Active Prosthetic

Preliminary Report

Team Members:
Jannell Broderick
Allison Cutler
Felicity Escarzaga
Antoinette Goss

2017-2018

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

DISCLAIMER

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:

Every day, 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 J1: 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 J2: 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 J2: 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 House of Quality (HoQ)

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	Number of Parts
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

	Customer Needs	Customer Weights	Technical Requirements: Scaleable Size	Weight	Budget	Material Properties	Force to actuate	Force of Grip	Number of Parts	Customer Opinion Survey: 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 J1: QFD displaying the comparison of customer and engineering requirements.

Figure J1 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 deriving engineering requirements. These were analyzed 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 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 [3.2.1]"

e-NABLE is a world-wide community of volunteers that design, fabricate, and assemble 3D printed prosthesis [3.2.1]. 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 designs 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 J2.**

Figure J2: Volunteer scouts assembling unique e-NABLE hands [3.2.1].

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 [3.2.1]. 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 [3.2.2]"

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 J3**, 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 are more covers available by request.

Figure J3: Bionic arm with Handala cover [3.2.2b].

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 [3.2.2]. These prices continue to make the arm unaffordable to low income clients.

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

Limbitless Solutions is much like e-NABLE. They have volunteers around the world that create custom arms at no cost to the recipient [3.2.3]. These arms meet the same five customer requirements as e-NABLE but they are also actively controlled. **Figure J4** shows three customized designs from Limbitless Solutions.

Figure J4: Arms provided by Limbitless solutions [3.2.3].

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.

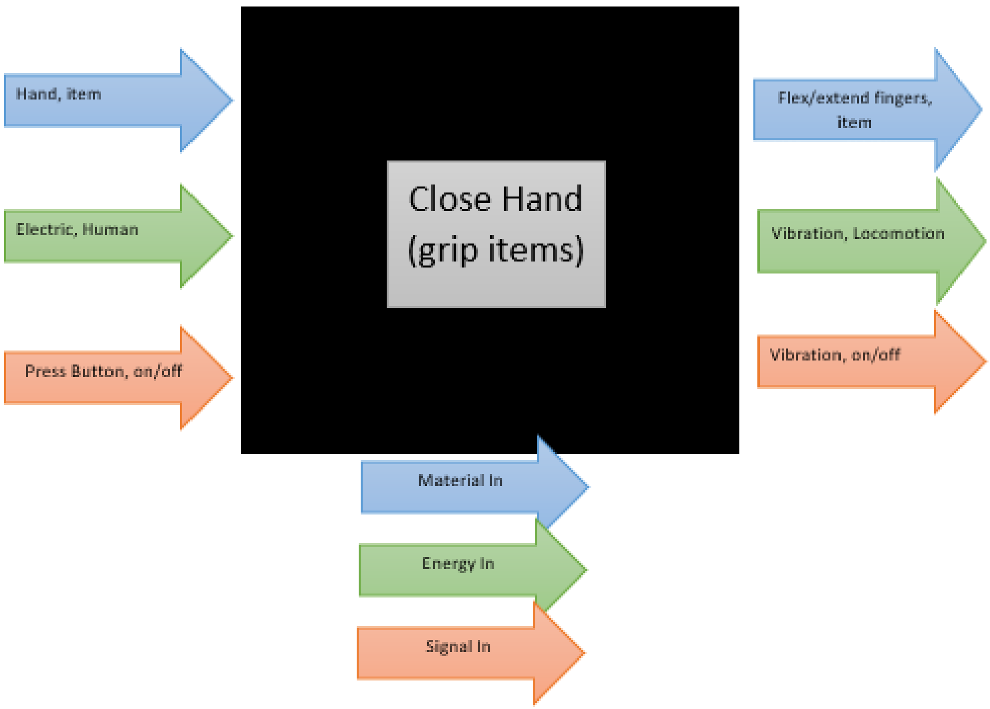


Figure (B1): Black Box Model

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 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.

