Active Prosthetic

Preliminary Report

Team Members:
Jannell Broderick
Allison Cutler
Felicity Escarzaga
Antoinette Goss

2018-2019

NORTHERN
ARIZONA
UNIVERSITY

Project Sponsor: Dr. Kyle Winfree
Faculty Advisor: Dr. Kyle Winfree
Instructor: Dr. Sarah Omen

DISCLAIMER

EXECUTIVE SUMMARY

There is a large need for inexpensive prosthetic for amputees. This project focuses on the below the elbow amputees. The active prosthetic capstone provides below the elbow amputees with a replacement hand that provides a sense of touch to the user. The project is important because it give the user a new hand that make daily tasks easier. This project has many requirements presented by the project sponsor, Dr. Kyle Winfree. The prosthetic must be able to sense touch, easily activated, lightweight, adjustable size, comfortable, customizable control, and more. The project was inspired by the ENABLE projects that provide simple prosthetic devices for amputees. The ENABLE prosthetic are provided on their website and the CADs allow people around the world to build inexpensive and effective prosthetics. The hands on the site are customizable for the individuals. It is the teams goal to create a more advanced that can provide a sense of touch and more control to the user. It will continue to be inexpensive and will be added to the ENABLE site for people around the world.

To achieve these goals the team analyses the needs and requirements to determine the most important factors. These are weighted against each other in a house of quality (QFD). The flow of inputs and outputs were used to determine the needed elements of the device. The team designed many possible prosthetics. These are unique and biologically inspired. The most important factors were used to determine the best design. The final design that was chosen was similar to many of the competing designs. The final design was based on the ENABLE hand. The changes to the ENABLE hand include sensors to detect touch, bluetooth control, and vibrating motors. The hand is designed in Solidworks and also include an altered thumb that has a large range of motion. The team also performed individual analysis of different aspects of the hand. These analyses include the percent infill, crossestional shape, arduino code, and thermoforming of plastic. The design will incorporate the results from these calculations. For example the design will incorporate a cross sectional area that has the smallest moment of inertia and include a code that will move the hand by the instruction of the user. The mechanical team is teamed with a group of Electrical Engineers. The Electrical engineers will aid the team to code the motors to move prosthetic fingers. This hand includes the bluetooth control from the toes and the sensors that respond to touch.

The Prototype for this new hand utilizes the original ENABLE Hand with alterations. The hand has motors that move the fingers and control sensors on the toes that give the user the ability to control the hand. At the fingertips, there are pressures sensors that sense signals and vibrate to notify the user of touch.

TABLE OF CONTENTS

1 BACKGROUND

1.1 Introduction

As technology continues to advance, change, and adapt, so do the needs of the community that creates them. In the current age, one important issue that many face today is finding a functional below-elbow prosthetic that can be adjusted for amputees of all ages and sizes. Without such a device, individuals cannot complete daily tasks as quickly or as efficiently as people with two hands. Others have stated that having a prosthetic provides them with a sense of normalcy compared to without. This project will approach this issue by creating an active prosthetic device for amputees in need. The objectives of the project are that the device be affordable, scalable, and provide sensory and haptic feedback technology for the user. Upon completion, not only will this device be useful for amputees, but it was also be affordable and easy to build, allowing for a larger group of people to benefit from this design. The design will also benefit the sponsor as well, as the successful design can be used as a basis to be improved upon for customers in the future.

1.2 Project Description

The following is the original project description provided by the sponsor:

> "Everyday, you take your sense of touch for granted. Your sense of touch is critical to how you interact with the world. Imagine for a moment that you have lost your hand. Maybe from an accident, maybe from an infection, or maybe even as a congenital condition. For persons with prosthetics, touch becomes a complex issue. Those with amputations are often eligible for prosthetic devices. However, for a variety of reasons such as cost and technology, these devices are rarely actively driven and almost never provide the user with a direct sense of touch. This project will seek to address the limitations of existing prosthetic technologies, by leveraging rapid prototyping technologies such as 3D printed materials and inexpensive embedded architectures, and will result in an inexpensive, customizable, actively controlled, and haptic enabled prosthetic for children in the Northern Arizona (NAZ) area who have a below the elbow amputation. It is expected then that this resultant product will be utilized by children in NAZ, changing how they interact with the world around them."

2 REQUIREMENTS

The requirements for the prosthetic hand project are determined by the needs of the customer and the engineering requirements. The customer requirements were provided by our sponsor, Dr. Kyle Winfree. These requirements were ranked based on their importance. In addition, the customer needs are used to clarify the objectives of the project. The provided customer needs were broken down into measurable parameters to produce the engineering requirements. Each engineering/technical requirement are verified against measurable parameters and conditions in order to display their respective importance. The customer and engineering requirements are compared to one another using a house of quality. This is an important part of the design process because it informs the team which needs should be focused on to satisfy the customer and engineering requirements.

2.1 Customer Requirements (CRs)

The customer needs were presented to the team by their sponsor, Dr, Kyle Winfree. The provided customer needs were extensive. In order to reduce and simplify the needs, there were many were clumped together to form the main customer needs. The list of requirements provided by Dr. Winfree can be seen in the table below.

Table 2.1: List of all Customer Needs and the Overarching Categories of Customer needs

Customer Need	**Overarching Need**
Scalable	Scalable
Lightweight	No pain or discomfort or strain/Lightweight
Electromechanical control	Haptic sensing system
Sense of Touch	Haptic sensing system
Relay aspects of touch	Haptic sensing system
Rechargeable	Customization
Customized Hardware	Customization
Customized Software	Customization
Available for download of design file	Customization
Aesthetically pleasing	Aesthetically pleasing
Easy to clean	Easy to clean
Durable	Durable
Comfortable	No pain or discomfort or strain

After condensing the many needs, the following main overarching needs were developed. The description of each need is provided below, and the rankings can be found in Table J2.

- Aesthetically pleasing -
    - This need involves the appearance of the device. The Prosthetic should have a pleasant appearance. This will please the user. The hand should be and look professional. This need received a low ranking is it is not as vital to the prosthetic design as the other needs.
- No pain or discomfort or strain-
    - The residual limb can be very sensitive. So, it is vital that the prosthetic hand should be comfortable for the user. If the hand causes pain or discomfort, then the

    individual will be unwilling to wear it. Thus, this is an extremely important requirement and as such is ranked highly.

- Scalable-
    - The Prosthetic needs to be scalable. This is because each individual has different physical dimensions. In order for the device to be successful, it must have features that allow the dimensions to change for each unique residual limb. This is kept in mind when developing concepts and choosing designs. So, this need received a ranking of 3 out of 4.
- Customization-
    - The customizability involves the hardware, software, and the design file. The client has asked that the prosthetic hand must be customizable to each person. This requirement is similar to scalability. By following this requirement the device can be manipulated in many ways, including the shape. The design CAD file should be replicable by other engineers and customers. Thus, the client will be able to change the sizes of the hand to fit individual amputees. The software for motors and signals should also be controllable by the user. Therefore, the arduino code should be manipulatable. Because of the many aspects involved this requirement is ranked highly.
- Easy to clean-
    - This is not as vital as others which is why it received a low ranking. The hand must be easy to clean. Thus, the materials and shape of the prosthetic should allow the amputee to cleanse the device with standard cleaning tools and their one other hand.
- Light weight-
    - It is important that the prosthetic hand is lightweight because the user needs to be able to lift it without struggling. The residual limb is a sensitive area. So, weight on the limb can cause pain. By keeping the device lightweight, it will increase the comfort to the amputee. This is why this need was ranked highly.
- Durable-
    - The customer will be using the prosthetic as if it were their original hand. The average person pushes, pulls, and lifts many items. The human hand also endures many impact stresses. Therefore, the prosthetic device must be made of strong materials and shaped to support heavy loads. The device must also be reliable and functional. Choosing durable materials and design shapes will the recipient with the most reliable and functioning hand.
- Haptic sensing system-
    - The prosthetic device will simulate the human hand by sensing touch. Within the human hand the nerves send signals that tell the human brain that the hand is gripping an object. The device will not be exactly like nerves but it can provide a

response to touching an object. This response can be heat, vibration, visual, etc. The most favorable by the client is vibration because it is the least distracting and still sends the message. The arm also should be able to move by the command of the user. The arm actuation should be easy. Therefore, this customer need received a high ranking.

Table 2.2: List of Condensed Customer Needs

Customer Needs	Rank
Aesthetically pleasing	1
No pain or discomfort or strain	4
Scalable	3
Customization	3
Easy to clean	2
Light weight	3
Durable	4
Haptic sensing system	4

These rankings show that the main objectives for this project. These objectives are to create a prosthetic arm that is comfortable, durable, and has haptic sensing. These highly ranked needs will be kept in mind as the concepts are developed and designs are chosen. In addition, these customer needs will be used to cultivate the engineering/technical requirements.

2.2 Engineering Requirements (ERs)

The engineering/ technical requirements are measurable parameters that the prosthetic hand must complete. These were derived from the customer needs and were created in a way that makes them quantifiable. Each of the technical requirements that were generated have set units and sizes.

The technical requirements are as follows:

- Scalable Size-
    - The active prosthetic must be able to change size to accommodate the customer need of scalability. The length of the forearm, fingers, and other parts of the hand must be adjustable to allow the device to be proportional to the amputee's body.

    The average human arm is 12 inches long. The individuals also have lost their limbs at differing locations along the arm. Thus, the size of the arm should be adjustable from approximately 6 to 18 inches. Similarly, the diameter of the human arm varies for each individual. The range for diameter should be between 1 and 3 inches. This can be achieved by creating Solidworks CAD drawings that accept dimensions while still keeping the hand at the proper proportions for functionality.

- Weight-
  - The weight engineering requirement is derived from the lightweight customer need. The user needs to be able to lift it without struggling. The residual limb is a sensitive area. So, weight on the limb can cause pain. By keeping the device light it will increase the comfort to the amputee. The weight of the arm should not exceed the patient's ability of lifting. The average weight of a human arm is 1.72 pounds. This should not be exceeded by the prosthetic arm.
- Budget -
  - The device should not cost more than $500 to create. One of the purposes of the project is to design a prosthetic that is affordable and functional. In order to do so, the materials to build the hand should not exceed the budget limit.
- Material Properties-
  - The material properties were derived from the durability customer requirement. The arm needs to be strong enough to support the forces, torques, stresses, and strains of common uses. The material must be able to withstand at least 1000 psi. This will allow the user to grab lightweight items and perform simple tasks. Another material property is malleability. If the material is easy to shape it makes it easier for the construction of the device.
- Force to actuate-
  - The arm actuation is the force required to activate the hand motion. The amount of force applied by the patient should not exceed 5 N. This parameter is derived from the need for the no discomfort. If the individual overexerts their muscles this causes pain. Therefore, actions should be taken to keep the actuation smooth and easy for the user.
- Force of Grip-
  - The hand must be able to grasp an item. This technical requirement stems from the customer need of functionality. If the prosthetic is not successful in grabbing an item then it is useless to the patient. The fingertips must be able to apply forces to close around and hold an object. The minimum force is 5 N. The figures must be able to support at least this weight and the arm must be able to handle of the torque caused by the weight and distance.
- Number of Parts-

- The number of parts should remain small in order to keep the cost and complexity of the design low. This allows it to be more customizable and fills the respective customer need. In order to keep the design simple and manipulatable, the number of parts should not exceed 100.

Table 2.3: List of technical requirements, target value, units, and overarching customer need

Technical Requirements	**Target value**	**Units**	**Overarching Customer Need**
Scalable Size	6-18	in	Scalable
Weight	1.72	lbs	Light weight
Budget	500	$	N/A
Material Properties	>1000	psi	Durable
Force to actuate	<5	N	No pain or discomfort or strain
Force of Grip	>5	N	Functionality
Number of Parts	<100	#	Customization

This table condenses the engineering requirements, their target values, units, and the customer need that it stemmed from. The table is a concise explanation of the technical requirements.

2.3 Testing Procedures

This section discusses the testing procedures for each of the engineering requirements. Each requirement is listed in the same order as above. These procedures will describe the methods to test scalability, weight, budget, material properties, for of actuation and grip, and number of part.

2.3.1 Scalable Size

To test the scalability more than one for arm will be printed. One arm will be printed using the client’s measurements the second arm will be printed using only the scale feature for the slicer. The second arm will be scaled to the smallest team members size and if the arm can still carry and function as designed then the arm can be considered scalable.

2.3.2 Weight

Once the arm is printed and assembled it can be weighed using a scale from the WIL lab. The client's functioning arm will be measures as well and either weighed using a scale or a calculated estimation. The weights will then be compared and if the printed arm is less than five percent above the weight of the functioning arm then it qualifies for the weight requirement.

2.3.3 Budget

The budget will be done using excel. After the arm is fully assembled, the cost of all parts will be added to an excel spreadsheet along with all identifiable information for each part and the supplier. Once all parts are tabulated the end cost will be calculated and if all parts both mechanical and electrical are below $1000 USD then the product meets the budget requirement.

2.3.4 Material Properties

The material properties must include strength, durability, and thermoformability. Strength will be tested using an impact load. This is done by releasing a mallet from a 90-degree angle that will swing into thin or joint features of a prototype arm. The impact force will be calculated by the weight of the hammer and gravity. The number of impacts before fracture will give an estimate of the durability and strength of the arm. As for thermoformability, this will be tested by applying a heat source to flat pieces of different plastics. If the plastics can be formed with temperatures no higher than 100 °C, then the materials meet the thermoformability requirement.

2.3.5 Force to actuate

Force of actuation can be tested by adding pressure sensors to the inside of the prototype cuff. When the device is being actuated, the force exerted by the client on the device will be measured by the pressure sensor. The force can then be calculated by dividing the pressure readout by the area of the pressure sensor. If the force is below 5 N then the device is within the requirement.

2.3.6 Force of Grip

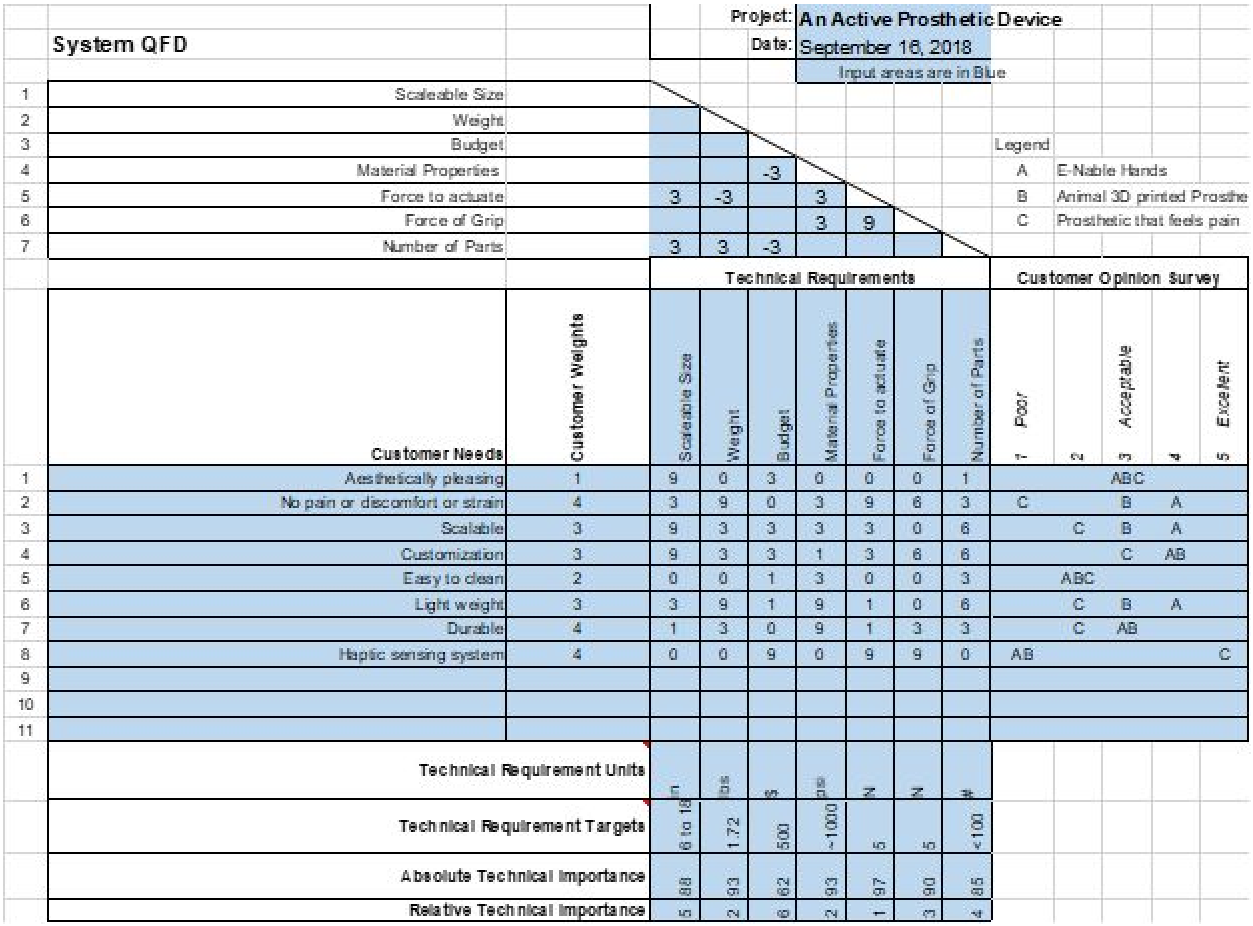
Similarly to the force of actuation, a pressure sensor will be place at the end of the fingertip between the thumb and first finger. The pressure will be divided by the area of the sensor and used to calculate the for exerted by the grip. If the force exceeds 5 N then the force of girp is within the requirement.

