Partial Hand Prosthesis: Core Function

A Major Qualifying Project Report:
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Abstract

The lack of 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 servo-driven artificial thumb controlled by motion in the residual bone fragment of the patient's biological thumb, and a passively actuated index finger controlled by the motion of the patient's middle finger, with special focus on form factor, mechanical simplification, and improving on various shortcomings of the previous versions. Qualitative and quantitative testing indicates that the prosthetic restores several manual capabilities to the amputee.

This project is a continuation of *Partial Hand Prosthesis*, advised by Professor Marko B Popovic, submitted on May 5, 2021.

Acknowledgements

This project would simply not be possible without the continued guidance of Professor Marko Popovic, our primary advisor, and Professor Gregory Fischer, our co-advisor. Their input kept the design focused and on track through many design sessions.

Chris Nycz from Practice Point Labs provided quick access to water jet cutting which kept the iterative design process moving. Without his prompt responsiveness and guidance, progress would not have gone as quickly as it did.

PH, the end user, as well as her family, were extremely enthusiastic and helpful in the development of the prosthetic device and were integral to the success of the project. The team is extremely grateful for PH's honesty in making suggestions, and for taking the time to travel to Worcester for the sake of testing.

1. Introduction

1.1 Motivation

Every amputation produces unique residual anatomy and function. In lower and most upper limb amputations prosthetic devices are most commonly attached using sockets. This means that there is little need for custom prosthetic devices and more custom socket technology, which are more cost-effective using imaging and molding techniques. Custom prosthetics with unique functions like the dexterity necessary for phlangal prosthetics are time-consuming to produce and test, and are therefore expensive and impractical. The project was motivated by the lack of partial hand prosthetics (PHP) on the market.

Our goal for this project was to produce a functional hand prosthetic for a user with a partial hand amputation that incorporated easily customizable components to make the final product as adaptable to as many partial hand amputees as possible. The current team shares these goals with the prior project team, and has set out to expand on the prior versions of the prosthetic. On top of the mechanical problems that stunted the effectiveness of the prior project's prosthetic, the new team set out to develop a more elegant and aesthetic solution that built off the successes of the prior team.

1.2 Background

Much of the more detailed background information can be found in the previous team's paper. This background will provide a brief literature review of the more important figures and an updated client statement but will primarily focus on reviewing the previous versions of the prosthetic developed by the previous team. This foundation was integral to the success of the prosthetic (Buccowich, Strauss, 2021).

1.2.1 Amputees

The term "amputee" encompasses a large number of people, as approximately 226,000 amputations occur each year (Kathryn Ziegler-Graham et al., 2018), adding to the 1.5 million Americans living with limb loss. Of these yearly amputations, approximately 61,000 are partial hand or finger amputations, primarily caused during the operation of heavy machinery such as factory equipment, cars, power tools, etc (Makoto Komoura et al., 2008). This subset of amputees must deal with a significant loss of manual dexterity. Many of these amputations include the thumb, which on its own accounts for nearly 50% of the hand's function (Daniel B.C. Reid et al., 2019).

Due to the complexity of the human hand, these partial hand amputations result in a diverse range of residual anatomy. Surgeons and prosthetic designers must therefore address each amputation with a unique solution. As a result, there is not always a viable or affordable commercial option available for every partial hand amputee.

1.2.2 Client Statement

The end user for whom the team is making the device will be referred to as PH throughout this paper. She is a 22 year old woman with a unique amputation of the index and thumb on her left hand. Both of these amputations occurred at the metacarpophalangeal joint (MCP), however, the surgeons left two pieces of the proximal interphalangeal joint (PIP) in her thumb that she is still able to control with a promising level of precision.

Figure 1: X-rays of PH's residual anatomy.

Since the writing of the previous paper, PH has lived with the amputation for enough time to restore much of the strength in her hand muscles. She has continued to adapt over time, which has aided the team in developing a simpler prosthetic device with a more focused set of manual capabilities.

1.2.4 Previous Versions

Work with PH began in August of 2019 very soon after the accident that took her digits. The previous project team set goals and developed four distinct versions of the partial hand prosthetic. The successes, failures, and feedback from each of these versions helped refine the designs of the current team.

1.2.4.1 Goals of Project Team 1

The goals set by the previous team were based on multiple whole hand devices that are already on the market. They originally made these comparisons due to the lack of devices that were made for PH’s unique use case. After several design cycles, it became apparent that these comparative goals were not feasible and were too ambitious for a device that could not be attached using a sturdy socket design.

Table 1: Previous project team goals.

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

1.2.4.2 Summary of Versions 1-4

Version 1 of the partial prosthetic hand was an index finger that actuated based on the motion of the middle finger using a pulley system located on the back of a hand harness. The harness could tighten using a ratchet system, and was therefore adjustable. The previous project team had decided that the index finger was more functionally important to PH, and therefore this version had no fully actuating thumb. Instead, it was designed as a stagnant digit that was fixed to the joint in which PH still had some residual movement.

Version 2 incorporated a bowden cable design that wove through the index finger and pulled on the upper joints to bend the finger. This substantially reduced friction in the cable. The thumb was updated to be actuated in the same manner. It was at this point in the design cycle that the previous team began working with EMG and pressure sensors, both of which introduced new challenges.

Version 3 was the first version of the prosthetic that PH was able to test. The main focus of this iteration was to simplify the mechanical components of the design. Unnecessary moving parts were removed, such as the bowden tube connection to the DIP joint, and was replaced with a simple four-bar linkage that facilitated the bending of the fingertip. It also included a method with which to adjust the range of motion of the index finger relative to the driving middle finger. This, however, was ultimately a failure, and was discontinued from future versions. Finally, it was the first version printed using stereolithography (SLA) 3D printing technology, which utilizes resins with adjustable material properties, and allowed for prints with higher resolution and accuracy.

Version 4, the last version that the previous team put together, was a major overhaul of the entire design. First, the harness was redesigned to grip the hand more tightly, wrapping around to the palm rather than primarily resting on the back. The harness naturally followed the contour of the human hand, and as a result could be designed to interfere with the biological hands movement as little as possible. The thumb harness was also substantially redesigned with the hope of increasing PH's comfort. It was designed to sit above the residual bones in PH's thumb, so as to avoid irritation. Some efforts were made to increase her comfort further with silicone padding, but these inclusions were ultimately dropped, as they added bulk to the already unwieldy thumb device.

This version also included some of the more experimental features explored by the team. The harness housed a passively reacting bladder that filled when the index finger was under load to fit tighter to PH's hand. Ideally, these bladders would increase the overall comfort of the device, tightening the harness to counter oppositional loads when in use while relaxing when no loads were present, reducing the amount of time that the harness gripped tightly to the hand. Furthermore, the thumb was controlled by two experimental EGaIn (eutectic Indium Gallium alloy) sensors that, when compressed and deformed by the residual bones of PH's thumb PIP, changed in resistance. This resistance change could be used to move the thumb forward when one pad was pressed, and backwards when the opposite pad was pressed.

Version 4 was the first version to include a wrist module that housed the electronics necessary to drive the prosthetic. This module housed the servo that drove the thumb, the ELEGOO Nano that processed the signals from the sensors and controlled the servo, and a solenoid/zip-tie locking system that increased the effective loads that the prosthetic thumb could exert.

1.2.4.3 Results and Feedback

It was necessary that the team looked carefully at the successes and failures of each of the previous versions of the hand prosthetic before designing further. Several key features conceived by the previous team proved to be both functional and reliable, while others complicated the design unnecessarily or introduced unforeseen challenges through their complexity.

While the ratchet design introduced in version 1 was rightfully discontinued, the bowden cable that weaved through the phalanges of the index finger in order to actuate it was kept through every version of the prosthetic, improving with each iteration, and would therefore remain in future versions. The SLA printing introduced with version 3 was deemed not only valuable, but necessary for developing a prosthetic with this level of desired precision. The four bar linkage design of the digits on this version closely informed the design of future versions, as well.

Version 4 of the prosthetic, while a notable improvement over the past versions, had several issues that the previous team diligently documented. In regards to the flexion of the prosthetic index finger, there were a number of flaws in the design that introduced friction to the bowden cable, which substantially reduced the effective force that could be exerted by the prosthetic, as well as reduced its range of actuation. Kinking of the bowden tube also added to the friction experienced by the cable, and therefore had the same effect. Full actuation of the index finger was a necessary function, so the team set out to quickly alleviate these issues.

Because of the inclusion of all of the experimental features mentioned, version 4 was deemed to be unnecessarily complex. The bladder system introduced tubing that would often interfere with assembly, and would presumably get caught on PH's surroundings if she were to wear it for extended periods of time. The thumb harness was bulky and heavy as a result of the efforts to rigidly attach it to the hand. The team decided to focus on simplifying the overall system while maintaining the structural integrity of the prosthetic.

This complexity demanded the attention of the previous project team in many different areas, both in the prosthetic's core function and its experimental features, and as a result, it was determined that a narrower and more focused approach would be beneficial going forward. Therefore, the focus of the current project team was to improve on the core functionality of the prosthetic first, which would mean utilizing simpler electrical systems in order to rapidly iterate on the mechanical design with as little external resistance as possible. The experimental features would be developed in tandem by a separate project team.

2. MQP Goals

The goals for this partial hand prosthetic were developed to ensure the device was comfortable, intuitive, and functional for PH. Through research on existing devices, conversations with the end user, and feedback on previous versions, we were able to produce a set of comprehensive and achievable goals. These goals fall into 3 categories: device control, strength and functionality, and end user experience. These categories focus on how the device operates and its range of motion, how effectively the final device assists the end user during everyday tasks, and how comfortable and intuitive the device is respectively.

2.1 Device Control

2.1.1 Index Finger

As seen in figure 1, the X-ray of PH's hand, there are no remaining fragments of the index finger's proximal phalanx. Therefore, we determined that there was no feasible method to capture any residual motion and directly translate it to the device. This meant that the movement of the index finger device must be coupled to another finger or the wrist. This constraint results in a mostly passive and assistive device, and the development of the goal of "passive deflection".

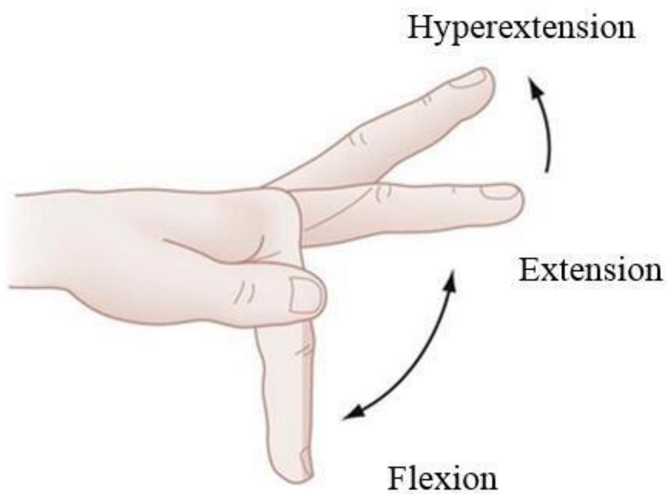

Figure 2: Flexion/extension movements of the fingers (A. Deaconescu).

