Partial Hand Prosthesis

A Major Qualifying Project Report:
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By:
Andrew Strauss
Mia Buccowich

Advisor:
Marko Popovic
Abstract

The lack of dexterity-restoring partial hand prosthetics for amputations at the metacarpophalangeal joint has necessitated the development of a solution that bridges this gap in prosthetic technology. This is addressed via a case study involving a patient with an amputation at the metacarpophalangeal joint of their index finger and nearly complete amputation of the proximal phalanx of the thumb. The resulting solution consists of a two degree of freedom passively actuated index finger, one degree of freedom actuator plus sensor driven thumb, solenoid locking system, and passive variable compression bladder. Both qualitative and quantitative testing has demonstrated that this device partially restores several gripping capabilities of the amputee.
Acknowledgements

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An immense thank you is also extended to both Julia D’Agostino and Mervyn Larrier who were with us at the beginning of this project, and with whom we established the foundation for the first design.

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1 Introduction

1.1 Motivation

Most people who need prosthetics do not get them.¹ There are many reasons for this, but assuming that the prosthetic helps the user, the main factors come down to price and availability. Prosthetics are prohibitively expensive as they are often custom one off pieces that require expensive manufacturing techniques and the use of expensive materials. The availability of prosthetics has a lot to do with the patient’s amputation. Some amputations have many good prosthetic solutions, such as amputations just below the knee or at the elbow, and others have virtually no options at all, such as partial hand amputations.

When it comes to partial hand amputations there are very few functional options. Companies such as Naked Prosthetics² offer some great options for amputees who still have their proximal or middle phalangeal bones (refer to Figure 1), however for amputations at the metacarpophalangeal (MCP) joint there are no commercial solutions. This is primarily because the majority of partial hand prostheses utilize the movement of these two bones (proximal or middle phalanx) to give the user length and actuation. With these bones removed there is no simple pivot point for the device, making the mechanics of actuation much more complicated.

![Figure 1: Anatomic labeled drawing of a human hand³](image)

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² Naked Prosthetics. Olympia, WA, USA. https://www.npdevices.com/
The motivation for this project stems from the fact that a device for patients with an amputation at the MCP simply does not exist, resulting in people who have just suffered a traumatic loss being told that there is nothing that can be done for them. Through this project we can prove that is not the case, while pushing at the boundaries of the prosthetics industry, paving the way for companies to create solutions for a broader range of partial hand amputations.

1.2 Background

1.2.1 Amputees: Causes and Common Problems

According to recent figures, there are approximately 1.5 million people living with limb loss in the United States, with approximately 226,000 amputations occurring each year. Trauma based amputations account for 16% of all amputation related hospital discharges and 75% of all upper extremity amputations. Of these upper limb amputations, 60% occur between the ages of 21 to 65, with the primary amputation occurring distal to the elbow. The majority of these injuries occur as a result of the use of heavy machinery, including power saws and cars. In the United States alone, approximately 61,000 partial hand and finger amputations occur every year. This subset of amputees must deal with a significant loss of motor skills that can have a direct impact on their ability to complete basic tasks, or carry out their jobs at the same level. These patients have returned to work at a rate of 73.2%, however 66% were forced to find a new job as a result of the amputation. The amputation of a thumb in particular results in the loss of approximately 40-50% of hand function. Attempts are generally made to salvage the use of the thumb via the transplant of the great toe as a means of restoring length to the phalange, however, this is not always a feasible option.

1.2.2 Evolution of Prostheses

The earliest recorded prosthetic is a wooden great toe dated to between 950-710 B.C.E. Prostheses have been interwoven throughout history for millenia, and have been steadily improving with time. The US Civil War was a turning point for prosthetic technology, with the

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5 Ibid.
9 Ibid.
invention of the first lower limb prosthetic with hinges to mimic both the knee and ankle joints.\textsuperscript{11} Since then there have been incremental improvements, including the recent use of carbon fiber and 3D printed materials, and biosignals to manipulate the device. While prostheses have come a long way since 950 B.C.E., finger prostheses have remained fairly stagnant within the commercial market. It is much easier to create an entirely new mechanical hand rather than interfacing aspects of a mechanical hand with a physical one, as there are individualities associated with each amputation. This is a large reason why most partial hand and finger amputees are provided only with the option of a cosmetic silicone finger (Figure 2) that offers no further actuation.

For some amputees the silicone replacement is sufficient; however, when the amputation is more extensive, or their area of work requires the use of fine motor skills, they must turn to other avenues.

As of late, prosthetists have begun to take inspiration from high functioning biomimetic devices. Biomimetic robots are designed to mimic human anatomy as much as possible to allow for natural actuation and higher performance. The coupling of 3D printing and computer aided


design (CAD) has been integral with these innovations as they allow for the designer to develop stronger and lighter solutions. Biomimetic design has been revolutionary for those with finger amputations because of the intricacy associated with these dexterous digits. Although 3D printing can reduce the cost of the device, the level of individuality of amputations and the nicheness of biomimetic design cause the prosthetics to sell for tens of thousands of dollars, making them unattainable for the average amputee. 13

While for some amputees receiving a prosthetic can be life changing, for many the device falls short of their expectations or needs. According to a study by Davidson et. al, conducted on a group of 70 upper limb amputees, 56% reported wearing their prosthetic, “once in a while” or “never”. 14 This occurs for a variety of reasons, often due to the failure of the device to improve upon their dexterity in a significant way. Davidson found that both prostheses and non-prostheses amputees reported a similar level of satisfaction with their ability to carry out tasks, indicating that the current devices do not do much to improve the users’ quality of life. Because the needs of the amputee are not appropriately addressed, and the device has an exuberant price tag, many upper limb amputees choose to adjust to their new life with minimal accommodations.

1.2.3 Client Statement

This Major Qualifying Project aims to demonstrate iterative engineering design and manufacturing applied to the challenge of lack of partial hand prosthetics. It satisfies the capstone, realization, and design requirements as our team completes the design and manufacturing process to create a device that bridges a glaring gap in the prosthetics market.

The overall goal for this project is to design a working partial hand prosthesis that works well for the user, PH. PH is a 21 year old woman from Houston, Texas who in August of 2019 was in a severe car crash that took the thumb and index finger of her dominant hand, as well as several toes. Both finger amputations occurred at the metacarpophalangeal (MCP) joint, however surgeons left two pieces of her proximal interphalangeal joint (PIP) that she is still able to actuate (see Figure 3).

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Figure 3: These two x-rays display PH’s amputation. The two bones of the thumb’s proximal phalanx can be seen in both images circled in red.

