Integration of a Sensory Driven Model for Hand Grasp Function in 3D Printed Prostheses

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INTEGRATION OF A SENSORY DRIVEN MODEL FOR HAND GRASP FUNCTION IN 3D PRINTED PROSTHESSES

By

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Submitted in Partial Fulfillment of the Requirements for Graduation with Honors from the South Carolina Honors College

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**Thesis Summary**

My Honors Thesis was completed through the Biomedical Engineering senior design project I worked on. Our project took a mechanically operated 3D printed prosthetic hand and automated the process by which it makes a grasp. The purpose of this project was to provide an affordable, automatic prosthetic hand to those either capable and incapable of wrist flexion. The current 3D printed prosthetic models require users to bend their wrist to initiate a simple grasp. However, our design took an alternative approach by using an EMG sensor placed on the ventral side of the forearm to record muscle activity, which, upon meeting a threshold value, would enact the grasp function. To achieve a fully-automated grasp, we also had to integrate a micro-linear actuator and an Arduino microcontroller to the base model. These three electronic sensors and processors worked together to communicate with each other, so that when muscle activations were strong enough in the forearm, the prosthetic device would appropriately execute a grasp.
Integration of a Sensory Driven Model for Hand Grasp Function in 3D Printed Prostheses

Final Report for Spring 2018
1 May 2018

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1. Introduction [Unchanged]

1.1 Problem Definition [Unchanged]

In the U.S. alone, incidence of congenital upper-limb reduction deficits is 3.64 out of every 10,000 births.\(^1\) An increasing number of children with traumatic or congenital motor debilitations now look to prosthetic solutions. Historically these have been ineffective, highly expensive, and largely unsuitable for long-term use due to child growth.\(^2\) In adults, upper-limb prostheses have been established as a way to provide restorative hand function to those missing or otherwise incapable of making full use of limb control within their own power.\(^3\) The most rudimentary of devices attach at the end of the arm and are mechanically driven by movement of peripheral remnants still physiologically controlled by the user’s intrinsic nervous system. Increasingly complex models provide much more extensive control of the prosthesis; however, these devices often require more invasive means of communicating with the user’s nervous system and can amount to staggering costs for state-of-the-art technology, ultimately rendering these a far less affordable solution to the problem.\(^4,5\) In an effort to mitigate the vast spread between these widely differing prosthetic solutions, our project aims to bring the mechanical prosthesis further along into the realm of the more integrated neural design, while staying true to the mission of providing upper-limb prostheses to children as an affordable, growth-adjustable, and readily available option to all.

Currently, one of the least expensive yet functionally useful options for upper-limb prostheses uses an open-source model integrating 3D printed materials and designs.\(^6\) Designs are made available on a platform known as Thingiverse, where prosthetic hand models are continually updated and modified. This has made it possible for non-profit organizations such as Hands On Prosthetic Engineering (HOPE) here at the University of South Carolina to provide child-specific prosthetic solutions – albeit purely mechanical – free of charge to those who need them. These are typically reprinted on a yearly basis to compensate for each child’s growth until they are eighteen. However, the 3D printed model does come with its limitations. Primary among them, the prosthetic requires wrist flexion from the user in order to grasp and release objects.\(^7\) This presents a major drawback to the otherwise highly useful and affordable prosthesis, as it excludes a substantial portion of the child population that need upper-limb prostheses at or above the wrist.

2. Problem Solution [Unchanged]
2.1 Current Design Rationale

2.1.1 EMG Sensory-Driven Model

To address the aforementioned limitations, our project will focus on expanding the functional scope of the 3D prosthetic so that the grasp mechanism may be activated simultaneously with muscle activation in the forearm. This mechanism will make use of a single EMG electrode sensor, designed to control onset and termination of grasp function. The EMG sensor will be placed on the surface of the muscles in the upper, ventral side of the forearm.\(^8\) We have identified the MyoWare EMG sensor as the device we will use to obtain myoelectric signals. This sensor utilizes a grounding electrode (to be placed on the bone at the elbow joint) as well as two electrodes to be placed above the muscles in the forearm. Additionally, the MyoWare EMG comes with an integrated and rectified signal processing function that minimizes the noise in the obtained EMG signal. Figure 1 shows the method by which this signal processing algorithm de-noises the raw EMG signal.

![Figure 1. EMG Signaling Processing.](image)

Sustained muscle activations will be used to provide a means for control of the electromyogram-driven prosthetic model. EMG signals are then directly sent to a mobile, attached microcontroller for real-time EMG data processing.

2.1.2 Microcontroller Processing Unit

The mini-computer we have selected to use in our sensory-driven prosthetic design is an Arduino UNO. This will serve as the control center for interpreting the signals received by the EMG using an algorithm-based design. This algorithm will require testing...
of muscle activation readings from the forearm area in order to properly specify the threshold. These trials will make use of our own recorded muscle activations for identifying the activation signal strength. The prosthesis will remain in a rest-state until muscle activation threshold is attained for grasp function. Release of prosthetic grasp will depend upon sustained relaxation.\(^9,10\) This sensor-to-computer communication serves as major a fix to a primary functional shortcoming we addressed in the current 3D printed wrist-flexion prosthetic mechanism; specifically, it provides an alternative for patients incapable of such wrist movements to regain identical motor control of the prosthesis via myoelectric activation. Directly from the microcontroller, the actuator will be connected, which is needed for effecting mechanical movement of the prothetic.