2.3.7 Number of Parts

When the final product is designed the number of parts will be counted using an excel sheet. If the number of parts does not exceed 100 pieces then the device is within requirements.

2.4 House of Quality (QFD)

The House of Quality (QFD) aided the team in computing the most important engineering/technical requirements. This is achieved by ranking the engineering requirements against themselves and the customer needs. The engineering requirements and customer needs are the same that were presented previously. The customer needs rank remains the same as do the target values for the technical requirements. This can be seen in the figure below. Within the QFD the engineering requirements are given rankings for how well they fulfill the requirements. The rank of each is weighted by the importance of the respective needs. This is summed and displays to the team which engineering requirement is most important when designing the prosthetic.



System QFD

Project: An Active Prosthetic Device
Date: September 16, 2018
Input areas are in Blue

		Scaleable Size	Weight	Budget	Material Properties	Force to actuate	Force of Grip
1	Scaleable Size						
2	Weight						
3	Budget						
4	Material Properties			-3			
5	Force to actuate	3	-3		3		
6	Force of Grip				3	9	
7	Number of Parts	3	3	-3			

Legend
A E-Nable Hands
B Animal 3D printed Prosthe
C Prosthetic that feels pain

			Technical Requirements							Customer Opinion Survey				
	Customer Needs	Customer Weights	Scaleable Size	Weight	Budget	Material Properties	Force to actuate	Force of Grip	Number of Parts	1 Poor	2	3 Acceptable	4	5 Excellent
1	Aesthetically pleasing	1	9	0	3	0	0	0	1			ABC		
2	No pain or discomfort or strain	4	3	9	0	3	9	6	3	C		B	A	
3	Scalable	3	9	3	3	3	3	0	6		C	B	A	
4	Customization	3	9	3	3	1	3	6	6			C	AB	
5	Easy to clean	2	0	0	1	3	0	0	3		ABC			
6	Light weight	3	3	9	1	9	1	0	6		C	B	A	
7	Durable	4	1	3	0	9	1	3	3		C	AB		
8	Haptic sensing system	4	0	0	9	0	9	9	0	AB				C
9														
10														
11														
	Technical Requirement Units		in	lbs	$	psi	N	N	#					
	Technical Requirement Targets		6 to 18	1.72	500	~1000	5	5	<100					
	Absolute Technical Importance		88	93	62	93	97	90	85					
	Relative Technical Importance		5	2	6	2	1	3	4					

Figure 2.1: QFD displaying the comparison of customer and engineering requirements.

Figure 2.1 shows the QFD. This QFD was successful in computing and ranking the most important technical requirements relative to the customer needs. According to the calculations, the most important engineering requirement is the force to actuate. As stated in the engineering requirement section, the force to actuate is important because the patient should not strain their muscles to move the prosthetic. Therefore, the team will make the ease of motion a priority. During design generation, devices should include ways to decrease the force needed to move the arm. Similarly, during concept selection the final design chosen should be actuated using the target force, 5N. The other main engineering requirements to consider during concept generation and selection are weight and material properties.

The engineering requirements are also plotted against themselves. Most requirements have positive or no correlation with the others. However, some requirements contradict one another. Thus, the team must decide which requirement is more important and compromise or forego the other. An example of this is budget vs material strength and number of parts. Since the material strength in highly ranked and important, the budget may need to be altered to accommodate the best materials. It is better to have a higher cost and quality prosthetic than a prosthetic that is non-functional. This will be important during concept design and selection.

By defining the customer needs the team was successful in derving engineering requirements. These were analysed using the QFD to rank the most important requirements.

3 EXISTING DESIGNS

In order to begin the concept generation in the design process, existing designs needed to be evaluated and compared in order to determine characteristics that are important in order to meet customer requirements. This section contains details of the benchmarking research process, system level benchmarks, subsystem level benchmarks, and flow charts of problem decomposition which were used to determine necessary components while researching quality benchmarks. The system level existing designs relate directly to below elbow prosthetics, while the subsystem existing designs relate to aspects or characteristics the prosthetic will need to contain.

3.1 Design Research

To start researching existing designs, the team looked at volunteer chapters of Enable [1] in order to consider the current design that is easily printed for anyone. While researching benchmarking, the team was looking for qualities that met the customer requirements. The specific characteristics used as reference were means of secure attachments, mechanisms for motion, and types of feedback sensing to the user. These characteristics are most important to our final design because the active prosthetic needs to be able to grip onto things in order to be usable, the user needs to be able to control the motion of the arm in an easy and logical manner, and the prosthetic needs to be active so that the user can feel a sense of touch or motion.

When benchmarking, the team conducted web searches of prosthetics for below elbow amputees that had the specific characteristics the team was looking for. This was done through web searches and meetings with the client in order to gain recommendations on areas of research. One of the criteria important when evaluating quality benchmarks were estimating the cost of production as well as the market cost of the design. Part of this project is to design an active prosthetic that is affordable and makeable for almost anyone, anywhere in the world. Thus, the team would evaluate the cost of the benchmark. The team also would evaluate the mechanism for motion; whether the prosthetic was actively controlled by a motor or controlled by motion. Finally, the team made sure to research existing active prosthetics in order to determine probable sensors to use and how the feedback would reach the user.

3.2 System Level

This section discusses organizations and their products that relate to affordable prostheses. The organizations selected are e-NABLE, Open Bionics, and Limbitless Solutions. Organizations were selected instead of individual products, because each of these institutions specialize in making unique prosthetic hands and arms, and all of the products meet at least one or more of the customer requirements.

3.2.1 e-NABLE: "Enabling the Future [1]"

e-NABLE is a world-wide community of volunteers that design, fabricate, and assemble 3D printed prosthesis [1]. This description is important because it shows that e-NABLE's designs meet five of the customer needs. First, it states that the arms are 3D printed, which meets one of the customer requirements. Since the group is volunteers from around the world, it can be assumed that these arms are easy to build, affordable, scalable, and customizable. This is insinuated because volunteering means that no one is being paid for their time and that resources are likely donated or out of pocket. Also, volunteers do not always share the same skills, therefore these design must be easy to build. The designs are given to both children and adults so they must be scalable. Finally, since this is a worldwide community, the designs must be customizable to fit with different sizes, interests, and cultures. All of these traits are displayed in **Figure 3.1.**

Figure 3.1: Volunteer scouts assembling unique e-NABLE hands [1].

There are some customer requirements not met by these designs. These designs are mechanically actuated by the elbow but the customer requires active actuation. In addition, there is no haptic feedback for object sensing, which is another customer requirement [1]. The hand systems designed by e-NABLE meet many but not all customer requirements. Therefore, they are a good example for benchmarking.

3.2.2 Open Bionics: "Turning Disabilities into Superpowers [2]"

Open Bionics' prostheses are 3D printed and use active actuation. Each arm is uniquely made for the recipient, and the company uses shells over the prosthesis to create aesthetically pleasing arms. In **figure 3.2**, the bionic arm is shown with an intricate pattern designed by the company called the Handala cover. The colors for this cover can be changed and there arm more covers available by request.

Figure 3.2: Bionic arm with Handala cover [2].

The Bionic arms meets three of the customer requirements and one customer need. The requirements are to be 3D printed, actively actuated, and customizable. The customer need that is satisfied is aesthetically pleasing. However, the arms do not give any indication that they are scalable or if each arm must be redesigned for the recipient. The arms are significantly cheaper than average prostheses but still cost about £5000 or $6523 USD and the covers cost more than a typical e-NABLE hand at £400 or $522 USD [2]. These prices continue to make the arm unaffordable to low income clients.

3.2.3 Limbitless Solutions: "Creating Hope with 3D Printed Limbs [3]"

Limbitless Solutions is much like e-NABLE. They have volunteers around the world that create custom arms at no cost to the recipient [3]. These arm meet the same five customer requirements as e-NABLE but they are also actively controlled. **Figure 3.3** shows three customized designs from Limbitless Solutions.

Figure 3.3: Arms provided by Limbitless solutions [3].

While this organization's hands appear to meet the majority of the customer requirements, they do not meet one of the most important requirements of including haptic feedback. The goal of this project is to not only meet but exceed these benchmarks and give the recipient a sense of touch.

3.3 Functional Decomposition

The functional decomposition of the prosthetic hand begins with a black box model. The model focuses on the inputs and outputs that lead to the hand closing and gripping an item. The hand grasping an item is the main function of the prosthetic. After these inflows and outflows are determined, the process diagrams for specific flow are detailed. This breaks down the action of gripping objects into subsystems. These subsystems are customized hardware and software, electronic control, arm actuation, and sensing touch. The process diagram includes details on how the flows changed at each step to perform the action of grabbing. These models and diagrams show the team that in order for the prosthetic to be successful, every change in the flow must be considered for energy, materials, and signals.

3.3.1 Black Box Model

The Black Box Model is important because it displays the required material, energy, and signals needed to perform a task. This is the most important customer need. The main task that the prosthetic hand executes is to close the hand and grip items. The Black Box Model also presents the outputs of material, energy, and signals from the action. This model is advantageous because it simplifies the customer needs to the inputs and outputs. The figure below shows the Black Box Model that aided in the decomposition of the prosthetic hand. It displays the inputs and outputs necessary for closing the prosthetic and gripping and item.

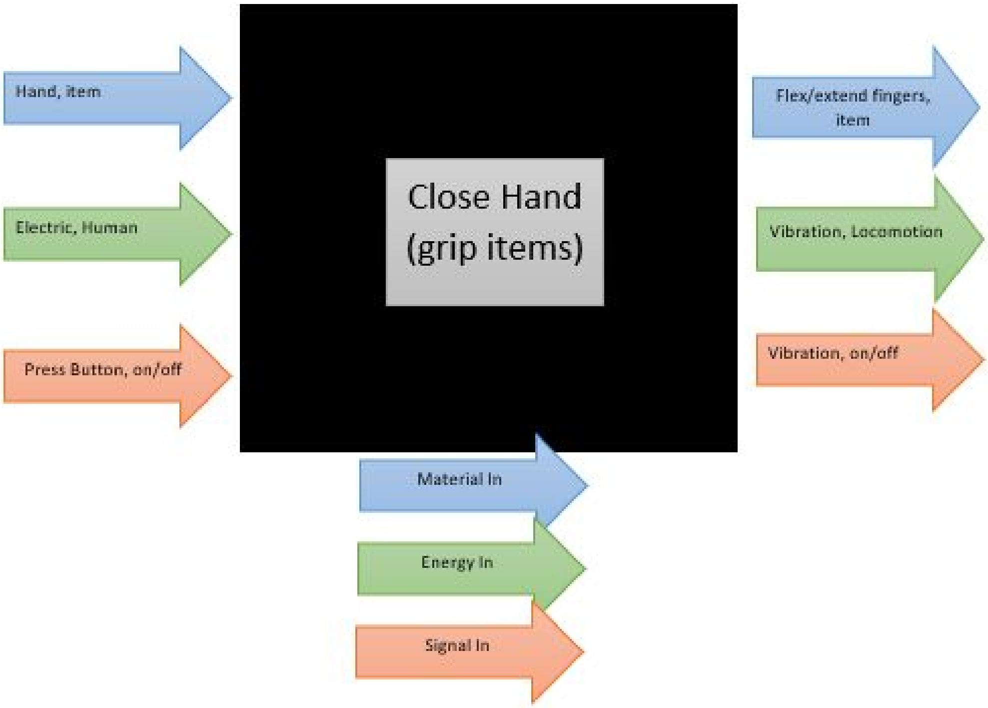


Figure 3.4: Black Box Model

The material inputs to grip items include the hand and an item. The hand is required to turn on and activate any switches. The item is needed because it will be gripped when the hand closes. These inputs and the other inputs can be viewed in the figure above. The energy input includes the electric and human energy. The electricity will supply energy to the motor to actuate the arm and the motors that vibrate the sensors. The signals that are sent in are pressing buttons and viewing on/off switches. Pressing the button will send a message to the motors and the hand will move. The on/off indicates whether the motors are on or off. Knowing the required inputs helps the team because it provides a basic understanding of what will needed in the conceptual and final designs.

The outputs of the Black Box Model are flexed/extended figures, the item, vibration, locomotion, and on/off. The item remains a material throughout the process. The energy is changed from the inlet into vibration and locomotion. This means that the hand will change position and the figures are flexed or extended. The vibration also is an output signal because it vibrates against the human skin to notify the user of the action that has been performed. By knowing the outputs the team will be aware of how the hand should respond. The final design will include a vibration signal, locomotion, and electricity.

3.3.2 Work-Process Diagram

The Process Diagram is a useful tool that breaks down the flow between inputs and outputs of the system. Each of the flows performs a task that is needed for completing a customer need. Unlike the black box model, these diagrams show how the flows change in order to perform the task at hand. The subsystems that were analyzed are are customized hardware and software, electronic control, arm actuation, and sensing touch. The figures for each and explanations are available below. Each provides unique flows and demonstrates that the completion of the action is dependent on more than the materials, signals, and energies that enter and exit.

The first process diagram breaks down the process to customize the hardware. A customer requirement is that the device design must be replicable. This allows the user to create the device on their own without the need of a trained engineer to build it. In order to do this, the user is provided a CAD file that can be changed to the desired dimensions. The figure below shows the flow from computer signal to customized hardware.

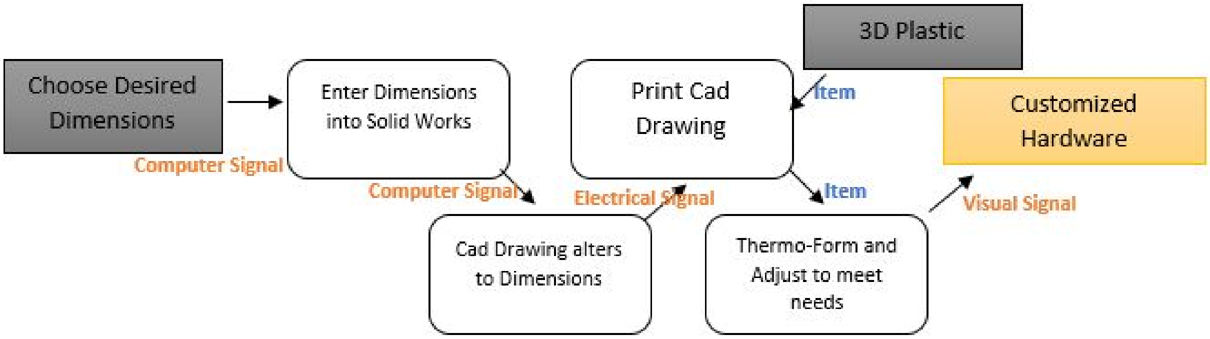


Figure 3.5: Process Diagram for Customized Hardware

The chosen dimensions are sent through a series of computer signals to electrical signals. The process also involves a 3D printer and the plastic to build the design. Thus, for the need to be met, the CAD files will need to be available and changeable. In addition, the 3D printer must have the proper signal and plastic that allows the hand to be printed and thermo-formed. The result is the visual signal that the hand is the appropriate size and shape. Each step of this process is important to consider when designing the active prosthetic.

The second subsystem is to give the hand a sense of touch. This process involves the passing of many signals. Below is the process diagram showing how the flow travels.