We approached this problem with the goal of creating a device that would be intuitive and comfortable to use, while not impeding PH’s remaining range of motion. This design was validated through the assessment and testing of functions, objectives, and constraints for the device, as well as an ongoing conversation with PH about her expectations of the device and evidenced areas for improvement.
2 MQP Goals

When creating the device for PH there were several constraints we had to work around. The major constraint was that we were attempting to make an individualized prosthetic for someone we could not physically be with. We were provided with a 3D scan of her hand which we were able to design on directly in SolidWorks, however, 8 months later this scan was no longer accurate. Other constraints we came across in the project included working during COVID which resulted in a majority of the work being conducted individually, and minimal testing of the device as a result of our access to the lab. Despite these significant constraints we were able to achieve our project’s objectives. These objectives will be discussed in further detail.

2.1 Device Control

Our first challenge was determining how the device was going to be actuated. We wanted the movement to be as natural as possible and so the following actuation techniques were decided upon.

2.1.1 Index Finger

Because of the unique nature of PH’s amputation, the amputation of the proximal phalanx on her index finger needed a solution that could be externally actuated. The index finger also required two degrees of freedom so that the solution could be as biomimetic as possible. In order to achieve this high level of accuracy in the movement of the finger, we established that a passive index finger coupled to the movement of the middle finger would be the best solution. This would ensure that the index finger would be able to move at each joint, but would not have the added complexity and unreliability associated with using EMG signals or another form of robotic control.

2.1.2 Thumb

As the thumb is an essential digit we established early on that we wanted to restore as much actuation to it as possible. The only way to provide full actuation to PH based on the nature of her amputation would be robotically, and so the thumb needed to be an active digit. The motion of the thumb was to be communicated with the use of two pressure sensors. PH is able to manipulate remaining pieces of bone atop her MCP enough to apply pressure to two separate areas within the thumb cap. This means of control served to be the most intuitive and natural for the user and so the design for the thumb was built around it.

We wanted to mimic the movement of a human thumb, which in day to day functions exhibits flexion speeds of 172 to 200deg/sec.\textsuperscript{15} The majority of commercial hand prostheses have a thumb actuation speed of 60 deg/sec, leading us to establish a goal of 50-75deg/sec for the

thumb.\textsuperscript{16} This is approximately two seconds for a full grasping cycle. While this is substantially lower than that of a human thumb, a mechanical thumb of that speed would be difficult for the user to actuate as they would not have the same level of fine control.

Another major goal is that the thumb is able to work throughout the day. Most commercially available prosthetics can achieve upwards of 1,200 grasping cycles per charge,\textsuperscript{17} however when considering the size of the battery we plan on using we aim to achieve 750 grasping cycles per charge. With an easily replaceable battery this should not pose much of an issue with regards to use.

2.2 Strength, Compliance, and Failure

The mechanical components of the device required the establishment of several baseline goals. The first of these goals was that the two prosthetic digits should be able to maintain a key grip force of 13N (~31bf) at the fingertips. The average key grip of both men and women between the ages of 20-64 is 88N.\textsuperscript{18} The iLimb, a commercially available prosthetic hand reports a key grip of 17-19.6N.\textsuperscript{19} Our goal is set lower than commercially available devices because our focus laid more substantially on returning dexterity rather than gripping strength.

They should also each individually be able to reach a breaking point of 44.4N (10.0lbf). Both of these goals are set in place to ensure that the digits are strong enough and will work well for daily use. They are set this high to make sure that the device can withstand any extraneous activity.

2.3 Weight of the Device

The weight of the device is also an essential factor especially for finger prosthetics. These small devices must be incredibly lightweight in order to mimic the weight of the amputees' lost digits. Biddiss et al, found that on a scale of 0 to 100 (with 100 being most important) amputees ranked the weight of the device as having an importance of 70 in terms of the design priorities of the hand.\textsuperscript{20} The average weight of a human hand is 400g, however studies have shown that when this value is replicated in prosthetics it is too heavy for the user because the device is no longer attached to their tendons and muscles for added support. We considered the weight of the materials we were planning on using and established a goal weight of 75g for the main harness and index finger and 50g for the thumb. When considering the things that have to be housed in


\textsuperscript{17} Ibid.


the wrist module, we decided that a weight of 250g would be appropriate while not being too heavy on the user's arm.

2.4 User Experience

No matter how well the mechanics of the device works if it is not an intuitive design then it will not be used. The prosthetic must be easy to put on, strapped on in under 10 minutes. This means that the user must also be able to put the device on by themselves. This includes both the partial prosthetic and the wrist module which houses the electronics and a removable battery. The ability of the patient to switch out the battery by themselves is also of high importance as it adds a level of independence to the device. Being able to replace and recharge the battery also ensures that the user is not limited in any way by their device.

The long term comfort of the device is also important if we want it to be used consistently. Ideally the user should be able to wear the device all day with minimal discomfort. There are many things that must be considered with regards to this including how the prosthetic interfaces with the patient's hand, what the points of contact are and how much pressure they apply. As well as other considerations such as how breathable it is and how well it moves with the user's hand.

2.5 Summary of Exact MQP Goals

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<td>1</td>
<td>Two degree of freedom index finger</td>
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<td>2</td>
<td>2s for full actuation</td>
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<tr>
<td>3</td>
<td>750 grasping cycles per charge</td>
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<td>4</td>
<td>Breaking point of 44N/m² at finger tip</td>
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<tr>
<td>5</td>
<td>Weight of main harness and index finger: Goal 75g</td>
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<td>6</td>
<td>Weight of thumb: Goal 50g</td>
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<td>7</td>
<td>Weight of wrist module: Goal 250g</td>
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<td>8</td>
<td>Easy to don and doff</td>
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<td>9</td>
<td>Intuitive control via embedded sensors</td>
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<td>10</td>
<td>Grip strength of 13N at actuated fingers</td>
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<td>11</td>
<td>Easily rechargeable</td>
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3 Methods

Forging the path ahead was no easy feat as we had very little idea of what type of prosthetic would make sense for PH. But we did have some things we knew we wanted. The most important thing was to have a solid anchor to her hand. This solid anchor is essential because it is where all of the force and torque being exerted is applied. Having a stable base for these reactionary forces ensures that the device is moving how we expect it to every time. The second goal was to have two degrees of freedom on the index finger and one degree of freedom on the thumb. The third design constraint was to use the middle finger’s motion to actuate the index finger and a motor to actuate the thumb. These goals proved to be the main parameters for each of the designs.