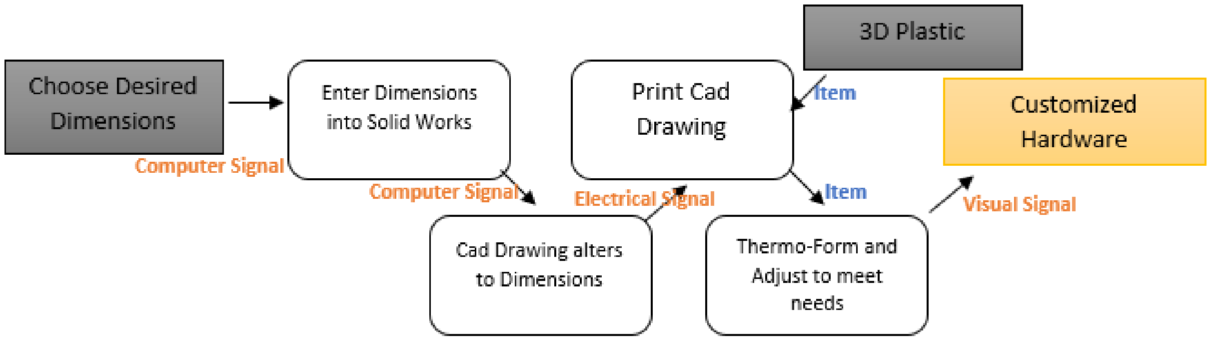


Figure (PD1): Process Diagram for Customized Hardware

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.

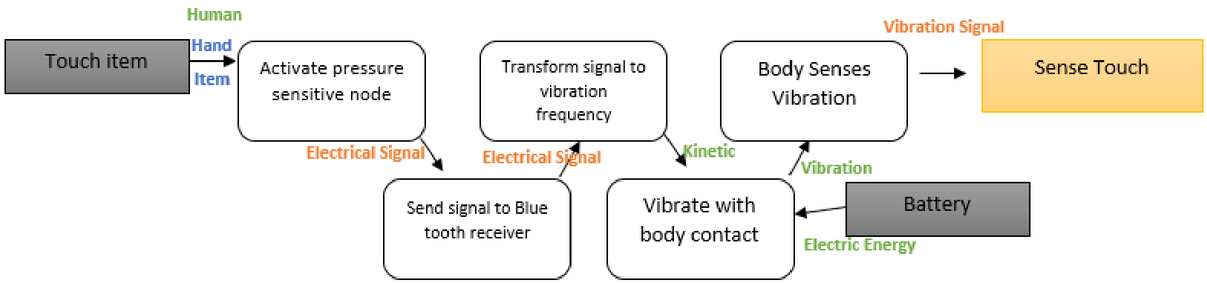


Figure (PD2): Process Diagram for Sense of Touch

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.

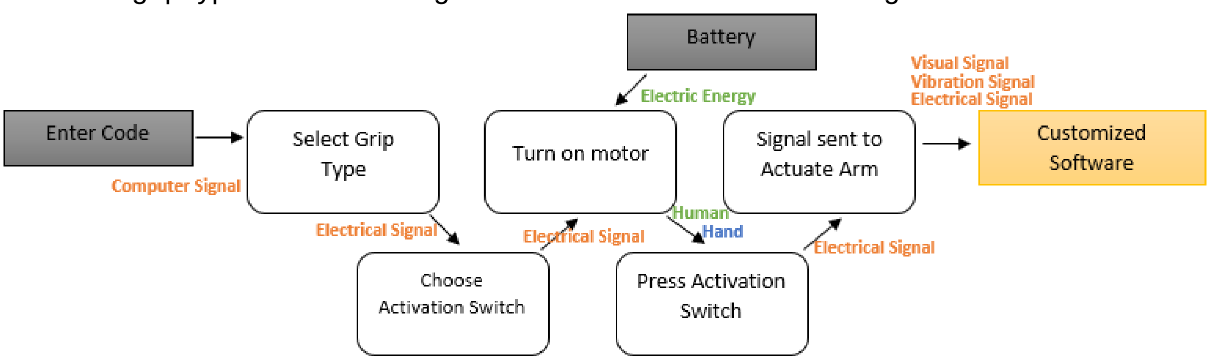


Figure (PD3): Process Diagram for Customized Software

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.

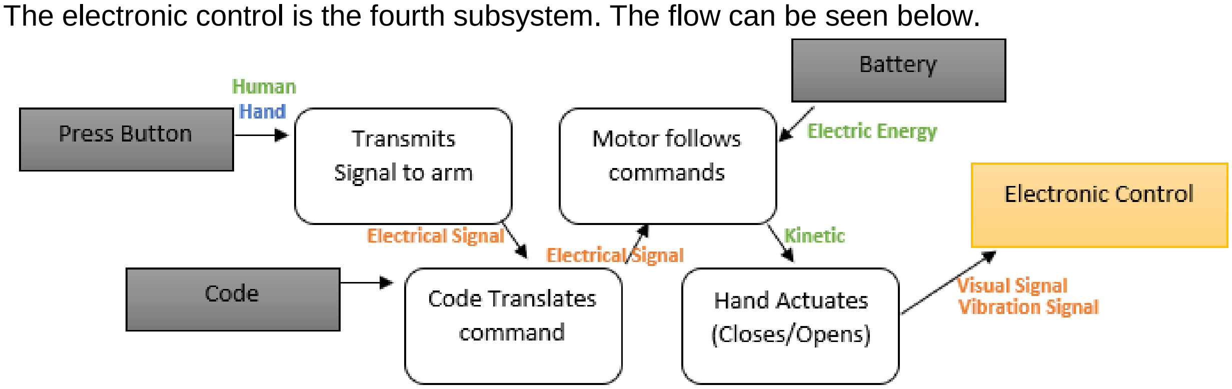


Figure (PD4): Process Diagram for Electronic Control

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.