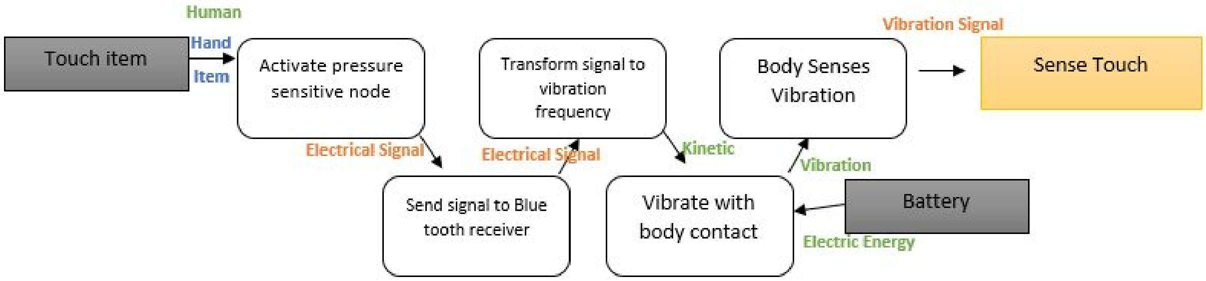


Figure 3.6: Process Diagram for Sense of Touch

This process begins with the prosthetic hand touching an object. At the fingertips, there are pressure sensors that send a bluetooth signal to the battery powered vibrators. The battery energy is changed to a vibration and kinetic energy. The vibration on the skin sends a signal to the nerves of the user. Thus, the hand stimulates the sense of touch. This process requires batteries, sensors, emitters, and receivers.

The next subsystem is to customize the software. The code is designed to perform different actions and grip types. The flow diagram can be viewed below in the figure.

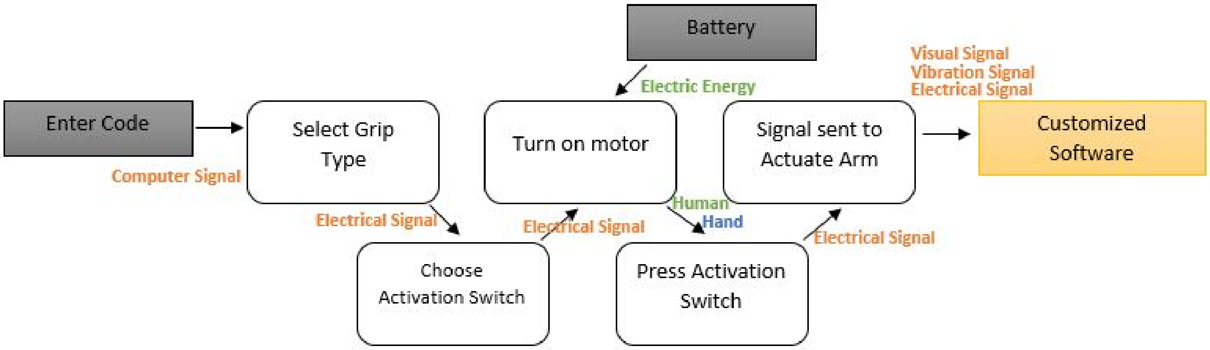


Figure 3.7: Process Diagram for Customized Software

This subsystem takes the coded signal and that signal is sent to a battery powered motor that actuates the arm. To complete the task, the team will need to include motors, batteries and switches. This is considered during concept selection and generation.

The electronic control is the fourth subsystem. The flow can be seen below.

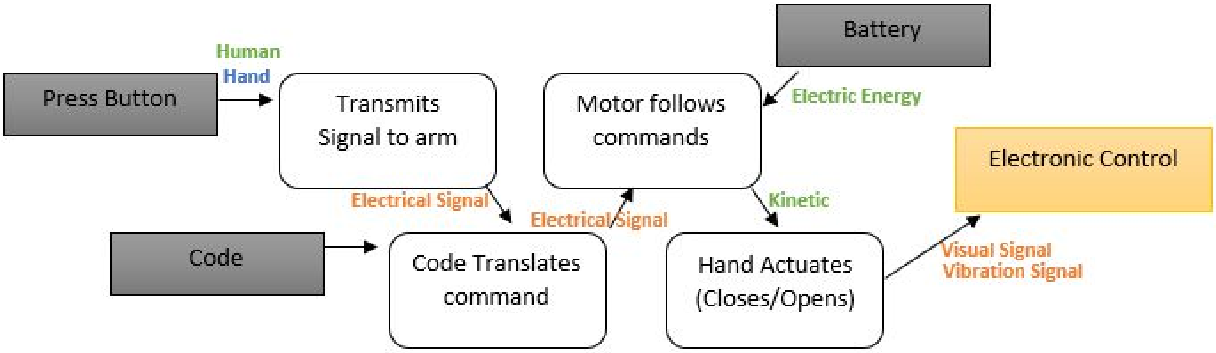


Figure 3.8: Process Diagram for Electronic Control

The electronic control requires code, button pressing and a battery as inputs. The button sends a signal to control the motor and actuate the hand. The energy from the battery become the motion of the arm. Therefore, a battery and code are needed to do the action.

The final subsystem is the arm actuation. This actuation can work separately or in tandem with the electronic control. The elbow bends and a series of kinetic energy transfers are sent through the arm and it is actuated. This can be seen below.

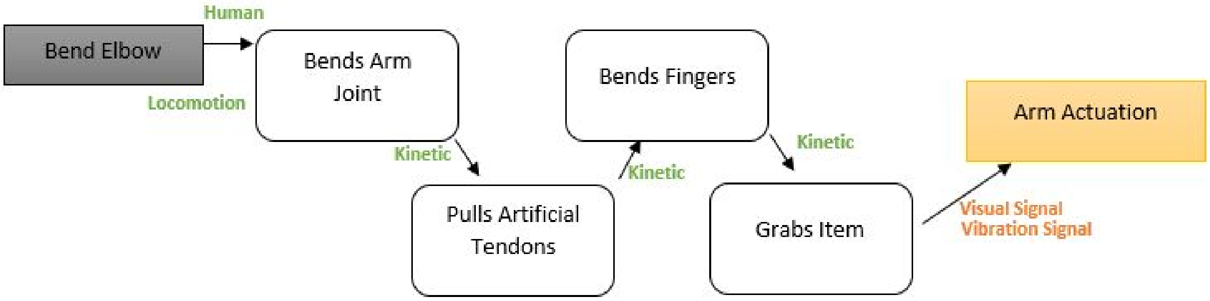


Figure 3.9: Process Diagram for Arm Actuation

This process diagram can be aided and linked to the electronic control because the electronic control also moves the arm and fingers. The electronic control will reduce the amount of work needed by the user. This is important to consider during the design of the arm.

The Process diagrams above aid the team by determining the many steps needed to complete a task. The needs will help determine if the design will fulfill the needs of the customer. For the prosthetic hand will be transmitters, receivers, batteries, motors, switches, codes, and adaptable solidworks drawings. All of these aspects will aid in creating a prosthetic hand that fulfills the needs of the user.

3.4 Subsystem Level

This section covers designs that could satisfy three different subsystems of the active prosthesis. These subsystems are haptic feedback, actuation for gripping, and attachment. Each of theses subsystems are important to the functionality of the design in order to meet the customer needs and requirements.

3.4.1 Haptic Feedback: Giving the User a Sense of Touch

Haptic Feedback is one of the most important subsystems because it is one of the main customer requirements. Different types of haptic feedback include tactile vibration, warming, and pressure. All of these types of user feedback can be shown or made similar to existing products.

3.4.1.1 Tactile Vibration: Cell Phone and Game Controller Vibration

Tactile vibration is used in everyday objects such as cell phones and video game controllers as a method of informing the user of some input [4]. This vibration can be used in the prosthetic design to notify the user that they are touching something. Vibrations could even intensify with increased grip as they are done in gaming controllers.

3.4.1.2 Warming: Electric and chemical Warmers and Gloves

Temperature feedback is not often addressed in prosthetics but could be implemented much like electric and chemical hand warmers. Since chemical warmers are for one time use, electric hand warmers may be more applicable to the prosthetic design [5]. This should be easier to implement in an active device since an energy source will already be needed. This energy source could cause a small heat pad to warm up with current when objects that are warmer are detected.

3.4.1.3 Pressure Sensing: Inflatable Pads

Inflatable pads such as blood pressure cuffs can be used to provide force feedback [6]. The tighter the grip on an object the tighter the pressure cuff can inflate. This could allow the user to pick up more delicate or heavier objects by informing them of the strength of their grip.

3.4.2 Actuation: Gripping Objects

Actuation is a necessity to any semi-function prosthesis. There are many solutions to actuation but they are often hard to implement into the device and usually cause the device to be more expensive and heavier. The listed solutions here are elbow actuation, motor actuation, and pressure actuation. Actuation in this subsystem is defined as what makes the prosthetic grip and not what starts or controls the gripping process. This subsystem is a key component to the functionality of the active prosthesis.

3.4.2.1 Elbow: Mechanical Actuation

Some bench marked designs mentioned previously use mechanical actuation from the elbow to grip objects. This forces the user to bend their elbow in order to actuate the device and can be uncomfortable and difficult to position the hand to grip an object. Though this in not an ideal actuation and does not satisfy the active prosthesis requirement, it is an important solution to making prostheses more affordable and lightweight. This actuation could still be used in parallel to another form of actuation that could result in a better gipping force while keeping the assisted actuation lightweight and inexpensive.

3.4.2.2 Motor: Electrical Actuation

Motor actuation would satisfy the need for the prosthetic to be active. This would increase the weight of the prostheses but is commonly used in myoelectric prostheses such as the bionic arms. This also increases the cost, however can be made affordable with gear systems and mechanical leverage.

3.4.2.3 Pressure: Pneumatic or Fluid Actuation

Increasing and decreasing pressure through a series of tubes can also be used for actuation. This is shown in productions that use pneumatic pistons or fluids to mechanically control and actuate different parts of a machine. Using hydraulics as a form of actuation could weight but may lower the cost of the system.

3.4.3 Attachment: Securing the Device to the User

Attachment of the device is another necessary component to a functional device. If the device does not properly attach then it cannot be used by the recipient for its intended purpose; being a prosthetics arm.

3.4.3.1 Cuff: Device Formed to Wrap Around User

Nearly all of the benchmarked designs use a cuff to engage the users arm. Though these cuffs often have additional properties that assist with securing the device, the cuff continues to be the most practical form of attachment. Cuffs allow the users arm to held in the device and add to the appearance that it is an extension of the arm and not a separate object.

3.4.3.2 Hook and Loop: Using Hook and Loop to Secure Attachment

The benchmarked system e-NABLE uses hook and loop attachment to secure their cuffs to the arm. Hook and loop makes the arm easy to attach and detach using one hand as needed. It also allows for adjustability for comfort and alignment to the arm. Hook and loop is a relatively inexpensive method for attachment.

3.4.3.3 Strings: Securing with Ties or Laces

Much like the laces of a shoe, strings allow the attachment to be adjusted and secured over an area of the appendage. This could be very comfortable as it can be tightened and loosened where needed and is also very inexpensive and easily replaced. However, strings would be very difficult for the user to adjust and attach on their own. It could also wear or cut off circulation to certain areas of the arm if not attached properly, which is why it is important the user be able to adjust their attachment on their own.

4 DESIGNS CONSIDERED

After researching existing designs, the team generated concepts by setting a deadline and having each member generate five concepts. This method was chosen due to each team member having unique ideas they wanted to contribute to the generation process, and the alternative methods limited the individual abilities of the team members to include these ideas. It was more beneficial for each member to come up with five ideas, and then meet as a team and evaluate and discuss the ideas. If there were aspects of different concepts that work well together, the team combined those characteristics or discussed the ability to combine them into a singular design.

4.1 Design 1: Adaptation

This design is similar to one of the existing designs because the arm is made up of connecting 3D printed parts, and wire or string is threaded on the back of the arm and through the elbow attachment. The threading imitates tendons and allows for the fingers to close when the wearer moved the remainder of their elbow. Changes to the existing design include a motor attachment at the elbow to help control the movement of the threaded wire, as well as sensors at the fingertips and feedback at the elbow. Advantages of this design include scalability of the design for different sized users as well as easy assembly of parts, but disadvantages include the weight of the prosthetic being too taxing on the user.

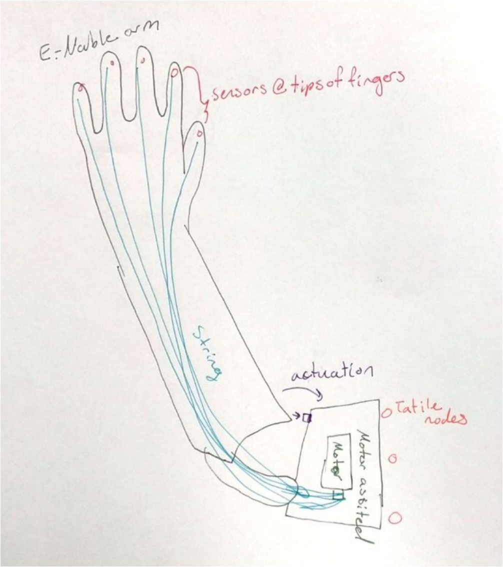


Figure 4.1: Adaptation Arm

4.2 Design 2: Customizable Skeleton

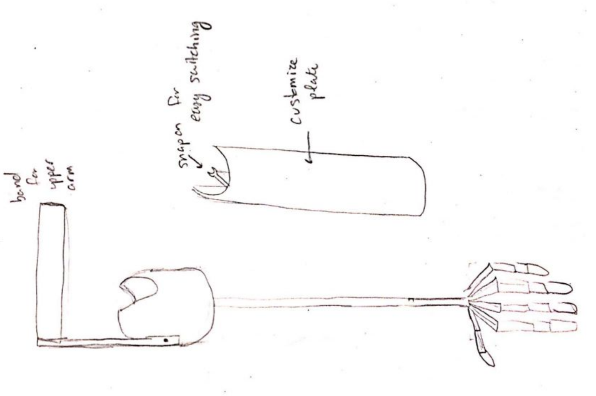


Figure 4.2: Customizable Skeleton Arm

This design uses a cup and upper arm band for attachment to the amputee, and the arm is a thin skeleton with skeletal fingers. Wires for the sensors at the fingertip travel up within the tube of the forearm. The forearm is thin like a skeleton to allow for customization, for different curved coverings can be 3D printed and clipped on to the arm. This arm allows for comfortable support and customizability with its design, but lacks mechanical motion. Advantages of this design are the customizability and the containment of the sensors and wires. Disadvantages are the grip strength due to not having a palm of the hand, and the motor control.

4.3 Design 3: Capt’n Crabby

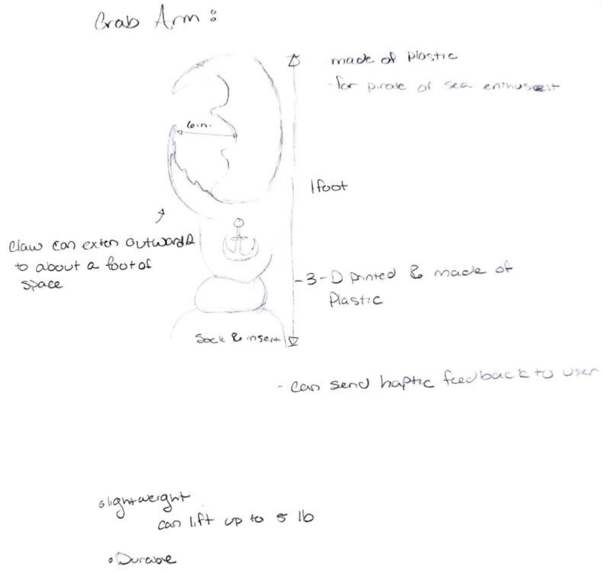


Figure 4.3: Crab Arm

This design is modeled after a crab claw. The 3D printed active prosthetics will be marketed as a toy, meaning the aesthetic can range from humanoid to fun. As the user moved their elbow, the claw would open and close accordingly. This design is intended for a younger recipient due to the crab claw appearance, but can give the wearer a unique prosthetic and fun outlook on their condition. Advantages of this design are the aesthetic and customizability, but disadvantages include the lack of sensors and weight of the design.

4.4 Design #4: Drawstring Tendons

Figure 4.4: Drawstring Tendons Arm

The Drawstring Tendons Arm design utilizes strings/wires that will pull the fingers closed. This is similar to how tendons are pulled to move fingers in the human body. Thus, the name for this design is derived. The design also includes a frame that is lightweight and minimalistic. This is advantageous because it will be easier for the user to lift the arm. However, it losses durability due to this. The prosthetic is attached to the are with a velcro strap. It will wrap around the residual limb and is adjustable to the proper size of the arm.

