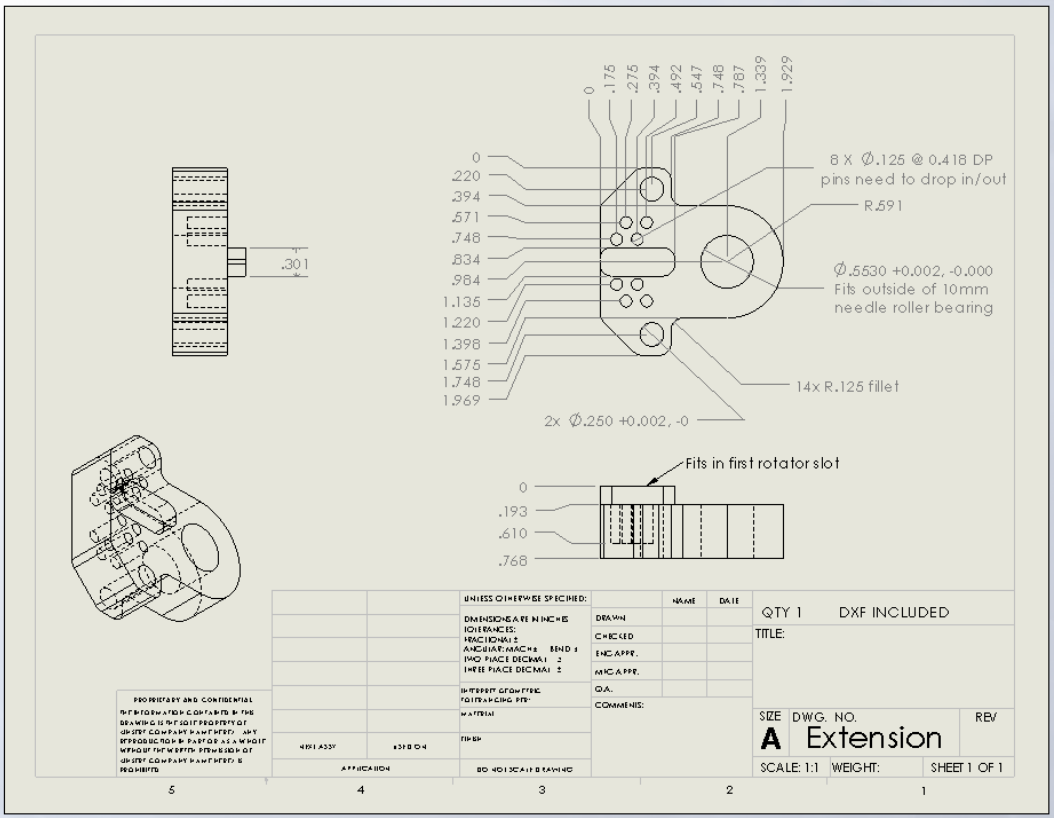
The following diagrams are samples of the engineering drawings submitted to the machine shop for fabrication of the parts. In some cases these files were also converted to DXF files for use in CNC milling operations.



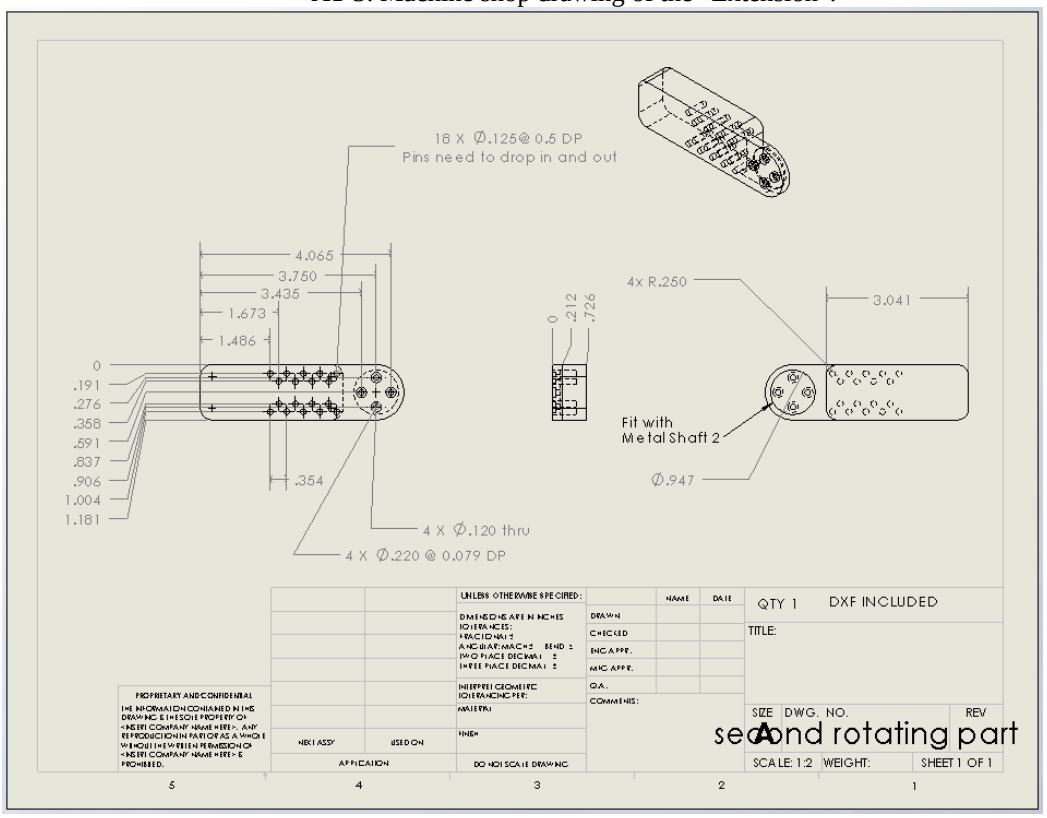
A1-1: Machine shop drawing of the “Frame”.



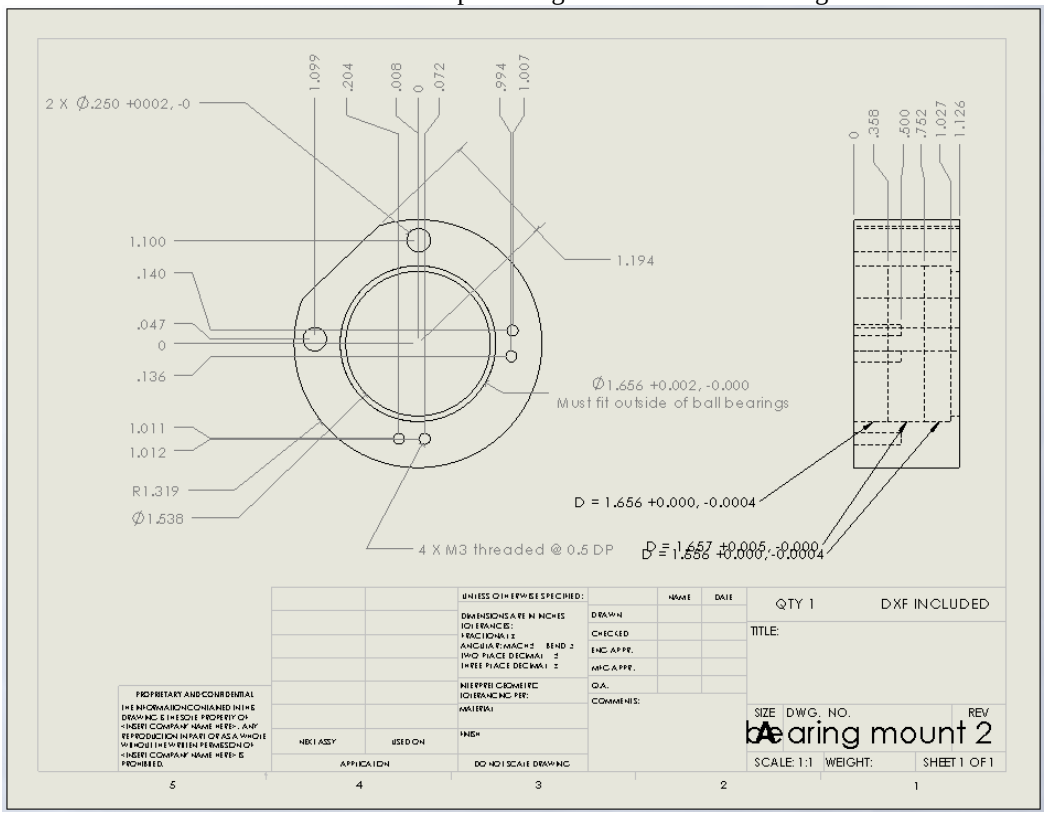
A1-2: Machine shop drawing of the “First Rotator”.



A1-3: Machine shop drawing of the “Extension”.



A1-4: Machine shop drawing of the “Second Rotating Part”.



A1-1: Machine shop drawing of the “bearing Mount” for the second motor.