3.1 Version One

For our first iteration we wanted to make a proof of concept for the index finger. To build the index finger we routed wire\textsuperscript{21} through the center of the finger to actuate the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joint, with a secondary wire to actuate the MCP joint. The PIP cable was routed carefully through the center of the joint so that it did not apply torque to the MCP joint when actuated. This design proved to be very high friction and complex to manufacture, leading us to reconsider our actuation method for the second prototype.

The thumb was designed as a stagnant digit, the movement of which was dependent upon PH’s ability to move her MCP.

We also created a harness to attach the index finger to PH’s hand. The harness has the important job of transmitting the motion from the middle finger to the prosthetic index finger. This iteration used a pulley system (Figure 4c) that pulled the PIP and DIP cables, applying torque to the corresponding joints of the prosthetic. The harness was created in CAD by shaping the exterior of the harness and then subtracting a model of PH's hand from the interior (Figure 4a, 4b). This led to a perfect fit which we were able to test on a plaster casting of her hand. This first harness was designed to have a strap that would go across the dorsal side of the hand and tighten onto the wrist via a ratcheting system (Figure 4a).

\textsuperscript{21} SuperPower Braided Fishing Line. KastKing. Shenzhen, Guangdong, China. 
We also began thinking about how the device would interface with PH’s hand. Several solutions were discussed, the most popular of which being a glove. We also talked about how to reduce the rubbing on her skin from the device. We settled on a low friction fabric\textsuperscript{22} popular with many lower limb amputees that would reduce the shear forces applied at the contact point of the device, and limit the possibility of sores developing there.

### 3.2 Version Two

For the second version we wanted to make sure we had a low friction, robust, and simple design for the index finger. This was done by moving the pulling cable to the exterior of the finger so it could bypass any earlier joint in the finger. This was achieved using a bowden cable to pull on upper joints without applying force to lower joints. This design used a strong structural skeleton to house all the critical geometry which was then covered in a protective and more biomimetic exterior (Figure 5). The complexity associated with the large number of intricate parts caused us to move away from this structural skeleton and cover design in further iterations.

\textsuperscript{22} Glidewear Prosthetic Liner Patch: Circle. Tamarack. Los Angeles, CA, USA. 
The thumb was updated with the same method of actuation, however the thumbs cables were joined together to actuate both joints at the same time. In order to actuate the thumb we explored EMG sensors, hoping to be able to read user intent from electronic signals beneath the forearm. However; given that there are 34 muscles that control a human hand, these signals were all too noisy to be a viable solution. As a result of this we began to look more substantially into pressure sensors.

The harness in our second iteration was made to be attached to a glove worn by the user. We discussed using fabrics that would restrict the stretching of the interface in certain directions, allowing the two digits to be held in place while still providing PH flexibility in her hand. It was determined that this solution would be fairly complex and would not add as much stability as we had anticipated, and so we purchased a copper compression glove\textsuperscript{23} as the first interface. This was chosen as a result of the compressive nature of the glove, and the fact that these gloves are designed to be worn for an extended period and as a result of which are breathable and comfortable. This more stable interface, theoretically, would allow us to ignore the need for heavy straps across the hand that could cause discomfort and decreased sensitivity. The addition of the glove resulted in a smaller and more natural looking harness. This simplification was also made possible by the switch to bowden cables, as the bulky pulley could be replaced by routing the bowden cable to the middle finger.

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3.3 Version Three

The third prototype, seen in Figure 6a, was the first that PH was able to try on, and so the first time every part of the design needed to be brought together. The main goal that was addressed from V2 was the overall simplification of the device, reducing the number of individual and moving parts. The unnecessary bowden cable on the DIP joint of the index finger and thumb was replaced with a simple linkage to actuate it along with the joint before it. The cover pieces were also removed and the aesthetic and functional geometry was built into the skeleton of the device (Figure 6b). Finally, tuning mechanisms were added into the joint to allow the user to tension the string in case it loosened or needed to be tuned.

Figure 6a: V3 back view  
Figure 6b: The parts of the V3 finger

This design was the first to have a motor driven thumb. The thumb was controlled by two force sensitive resistors\(^24\) on the inside of the thumb harness that sense the little bit of movement PH has at the top of her metacarpal. These sensors worked well in that they were able to pick up on small movements; however, they proved to be extremely delicate and therefore not the ideal solution for a device that would get daily use.

In order to reduce the size of the battery needed to drive this system for a whole day, we opted for a semi-passive motion of the thumb, meaning that when PH is not moving the thumb to a new position it is mechanically locked in place and needs no motor power to hold position. This is achieved by using a non-back-drivable transmission system, in our case, a worm drive with low angular pitch\(^25\).

The third iteration of the harness used an adjustable “seesaw” mechanism to allow for the user to adjust the relative movement between the actuating finger and the prosthetic (Figure 7). This adjustment mechanism was largely a failure due a lack of clearance for the thread to be

\(^{24}\) 1695. Force-Sensing Resistor: 0.2” Diameter Circle. Pololu. Las Vegas, NV, USA. https://www.pololu.com/search?%5Bsearch_type%5D=&query=fsr\&x=0\&y=0

successfully attached to the “seesaw” and as a result of the large amount of friction inside the housing [it was meant to be machined out of aluminum for strength and precision].

![Figure 7: V3 inside harness](image)

This iteration used a copper compression glove as the interface, sewing the index and thumb harnesses directly to it and attaching ribbon at the PIP and DIP joints of the middle finger to couple that motion. After testing this device on PH we quickly realized a substantial issue. The harnesses themselves moved a great deal as PH moved her hand resulting in a lack of consistency in the length of the bowden cable, making it impossible to actuate precisely. The harnesses as a whole needed to be rethought so that they were structured around more stable portions of PH’s hand providing a consistent place to actuate the movement from.

### 3.4 Version Four

The fourth iteration involved a major overhaul of the entire design. In order to address the issue of the harnesses moving on the hand a couple of changes were made. The first of which was changing the design of the harness to be one harness for index finger and thumb. To address the slipping issue we designed it to clamp more substantially around the palm instead of resting primarily on the back. By following the natural curves of a human hand the harness (Figure 8a & 8b), can be both lightweight and allow the user to retain both dexterity and haptic sensation.

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26 The CAD drawings for this iteration can be found in Appendix C
The harness also houses a passively reactive bladder which expands when the index finger is under load, thus increasing the compression on the user. The bladder in the harness is connected to two bladders in the MCP and PIP of the index finger. When the index finger faces resistance the water is pushed from these two bladders into the harness, causing it to grasp more tightly to the patient’s hand. The bladders were made from 260q animal balloons, protected by a layer of silicone, and are connected via tubing and a 6 way valve which is located in the harness. The housing for the harness bladders can be seen in Figure 9a and the cutout for the index finger bladders can be seen in Figure 9b.