4.5 Design 5: Faux Flesh

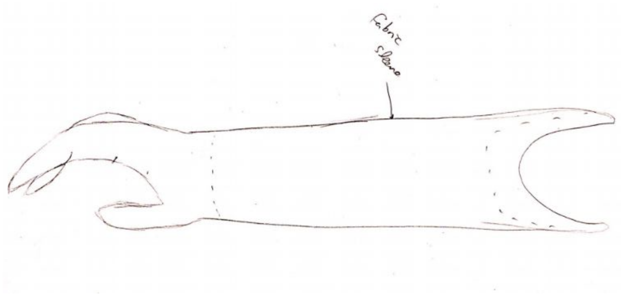


Figure 4.5: Fabric Sleeve over Skeleton Arm

The Faux Flesh is a sleeve made out of a material that was to be determined, but the material would be sewn in the form of a forearm and hand. This glove would then be slipped over a skeleton of a prosthetic arm, which would be similar to the Customizable Skeleton base design. The material sleeve is advantageous because it would improve the grip while also making the arm look more realistic, and should be easy to clean because the sleeve could be removed for washing, but disadvantages include ease of assembly and durability.

4.6 Design 6: Foot Control

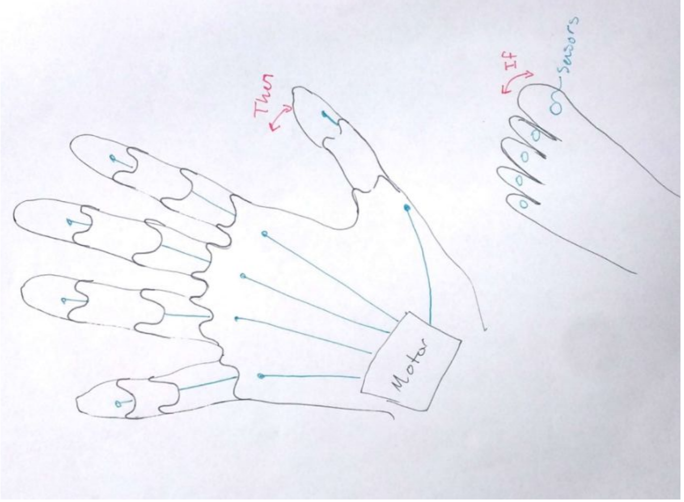


Figure 4.6: Foot Controlled Sensors

The idea behind this design was for the motion control of the fingers to be controlled by sensors on the foot. When the user clinches his/her toes, the fingers on the prosthetic will also clinch. The physical design of the prosthetic will be similar to the Adaptation arm, with the main modification being the actuation provided by movement of the toes. Advantages of this design include more control over movement as well as ease of assembly, but disadvantages are in the reliability of the sensors on the foot.

4.7 Design 7: Shape Memory

Shown in Figure 1 of Appendix B, the Shape Memory hand has a nitinol skeleton. Nitinol has shape memory and returns to its original shape when heated. Thus, it gets its name from this feature. The design also has a glove like covering that makes it more aesthetically pleasing. The hand is attached to the residual limb with a strap. The disadvantage of this design is that fingers do not open without assistance. It would not be easily controlled by the user due to the necessity of temperature difference to get the wire to move.

4.8 Design 8: Cool Hand Squid Man

Shown in Figure 2 of Appendix B, Cool Hand Squid Man is modeled after the tentacle of a squid. This design is a long arm of varying diameters that takes the shape of a tentacle, and it has suckers on the end to improve grip. It also has sensors along the inside of the arm to grab objects of varying sizes. This design's sensing capabilities allow the arm to automatically close when a receiver picks up the shape or weight of an object within range. Advantages of this design include the aesthetic and the grip, but disadvantages include the motor control.

4.9 Design 9: Clip-o-Grip

Shown in Figure 3 of Appendix B, the Clip-o-Grip is an arm made of several components that could be clipped together to form the full functioning prosthetic. The battery for the sensors and motors would be stored on the back of the hand of the prosthetic, and each finger would have a sensor. Advantages of this design include customizability, but disadvantages include ease of assembly and reliability of the sensors.

4.10 Design 10: Vine Grab

Shown in Figure 4 of Appendix B, the Vine Grab is an arm made up of five tubes full of pressurized fluid. As the fluid pressure changes with the motion of the arm, the five vines move in order to grasp things around it. Each vine also has sensors located at designated areas. The advantages of this design include the grip strength and sensor reliability, but disadvantages include the active control and probability of creating a functioning model.

The remaining ten designs generated are shown in Figures 5-14 of Appendix B.

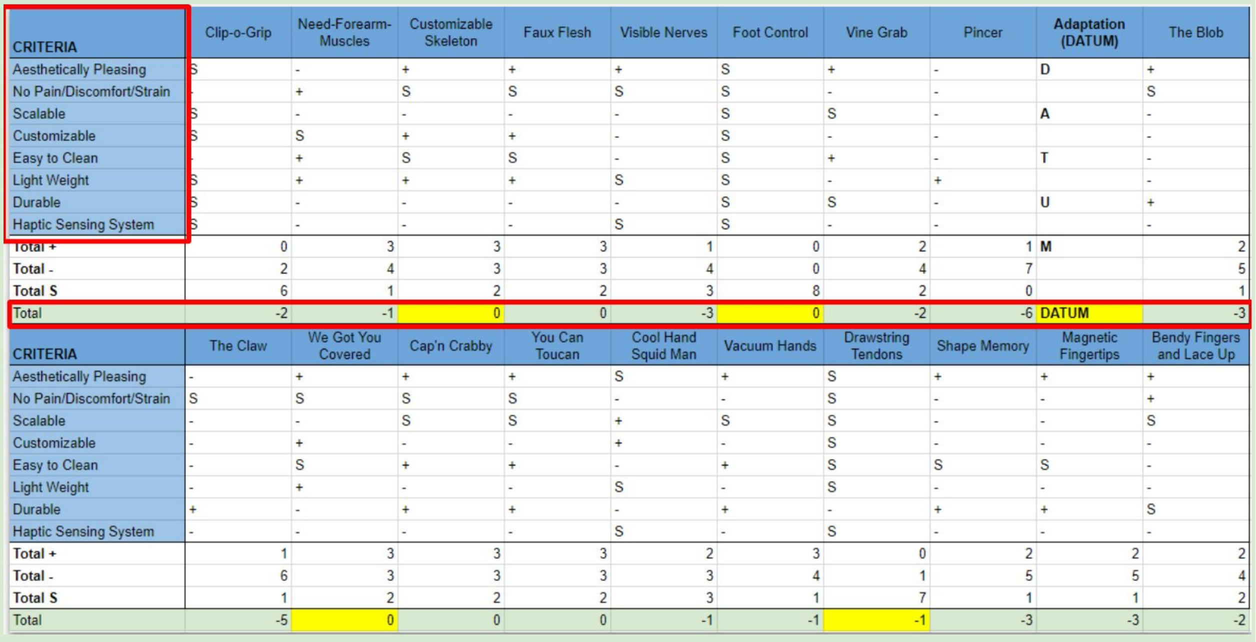
5 DESIGN SELECTED

After the designs were created, they had to go through a series of evaluations to determine which design is the most useful, durable, and aesthetically pleasing design. The design chosen would be able to provide haptic feedback and sense touch for the user. In order to determine which design met or even exceeded the need and requirements, all 20 designs would be evaluated using a Pugh chart and the final 5 using a Decision Matrix.Once this was completed, the final design was chosen. This section includes the selection and justification of the final design.

5.1 Rationale for Design Selection

The requirements for the active prosthetic device were for it to provide haptic feedback and sensing capabilities as well as be scalable and customizable for multiple users. It would also need to be comfortable, secure, and easy to build for the user. No design met all of the criteria but several were advantageous in different fields. Based on the criteria, all designs could be narrowed to one final selection. After the evaluations were completed, the final design was chosen to be the Foot Controlled design. This is mainly due to its advantages of control, customization, and haptic sensing abilities, which were the most important requirements of this project. The justifications can also be seen from the Pugh chart and the final Decision Matrix in Figure P1 and P2 respectively.

For the first part of the design selection, all 20 designs were placed into a Pugh chart. The designs were weighted against the following chosen criteria: Aesthetically pleasing, no discomfort, scalable, customization, easy to clean, lightweight, durable, and haptic sensing ability. The adaptation model was chosen as the datum due to the fact that it was similar to an already working model and met all criteria of the project. Each design was judged on whether they were less than, met, or exceeded the ability of the datum for each criteria. Once all designs were evaluated, it was clear that the Foot Control met all requirements for the device compared to the datum, which gave the design a total of 0. This design along with the Customizable Skeleton, Datum, We Got You Covered, and the Drawstring Tendons were selected for further analysis in the Decision Matrix.

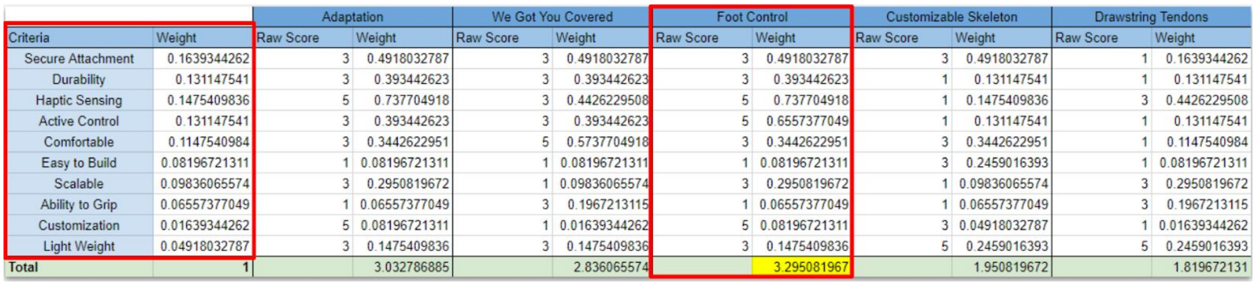


CRITERIA	Clip-o-Grip	Need-Forearm-Muscles	Customizable Skeleton	Faux Flesh	Visible Nerves	Foot Control	Vine Grab	Pincer	Adaptation (DATUM)	The Blob
Aesthetically Pleasing	S	-	+	+	+	S	+	-	D	+
No Pain/Discomfort/Strain	-	+	S	S	S	S	-	-		S
Scalable	S	-	-	-	-	S	S	-	A	-
Customizable	S	S	+	+	-	S	-	-		-
Easy to Clean	-	+	S	S	-	S	+	-	T	-
Light Weight	S	+	+	+	S	S	-	+		-
Durable	S	-	-	-	-	S	S	-	U	+
Haptic Sensing System	S	-	-	-	S	S	-	-		-
Total +	0	3	3	3	1	0	2	1	M	2
Total -	2	4	3	3	4	0	4	7		5
Total S	6	1	2	2	3	8	2	0		1
Total	-2	-1	0	0	-3	0	-2	-6	DATUM	-3

CRITERIA	The Claw	We Got You Covered	Cap'n Crabby	You Can Toucan	Cool Hand Squid Man	Vacuum Hands	Drawstring Tendons	Shape Memory	Magnetic Fingertips	Bendy Fingers and Lace Up
Aesthetically Pleasing	-	+	+	+	S	+	S	+	+	+
No Pain/Discomfort/Strain	S	S	S	S	-	-	S	-	-	+
Scalable	-	-	S	S	+	S	S	-	-	S
Customizable	-	+	-	-	+	-	S	-	-	-
Easy to Clean	-	S	+	+	-	+	S	S	S	-
Light Weight	-	+	-	-	S	-	S	-	-	-
Durable	+	-	+	+	-	+	-	+	+	S
Haptic Sensing System	-	-	-	-	S	-	S	-	-	-
Total +	1	3	3	3	2	3	0	2	2	2
Total -	6	3	3	3	3	4	1	5	5	4
Total S	1	2	2	2	3	1	7	1	1	2
Total	-5	0	0	0	-1	-1	-1	-3	-3	-2

Figure 5.1.1: Pugh Chart

The Decision matrix gave the ability to weigh certain criteria to determine the best design of the final 5. Part of the previous criteria were weighted along with new additional properties such as being easy to build, actively controlled, and having a secure attachment. Once these additional criteria were added and weighed on its importance, it is clear why the Foot Controlled option was selected.



		Adaptation		We Got You Covered		Foot Control		Customizable Skeleton		Drawstring Tendons	
Criteria	Weight	Raw Score	Weight	Raw Score	Weight	Raw Score	Weight	Raw Score	Weight	Raw Score	Weight
Secure Attachment	0.1639344262	3	0.4918032787	3	0.4918032787	3	0.4918032787	3	0.4918032787	1	0.1639344262
Durability	0.131147541	3	0.393442623	3	0.393442623	3	0.393442623	1	0.131147541	1	0.131147541
Haptic Sensing	0.1475409836	5	0.737704918	3	0.4426229508	5	0.737704918	1	0.1475409836	3	0.4426229508
Active Control	0.131147541	3	0.393442623	3	0.393442623	5	0.6557377049	1	0.131147541	1	0.131147541
Comfortable	0.1147540984	3	0.3442622951	5	0.5737704918	3	0.3442622951	3	0.3442622951	1	0.1147540984
Easy to Build	0.08196721311	1	0.08196721311	1	0.08196721311	1	0.08196721311	3	0.2459016393	1	0.08196721311
Scalable	0.09836065574	3	0.2950819672	1	0.09836065574	3	0.2950819672	1	0.09836065574	3	0.2950819672
Ability to Grip	0.06557377049	1	0.06557377049	3	0.1967213115	1	0.06557377049	1	0.06557377049	3	0.1967213115
Customization	0.01639344262	5	0.08196721311	1	0.01639344262	5	0.08196721311	3	0.04918032787	1	0.01639344262
Light Weight	0.04918032787	3	0.1475409836	3	0.1475409836	3	0.1475409836	5	0.2459016393	5	0.2459016393
Total	1		3.032786885		2.836065574		3.295081967		1.950819672		1.819672131

Figure 5.1.2: Decision Matrix

The Foot Controlled design met all previously mentioned requirements, but it was advantageous in that its haptic feedback and customization were better than most other designs. The design even surpassed the adaptation model because it provides more control for the user. This design still has disadvantages by being more difficult to build and having a weaker grip ability. Some possible fixes to this could be to add better gripping material or to simplify the design. These disadvantages will likely improve as the design is created and adjusted for ultimate customer satisfaction.

5.2 Design Description

Before prototyping of the arm can begin, analytical analyses had to be done in order to mathematically determine what the arm needs to withstand in order to meet customer needs and how to to design it. There were a variety of different aspects and parameters to consider in order to have a well working and consistent design. Each parameter and physical barriers of the design will be tested using experimental procedures, code prototypes and consistent calculations.

5.2.1 Percent Infill Analysis

When it came to determining the most efficient and durable way to manufacture the prosthetic arm, the percent infill of material needed to be evaluated. By examining the percent infill, the durability of the arm can be maximized. In order to pick an optimum percent infill, the volume of a segment of 3D printed material with varying percent infills will be used to calculate the weight the segment can withstand under yield strength. The weight will be compared to the yield strength to visualize a fracture point. This process will be repeated with different percent infills to determine the one that lasts the longest before fracture. This analysis is important in order to help reduce funding by lowering the mass of the 3D printed part, as well as ensure the arm is lightweight and durable.

The modulus of elasticity (E) and the density (ρ) of PLA were researched in order to begin the analysis [7]. The found modulus was 3.5 GPa and the found density was 1.3 g/cm^3. The force was set at 22.2 N because the hand needs to withstand a minimum of 5 pounds. The cross sectional area was estimated to be 45.6 cm^2, and this value can be manipulated depending on the diameter of the arm being manufactured. Using equation 1, the stress was calculated using these inputs.

$$\sigma = \frac{F}{A} \tag{1}$$

Using the calculated stress of 4868.4 Pa and the found modulus of elasticity reduced to Pascals, equation 2 was used to calculate the strain which was found to be 1.3909e-6. .

$$\sigma = E\varepsilon \tag{2}$$

The dimensions of the tested segment were set using a thickness of 1.2 mm, which is standard for the nozzle used for 3D printing. Figure 5.2.1 shows a diagram of the rectangular segment and the dimensions used. The percent infill (p_{infill}) varied between 0.05 and 1 in increments of 0.5. In this section, the steps will be shown for a percent infill of 0.15. Using this value and the dimensions, the volume calculated using equation 3 was 167.143 cm^3. These dimensions were picked because the cross sectional area of the rectangular section was approximate to the resulting circular cross sectional area. A rectangular shape could be assumed for these calculations because if a differential section of the curved surface of the arm was taken, the differential would also be rectangular.