Appendix B – C Code for User Interface

```
void main()
{
 initialize();
 init_variables();
 init_UART();
 init_LCD();
 putc_LCD("\rUVic Mech. Eng.");
 putc_LCD("\nHand Rehab. Unit");
 delay_ms(1000);
 KEY_STROBE=0;
 /**** Main Menu ****
do {
 Switch (menu_state)
 {
  CASE 0:
   case0_message();
   while(!SW_ONE);
   ++menu_state;
   break;

  CASE 1:
   case1_message();
   Safety_Sensor_2();
   while((!SAFE_SNS1) && (!SAFETY_SNS_2))
   {
    Back_switch();
    Safety_Sensor_2();
   }
   if (SAFETY_SNS_2)
   {
    HAND_IN_USE = 0;
    MOT_DIR1 = 1;
    MOT_DIR2 = 1;
   }
   else
   {
    HAND_IN_USE = 1;
MOT_DIR1 = 0;
    MOT_DIR2 = 0;
   }
   ++menu_state;
break;

  CASE 2:
   case2_message();
   delay_ms(1000);
   if(SW_BACK)
   {
    menu_state=0;
    break;
   }
   PWM1_value = 95;
   program_PWM_val(1);
   get_torque_value();
   While(MCP_torque>23000)
   {
    get_torque_value();
   }
   PWM_off();
   delay_ms(100);
   mcp_encoder_value = 200;
   PWM2_value = 95;
   program_PWM_val(2);
   While(PIP_torque>24000)
   {
    get_torque_value();
   }
   PWM_off();
   delay_ms(100);
   pip_encoder_value = 200;
   input_number=torque_limit;
   ++menu_state;
  break;

  CASE 3:
   case3_message();
   long_low_number = input_number;
   number_input_message();
   while (!KEY_STROBE);
   if (SW_ONE)
   {
    ++menu_state;
    torque_limit=input_number;
    MCP_torque_limit_high=37500+((long)torque_limit*250);
    PIP_torque_limit_high=36000+((long)torque_limit*250);
    MCP_torque_limit_low=22000-((long)torque_limit*180);
    PIP_torque_limit_low=23000-((long)torque_limit*180);
    MCP_current_limit=(MCP_torque_limit_high/100)-306;  //
uncalibrqated
    PIP_current_limit=(PIP_torque_limit_high/79)-391;   //
uncalibrated
   }
   input_percentage();
   if(SW_BACK)
   {
    menu_state=0;
   }
   break;

  CASE 4:
   case4_message();
   while(!KEY_STROBE);
   if(SW_ONE) menu_state=5;
   if(SW_TWO) menu_state=6;
   if(SW_THREE)
   {
    spring_constant=0;
    input_number=0;
    menu_state=7;
   }
   if(SW_BACK)
   {
    --menu_state;
    input_number=torque_limit;
    break;
   }
   break;

  CASE 5:
   putc_LCD("\fGo to start position");      // CPM start position
   position_message();
   while(!KEY_STROBE);
   if (SW_ONE)
   {
    CPM_MCP_positions[0]=(mcp_encoder_value);
    CPM_PIP_positions[0]=(pip_encoder_value);
    menu_state = 12;
    position_index = 1;
```

```
    }
    Back_switch();
    Manual_drive();
    break;

  CASE 6:
    putc_LCD("\fGo to start position");      // resistance start
position
    position_message();
    while(!KEY_STROBE);
    if (SW_ONE)
    {
     MCP_starting_position = mcp_encoder_value;
     PIP_starting_position = pip_encoder_value;
     menu_state = 18;
    }
    Back_switch();
    Manual_drive();
    break;

  CASE 7:
    case7_message();
    long_low_number = input_number;
    number_input_message();
    while(!KEY_STROBE);
    if (SW_ONE)
    {
     ++menu_state;
     spring_constant=input_number;
    }
    input_percentage();
    if(SW_BACK)
    {
     menu_state = 4;
    }
    break;

  CASE 8:
    putc_LCD("\fGo to start position");        // haptic start position
    position_message();
    while(!KEY_STROBE);
    if (SW_ONE)
    {
     if (!HAND_IN_USE)
     {
      MCP_starting_position=(mcp_encoder_value)/6;
      PIP_starting_position=(pip_encoder_value)/6;
     }
     else
     {
      MCP_starting_position=(mcp_encoder_value)/6;
      PIP_starting_position=(pip_encoder_value)/6;
     }
     ++menu_state;
    }
    Manual_drive();
    if(SW_BACK)
    {
     --menu_state;
     input_number=spring_constant;
     break;
    }
    break;

  CASE 9:
    putc_LCD("\fGo to end position");          // haptic ending
position
    position_message();
    while(!KEY_STROBE);
    if (SW_ONE)
    {
     if (!HAND_IN_USE)
     {
      MCP_ending_position=(mcp_encoder_value)/6;
      PIP_ending_position=(pip_encoder_value)/6;
     }
     else
     {
      MCP_ending_position=(mcp_encoder_value)/6;
      PIP_ending_position=(pip_encoder_value)/6;
     }
     ++menu_state;
    }
    Manual_drive();
    Back_switch();
    break;

  CASE 10:
    putc_LCD("\fDriving to start...");     // go to start position
    MCP_drive_to = (long)(MCP_starting_position);
    PIP_drive_to = (long)(PIP_starting_position);
    drive_to();
    putc_LCD("\fPress 1 to start.");
    putc_LCD("\nPress 2 for Mode.");
    while(!KEY_STROBE)  ;
    if (SW_ONE)
    {
     ++menu_state;
     MCP_torque_set=0;   // check
     PIP_torque_set=0;   // check
     MCP_p=1;
     MCP_d=1;
     MCP_err=0;
     MCP_PW=0;
     MCP_dir=HAND_IN_USE;
     PIP_p=1;
     PIP_d=1;
     PIP_err=0;
     PIP_PW=0;
     PIP_dir=HAND_IN_USE;

     putc_LCD("\fRunning...");
     PWM_max=200;
     putchr(200);
     if (!HAND_IN_USE) putchr(0);
     else putchr(1);
     putchr(MCP_starting_position);
     putchr(PIP_starting_position);
     putchr(MCP_ending_position);
     putchr(PIP_ending_position);
     putchr(spring_constant);
    }
    Back_switch();
    if(SW_TWO)
    {
     menu_state=4;
    }
    break;

  CASE 11:
    get_current_value();
    get_torque_value();
    if (SHUTDOWN)  //kill switch
    {
     PWM_off();
     haptics_stopped_message();
     putc_LCD("\nKill switch pressed.");
     putc_LCD("\nRestart machine");
     while (1);
    }
```

```
 if (SW_BACK)
 {
   PWM_off();
   haptics_stopped_message();
   putc_LCD("\nback pressed.");
   delay_ms(1000);
   menu_state=8;
   break;
 }
 /*if (MCP_torque>MCP_torque_limit)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge MCP torque.");
  delay_ms(1000);
  --menu_state;
  break;
 }
 if (PIP_torque>PIP_torque_limit)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge PIP torque");
  delay_ms(1000);
  --menu_state;
  break;
 }
 if (MCP_current>MCP_current_limit)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge MCP current");
  delay_ms(1000);
  --menu_state;
  break;
 }
 if (PIP_current>PIP_current_limit)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge PIP current");
  delay_ms(1000);
  --menu_state;
  break;
 }*/
 Haptic_loop();
 break;

CASE 12:
 putc_LCD("\fGo to end position");          // cpm ending position
 long_low_number = position_index;
 print_number_LCD(dec,1);
 position_message();
 while(!KEY_STROBE);
 if (SW_ONE)
 {
  CPM_MCP_positions[position_index]=mcp_encoder_value;
  CPM_PIP_positions[position_index]=pip_encoder_value;
  ++menu_state;
 }
 if (SW_BACK)
 {
  if (position_index == 1)
  {
    menu_state = 5;
  }
  else
  {
    --position_index;
  }
  }
  Manual_drive();
  break;

 CASE 13:
  if (position_index == 3)
  {
   menu_state = 14;
   position_number = position_index;
   input_number = rep_duration/1000;
   break;
  }
  case13_message();
  while(!KEY_STROBE);
  if (SW_ONE)
  {
   ++position_index;
   --menu_state;
  }
  if (SW_TWO)
  {
   menu_state = 14;
   input_number=rep_duration/1000;
   position_number = position_index;
  }
  Back_switch();
  break;

 CASE 14:
  putc_LCD("\fRep duration: ");
  long_low_number=input_number;
  print_number_LCD(dec,2);
  putc_LCD("s");
  putc_LCD("\n2 adds 1 second");
  putc_LCD("\n4 subtracts 1 second");
  putc_LCD("\n1 for OK.");
  while(!KEY_STROBE);
  if (SW_ONE)
  {
    ++menu_state;
    rep_duration=input_number * 1000;    // 2000-20000 milli
seconds   ie 1-20 seconds
  }
  if(SW_TWO)
  {
   if (input_number<20) input_number=input_number+1;
  }
  if(SW_FOUR)
  {
   if(input_number>2) input_number=input_number-1;
  }
  if(SW_BACK)
  {
   menu_state = 12;
  }
  break;

 CASE 15:
  putc_LCD("\fDriving to start...");     // go to start position
  MCP_drive_to = (long)(CPM_MCP_positions[0]);
  PIP_drive_to = (long)(CPM_PIP_positions[0]);
  drive_to();
  putc_LCD("\fPress 1 to start.");
  putc_LCD("\nPress 2 for Mode.");
  while(!KEY_STROBE) ;
  if (SW_ONE)
  {
   ++menu_state;
   Putc_LCD("\fRunning...");
   putc_LCD("\nRepititions: 000");
```

```
  CPM_init_case2();
 }
 if (SW_TWO)
 {
  menu_state = 4;
 }
 if (SW_BACK)
 {
  --menu_state;
  input_number=rep_duration/1000;
  PWM_off();
 }
 break;

CASE 16:  // repeatedly calls the CPM Loop
 get_current_value();
 get_torque_value();
 CPM_loop_case2();
 if (SW_BACK)
 {
  menu_state = 14;
  position_index=position_number;
  PWM_off();
 }
 if (MCP_torque>MCP_torque_limit_high)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge MCP torque. +");
  putc_LCD("\nValue: ");
  long_low_number=MCP_torque;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=MCP_torque_limit_high;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=14;
  input_number=rep_duration/1000;
  position_index=position_number;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (MCP_torque<MCP_torque_limit_low)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge MCP torque. -");
  putc_LCD("\nValue: ");
  long_low_number=MCP_torque;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=MCP_torque_limit_low;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=14;
  input_number=rep_duration/1000;
  position_index=position_number;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (PIP_torque>PIP_torque_limit_high)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge PIP torque. +");
  putc_LCD("\nValue: ");
  long_low_number=PIP_torque;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=PIP_torque_limit_high;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=14;
  input_number=rep_duration/1000;
  position_index=position_number;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (PIP_torque<PIP_torque_limit_low)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge PIP torque. -");
  putc_LCD("\nValue: ");
  long_low_number=PIP_torque;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=PIP_torque_limit_low;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=14;
  input_number=rep_duration/1000;
  position_index=position_number;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (MCP_current>MCP_current_limit)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge MCP current.");
  putc_LCD("\nValue: ");
  long_low_number=MCP_current;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=MCP_current_limit;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=14;
  input_number=rep_duration/1000;
  position_index=position_number;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (PIP_current>PIP_current_limit)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge PIP current.");
  putc_LCD("\nValue: ");
  long_low_number=PIP_current;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=PIP_current_limit;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=14;
  input_number=rep_duration/1000;
  position_index=position_number;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 break;


 CASE 18:
  putc_LCD("\fGo to end position");        // Active ending
position
  position_message();
  while(!KEY_STROBE);
```

```
 if (SW_ONE)
 {
  MCP_ending_position = mcp_encoder_value;
  PIP_ending_position = pip_encoder_value;
  ++menu_state;
  set_resistance = 50;
  input_number = 50;
 }
 if (SW_BACK)
 {
  menu_state = 6;
 }
 Manual_drive();
 break;


CASE 19:
 putc_LCD("\fResistance:");
 long_low_number=input_number;
 number_input_message();
 while(!KEY_STROBE);
 if (SW_ONE)
 {
  ++menu_state;
  set_resistance=input_number;
 }
 input_percentage();
 if(SW_BACK)
 {
  menu_state = 18;
 }
 break;

CASE 20:
 putc_LCD("\fDriving to start...");     // go to start position
 MCP_drive_to = (MCP_starting_position);
 PIP_drive_to = (PIP_starting_position);
 drive_to();
 putc_LCD("\fPress 1 to start.");
 putc_LCD("\nPress 2 for Mode.");
 while(!KEY_STROBE) ;
 if (SW_ONE)
 {
  ++menu_state;
  Putc_LCD("\fRunning...");
  //CPM_init();
  resistance_init();
 }
 if (SW_TWO)
 {
  menu_state = 4;
 }
 if (SW_BACK)
 {
  --menu_state;
  input_number=set_resistance;
  PWM_off();
 }
 break;

CASE 21:  // repeatedly calls the active resistance Loop
 get_current_value();
 get_torque_value();
 resistance_loop();
 if (SW_BACK)
 {
  menu_state = 19;
  PWM_off();
 }
 if (MCP_torque>MCP_torque_limit_high)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge MCP torque. +");
  putc_LCD("\nValue: ");
  long_low_number=MCP_torque;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=MCP_torque_limit_high;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=19;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (MCP_torque<MCP_torque_limit_low)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge MCP torque. -");
  putc_LCD("\nValue: ");
  long_low_number=MCP_torque;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=MCP_torque_limit_low;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=19;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (PIP_torque>PIP_torque_limit_high)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge PIP torque. +");
  putc_LCD("\nValue: ");
  long_low_number=PIP_torque;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=PIP_torque_limit_high;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=19;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (PIP_torque<PIP_torque_limit_low)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge PIP torque. -");
  putc_LCD("\nValue: ");
  long_low_number=PIP_torque;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=PIP_torque_limit_low;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=19;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (MCP_current>MCP_current_limit)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge MCP current.");
  putc_LCD("\nValue: ");
  long_low_number=MCP_current;
```

```
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=MCP_current_limit;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=19;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
 }
 if (PIP_current>PIP_current_limit)
 {
  PWM_off();
  haptics_stopped_message();
  putc_LCD("\nlarge PIP current.");
  putc_LCD("\nValue: ");
  long_low_number=PIP_current;
  print_number_LCD(dec,5);
  putc_LCD("\nLimit: ");
  long_low_number=PIP_current_limit;
  print_number_LCD(dec,5);
  delay_ms(2000);
  menu_state=19;
  While (!SW_BACK)  KEY_STROBE=0;
  break;
    }
   break;
  }
  KEY_STROBE=0;
 }
 while(TRUE);
}
```

