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ABSTRACT
Objective: To design and develop an affordable battery-powered prosthetic thumb for a low-income, uninsured individual who lost all of his dominant hand except pinky and non-functional ring finger.
Design: The design was created to custom fit the client with the understanding that simple measurements and calibrations can be made to adapt the design to others in the future. The client provided a 3D scan of the residual hand and fingers. In addition, measurements of circumference were taken along the forearm to create a model for reference when fabricating the forearm sleeve attachment.
Setting: University of Wisconsin - Madison, Community
Participants: Individual who is a patient at Athletico Ltd.
Interventions: Not Applicable
Main Outcome Measures: A functional electrical prosthetic thumb that works in opposition to the currently semi-functioning pinky finger to increase hand function for this individual validated by the ability of the patient to use the prosthetic to pick up various items , pinch force test, and battery life testing.
Results: A functioning electrical prosthetic was successfully created. The device increases the functionality of the patient's right hand, and helps him pick up items ranging in size from 1-10 cm. Design was effective at replicating quick, accurate motion and able to hold approximately .815 kg in both clinical and theoretical testing scenarios.
Conclusions: The design works as a functional hand prosthetic for the client. The patient found the prosthetic to be comfortable and functional for picking up objects of various sizes and shapes on the smaller side. This fulfilled the major desired features for the patient. As a result, the device is satisfactory and ready to be sent to the user. If a future team were to make improvements, some of the components they could focus on would be increasing strength and dexterity. At the moment, the thumb allows the user to complete minor tasks to regain independence but there is still a clear functional gap between the abilities of the prosthetic and the abilities of a natural appendage.
Key Words: Prosthetics, Hand, Amputation, Custom, Design

Introduction

The motivation behind this project is to help improve the life of an uninsured individual who lost part of his dominant hand from an infection. Building a functional prosthetic for him will allow him to return to work and regain independence in his life. Additionally, there is a gap in the market for affordable and functional prosthetics. A customizable, functional prosthetic controlled by the push of a button fulfills that need. To provide a prosthetic for a man who lost part of his dominant hand is enough motivation, however to create an inexpensive option for many people in this situation offers even more motivation. Amputations are a common occurrence in the United States with between 500,000 and 100,000 limb amputations (including trans-carpal amputations) occurring per year [12]. As of 2008 approximately 1.7 million people in the United States are amputees and of those people an estimated 500,000 have minor upper limb amputation, defined as amputation at the fingers, the hand, or the forearm distal to the elbow [13]. The US census reports that in 2019, 8.0% of people were uninsured for the entire year, however this does not give an accurate understanding of how many people are uninsured at any given point in time [14]. The CDC reported that at the time of an interview in 2019, 14.7% of people ages 18-64 were uninsured [15]. The percentage of uninsured people ages 18-64 has been increasing again since 2016, showing a peak in 2019 [16]. A body-powered hand prosthetic costs from $4,000 to $20,000, and a myoelectric prosthetic can cost between $25,000 and $75,000 which also does not account for the medical bills that come with some of the most common ways someone becomes an amputee: trauma, vascular disease, infection, etc. [17][18][12]. With the population of amputees in the United states rising, and the percentage of insured people declining, a more affordable prosthetic option is urgently needed [13]. Additionally there are approximately 1:18,000 people in the Western world with partial hand amputations, as in they have lost some but not all of their fingers [28]. This is a huge population that could benefit from an extra finger in order to counter their movements.

Methods

Electronics

The main electronic elements of the design include an Arduino nano, motor driver, linear actuator, and a button. The linear actuator is attached directly to the 3D printed thumb using a nut and bolt. When the linear actuator is extended, it will pull a string downward, resulting in the flexion of the thumb which allows the user to grasp. When the linear actuator retracts, the thumb extends, allowing the user to release their grip. The linear actuator moves when the button is pushed against the user's side. When the button is pushed, the Arduino recognizes this and sends a signal to the motor driver, which powers the motor either in forward or reverse. For example, if the thumb is flexed, the button will command the circuitry to extend the thumb, and vice versa. The button is encased in a wedge, seen in figure 1, to allow for a greater surface area and more ease when pressing the button against the user's side.

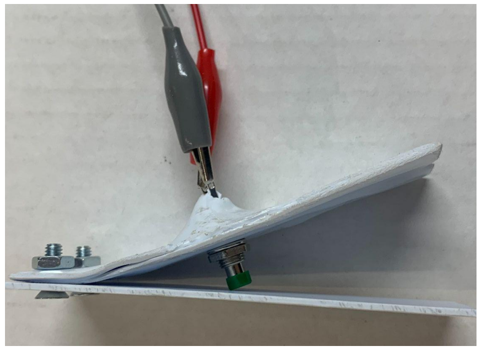

Figure 1: Image of the wedge encasing the button to allow for easier use

<u>Mechanical Thumb</u>

The mechanical thumb was 3D printed using PLA with 60% infill. The pieces of the thumb were joined by stainless steel clevis pins. The mechanical model utilizes a cable transmission system, meaning the pieces of the design are attached by the clevis pins and two cables, one positioned posteriorly and one anterior, that are run vertically through each piece. The posterior cable running through the thumb design is elastic. An elastic was used in order to position the thumb in a neutral position while allowing for flexion movement when the elastic was stretched, as is demonstrated in figure 2. The anterior cable is a non-elastic string. The design moves in a flexion motion when this string is pulled. The tip of the thumb was dipped in flex seal and texturized to reduce slippage. The base of the thumb encases the linear motor and attaches to the cuff using nuts and bolts.