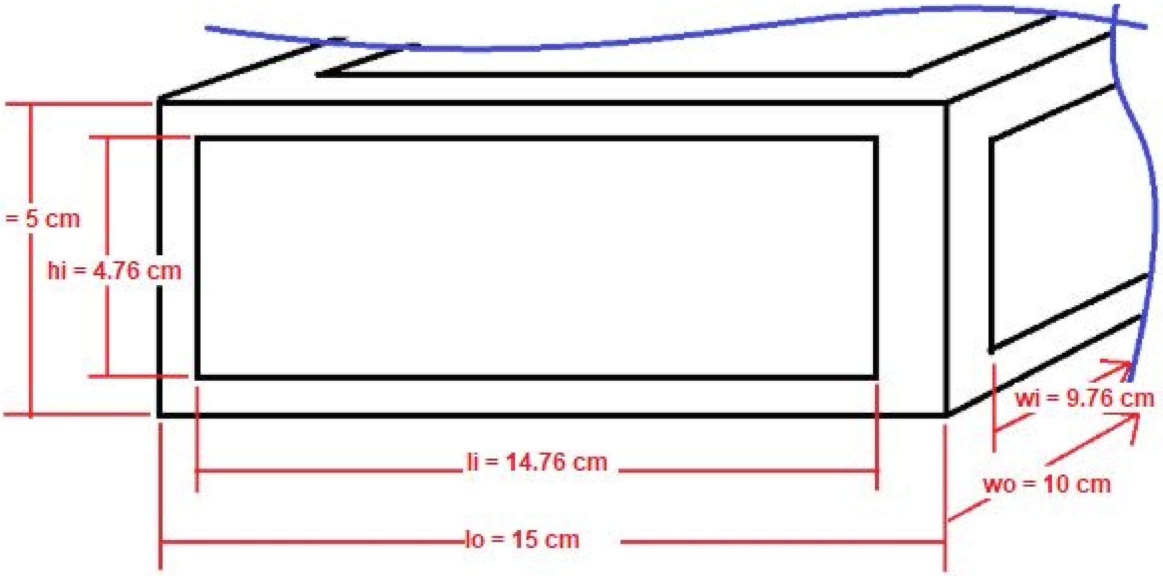


Figure 5.2.1: *Segment Schematic*

$$V = l_o w_o h_o - l_i w_i h_i (1 - p_{infill}) \tag{3}$$

Taking this volume and the calculated density, the mass is found using equation 4. This mass was 217.285 grams.

$$m = V\rho \tag{4}$$

Using mass and the gravitational constant, the weight was found to be 212940.1 gcm/s^2 or 0.021294 N using equation 5.

$$W = mg \tag{5}$$

Using equation 6 to calculate the yield strength at 0.2% offset from the original stress-strain graph, the resulting yield is 9.7363 N/m^2

$$\sigma_y = 0.002\varepsilon E \tag{6}$$

The weight was then compared to the yield strength times the area in order to make the units equal to each other, shown in equation 7.

$$W = \sigma_y A \tag{7}$$

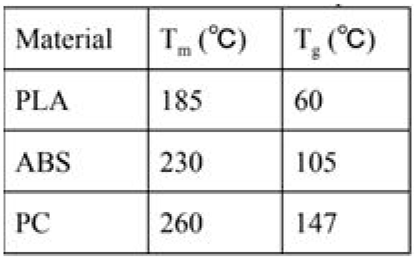
The resulting yield strength times area is 0.044 N. This means the weight needs to be less than 0.044 N in order to resist permanent deformation under stress. This process was repeated for the other percent infills. Once all percent infills were analyzed, it was determined that 40% infill would result in the most efficient arm design.

5.2.2 Material Thermoforming Ability

In order to make a durable, malleable, and well-functioning arm, there are a number of parameters to consider. One such aspect is the thermoforming ability of different 3-D materials. This aspect is important to consider because this 3D printed material will make up most of the base and cast of the arm. This cast will need to be able to hold all gears and sensors incorporated on the arm and be malleable enough to bend to the proper dimensions for the client. It is important to understand that the material must not be too hot to touch or too brittle else the casting will fail. Because this parameter is incredibly important, the analysis will need to be accurate.

To complete this analysis, hard data and calculations will need to be collected. The lab will mainly focus on deflection and how it relates to the temperature of the plastic. The Hypothesis is that the more flexible plastics will have a much larger deflection length. It is assumed that a high temperature will cause the deflection length to increase and that the closer the plastic reaches its glass temperature, the likelier the plastic will begin to deform. The glass temperatures for each material, PLA, ABS, and PC can be seen below.

Table 5.2.1: Glass Temperatures of the Different Materials



Material	T_m (°C)	T_g (°C)
PLA	185	60
ABS	230	105
PC	260	147

The test will incorporate the stress and strain of thermoforming ability. The following equation can be made when considering the thermal activation of the material.

$$\Delta L/L = a * \Delta T \tag{8}$$

Where (L) is length, (a) is the coefficient of thermal expansion, and (T) is the Temperature at Celsius. Heat flux may also be considered when testing the material and is displayed in equation (2).

$$q =- Ak\frac{dT}{dx} \tag{9}$$

Where (K) is the thermal conductivity, (A) is the cross-sectional area, (dt) is the change in temperature, and (dx) is the change in distance. Finally, the strain of the material must be considered by relating the force to Hooke’s law.

$$\sigma = F/A \tag{10}$$

$$\varepsilon E = \sigma \tag{11}$$

Where (F) is force, (A) is area, (σ) is stress, is strain, and (E) is the Young's Modulus. Once the temperature and deflection graph is created, an equation can be derived from the data. The equation can then be compared to the theoretical deflection of the plastic. This will determine if the materials will behave as expected and determine which plastic is more malleable.

Procedure:

This experiment will take the various temperatures and deflection of the three different potential materials: ABS, PLA, and PC. The factors of safety are .0073, .0126, and .0026 respectively. Each material was approximately 150 x 60 x 60 mm. The schematic of the area can be seen below.

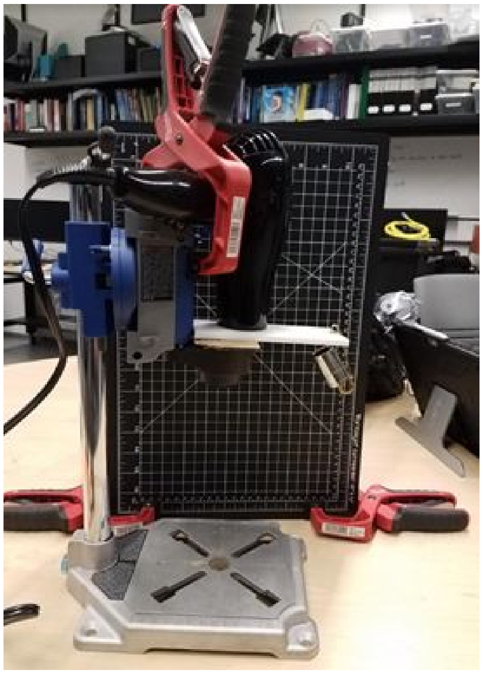


Figure 5.2.2: Schematic of lab

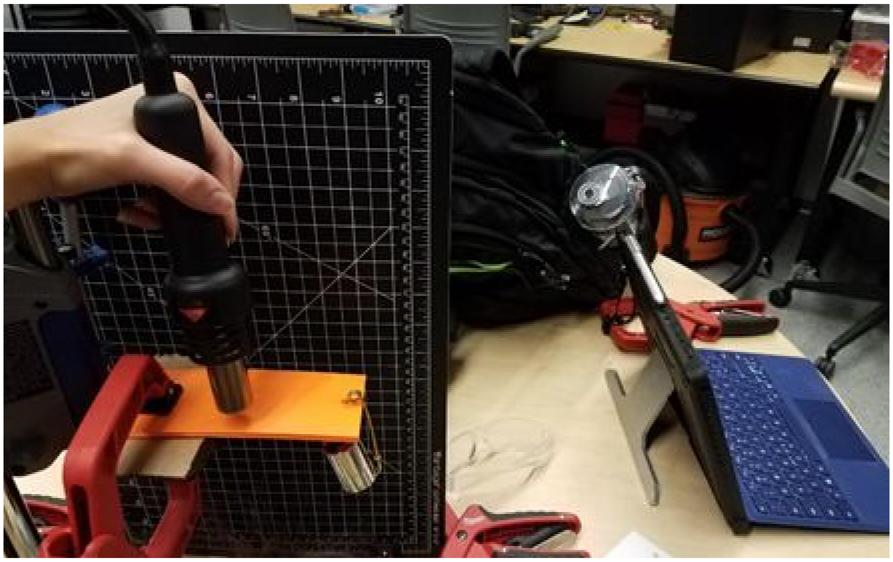
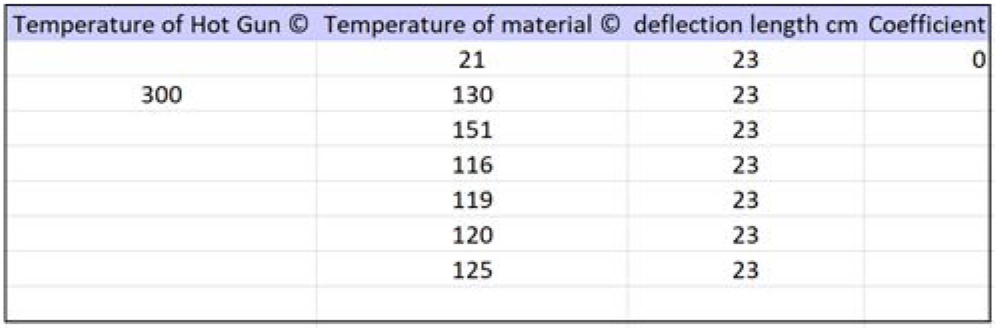


Figure 5.2.3: Visual of How the Heat Was Applied

The materials are to hang of the end of the dremel. A ruler board was placed behind the three plastics to accurately measure the length the plastic deforms in cm. A weight of 70g was hung off the end to ignore the weight of the plastic themselves. this allows for a controlled force for the stress analysis of the experiment. Because the critical temperatures of the three plastics were so high, a heat gun would need to be used to heat the material. Once the plastic was in place, the heat gun was turned to 300C. The nozzle could then be placed onto the plastic and the temperature was measured using a temperature gun.

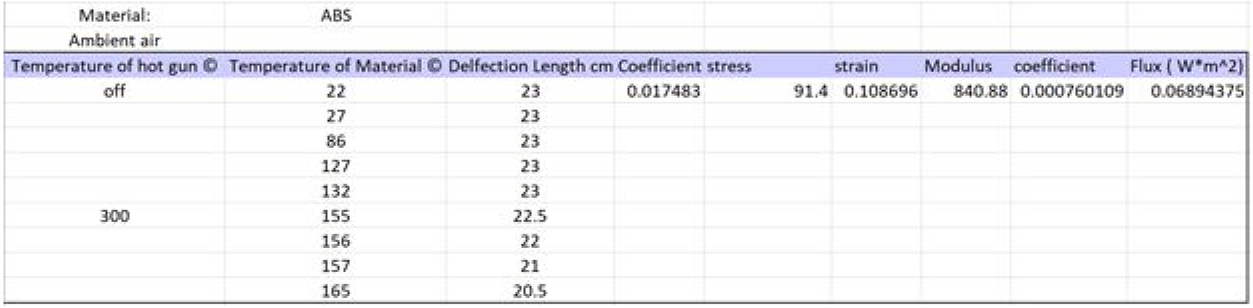
The raw data can be found below. One of the main requirements is to find a material that would be durable but also able to be made by anyone, instead of requiring special tools. PC immediately fails this test as it did not have any displacement and loss heat fairly quickly. It was therefore not necessary for further analysis. The two other materials were collected for the stress and strain analysis. Below are the data tables that correspond with the following graphs.

Table 5.2.2: Raw Data of PC



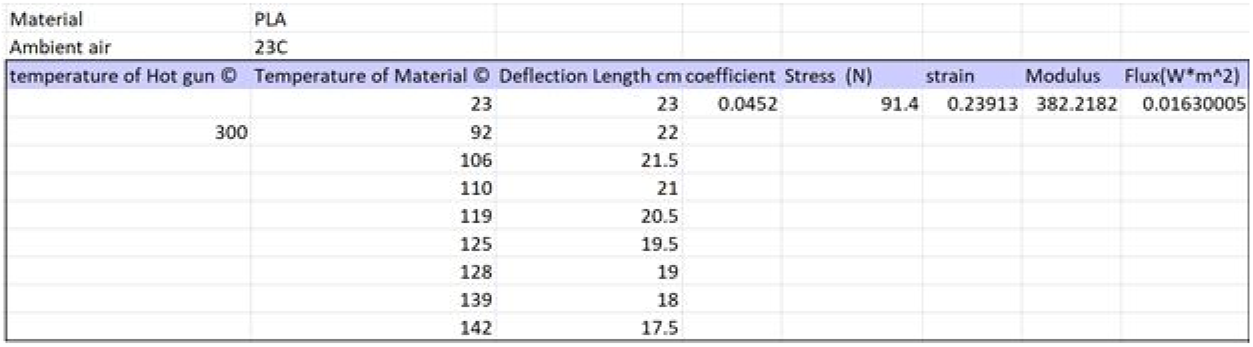
Temperature of Hot Gun ©	Temperature of material ©	deflection length cm	Coefficient
	21	23	0
300	130	23	
	151	23	
	116	23	
	119	23	
	120	23	
	125	23	

Table 5.2.3: Raw Data for ABS



Material:	ABS							
Ambient air								
Temperature of hot gun ©	Temperature of Material ©	Delfection Length cm	Coefficient	stress	strain	Modulus	coefficient	Flux (W*m^2)
off	22	23	0.017483	91.4	0.108696	840.88	0.000760109	0.06894375
	27	23						
	86	23						
	127	23						
	132	23						
300	155	22.5						
	156	22						
	157	21						
	165	20.5						

Table 5.2.4: Raw data for PLA



Material PLA

Ambient air 23C

temperature of Hot gun ©	Temperature of Material ©	Deflection Length cm	coefficient	Stress (N)	strain	Modulus	Flux(W*m^2)
	23	23	0.0452	91.4	0.23913	382.2182	0.01630005
300	92	22					
	106	21.5					
	110	21					
	119	20.5					
	125	19.5					
	128	19					
	139	18					
	142	17.5					

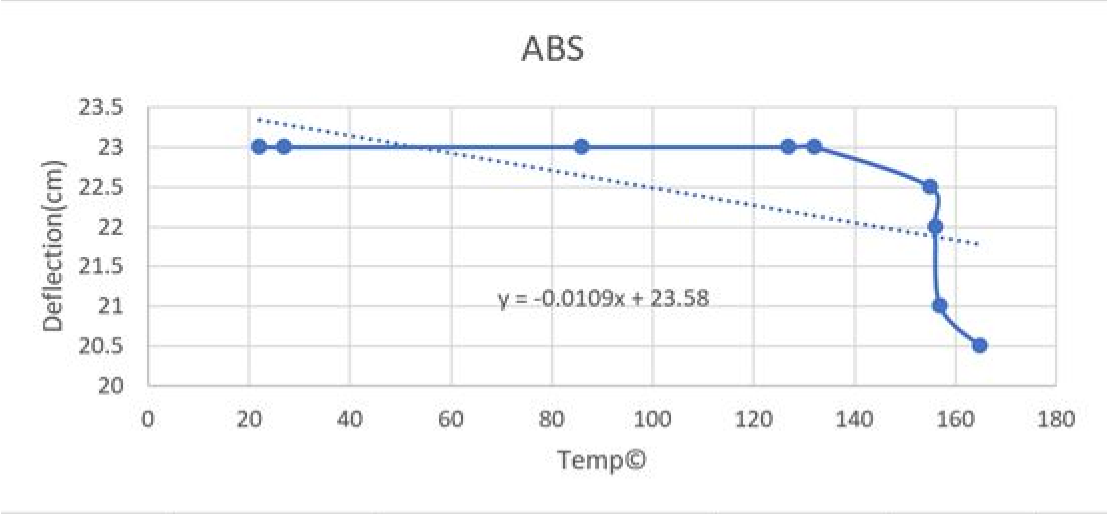


Figure 5.2.4: APS Deflection

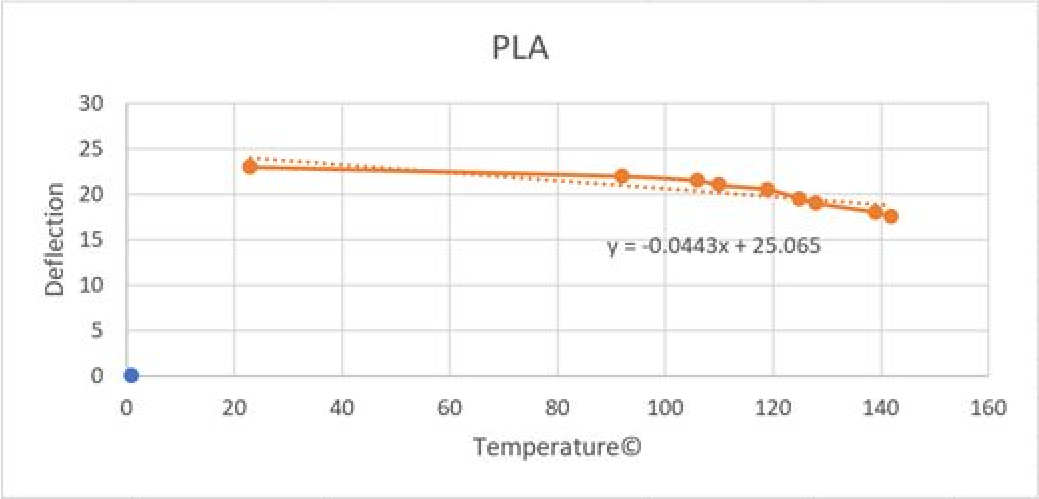


Figure 5.2.5: PLA Deflection

The collected graph essentially gives us a force deflection curve and the equation from the slope give a relationship(coefficient) of deflection vs temperature. Using the experimental values, the equation can be compared to the calculated values in the table.