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29 353092711873. 3mm ID 4mm OD PTFE Tubing. Ebay. San Jose, CA, USA. https://www.ebay.com/itm/353092711873
This solution eliminates the problem seen in earlier iterations of the harness moving as it is now fully secured and can withstand oppositional forces applied to the index finger. It also increases comfort of the device while not being used as there is no need to grab the user tightly when they are not trying to grip something.

The harness also has a few other improvements that improve the motion of the index finger. The harness was fitted with a spring steel pusher plate that can transfer motion from the middle finger to the index finger (Figure 10). This design was an improvement over the bowden tube as it can push and pull, as well as handle much higher applied loads.

![Spring steel pusher](image)

*Figure 10: Spring steel pusher. The left channel attaches to the MCP ring of the middle finger and the right channel attaches to the MCP of the index finger*

The spring steel worked well because arbitrary amounts of material can be removed from the inside of the plate to reduce its stiffness until it is well tuned. The shape of this cut away material can also allow us to twist the spring steel [this is a good form of compliance to have when interfacing with a growing and shifting human hand]. The main issue associated with this mechanism was that if not constrained well, it would cam due to the lopsidedness of the applied forces from both the middle finger and prosthetic. To solve this issue a small linear slider\(^\text{31}\) was used to constrain the motion of the spring steel. The PIP joint of the index finger worked the same as in version 2 and 3, with the bowden cable jumping over the MCP joint and transferring motion across the two PIP joints. One change to the bowden cable however, was the new found need to add a semi-rigid sheath that prevented the tubing from kinking under load. This kinking drastically increased the friction in the system while also effectively lengthening the actuation distance of the cable, thus causing the PIP to rarely move. Our solution to this problem was to

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string 3D-printed O-rings onto the bowden tube to prevent it from kinking. This change made a huge improvement in the overall force to actuate.

The thumb harness was also redesigned to be raised from the residual bone in order to ensure that the sensitive bones left on PH’s thumb would not be irritated by the device during use. After PH’s initial visit it became clear that user adjustability was a major part of designing a comfortable device. As a result of this the harness was split into two pieces, allowing the user to tighten it to their desired state (Figure 11a).

![Figure 11a: The tightenable thumb harness](image1)

![Figure 11b: EGaIn sensors inside the thumb harness](image2)

The movement of the thumb was driven by PH’s residual bones, using two experimental liquid metal EGaIn pressure sensors (Figure 11b). These sensors change resistance when deformed and as such can be used to sense when PH moves what remains of her thumb’s PIP. As PH pressed on one and deformed it, the thumb moved forward and as she deformed the other, it moved backwards.

We initially added a silicone layer between the thumb harness and the thumb in order to protect PH’s hand but it proved to be too bulky and made it more difficult for PH to tighten the harness to her metacarpal. One benefit of the silicone was that we were able to build in channels for the sensors, ensuring that they were in a constant position each time. Despite this benefit, the silicone was eliminated because it destabilized the thumb harness and didn’t allow PH to feel the sensor position.

33 881540. Mold Putty. Hobby Lobby. Oklahoma City, OK, USA.
https://www.hobbylobby.com/Crafts-Hobbies/Clay-Molding-Sculpting/Casting/Mold-Putty/p/27710
The signals gathered from these EGAln sensors were analyzed through code\textsuperscript{34} written in C++ and executed on an ELEGOO Nano\textsuperscript{35}. Once the baseline value for the sensors was established, the code was modified so that any increase in deformation would translate to bilateral movement of the digit.

Version 4 is the first to include a functional wrist module (Figure 12), which houses the electronics for sensing and controlling the thumb prosthetic.

![Figure 12: Wrist Module](image)

The thumb is driven by a small servo\textsuperscript{36} housed in this module which can move the thumb with precise motion control. The liquid metal sensors and ELEGOO control the movement of this servo. While the servo is not active the thumb is locked in place by a solenoid\textsuperscript{37} which pushes together the teeth of two zip ties\textsuperscript{38} locking the thumb in its position. This design makes sense because the non-back-drivability of the servo is unreliable with regards to the holding strength of the prosthetic. This means with the solenoid locking system the thumb can handle much higher loads without failing, while still being able to use a small low profile actuator.

The solenoid was chosen for its ability to toggle between two positions and stay passively in one of them. This made it a good choice for the locking mechanism of the thumb. Its overall effect on the battery life is low because it only draws power for the time that the thumb is moving. The solenoid is used to drive a reusable zip tie which effectively turns the zip tie on and off. The end result of this mechanism is a thumb that will hold position against tremendous loads without putting any strain on a motor or burning through the battery.

\textsuperscript{34} See Appendix B
\textsuperscript{35} ELEGOO Nano V3.0. ELEGOO. Shenzhen, Guangdong, China. https://www.elegoo.com/products/elegoo-nano-v3-0.
\textsuperscript{36} 2820 FEETECH FS90R Micro Continuous Rotation Servo. FEETECH. Shenzhen, Guangdong, China. https://www.pololu.com/product/2820
The system logic is outlined in Figure 13:

![Electrical Schematic](https://www.aliexpress.com/item/4001153005756.html?spm=2114.12010615.8148356.2.294d7eccyPThBB)

**Figure 13: The electrical schematic used to control the movement of the thumb**

An 18650 battery cell\(^ {39} \) was chosen because of its price, rechargeability, availability, and weight. One main concern for this device was range anxiety, we never wanted our user to feel like they were tethered to a wall. For this reason we opted to use an inexpensive, reliable, high capacity battery that could be swapped out easily. The aim of this was to provide PH with ease of mind when it came to the lifetime of the battery. The common and low cost nature of 18650 batteries means they are easy to acquire. A charging port was also built into the wrist module so that the user could charge the battery if they did not have a replacement on hand.

We used a continuous rotation servo for this iteration because it is easy to control and requires only one pin on the ELEGOO. The servo also has built in gear reduction, making it suitable for our use.

The electronics were controlled using an ELEGOO Nano, which was chosen both for it’s small profile and ease of use. The programmable nature of the ELEGOO meant we could adjust our code rapidly as we iterated through our design.

### 3.5 Material Experimentation

Material experimentation was limited as we did not have many of the testing tools needed to do comprehensive testing of our materials properties, nor was it needed, testing by feel was

\(^{39} \) 18650 Battery Li-ion 3.7V 5000mAh. YCDC.
https://www.aliexpress.com/item/4001153005756.html?spm=2114.12010615.8148356.2.294d7eccyPThBB
good enough. However, we believe it is relevant to include our testing so others can try and recreate the materials we used.