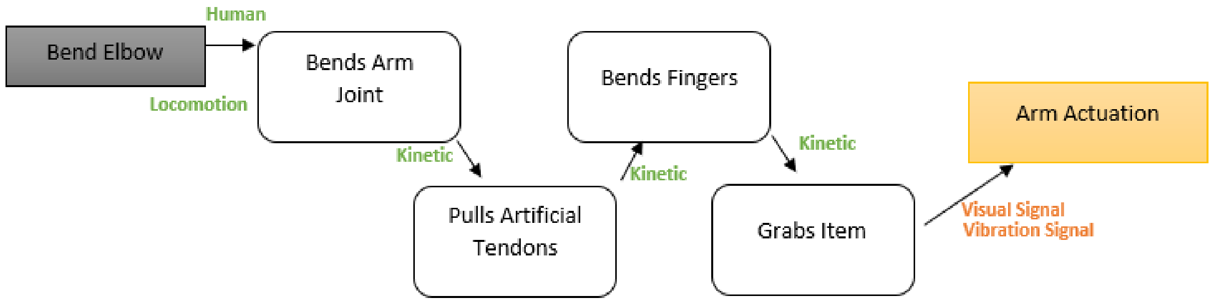


Figure (PD5): Process Diagram for Arm Actuation

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 these 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. 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. 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. 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 is 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 user's 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

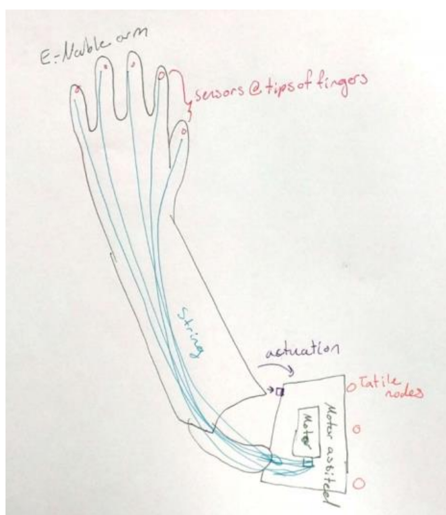


Figure D1: Adaptation Arm

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. 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.

4.2 Design #2: Customizable Skeleton

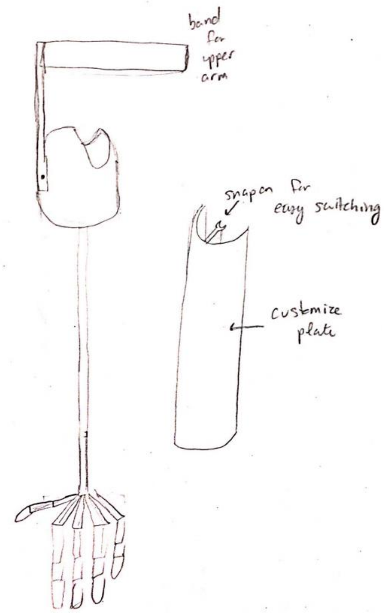


Figure D2: Customizable Skeleton Arm

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. 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

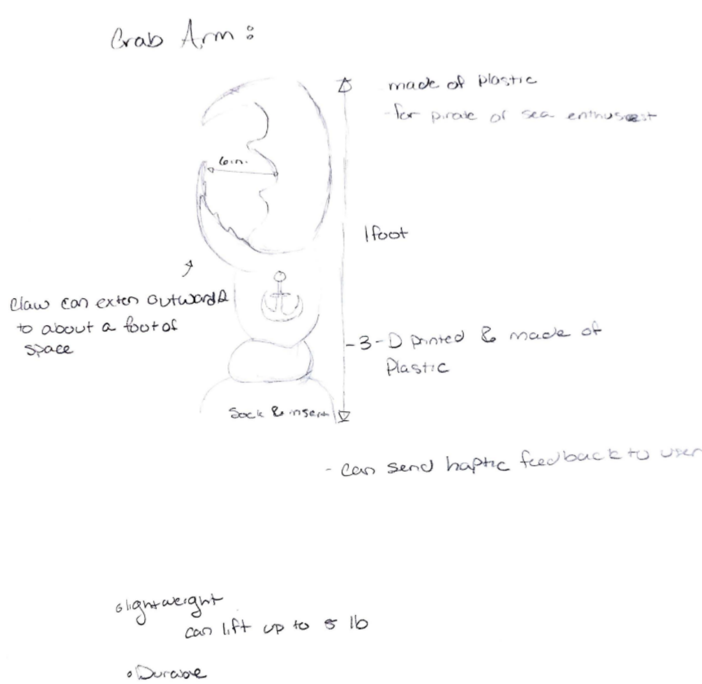


Figure D4: Crab Arm

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. 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