As shown, both materials appear to be incredibly flexible once thermally activated. It can also be confirmed by examining the Young's Modulus of the materials. Because PLA had a much smaller modulus, it can be concluded that the PLA is mathematically proven as the most flexible material. The team will likely use PLA going forward as it is more likely to mold with little heat. It is probable that it will form after placing the material in boiling water. There are some differences with the graph, however, when comparing the experimental coefficients with that of the calculated value in the table. The displacement from the experiment in ABS will be lower than the calculated values while the displacement is higher that the calculated values of the PLA. the difference could be due a few reasons. It is possible that there is human error or it could be that the equation is not an effective model to calculate the displacement of ABS material. On the contrary, the calculated and experimental values of the PLA were very close in proximity to each other. A visual understanding of how the plastics were affected can be seen in the picture below.

Figure 5.2.6: Newley Warped Material

This shows just how much each material can bend given the heat and force applied to it. There are some errors when completing this experiment. One of which was how the heat gun did not give an equal amount of heat to the material. This could affect the results as the material might not have deformed properly. Another source was human error as the displacement had to be analyzed using a rough estimate. Ultimately, the project was useful in that it demonstrated how useful PLA will be for the project going forward.

5.2.3 Forearm Shape and Mechanical Forces:

For this analytical analyses the strength of the forearm is found for many cross sectional shapes. The calculations are based on the assumption that the forearm is treated as a cantilever beam. This is because like the cantilever beam, the forearm is fixed at one location. This location is at the elbow. The forearm will be treated as a cantilever beam because it will be fixed to the patient's limb much like a cantilever is fixed in one location. From this analysis the necessary force to hold the prosthetic securely on the residual limb will be found. The change in shape will change the deflection and the bending stress is affected. This is important to the prosthetic, because the user should know the amount of force the arm can withstand without bending and breaking. Strength is determined by the crossection's ability to distribute stresses. The stress on a cantilever beam is a function of the force, moment of inertia, length of beam, and the elasticity of the material. To keep the analysis focused on the cross sectional shape, all except the moment of inertia are constant. Each shape has a different moment of inertia. The stress is inversely related to the moment of inertia. The most successfully strong shape was the hollow semi circle. Based on the calculations the moment of inertia of this shape was the largest. Therefore, the stresses along the arm are smaller. This is important to the project because the arm needs to support the forces that are applied to it. Thus, the optimal shapes must be chosen to increase the durability of the prosthetic.

This is important because the attachment to the amputee must be strong and not fall off the user. The creation of Free Body Diagrams and Excel code to display the effects that different forearm design shapes will have on reaction forces, moments, and arm deflection at the joint. This will also factor in the location of forces. These forces can be distributed loads or point loads. So, this analysis will discover the optimal shape for a forearm that will withstand forces and the required reaction forces at the joint will be known. Thus, the proper shape and joint can be selected for the prosthetic.

For this analysis there are many assumptions made. The first and main assumption is that the forearm can be compared to a cantilever beam. The prosthetic arm will need to be secured to the residual limb. This will be done by fixing one end of the arm to the limb. This provides one fixed location to hold the weight of the arm and any other forces applied. Thus, it is comparable to a cantilever beam that is, by definition, fixed in one location. It is also assumed that the weight forces of the arm are distributed loads and that the weight of the hand is a point load located at the end of the forearm. In addition, it is assumed that the arm is uniformly straight. All of these assumptions will cause the calculations to be simpler.

In order to calculate the bending stress and the deflection of the arm, the moment of inertia must be found for each cross-sectional shape. Each of the shapes have unique moments of inertia as seen in the following figures and equations.

Cross-Sectional Shapes

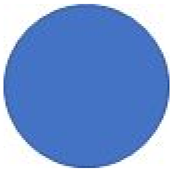


Figure 5.2.7: Cross-section Assuming Arm is Circular

$$I = \frac{\pi D^4}{64} \qquad (12)$$

The moment of inertia (I) depends on diameter (D).

Figure 5.2.8: Cross-section Assuming Arm is Circular and Hollow [2]

$$I = \frac{\pi}{64}(D^4 - d^4) \qquad (13)$$

The moment of inertia (I) depends on external diameter (D) and internal diameter (d).

Figure 5.2.9: Cross-section Assuming Arm is Semicircular and Hollow

$$I = \frac{\pi}{8}(R^4 - r^4) \qquad (14)$$

The moment of inertia (I) depends on external radius (r) and internal radius (r).

Figure 5.2.11: Cross-section Assuming Arm is Square and Hollow

$$I = \frac{b^3 h}{12} \tag{15}$$

The moment of inertia (I) depends the length of the base (b) and the height (h).

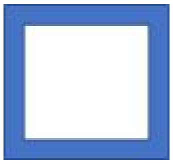


Figure 5.2.12: Cross-section Assuming Arm is Square and Hollow

$$I = \frac{B^3 H}{12} - \frac{b^3 h}{12} \tag{16}$$

The moment of inertia (I) depends the length of the internal (b) and external (B) base and the internal (h) and external (H) height.

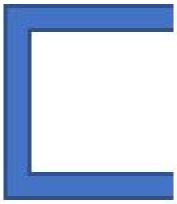


Figure 5.2.13: Cross-section Assuming Arm is "C" shaped and Hollow

$$I = \frac{2sb^3hht^3}{3} - A(b-y)^2 \tag{17}$$

The moment of inertia (I) depends the length of the internal (b) and external (B) base, the internal (h) and external (H) height, and the base thickness (t) and height thickness (s).

The results for the analysis were calculated in excel. These results varied based on dimensions, load sizes, and the Modulus of elasticity of the forearm. The inputs can be changing in the attached excel sheet to fit the needs of the individual user. The results show that the shape with the largest moment of inertia resulted in the smallest deflection and the smallest bending stress.

This shape is the hollow semicircle. Therefore, the team should consider this shape for the design of the forearm.

5.2.4 Hardware and Code

Three distance sensors were compared from three different companies Sparkfun, Amazon, and Polulu [1-3]. All sensors collected to meet a distance range from 0.5 in to 6 in, which is approximately the distance needed to determine if the prosthetic is reaching to grab an object. **Table 2.1** compares the important properties of each sensor which includes range, voltage needed, type, pins needed, and cost.

Table 2.1- Distance Sensors

Distance Sensor	Range	Voltage	Type	Pins Needed	Cost
ZX Distance and Gesture Sensor	0 - 12 in	3.3V - 5V	Laser	5	24.95
Elegoo HC-SR04	0.78 - 157 in	5 V	Sound	4	9.78
Pololu Carrier with Sharp GP2Y0D815Z0F Digital Distance Sensor 15cm	0.2 - 6 in	5 V	Laser	6	9.75

The three motors listed in **Table 2.2** are from the same companies listed in section 2.1. Each motor was evaluated using the properties: input voltage, current required, speed, shaft size, and cost. All properties are important, however, shaft size is not important until further in the design when the attachment is determined.

Table 2.2 - Motor

Motor	Input Voltage	Amps	Speed	Shaft	Torque	Cost
URBEST	12V	0.6 A	300 RPM	3 mm /0.118"	7 oz-in	11.99
131:1 Metal Gearmotor 37Dx57L mm	12V / 6V	300 mA	80 RPM	6 mm	250 oz-in	24.95
Stepper Motor	3.2 V	2.0 A	200 SPR	6.35 mm	125 oz-in	30.95

In **Table 2.3**, the motor drivers are compared by the number of motors they can operate at the same time, the current that can be ran per channel, whether an additional power supply (other than the microcontroller vin) can be added, the shield compatibility, and the cost. An additional company's board was considered from adafruit.

Table 2.3 - Motor Drivers

Motor Driver	Number of Motors	Amps/Channel	Additional Power Supply	Shield Compatible	Cost
SparkFun Ardumoto	2	2 A	no	R3	20.95
SparkFun Wireless Motor Driver Shield	2	1.2 A	yes	R3, Xbee	26.95
Pololu Dual VNH5019 Motor Driver Shield for Arduino	2	12 A	yes	R3	49.95
Adafruit Motor/Stepper/Servo Shield for Arduino v2 Kit - v2.3	4	1.2 A	yes	R3	19.95

Since Arduino is open source and available around the world, these microcontrollers were chosen and compared amongst each other in **Table 2.4**. The controllers would need to meet the previous hardware requirements from the components selected above and be able to accommodate possibly multiple sensors.

Table 2.4 - Arduino Boards

Microcontroller	Attach-Interrupt Pins	Operating/Input Voltage	CPU Speed	Analog In/Out	Digital IO/PWM	Serial Read Pins	Shield Compatible	Cost
Mega 2560	2, 3, 18, 19, 20, 21	5 V / 7-12 V	16 MHz	16/0	54/15	3	R3	38.5
Micro	0, 1, 2, 3, 7	5 V / 7-12 V	16 MHz	12/0	20/7	1	N/A	19.8
Uno	2, 3	5 V / 7-12 V	16 MHz	6/0	14/6	1	R3	22
Zero	all digital pins, except 4	3.3 V / 7-12 V	48 MHz	6/1	14/10	1	R3	42.9

Due	all digital pins	3.3 V / 7-12 V	84 MHz	12/2	54/12	3	R3	35.5
SparkFun RedBoard	2, 3	3.3 V / 7-15 V	16 MHz	6/0	14/6	1	R3	19.95

The hardware chosen from this analysis is ZX sensor, Polulu motor, adafruit motor shield, and arduino due. All the hardware is compatible with the microcontroller chosen and allows for wireless connectivity, additional motors, extra sensors, and other future design modifications. The code available in **appendix 6.1** does run the motor as expected, however the distance sensor could not be tested since it was not available before the deadline for the analysis.

5.2.5 Prototype

Using the results from each analysis, A final design could be made. A 3D model was created in order to have a visual understanding of what the arm will look like and where each electrical component will likely be placed. It is also important to keep in mind that the arm will need to be printed flat using different software and thermoformed into its final design. The rubber bands, wires, and electrical components can be added afterwards. A final prototype was constructed using the CAD model and conclusions from the analytical analysis followed by a completed prototype.

Below showed a picture of the CAD model and included drawings that give more detail as to how the arm will be likely move. The pictures of some of the parts can be found in the appendix.

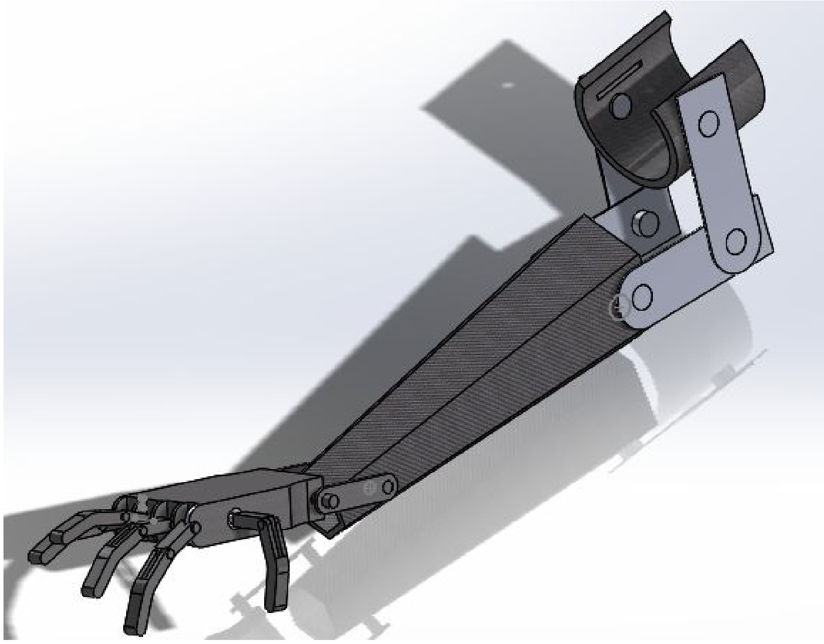


Figure 5.2.14 : Figure of Cad Model

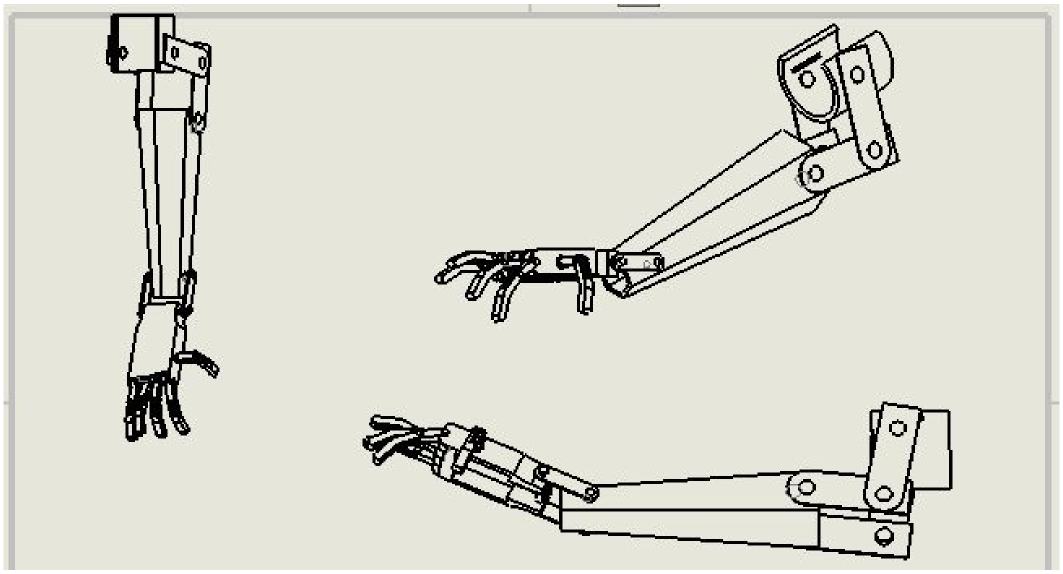


Figure 5.2.15: Drawing of CAD Model

Although not shown, the rotors will likely be at the base of the arm as well as the haptic feedback and bluetooth for the user to avoid a large load at the end of the hand. Our client is a nine year old boy and it is key to avoid too much load in one concentrated area as suggested in the previous analysis.The motors will be connected to durable strings and rubber bands through the palm of the hand and through the fingers to give as much mobility to the user as possible. All this will be placed in a 3D thermoformed cast made of PLA with possible APA components for the fingers. Sensors will be placed on each fingertip so that the hand will be able to sense when an item is near and close around the object. This movement should activate the haptic sensor and respond(vibrate) to give the user a sense of touch.

This model will include a shoe insole that has not been designed yet. Each toe will correspond to a pressure sensor. This sensor is connected via bluetooth to the arm which is connected to a motor for each finger. This allows for optimal control for each finger and was one of the larger focuses on the design as per the client's request. The team hopes that the sensor in the big toe will allow for the thumb to move horizontally and vertically much like a thumb in real life. Final meetings will help decide what electrical components to incorporated for the best design.

Using the CAD model, the prototype can then be created that gives a better representation of where the sensors and electrical components can be placed. Below shows a figure of the completed design.