Appendix C – CPM Loop C Code

```
void CPM_loop_case2()
{
 if (position_index==10)
 {
  //   initialization of constants for loop
MCP_err = 0;
   MCP_err_neg=0;
MCP_old_err=MCP_err;
   MCP_old_err_neg=MCP_err_neg;
   MCP_actual = MCP_encoder_value;
   MCP_desired = CPM_MCP_positions[0];
PIP_err = 0;
   PIP_err_neg=0;
PIP_old_err=PIP_err;
   PIP_old_err_neg=PIP_err_neg;
   PIP_actual = PIP_encoder_value;
   PIP_desired = CPM_PIP_positions[0];
   position_index=1;
   position_old=0;
   time_elapsed=0;
   time_elapsed_new=0;
   update_direction();
 }
 else if (time_elapsed <= rep_duration)
 {
  time_elapsed_old=time_elapsed_new;
  time_elapsed_new=time_elapsed;
  temp2 = (float)(time_elapsed_new)/(float)(rep_duration);
  MCP_desired_flt = 10*(temp2*temp2*temp2) +
6*(temp2*temp2*temp2*temp2*temp2) -
15*(temp2*temp2*temp2*temp2);
   PIP_desired_flt = MCP_desired_flt;
   if
(CPM_MCP_positions[position_index]>CPM_MCP_positions[pos
ition_old])
   {
    MCP_desired_flt = MCP_desired_flt *
((float)(CPM_MCP_positions[position_index])-
(float)(CPM_MCP_positions[position_old]));
    MCP_desired_flt = MCP_desired_flt +
(float)(CPM_MCP_positions[position_old]);
   }else
   {
    MCP_desired_flt = MCP_desired_flt *
((float)(CPM_MCP_positions[position_old])-
(float)(CPM_MCP_positions[position_index]));
    MCP_desired_flt =
(float)(CPM_MCP_positions[position_old]) - MCP_desired_flt;
   }
   MCP_desired = (long)(MCP_desired_flt);
   if
(CPM_PIP_positions[position_index]>CPM_PIP_positions[positio
n_old])
   {
    PIP_desired_flt = PIP_desired_flt *
((float)(CPM_PIP_positions[position_index])-
(float)(CPM_PIP_positions[position_old]));
    PIP_desired_flt = PIP_desired_flt +
(float)(CPM_PIP_positions[position_old]);
   }else
   {
    PIP_desired_flt = PIP_desired_flt *
((float)(CPM_PIP_positions[position_old])-
(float)(CPM_PIP_positions[position_index]));
    PIP_desired_flt = (float)(CPM_PIP_positions[position_old]) -
PIP_desired_flt;
   }
   PIP_desired = (long)(PIP_desired_flt);
   ////////PD comparison of MCP adn PIP desired to actual; //////////
  PD_loop_case2();
 }
 else if (position_index == 0)
 {
  if (position_old < position_number)
  {
   position_index=position_old + 1;
  }else
  {
   position_index= 1;
   ++repititions;
   putc_LCD("\fRunning...");
   putc_LCD("\nRepititions: ");
   long_low_number=repititions;
   print_number_LCD(dec,3);
  }
  position_old=0;
  time_elapsed=0;
 }else
 {
  position_old = position_index;
  position_index=0;
  time_elapsed=0;
  //update_direction_case2();
 }
mcp_encoder_value, pip_encoder_value, MCP_torque,
PIP_torque.
 print_data_hyperterminal();
}
update_direction()
{
 if (!HAND_IN_USE)
 {
  if (CPM_MCP_positions[position_index] >
CPM_MCP_positions[position_old])
  {
   MOT_DIR1 = 0;
  }else
  {
   MOT_DIR1 = 1;
  }
  if (CPM_PIP_positions[position_index] >
CPM_PIP_positions[position_old])
  {
MOT_DIR2 = 0;
}else
  {
   MOT_DIR2 = 1;
}
 }else
 {
  if (CPM_MCP_positions[position_index] >
CPM_MCP_positions[position_old])
  {
MOT_DIR1 = 1;
}else
  {
   MOT_DIR1 = 0;
}
  if (CPM_PIP_positions[position_index] >
CPM_PIP_positions[position_old])
  {
   MOT_DIR2 = 1;
  }else
  {
   MOT_DIR2 = 0;
  }
```

```
 }
 PWM_off();
 reset_CPM_MCP();
 reset_CPM_PIP();
}


void PD_loop_case2()    // CPM PID loop code
{
 MCP_PW = 0;
 PIP_PW = 0;

 //   MCP  Proportional
 MCP_old_err=MCP_err;
 MCP_old_err_neg=MCP_err_neg;
 MCP_actual = MCP_encoder_value;

 if(MCP_desired > MCP_actual)
 {
  MCP_err = MCP_desired - MCP_actual;
  MCP_err_neg = 0;
  MCP_PW = MCP_err*MCP_p/MCP_p2;
  MCP_PW_neg =0;

  // integral MCP
  if (MCP_i_err_neg==0)
{
    MCP_i_err = MCP_i_err + MCP_err;
if (MCP_i_err>8184)   /// added Jan 14
    {
     PWM1_value=8184;
    }
    MCP_i_err_neg=0;
    MCP_PW = MCP_PW + MCP_i_err * MCP_i / MCP_i2;
    MCP_PW_neg =0;
  } else if(MCP_err > MCP_i_err)
{
    MCP_i_err = MCP_err - MCP_i_err;
    MCP_i_err_neg=0;
    MCP_PW = MCP_PW + MCP_i_err * MCP_i / MCP_i2;
    MCP_PW_neg =0;
  } else
  {
    MCP_i_err = MCP_i_err - MCP_err;
    MCP_i_err_neg = 1;
    CPM_temp = MCP_i_err * MCP_i / MCP_i2;
if (MCP_PW > CPM_temp)
    {
     MCP_PW = MCP_PW - CPM_temp;
     MCP_PW_neg = 0;
    } else
    {
     MCP_PW = CPM_temp - MCP_PW;
     MCP_PW_neg = 1;
    }
  }
 }else
 {
  MCP_err = MCP_actual - MCP_desired;
  MCP_err_neg=1;
  MCP_PW = MCP_err*MCP_p/MCP_p2;
  MCP_PW_neg =1;

  // MCP integral
  if (MCP_i_err_neg==1)
{
    MCP_i_err = MCP_i_err + MCP_err;
if (MCP_i_err>8184)
    {
     PWM1_value=8184;
    }
    MCP_i_err_neg=1;
    MCP_PW = MCP_PW + MCP_i_err * MCP_i / MCP_i2;
    MCP_PW_neg =1;
  } else if(MCP_err > MCP_i_err)
{
    MCP_i_err = MCP_err - MCP_i_err;
    MCP_i_err_neg=1;
    MCP_PW = MCP_PW + MCP_i_err * MCP_i / MCP_i2;
    MCP_PW_neg =1;
  } else
  {
    MCP_i_err = MCP_i_err - MCP_err;
    MCP_i_err_neg = 0;
    CPM_temp = MCP_i_err * MCP_i / MCP_i2;
if (MCP_PW > CPM_temp)
    {
     MCP_PW = MCP_PW - CPM_temp;
     MCP_PW_neg = 1;
    } else
    {
     MCP_PW = CPM_temp - MCP_PW;
     MCP_PW_neg = 0;
    }
  }
 }

// differential conroller MCP
 if (MCP_err_neg == 0)
 {
  if (MCP_old_err_neg==0)
  {
   if (MCP_err > MCP_old_err)
   {
    MCP_d_err = ((MCP_err - MCP_old_err) * MCP_d )/
(MCP_d2 * (time_elapsed_new - time_elapsed_old));
    MCP_d_err_neg = 0;
   }else
   {
    MCP_d_err = ((MCP_old_err - MCP_err) * MCP_d )/
(MCP_d2 * (time_elapsed_new - time_elapsed_old));
    MCP_d_err_neg = 1;
   }
  } else
  {
   MCP_d_err = ((MCP_old_err + MCP_err) * MCP_d )/
(MCP_d2 * (time_elapsed_new - time_elapsed_old));
   MCP_d_err_neg = 0;
  }
 }else
 {
  if (MCP_old_err_neg==0)
  {
   MCP_d_err = ((MCP_old_err + MCP_err) * MCP_d )/
(MCP_d2 * (time_elapsed_new - time_elapsed_old));
   MCP_d_err_neg = 1;
  }else
  {
   if (MCP_err > MCP_old_err)
   {
    MCP_d_err = ((MCP_err - MCP_old_err) * MCP_d )/
(MCP_d2 * (time_elapsed_new - time_elapsed_old));
    MCP_d_err_neg = 1;
   }else
   {
    MCP_d_err = ((MCP_err - MCP_old_err) * MCP_d )/
(MCP_d2 * (time_elapsed_new - time_elapsed_old));
    MCP_d_err_neg = 0;
   }
  }
```

```
 }
 if (MCP_d_err_neg ==0)
 {
  if(MCP_PW_neg == 0)  // both pos
  {
   MCP_PW = MCP_PW + MCP_d_err;
   MCP_PW_neg = 0;
  }else
  {
   if (MCP_d_err > MCP_PW)
   {
    MCP_PW = MCP_d_err - MCP_PW;
    MCP_PW_neg = 0;
   }else
   {
    MCP_PW = MCP_PW - MCP_d_err;
    MCP_PW_neg = 1;
   }
  }
 }else
 {
  if(MCP_PW_neg == 1)  // both neg
  {
   MCP_PW = MCP_PW + MCP_d_err;
   MCP_PW_neg = 1;
  }else
  {
   if (MCP_d_err > MCP_PW)
   {
    MCP_PW = MCP_d_err - MCP_PW;
    MCP_PW_neg = 1;
   }else
   {
    MCP_PW = MCP_PW - MCP_d_err;
    MCP_PW_neg = 0;
   }
  }
 }

   //   PIP  Proportional and integral controler
 PIP_old_err=PIP_err;
 PIP_old_err_neg=PIP_err_neg;
 PIP_actual = PIP_encoder_value;
 if(PIP_desired > PIP_actual)
 {
  PIP_err = PIP_desired - PIP_actual;
  PIP_err_neg = 0;
  PIP_PW = PIP_err*PIP_p/PIP_p2;
  PIP_PW_neg =0;

  // integral PIP
  if (PIP_i_err_neg==0)
{
    PIP_i_err = PIP_i_err + PIP_err;
    PIP_i_err_neg=0;
    PIP_PW = PIP_PW + PIP_i_err * PIP_i / PIP_i2;
    PIP_PW_neg =0;
} else if(PIP_err > PIP_i_err)
{
    PIP_i_err = PIP_err - PIP_i_err;
    PIP_i_err_neg=0;
    PIP_PW = PIP_PW + PIP_i_err * PIP_i / PIP_i2;
    PIP_PW_neg =0;
} else
  {
    PIP_i_err = PIP_i_err - PIP_err;
    PIP_i_err_neg = 1;
    CPM_temp = PIP_i_err * PIP_i / PIP_i2;
    if (PIP_PW > CPM_temp)
    {
     PIP_PW = PIP_PW - CPM_temp;
     PIP_PW_neg = 0;
    } else
    {
     PIP_PW = CPM_temp - PIP_PW;
     PIP_PW_neg = 1;
    }
  }
 }else
 {
  PIP_err = PIP_actual - PIP_desired;
  PIP_err_neg=1;
  PIP_PW = PIP_err*PIP_p/PIP_p2;
  PIP_PW_neg =1;

  // integral
  if (PIP_i_err_neg==1)
{
    PIP_i_err = PIP_i_err + PIP_err;
    PIP_i_err_neg=1;
    PIP_PW = PIP_PW + PIP_i_err * PIP_i / PIP_i2;
    PIP_PW_neg =1;
} else if(PIP_err > PIP_i_err)
{
    PIP_i_err = PIP_err - PIP_i_err;
    PIP_i_err_neg=1;
    PIP_PW = PIP_PW + PIP_i_err * PIP_i / PIP_i2;
    PIP_PW_neg =1;
} else
  {
    PIP_i_err = PIP_i_err - PIP_err;
    PIP_i_err_neg = 0;
    CPM_temp = PIP_i_err * PIP_i / PIP_i2;
    if (PIP_PW > CPM_temp)
    {
     PIP_PW = PIP_PW - CPM_temp;
     PIP_PW_neg = 1;
    } else
    {
     PIP_PW = CPM_temp - PIP_PW;
     PIP_PW_neg = 0;
    }
  }
 }

// differential conroller PIP
 if (PIP_err_neg == 0)
 {
  if (PIP_old_err_neg==0)
  {
   if (PIP_err > PIP_old_err)
   {
    PIP_d_err = ((PIP_err - PIP_old_err) * PIP_d )/ (PIP_d2 *
(time_elapsed_new - time_elapsed_old));
    PIP_d_err_neg = 0;
   }else
   {
    PIP_d_err = ((PIP_old_err - PIP_err) * PIP_d )/ (PIP_d2 *
(time_elapsed_new - time_elapsed_old));
    PIP_d_err_neg = 1;
   }

  } else
  {
   PIP_d_err = ((PIP_old_err + PIP_err) * PIP_d )/ (PIP_d2 *
(time_elapsed_new - time_elapsed_old));
   PIP_d_err_neg = 0;
  }
 }else
 {
```

```
    if (PIP_old_err_neg==0)
    {
     PIP_d_err = ((PIP_old_err + PIP_err) * PIP_d )/ (PIP_d2 *
(time_elapsed_new - time_elapsed_old));
     PIP_d_err_neg = 1;
    }else
    {
     if (PIP_err > PIP_old_err)
     {
      PIP_d_err = ((PIP_err - PIP_old_err) * PIP_d )/ (PIP_d2 *
(time_elapsed_new - time_elapsed_old));
      PIP_d_err_neg = 1;
     }else
     {
      PIP_d_err = ((PIP_err - PIP_old_err) * PIP_d )/ (PIP_d2 *
(time_elapsed_new - time_elapsed_old));
      PIP_d_err_neg = 0;
     }
    }
   }
   if (PIP_d_err_neg ==0)
   {
    if(PIP_PW_neg == 0)  // both pos
    {
     PIP_PW = PIP_PW + PIP_d_err;
     PIP_PW_neg = 0;
    }else
    {
     if (PIP_d_err > PIP_PW)
     {
      PIP_PW = PIP_d_err - PIP_PW;
      PIP_PW_neg = 0;
     }else
     {
      PIP_PW = PIP_PW - PIP_d_err;
      PIP_PW_neg = 1;
     }
    }
   }else
   {
    if(PIP_PW_neg == 1)  // both neg
    {
     PIP_PW = PIP_PW + PIP_d_err;
     PIP_PW_neg = 1;
    }else
    {
     if (PIP_d_err > PIP_PW)
     {
      PIP_PW = PIP_d_err - PIP_PW;
      PIP_PW_neg = 1;
     }else
     {
      PIP_PW = PIP_PW - PIP_d_err;
      PIP_PW_neg = 0;
     }
    }
   }

// setting motor values
  if (MCP_PW>8184)
  {
   PWM1_value=1023;
  }else
  {
   PWM1_value = MCP_PW/8;
  }
  MOT_DIR1 = (HAND_IN_USE + MCP_PW_neg) % 2;
  program_PWM_val(1);
  if (PIP_PW>8184)
  {
   PWM2_value=1023;
  }else
  {
   PWM2_value = PIP_PW/8;
  }
  MOT_DIR2 = (HAND_IN_USE + PIP_PW_neg) % 2;
  program_PWM_val(2);
}

void reset_CPM_MCP()
{
  MCP_PW = 0;
  MCP_err = 0;
  MCP_i_err = 0;
  PWM1_value = 0;
}

void reset_CPM_PIP()
{
  PIP_PW = 0;
  PIP_err = 0;
  PIP_i_err = 0;
  PWM2_value = 0;
}
```