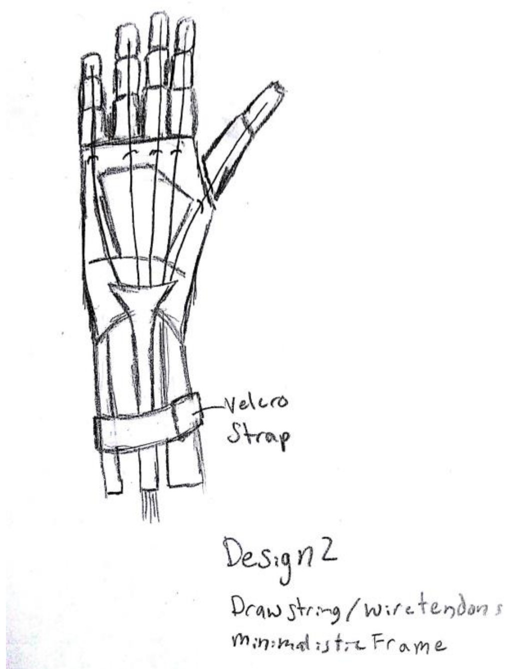
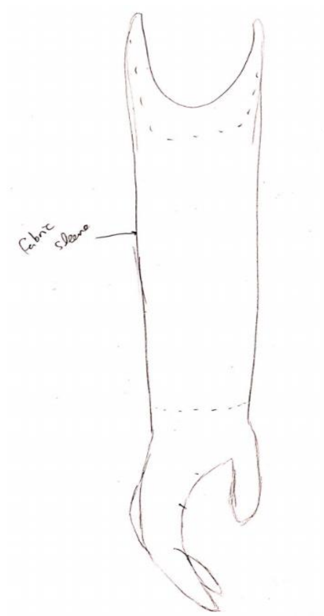


Figure D5: Drawstring Tendons Arm

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 area 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



FigureD6]: 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 an 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

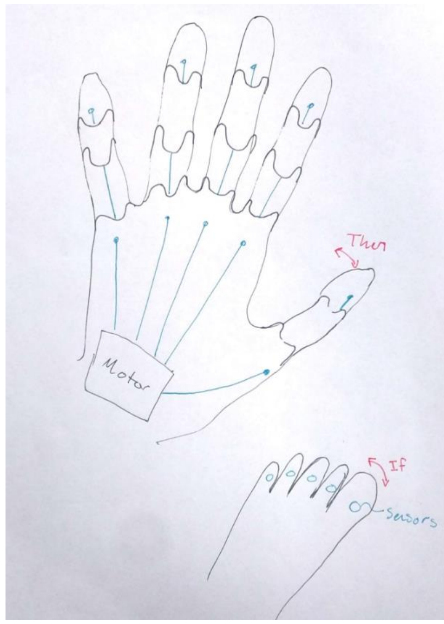


Figure D7: Foot Controlled Sensors

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. 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 controllable by the user.

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. 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 criterion. 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 P1: 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 P2: 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.