Figure 5.2.16 : Picture of prototype

This prototype looks very different from the CAD for a few reasons. It was decided that the stronger attachment could be better made to handle a larger weight distribution and allow for better arm customisation for the user. It was also decided that a partially thermoformed forearm would be better for the design and easier to assemble when placing the wires. The fingers have a third limb attachment to allow for better mobility and more natural look for the fingers. Finally, a top was added to the palm of the hand to better protect the motors and sensors within. It is possible the prototype will be altered during construction because the sensors' weights could mean that the team will need a more durable forearm. Alterations will also take place during the fitting with the client to ensure the fit is accurate and comfortable.

6 PROPOSED DESIGN - First Semester

To begin implementation of the design, the team met with the Electrical Engineering Capstone team to discuss the feasibility of having a foot-controlled prosthetic. The programming of the sensors that would be placed within a shoe insole are still under development, but the mechanical aspect of the design can be prototyped. To prototype the final design, the Enable prosthetic design was used as a base and modifications were made to include placement of the sensors and motors. While the Enable design is used for the prototype this semester, edits will be made to the design to improve weight, comfortability, and actuation by the time Capstone is over. The team will be coordinating with the EE Team to program a heel-strike to toe-off sensing capability within the insole and bluetooth it to sensors within the finger.

There is also the proposed idea of including a touch screen on the arm with different modes programmed into the arm, and the user can select a mode type and the arm will react accordingly. For example, if the mode selected is “Video Games”, the arm will know to only allow motion within certain fingers in certain directions via input from the sensors in the insole. This idea was proposed after a meeting with the client, Nate, who has an interest in the ability to play video games and baseball. This idea will not be programmed for this semester’s prototype but the team aims to include it in the final design.

Multiple arms will be prototyped and tested for their durability, wearability, and ease of use. Meetings with the client will allow the arm to be properly fitted, sized, and tested for comfortability and likeability according to the client’s preference in prosthetic. This will allow the team give Nate an arm he will be happy with come Spring. In terms of the budget used through this design process, Dr. Winfree has supplied $500.00 to each the ME Capstone team and the EE Capstone team. By the EE Team also being a part of the project, some of the prototyping expenses related to the sensors and motors may be taken from their $500.00 budget while the ME Team’s budget will focus on the physical and mechanical side of prototyping. However, it is more safe to assume the prototyping, purchasing of sensors and motors, and other materials will all be covered by the ME Team. Table 6.1 holds the Bill of Materials for a single prosthetic arm. The plan is to reuse sensors and motors between prototypes in order to save on money, but each prototype will be a new 3D printed arm or part of an arm. Assuming a minimum of five prototypes including the final arm to be given to the client, the only change to the expected cost is saying the quantity of PLA filament is 5 instead of 1. This makes the price $323.04, which is still within the $500.00. However, shipping fees have been omitted and sensor and motor types or susceptible to change which will also change in price. Thus, this value is an estimate.

Table 6.1: *Bill of Materials*

Material	Quantity	Quantitiy/Pack	Cost/Part	Cost
PLA Filament	1	1 ct	15.99	15.99
Small rubber bands	1	100 ct	4.75	4.75
Velcro Straps	1	24 ct	8.99	8.99
Foam pad	1	6 ft	12.79	12.79
Arudino: Duo	1	1 ct	35.5	35.5
Large Motor	1	1 ct	24.95	24.95
Small Motor	5	1 ct	8.99	44.95
Motor Driver	1	1 ct	19.95	19.95
Pressure Sensor	10	1 ct	7	70
Battery	2	2 ct	6.59	6.59
Battery connector	1	5 ct	5.39	5.39
Insoles	1	1 pair	9.23	9.23
				259.08

The current implementation plan includes coordinating a weekly or bi-weekly meeting time with the EE Team to make sure each aspect of the project is up to date and still feasible with each other. In finishing the first semester, both teams have a modified Enable arm and mapped out insole for sensor location, and a brainstorm for the programming behind the bluetooth. Second semester will focus on the programming side within the first few weeks and once the program starts to solidify, modifications to support the software will be made to the current prototype. While the EE Team works on the program the first few weeks, the ME Team will focus on modifying the CAD to properly include placement holders for sensors and motors. The rest of the semester will be a cycle of testing, prototyping, and retesting by contacting the client.

The design can be seen in the exploded view below.