Labeled as hyperextension (figure 2), our goal was to create a device that was capable of passive deflection when a force is applied to the palm side of the index finger. Furthermore, the device should return to a neutral position when under no load. The bending stiffness should be selected based on qualitative feedback from testing with PH, meaning it should be easily adjustable to the end user's needs.

The second goal for passive movement of the index finger device was to be able to achieve 30 degrees of splay relative to the biological middle finger and returning to neutral position when under no load. This "peace sign" motion will help to stabilize PH's hand on objects when gripping larger objects and with the previous goal of deflection accounting for tapered surfaces. 30 degrees of splay is plenty of motion to account for everyday tasks, such as picking up a coffee cup or grabbing a circular doorknob.

2.1.2 Thumb

As discussed in the client statement, the remaining anatomy in PH's thumb provided a unique method of actuating the thumb device. The proximal phalanx fragments retained motion and control, so it was decided that by implementing a 2-button input system placed inside of a custom "cap", PH would be able to control the thumb device with reasonable precision. The thumb cap would hover over the residual fragments and be positioned in such a way to mimic the natural gripping motion with which PH was already familiar. Pressing the front button began the forward/grasping motion. Releasing the front button will lock the thumb and re-engaging the button will continue the forward motion until it hits an extreme position. The device could then be returned to the "Home" position using the back button. The thumb attached to the top of the thumb cap would be a bowden cable operated four-bar mechanism that would reset using an elastic band. To ensure the thumb could remain functional while PH carried out tasks, we sought to achieve a full actuation time of 2 seconds. This means that the device would start in its upwards and homed position, complete a cycle of full actuation, and return to the homed position. Previous versions attempted to use variable force sensors, but due to their complexity brought up issues with precision and controllability. We determined that the simpler 2-button system would be sufficient.

2.2 Strength and Practicality

2.2.1 Lateral Pinch

Since the accident in 2019, PH has regained significant muscular control with her left hand. To prove the efficacy of the final device, the grips chosen will be those associated with tasks she could not perform one handed or struggles to perform without the device. The key grip, or lateral pinch (figure 4) is a grip found in the taxonomy of everyday grasps commonly used for gripping keys to put into a lock, turning the knob handle of a washing machine, and pressing buttons on the television remote (T. Feix, J. Romero, H. -B. Schmiedmayer et al., 2016). None of those actions require much force to carry out; however, the force must be maintained over a period of multiple seconds. The goal to prove the functionality of the device while in the key grip is to perform a user independent test and maintain at least 22.24N over 10 seconds.

Figure 3: Lateral pinch.

2.2.2 Large Diameter grip

As mentioned, there are a lot of actions that PH has adjusted to perform with the remaining anatomy. She was even talented at rock climbing when she went with the project team. However, larger, smooth, objects pose a problem for PH and so the large diameter grip(figure 5), will be a test to prove the device is aiding the user. A large mason jar with a diameter of approximately 86 mm will be filled with water so its final weight is 200g. Will be asked to complete 2 tasks. In the first task, PH will be asked to grip the jar as seen in the figure and hold it for 10 seconds above the resting surface. The second task asks PH to grasp the mason jar as it is standing up right and simulate taking a sip from the jar and returning it to the table. Other testing was conducted to determine the strength and practicality of the final device but the tests above were determined as goals to guide the design process.

Figure 4: Large diameter grip.

2.3 End User Experience

2.3.1 Weights

The final device was designed to be as biomimetic as possible. The goal was to create a prosthetic finger and thumb to match the weight of the average biological finger and thumb weights +/- 10% 38g and 25g respectively. These values were determined from calculations using values from Winter's tables (Tesio, Rota, 2019). The calculations are included as part of appendix B.

2.3.2 Cycles per charge

The team wanted to build an efficient enough prosthetic to achieve at least 3,000 grasping cycles per charge. This number is an attempted improvement over the achieved cycles per charge of the previous project. Their original goal was 750 cycles per charge, but they managed to theoretically achieve close to 5,000 cycles. The current team sought to get a more accurate prediction of the device's battery life and run tests to determine that value and chose 3000 as a goal to account for possible losses.

2.5 Summary of Exact MQP Goals

Table 2: Summary of MQP goals.

1. Index finger capable of passive deflection and returning to a neutral position when under no load. Stiffness selected based on testing with the end user.
2. Index finger capable of passive splay to 30 degrees relative to biological middle finger, returns to a neutral position when under no load.
3. 4-bar thumb controlled via 2-button input inside thumb cap. Pressing the front button begins the forward/grasping motion. Releasing the front button will lock the thumb and re-engaging the button will continue the forward motion until it hits an extreme position. The device can then be returned to the "Home" position using the back button.
4. The thumb travels the full range of motion (from neutral to grasping) in 2 seconds.

5. Prosthetic finger and thumb match the weight of the average biological finger and thumb weights based on calculations using Winter's tables. (+/- 10% 38g and 25g respectively)
6. Prosthetic device achieves at least 3000 cycles per single charge of a battery.
7. The end user can complete the large diameter grip shown below, on a smooth, dry, glass mason jar with 86 mm diameter, and weight of approx. 200g for at least 10 seconds.
8. Maintain at least 5 lbf applied solely by thumb in a test that does not include the user for 10 seconds.
9. Receive, integrate, and report on feedback from the device user on: ease of use, comfort, and performance of hardware, performance of software.

3. Methods

3.1 Thumb Attachment and Actuation

Figure 5: CAD rendering of thumb with individual components labeled.

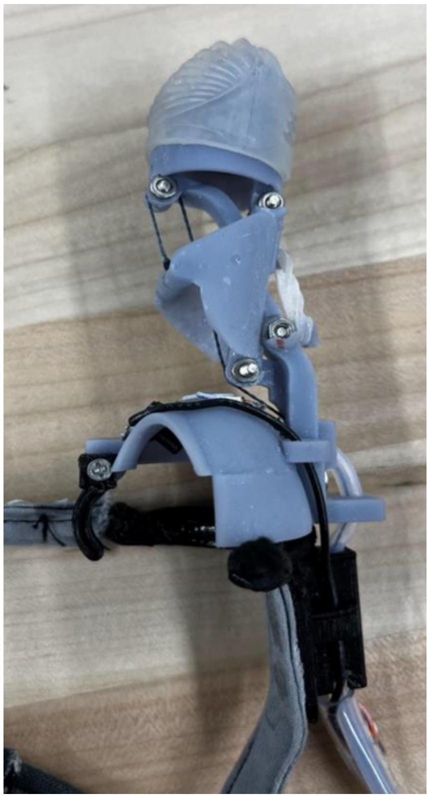

Figure 6: Thumb assembly.

3.1.1 Attachment Method

The characteristic of PLA to be malleable when heated allowed for customizable pieces to be created out of standard components. These “thermoforms” are utilized in two places for attaching the thumb to the residual anatomy. The first, called thermoform 1 or TH1 (figure 5, component 14) has a straight spine and two wings. The straight portion is designed to be placed on the metacarpal of the thumb with two wings wrapping around the flesh and clamping to the portion of PHs metacarpal the team assumed were left exposed as muscles connected to the amputated phalanges retracted. However, the location of these gaps left by the lack of flexor and extensor pollicis longus muscles were approximations, as these couldn’t be seen in the model of the hand and as PH was not nearby in the design stage. The components were designed to be easily modifiable and quickly and inexpensively FDM printed in PLA so different wing sizes could be made and tested quickly for the patient visit.

Thermoform 2 or TH2 (component 15), is in the front of the thumb cap and hooks under the head of the metacarpal bone for a tight fit on the hand. These thermoforms with attachments to where old muscles attached were also designed to create a mind/body connection to the device, hopefully, appling a comfortable amount of force to places where she may have felt forces before the amputation. The snapping harness further secures these components in place and working together with TH1 and TH2, the residual thumb fragments are then free to engage the buttons located in the thumb cap (component 16), without restricting any residual motion.

The attachment method was tested during the patient visit for stability and comfort. This was done by assembling each component one at a time and taking detailed notes in three separate categories: Initial fit and PH feedback, rapid on the spot iterations, and CAD changes to be made. The patient visit lasted five days and the detailed iteration process and patient feedback can be seen in Appendix A. The team developed the harness system through on the spot additions that evolved from elastic bands into comfortable cloth straps. The straps contain snaps that make donning and doffing easy and to make it adjustable. Being designed in tandem with testing the thermoforms, the harness contains only necessary straps to be as minimal as possible.

3.1.1 Thumb Linkage and Actuation

The thumb cap was built to surround the residual thumb anatomy as tightly as possible while still allowing the PIP fragments to engage two separate buttons. This was done by measuring the largest portion of the residual knuckle on the hand mold and the team's own thumbs and creating a dome shape on top of that, to house two tactile square momentary switches. To allow for adjustability in the height of the buttons the team purchased the button set (figure 7) and multiple difference sizes were tested before selecting the 6mm x 6mm x 9mm for the front and the 6mm x 6mm x 8mm for the back, which PH found to be the easiest to engage. Threaded through the square holes in the thumb cap the buttons are secured in place using superglue and wires are soldered and guided down the spine of TH1 and into a large housing tube along with the bowden cable tubing (figure 5.)

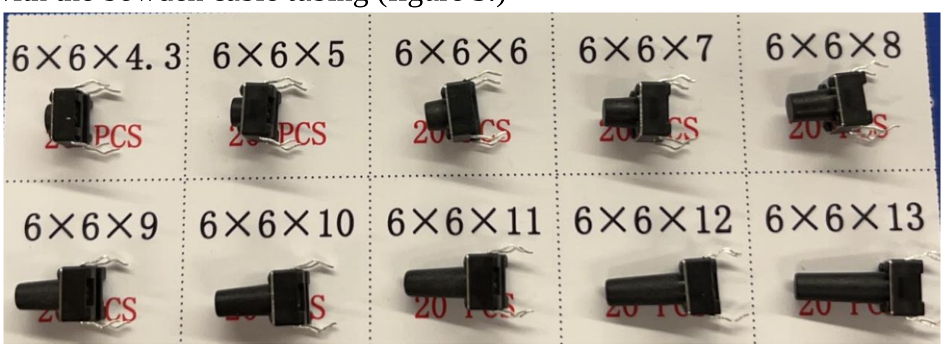

Figure 7: Variety of button sizes for thumb cap.

The proximal and distal phalanges are a four-bar linkage and the synthesis was performed by solving a motion generation problem. With the coupler defined as the width of the thumb (figure 8) and using flexion and extension as the two positions of the coupler, the synthesis was performed in Fusion 360. The dimensions of the links were obtained with respect to the coupler, which was measured from the thumb of another 22-year-old female with similar hand dimensions to PH's model. Using the dimensions of the links the linkage could be designed to look like a thumb. The ground link was built into the thumb cap and raised enough to allow for clearance to assemble the buttons and to make the thumb sit at a natural angle and height.