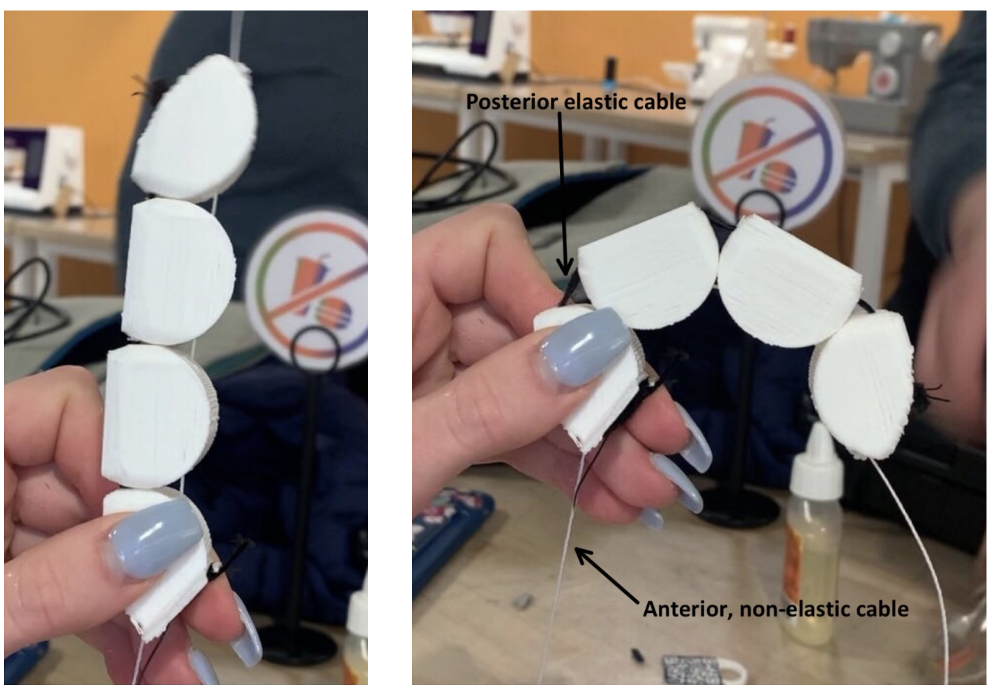

Figure 2: Example of cable transmission motion using preliminary thumb design

SolidWorks and 3D Printed Thumb

The SolidWorks model was constructed with the aim of mimicking the natural motion of a thumb joint. By creating rounded edges that when flexed moved similar to finger joints flexing, the motion looked more life-like. Each piece is connected by a stainless steel pin to allow for appropriate joint movement while maintaining stability. A base piece was designed and printed to integrate the thumb model with an easily attachable base(see figure 3). The base of the thumb is screwed into the cuff over the linear actuator, holding it in place. The tip of the motor is tied to a string that runs along the inside of the thumb. When the motor is extended, the string is pulled down and the thumb is flexed. This is able to transform linear motion from the moor into a flexion of the full thumb. The pieces included in the SolidWorks design were designed and evaluated multiple times throughout the semester. After several iterations of thumb models, the final design optimizes range of motion, length of the pieces, efficiency of movement, and stabilization. All pieces were designed with tolerances (+ 0.02in) that created easy assembly once printed. A CAD model of the purchased stainless steel clevis pins were input into the SolidWorks assembly and tested with the design. The pieces were then 3D printed in PLA with 20% infill on prototypes and 60% on the final design before being assembled, with sanding as needed.

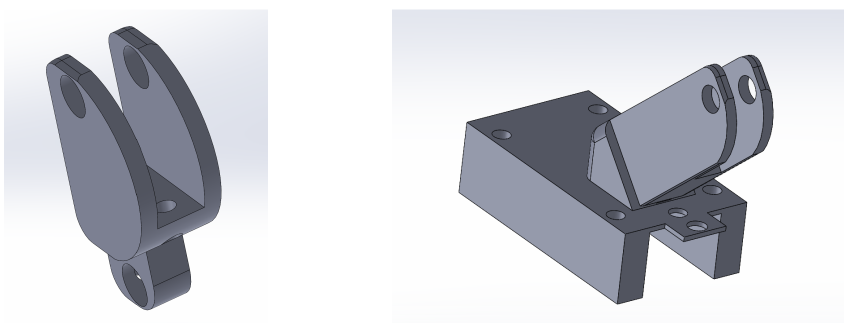

Figure 3: Example pieces of SolidWorks final design

Circuitry and Code

The electronic elements of the prosthetic device are connected and controlled through the circuitry and code. The code utilizes the decision tree method, shown in figure 4, to determine when the linear actuator needs to be extended, retracted, or remain in place. The components used are a button circuit, the motor driver, a power source of two 9 volts batteries, and an arduino nano. The button circuit is powered off the arduino, and consists of a standard button as well as a 1000 ohm resistor. The L298N motor driver is powered by the 2 9V batteries, and supplies power to, as well as being commanded by the arduino nano. The code takes input from the button, sends the button state through the decision tree, and then outputs a command to the linear actuator based on the resulting decision. The circuit always starts with an inwards retraction because it is the in position it is at full retraction but the out position is not full extension. If the button is pushed, and the thumb is not flexed, the linear actuator is commanded to extend. If it is already flexed, the linear actuator is commanded to retract. Once the thumb is either extended or flexed, the motor is disabled until the next push of the button. The code continues to cycle through constantly checking the status of the button. This circuitry design can be seen in Appendix C.

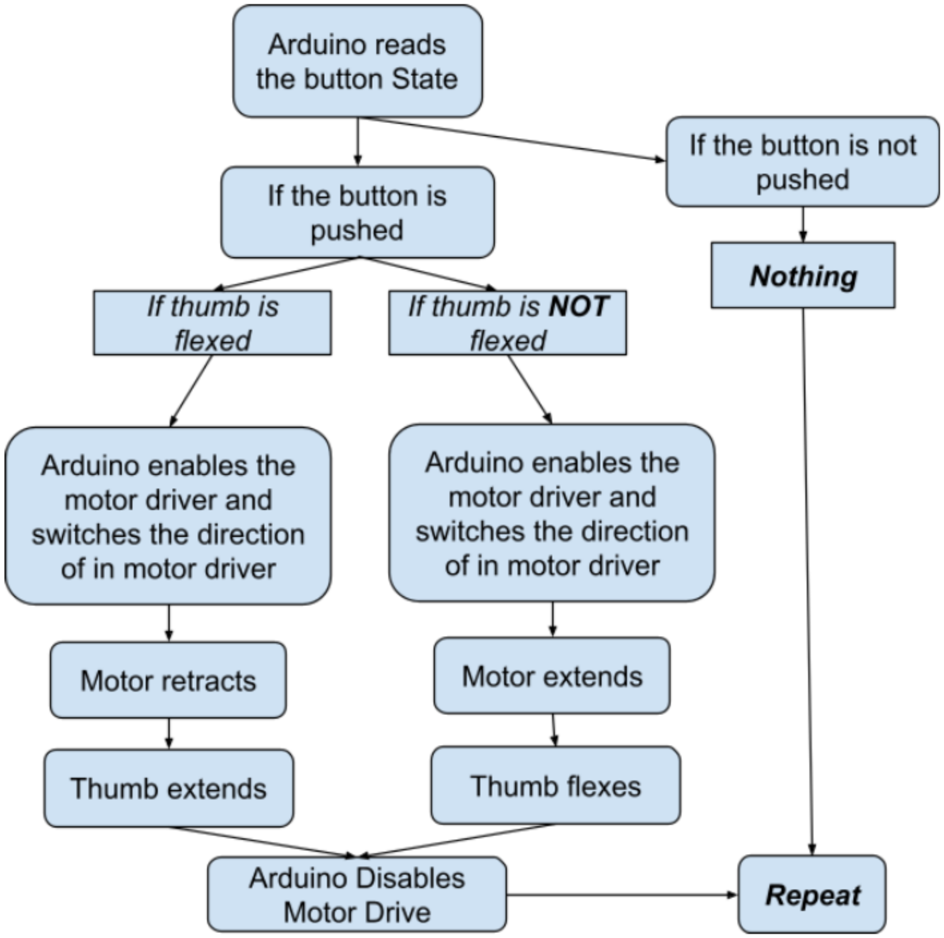

Figure 4: Flow chart depicting the decision tree of the Arduino code shown in Appendix C

<u>Forearm Cuff</u>

The forearm cuff provides a surface to attach the thumb mechanism and motor. It is the basis of how the prosthetic thumb can support 8 N of force. The fit needed to be secure and sturdy on the patient without touching the painful areas of his hand. A model of the patient's forearm was created using measurements shown in Appendix E. The model consisted of a layer of clay overtop plywood to provide stability (Figure 5). More in depth specifications of this process are shown in Appendix G. The model was used to create the cuff using a thermoforming machine (Appendix H).