The prosthetic itself was made using a resin 3D printer, specifically an Anycubic Photon Mono SE.\(^{40}\)

Procedure:
1. Mix resin in a bottle and shake hard for 2 minutes to mix.
2. Allow resin to sit for 3 hours to let the bubbles settle out of the mixture.
3. Gently mix the resin being mindful not to create bubbles.
4. Pour the resin into the vat slowly being mindful of bubbles.
5. Print.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Test & Resin 1 & Resin 2 & Ratio & Additive & Exposure Time (s) \\
\hline
R1\(^{41}\) & Siraya Tech Blu V1 blue\(^{42}\) & none & N/A & none & 1.5 \\
R2 & Siraya Tech Blu V2 clear\(^{43}\) & none & N/A & none & 1.2 \\
R3 & Siraya Tech Tenacious\(^{44}\) & none & N/A & none & 2.2 \\
R4 & Siraya Tech Blu V1 blue & Siraya Tech Tenacious & 2:1 & none & 2.2 \\
R5 & Siraya Tech Blu V1 blue & Siraya Tech Tenacious & 3:1 & none & 2.2 \\
R6 & Siraya Tech Blu V1 blue & Siraya Tech Tenacious & 3:2 & Graphite & 5 \\
R7 & Siraya Tech Blu V2 clear & Siraya Tech Tenacious & 2:1 & Graphite & 4.5 \\
R8 & Siraya Tech Blu V2 clear & Siraya Tech Tenacious & 3:1 & Graphite & 4.5 \\
R9 & Siraya Tech Blu V2 clear & Siraya Tech Tenacious & 3:2 & Graphite & 4.5 \\
\hline
\end{tabular}
\caption{Resin ratios for best material properties.}
\end{table}

Orange denotes the mixture we went with. In Table 2 we outline the properties that we were able to qualitatively analyze based on multiple parts printed in R1-R9.

---


\(^{41}\) Resin 1 = R1


### Table 2: Properties from resin testing

<table>
<thead>
<tr>
<th>Test</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Tough Engineering ABS like resin. Can handle shock loads.</td>
</tr>
<tr>
<td>R2</td>
<td>Tough Engineering ABS like resin. Can handle shock loads. But clear slightly better resolution.</td>
</tr>
<tr>
<td>R3</td>
<td>Durable highly flexible tough resin. When printed in a thin part that part is very flexible, but when made thick it feels like a car tire.</td>
</tr>
<tr>
<td>R4</td>
<td>Low print resolution (for SLA) parts were a little too gummy from the tenacious which prints flexibly and as such requires high cure times.</td>
</tr>
<tr>
<td>R5</td>
<td>Higher resolution, used this for most of initial prototyping.</td>
</tr>
<tr>
<td>R6</td>
<td>Similar properties to test 5 however, the graphite has two benefits, increases the resolution of the final part by preventing light bleed in the transparent resin and making the part matte black.</td>
</tr>
<tr>
<td>R7</td>
<td>Similar properties to test 4, but much higher resolution, still a little too gummy.</td>
</tr>
<tr>
<td>R8</td>
<td>Perfect for our needs, stiff, shock resistant, can bend almost in half before breaking, black, extremely high print resolution.</td>
</tr>
<tr>
<td>R9</td>
<td>Similar to test 8, but more flexible and less stiff. Excellent properties for some applications but not ours.</td>
</tr>
</tbody>
</table>

R8 was established to be the best ratio of the resins for this project as it would provide the flexibility we wanted while still maintaining a high strength and high aesthetic qualities.
4 Initial Experiments and Tests

4.1 Thumb Timing

There were two values from the movement of the thumb that we were interested in. These included the time for total actuation, as well as the overall battery life of the thumb and wrist module. These were measured by evaluating a video of PH actuating the thumb and calculating the current draw of the solenoid, motor, and sensors in relation to the battery. The calculations for both of these are outlined in Chapter 5.

4.2 Key Grip

In order to determine the force PH was able to apply between both of her prosthetic fingers we used a small load cell. PH was able to hold the sensor between both of her prosthetic digits in a key grip (Figure 14), and was instructed to apply as much force as she could. She held this position for 5 seconds during 3 repeated tests. We pulled the most constant force recorded by the oscilloscope over one second for analysis.

![Figure 14: Displays 6 common grip types](https://www.tek.com/datasheet/digital-storage-oscilloscope)

---


4.3 Real World Use of the Device

While quantifiable tests are important for this project, the qualitative data garnered directly from PH was of incredible value and importance. In order to test the overall success of the device we went to WPI’s Practice Point and spent time in their mock apartment. Here, we identified several objects for PH to manipulate in order to understand the successes and failings of the device. The objects we had her grasp required her to use a key, hook, tool, and power grip as pictured in Figure 14. She also used just the pointer finger to press buttons, demonstrating the cooperation of the joints of the prosthetic index finger with the user's intent.
5 Results

5.1 Key Grip Strength Test

The key grip strength tests were conducted using a 1 inch thick load cell\(^4^8\). The following graphs display three repeated tests with the same cell.

---

5.2 Thumb Timing

5.2.1 Time for Full Grasping Cycle

A full grasping cycle is defined as the time it takes for the thumb to close and open. The speed for one grasping cycle was calculated via the following equation.

\[
\frac{RPM \times \text{perimeter}}{60 s} = \frac{130RPM \times (2\pi \times 1.6cm)}{60 s} = 21.78 \text{cm/s} = 21.775 \text{cm/s}
\]

1 cm for full actuation

\[
\frac{1 \text{cm}}{21.78 \text{cm/s}} = 0.046 \text{s for closure}
\]

Full Grasping Cycle

\[
0.046 \text{s} \times 2 = 0.092 \text{s for full grasping cycle}
\]

The actual time for this grasping cycle was demonstrated to be 2.96 seconds. Time for full grasping cycle in hours for future calculation.

\[
2.96 \text{s} \times \frac{1 \text{min}}{60 \text{s}} \times \frac{1 \text{hr}}{60 \text{min}} = 8.2 \times 10^{-4} \text{hr}
\]

5.2.2 Grasping Cycles per Charge

To determine the number of grasping cycles per charge we had to consider the current draw from the solenoid, motor and two sensors when attached to a 5000mAh battery and a power supply of 5v. The calculations for this are seen below:

Battery Wh

\[
\frac{(5000mAh \times 5v)}{1000} = 25 \text{Wh}
\]