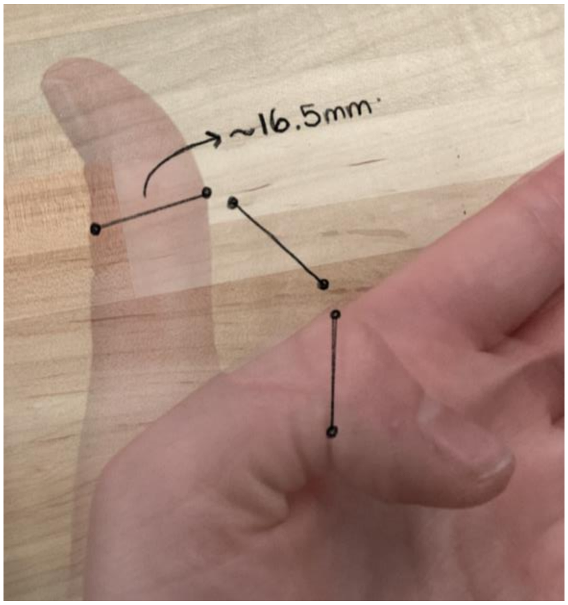

Figure 8: Approximate coupler positions to achieve thumb actuation.

A bowden cable was then attached to drive the linkage and routed down TH1 and to the wrist module. The cable selected was a braided fishing line with a 50kg weight rating. To minimize force losses to friction the cable follows inset paths in the thumb cap until enclosed in the 3mm tubing. The cable is attached to a spool inside of the wrist module, the cable will be pulled along 180 degrees of arch length and so measure so after assembling the linkage and measuring the change in length L after full flexion equation 2 was used to find the required radius r of the spool.

$$L = 2\pi r \cdot \left(\frac{180}{360}\right) \qquad (1)$$

$$r = \frac{L}{\pi} \qquad (2)$$

Two hooks, one on the thumb cap and one on the proximal phalanx link(component 17) hold a small dental elastic which homes the device from flexion back to extension when the spool releases the cable. To assist with stability and assembly, hex nut holders were added to keep M2 screw pin joints in place. A silicone gripping finger pad is slipped over the distal phalanx to help to increase friction between the thumb and objects PH may try to grip. Finally to address the issue of the weight of the thumb, the distal phalanx was designed as a solid structure but if patient testing yielded comments citing an unnatural weight this structure could hollow out further or hollowed and filled with a more dense material.

3.2 Index Finger Assembly

Contrary to the residual anatomy of the thumb, the index finger had no remaining bone fragments of the first phalanx that PH could move. Therefore, developing an index finger solution proved to be a unique challenge. Ultimately, the team decided that the index finger would be primarily assistive and compliant to gripped objects, with its flexion and movement linked to the biological middle finger. Figures 9 show renders of the final design, with minor features like bowden tubing and cable hidden.

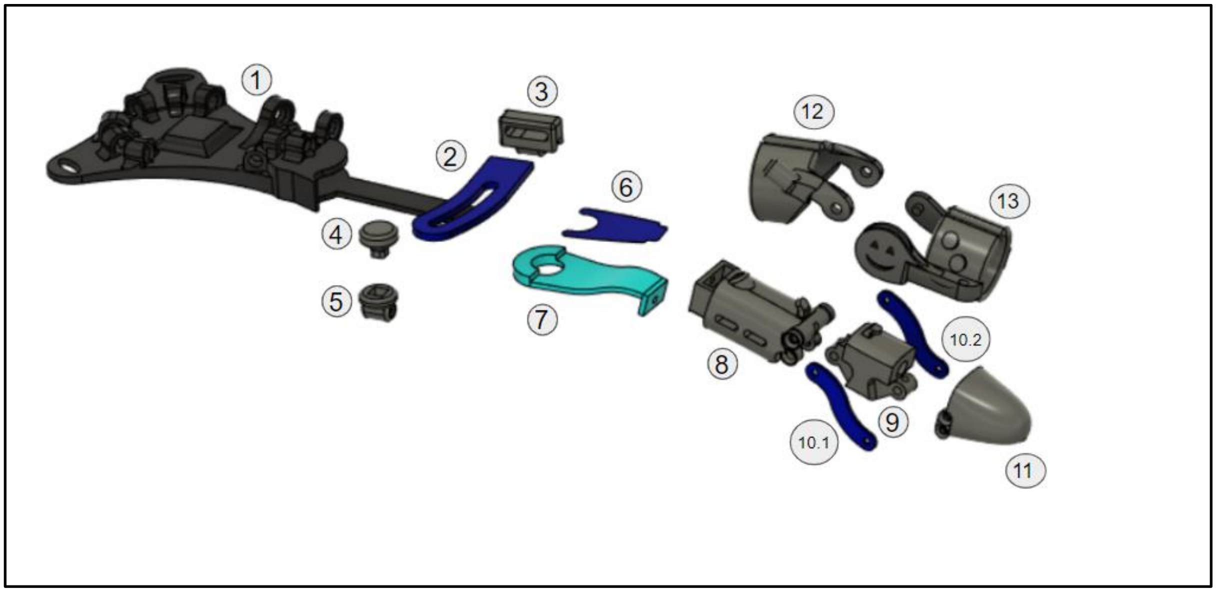

Figure 9: Exploded view of the index finger assembly, with individual parts labeled for reference.

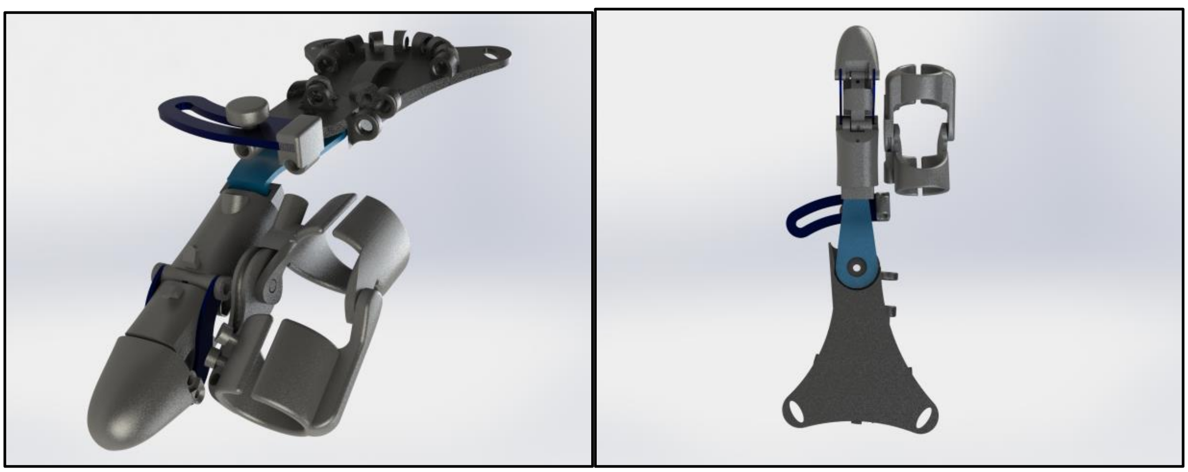

Figure 10: Render of index finger assembly.

3.2.1 Backplate (1)

The first version of the backplate was a small resin printed “triangle” with 2 cutouts for straps and a simple through hole for a pin to attach the index finger (see Figure 11).

Figure 11: First backplate design.

As the malleable nature of PLA became evident in the development of the thumb, the team decided that switching the material of the backplate would be beneficial. When printed in resin, the backplate had to be designed with a slight contour to fit the back of the hand for comfort purposes. When printed in PLA, the backplate could be designed flat on the print bed and then formed to the hand as PH saw fit, which proved to be helpful in designing the auxiliary features that became necessary as the index finger assembly evolved.

The first of these auxiliary features are the rings that route the bowden tube in a smooth arc along the back of the hand. The routing holds the tubing in place so that it lays flat on the device, and prevents unnecessary stresses on the bowden tube, which could lead to kinking and unnecessary friction. The routing of the tube is divided into small sections that help in taking off the supports from 3D printing and are useful when routing the bowden tube through the holes. The slight rise in the center of the backplate is to thicken the material for a heat set snap for the harness. The last 2 rings are in the same height, this ensures that the couplers for the rail that transmits downwards force to start at the same height. The last of the rings prior to the index finger has to be directly above the center of rotation of the index for the rotating element and the bowden tube link (4, 5) to move smoothly along the rail.

Finally, and most fundamental for the index finger's function, is the bearing housing. The circular housing fits a small bearing of approximately 8 millimeters in diameter and 4 millimeters in height, with a 2 millimeter diameter through-hole to fit the bearing shaft. The housing also has a built-in mechanical stop to prevent the bearing from rotating beyond the desired 30 degrees of splay. Under this bearing housing, a PLA thermoform extends about 20 millimeters that when heated and formed wraps around to PH's palm and anchors the backplate and prevents it from rocking.

3.2.2 Splay Mechanism (2, 3, 4, 5)

The splay mechanism is constructed from four distinct parts. The primary piece is a 1.6-millimeter-thick curved spring steel track (2). This spring steel is thick enough to deliver downward force to the index from the biological middle finger. The track guides the motion of a peg (4) that slots into a piece that attaches to the bowden tube (5). A cross section of this piece shows that the inside is lined with ridges so that it grips the bowden tube tightly and does not rotate around the tube at all (figure 12).

Figure 12: Section view of bowden tube link (5).

This rigid connection is integral to the function of the splay mechanism; if the peg spun around the bowden tube, it would not be able to reliably deliver the downward force that allows the index finger deflection to be controlled by the middle finger.

3.2.3 Flexing Element (6, 7)

The method of connecting the index finger to the backplate saw several different iterations, with the flexing element being the final solution that the team implemented and had the solution that had the most success. Early on, this connection was a dovetail slider. The female portion of the slider was set in a rail that wrapped around PH's knuckle, and the male portion was attached to the proximal phalanx. The male slider would slide along the rail and follow a set radius. This solution proved to introduce too much friction, and the male slider would often get caught in the rail.

The next solution was a simple rail with a circular cross section, and a circular guide attached to the proximal phalanx that would run along the rail. The principal was similar to the dovetail design, but the hope was that there would be far less friction, and because of the circular cross section of the rail, the index finger would be able to rotate around the rail freely and achieve the desired goal of index finger splay. The issues that arose from this solution were similar to the dovetail, however. The guide would often get caught on the rail. PH cited that the rail was uncomfortable, and since it was metal (often cut sections of spring), it was difficult to size it precisely in the same way printed components could be.

These two methods were failures, but they did achieve one thing that was deemed important for the next iteration. The effective pivot point of the artificial index finger was located inside PH's biological knuckle, rather than at some unnatural point outside the knuckle. The flexing element was the final solution the team brought forward.

The flexing element is a composite piece of 0.5 millimeter spring steel (6) stacked on a piece printed from TPU (7), an extremely flexible FDM printing filament. This element attaches the index finger assembly to the backplate. The bearing is fit into the hole in this flexing element with carefully applied adhesive so as to not interfere with the bearing spin.

The primary function of the flexing element is cause the index finger to form to an object that PH is gripping. If a force is applied at the index finger tip as if to facilitate hyperextension, the flexing element allows the index finger to comply with this force to a reasonable degree without any damage being done to the device. Because of the spring-like nature of the flexing element, when the force is removed, the index finger returns to a neutral position. The flexing element is able to perform this function with a force in the opposite direction, as well. The front tab of the flexing element contains a 2 millimeter through-hole for a screw to fasten the index finger to the flexing element securely.

3.2.4 Index Finger (8, 9, 10, 11)

The index finger is connected to the backplate via the composite flexing element. It is fixed to the flexing element with an M2 screw and nut in the proximal phalanx (8). The proximal phalanx consists of a 3.6-millimeter diameter hole that houses the bowden tube, which then narrows to less than a millimeter in diameter to guide the bowden cable itself through the digit to facilitate flexion.