Appendix D – Active Resistance C Code

```
void Haptic_loop()          // main loop during haptics
{
 getchr();

 if (!comm_err_0)
 {
  //putc_LCD("\fchar recieved.");   // testing only
  //delay_ms(500);                  // testing only
  switch(char_in)
  {
    case 201:  report_joint_angles();   // sends joint angles to PC
               break;
    case 202:  get_desired_torque();    // recieves torque from PC
               break;
    default :  break;
  }
 }

 /******  PD LOOP  *********/
/*  if (MCP_torque_set < 110 && PIP_torque_set < 110)  // turns
motors off if near start position
 {
   PWM_off();
   time_elapsed=0;
 }else                                  //  does proportional section of
controller
 {
  MCP_old_err=MCP_err;

  if(MCP_torque_set > MCP_torque)
  {
    MCP_err = MCP_torque_set - MCP_torque;
    MCP_PW = MCP_PW + MCP_err*MCP_p/4;
  }
  else
  {
    MCP_err = MCP_torque - MCP_torque_set;
    if (MCP_PW > (MCP_err*MCP_p/4))
    {
      MCP_PW = MCP_PW - MCP_err * MCP_p/4;
    }else
    {
      //MCP_PW = MCP_err * MCP_p - MCP_PW;
      //MCP_dir = !MCP_dir;
      MCP_PW=0;
    }
  }


  PIP_old_err=PIP_err;
  if(PIP_torque_set > PIP_torque)
  {
    PIP_err = PIP_torque_set - PIP_torque;
    PIP_PW = PIP_PW + PIP_err*PIP_p/4;
  }
  else
  {
    PIP_err = PIP_torque - PIP_torque_set;
    if (PIP_PW > (PIP_err*PIP_p/4))
    {
      PIP_PW = PIP_PW - PIP_err * PIP_p/4;
    }else
    {
      //PIP_PW = PIP_err * PIP_p - PIP_PW;
      //PIP_dir = !PIP_dir;
      PIP_PW=0;
    }
  }


  /*  if(MCP_old_err>MCP_err)   // does differential section of
controller
  {
    MCP_diff=(MCP_old_err - MCP_err) / time_elapsed;
    if (MCP_PW > (MCP_diff* MCP_d/30))
    {
      MCP_PW=MCP_PW - MCP_diff * MCP_d/30;
    }
    else
    {
      MCP_PW = 0;
    }
  }
  else
  {
    MCP_diff=(MCP_err - MCP_old_err) / time_elapsed;
    MCP_PW=MCP_PW + MCP_diff * MCP_d/30;
  }

  if(PIP_old_err > PIP_err)
  {
    PIP_diff=(PIP_err - PIP_old_err) / time_elapsed;
    if (PIP_PW > (PIP_diff* PIP_d/30))
    {
      PIP_PW=PIP_PW + PIP_diff * PIP_d/30;
    }
    else
    {
      PIP_PW = 0;
    }
  }
  else
  {
    PIP_diff=(PIP_old_err - PIP_err) / time_elapsed;
    PIP_PW = PIP_PW - PIP_diff * PIP_d/30;
  }
*/
/*   time_elapsed=0;   // used for differential to determine timestep
  MOT_DIR1 = MCP_dir;
  PWM1_value = MCP_PW/8;
  if (PWM1_value >1023) PWM1_value=1023;
  program_PWM_val(1);
  MOT_DIR2 = PIP_dir;
  PWM2_value = PIP_PW/8;
  if (PWM2_value >1023) PWM2_value=1023;
  program_PWM_val(2);

  //test to see what PWM is used
  /*putc_LCD("\f");
  long_low_number = MCP_PW;
  print_number_LCD(dec,4);

  putc_LCD("\n");
  long_low_number = PIP_PW;
  print_number_LCD(dec,4);
  delay_ms(500);*/
 /* }*/
}

// send encoder values to computer
void report_joint_angles()
{
 if (!HAND_IN_USE)
 {
```

```
  putchr((mcp_encoder_value)/6);
  putchr((pip_encoder_value)/6);
  }
  else
  {
  putchr((mcp_encoder_value)/6);
  putchr((pip_encoder_value)/6);
  }
}

void get_desired_torque()        //  revieves desired torques from PC
{
    putchr(203);
    while (TRUE)
    {
      getchr();
      if (!comm_err_0) break;
    }
    low_MCP_torque_set = char_in;
    while (TRUE)
    {
      getchr();
      if (!comm_err_0) break;
    }
    high_MCP_torque_set = char_in;
    putchr(203);
    while (TRUE)
    {
      getchr();
      if (!comm_err_0) break;
    }
    low_PIP_torque_set = char_in;
    while (TRUE)
    {
      getchr();
      if (!comm_err_0) break;
    }
    high_PIP_torque_set = char_in;
    if(!HAND_IN_USE)
    {
      MCP_torque_set=(MCP_torque_set / 13) + 300;   // out of date
      PIP_torque_set=(PIP_torque_set /  24) + 300;  // out of date
    }
    else
    {
      MCP_torque_set=(MCP_torque_set / 12) + 300;   // out of date
      PIP_torque_set=(PIP_torque_set /  30) + 300;  // out of date
}

}
```

Appendix E - Haptics C Code

C Code on Microcontroller

```
void Haptic_loop()
{
 getchr();
 if (!comm_err_0)
 {
  switch(char_in)
  {
   case 201:  report_joint_angles();   // sends joint angles to PC
              break;
   case 202:  get_desired_torque();    // recieves torque from PC
              break;
   default :  break;
  }
 }
/******  PD LOOP  *********/
 if (MCP_torque_set < 110 && PIP_torque_set < 110)
 {
    PWM_off();
    time_elapsed=0;
 }else
 {
  MCP_old_err=MCP_err;

  if(MCP_torque_set > MCP_torque)
  {
   MCP_err = MCP_torque_set - MCP_torque;
   MCP_PW = MCP_PW + MCP_err*MCP_p/4;
  }
  else
  {
   MCP_err = MCP_torque - MCP_torque_set;
   if (MCP_PW > (MCP_err*MCP_p/4))
   {
    MCP_PW = MCP_PW - MCP_err * MCP_p/4;
   }else
   {
    //MCP_PW = MCP_err * MCP_p - MCP_PW;
    //MCP_dir = !MCP_dir;
    MCP_PW=0;
   }
  }
  PIP_old_err=PIP_err;
  if(PIP_torque_set > PIP_torque)
  {
   PIP_err = PIP_torque_set - PIP_torque;
   PIP_PW = PIP_PW + PIP_err*PIP_p/4;
  }
  else
  {
   PIP_err = PIP_torque - PIP_torque_set;
   if (PIP_PW > (PIP_err*PIP_p/4))
   {
    PIP_PW = PIP_PW - PIP_err * PIP_p/4;
   }else
   {
    //PIP_PW = PIP_err * PIP_p - PIP_PW;
    //PIP_dir = !PIP_dir;
    PIP_PW=0;
   }
  }
 if(MCP_old_err>MCP_err)
  {
   MCP_diff=(MCP_old_err - MCP_err) / time_elapsed;
   if (MCP_PW > (MCP_diff* MCP_d/30))
   {
    MCP_PW=MCP_PW - MCP_diff * MCP_d/30;
   }
   else
   {
    MCP_PW = 0;
   }
  }
  else
  {
   MCP_diff=(MCP_err - MCP_old_err) / time_elapsed;
   MCP_PW=MCP_PW + MCP_diff * MCP_d/30;
  }
 if(PIP_old_err > PIP_err)
  {
   PIP_diff=(PIP_err - PIP_old_err) / time_elapsed;
   if (PIP_PW > (PIP_diff* PIP_d/30))
   {
    PIP_PW=PIP_PW + PIP_diff * PIP_d/30;
   }
   else
   {
    PIP_PW = 0;
   }
  }
  else
  {
   PIP_diff=(PIP_old_err - PIP_err) / time_elapsed;
   PIP_PW = PIP_PW - PIP_diff * PIP_d/30;
  }
  time_elapsed=0;
  MOT_DIR1 = MCP_dir;
  PWM1_value = MCP_PW/8;
  if (PWM1_value >1023) PWM1_value=1023;
  program_PWM_val(1);
  MOT_DIR2 = PIP_dir;
  PWM2_value = PIP_PW/8;
  if (PWM2_value >1023) PWM2_value=1023;
  program_PWM_val(2);
putc_LCD("\f");
  long_low_number = MCP_PW;
  print_number_LCD(dec,4);
  putc_LCD("\n");
  long_low_number = PIP_PW;
  print_number_LCD(dec,4);
 delay_ms(500);*/
}
}



void report_joint_angles()   //sends joint angles to PC
{
 if (!HAND_IN_USE)
 {
 putchr((mcp_encoder_value)/6);
 putchr((pip_encoder_value)/6);
 }
 else
 {
 putchr((mcp_encoder_value)/6);
 putchr((pip_encoder_value)/6);
 }
}
```

```
void get_desired_torque()  //  revieves desired torques from PC
{
   putchr(203);
   while (TRUE)
   {
    getchr();
    if (!comm_err_0) break;
   }
   low_MCP_torque_set = char_in;
   while (TRUE)
   {
    getchr();
    if (!comm_err_0) break;
   }
   high_MCP_torque_set = char_in;
   putchr(203);
   while (TRUE)
   {
    getchr();
    if (!comm_err_0) break;
   }
   low_PIP_torque_set = char_in;
   while (TRUE)
   {
    getchr();
    if (!comm_err_0) break;
   }
   high_PIP_torque_set = char_in;
   if(!HAND_IN_USE)
   {
    MCP_torque_set=(MCP_torque_set / 13) + 300;   // out of date
    PIP_torque_set=(PIP_torque_set /  24) + 300;  // out of date
   }
   else
   {
    MCP_torque_set=(MCP_torque_set / 12) + 300;   // out of date
    PIP_torque_set=(PIP_torque_set /  30) + 300;  // out of date
   }
}
```