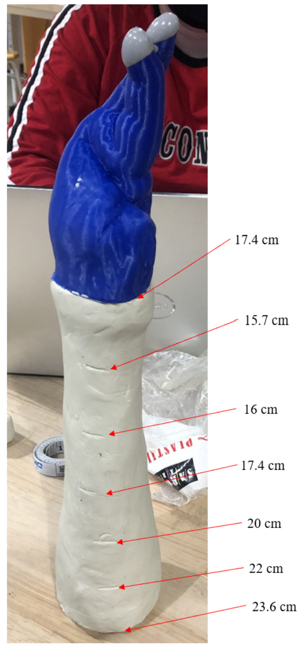

Figure 5: The completed forearm mold with a 3D model of the patient's hand set on top. Measurements depict the cross sectional circumference at various points along the arm

Once the cuff was thermoformed, the forearm model was removed and reformed after being stuck to the inside of the thermoformed plastic mold. The model was remeasured to ensure the same size for the plastic mold of the anterior side of the forearm. The same thermoforming process was followed for the second mold. After both sides of the molds were cooled, they were cut out of the surrounding plastic with a bandsaw, and sanded down using sandpaper. Slits were created along the outside of the cuff by using a heat gun to soften the plastic, then cutting 2 cm slits with a utility knife. A flathead screwdriver was then used to widen the slits so that velcro straps could fit through them to secure the cuff onto the user's arm. The cuff was then painted to match the patient's skin tone to provide cosmesis in the device. A piece of 6mm thick Ethylene-vinyl acetate (EVA foam) was adhered to the inside of the cuff to provide comfort and protection to the user's arm.

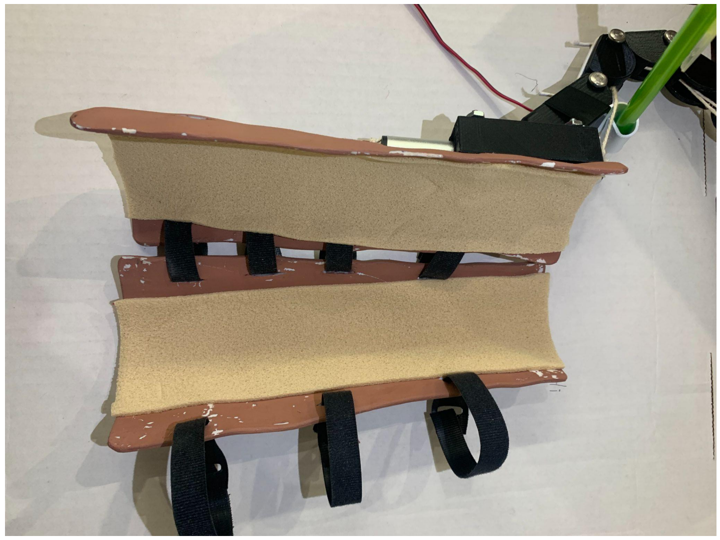

Figure 7: Final forearm cuff design.

Final Design

The final design consisted of a forearm cuff, a mechanical thumb, a linear actuator, motor driver, arduino microcontroller, two 9V batteries and a button. The forearm cuff was customized to fit the patient's arm. It was attached with velcro straps on each side. A cord running through the mechanical thumb flexes the thumb when the linear actuator pulls on it. Elastic running along the back of the design extends the thumb again when the cord is slackened. The linear actuator is controlled by the button encased in a wedge (Figure 1) that is attached to an elastic strap secured on the upper arm. When the button is pushed against the user's side, the linear actuator will activate and the gripping function and the prosthetic thumb will move toward the pinky. Flex seal was painted onto the mechanical thumb to provide better grip. The design works in opposition to the existing pinky finger, which is the only remaining functional finger on the client's affected hand. The design also includes an attachment to hold a writing utensil shown in figure 9.

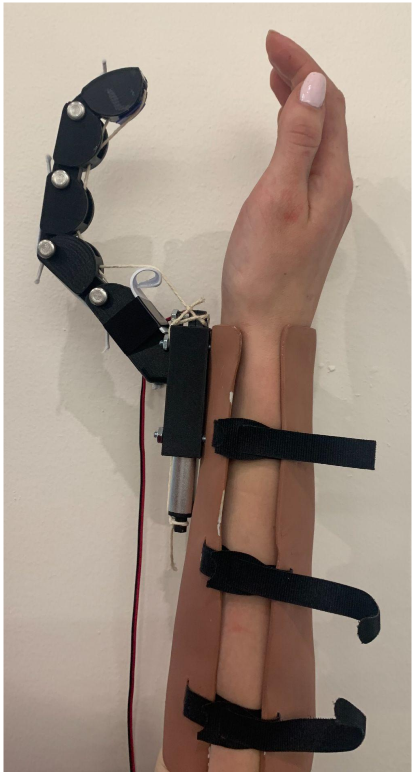

Figure 8: Picture of the final design.

Figure 9: Attachment for holding a writing utensil

Testing

Bench Testing

The device was evaluated with a series of tests, each of which analyzed various aspects of the prototype. Initially, a test of motion was performed (n=5) to determine if prototype motion was replicable and reliable. To perform this test, the button was pressed, and if the device was fully flexed, the device passed. The movement of each trial was noted, specifying if any abnormal movement was detected. The general motion test was evaluated on a pass fail basis, and no further testing was performed until the device had consistent passes.

The battery life was first calculated (see Equation 1) and determined to give over 12 hours of continuous cycling on a full charge. Following this a test was performed which had the circuit continuously cycle for 2 hours to ensure it was appropriately functioning. After 2 hours and over 2000 cycles the test was stopped. This test was done to ensure the patient's device could be powered for a day's use or at least 8 hours. This gave confidence to the battery life calculations.

Second, a range of motion test is performed on the thumb by deploying the device to full flexion to determine the full grasp range of the device. The distance between a straight line extended up the cuff to where a hand would be, and to the prosthetic thumb tip was measured with a ruler at full flexion, and at full extension. The range of motion was determined to be between 1-10 cm.

Third, a force test was performed to determine the peak force the thumb could produce at the distal portion of the prosthetic thumb. This was done by fixing the cuff attachment to a rigid surface and attaching a force scale to the second phalanx. From here the thumb was set in motion and the peak force recorded by the thumb was 8 Newtons. The aim of this trial is to determine whether the thumb could produce an adequate counter for the pinky finger of the patient. The patient's pinky finger can hold 17N, meaning the thumb could be improved to provide more force, but does work to pick up many items [2].

A reaction time test was performed. The aim of this test was to determine if the time from sensor bending to full flexion of the thumb could be done in under 2s. This time is to ensure the patient has a relatively quick reaction. This test is performed by timing the action from the push of the button to full flexion of the thumb, and repeated for a total of 10 trials. The device averaged a 1.53s reaction time which aligned with the duration the motor is being powered (1.50s). Overall this was less than 2.00s and indicates the patient will have a quick reaction time suited to his needs.

$$T = \frac{Battery\ Capacity\ (mAh)}{Current\ Use\ (mA)} \qquad \textit{Equation 1}$$

Where:

$Battery\ Capacity\ =\ 600mAh$

$Measured\ Current\ =\ 49\ mA$

Therefore:

$T\ =\ 12\ hours\ and\ 14\ minutes$

Materials Testing

Testing was additionally done on 60% infill 3D printed Acrylonitrile Butadiene Styrene (ABS) to find material properties of the model. This was done on a Sintech MTS and a tensile test was conducted on a 3D printed dogbone shape object (thinner but uniform cross section in the middle of the length, and larger cross sectional area where it will be gripped by the MTS). The dogbone is a device that is printed with the ABS material to determine the maximum force that can be applied to the material. The resulting stress-strain curve can be seen in Figure 10, and Young's Modulus was determined to be 1500 MPa, with an ultimate tensile strength of 10.8 MPa. Since this is a rigid material the yield strength can be approximated to ¾ which is 7.7 MPa, significantly higher than needed for any model.