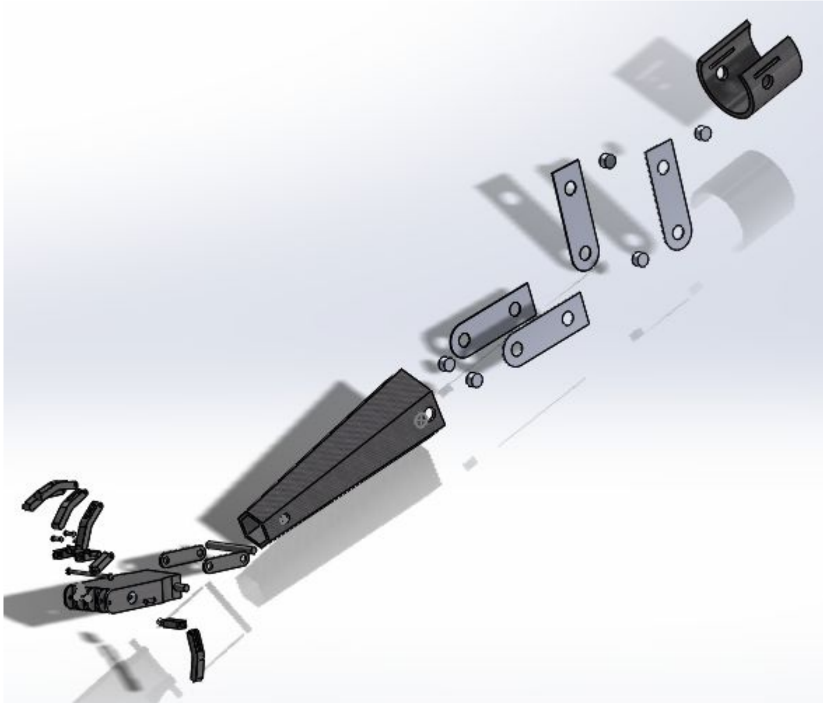


Figure 6.1: Exploded View

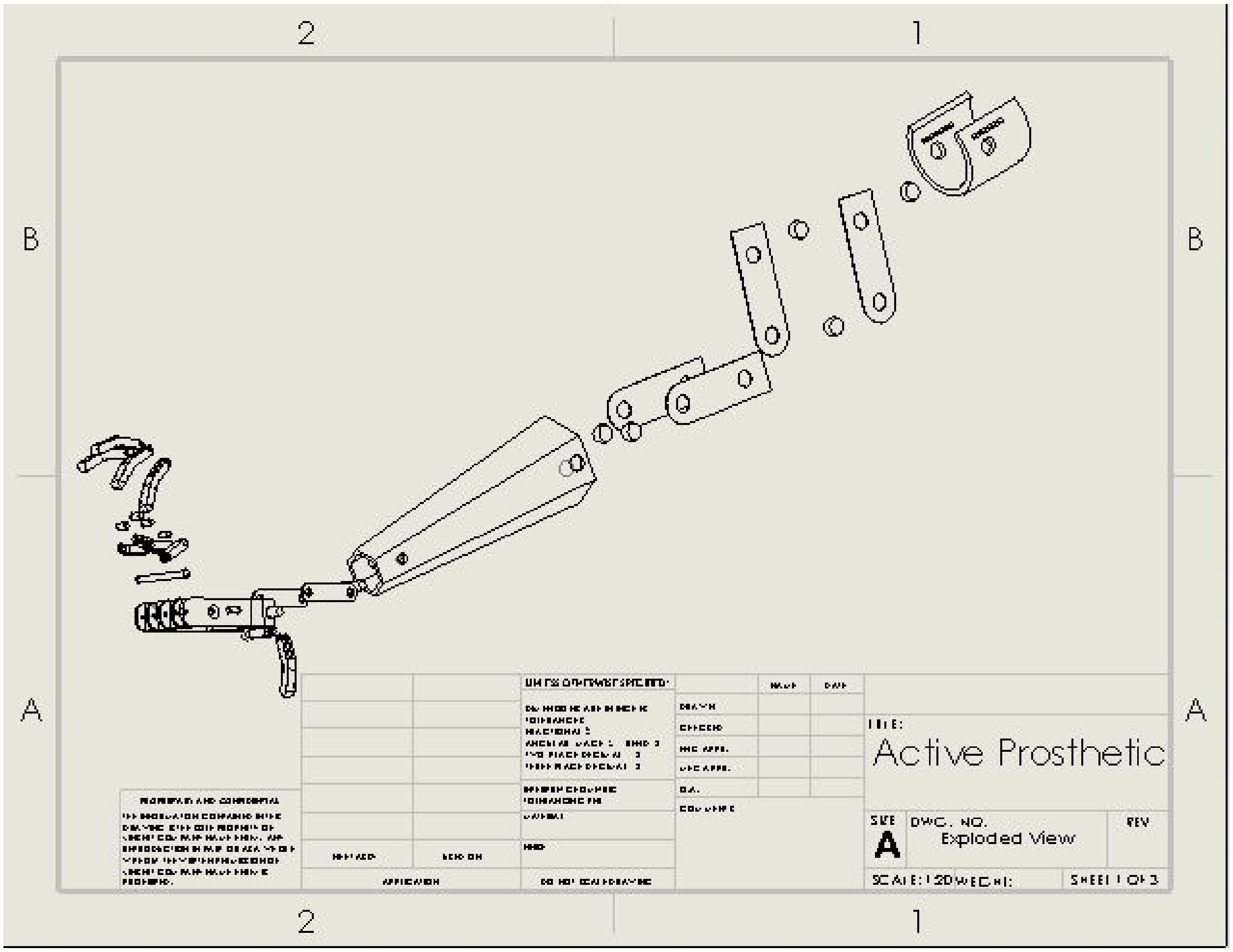


Figure 6.2: Exploded View Drawing

7 APPENDICES

7.1 Appendix A: Additional Concepts

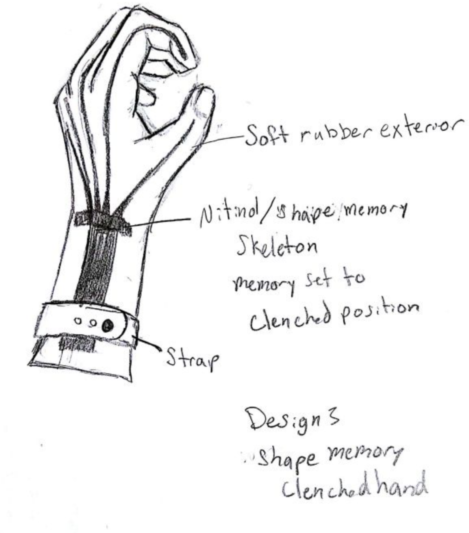


Figure A1: Shape Memory

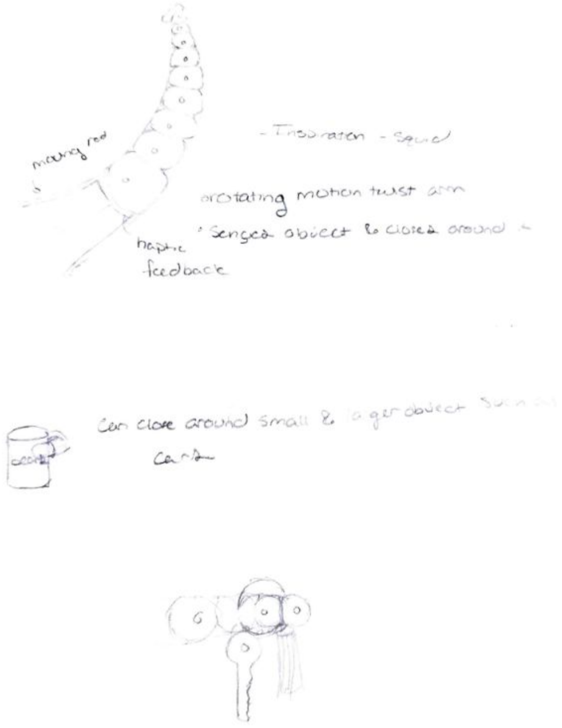


Figure A2: Cool Hand Squid Man

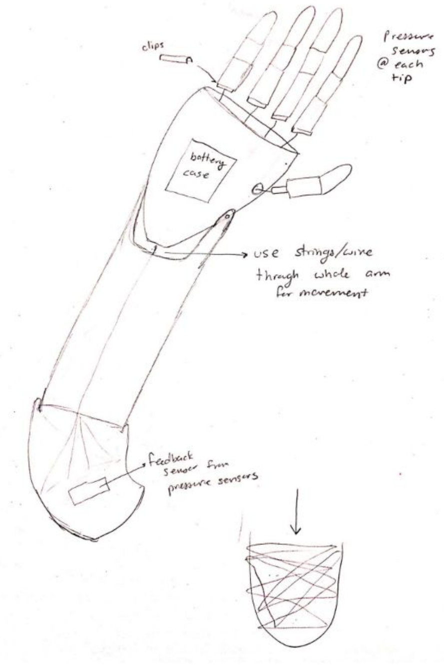


Figure A3: Clip-o-Grip

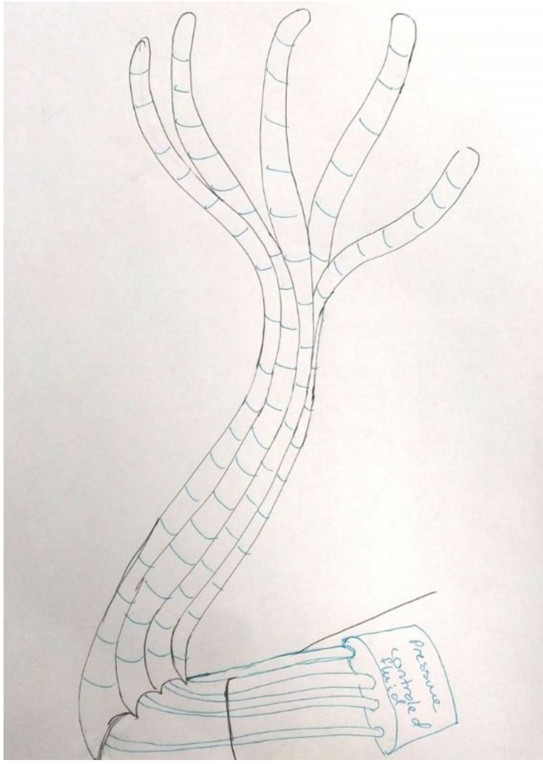


Figure A4: Vine Grab

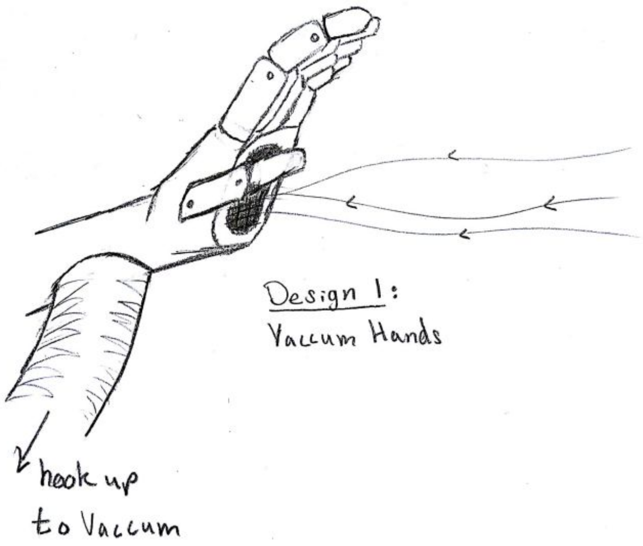


Figure A5: Vacuum Hands

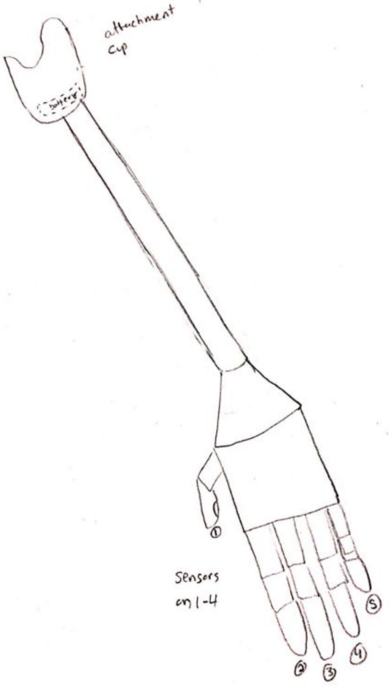


Figure A6: Need-Forearm-Muscles

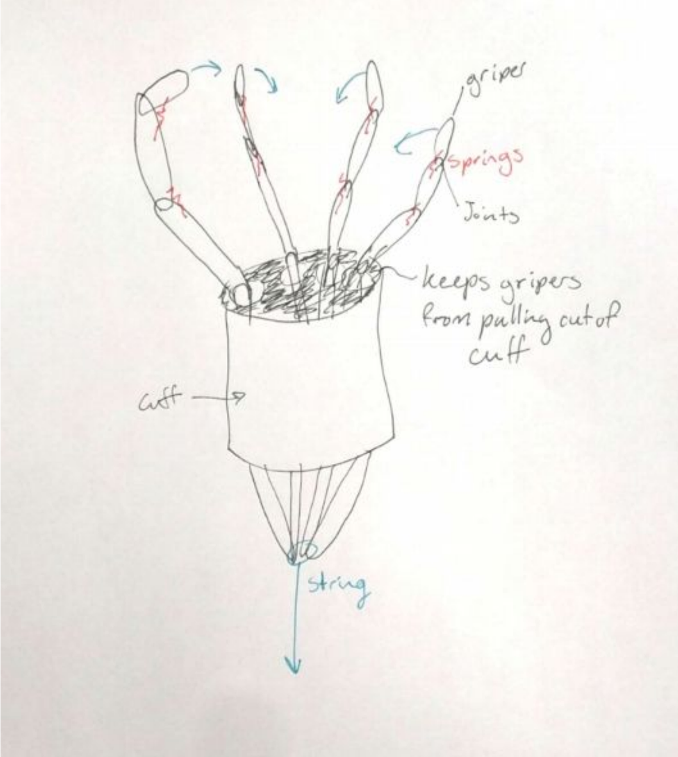


Figure A7: Pincer

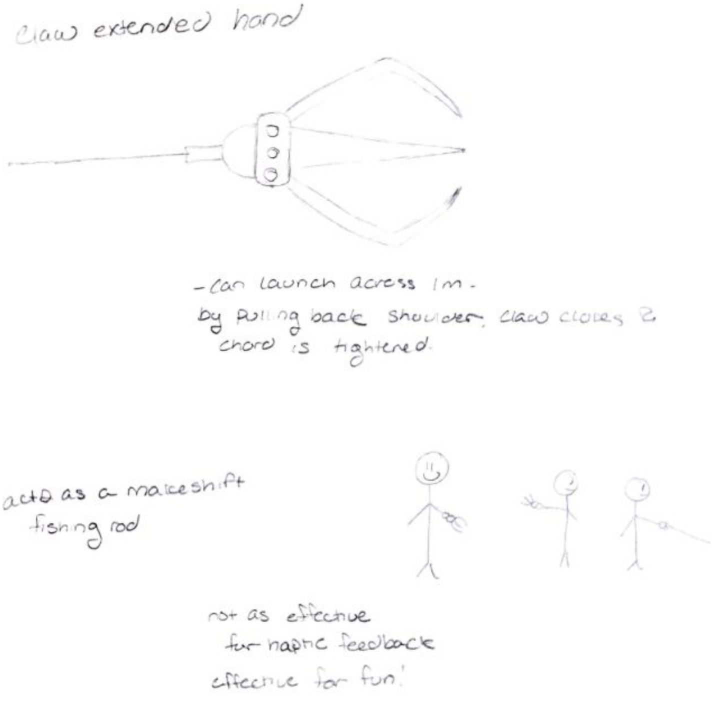


Figure A8: The Claw

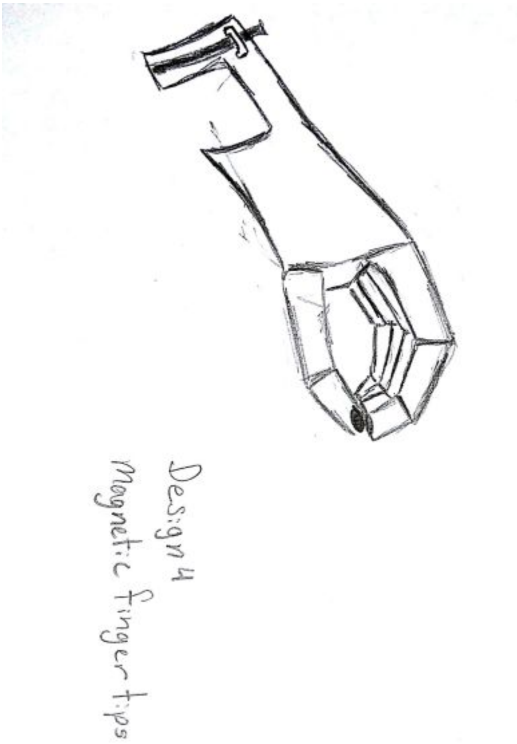


Figure A9: Magnetic Fingertips

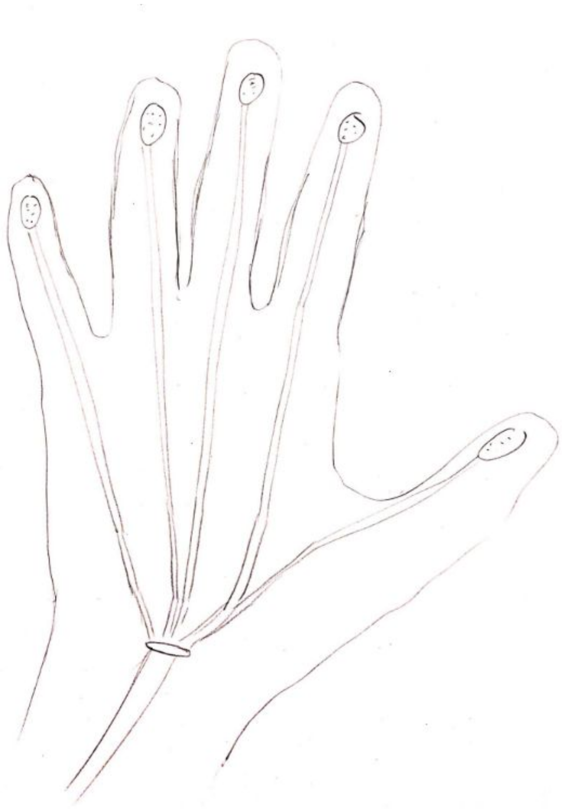


Figure A10: Visible Nerves

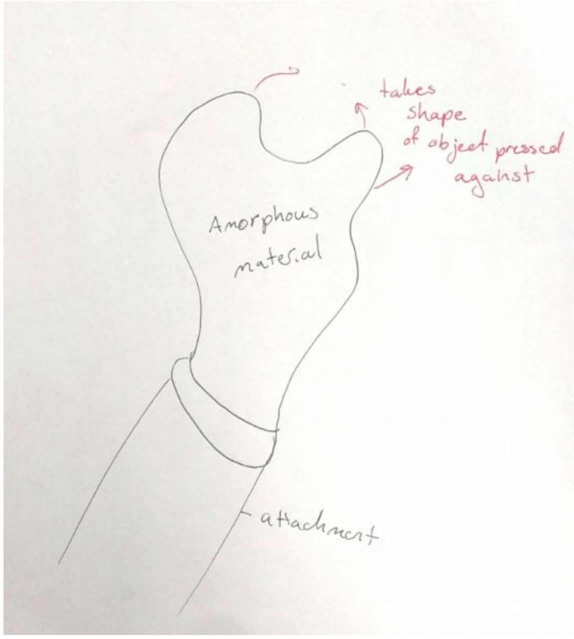


Figure A11: The Blob

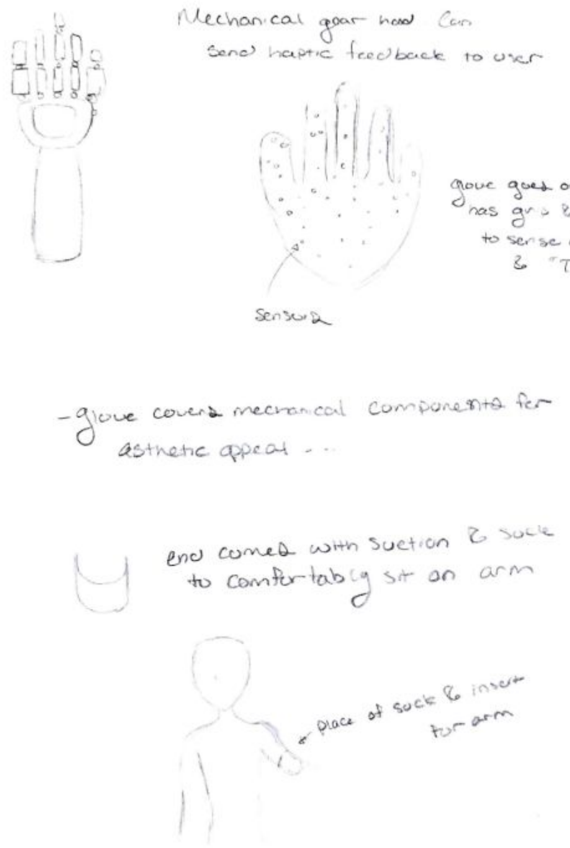


Figure A12: We Got You Covered

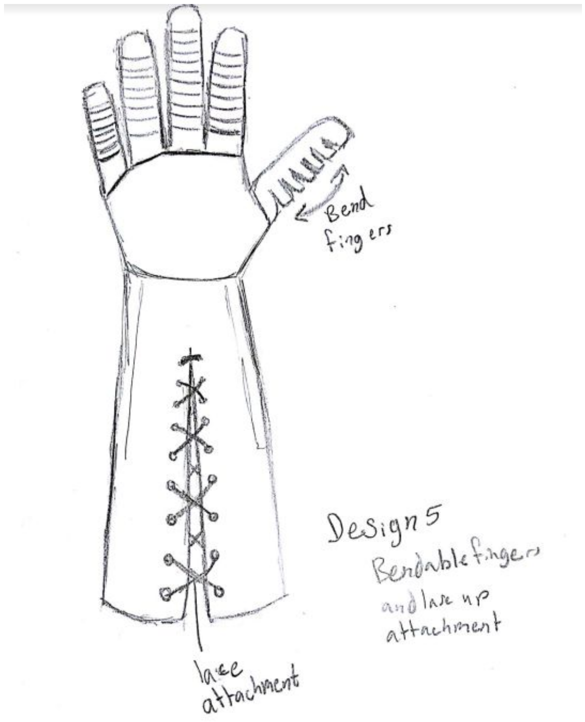
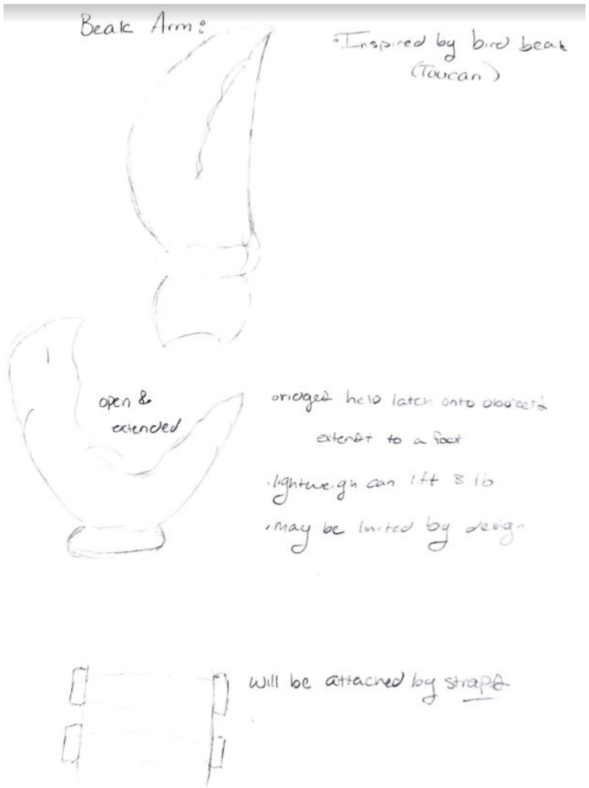


Figure A13: Bendy Fingers and Lace Up



· Inspired by bird beak (Toucan)

· ridges help latch onto objects

extends to a foot

· lightweigh can lift 3 lb

· may be limited by design

Will be attached by straps

Figure A14: You Can Toucan

7.2 Appendix B: Code Analysis

```
//Library
#include <Wire.h>
#include <ZX_Sensor.h>
#include <Adafruit_MotorShield.h>

// Create motor shield object
Adafruit_MotorShield AFMS = Adafruit_MotorShield();

// Select motor
Adafruit_DCMotor *myMotor = AFMS.getMotor(1);

// Constants
const int ZX_ADDR = 0x10;  // ZX Sensor I2C address

// Global Variables
ZX_Sensor zx_sensor = ZX_Sensor(ZX_ADDR);
uint8_t x_pos;
uint8_t z_pos;
uint8_t z_posnew = 0;
uint8_t z_posold = 0 ;
uint8_t dz_pos = 0;

void setup() {

  uint8_t ver;

  // Initialize Serial port
  Serial.begin(9600);

  // Initialize ZX Sensor (configure I2C and read model ID)
  if ( zx_sensor.init() ) {
    Serial.println("ZX Sensor initialization complete");
  } else {
    Serial.println("ZX Sensor initialization incomplete!");
  }

  // Read the model version number and ensure the library will work
  ver = zx_sensor.getModelVersion();
  if ( ver == ZX_ERROR ) {
    Serial.println("Error reading model version number");
```

```
  } else {
    Serial.print("Model version: ");
    Serial.println(ver);
  }
  if ( ver != ZX_MODEL_VER ) {
    Serial.print("Model version needs to be ");
    Serial.print(ZX_MODEL_VER);
    Serial.print(" to work with this library. Stopping.");
    while (1);
  }

  // Read the register map version and ensure the library will work
  ver = zx_sensor.getRegMapVersion();
  if ( ver == ZX_ERROR ) {
    Serial.println("Error reading register map version number");
  } else {
    Serial.print("Register Map Version: ");
    Serial.println(ver);
  }
  if ( ver != ZX_REG_MAP_VER ) {
    Serial.print("Register map version needs to be ");
    Serial.print(ZX_REG_MAP_VER);
    Serial.print(" to work with this library. Stopping.");
    while (1);
  }
}

void loop() {
  // If there is position data available, read and print it
  if ( zx_sensor.positionAvailable() ) {
    z_posnew = zx_sensor.readZ();
    dz_pos = z_posold - z_posnew;
  }
  uint8_t i;
  Serial.print("tick");
  if (abs(dz_pos) > 0) {
    if (dz_pos > 10) {
      myMotor->run(FORWARD);
      myMotor->setSpeed(150);
      delay(10);
    }
    if (dz_pos < -10) {
      myMotor->run(BACKWARD);
```

```
      myMotor->setSpeed(150);
      delay(10);
    }
  }
  if ( zx_sensor.positionAvailable() ) {
    z_pos = zx_sensor.readZ();
    if ( z_pos != ZX_ERROR ) {
      Serial.print(" Z: ");
      Serial.println(z_pos);
    }
  }
  Serial.print("tock");

  z_posold = z_posnew;
  Serial.print("tech");
  myMotor->run(RELEASE);
  delay(1000);
}
```

8 REFERENCES

[1] “Enabling The Future,” *Enabling The Future*. [Online]. Available: http://enablingthefuture.org/. [Accessed: 10-Oct-2018].

[2] “Open Bionics,” *Open Bionics*. [Online]. Available: https://openbionics.com/. [Accessed: 10-Oct-2018].

[3] “Limbitless Solutions,” *Limbitless Solutions*. [Online]. Available: https://limbitless-solutions.org/. [Accessed: 10-Oct-2018].

[4] “How Stuff Works,” *howstuffworks.* [Online]. Available: https://electronics.howstuffworks.com/question368.htm

[5] “Walmart,” *Walmart.* [Online]. Available: https://www.walmart.com/

[6] "Amazon," Amazon, 2018. [Online]. Available: https://www.amazon.com/dp/B079SBZCSS/ref=sspa_dk_detail_6?psc=1&pd_rd_i=B079SBZCSS&pf_rd_m=ATVPDKIKX0DER&pf_rd_p=21517efd-b385-405b-a405-9a37af61b5b4&pd_rd_wg=VViI4&pf_rd_r=PCYBCRW2DG53XQ71T5Y0&pf_rd_s=desktop-dp-sims&pf_rd_t=40701&pd_rd_w=VcluH&pf_rd_i=desktop-dp-sims&pd_rd_r=8222f038-eda3-11e8-9f0a-0f336f5f387a

[7] MakeitFrom, “Other Material Properties*” Polylactic Acid.* [Online]. 2018. Retrieved: https://www.makeitfrom.com/material-properties/Polylactic-Acid-PLA-Polylactide