The index finger is a simple four bar linkage, with the proximal phalanx being the ground link and the distal phalanx (11) being the coupler. The middle phalanx (9) and the curved metal links (10.1 and 10.2) make up the other two links. The linkage was synthesized by deciding the desired motion of the fingertip coupler, and approximating the length of the middle phalanx (the input link) to an acceptable biological length. In order to achieve a biomimetic level of flexion, the coupler would have to rotate 180 degrees to its furled position. Figure 13 illustrates the initial and final position of this actuation.

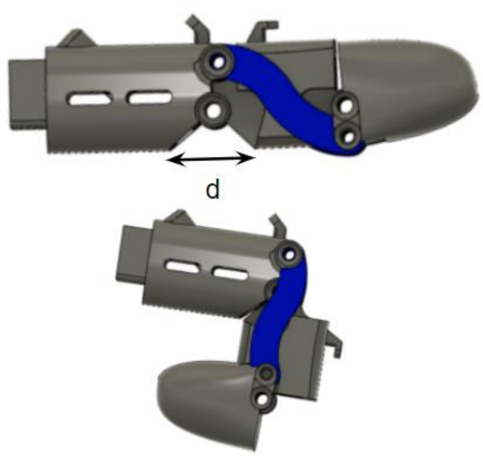

Figure 13: Furling of the index finger.

This furling motion is facilitated by a bowden cable that runs through the proximal phalanx and is tied off on the middle phalanx. When the bowden is pulled the length *d* illustrated in the finger, the four-bar linkage facilitates the furling of the distal phalange to mimic the motion of a furled finger. When the tension in the bowden cable is released, the index finger is unfurled using a spring force created by an orthodontic elastic attached to the two hooks on the back of the index, visible in the figure.

3.2.5 Exoskeleton (12, 13)

To capture the motion of the middle finger and mirror it in the index finger, the team constructed a slim exoskeleton that is worn on the biological middle finger. The size of the rings was chosen for comfort specifically for PH's finger. Figure 14 shows the mirrored flexion of the exoskeleton and the index finger.

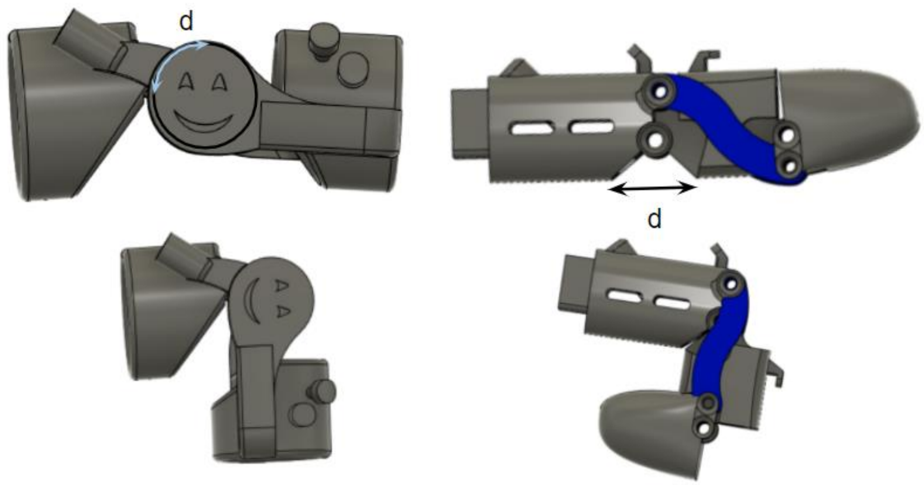

Figure 14: Furling of index finger with respect to middle finger exoskeleton.

When the middle finger is furled, the bowden cable is pulled a distance *d* over the circular radius at the exoskeleton's pivot point. If the middle finger bends 90 degrees, this distance is a quarter of the circumference of the pulley, and can be modeled simply using the following equation:

$$d = \frac{2\pi r}{4} \qquad (3)$$

This distance translates to the other end of the bowden cable, pulling on the middle phalanx and causing the index finger to furl. The bowden cable is securely tied off to two pegs on the exoskeleton to prevent any slipping and keep the distance *d* as constant as possible over extended periods of use.

In order to make the exoskeleton as slim as possible, it follows the curvature of the middle finger. The thickness of human fingers is constantly changing; they expand when its warm and become thinner when it's cold. In order to account for these constant changes, the rings are uniquely sized for the user. The rings are initially sized at room temperature. As seen on figure 10, the rings have 2 lines on the top that allow deformation on the rings for when the fingers expand. There are two diagonal cuts on each ring that allow skin movement when it's flexed.

One of the main goals was to make the design as simple to assemble as possible given the limitations. For this reason the exoskeleton consists of only two parts that snap into place once printed without the use of any extra fasteners. The high accuracy and durability of SLA 3D printing allowed intricate and precise geometries. All the edges of the device are rounded for user comfort.

The bowden tube is attached to the exoskeleton with a dedicated housing, similar to that on the proximal phalanx. This tube also makes use of dents that prevent the tube from rotating around the hole. Once the tube ends, the cable is routed through a channel that leads to the pulley. Two walls prevent the wire from coming out of the route. There is a tunnel that starts at the end of the pulley which directs the string to two anchor pegs where it is attached. Square knots are used to tie it off, since they tend to stay tight over time. Given the slippery nature of the wire it is essential to tie the knots correctly or the system will experience losses over time. Adding a drop of glue on the knots helps in minimizing this effect.

3.3 Wrist module assembly

Figure 15 shows an exploded view of the structural components of the wrist module assembly.

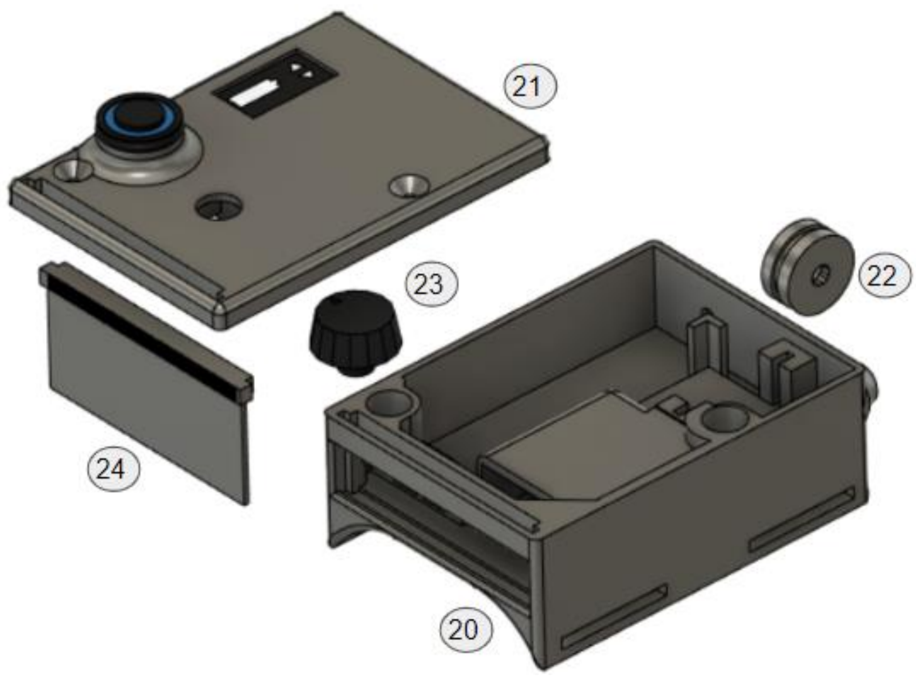

Figure 15: Exploded view of the wrist module with individual parts labeled.

The primary focus of the wrist module assembly was to improve the user experience for PH as much as possible. When deciding which components would be integrated into the circuit, the team sought to create a user-friendly interface. The final design implemented an OLED screen that displayed battery level and power, as well as button feedback and the selected speed setting. A PLA printed knob (23) was fixed to a potentiometer and used to select the speed setting for the servo, so PH could adjust the speed of the thumb's movement depending on the activity. The wrist module was fitted with a simple system to connect and disconnect batteries when needed (20), with a removable cover to protect them (24). The spool (22), which was attached to the servo, was designed with a specific radius to pull the bowden cable enough to actuate the thumb.

3.3.1 Electronic components

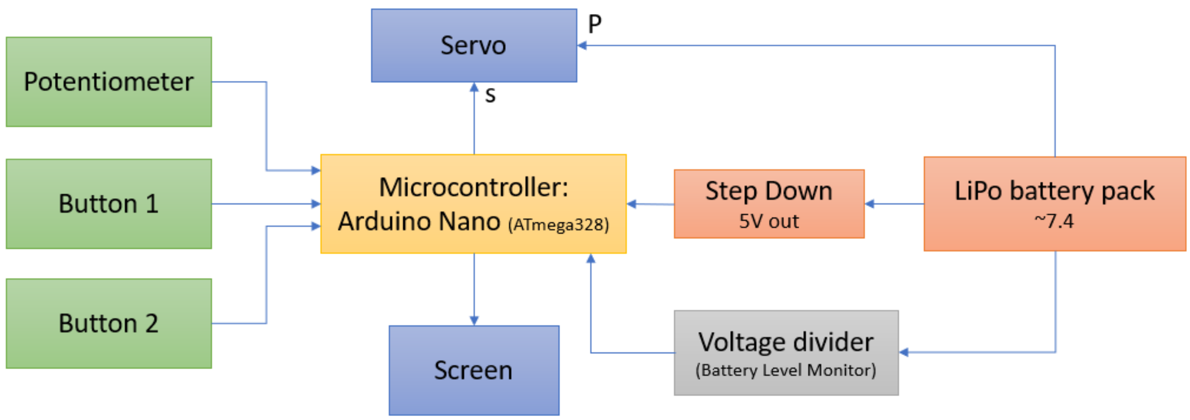

Figure 16: Electronics schematic.

The heart of the circuit is an Arduino Nano with an Atmega328 chip that is used as a microcontroller. We have two buttons that work as inputs for actuating the button and a potentiometer for selecting a speed setting for the servo.

To monitor the battery level, two 10k ohm resistors are used as a voltage divider to approximate the battery level through the decaying voltage. The batteries themselves are rated for 1100 mAh each, and two are placed in series for a total capacity of 2200 mAh. Each of these batteries provides an average 3.7 volts, with 4.2 volts at full charge. In order to ensure the longevity of the battery, the display will show the battery as empty when the voltage of one of the batteries drops to 3.3 volts. Figure 17 shows the discharge curve of a Li-po battery. In order to provide a safe operating voltage to the Arduino Nano, a buck converter is used to step down the voltage to a stable 5 volts.