Additional computational testing was done on the semester one model which inspired the new model. A finite element analysis was conducted on the model using an elastic neo-hookean material with a Young's Modulus of 1500 MPa and Poisson of 0.26, with the pins modeled as rigid bodies, since the steel will be so much stronger. A displacement was applied to the tip and the resulting compressive stress can be seen in Figure 11. Additionally the resulting strains can be seen in Figure 12. There is a larger amount of strain shown in the joints which was cause for concern. This resulted in the new design containing more uniform joints.

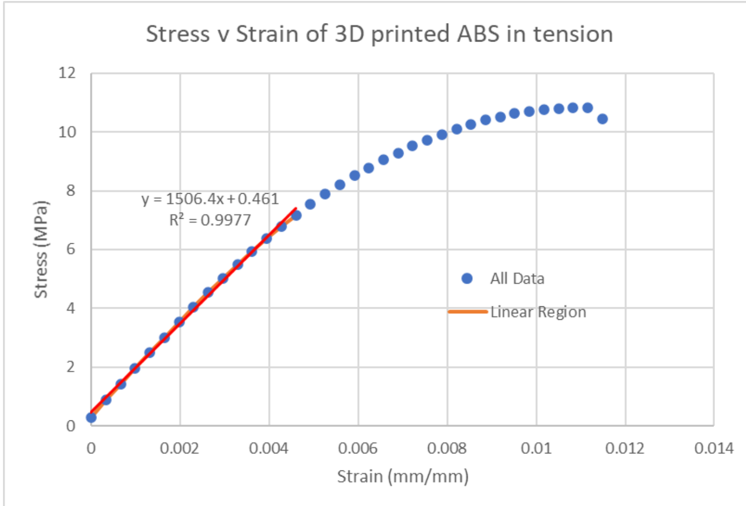

Figure 10: Stress-Strain Curve of 3D printed 60% infill ABS plastic, with linear region in orange, and the equation of the linear region is displayed with the Young's Modulus being 1504 MPa, equal to the slope.

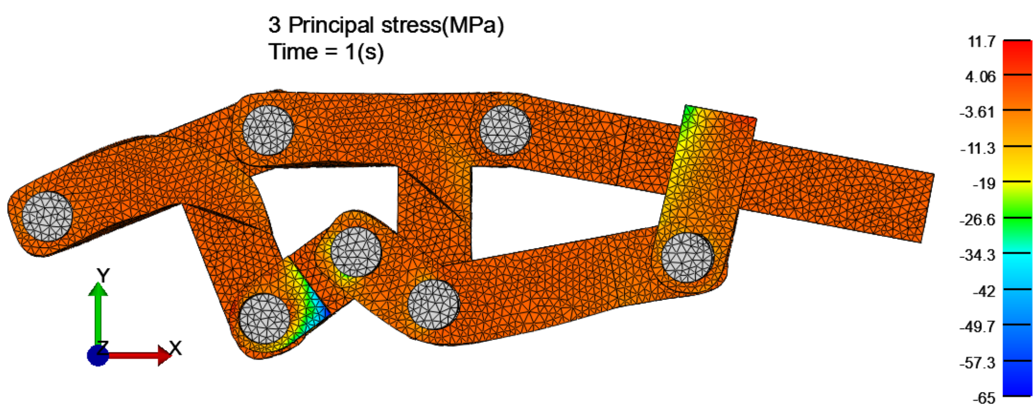

Figure 11: The 3rd principal Cauchy stress of the FEA model, this is the compressive force on the model.

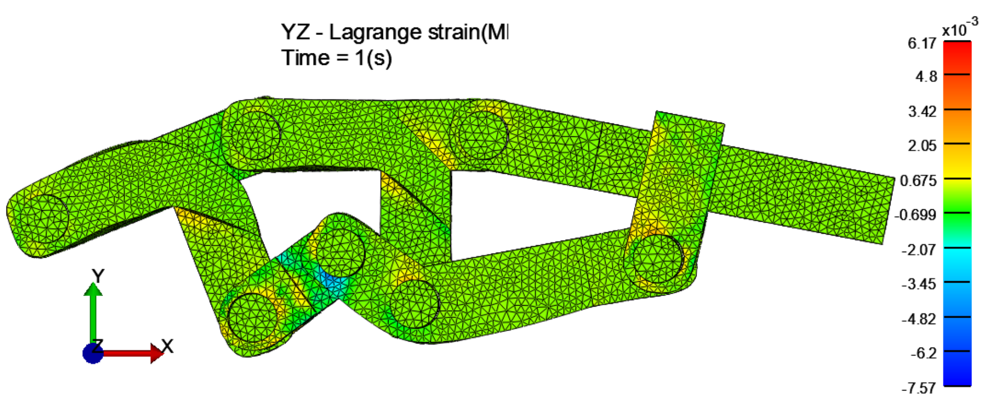

Figure 12: Image of the YZ strain of the FEA model.

Clinical Performance Assessments

Clinical testing was performed with the patient to determine any changes that needed to be made to the prototype prior to completing a final product. The team communicated with the patient through a translator in order to get the patient's feedback. The patient was satisfied with the comfort of the prosthetic and did not foresee any comfort problems with extended daily wear. The patient was able to understand and use the button to control the prosthetic within a few minutes of trying on the device. The patient then attempted to pick up a variety of items, including wooden blocks, keys, and a bottle of lotion. Initially, some items made of plastic were difficult for the patient to pick up using the device because they were slipping on the plastic thumb mechanism. Dycem, a non-slip patch, was temporarily taped to the tip of the thumb mechanism to provide more traction. There was an immediate improvement in the success of the patient picking up objects.

Clinical testing was performed with the patient. This consisted of the patient trying on the prosthetic thumb for the first time and testing how well he was able to use it. The patient was asked to pick up objects of varying sizes and textures. The objects provided were wooden blocks, wooden pegs, keys, a small plastic bottle of glue, and a plastic lotion bottle.

Results

The results of motion testing proved that the thumb reliably extends when triggered. The force test produced a maximum force of 0.815 Kg. This was lower than the 2.5 Kg desired to counter the patient's pinky finger [2]. The range of motion test produced a range of 10 cm of motion. A range of motion 10 cm signifies the variable lengths of objects that can be held by the design. The range of motion and the degree of flexion have a direct relationship. Thus, increasing the degrees of flexion produced by the prototype increases the range of motion. See Appendix D for full data. The device runs off of two 9V batteries, which were calculated to last 12 hours and 14 minutes. This is well over the goal time of 8 hours.

The results of the clinical testing were successful. The patient was able to confirm through a translator that the attachment to his arm was very comfortable, and he saw no possibility of discomfort if he were to wear the device for an extended period of time. Initially, some of the plastic materials were slipping out of the patient's grasp. Dycem was added to the thumb tip to provide more friction. Following this addition, the patient was then able to successfully pick up all of the objects. The prosthetic prototype that was tested had a few key issues that the team fixed. One was that the linear actuator did not fit fully under the housing on the arm cuff. Additionally, the pieces of the 3D print were not pinned together. This caused the device to slip backwards when the patient tried to pick up heavy objects. These issues were fixed through redesign of the 3D print. Pins were added between articulating pieces to stop slippage.

Discussion

Due to the unique amputation of the patient, the device needed to be highly customized. Every part of this design considered how it would impact the patient. The attachment was specialized to avoid uncomfortable contact with the patient. Because of the sensitivity at the site of amputation, the design was limited to being attached somewhere other than the hand. For this design, the forearm was chosen as it is a stable appendage that is near the hand. In addition to avoiding sensitive areas, the design had to accommodate the areas that have minimal sensation, such as the forearm. The concern for these areas would be the device causing irritation to the skin without the user knowing. Since the design is placed on the forearm, a thin piece of foam was adhered to the inside to provide comfort.