Visual Basic on PC

```
While (MSComm1.InBufferCount < 6) And (reset_program =
False)
  DoEvents
Wend
' recieve initialization variables from microprocessor
If (reset_program = False) Then
  hand_in_use = Asc(MSComm1.Input)
  MCP_starting_position = CSng(Asc(MSComm1.Input))
  PIP_starting_position = CSng(Asc(MSComm1.Input))
  MCP_ending_position = CSng(Asc(MSComm1.Input))
  PIP_ending_position = CSng(Asc(MSComm1.Input))
  spring_constant = CInt(Asc(MSComm1.Input))
'convert to rad from counts
  If hand_in_use = 0 Then
    'convert to rad and adjust direction
    MCP_starting_position = pi / 2 - (MCP_starting_position - 33) *
pi / 370
    PIP_starting_position = pi / 2 - (PIP_starting_position - 33) * pi
/ 370
    MCP_ending_position = pi / 2 - (MCP_ending_position - 33) *
pi / 370
    PIP_ending_position = pi / 2 - (PIP_ending_position - 33) * pi /
370
  Else
    'convert to rad and adjust direction
    MCP_starting_position = pi - (MCP_starting_position - 33) * pi
/ 370
    PIP_starting_position = pi - (PIP_starting_position - 33) * pi /
370
    MCP_ending_position = pi - (MCP_ending_position - 33) * pi /
370
    PIP_ending_position = pi - (PIP_ending_position - 33) * pi / 370
  End If
  ' calculate initial spring length for force calculations
  initial_spring_length = (100 + 100 * Cos(MCP_starting_position)
+ 100 * Cos(MCP_starting_position + PIP_starting_position)) ^ 2
  initial_spring_length = initial_spring_length + (100 *
Sin(MCP_starting_position) + 100 * Sin(MCP_starting_position +
PIP_starting_position)) ^ 2
  initial_spring_length = initial_spring_length ^ 0.5
  reps = 0
  direction = 0
Else
  reset_program = True
  Command1.BackColor = &HFF00&
End If
'****  draw first start of hand  ***************
mp1.Visible = False
ip1.Visible = False
MP_X = 3000 - 2000 * Sin(MCP_starting_position) / 2
MP_Y = 3300 - 2565 * Cos(MCP_starting_position) / 2
IP_X = 3360 - 2000 * Sin(MCP_starting_position) - 1500 *
Sin(MCP_starting_position + PIP_starting_position) / 2
IP_Y = 3680 - 2205 * Cos(MCP_starting_position) - 1700 *
Cos(MCP_starting_position + PIP_starting_position) / 2
RotateSurface CDbl(MCP_starting_position),
CDbl(PIP_starting_position)
ready_position = False
'loop till close to start position - new code
While (ready_position = False) And (reset_program = False)
  MSComm1.InBufferCount = 0
  MSComm1.Output = Chr(201)
  While (MSComm1.InBufferCount < 2) And (reset_program =
False)
    DoEvents
  Wend
  If MSComm1.InBufferCount = 2 Then
    MCP_angle = CSng(Asc(MSComm1.Input))
    PIP_angle = CSng(Asc(MSComm1.Input))
    'convert to rad from counts
    If hand_in_use = 0 Then
      MCP_angle = (pi / 2) - (MCP_angle - 33) * pi / 370
      PIP_angle = (pi / 2) - (PIP_angle - 33) * pi / 370
    Else
      MCP_angle = (MCP_angle - 33) * pi / 370
      PIP_angle = (PIP_angle - 33) * pi / 370
    End If
    If hand_in_use = 1 Then
      MCP_angle = -1 * MCP_angle
      PIP_angle = -1 * PIP_angle
    End If
  Else
    reset_program = True
    Command1.BackColor = &HFF00&
  End If
  If ((MCP_starting_position - MCP_angle) < 0) And ((MCP_angle
- MCP_starting_position) < 2) Then
    If ((PIP_starting_position - PIP_angle) < 0) And ((PIP_angle -
PIP_starting_position) < 2) Then
      ready_position = True
    End If
  End If
Wend
'*********************************

While reset_program = False
  MSComm1.InBufferCount = 0
  MSComm1.Output = Chr(201)
    While (MSComm1.InBufferCount < 2) And (reset_program =
False)
    DoEvents
  Wend
  If MSComm1.InBufferCount = 2 Then
    MCP_angle = CSng(Asc(MSComm1.Input))
    PIP_angle = CSng(Asc(MSComm1.Input))

    'convert to rad from counts
    If hand_in_use = 0 Then
      MCP_angle = (pi / 2) - (MCP_angle - 33) * pi / 370
      PIP_angle = (pi / 2) - (PIP_angle - 33) * pi / 370
    Else
      MCP_angle = pi - (MCP_angle - 33) * pi / 370
      PIP_angle = pi - (PIP_angle - 33) * pi / 370
    End If
  Else
    reset_program = True
    Command1.BackColor = &HFF00&
  End If
Text1.Text = Format(MCP_angle)
Text2.Text = Format(PIP_angle)
  If reset_program = False Then
    Y_spring_length = 100 + 100 * Cos(MCP_angle) + 100 *
Cos(MCP_angle + PIP_angle)
    X_spring_length = 100 * Sin(MCP_angle) + 100 *
Sin(MCP_angle + PIP_angle)
    spring_length = ((X_spring_length ^ 2) + (Y_spring_length ^ 2))
^ 0.5
    force = ((spring_constant * 0.99) + 1) * (initial_spring_length -
spring_length)
    spring_angle = Atn(X_spring_length / Y_spring_length)
    PIP_torque = force * Sin(MCP_angle + PIP_angle -
spring_angle)
    MCP_torque = PIP_torque + force * Sin(MCP_angle -
spring_angle)
    'If hand_in_use = 0 Then
      'MCP_torque = 3.4286 * (MCP_torque) + 1.7185
```

```
'PIP_torque = 2.9488 * (PIP_torque) - 11.993
   'Else
     'MCP_torque = 3.9954 * (MCP_torque) + 5.5267
'PIP_torque = 4.3547 * (PIP_torque) + 4.1801
   'End If
   '4 chars sent - 2 for each
   MSComm1.Output = Chr(202)
   While MSComm1.OutBufferCount <> 0
     DoEvents
   Wend
   If MCP_torque < 0 Then
     MCP_torque = 0
   End If
   If PIP_torque < 0 Then
     PIP_torque = 0
   End If
Text3.Text = Format(MCP_torque)
Text4.Text = Format(PIP_torque)
   While MSComm1.InBufferCount < 1
     DoEvents
   Wend
   data_char = MSComm1.Input
   data_output = CInt(MCP_torque Mod 256)
   MCP_torque = MCP_torque / 256
   MSComm1.Output = Chr(data_output)
   While MSComm1.OutBufferCount <> 0
     DoEvents
   Wend
   data_output = CInt(MCP_torque Mod 256)
   MSComm1.Output = Chr(data_output)
   While MSComm1.OutBufferCount <> 0
     DoEvents
   Wend
   While MSComm1.InBufferCount < 1
     DoEvents
   Wend
   data_char = MSComm1.Input
   data_output = CInt(PIP_torque Mod 256)
   PIP_torque = PIP_torque / 256
   MSComm1.Output = Chr(data_output)
   While MSComm1.OutBufferCount <> 0
     DoEvents
   Wend
   data_output = CInt(PIP_torque Mod 256)
   MSComm1.Output = Chr(data_output)
   While MSComm1.OutBufferCount <> 0
     DoEvents
   Wend
   'UPdate visuals every 10 times
   If visual_count = 2 Then                ' should be 10, but 1 for
testing

     'update visuals here
*************************************************
     MP_X = 3000 - 2000 * Sin(MCP_angle) / 2
MP_Y = 3300 - 2565 * Cos(MCP_angle) / 2
IP_X = 3360 - 2000 * Sin(MCP_angle) - 1500 * Sin(MCP_angle +
PIP_angle) / 2
     IP_Y = 3680 - 2205 * Cos(MCP_angle) - 1700 *
Cos(MCP_angle + PIP_angle) / 2
     RotateSurface CDbl(MCP_angle), CDbl(PIP_angle)
     '*****************************************
     visual_count = 0
   Else
     visual_count = visual_count + 1
   End If
 End If
' While (MSComm1.InBufferCount < 1) And (reset_program =
False)
 '   DoEvents
 ' Wend
  data_char = MSComm1.Input
Wend
While reset_program = True
  DoEvents
Wend
Timer1.Enabled = True
End Sub


‘ The function itself. It takes a the parameters of a source picture,
the destination picture, the angle, and optional x & y co-ords for
the destination image
Public Function RotateSurface(theta As Double, theta2 As Double)
Dim X&, Y&, x1&, y1&, c&, r#
Dim iMethod%
theta2 = theta + theta2
'for every pixel in picture1, copy it to picture2 after moving it
around theta degrees
For X& = 0 To 189
  For Y& = 0 To 189
x1& = 95 + (X& - 95) * Cos(theta) - (Y& - 95) * Sin(theta)
    y1& = 95 + (Y& - 95) * Cos(theta) + (X& - 95) * Sin(theta)
If (x1&> 0) And (x1&< 190) And (y1&> 0) And (y1&< 190) Then
     'direct memory read/write
     c& = TextureData(X&, Y&)
     ViewData(x1&, y1&) = c&
   End If
  Next Y&
Next X&
mp2.Left = MP_X
mp2.Top = MP_Y
mp2.Refresh      'refresh to show new image

'for every pixel in picture1, copy it to picture2 after moving it
around theta degrees
For X& = 0 To 141
  For Y& = 0 To 141
x1& = 71 + (X& - 71) * Cos(theta2) - (Y& - 71) * Sin(theta2)
    y1& = 71 + (Y& - 71) * Cos(theta2) + (X& - 71) * Sin(theta2)
If (x1&> 0) And (x1&< 142) And (y1&> 0) And (y1&< 142) Then
     'direct memory read/write
     c& = TextureData2(X&, Y&)
     ViewData2(x1&, y1&) = c&
   End If
  Next Y&
Next X&

ip2.Left = IP_X
ip2.Top = IP_Y
ip2.Refresh      'refresh to show new image
End Function
```

Appendix F – Ethics application excerpts

The Tri-Council Policy Statement (TCPS) definition of "minimal risk" is as follows:
The research can be regarded as within the range of minimal risk if potential participants can reasonably be expected to regard the probability and magnitude of possible harms implied by participation in the research to be no greater than those encountered by the participant in those aspects of his or her everyday life that relate to the research. The designation of minimal or non-minimal risk affects the way the application is reviewed not the substance of the ethical review."
Based on this definition, do you believe your research qualifies as "minimal risk" research?

☐ Yes ☒ No

Explain your answer by referring to the level of risk stated in the TCPS definition:

This research will ask potential participants to use the proposed Hand in Motion Device (HMD), which is not an ordinary part of their regular rehabilitation program. Hence, this proposal does not qualify as "minimal risk" research. However, the HMD performs guided exercises (i.e. used under the direct supervision of a hand therapist) very similar to those normally performed in the standard rehabilitation program, with the main difference being that the HMD is used in place of the existing tools. The HMD is designed to mimic the rehabilitation exercises of: continuous passive motion, active resistance, ball squeezing and grip strength, which are commonly used as part of a participant's rehabilitation. The fact that the participant is involved in this study due to a prior hand injury creates a risk of re-injury, but this risk is inherent to undergoing any hand rehabilitation program.

Technological and procedural precautions have been taken to ensure the participant's safety and to ensure the reliable operation of the HMD. There are three levels of safety stops in effect to limit the position and torque of the device. There is a mechanical stop to avoid the device going outside the normal ROM, there are software checks on the position (encoders), torque (force sensors) and current drawn by the motor, and there is a shut off button for both the user and the therapist. The HMD is designed to be more repeatable (due to consistent application of loads), reliable and controllable than the current standard rehabilitation tools.

Purpose and Rationale of Research

Briefly describe in non-technical language:
Please use 150 words or less. The form will expand to the length of your answers.

1a. The research objective(s) and question(s)

The purpose of this study is to test a novel hand rehabilitation device, the Hand-in-Motion Device (HMD) [1]. This study will assess the physical and psychological comfort of a number of participants while they are participating in hand rehabilitation exercises using the HMD. The HMD is designed to assist a hand therapist in offering continuous passive motion (CPM), active resistance and haptic feedback to users recovering from hand injuries (such as tendon repair surgery, hand fractures, hemiplegic hand, Complex Regional Pain Syndrome, and dislocations). Subject testing is required to determine the ability of the HMD to meet this goal. Feedback from a participant in terms of their physical and mental comfort, range of motion, level of involvement, and functional gain, is crucial to further develop the HMD to best meet the needs of participants and the therapists. Hence, feedback from the therapist, as he/she works with the participant, is also essential. The data gathered from this preliminary trial will identify any functional and technical deficiencies of the HMD, which can then be redesigned to improve its capability as a rehabilitation tool to be used in a full clinical study.