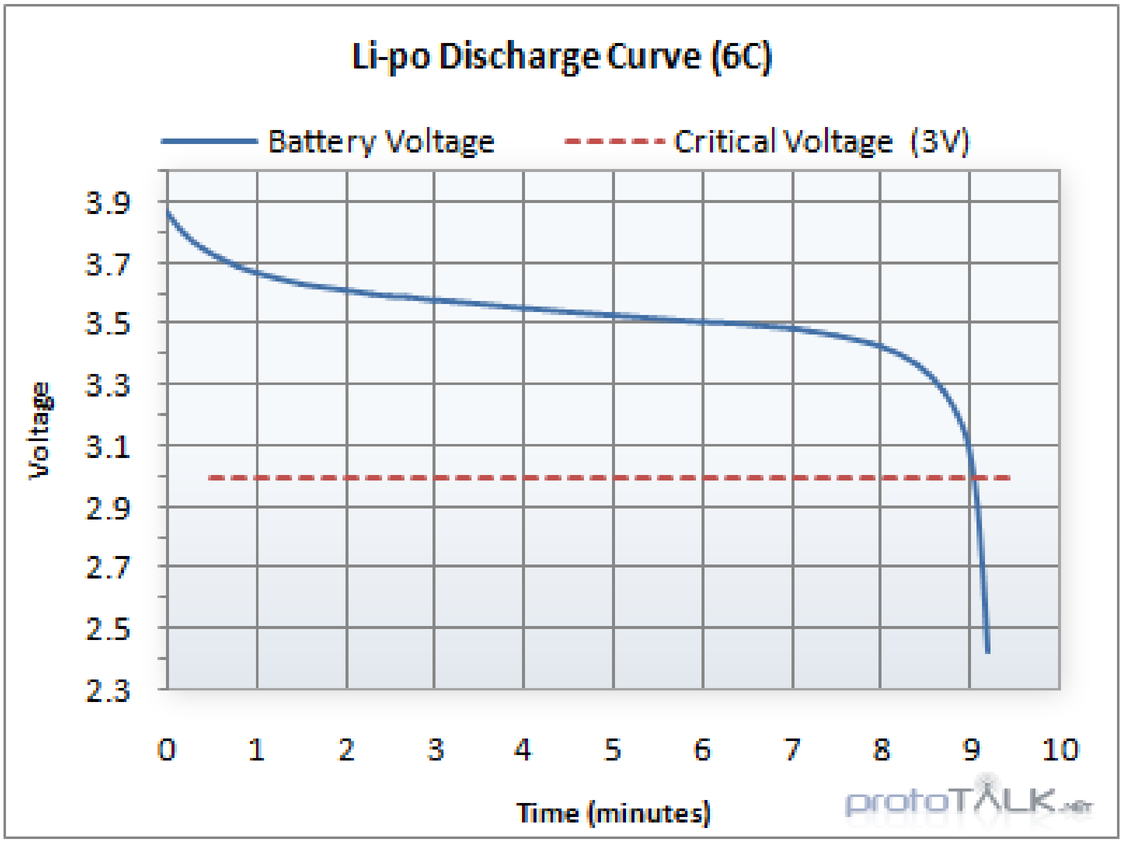

Figure 17: Discharge rate of Li-po battery (P. Fabe).

The OLED screen has a resolution of 64 by 128 pixels, which is high enough that the battery level, speed setting, and voltage reading are easily visible to the user. The servo that actuates the thumb is a 7.5-kilogram mini servo. The power button is a simple button switch with a built in LED that can disconnect the entire circuit. When the device is turned on, the LED ring on the power button lights up. The wiring diagram for all of these components can be seen in figure 18.

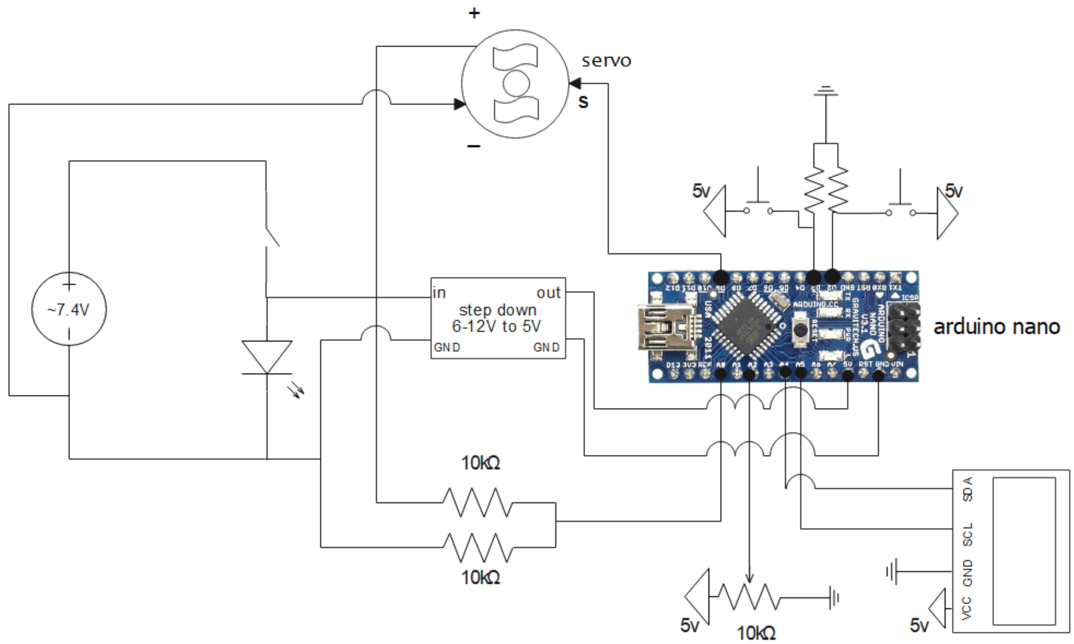

Figure 18: Wiring diagram.

3.3.2 Design

When designing the module, special attention was paid to routing the tube for the bowden cable as efficiently as possible to avoid friction losses. Figure 19 shows the tubing housing with a double fitting. The slimer bowden tube connects first (25), contained by the outer ring of the fitting. An aperture at the end of the outer boating tube (26) allows the wires coming from the thumb to get through the channels.

The wrist module was designed to be as low-profile as possible. Auxiliary components, such as the potentiometer and a 128x64 pixel OLED screen, are embedded on the lid. This is possible due to the tight tolerances achievable by SLA printing. The potentiometer, for example, is fit into the lid so tight that the wrist module is effectively watertight, and is covered by a user-friendly knob with ridges for easy use. The OLED screen is protected by a precisely cut piece of acrylic.

The servo is housed close to the opening where the bowden cable enters the module, to simplify the bowden tube routing as much as possible. The servo housing uses no screws, and instead uses a slight extrusion on the lid to make the servo sit tightly in its intended location.

The wrist module case itself is designed with human anatomy in mind. The bottom of the case contours to PH's wrist, which allows the module to sit comfortably on the forearm without shifting around, and minimizes rubbing. The module is then anchored to the forearm using straps that PH can adjust to her liking.

The lid is connected securely with 2 M3 screws, epoxy is used to attach the female components to the base of the wrist module (20). The gate (24), sits tightly into place and can be removed easily with one hand. Ridges at the top provide grip for the user to grab.

Figure 21 shows how all of the electronic components fit into the wrist module. The batteries are connected to jst connectors individually. It is recommended for the wires of the Li-po batteries to be shortened prior to connection in order to save space but the stock ones also fit as seen in Figure 22. The on button sits right next to the jst connectors in order to safe space on wiring. As seen on Figure 24, wires are just long enough to enable aperture of the device but not too long for them not to fit. Wires where chosen based on maximum recorded current flow in order to provide safety (Table 6)

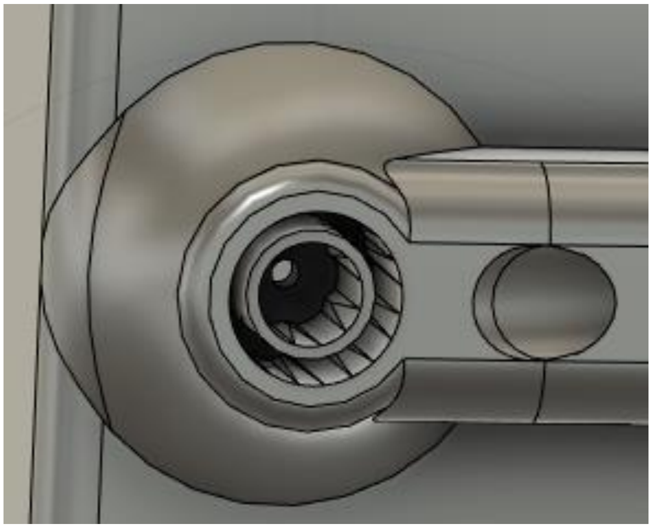

Figure 19: Bowden tube female plug ins.

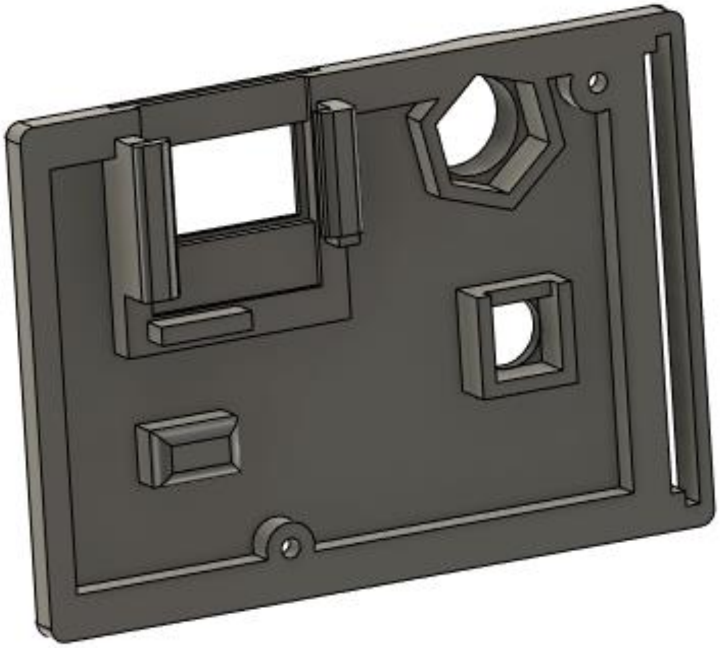

Figure 20: Bottom of wrist module lid (21)

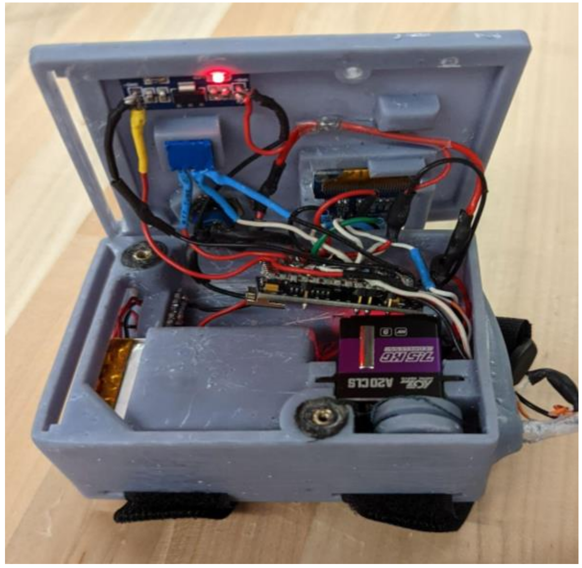

Figure 21: Opened wrist module showing wiring and component position.

Figure 22: Wrist module with battery cover open and batteries plugged in.