The prosthetic thumb provides a stable force to counter the patient's pinky through the entire range of motion. The objects are stabilized by friction on the thumb provided by a texturized flex seal coating on the surface. The pins in the model were added to prevent any backward slipping of the mechanical device and provide side-to-side stability.

Throughout the project, there were multiple design iterations. The final design from semester one is shown in figure 13. This design had a maximum average force output of 4.36 N. The latest design nearly doubled the maximum average force output at 8 N. This was a large improvement from the mechanical thumb design. The latest design also had a larger contact area with objects, which provides more friction between objects as well as a more natural looking movement. The method of activation was also improved during semester two. The flex sensor was switched to a button, resulting in a reduced reaction time. This greatly helps the user to complete tasks more quickly.

Figure 13: Picture of the final design from fall 2021 semester

Conclusions

A functioning bionic thumb was successfully created that has the ability to pick up and hold objects of approximately 0.5kg (see Appendix D). The thumb reacts in 1.50 seconds and has a range of motion of 10cm. This allows the patient to successfully pick up and hold objects.

The final mechanical design of the thumb was able to emphasize natural hand movement and increase force output from previous design iterations. The natural movement of the joints was obtained by using a cable tension system, which also helps with object gripping. Because the thumb is able to flex individually at each joint, the thumb can conform to the shape of the object it is grabbing.

The electronics are secured in a pouch that can be worn by the user on their hip. The wiring is secured with solder to allow for more stability in the circuitry. In addition to the pouch, the button is secured onto the upper arm using an elastic strap attached to a custom wedge piece (Figure 1) to allow for easy and independent use. The patient was comfortable while using the button to activate the thumb. There was a learning curve during the testing process but once he figured out how to effectively utilize the device, he was successful in picking up various objects of different shapes and sizes.

The cost of prototyping, testing, and fabricating the prosthetic thumb over the course of a year cost a total of $403.63. The estimated cost of the materials for building one prosthetic thumb is a total of $200. The goal of this project to keep the prosthetic thumb very affordable so that it is accessible to all demographics of people was successful.

Finally, the design can be adapted for public use due to the versatility of the design. The forearm attachment allows the prosthetic to be used by other individuals who have residual digits on their hand. Any unique residual digits will be compatible with the device because of this attachment style. In addition, the thumb can counter any residual digits, making the design functional for a variety of different amputees.

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Appendix

<u>Appendix A: PDS</u>

Prosthetic Hand

PDS | Sept. 24, 2021

Client: Ms. Shirley Katz

Advisor: Mitchell Tyler

Team: Emmalina Groves - Team Leader

Karen Scharlau - BWIG and BPAG

Danielle Lefko - BSAC

Stephanie Silin - Communicator

PDS Table of Contents

Function

Losing part of a hand is an incredibly difficult obstacle to overcome considering how much a person uses their hands throughout any given day. Not only does it affect many physical aspects in a person's life, but it can cause mental hardships as well. Unfortunately, state of the art prosthetics can cost a fortune, which is not an option for many people. In this case, the patient has lost their thumb, pointer, middle finger, and much of their palm to a serious infection. They retain their ring finger and pinky finger, however movement is severely restricted. The ring finger is immobile, and the pinky finger can bend at the metacarpophalangeal joint a maximum of 10 degrees. Our team will work to help this patient restore functionality to his hand while making it look as real as possible. The goal is to create an affordable solution so that more people like our patient can regain use of their hands.

Client requirements:

- Prosthetic must be able to stabilize and hold objects.
- Cosmetic appearance of prosthetic is more important than the function.
- Prosthetic needs to be comfortable for extended, daily wear.
- Prosthetic should include at least a thumb, preferably 2-3 additional digits.
- Prosthetic needs to be water-resistant or water-proof.

Design requirements:

1. Physical and Operational Characteristics

a. *Performance requirements*:

The prosthetic must provide the user with the ability to stabilize and hold objects that are light to moderate in weight. The prosthetic hand should give a gripping force of 2.5kg. It should be able to manipulate any utensils, i.e. pencil, fork, etc. Additionally, the attachment to the body should not put the user in danger, or be too costly as this is intended to be a cost-efficient device.

b. *Safety*:

The prosthetic must be safe for continuous wear for 3 to 5 years[1]. All materials used must be safe for extended contact with skin, and sharp edges or pinch points must be covered.

c. *Accuracy and Reliability*:

The prosthetic hand must move in a controlled manner so the patient is able to benefit from understanding the consistent movements. Hand must be able to continuously function for 8 hours of use so the user is able to work without changes in function.

d. *Life in Service*:

The prosthetic must be functional for constant wear by the user for 3 to 5 years, and be durable enough to withstand common daily tasks [1].

e. *Shelf Life*:

The prosthetic should not have any problems being stored for several years.

f. *Operating Environment*:

The prosthetic must be functional in all environments the user encounters in daily life. This includes rain and very cold weather. It would be ideal for it to function fully submerged in water, but not necessary. The device should be able to be cleaned with soap and water.

g. *Ergonomics*:

The prosthetic should be comfortable for writing, picking items up, and holding items. It should act as an extension of the body, and prolonged use should not cause any discomfort.

h. *Size*:

The prosthetic must blend in with the size of the user's natural hand. A 3D scan of the user's affected hand was obtained and can be used to reference specific measurements.

i. *Weight*:

According to the prosthetic development community, there is no specific maximum weight of prosthetic hands. However, the general consensus is that the prosthetic hand should remain below 400 grams, which is the average weight of an adult human hand. Many current users indicated that when wearing a prosthetic hand that weighed the same as a natural hand, it felt too heavy. This is a direct result of the attachment. [2] A smaller weight would be ideal as it would be easier to stabilize and reduce wrist torque. The goal is to produce a device that is around 300 grams.

j. *Materials*:

The materials used should not cause any adverse effects to the user after prolonged use. They should provide both structural support and grip in order to pick up and hold various objects. A plastic 3D printing material such as PLA (polylactic acid) or ABS (Acrylonitrile Butadiene Styrene), a prosthetic structural material, cushioning, and electronic components will make up the bulk of the design.

k. *Aesthetics, Appearance, and Finish*:

The user desires a more cosmetic approach to this device. This means that the prosthetic hand must maintain cosmesis and blend appropriately with the rest of the body. The device should achieve the closest to a natural look as possible, and if possible include natural features such as fingernails.

2. Production Characteristics

a. Quantity:

The device is being made for a specific patient, so only one device is necessary to manufacture. However, the prosthetic device will be made so that others who have lost some or all digits can use the same design principles with aspects of the design tailored to the limb of the patient.

b. Target Product Cost:

The prosthetic device must be as economical as possible because the client did not provide a budget. All funding will be coming from an outside source.

3. Miscellaneous

a. *Standards and Specifications*:

1. Grip light-medium objects with 2.5 kg of force . This max force should be for steady grip of smaller rectangular objects such as a phone.
2. Remain around 300 grams [3]
3. Match size of the client's hand provided by .stl file
4. Must be reproducible in multiple skin tones.
5. Velcro adjustable brace will attach to lower forearm above the wrist. This will be accompanied by a 'sweatband'/sock type material to go underneath and prevent frictional irritation and distribute uneven stresses on the wrist.
6. Strings pulled by motors will close the fingers into a grip. The motors will engage when an electrode, attached to the skin of the forearm, registers muscular movement.
7. The user should be able to pick up a cup and small items off of a flat surface.

b. *Customer*:

The customer for this project is the client's patient. However, this project will be applicable for other users down the line. These users will be individuals who have had one or more compromised digits on their hand that has limited functionality.

c. *Competition*:

The client has reached out to other organizations for additional assistance. One company includes Enabling the Future. E-nable is a company that produces 3D printed mechanical prosthetic hands for individuals who have at least some movement of the wrist.