Solenoid Wh

\[
1.1A \times 5v = 5.5W
\]

\[
5.5W \times (8.2 \times 10^{-4} \text{hr}) = 0.00451 \text{Wh}
\]

Motor Wh

\[
0.120A \times 5v = 0.7W
\]

\[
0.7W \times (8.2 \times 10^{-4} \text{hr}) = 5.74 \times 10^{-4} \text{Wh}
\]
EGaIn Sensor Resistance

\[ \rho = 29.4 \times 10^{-6} \Omega/cm \]

\[ L = 1.37\text{cm} \]

\[ S = 14.741\text{cm}^2 \]

\[ R = \frac{(\rho \times L)}{S} \]

\[ R = \frac{(29.4 \times 10^{-6}\Omega/cm) \times 1.37\text{cm}}{14.741\text{cm}^2} \]

\[ R = 2.73 \times 10^{-6}\Omega \]

Sensor Wh

\[ \frac{2.73 \times 10^{-6}\Omega}{5\text{V}} = 5.46 \times 10^{-7}\text{W} \]

\[ 5.46 \times 10^{-7}\text{W} \times (8.2 \times 10^{-4}\text{h}) = 4.47 \times 10^{-10}\text{Wh} \]

\[ 2 \times (4.47 \times 10^{-10}\text{Wh}) = 8.95 \times 10^{-10}\text{Wh} \]

Battery Life

\[ \frac{25\text{Wh}}{0.00451\text{Wh} + 5.74 \times 10^{-4}\text{Wh} + 8.94 \times 10^{-10}\text{Wh}} = 4,917 \text{ grasping cycles/charge} \]

5.3 Analysis of Main Objectives

The success of the device can be evaluated primarily through the analysis of the 11 criteria we outlined at the start of this paper. Below we list each objective and assess the device’s ability to reach each stated goal.

Table 3: The success and failure of our objectives.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two degree of freedom index finger</td>
<td>Completed</td>
</tr>
<tr>
<td>2s for full actuation</td>
<td>2.96s for full actuation; however, this project is ongoing and</td>
</tr>
</tbody>
</table>

---

methods to increase the efficiency of this digit will be addressed.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>750 grasping cycles per charge</td>
<td>Completed: 4.917 cycles/charge</td>
</tr>
<tr>
<td>Breaking point of 44N/m² at finger tip</td>
<td>Completed: 3.9E7 N/m²</td>
</tr>
<tr>
<td>Weight of main harness and index finger: Goal 75g</td>
<td>88.5g; while this objective was not achieved, the user reported being happy with the weight and as it is only a difference of 13.5g we are happy with this result.</td>
</tr>
<tr>
<td>Weight of thumb: Goal 50g</td>
<td>Completed: 31.9g</td>
</tr>
<tr>
<td>Weight of wrist module: Goal 250g</td>
<td>Completed: 110.9g</td>
</tr>
<tr>
<td>Easy to don and doff</td>
<td>Took ~10 minutes and no consistency with thumb and sensor placement; however, this project is on-going and we have plans to improve upon this.</td>
</tr>
<tr>
<td>Intuitive control via embedded sensors</td>
<td>Completed</td>
</tr>
<tr>
<td>Grip strength of 13N at actuated fingers</td>
<td>2.7N at actuated fingers; however, this project is on-going and we have plans to improve upon this.</td>
</tr>
<tr>
<td>Easily rechargeable</td>
<td>Completed: exchangeable batteries and charging port</td>
</tr>
</tbody>
</table>
6 Discussion and Future Work

One of the biggest takeaways from this project was the realization that there is such a large disconnect between surgeons and prosthetists. Surgeons are traditionally trained to clean up a wounded area as much as possible during an amputation because residual structure is often seen as a potential risk down the road. What this project proves is that by leaving excess bone structure prosthetists are able to take advantage of this movement to make a more intuitive device. If surgeons had removed PH’s bone fragments atop her thumb like they had wanted to, the solution we developed simply would not work. A thumb in particular is an incredibly difficult digit to recreate. This is because not only does it have two degrees of freedom, but the flexibility of the metacarpal eliminates the option of articulating the movement based on the position of the thumb. Currently the only prosthetic thumbs on the market are either invasive or silicone aesthetic solutions. Both of these have soaring price points for the dexterity they return.

One of the focuses for version 4 was the development of a harness that could fit to nearly any partial hand amputation with few modifications. The development of a general interface is important because when only modular parts need to be made the cost of manufacturing drops significantly. By eliminating the need to design around individualities the prosthetists job becomes much easier. To achieve this goal we recognized that the most important design parameter was to create a static and rigid structure that would stay on the hand and not move. From there it is almost trivial to attach fingers with many different choices for actuation. Once the solid base has been established the problem of creating a prosthetic becomes much easier, nearly akin to making a robotic hand. Our solution succeeds in creating a rigid structure, as well as a good general design concept that can be easily modified to fit nearly all hand amputations. This is largely due to the way the design follows the natural curves of the hand, it is easy to wear and makes many points of contact with the hand reducing any pressure points and making it very comfortable.

6.1 Analysis of Results

6.1.1 Grip Strength

The pinch strength of the device was a very telling experiment for the prosthetic. Despite the fact that the finger was strong and well attached, it did not apply much force because PH had trouble holding the load cell. One reason for this was that the load cell we used was one inch thick meaning that the key grasp was compromised as she was really holding her thumb about an inch away from her prosthetic index finger. However, the main cause for low grip force was the lack of any sort of high friction surface that would have allowed her to get a good grip and press harder. The max force observed happened during an instance when the load cell slipped from PH’s grip maxing out at 7.8N of force. We were also able to have her demonstrate a steady force over a longer period of time at about 2N. These results are important to show that the finger can
withstand higher forces if a good grip is added, as well as proved that PH can produce a consistent load on an object she is trying to hold.

Figure 16: Finite Element Analysis of the strength of a simplified index finger

Additionally, while we could not test the breaking point of the device, we were able to simulate it in SolidWorks (Figure 16) and find that the maximum stress of the part under a 45N load is still within a 8x factor of safety modifier, which is acceptable since this device does not expect to see any large dynamic loads.

6.1.2 Thumb Timing

The time for a full grasping cycle was established to be 2.96s. This is a commendable achievement for a prosthetic thumb, however when comparing the value to that of a human thumb it cannot compare. The testing of this was a successful proof of concept. The timing of the thumb movement will be reduced with a more natural placement of the sensors as well as a reduction in the length of the bowden tubes.