3.4 Control

The Arduino Nano oversees the control of the system. The control architecture can be seen in detail in figure 23. The most important functionality of the electronics is that the servo rotates towards the desired position when the thumb buttons are pressed at the speed selected by the potentiometer. In each cycle, the Arduino receives and processes several inputs. The first value is an analog input from 0 to 1023 from the battery. Equation 4 (the voltage divider equation) is used to find a ratio of ½ from R1 and R2 to read the output voltage of the batteries. We map the value from 1:1023 to 0:5 and multiply it by 2 which will give the Voltage that the battery is providing(Vol). Simultaneously, the input of a 10KΩ potentiometer is read by another analog pin, and this value gets mapped from 1 to 15 (Pot).

The speed of the servo at different voltages can be found in table 4, the found speeds of the motor can be seen on table, taking the speed of the motor at a given Vol and using equation 5, we calculate the speed of actuation per degree (M). The servo is controlled from one of the digital pins. We store the variable of current position (x) to know where the servo is at any given time. In order to make the servo move smoothly we calculate the necessary delay between outputs based on equation 6. Y is a cyclic variable that has been found through trial and error.

In order to make the code more efficient, some of the more calculation-heavy non-trivial tasks such as updating voltage and battery level are only performed every 10000 cycles. This also helps with making the device feel like it's been actuated in real time.

Table 3: List of variables.

Variable	Description
Vol	Battery voltage
M	Time per unit of actuation (s/u)
Sp	Calculated Speed of actuation (s/60°)
T	Time to position(s)
Pot	Mapped potentiometer value{1:15}
y	Cyclic variable
x	Current position {1:180}
R1	Resistor 1 value (10kΩ)
R2	Resistor 2 value (10kΩ)

Table 4: Servo speed and torque at different voltages.

Servo Operating Voltage	Speed	Torque
6.0V	0.11s/60°	5.8kg-cm
7.4V	0.09s/60°	6.8kg-cm
8.4V	0.08s/60°	7.5kg-cm

Battery Level

$$V_{out} = V_{in} \cdot \left(\frac{R2}{R1 + R2}\right) \quad (4)$$

Servo Control

$$M = \frac{Sp}{60} \quad (5)$$

$$T = M * Pot + y \quad (6)$$

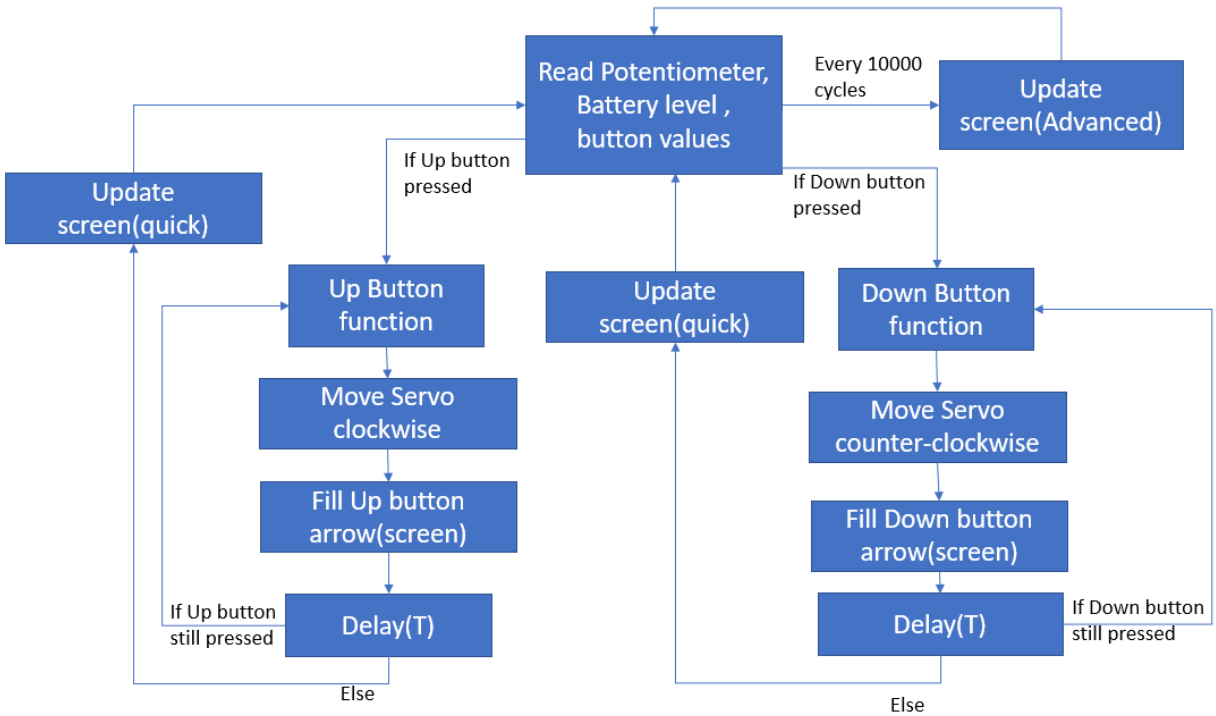

Figure 23: Control architecture.

4. Tests and Results

Due to geographic distance between the team and the patient for the majority of the project, the team was required to design and perform as many tests as possible without PH. These independent tests were designed to prove the functionality of the device to the user despite the lack of in-person testing.

4.1 Device Control Testing

4.1.1 Index Finger

While not explicitly required by project goals, the team ran index finger force tests to gain a deeper understanding of the prosthetic's effective grip strength. Because the index finger's actuation mirrors that of the biological middle finger, the strength of this grip is limited by the strength of PH's middle finger and the index finger's point of failure. Furthermore, this testing was done independently of PH, and therefore is not an entirely accurate representation of the force she could apply using the index. Despite this, it does show that the index finger is capable of delivering a functional grip strength without catastrophic failure. Figure 24 shows a consistent grip strength of about 4.5 Newtons over 5 seconds.

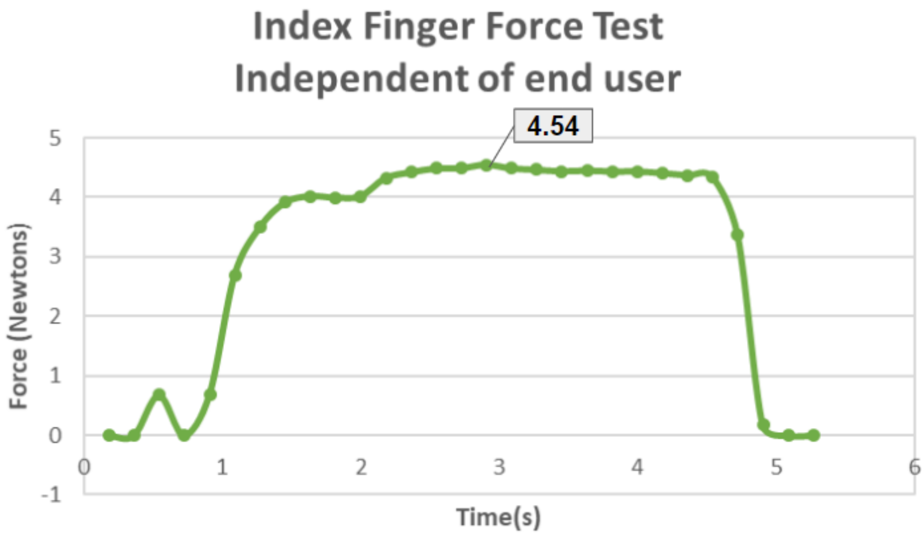

Figure 24: Index finger force tests independent of end user.

Testing the index finger to failure resulted in a maximum force of 5.8 Newtons. The exoskeleton ring arm failed first. Better material selection, such as machined metal or a stronger resin composition would likely increase this value.

Figure 25 shows the testing rig for this force test. The index finger is fixed by the proximal phalanx and the load cell is set up in the index's path of actuation.

Figure 25: Index finger force testing rig.

Figures 26 shows the splay and deflection as defined by the goals. The index finger is capable of splaying outwards at least 30 degrees, as evidenced by the figure. Furthermore, due to the TPU and spring steel flexing element, the index finger is capable of deflecting both up and down and returning to its neutral position when under no load.

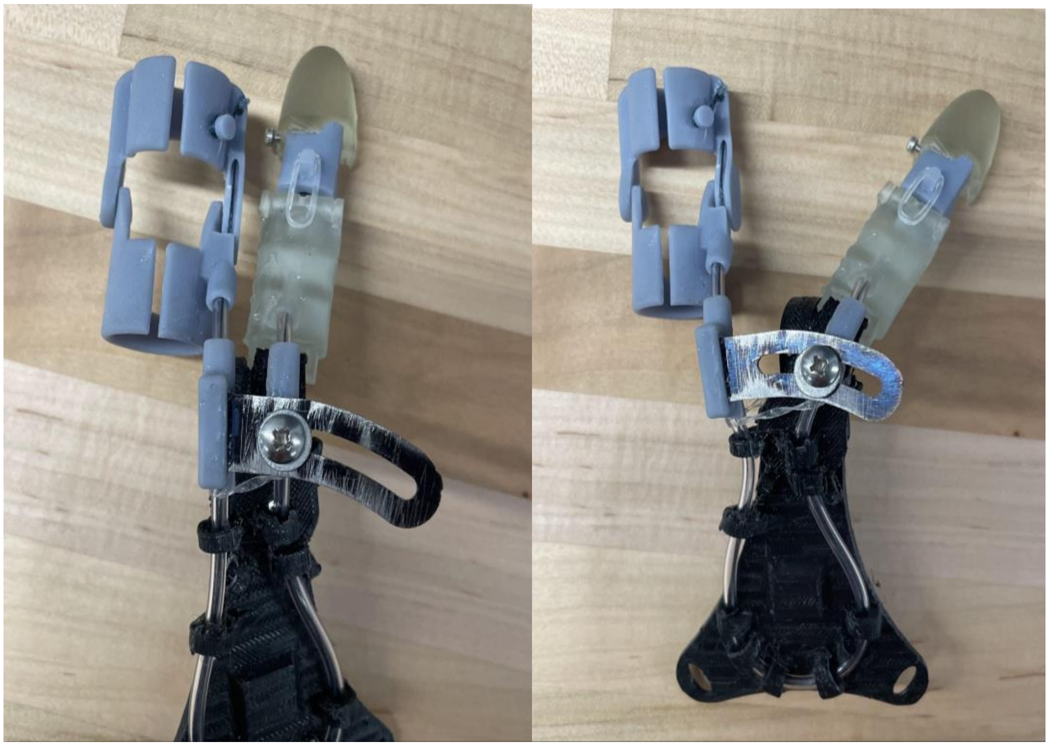

Figure 26: Resting index and splayed index at 30 degrees, respectively.

Figure 27: Flexing element under passive deformation.

4.1.2 Thumb

The goal of the thumb was to have actuation occur via PH's residual PIP engaging buttons inside the thumb cap. This was tested by having PH wear the device telling her to click the front button then back actuating it fully to the best of her ability. Screen shots from a video of PH flexing and extending an earlier prototype of the thumb can be seen in figure 28 and the full flexion of the final prototype can be seen in figure 29.