1b. The importance and contributions of the research

The HMD is designed to allow a single therapist to work with multiple participants. The therapist would be able to setup the HMD to administer a number of different passive and active exercises. These exercises are able to be customized by the therapist and have the benefit of being more reliable, repeatable, and easily monitored as it is handled by a device which monitors torque and position of both the Metacarpophalangeal (MCP) and Proximal interphalangeal (PIP) during the exercise. The HMD is a novel device as it is able to control the MCP and PIP independently over a range of 0° to 90° with either hand in three different modes. The HMD is capable of continuous passive motion, active resistance, and haptic feedback. These are techniques designed to simulate common therapy techniques used in rehabilitation. This HMD will be able to replace a wide variety of therapy equipment while allowing the therapist greater control and feedback than currently offered.

Recruitment and Selection of Participants

2a. Briefly describe the target population(s) for recruitment. Ensure that all participant groups are identified (*e.g. group 1 - teachers, group 2 - administrators, group 3 - parents*).

The target population is adults with a hand injury that uses a rehabilitation process involving exercises capable of being performed by the HMD (such as continuous passive motion (CPM), active resistance and strength training). The injury groups that will be focused on for this trial are:
Flexor Tendon Repair – Post-surgery rehabilitation of a severed flexor tendon in the pointer, middle or ring fingers. Prior to 6 weeks post repair, it could be used in its CPM mode within the safe ranges. After 6 - 8 weeks, active resistance could be added, and by 8 weeks, strength training would be appropriate. See Appendix B – Figure 2 and Figure 4 for a diagram.
Extensor Tendon Repair – Post-surgery rehabilitation of a severed extensor tendon in the pointer, middle or ring fingers. Prior to 6 weeks post repair, it could be used in its CPM mode within the safe ranges. After 6 - 8 weeks, active resistance could be added, and by 8 weeks, strength training would be appropriate. See Appendix B – Figure 2 and Figure 3 for a diagram.
Hand Fracture – Rehabilitation of a hand fracture in regions affecting the motion of the MCP and/or the PIP of the in the pointer, middle or ring fingers. At 4 to 6 weeks post injury or surgery, it could be used in its CPM mode within the safe ranges. After 6 - 8 weeks, active resistance could be added, and by 8 weeks, strength training would be appropriate.
Dislocations – Rehabilitation of dislocations of the MCP and/or PIP in the pointer, middle or ring fingers. At 4 to 6 weeks post injury or surgery, it could be used in its CPM mode within the safe ranges. After 6 - 8 weeks, active resistance could be added, and by 8 weeks, strength training would be appropriate.
Complex Regional Pain Syndrome (CRPS) – Rehabilitation of pain, swelling and damage to the MCP and/or the PIP of the in the pointer, middle or ring fingers caused by CRPS. The client will be selected on the basis of their pain level and tolerance to exercise. If they are able to tolerate stretching, the CPM will be used. If they can do light exercises, then the active resisted mode will be initiated, then progressed to strength training as able.
Hemiplegic Hand – Rehabilitation of a loss of movement in the hand due to a stroke. The client must have some active movement of their arm and evidence of some return in the hand muscles.
The target population will also be limited to participants whose hand is of a suitable size to fit in the current prototype version of the HMD (the device at this stage will not except hands wider than 44mm between the palm and back of the hand or shorter than 52mm between the MCP and PIP), and who are at a stage in recovery where this type of therapy is required. Participants who are at a stage where only light passive motion is advisable will be treated with only the CPM mode, while participants who are able to (and are currently) doing resistance training will be tested on the CPM, active and haptic modes. Only participants over the age of 18 will be considered for this study.
It should also be noted that the therapists helping with the study (most notably Clare), will also be considered participants as they will have direct involvement with the device and will fill out a questionnaire about their experience with the device. Clare has already agreed to be a part of this study and has been involved in the organization and preparations.
Please note there will be an initial round of pre-testing with 6-10 healthy participants to ensure the safety of the device prior to the tests with injured patients. The target population for this test is based solely on participants having the correct hand size for the device and having injury free hands.

2b. Why is this population of interest?

This population is of interest as it is the recovery from these particular illnesses and injuries which can be most effectively assisted by the HMD. These patients suffer from reduced motion, loss of strength and poor motor control of the hand. The HMD is designed for gentle range of motion, strengthening and movement training exercises based on fundamental principles of exercise physiology and motor learning.
The initial round of pre-testing uses healthy participants to confirm the safety of the device prior to use with injured patients.

4b. Provide a sequential description of the procedures/methods to be used in your research study.
List all of the research instruments and interview/discussion questions, and in an appendix provide copies of all instruments. If not yet available, provide drafts or sample items/questions. For multi-method or other complex research, use the following sections in ways best suited to explain your project. If you have more than one participant group, be sure to explain which participant group(s) will be involved in which activity/activities.

The selection of participants will proceed as discussed in Section 2. When participants have indicated an interest in participating in the study, they will be contacted and a time will be arranged (likely on a Friday due to scheduling of the researchers). Upon meeting on the day of the tests the participant will go through the procedure outlined in Section M to ensure they are informed of their rights, have given consent, and know the procedure of the test.

At this time the participant will fill out a brief survey to determine the functional levels of their injured hand. The survey selected is the Disabilities of the Arm, Shoulder, and Hand (DASH). The survey and scoring method are attached in Appendix C. After this, Clare Faulkner will assess the range of motion (ROM) of the participant using a goniometer (see Appendix D – Figure 7) and the grip strength of the participant using the Jamar hand dynamometer (see Appendix D – Figure 8). These are standard diagnostic tools for assessing the state of the participant's hand and will compliment the survey's results.

The participant will then have his/her non-injured hand placed in the HMD. The device will be adjusted to fit the user. At this time they will be able to experience the modes of use they will be using later on their injured hand and gain familiarity with the device.

The participant will then have his/her hand placed in the HMD and it will be adjusted to fit the hand. The choices and sequences of the exercises (i.e. CPM, active resistance, or Haptic response modes) performed with the HMD will vary based on the condition of the participant's hand. Every participant, however, will begin with the CPM mode.

The CPM mode consists of the therapist setting the HMD to move the participant's hand passively based on the movement range of the participant. This is set by choosing the CPM mode then setting the maximum torque safety stop (a torque value that if reached will completely shut off the motors), number of repetitions, duration of each repetition (controls the speed of the exercises) and the initial and final positions for the exercise. The initial and final positions are set by moving the HMD manually to the start then to the end and setting these points into the microprocessors memory with a button press. The machine can use multiple end points and cycle through them to achieve multiple hand positions if this is desired. Once this is set, the HMD is activated and it will move the participant between the preset start and end points while the participant remains passive and applies no force. The CPM is designed to help increase the range of motion of the participant and to reduce swelling and remove edema from the joints. It is a commonly used technique.

If the participant is at a stage in their regular recovery where active resistance is a part of their rehabilitation, then the active resistance mode will also be used. This mode requires a similar setup of maximum torque safety stop, number of repetitions, a manually input start and end point, and a desired resistance value (input as a torque value for the PIP and MCP). This mode requires the participant to move from the start to the end point and back, while the HMD produces a constant torque on both the MCP and PIP opposing the motion. This exercise is akin to standard strength training exercises and can be performed as a resistance to opening or closing of the hand.

The final mode, a haptic response mode, will be used if the participants are able to perform the active resistance mode with no discomfort or fatigue. The participant is prompted by an onscreen visual to move their hand to a certain position while interacting with a virtual environment. The virtual environment will be a virtual single spring between the participant's palm and middle phalanges and then a virtual ball held in the participant's hand. For both these exercises the stiffness of the ball or spring can be set to make the exercise easier or harder. The participant will then move their hand from an open to closed position and as the virtual hand on screen encounters the virtual spring or ball the forces for this contact will be applied by the HMD to the participant. In this way the participant will feel as if they are squeezing a spring or ball and that the hand on the screen is actually their own. This allows the HMD to mimic grip strength and ball gripping exercises commonly used in the clinical setting. The addition of the visual feedback and realistically computed contact forces is designed to draw the participant into the exercise to avoid boredom and increase the effort of the participant.

After the testing the participant will again perform the grip strength and ROM tests with the Jamar hand dynamometer and the goniometer. Finally the participant will be asked to fill out a quick survey about their response to the HMD, ease of use, comfort, and perceived effectiveness. The survey is attached in Appendix C and will be given to the participant by Mr Birch to fill out in private.

There will also be a brief survey to be completed by all therapists who operate the HMD. This survey will cover their response to the HMD, ease of use, perceived effectiveness, and suggested improvements.

For the initial pre-test the procedure will be similar. The participants will be approached by Benj Birch and if willing they will book a time to come to ELW A233. Upon arrival they will be informed of the risks of

using the device, including injury and fatigue. The participants will also be informed that the device has not been formally tested on participants before. Finally the participant will be informed of the safety features in place and directed on how to use the kill switch. Next the participant will be given a consent form and informed of their right to withdraw from the tests.

If the participant wishes to continue and has signed the consent form they will then be fitted to the device and they will test all the modes of the device with both hands. The tests are designed to mimic the later tests with injured participants. The safety limits will be increased with the comfort level of the participant to cover the full range.

The participants will then be asked to fill out the quick survey about their response to the device. This is the same survey used in the main study.

Appendix G – Ethics Approval

Human Research Ethics Board

Office of Research Services
University of Victoria
Administrative Services Building B202
Tel (250) 472-4545 Fax (250) 721-8960
Email ethics@uvic.ca Web www.research.uvic.ca

University of Victoria

Human Research Ethics Board
Certificate of Approval

Principal Investigator	Department/School	Supervisor
Benjamin Birch Master's Student	MENG	Dr. Edward Park Nick Dechev

Co-Investigator(s):

Dr. Murray Maitland, Co-Investigator, Professor of Rehab Medicine, University of Washington
Clare Faulkner, Collaborator, Island Hand Therapy
Ed Haslam, Technician, UVic

Project Title: **Hand In Motion: Rehabilitation Device for the Hand**

Protocol No.	Approval Date	Start Date	Expiry Date
09-274	28-Aug-09	28-Aug-09	27-Aug-10

Certification

This certifies that the UVic Human Research Ethics Board has examined this research protocol and concluded that, in all respects, the proposed research meets the appropriate standards of ethics as outlined by the University of Victoria Research Regulations Involving Human Participants.

This Certificate of Approval is valid for the above term provided there is no change in the protocol. Extensions and/or amendments may be approved with the submission of a "Request for Annual Renewal or Modification" form.

Dr. Richard Keeler
Associate Vice-President Research

09-274 Birch, Benjamin

Appendix H – Consent Form

Participant Consent Form

Hand In Motion

You are invited to participate in a study entitled Hand in Motion, being conducted by Benj Birch.
Benj Birch is a graduate student in the department of Mechanical Engineering as the University of Victoria. He is performing this research as part of his requirements for graduation under the supervision of Dr. Ed Park and Dr. Nikolai Dechev. You may contact Benj or either of his supervisors at the contacts listed below if you have any further questions or concerns.

This research is being performed in collaboration with Clare Faulkner, a practicing certified hand therapist. Clare can also be contacted (see below) if there are any questions.

Purpose and Objectives
The purpose of this research is to test a novel hand rehabilitation device, the Hand in Motion Device (HMD). The HMD is designed to assist a hand therapist in treating a number of different hand ailments including dislocations, complex regional pain syndrome, hand fractures, hemiplegic hand, flexor tendon repair and extensor tendon repair. The test will gather data on comfort, appeal, ease of use and effectiveness of the HMD. The test will gather information about the personal response of the participants and therapists to the HMD and the physical response measured by the range of motion and grip strength of the participants.

Importance of this Research
Research of this type is important because it will advance the field of rehabilitation robotics. Using robotics in rehabilitation will hopefully allows for a reliable and repeatable interaction which can offer the therapist and participant more control and better feedback. Devices like this will hopefully allow therapists to help multiple participants at the same time while still having control over the finer points of the participant's therapy routine. This research is important to advancing the knowledge base in this field as well as the state of this device.

Participants Selection
We have selected potential participants based on the nature of their hand injury. Participants were selected who had an injury for which the standard treatment coincides with the intended capabilities of the Hand in Motion Device. All the injury types selected require movement and/or resistance of the first two joints in the fingers.

What Is Involved
If you agree to voluntarily participate in this research, your participation will include a one hour session with our certified hand therapist. The process will start with a short questionnaire about your current hand functionality and an assessment of range of motion and grip strength. The Hand in Motion will then be used to passively move your first and second joints of your fingers through a range of motion deemed appropriate by the therapist. Finally you will again perform the grip strength and range of motion tests. At this time you will be asked to fill out a brief survey on your experience with the HMD. You may be asked if a photo, of your hand only, can be taken to assist in disseminating the results.