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Appendix B:Prosthetic Thumb User Manual

PROSTHETIC THUMB USER MANUAL

English:

1. Safety

1.1. Thumb should not be used when wet or submerged in water.

1.2. If any component of the electrical circuit gets hot, disconnect the batteries immediately and take off the device.

1.3. Arm sleeve should always be used with the forearm cuff to prevent rubbing, chafing, blisters, or any other injury.

1.4. If the device becomes uncomfortable in any way, discontinue use and check discomfort for signs of injury.

2. How to use

2.1. Put arm sleeve on arm

2.2. Ensure charged batteries are attached

2.3. Put on the arm band and ensure a comfortable fit.

2.4. Put on the forearm cuff by sliding the hand up through velcro straps. Tighten straps.

2.5. Adjust button on arm as needed for ease of use.

3. Troubleshooting

3.1. If components of the electrical circuit ever get hot, make sure the circuit is not shorting out. Look for any exposed metal that may be in contact with something it shouldn't be.

3.2. If the device is not working, ensure batteries are charged. It is best to check that the batteries are outputting voltage by testing with a voltmeter.

3.3. If a part of the device begins rubbing uncomfortably, consider adding foam or other padding. Ensure the velcro is tight enough to provide a snug fit.

4. Contact

4.1. If you have any questions, feel free to contact:

4.1.1. Emily Groves at eraegroves@gmail.com

4.1.2. Stephanie Silin at ssilin90@hotmail.com

4.1.3. Karen Scharlau at kscharlau99@gmail.com

4.1.4. Danielle Lefko at danilefko@gmail.com

Español:

1. La Seguridad

a. El pulgar no debe usarse cuando está mojado o sumergido en agua.
b. Si algún componente del circuito eléctrico se calienta, desconecte inmediatamente las baterías y retire el dispositivo.
c. La manga del brazo siempre debe usarse con el manguito del antebrazo para evitar roces, rozaduras, ampollas o cualquier otra lesión.
d. Si el dispositivo se vuelve incómodo de alguna manera, deje de usarlo y verifique que no haya signos de lesión.

2. Cómo Utilizar

a. Poner la manga del brazo en el brazo
b. Asegúrese de que las baterías cargadas estén conectadas
c. Póngase la banda para el brazo y asegúrese de que le quede cómodo.
d. Colóquese el manguito del antebrazo deslizando la mano hacia arriba a través de las tiras de velcro. Apriete las correas.
e. Ajuste el botón en el brazo según sea necesario para facilitar su uso.

3. Solución de problemas

a. Si los componentes del circuito eléctrico alguna vez se calientan, asegúrese de que el circuito no esté en cortocircuito. Busque cualquier metal expuesto que pueda estar en contacto con algo que no debería estar.
b. Si el dispositivo no funciona, asegúrese de que las baterías estén cargadas. Lo mejor es verificar que las baterías estén generando voltaje probando con un voltímetro.
c. Si una parte del dispositivo comienza a frotarse de manera incómoda, considere agregar espuma u otro acolchado. Asegúrese de que el velcro esté lo suficientemente ajustado para proporcionar un ajuste perfecto.

4. Contacto

Si tiene alguna pregunta, no dude en ponerse en contacto con:

a. Emily Groves: eraegroves@gmail.com
b. Stephanie Silin: ssilin90@hotmail.com
c. Karen Scharlau: kscharlau99@gmail.com
d. Danielle Lefko: danilefko@gmail.com

Appendix B: Material Cost Spreadsheet

Table 2: Summary of project Costs

Item	Manufacturer	Quantity	Price	Total
Glue	Buy On Purpose	1	$10.13	$10.13
Velcro Ties	Buy On Purpose	1	$5.79	$5.79
Clevis pins	Grainger	10	$1.66	$16.60
Arduino Nano Every	Arduino	1	$12.90	$12.90
9 V Rechargeable Batteries	EBL	1	$26.99	$26.99
Arm Sleeve	IovyoCoCo	1	$13.24	$13.24
Flex Seal	Flex Seal	1	$14.99	$14.99
Motor Driver	HiLetgo	1	$10.99	$10.99
3D Printing	N/A	N/A	N/A	$20.00
Flex Sensor	Adafruit	1	$12.00	$12.00
Polystyrene	Makerspace	4	$15.00	$60.00
3D printing, motor driver, arduino, wires, batteries, screws, nuts.	Makerspace	N/A	$200	$200
			Total:	$403.63

Appendix C: Arduino Code

```
int b_state = 0;
int but_state = 0;
int but = 0;
int counter = 1;
const int ButtonPin = 2; //D2
const int RPWM_Output = 6; // Arduino PWM output pin 7; connect to IBT-2 pin 1 (RPWM)
const int LPWM_Output = 5; // Arduino PWM output pin 6; connect to IBT-2 pin 2 (LPWM)
const int ENA = 9; //Enable pin

void setup() {
 pinMode(ButtonPin, INPUT);
 Serial.begin(9600);
 pinMode(RPWM_Output, OUTPUT);
 pinMode(LPWM_Output, OUTPUT);
 pinMode(ENA, OUTPUT);
}

void loop() {
 b_state = digitalRead(ButtonPin);
 if (b_state == HIGH) {
  analogWrite(ENA, 255);
  but = 1;
  Serial.print(but);
  Serial.print(counter);
  if (counter == 0){
   Serial.print("going out");
   digitalWrite(LPWM_Output, 0);
   digitalWrite(RPWM_Output, HIGH);
   delay(1500);
   analogWrite(ENA, 0);
   but_state = "OUT";
   counter = 1;
   }
  else {
   Serial.print("going in");
   digitalWrite(RPWM_Output, 0);
   digitalWrite(LPWM_Output, HIGH);
   delay(1500);
   analogWrite(ENA, 0);
   but_state = "IN";
   counter = 0;
  }

 }
 if (b_state == LOW) {
  but = 0;
 }
 Serial.print(but);

}
```

Appendix D: Force Reaction Data

Semester 1 Force Data:

Trial	kg		N
1	0.45		4.4145
2	0.5		4.905
3	0.4		3.924
4	0.4		3.924
5	0.45		4.4145
6	0.5		4.905
7	0.45		4.4145
8	0.5		4.905
9	0.35		3.4335
10	0.45		4.4145
Avg	0.445		4.36545
Variance	0.0025		0.2141

Semester 2 Force Data:

Trial	kg		N
1	.765		7.50
2	.762		7.47
3	.801		7.85
Avg	.776		7.61
Variance	.0003		.029

Appendix E: Client Arm Measurements

Length Proximal to the Wrist	Circumference (cm)
At elbow	25.0
+7.5	23.6
+6	22.0
+4.5	20.0
+3	17.4
+1.5	16.0
+0	15.7
-1.5	17.4

Appendix F: Preliminary Designs

Design 1 - Cosmetic

Figure 8: Example of a cosmetic silicone hand mold (on the right) intended to blend seamlessly with the natural hand (on the left) [25].