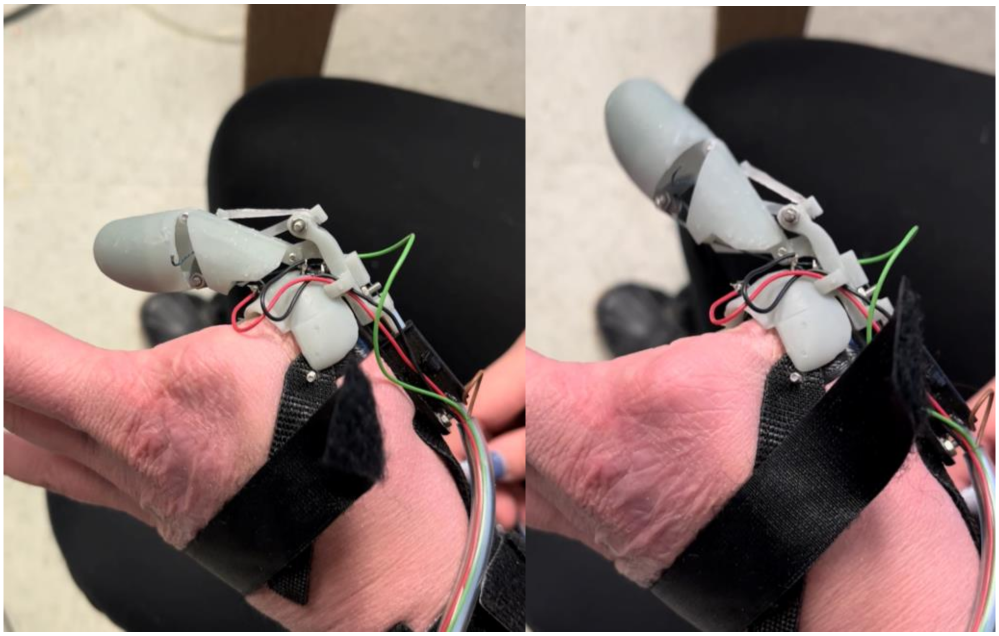

Figure 28: Thumb assembly on PH's hand at full actuation and home, respectively.

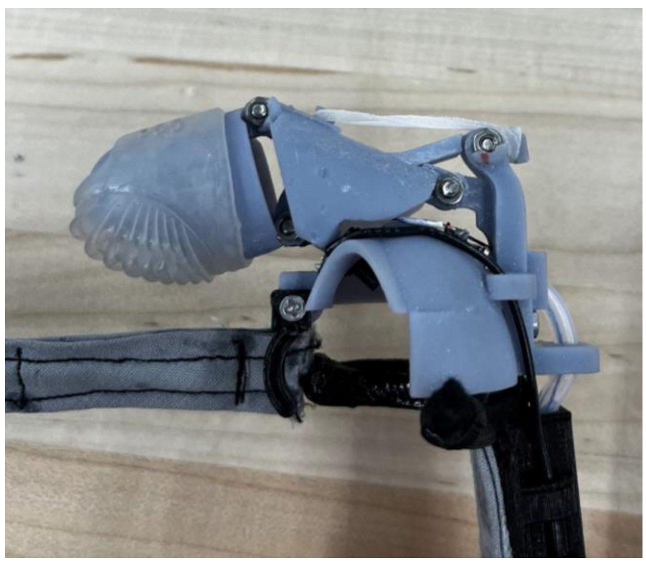

Figure 29: Fully actuated thumb.

In addition to simply being able to complete flexion and extension the team tested the goal of a full cycle in 2 seconds. This testing was conducted independent of the user because of lack of in-person access and is expected to change when the device is under user control. To test the time for a flexion/extension cycle at each potentiometer speed setting P0-P15, the team timed using a stopwatch the time for an entire cycle, did this three times and averaged the results. The results for each speed setting is shown in Table 1.

Table 5: Total time for flexion and extension testing.

Potentiometer Setting	Total time for Flexion and Extension (seconds)
P0	No movement
P1	23.31
P2	12.87
P3	8.56
P4	7.00
P5	5.56
P6	4.63
P7	3.91
P8	3.51
P9	3.16
P10	2.96
P11	2.61
P12	2.27
P13	2.01
P14	1.96
P15	1.81

4.2 Strength and Practicality

4.2.1 Lateral Pinch

To test that the device can provide a functional grip strength in the lateral or key grip the team set up a force experiment with a 10lb interface load cell (figure 30).

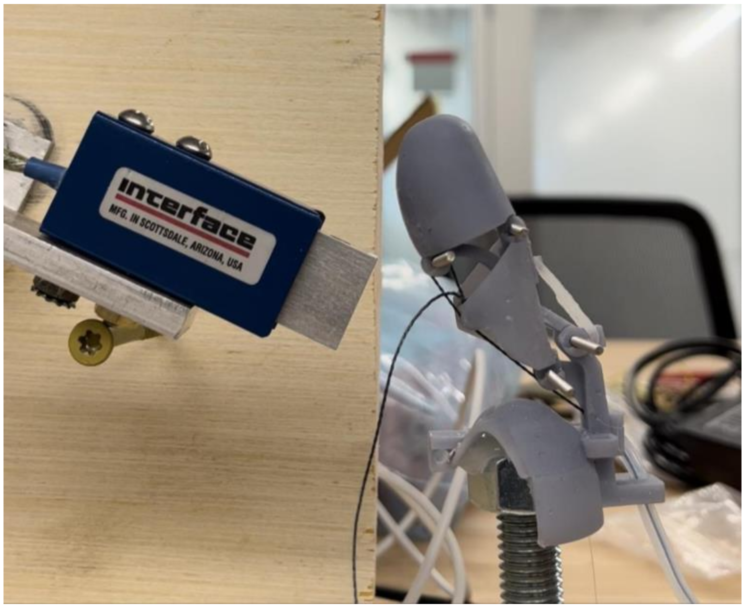

Figure 30: Testing rig for thumb.

The initial goal set for the force exerted by the thumb in the lateral grip was 5lb force or 22.24 newtons. However, the team quickly realized this would be unattainable based on the SLA resin composite and integrity of the linkage. This was proven to be the case as the force tests showed the maximum force exerted by the thumb distal phalanx was 3.2N(figure 31). However, the graph also shows the system is able to provide constant force when the front button is pressed.

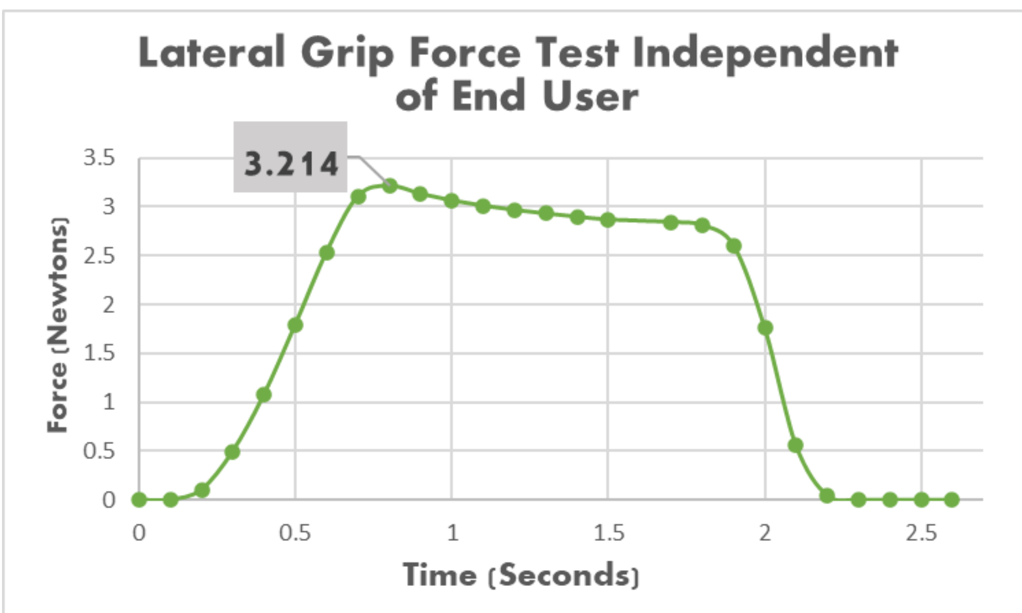

Figure 31: Graph of thumb force testing.

4.2.2 Wide Diameter Grip

Restoring the wide diameter grip was the second functional grip included in the goals. To test this the team planned to have PH lift a weighted jar and hold it for 10 seconds. While the team was unable to test with the final device, informal testing was conducted with an earlier prototype. PH was able to lift and hold a 100mm diameter tapered ice coffee cup for more than 10 seconds (figure 32). This informal testing proves that even without the index finger the addition of the thumb restores the wide diameter.

Figure 32: User holding large iced coffee (wide diameter grip)

4.3 User Experience

4.3.1 Battery Usage

When setting our goals we thought that for the device to be usable the battery needed to last at least 3000 cycles. Having to change the batteries too often would end up becoming an annoyance, and would result in PH not wanting to don the prosthetic for everyday use. As a secondary goal, the team decided that the batteries should be easy to access and replace.

$$Battery_h = Capacity_{Ah}/I_{Ah} \quad (7)$$

To calculate how long the battery would last we divided the known capacity of the system by the current flowing through the circuit at different states as seen in equation 7. The device uses two 1100mAh batteries in series, so the total capacity is 2200mAh. We connected a multimeter measuring current to the circuit from which we took the values displayed on table 6. At maximum speed, the device would last for 7h, but because batteries are imperfect, it is more likely to last 75% of that, or around 5h. This second time still would give us 10541 cycles at 1.81s/cycle. This is more than three times the desired goal of the device. When the device is powered on but not active it can last for 24h before full discharge. Even if the device can last a long time, the user also has the possibility to turn it completely on and off with an Analog button that disengages the batteries from the rest of the circuit.

The user can easily take the gate out (24) to detach the used batteries and replace them for new ones. The display makes it easy to determine when the batteries need to be replaced. The speed and torque of operation slightly decreases over time which is accounted for digitally

Table 6: Current use at different stages.

Max. Current Use	315 mA
Avg. Current Use	185mA
Resting Current	67mA

4.3.2 User Feedback and Digit Weight

Due to PH's distance from Worcester, it was particularly challenging to find time to test with her in person. As a result, PH was able to get hands-on experience with the thumb only. She described the two-button scheme as natural to control, and she cited that she would be able to learn the system and make it a natural process with some time with the device.

PH gave feedback that the weights of the digits felt natural. When weighed, the index finger was 17.66 grams, and the thumb was 18.38 grams.

5. Discussion and Future Work

5.1 Analysis of Results and Discussion

Results obtained through testing the thumb yielded obvious successes and failures. A major success of the thumb device was how well the thermoforms were able to attach the thumb cap to the hand and how PH reported only slight discomfort in the very first design, which was able to be corrected. This early success in the method of attachment allowed success of the device control goal. "These thermoforms are tight, but I know they have to be tight to stay on and work and it's not uncomfortable" was a quote from PH when trying on the thermoforms for the first time. The team also recorded PH saying "Once I can find where the buttons are in the cap I can get them easily, it's definitely something I could learn with practice." This was all very encouraging feedback and with the addition of the sewn adjustable strap harness and finalized components, the team believes PH will be even more stratified with how the device is attached and controlled. PH also shared that the thumb didn't feel too heavy or too light and was pleased with the way the team recorded and incorporated her feedback.