Inconvenience
Participation in this study may cause some inconvenience to you, including one hour of your time and the requirement of filling out two surveys during this time. We appreciate your assistance in this research.

Risks
There are some potential risks to you by participating in this research and they include damage to the participants hand due to an error in using the device. There are risks as the device has not been used with participants with these

types of injuries yet. To prevent or to deal with these risks the following steps will be taken. There are multiple safety checks to ensure the force applied to the participant does not exceed a set limit. These include current sensors, torque sensors and a manual kill switch. There are also position sensors to ensure the HMD is in the intended position and a safety stop to limit the direction of travel to the appropriate hand and a sensor to ensure the safety stop is in use. There is also risk of increased post-treatment pain that is normally associated with rehabilitation.
If the participant is in any way harmed by the HMD an incident form would be filled out, and the participant advised to see his/her physician. A detailed description would be recorded by the attending hand therapist, and the participant would be monitored for recovery and/or required interventions. Information about the injury would also be forwarded to the UVic Human Research Ethics Board.

Benefits
The potential benefits of this research include the advancement of a device which will hopefully aid in hand rehabilitation in the clinical setting and furthering of research in the field of robotic rehabilitation.

Compensation
As a way to compensate you for any inconvenience related to your participation, you will be given a girt card worth $10. If you agree to participate in this study, this form of compensation to you must not be coercive. It is unethical to provide undue compensation or inducements to research participants. If you would not participate if the compensation was not offered, then you should decline.

Voluntary Participation
Your participation in this research must be completely voluntary. If you do decide to participate, you may withdraw at any time without any consequences or any explanation. If you do withdraw from the study you will tell us if you would like your data used in the study. We will only include your data with your consent. We will also include any reasons you may give for discontinuing only with your content. Declining from this study will in no way effect the service received from Clare or the Island Hand Therapy Clinic.

Researcher's Relationship with Participants
The researcher may have a relationship to you as Clare Faulkner may be your current physiotherapist. To help prevent this relationship from influencing your decision to participate, steps to prevent coercion have been taken. You have been approached by a receptionist, if interested you will be contacted by Benj Birch to answer questions and inform you of the study and if you decide not to participate it will not be passed on to the researchers.

Anonymity
Your anonymity will be protected by not attaching the participant's names to teh data. The data will be stored based on a number system and no name.

Confidentiality
Your confidentiality will be assured by not attaching a name to the data and by password protecting data.

Dissemination of Results
It is anticipated that the results of this study will be shared through conferences, research papers, and a thesis.

Commercial Use of Results
This research may lead to the commercialization of the Hand in Motion Device for clinical use in the rehabilitation of hand injuries.

Disposal of Data
Data from this study will be held until the completion of Benj Birch's Master's study plus one year or two years from the data collection (whichever is first) and disposed of by deleting electronic copies and shredding paper copies.

Contacts
Individuals that may be contacted regarding this study include the following:

Name	Position	Phone #	E-mail
Benj Birch	Graduate Student	250-720-6292	benbfg@uvic.ca
Clare Faulkner	Certified Hand Therapist	250-474-1128	cfaulkner@shaw.ca
Dr. N. Dechev	Assistant Professor	250-721-8933	dechev@me.uvic.ca
Dr. E. Park	Associate Professor	778-782-8662	ejpark@me.uvic.ca

In addition, you may verify the ethical approval of this study, or raise any concerns you might have, by contacting the Human Research Ethics Office at the University of Victoria (250-472-4545 or ethics@uvic.ca).

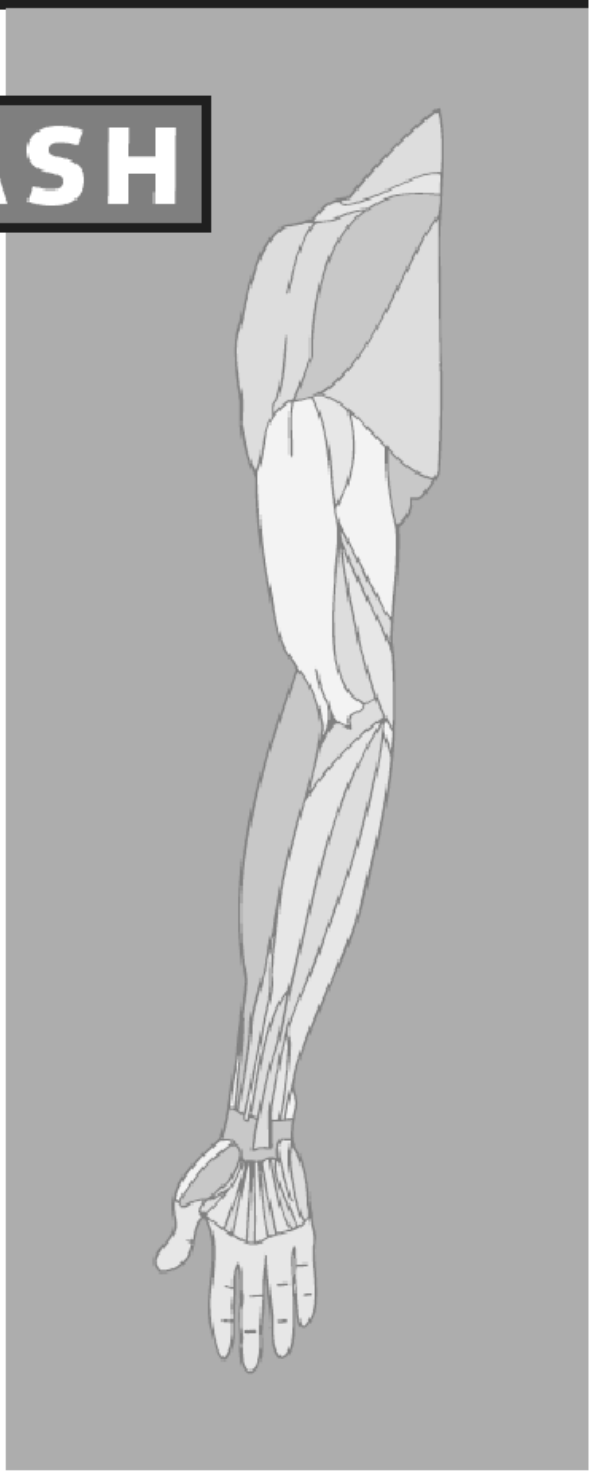
Your signature below indicates that you understand the above conditions of participation in this study and that you have had the opportunity to have your questions answered by the researchers.

_____	_____	_____
Name of Participant	*Signature*	*Date*

Appendix I – DASH Survey

DISABILITIES OF THE ARM, SHOULDER AND HAND

THE DASH



INSTRUCTIONS

This questionnaire asks about your symptoms as well as your ability to perform certain activities.

Please answer *every question*, based on your condition in the last week, by circling the appropriate number.

If you did not have the opportunity to perform an activity in the past week, please make your *best estimate* on which response would be the most accurate.

It doesn't matter which hand or arm you use to perform the activity; please answer based on your ability regardless of how you perform the task.

DISABILITIES OF THE ARM, SHOULDER AND HAND

Please rate your ability to do the following activities in the last week by circling the number below the appropriate response.

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE
1. Open a tight or new jar.	1	2	3	4	5
2. Write.	1	2	3	4	5
3. Turn a key.	1	2	3	4	5
4. Prepare a meal.	1	2	3	4	5
5. Push open a heavy door.	1	2	3	4	5
6. Place an object on a shelf above your head.	1	2	3	4	5
7. Do heavy household chores (e.g., wash walls, wash floors).	1	2	3	4	5
8. Garden or do yard work.	1	2	3	4	5
9. Make a bed.	1	2	3	4	5
10. Carry a shopping bag or briefcase.	1	2	3	4	5
11. Carry a heavy object (over 10 lbs).	1	2	3	4	5
12. Change a lightbulb overhead.	1	2	3	4	5
13. Wash or blow dry your hair.	1	2	3	4	5
14. Wash your back.	1	2	3	4	5
15. Put on a pullover sweater.	1	2	3	4	5
16. Use a knife to cut food.	1	2	3	4	5
17. Recreational activities which require little effort (e.g., cardplaying, knitting, etc.).	1	2	3	4	5
18. Recreational activities in which you take some force or impact through your arm, shoulder or hand (e.g., golf, hammering, tennis, etc.).	1	2	3	4	5
19. Recreational activities in which you move your arm freely (e.g., playing frisbee, badminton, etc.).	1	2	3	4	5
20. Manage transportation needs (getting from one place to another).	1	2	3	4	5
21. Sexual activities.	1	2	3	4	5

DISABILITIES OF THE ARM, SHOULDER AND HAND

	NOT AT ALL	SLIGHTLY	MODERATELY	QUITE A BIT	EXTREMELY
22. During the past week, *to what extent* has your arm, shoulder or hand problem interfered with your normal social activities with family, friends, neighbours or groups? *(circle number)*	1	2	3	4	5

	NOT LIMITED AT ALL	SLIGHTLY LIMITED	MODERATELY LIMITED	VERY LIMITED	UNABLE
23. During the past week, were you limited in your work or other regular daily activities as a result of your arm, shoulder or hand problem? *(circle number)*	1	2	3	4	5

Please rate the severity of the following symptoms in the last week. *(circle number)*

	NONE	MILD	MODERATE	SEVERE	EXTREME
24. Arm, shoulder or hand pain.	1	2	3	4	5
25. Arm, shoulder or hand pain when you performed any specific activity.	1	2	3	4	5
26. Tingling (pins and needles) in your arm, shoulder or hand.	1	2	3	4	5
27. Weakness in your arm, shoulder or hand.	1	2	3	4	5
28. Stiffness in your arm, shoulder or hand.	1	2	3	4	5

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	SO MUCH DIFFICULTY THAT I CAN'T SLEEP
29. During the past week, how much difficulty have you had sleeping because of the pain in your arm, shoulder or hand? *(circle number)*	1	2	3	4	5

	STRONGLY DISAGREE	DISAGREE	NEITHER AGREE NOR DISAGREE	AGREE	STRONGLY AGREE
30. I feel less capable, less confident or less useful because of my arm, shoulder or hand problem. *(circle number)*	1	2	3	4	5

DASH DISABILITY/SYMPTOM SCORE = $\left[\left(\frac{\text{sum of n responses}}{n}\right) - 1\right] \times 25$, where n is equal to the number of completed responses.

A DASH score may not be calculated if there are greater than 3 missing items.

DISABILITIES OF THE ARM, SHOULDER AND HAND

WORK MODULE (OPTIONAL)

The following questions ask about the impact of your arm, shoulder or hand problem on your ability to work (including homemaking if that is your main work role).

Please indicate what your job/work is:_____

p I do not work. (You may skip this section.)

Please circle the number that best describes your physical ability in the past week. Did you have any difficulty:

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE
1. using your usual technique for your work?	1	2	3	4	5
2. doing your usual work because of arm, shoulder or hand pain?	1	2	3	4	5
3. doing your work as well as you would like?	1	2	3	4	5
4. spending your usual amount of time doing your work?	1	2	3	4	5

SPORTS/PERFORMING ARTS MODULE (OPTIONAL)

The following questions relate to the impact of your arm, shoulder or hand problem on playing *your musical instrument or sport or both*.
If you play more than one sport or instrument (or play both), please answer with respect to that activity which is most important to you.