The cosmetic design was created with cosmesis at the forefront of importance. This design would focus on materials and details that blended in seamlessly with the user's natural hand. Therefore silicone would be used for the majority of the device and details would be added with paint or artificial hair. In addition to cosmetics, this design would be extremely comfortable for the user, as their natural hand is only in contact with the flexible silicone material. With the specific patient's specific injury and needs in mind, the design would have to consist of the thumb, index, and middle finger. Considering the sensitivity the patient has where the original fingers were removed, the design would have to avoid contact with this area, and add padding around the area. This would mean forcing the resting points to be elsewhere on the patient's hand and create a gap to avoid contact at this point.

Design 2 - Mechanical

Figure 9: CAD model of the mechanical design intended to provide more functionality.

The mechanical design takes a similar approach as the competing design from e-NABLE. However, this design is more effective for the patient because it allows for the user to have pre-existing digits. The competing e-NABLE design requires the user to have no fingers, so this is not a feasible option for the patient. This design functions when the user bends their wrist. Wrist flexion causes the finger(s) to close by pulling on a chord that is attached at the wrist on one end and the finger on the other (see Figure 10). This design would be easily fabricated through 3D printing. The device would be attached at the wrist with a sturdy cuff to counteract the force when bending the wrist. Which will be padded with a sleeve to go underneath the cuff and prevent abrasion.

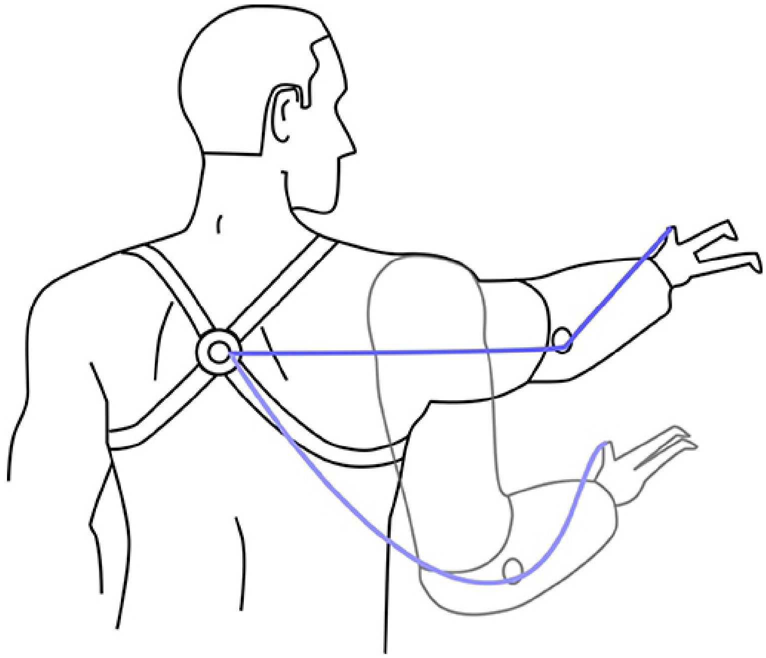


Figure 10: Example of a body-powered upper limb prosthesis. In this instance when the elbow is in extension a tension force is produced on the cord causing the device to extend [26].

Design 3 - Bionic

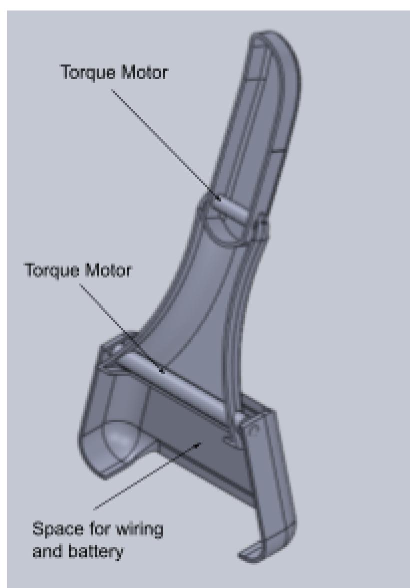


Figure 11: Example of a bionic addition to provide better functionality.

The bionic design utilizes EMG sensor electrodes attached on the skin of the forearm. These sensors read electrical signals emitted by the muscles in the user's forearm. These signals are then read by a microcontroller and translated into movement of the fingers. Because the patient experienced an infection that went up part of his forearm, the EMG signals will likely have to be rectified, amplified, and conditioned (filtered) satisfactory output to drive the torque motors if they are to generate sufficient grip.

Three EMG sensors will be used to sense the muscle activity in the patient's arm. One negative, one positive, and one grounded. The positive and negative electrodes will be placed in the middle and at the insertion of the flexor carpi ulnaris. For consistency of electrode placement, the same forearm will be used; the middle will be measured as exactly halfway between the origin and insertion of the muscle. The ground electrode will be placed on an adjacent bony prominence to ground the signal. The signal will then be passed through a differential amplifier. This is what will allow the signal to be amplified. Then the signal will pass through a band pass filter. These are simple filters that use resistors in order to only use signals within a specified range. This will lessen the noise of the signal. Expected signal range from the muscle is between 50 and 150 Hertz [22]. Anything out of this range will be filtered out [22]. The mechanical element would be a deconstructed robotic claw design with the thumb acting as one half of a claw for the user to push against with their existing pinky finger. This would provide much more force for the user to be able to grasp and hold different items because it is not dependent on the amount of wrist flexion they have.

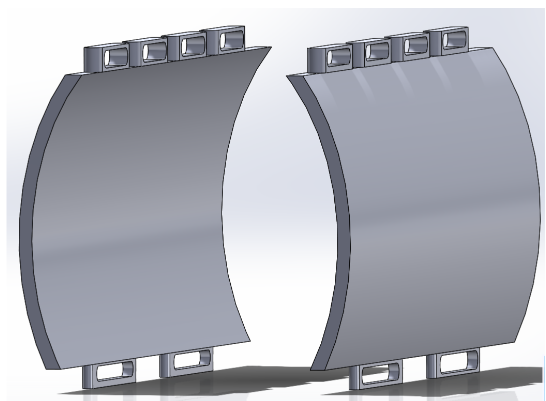


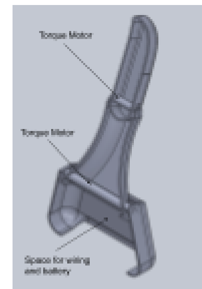
Figure 12: The patient has sensitivity on the hand at the amputation points, so the thumb will be anchored to this custom cuff that will fit on the forearm. Velcro straps will join the halves. The two straps on the bottom are to reduce the time it takes to secure and remove the device.

The prosthetic thumb must be anchored securely in order to support any weight being lifted. It cannot slip, so it needs to have a tight, secure fit without being too tight. One major challenge is that the patient's hand has sensitivity at the points of amputation. It was suggested by the client to stay away from those areas. This can be especially difficult with a moving part, as the additional weight of the motor and motion of the device provides different loading compared to both other designs. For this reason, the thumb was anchored onto a cuff that is supported by the forearm, and the motor will be contained within the cuff. This way, the patient's hand will not be bothered by coming into contact with any solid materials. In this design, Velcro straps will connect each pair of slots. The side with 4 slots will be adjusted to the patient, then can stay at this adjustment. The side with two slots will be the side the patient uses to put on and take off the prosthetic. The client will need to put the prosthetic on with one hand, so the simple velcro straps will allow him to do so. To maximize the comfort and safety of the patient, a silicone sleeve will be fitted to the patient's arm, and rest in between the prosthetic and the skin. To provide additional padding, closed-cell foam will be attached to the inside of the cuff [23]. Finally, any sharp edges or corners on the cuff will be removed to ensure it does not catch on anything or cause discomfort.