6.1.3 Goals

This project is an ongoing MQP and for the first part of this massive project we have still much to improve upon. However, this project still found success in most of the goals we set out to achieve. This project is more than just an MQP, as the end result will have a real impact on a human patient. Because of this, we plan to continue to work with PH until each of these goals are fully addressed.
6.2 Future Work

This iteration of the project has been an incredible proof of concept for us, however there is still much work to be done. The work to be done can be broken down into five sections, the main harness, index finger, thumb, and wrist module as well as any other general improvements. These improvements will be addressed by the team who is taking on this MQP next year. One area that generally needs improvement however and will be brought up in most of the sections is aesthetics. The looks of the device are irrelevant to the function, however, to achieve the goal of making this device something PH wants to use everyday it is critical that she wants to wear it, and feels good wearing it. As such, aesthetics are a critical consideration for this project.

6.2.1 Harness

The harness is the most critical part of the prosthetic and while our current design functioned well there are still a couple things that can be improved in later iterations. Our current prototype has lots of wires and tubes that stick out. These tubes do not affect the functionality of the device but they do reduce the usability. To mitigate this issue in future designs we would have to decide which of these tubes are truly critical. In addition, by reducing the area they take up, we could fit them directly into the harness mechanism and make them completely internal to the prosthetic. This would not only make the overall design more sleek and professional, but it would prevent the wires from getting caught on anything during use. One other important consideration for the looks of the device is the thickness. The device as it stands is very thick, but it could be much thinner if the spring steel rode on an integrated flat linear rail, or similar anti-camming mechanism.

The next important change critical for taking this device from functional to usable is creating a mold so that we can pour many silicone inserts for the harness with precisely chosen thickness and shapes. Once again this would make the design look better, but also improve the fit of the device. This also opens other options as it is now easier to embed structures into the silicone as well as color it.

6.2.2 Index Finger

The improvements to the index finger circle mainly around making it easier for the user to actuate both degrees of freedom. The first design change that needs to be made is to the rings. Both of the rings need to be tightenable so that they can hold the middle finger securely. The ring that rests atop the intermediate phalange of the middle finger will be made longer so that the torsion placed on it will be distributed over a larger area. In order to ensure that the intermediate phalange ring remains in a constant position a linkage between the rings is necessary. The position of the index finger needs to be altered as well, as it currently rests too far forwards and too high in relation to her other digits.

Other areas of improvement include removing compliance from the MCP joint of the device. This compliance often causes it not to actuate fully which makes the device inconvenient
to use. To achieve this the spring steel, similar to the bowden cable, must be guided through a channel to constrain its movement. This would also add strength to the spring steel meaning we could reduce its size and shape its path to be the most optimal for maximizing actuation distance. Again this alludes to routing the tubing through the prosthetic, but one major area of improvement is again integrating the wires and tubes into the index finger, improving the usability of the device.

One possible area to explore is to swap out the braided fishing line we are using for the bowden cable with steel wire. This could potentially offer the ability to push and pull on the coupled joint without having to add to the actuation force with rubber bands. I also believe that this will help with our issue of kinking the tubing, however measures will still be taken to stiffen the tube. One of the most promising anti-kinking solutions could simply be a small gauge extension spring that will act as a sheath for the tube, or potentially even as the tube itself. This however, would require testing as the spring would need to have its length completely constrained.

One other critical avenue for the prosthetic is to add high friction pads to the surfaces of the fingers that will be used, or simply make them compliant so they can conform to the object or item being picked up. The lack of this capability was the main reason PH had trouble applying high forces to the load cell during testing as it kept slipping from her grasp.

6.2.3. Thumb

The CAD for the thumb needs to be addressed in a pretty substantial way. In order to improve the positioning of the thumb we will consult an anatomy book and determine the most natural angular positioning. The overall look of the thumb will be addressed so that the thumb’s distal phalange mimics that of a human hand more. The overall positioning of the thumb also needs to be improved and will be done in two ways. First the harness will be redesigned so that it can be tightened more, ensuring that it remains in the same position. Velcro straps will be added to the base of the harness that will allow the amputee to tighten the thumb down for added rigidity.

The sensors also need to be readdressed. Housing for the sensors will be built into the thumb cap and will be protected with flexible TPU. This will ensure that they are in the same spot each time and the TPU cover will not only protect them, but will allow the user to intuit where they are by feeling the flexible material. The sensors for the next iteration will also be created specifically for this device and will be made smaller to fit into the harness.

Again the thumb would also benefit greatly from friction pads or compliant surfaces on parts of the thumb that are used for grasping.

6.2.4. Wrist Module

One major area of improvement for the wrist module would be to create a custom PCB board to clean up all the wires and chips that are taking up space in the device. Doing this would allow for the case to be redesigned to be smaller, lighter, better looking, and more reliable.
Another piece that will be improved is the locking mechanism for the thumb. The solenoid had a few issues mainly that it had a hard time actually locking the zip tie due to lack of strength at the beginning of its range of motion. In the future we will look at other locking mechanisms such as a mechanism that cams when the thumb is moved but not when the motor moves it, or simply using another motor to actuate the lock. The ideal solution would involve using the servo to drive a mechanism that is only unlocked as the motor is moving and locks when the motor is off. This should be possible, but no design has been fleshed out. One other potential area to explore for this would be compliant mechanisms, which would potentially offer solutions like the one just described.

6.2.5. General Improvements

In order to reduce the amount of time it takes to don and doff the device we plan on creating a sleeve that the wrist module and thumb are attached to. This will make it so that the patient can simply pull on the sleeve and then don the index finger harness, reducing the time to don and doff significantly. The sleeve itself will need to be compressive so that everything remains in the same spot, and the material for this will be investigated in the future. PH had also mentioned that she liked the compression glove from V3 which had silicone ribbing to increase the friction on the surface, so some sort of sleeve with this feature would be implemented. Not only would this help with her ability to grasp on to various items, but it would aid with maintaining the position of the rings on her middle finger.
7 Conclusion

The goal of this Major Qualifying Project was to create a partial hand prosthesis that would fulfill the needs of our user PH. We wanted to create something that would improve upon her current dexterity and would become something that might be worn day to day. Our final iteration of this device was able to accomplish a good portion of that. Version 4 restored the key grip as well as providing a dexterous thumb and index finger. We recognize that a large failing within the prosthetics market is that there is a lack of access to partial hand prosthetics and little innovation for those with amputations at the MCP. Our device proves that such a solution is possible. This project is not complete and there are many evidenced areas for improvement but we are confident that this proof of concept has set us up for the creation of a high level working prototype.