Please indicate the sport or instrument which is most important to you:_

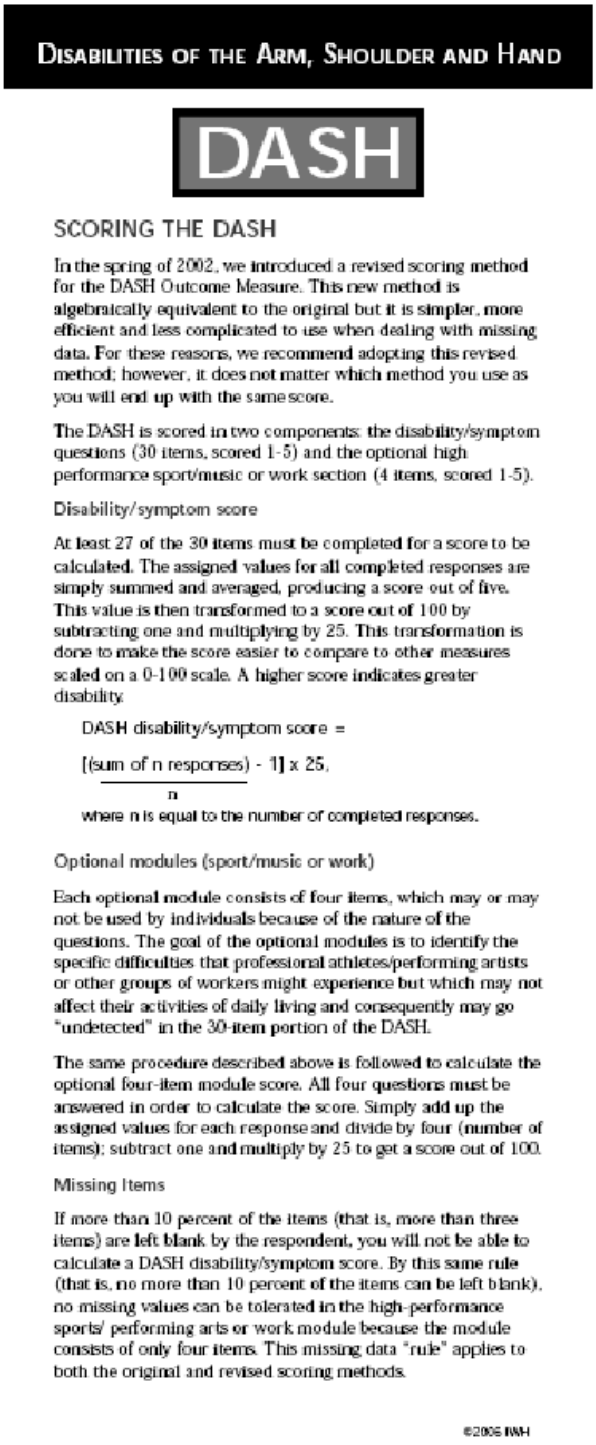
o I do not play a sport or an instrument. (You may skip this section.)

Please circle the number that best describes your physical ability in the past week. Did you have any difficulty:

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE
1. using your usual technique for playing your instrument or sport?	1	2	3	4	5
2. playing your musical instrument or sport because of arm, shoulder or hand pain?	1	2	3	4	5
3. playing your musical instrument or sport as well as you would like?	1	2	3	4	5
4. spending your usual amount of time practising or playing your instrument or sport?	1	2	3	4	5

SCORING THE OPTIONAL MODULES: Add up assigned values for each response; divide by 4 (number of items); subtract 1; multiply by 25.
An optional module score may <u>not</u> be calculated if there are any missing items.

Scoring the DASH



DISABILITIES OF THE ARM, SHOULDER AND HAND

DASH

SCORING THE DASH

In the spring of 2002, we introduced a revised scoring method for the DASH Outcome Measure. This new method is algebraically equivalent to the original but it is simpler, more efficient and less complicated to use when dealing with missing data. For these reasons, we recommend adopting this revised method; however, it does not matter which method you use as you will end up with the same score.

The DASH is scored in two components: the disability/symptom questions (30 items, scored 1-5) and the optional high performance sport/music or work section (4 items, scored 1-5).

Disability/symptom score

At least 27 of the 30 items must be completed for a score to be calculated. The assigned values for all completed responses are simply summed and averaged, producing a score out of five. This value is then transformed to a score out of 100 by subtracting one and multiplying by 25. This transformation is done to make the score easier to compare to other measures scaled on a 0-100 scale. A higher score indicates greater disability.

$$\text{DASH disability/symptom score} = \left[\frac{(\text{sum of n responses})}{n} - 1\right] \times 25,$$

where n is equal to the number of completed responses.

Optional modules (sport/music or work)

Each optional module consists of four items, which may or may not be used by individuals because of the nature of the questions. The goal of the optional modules is to identify the specific difficulties that professional athletes/performing artists or other groups of workers might experience but which may not affect their activities of daily living and consequently may go "undetected" in the 30-item portion of the DASH.

The same procedure described above is followed to calculate the optional four-item module score. All four questions must be answered in order to calculate the score. Simply add up the assigned values for each response and divide by four (number of items); subtract one and multiply by 25 to get a score out of 100.

Missing Items

If more than 10 percent of the items (that is, more than three items) are left blank by the respondent, you will not be able to calculate a DASH disability/symptom score. By this same rule (that is, no more than 10 percent of the items can be left blank), no missing values can be tolerated in the high-performance sports/ performing arts or work module because the module consists of only four items. This missing data "rule" applies to both the original and revised scoring methods.

Appendix J – Healthy Participant's Data

Participant	1	Dash Score	0	Hand	R	Dominant?	Y	test	healthy
Finger	Joint	Pre				Post		Difference	
Limiting finger	MCP	90				91			1
	PIP	96				97			1

Participant	2	Dash Score	5	Hand	R	Dominant?	Y	test	healthy
Finger	Joint	Pre				Post		Difference	
Limiting finger	MCP	88				92			4
	PIP	105				100			-5

Participant	3	Dash Score	8.333	Hand	L	Dominant?	N	test	healthy
Finger	Joint	Pre				Post		Difference	
Limiting finger	MCP	90				90			0
	PIP	60				62			2

Participant	4	Dash Score	0	Hand	R	Dominant?	Y	test	healthy
Finger	Joint	Pre				Post		Difference	
Limiting finger	MCP	76				72			-4
	PIP	99				103			4

Participant	5	Dash Score	7.5	Hand	L	Dominant?	Y	test	healthy
Finger	Joint	Pre				Post		Difference	
Limiting finger	MCP	80				80			0
	PIP	105				105			0

Participant	6	Dash Score	16.667	Hand	R	Dominant?	Y	test	healthy
Finger	Joint	Pre				Post		Difference	
Limiting finger	MCP	76				75			-1
	PIP	106				107			1

Participant	7	Dash Score	4.167	Hand	L	Dominant?	N	test	healthy
Finger	Joint	Pre				Post		Difference	
Limiting finger	MCP	84				90			6
	PIP	82				92			10

Participant	8	Dash Score	0	Hand	R	Dominant?	Y	test	healthy
Finger	Joint	Pre				Post		Difference	
Limiting finger	MCP	79				75			-4
	PIP	104				104			0

Participant	9	Dash Score	0	Hand	R	Dominant?	Y	test	healthy
Finger	Joint	Pre				Post		Difference	
Limiting finger	MCP	85				82			-3
	PIP	104				106			2

Appendix K – Injured Hands Participant's Data

Participant	1	Dash Score	65.8	Hand	R	Dominant?	Y	Injured		
			Pre - Visit			Test		Post visit		
Finger	Joint	Direction	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
Pointer	MCP	Extension				0	-2	2			
		Flexion				50	65	15	50	72	
	PIP	Extension				25	20	5			
		Flexion				40	47	7	46	50	
Middle	MCP	Extension				5	-2	7			
		Flexion				55	65	10	50	69	
	PIP	Extension				25	20	5			
		Flexion				30	45	15	42	48	
Ring	MCP	Extension									
		Flexion									
	PIP	Extension									
		Flexion									
Pinky	MCP	Extension									
		Flexion									
	PIP	Extension									
		Flexion									

Participant	2	Dash Score	58.3	Hand	R	Dominant?	Y	Injured		
			Pre - Visit			Test		Post visit		
Finger	Joint	Direction	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
Pointer	MCP	Extension				10	10	0			
		Flexion				70	77	7		70	
	PIP	Extension				10	10	0			
		Flexion				52	52	0		45	
Middle	MCP	Extension				0	5	-5			
		Flexion				70	70	0		70	
	PIP	Extension				20	10	10			
		Flexion				62	67	5		60	
Ring	MCP	Extension				0	0	0			
		Flexion				55	70	15		65	
	PIP	Extension				12	5	7			
		Flexion				70	77	7		85	
Pinky	MCP	Extension				0	0	0			
		Flexion				67	65	-2		47	
	PIP	Extension				10	0	10			
		Flexion				72	75	3		65	

Participant	3	Dash Score	4.17	Hand	R	Dominant?	N	Injured		
			Pre - Visit			Test		Post visit		
Finger	Joint	Direction	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
Pointer	MCP	Extension				-2	-5	3			
		Flexion				90	90	0			
	PIP	Extension				0	0	0			
		Flexion				90	100	10			
Middle	MCP	Extension				-5	-5	0			
		Flexion				85	95	10			
	PIP	Extension				0	0	0			
		Flexion				100	107	7			
Ring	MCP	Extension				-5	-10	5			
		Flexion				75	75	0			
	PIP	Extension				0	0	0			
		Flexion				95	105	10			
Pinky	MCP	Extension				-5	-10	5			
		Flexion				80	82	2			
	PIP	Extension				5	0	5			
		Flexion				85	90	5			

Participant	4	Dash Score	91.4	Hand	R	Dominant?	Y	Injured		
			Pre - Visit			Test		Post visit		
Finger	Joint	Direction	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
Pointer	MCP	Extension		30		45	30	15		30	
		Flexion		65		62	75	13		60	
	PIP	Extension		45		-2	-2	0		0	
		Flexion		55		20	25	5		?	
Middle	MCP	Extension		37		30	20	10		15	
		Flexion		65		50	65	15		50	
	PIP	Extension		45		5	5	0		0	
		Flexion		55		25	35	10		15	
Ring	MCP	Extension		20		0	0	0		0	
		Flexion		45		15	40	25		30	
	PIP	Extension		75		47	47	0		0	
		Flexion		80		65	65	0		50	
Pinky	MCP	Extension		12		0	0	0		0	
		Flexion		55		15	35	20		1	
	PIP	Extension		55		17	17	0		20	
		Flexion		65		40	45	5		30	

Participant	5	Dash Score	15.8	Hand	R	Dominant?	Y	Injured		
			Pre - Visit			Test			Post visit	
Finger	Joint	Direction	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
Pointer	MCP	Extension									
		Flexion									
	PIP	Extension									
		Flexion									
Middle	MCP	Extension			0	0	0	0			
		Flexion			0	95	95	0			
	PIP	Extension		22	-22	15	15	0			
		Flexion		80	80	72	72	0			
Ring	MCP	Extension									
		Flexion									
	PIP	Extension									
		Flexion									
Pinky	MCP	Extension									
		Flexion									
	PIP	Extension									
		Flexion									

Participant	6	Dash Score	25.8	Hand	R	Dominant?	N	Injured		
			Pre - Visit			Test			Post visit	
Finger	Joint	Direction	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
Pointer	MCP	Extension		0	0	-2	-2	0		0	0
		Flexion		75	75	70	80	10		75	75
	PIP	Extension		0	0	12	10	2		0	0
		Flexion		80	80	72	82	10		70	70
Middle	MCP	Extension									
		Flexion									
	PIP	Extension									
		Flexion									
Ring	MCP	Extension									
		Flexion									
	PIP	Extension									
		Flexion									
Pinky	MCP	Extension									
		Flexion									
	PIP	Extension									
		Flexion									

Participant	7	Dash Score	10.8	Hand	R	Dominant?	Y	Injured		
			Pre - Visit			Test		Post visit		
Finger	Joint	Direction	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
Pointer	MCP	Extension				5	-5	10			
		Flexion				75	85	10			
	PIP	Extension				0	5	-5			
		Flexion				95	102	7			
Middle	MCP	Extension				0	0	0			
		Flexion				75	90	15			
	PIP	Extension				7	0	7			
		Flexion				95	102	7			
Ring	MCP	Extension				0	-10	10			
		Flexion				65	82	17			
	PIP	Extension				0	7	-7			
		Flexion				95	100	5			
Pinky	MCP	Extension				0	-12	12			
		Flexion				65	82	17			
	PIP	Extension				2	2	0			
		Flexion				70	90	20			

Participant	8	Dash Score	76.7	Hand	R	Dominant?	Y	Injured		
			Pre - Visit			Test		Post visit		
Finger	Joint	Direction	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
Pointer	MCP	Extension				15	10	5		7	
		Flexion				82	82	0		85	
	PIP	Extension				15	5	10		10	
		Flexion				62	70	8		75	
Middle	MCP	Extension				10	10	0		7	
		Flexion				80	85	5		80	
	PIP	Extension				15	10	5		10	
		Flexion				67	70	3		75	
Ring	MCP	Extension				5	5	0		0	
		Flexion				75	80	5		80	
	PIP	Extension				20	5	15		10	
		Flexion				62	75	13		85	
Pinky	MCP	Extension				0	0	0		0	
		Flexion				75	80	5		85	
	PIP	Extension				17	10	7		15	
		Flexion				60	70	10		75	