Preliminary Design Evaluation

Design Matrix

Table 1: Design matrix demonstrating how the bionic design is chosen

Name		Cosmetic		Mechanical		Bionic	
Criteria:	Weight:						
Comfort	20%	5/5	20	(1/5)	4	(3/5)	
Ease of use	15%	1/5	3	(3/5)	9	(5/5)	
Cost	15%	4/5	12	(4/5)	12	(1/5)	
Cosmesis	5%	5/5	5	(1/5)	1	(2/5)	
Functionality	15%	1/5	3	(2/5)	6	(5/5)	
Ease of Fabrication	10%	4/5	8	(5/5)	10	(1/5)	
Strength	15%	1/5	3	(2/5)	2	(5/5)	
Response Time	5%	1/5	1	(5/5)	5	(3/5)	
Total	100%	55		49		57	

Design Matrix Summary

Design 1: Cosmetic

This purely cosmetic design would be made with materials that best resemble the touch and feel of skin, however would not provide much additional functionality past a backbone for the patient to pinch against with his pinky finger. This design would be easier to fabricate as it would have less moving pieces, but creating a realistic looking finger could be challenging. Additionally without any moving pieces this design would have less potential pinch points, or electrical issues making it comfortable and more easily worn in the rain/water. However, this design does provide much functionality or strength to the patient as some of the other designs and therefore it was not selected.

Design 2: Mechanical

The fully mechanical design is the most simple design. The string is shortened by flexion of the wrist, allowing the user to grasp items. The major shortcoming in this design with regards to the patient, is that they are unable to move their wrist more than 20-30 degrees. This would severely limit either the range of motion of the thumb or grip strength of the prosthetic, as with increased range of motion the force provided would decrease. It is a straight forward design, so it scored well in the ease of use, cost, and ease of fabrication. One of the major benefits of this design is the low cost. However, since the client did not provide a budget, it is crucial to keep the cost relatively low so that it can be funded from outside sources. The response time in the mechanical design would also be the best because there will be no lag time that some of the electronic components in other designs may have.

Design 3: Bionic

The bionic design meets some of the client's most important requirements, which are strength and functionality. These criteria would allow the patient to go back to work. The design would be far more complex and therefore expensive than the other designs. However, based on the criteria of making an inexpensive model, this is a trade-off for making a prosthetic that works for the user. There would also be a larger learning curve for the user, resulting in a lower score in the ease-of-use category. Finally, when considering the difficulty of designing a base mechanical support, the electronics required, and the timeframe available, it was concluded that the bionic design is too difficult to fabricate in the given amount of time, resulting in a low ease of fabrication score. However, it came to light that the patient experiences sensitivity and pain during palpation of the amputation site. Due to this, the prosthetic design was limited to the thumb, and thus the decision was reversed and the bionic model became feasible.

Proposed Final Design

The overall winner of the design matrix was the bionic design. This design won because it scored the highest in the most valued categories. The bionic design provides the user with the greatest amount of force and strength when grasping and holding objects. This was the most important quality to consider for the patient because he is looking for a solution to help him get back into the workforce. In addition to strength, the bionic design is also easier to use for the patient because of the limited flexion in his wrist. The use of a microcontroller allows for the patient to be able to grasp many objects of different sizes and weights. The microcontroller is able to amplify any signal read from the forearm into any movement response necessary. This is valuable to the patient because he will be able to hold larger and heavier objects as well as utilize smaller movements for tasks such as writing. This solution will take some adjustment initially, but it will ultimately be a better solution for the patient.

Final Design

For the final design, the bionic design was used, but the sensors were changed from myoelectric sensors to a flex sensor. Myoelectric electrodes were attached to the left forearm of a test subject and connected to an electrical circuit in order to read the signals. Clear signals could not be obtained from myoelectric sensors. For this reason, the myoelectric sensor was replaced with a flex sensor for the final bionic design. This was chosen because it is a simpler mechanism that will give clear changes in resistances based on flexion. The flex sensor will be placed on the wrist and be attuned to the patient's wrist flexion, which will determine the degree of flexion of the thumb. The flex sensor was also a better option because the myoelectric electrodes were not reusable.

Appendix G: Forearm Model Fabrication

First, two ½” x 1” x 10” pieces of plywood were glued together to act as the core material for the mold. This was to ensure the mold was strong and would hold its shape under the pressure applied in the thermoforming process.

Figure 1: Two pieces of plywood being glued together to act as the core material for the model forearm. The strong core provided a backbone for the clay to be molded onto.

Next, non-drying clay was stuck to the plywood in the shape of the patient’s forearm. Circumference measurements and pictures with scale were provided to make the model as accurate as possible to the patient’s forearm.

Appendix H: Thermoform Fabrication

After the forearm model was created, the thermoforming machine was turned on and preheated. After 15 minutes, the model was set into the thermoforming machine so that the posterior side of the forearm was facing up to get molded. The ⅛" polystyrene was then set above the model on top of the foam seal of the machine so that it could create a vacuum seal. The heating hood of the thermoforming machine was pulled forward, and the plastic was heated. After about 3 minutes, parts of the plastic began to droop, signaling that it was pliable. The heating hood was pushed back, and a lever that raised the model into the plastic was pulled.

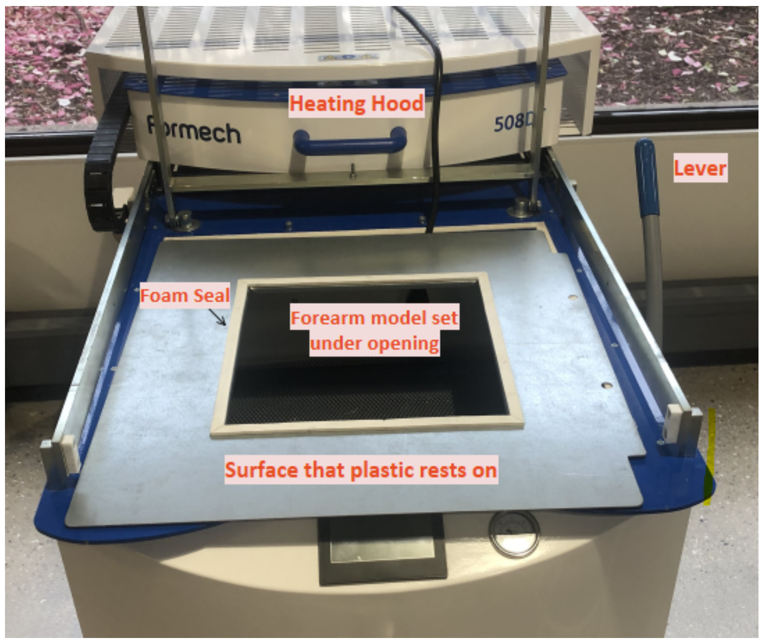


Figure 1: Thermoformer machine with various parts labeled.

A button was then pressed to activate the vacuum function of the thermoformer. It was pushed on and off for approximately 8 seconds in order to reach a balance between following the contours of the model and not stretching the plastic to the point of tearing. If the vacuum is left on too long, the plastic may be suctioned too strongly, and the plastic may stretch too far and become too thin with the possibility of tearing. If the vacuum is not left on long enough, the contours of the forearm model would have been lost. The plastic was allowed to cool for 1 minute before being removed from the thermoformer.