6 APPENDICES

6.1 Appendix A: Additional Concepts

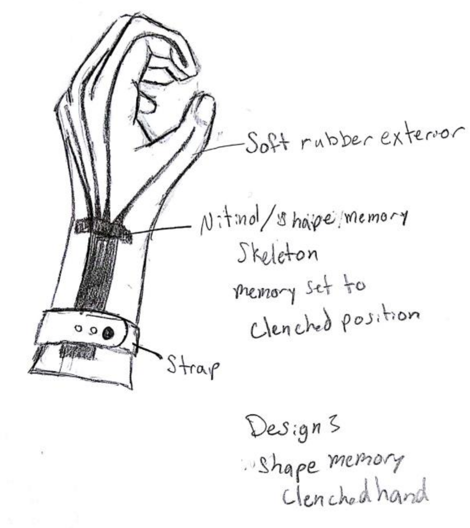


Figure 1: Shape Memory

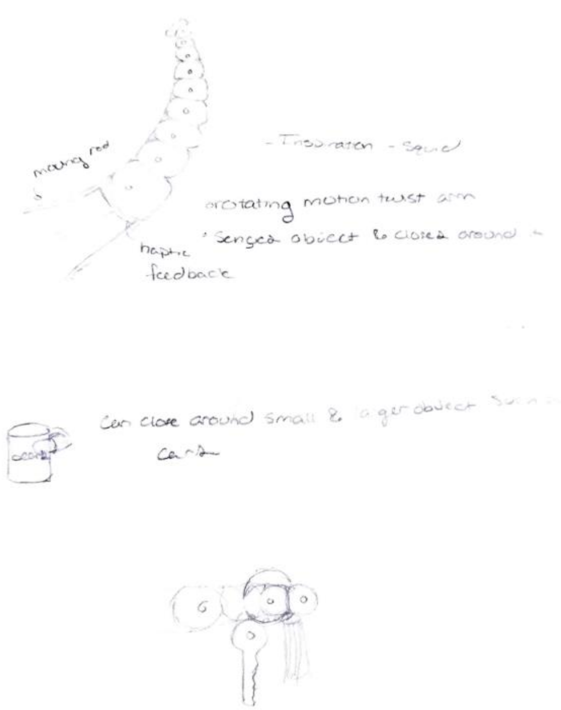


Figure 2: Cool Hand Squid Man

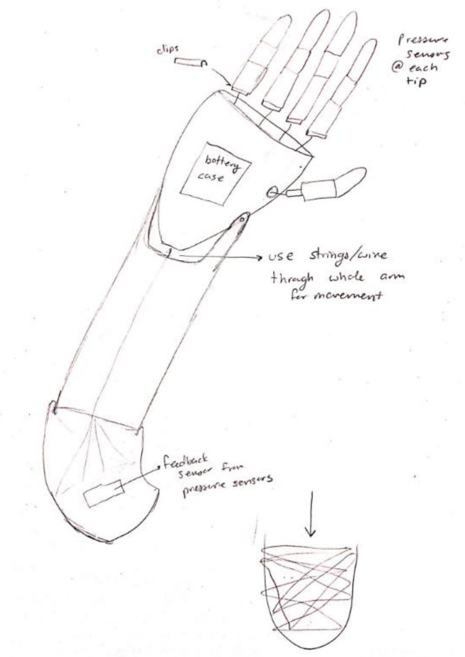


Figure 3: Clip-o-Grip

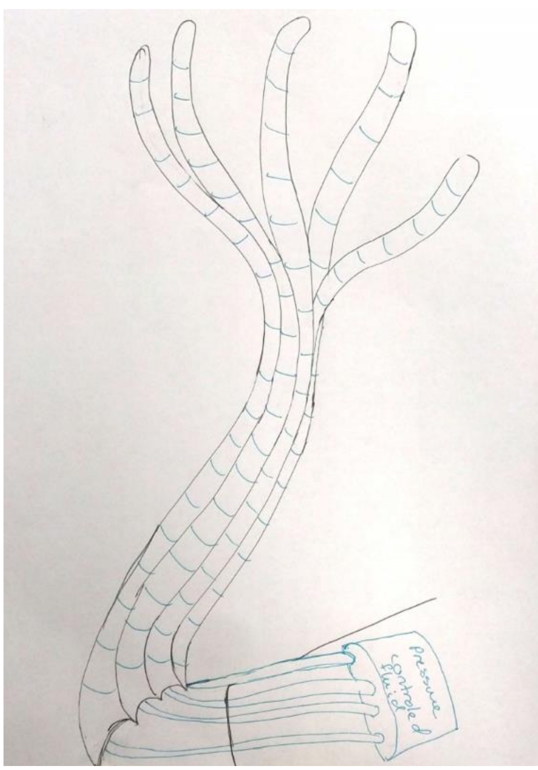


Figure 4: Vine Grab

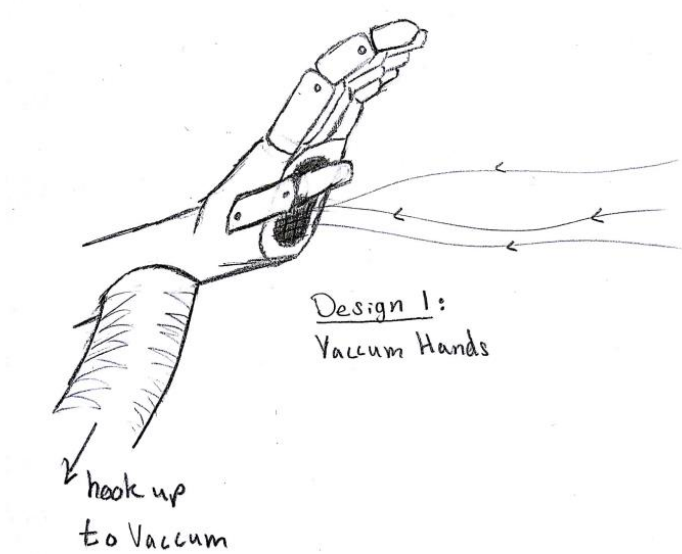