When PH approached prosthetists and surgeons after her accident she was told that there were no commercial options for her, and that she would have been better off losing her entire hand. This is as a result of the complexities associated with interfacing mechanical and natural movement. The general solutions investigated through this paper have the potential to act as the intermediary between the mechanical and physical, ensuring that no one has to hear that there is nothing to be done to help them.
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## Appendix A: Bill of Materials

### Total Bill of Materials

<table>
<thead>
<tr>
<th>Item Name</th>
<th>Source/Part Num</th>
<th>Quantity</th>
<th>Cost Per Item</th>
<th>Tax/Shipping Cost</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slotted 18-8 Stainless Steel Precision Shoulder Screw</td>
<td>91829A770 McMaster</td>
<td>5</td>
<td>$4.77</td>
<td>$7.13</td>
<td>$23.85</td>
</tr>
<tr>
<td>18-8 Stainless Steel Hex Nut</td>
<td>96537A145 McMaster</td>
<td>1</td>
<td>$10.24</td>
<td>$12.00</td>
<td>$10.24</td>
</tr>
<tr>
<td>Mil. Spec. Low-Strength Steel Hex Nut</td>
<td>91813A110 McMaster</td>
<td>1</td>
<td>$7.78</td>
<td></td>
<td>$7.78</td>
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<tr>
<td>Alloy Steel Shoulder Screw</td>
<td>91259A505 McMaster</td>
<td>1</td>
<td>$4.08</td>
<td></td>
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<tr>
<td>Brass Heat-Set Inserts for Plastic</td>
<td>94459A230 McMaster</td>
<td>1</td>
<td>$8.79</td>
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<td>$8.79</td>
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<td>Alloy Steel Low-Profile Socket Head Screw</td>
<td>92220A310 McMaster</td>
<td>1</td>
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<td>$14.80</td>
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<tr>
<td>Lubricant-Filled Nylon Plastic Washer</td>
<td>91545A610 McMaster</td>
<td>2</td>
<td>$3.95</td>
<td></td>
<td>$7.90</td>
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<tr>
<td>Black-Oxide Alloy Steel Socket Head Screw</td>
<td>91251A052 McMaster</td>
<td>1</td>
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<td>$3.40</td>
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<tr>
<td>Tapered Heat-Set Inserts for Plastic</td>
<td>93365A102 McMaster</td>
<td>1</td>
<td>$12.34</td>
<td></td>
<td>$12.34</td>
</tr>
<tr>
<td>1/32&quot; ID X 1/16&quot; OD - (PTFE Tube)</td>
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<td>Extended Cost</td>
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Appendix B: Code

```c
#include <Servo.h>
Servo myservo;
int servoPWM = 0; // initializing variable
unsigned long previousMillis = 0;
unsigned long currentMillis = 0;
float max_rate = .05; //rad/ms
int solenoidPin = 5;
const int buttonPin1 = 3; // the number of the pushbutton pin
const int buttonPin2 = 4; // the number of the pushbutton pin
int lastangle;
const int servopin = 6;

float curAngle = 0;

int maxTime = 1300; //ms
int cumTime = 0;

#define MAX_PWM 2150
#define MID_PWM 1500
#define MIN_PWM 850

int fsrAnalogPin1 = 0; // FSR is connected to analog 0
int fsrAnalogPin2 = 1;
int p1; // analog reading from the sensor
int p2;
bool button = false;
float deltaP = 0;
int deadband = 100;
bool forward;
bool deadband_overcome;
bool hardcode = false;

int p1Neutral = 791.8133333;
int p2Neutral = 797.9066667;

void setup() {
    Serial.begin(9600);
    myservo.attach(servopin);
}
```
pinMode(LED_BUILTIN, OUTPUT);
pinMode(solenoidPin, OUTPUT);
pinMode(buttonPin1, INPUT);
pinMode(buttonPin2, INPUT);
}

void loop() {
  if (hardcode) {
    cumTime = 0;
    while (cumTime < 1200) {
      previousMillis = currentMillis;
      unsigned long currentMillis = millis();
      long int deltaT = currentMillis - previousMillis;
      cumTime += deltaT;
      myservo.write(MAX_PWM);
    }
    cumTime = 0;
    while (cumTime < 1200) {
      previousMillis = currentMillis;
      unsigned long currentMillis = millis();
      long int deltaT = currentMillis - previousMillis;
      cumTime += deltaT;
      myservo.write(MIN_PWM);
    }
  }
  else {
    previousMillis = currentMillis;
    unsigned long currentMillis = millis();
    long int deltaT = currentMillis - previousMillis;
    bool buttonState1 = digitalRead(buttonPin1);
    bool buttonState2 = digitalRead(buttonPin2);
    if (button) {
      bool buttonState1 = digitalRead(buttonPin1);
      bool buttonState2 = digitalRead(buttonPin2);
      Serial.print("B1:");
      Serial.print(buttonState1);
      Serial.print("\t");
      Serial.print("B2:");
      Serial.println(buttonState2);
      if (buttonState1) {
        forward = true;
deadband_overcome = true;
digitalWrite(LED_BUILTIN, HIGH);
} else if (buttonState2) {
    forward = false;
deadband_overcome = true;
digitalWrite(LED_BUILTIN, HIGH);
} else {
    deadband_overcome = false;
digitalWrite(LED_BUILTIN, LOW);
}
deltaP = 1023;
    //    Serial.print("deltaP:");
    //    Serial.println(deltaP);
} else {
    p1 = analogRead(fsrAnalogPin1) - p1Neutral;
p2 = analogRead(fsrAnalogPin2) - p2Neutral;
    Serial.print(p1);
    Serial.print("\t");
    Serial.println(p2);
    deltaP = p1 - p2;
deadband_overcome = true;
    if (deltaP > 0) {
        forward = true;
    } else if (deltaP < 0) {
        forward = false;
    }
    if (abs(deltaP) < deadband) {
        deadband_overcome = false;
    }
}
if (deadband_overcome) {
    float max_change = max_rate * deltaT;
    float pRatio = deltaP / (1023 / 2);
    if (forward) {
        cumTime -= deltaT * pRatio;
        servoPWM = servoPWM - (max_change * pRatio);
    } else {
        cumTime += deltaT * pRatio;
    }
servoPWM = servoPWM + abs(max_change * pRatio);
}
}
else {
    servoPWM = MID_PWM;
}

if (servoPWM < MIN_PWM) {
    servoPWM = MIN_PWM;
} else if (servoPWM > MAX_PWM) {
    servoPWM = MAX_PWM;
}

myservo.write(MIN_PWM);
delay(100);
Appendix C: V4 CAD Drawings

Index Finger
Thumb

Main Harness
MCP Ring (left) and PIP Ring (right)