Despite this positive feedback from the user, the force tests conducted independent of her fell far below the goal set by the team. However, when reflecting on the goals set, it was realized that without some form of force control, allowing the thumb to reach 22.24 newtons might not be safe. With this conclusion and the proof in the wide diameter grip that the gripping force of the thumb on the hand is functional the team is satisfied despite not reaching the set goal.

Testing with the index finger was performed without PH present, due to scheduling and shipping challenges. However, the goals related to the index were met - passive deflection and 30 degrees of splay - and could be demonstrated independent of PH. Furthermore, despite not being an explicit goal set by the team, the index finger force tests resulted in a functional grip strength, similar to that of the thumb. The index finger has the most room for improvement with tolerances, material selection, and a better splay mechanism that experiences less friction.

5.1.1 Review of Project Goals

Table 7: Review of project goals.

Index finger is capable of passive deflection and returning to a neutral position when under no load.
Index finger capable of passive splay to 30 degrees relative to biological middle finger, returns to a neutral position when under no load.
4-bar thumb controlled via 2-button input inside thumb cap. Pressing the front button begins the forward/grasping motion. Releasing the front button will lock the thumb and re-engaging the button will continue the forward motion until it hits an extreme position. The device can then be returned to the "Home" position using the back button.
The thumb can complete a flexion and extension cycle in 1.81 seconds independent of the user.
Prosthetic index and thumb feel natural to the end user and 17.66 and 18.38g which falls into the range of weights based on calculations using Winter's tables.
Prosthetic device achieves at least 10541 cycles per single charge of a battery.
The end user can complete the large diameter grip and hold, on a tapered cup with the maximum diameter of 100mm.
The thumb can apply an average of 3N of force in the lateral grip tests independent of the end user for 1.5 seconds.
End user reports that tested components were comfortable or gave feedback on how to correct the discomfort. End user also expressed feelings of being listened to and was happy with how her feedback was integrated into design.

5.2 Future Work and Recommendations

One of the primary challenges when designing the index finger was the lack of residual anatomy that could be used to control it. In the case of the thumb, the remaining bone fragments of the proximal phalanx could be used to actuate buttons, but the index finger had no such residual anatomy. A possible solution to this would be to implement EMG sensors to read and utilize muscle or tendon impulses in the hand to drive an active index finger that functions similar to the thumb. This would elevate the function of the index finger beyond being just an assistive member.

Along with this experimental EMG sensor work, some sort of force control should be implemented, especially if future iterations increase the grip strength of the prosthetic. As it currently stands, the thumb provides a small but functional grip strength, but if efforts were made to make the index finger actively driven by a servo in a similar way, this force control would be necessary.

The wrist module proved to be bulkier than was originally intended. While it is capable of being concealed underneath a jacket, the team believes that it would be beneficial to attempt to slim down the wrist module as much as possible. The manufacture of a dedicated PCB for the wiring, rather than the haphazard array of jumper cables currently in place, would allow the electronics to take up a much smaller footprint.

Finally, the team recommends a more careful attention to material selection. The composite used to print most of the resin-printed parts proved to be both durable and flexible, but the team feels that this composition could be improved with more research. Certain failure points, such as the middle finger exoskeleton, could be machined or cast in either metal or a more robust material, which would therefore increase the grip strength of the prosthetic.

Beyond these targeted suggestions, the team has a number of broad considerations for any future work on the prosthetic. The team found more success when they focused their design process towards simplicity and comfort. A “patient first” approach resulted in a device that PH found both comfortable and easy to learn. Complexity introduces issues in the mind-body connection between PH and the prosthetic, and comfort is one of the most influential factors in the continued use of a prosthetic. The team strongly recommends continued and open communication with PH and weighing her input strongly in design phases.

6. Conclusion

The primary goal of this project was to provide PH with a functioning prosthetic device that restored a satisfactory amount of manual dexterity, as defined by the project objectives. The final device achieves these goals, and does so while simplifying the overall design from previous versions, making it more reproducible and affordable. While there is still room for improvement, this device is another step forward towards a high-level, high-functioning prototype. This device is proof that solutions exist for unique partial hand amputations, and it is the hope of the team that this work continues to make those solutions more accessible.

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Appendix A: Patient Visit Testing Feedback

CORE TEAM THUMB TESTING ------------Day 1:

Notes from thumb Cap #1 and thermoform set 1: (images 1&2)

Initial thoughts from PH: It Gripped well, she repeated multiple times that she knows for this prosthetic to work it has to be anchored tightly to the hand. However, knowing this, the thermoforms were more comfortable and tightly gripping than she expected.

Feedback for rapid iteration:

- Both front and back arms of thermoform #1 could be longer to wrap around better, and the arm that reaches to the palm could be lower
- Thermoform #1 is a little pointy, grips well and in the right spot after forming but the contact point was really small.
- The size of the cap was also slightly small and so instead of the joint moving freely it was taking the cap with it in the movement mostly the backside of the joint in the free space between the thermoform arm and the cap.
- Buttons were then inserted....
- In order to click the buttons she had to be pressing down on the little ledge where the bowden tube would eventually run (yellow circle) and it was still a struggle because they were set too far up into the cap.

On the Spot Iterations:

- I made a hole in the base of the thermoform and ran an elastic band through it and then looped it around the wrist to have it mimic the backwards pulling motion she was doing on the ledge in order to hit the button using only one hand. However the buttons are still too short.

Changes that were CADded and reprinted:

- Larger cap size to reduce movement and a "flap" to extend and cover the part of the joint that flipped the cap out of place before.
- Thicker Thermoform #1 Arms
- Longer thermoform #1 Arms
- Wider Thermoform #2
-

Day 3: See Day 3 in the video.

Initial feedback on thumb assembly with the servo and hot glue buttons:

- She was able to occasionally hit the buttons when it was in exactly the right position and there was more tension in the elastic than just being around her hand. Buttons need to be longer
- Elastics need to be adjustable straps for comfort and more tension.

Day 4:

See video for actuation.

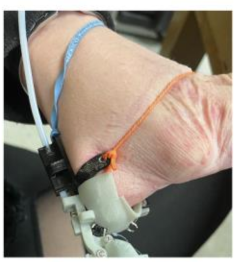
Initial feedback on the thumb with longer buttons and straps:

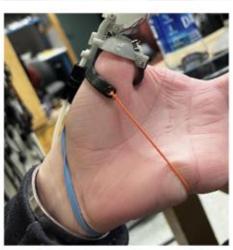
- She can hit each button and there is very little stalling when she hits both buttons at the same time.
- She likes the velcro straps and they are comfortable.
- She can put it on by herself and because she can tighten it down further she was able to actuate it with one hand, fingers open and closed.
- It takes her a second to find the locations of the buttons in the cap but once she does she's able to actuate it with a little accuracy.

Feedback for Iteration:

- Inset holes for the screw holes for the velcro and better more polished straps.
- Lower the button holes if possible.
- Maybe some rubber or silicone grippers on the thermoforms.

Day 2:





Initial feedback on thumb cap 2(with flap) and whole finger assembly: (images 3&4)

- The larger cap diameter helped her finger be able to "hover between the 2 buttons, and the flap did help the cap from being pushed off by the joint.
- The thumb looked nice and matched the shape of her other thumb. Was the right length and felt like the correct weight.
- can't reach short buttons in the big cap.
- When going for the forward button the thumb would slip out of place slightly and the buttons become even more out of reach.
- Wrist module is bulky but comfortable.

On the Spot Iterations:

- Added the elastic band that connects the arms of the thermoforms. Still can't reach the buttons but no longer slips when she reaches for the front button.
- Added small drops of hot glue to each of the buttons (before the new longer buttons arrived) added dots of glue until she was able to reach the buttons each dot added about 3 millimeter and the front need 1.5 and back needed 2, a problem came when we needed to reheat the thermoforms and the hot glue buttons fell off.

Feedback for rapid iteration:

- The elastics help but need to be straps that don't roll up and down on the palm.
- The position of the strap across the palm and to the side of the hand influences if she can hit the button so that strap needs to be sturdy.
- Thermoforms need to still be a little longer and more solid than the hot glue.
- The edge of the cap that holds thermoform #2 is sharp.

Day 5:

Exit interview:

- Thermoform #1:
    - Screws need inset holes so they don't poke.
    - Maybe something squishy covering the black (PLA). maybe over the screws too.
    - Front arm palm deforms and the way it was printed the arm is ripping off the base part.
    - The back arm never hurts.
    - She says she knows it has to clamp down hard and she thinks it's all something she could get used to but that as of right now all of this feedback is coming from wearing the device in MAX 10 minute intervals.
- Thermoform #2:
    - Pointy and a little annoying.
    - Needs a more solid SLA base because it spins and loosens.
- Buttons:
    - Were comfortable and caused no issue for the couple of minutes she had it on but agreed with the suggestion to put a little silicon dot on the top.
- Straps:
    - Didn't bother her at all and knows they are rapid iteration so they can be better.
- Wrist Module:
    - Likes the screen and the potentiometer.
    - Agrees that it will have to go over shirts but the goal to maybe get it under a jacket is something she would like.
    - Is very comfortable.

Informal Testing to get a sense of useability: Silicon grip pad on finger tip

- It was difficult to control attached to the extension cord because it twisted the wrist module and eventually the thumb.
- She will have to get used to wearing it to be able to more easily locate the buttons more consistently as well as adjusting to utilize the thumb instead of the anatomy she has adapted to find useful.
- Conclusion is that the thumb is strong enough to grip heavy things and hold them.
- With the grip pad the thumb is very useful at gripping large objects.

Appendix B: Calculations for the weight of biological fingers

Using Winter's anthropometric tables averaging based on the number of bones.

i. hand weights= BM(.006)
ii. BM of an average 21 year old female at about 5’5 is 55kg
iii. Hand =33kg
iv. Assume there is equal skin flesh, tendon, etc attachment on each of the 26 bones
v. weight of bone = .0127 kg
vi. Weight of Thumb= 2 bones=.025kg
vii. Weight of index=3 bones= .038kg

Appendix C: Components and Materials Table

	Name	Material		Name	Material
1	Backplate	PLA	15	Thumb thermoform 2	PLA
2	Rail	Spring Steel(1.6mm)	16	Thumb Cap	Resin Composite
3	Rail Coupler	Resin Composite[1]	17	Thumb intermediate phalanx	Resin Composite
4	Rotating element	Resin Composite	18	Thumb linkage	Resin Composite
5	Bowden tube link	Resin Composite	19	Thumb distal phalanx	Resin Composite
6	Composite	Spring Steel(0.15mm)	20	Wrist Module Base	Resin Composite
7	Flexing element	TPU	21	Wrist Module Lid	Resin Composite
8	Index finger proximal phalanx	Resin Composite	22	Spool	Resin Composite
9	Index finger intermediate phalanx	Resin Composite	23	Knob	PLA
10	Index finger links(X2)	Spring Steel(0.15mm)	24	Wrist module Gate	Resin Composite
11	Index finger distal phalanx	Resin Composite	25	Bowden tube A	diameter=3.11mm thickness=.7mm
12	Exoskeleton Proximal ring	Resin Composite	26	Bowden tube B	Diameter=5.6mm thickness= .57mm
13	Exoskeleton external ring	Resin Composite		Spider wire	50kg

[1] *Resin composite = 70% Anycubic basic grey resin, 20% Siraya Tech Blu resin, 10% Siraya Tech Tenacious resin