Figure 5: Vacuum Hands

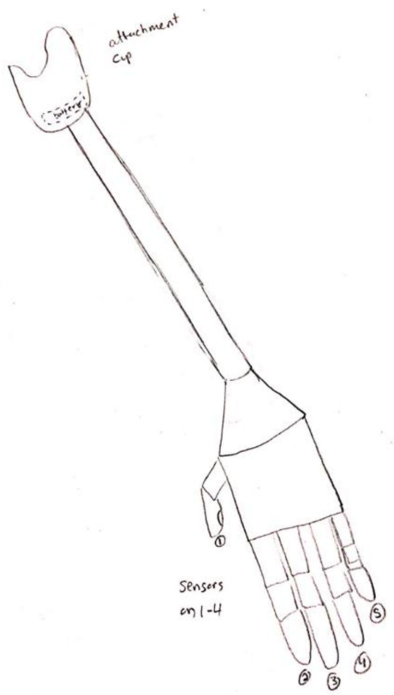


Figure 6: Need-Forearm-Muscles

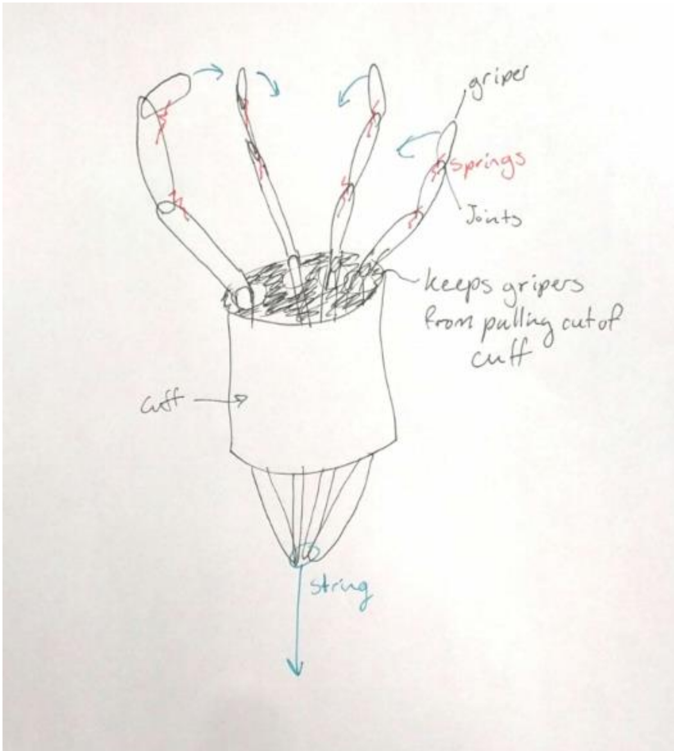


Figure 7: Pincer

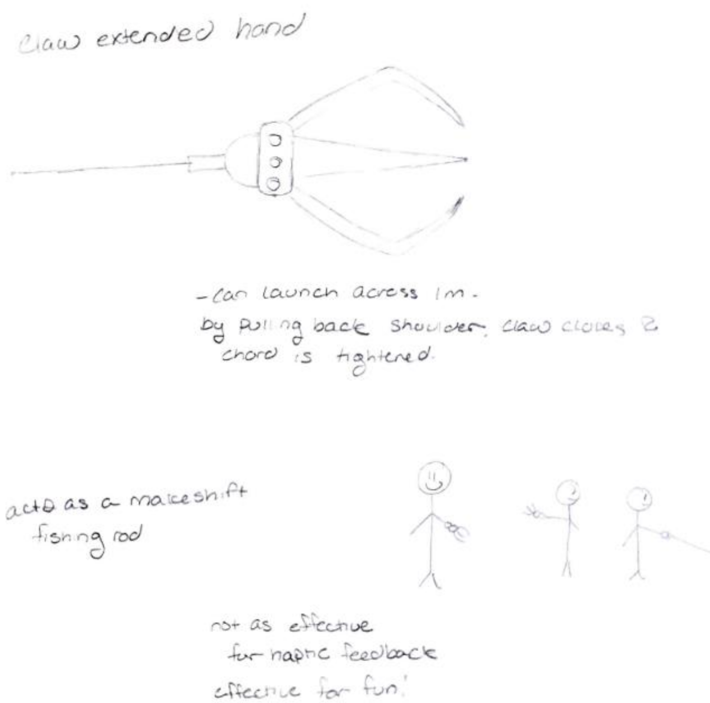


Figure 8: The Claw

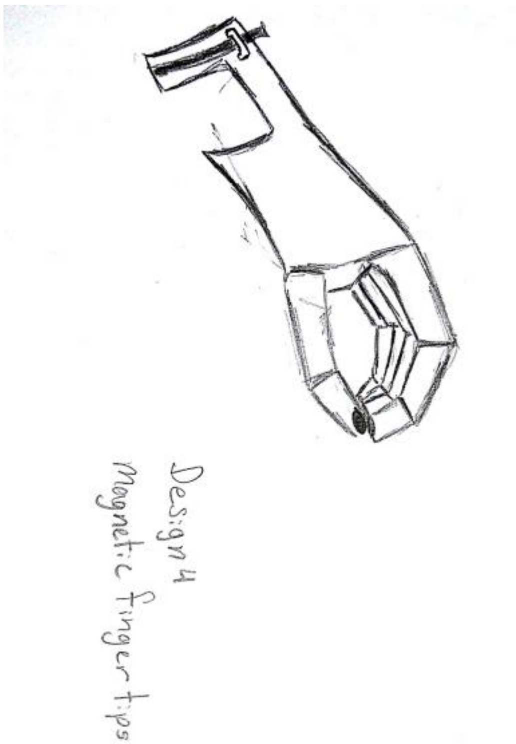


Figure 9: Magnetic Fingertips

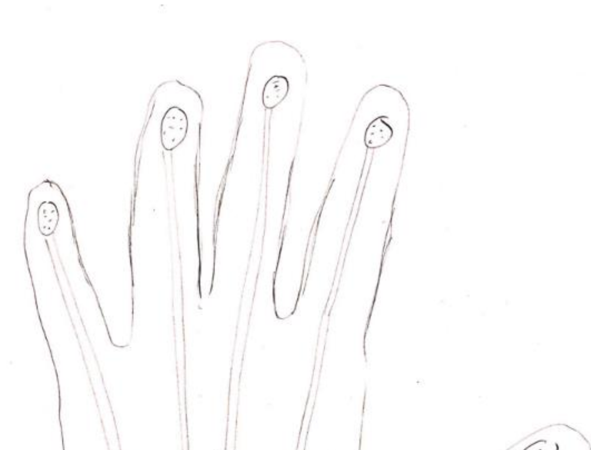


Figure 10: Visible Nerves

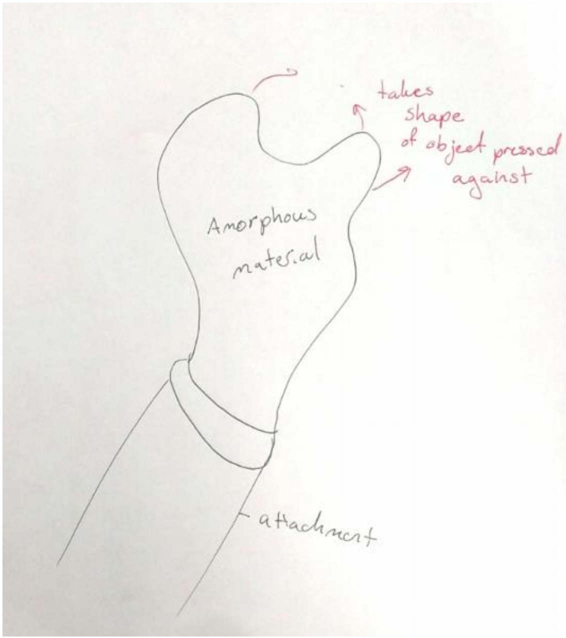


Figure 11: The Blob

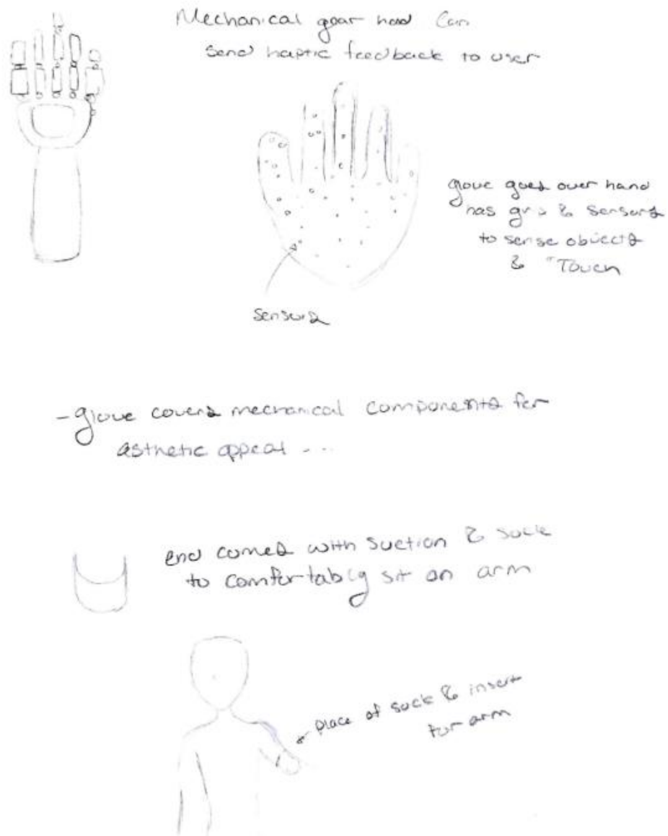


Figure 12: We Got You Covered

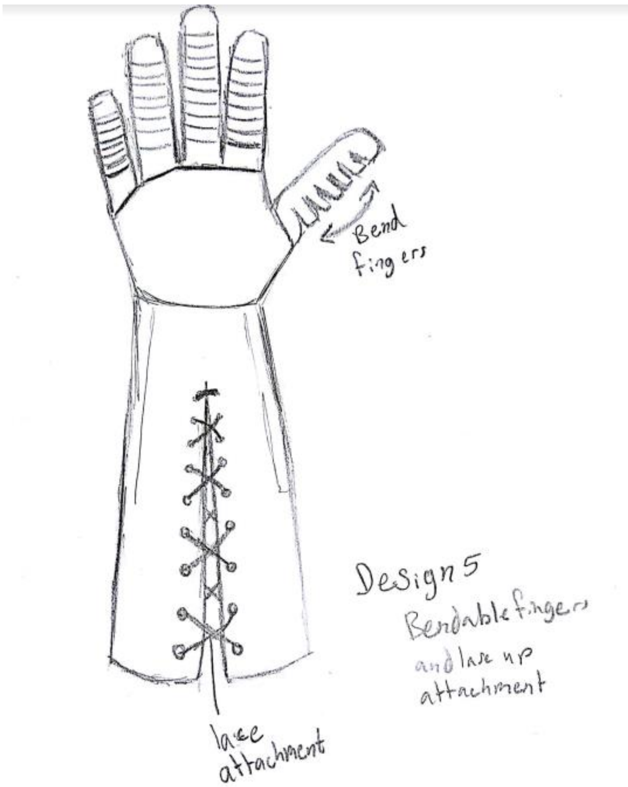


Figure 13: Bendy Fingers and Lace Up

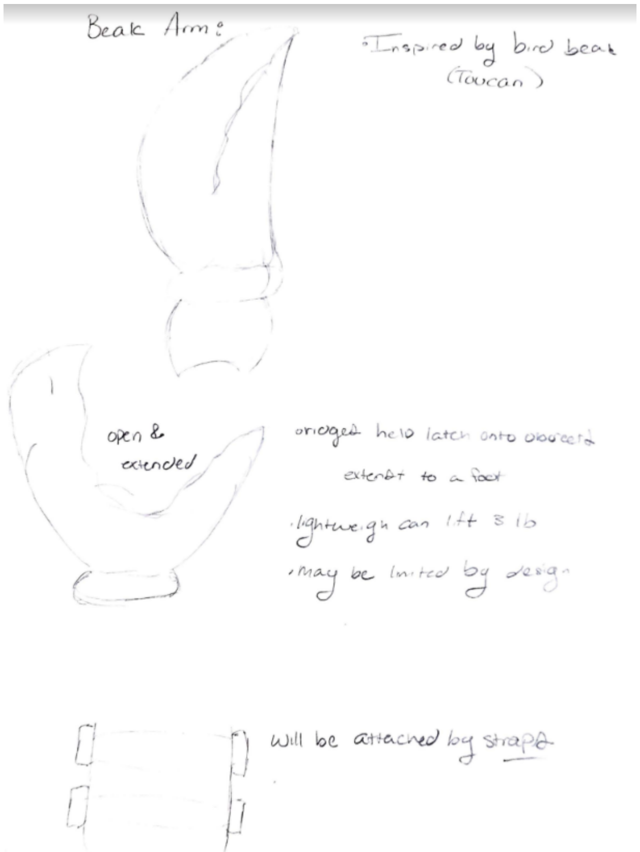


Figure 14: You Can Toucan

7 REFERENCES

[3.2.1]	“Enabling The Future,” *Enabling The Future*. [Online]. Available: http://enablingthefuture.org/. [Accessed: 10-Oct-2018].
[3.2.2]	“Open Bionics,” *Open Bionics*. [Online]. Available: https://openbionics.com/. [Accessed: 10-Oct-2018].
[3.2.3]	“Limbitless Solutions,” *Limbitless Solutions*. [Online]. Available: https://limbitless-solutions.org/. [Accessed: 10-Oct-2018].
[5]	
[6]	
[7]	
[8]	