2.1.3 Actuation of Grasping Mechanism

We selected to use the Actuonix L12-I Micro Linear Actuator for this project because of the superior mechanical features provided by using a linear actuator. One of the most attractive design features of using a linear actuator is that the force provided throughout extension and contraction remains constant. Unlike its step-remoter counterpart, the linear actuator does not modulate force exerted based upon position in movement. Also, we were presented with options to specify the gear ratio and stroke lengths desired for use in this project. Our model will currently utilize the 210:1 gear ratio to provide superior back-drive force of 45 N. This was selected because of the maximal grasping strength it can provide. We then selected a stroke length of 100 mm. However, in examining the appropriateness of this choice, we are currently discussing whether to select a smaller size, since the 100 mm stroke length is far greater than our needs require and also decreases the side-load force able to be withstood by the actuator at full-extension.

2.1.4 Summary of Sensory-driven Model

In summary, our model will integrate three key components to produce a sensory-driven grasping mechanism of a 3D printed prosthetic, those being: the MyoWare EMG Sensor, the Arduino UNO Microcontroller, and the Actuonix Micro Linear Actuator. Additionally, we will utilize a portable battery source to power the microcontroller and actuator. Figure 2 below provides a graphical visualization of how the respective components will be integrated in our sensory-driven model.
Figure 2. *Full Prosthetic Device Integration.* This figure shows the orientation of the final integrated prosthetic. The components of the prosthetic include; the Phoenix V₂ Hand, the linear actuator, the EMG sensor, and the armband that will hold the Arduino microcontroller as well as the battery. Wiring of components is not shown in this figure.

2.1.5 Safety Concerns

Safety always needs to be taken into consideration, especially when electrical components are involved. Figure 3 below shows the wiring diagram of the battery that will be supplying all of the power to the prosthesis. With this configuration, no components are connected to the electrical grid and further isolation is not necessary. The configuration is set up this way so that the patient will not be shocked during use.

![Battery Wiring Diagram](image)

Note: Since no component is connected to electrical grid, further isolation is not required. It is also acceptable to power the MCU with a battery via the USB or barrel ports.

Figure 3. *Electrical Wiring Diagram.* This figure outlines the configuration of the wiring between the battery, Arduino, and EMG sensor. The battery however, will be plugged into the USB port and still be isolated.

2.2 Alternative Considered Solutions

2.2.1 Outdated 3D Printed Hand Model
One of the earlier 3D-printed prosthetic hand-models we looked to incorporate as our base structure for this project was the Raptor hand, available from the open-source Thingiverse website. We ultimately decided to stay away from this design as it did not adequately comply in hand-grasping tests. When the hand was contracted, the thumb’s placement and orientation prohibited successful grasping of ordinary objects, especially those that were cylindrically shaped (e.g., plastic cups, or bowls). For this reason, we did further research and identified the newer Phoenix V2 hand model - also available on Thingiverse - to have appropriately addressed this grasping deficit. The Phoenix V2 utilizes an adjusted thumb orientation in which the thumb no longer constricts the ability to grasp cylindrical objects.

2.2.2 Increasingly Integrative Microcontroller

Another aspect of our prosthetic model which we altered from our initial proposal was the microcontroller. Originally, we had planned on using a Raspberry Pi Zero W microcontroller computer instead of the Arduino UNO. The reason for this is because the Raspberry Pi had a much sleeker and smaller design, had wireless Bluetooth capabilities, and we planned on coding our algorithm in Python (which comes pre-downloaded on the Raspberry Pi). Once we received our Raspberry Pi Zero W, it was indeed very sleek, but its processing power was extremely slow. Also, after some initial coding in Python and further research, we found that using Arduino IDE (comes pre-downloaded on Arduino microcontrollers) to build our algorithm would be much easier than Python. On top of this, the Myoware EMG sensor was originally designed for Arduinos, and similar projects using both the Myoware EMG sensor and Arduino IDE are available on Github for our reference.

2.2.3 Sliding Grasp Function

The most recent design change implemented with our prosthetic device pertains to the mechanical functioning of executing the grasp. Our initial thought was to attach each of the individual digits’ tension wires to a central point at which the actuator would be connected. However, in discussing the efficacy of such a design with one of the mechanical implementationists at HOPE, he believed it would be more feasible to approach this goal from another angle. We settled upon going with a design that attaches the actuator directly to the gripper-box (the encasement where the tension wires typically are embedded above the wrist). The utility of this modification is found in the reduced interference when performing a grasp. It is in the gripper-box that all tension wire
connections are contained; thus, by alone moving this one piece smoothly along its track, we minimize the impedance met in executing this movement. Our updated design will require making some minor size changes to the sliding insert used to connect the gripper-box with the prosthetic hand. The sliding insert must be shrunk to 98% of full-size printing in order to provide motility along the hand model’s connective track. Friction will be minimized by inserting a thin strip of Teflon between the connective track and sliding insert pieces.

2.2.4 Placement of Electrical Components

Originally, it was our intent to design a 3D printed compartment where each of the electrical components would be situated. Unfortunately, we did not foresee the amount of time it would require to first learn how to edit 3D models using CAD software, much less precisely apply these designs in making a fully-protective encasement. We alternatively looked for a more temporary solution that gave us the ability to still integrate each of the sensor and actuator parts for testing and display of our prosthetic device. This led us to settle on an arm band solution where both the Arduino and the battery can attach, much like an iPhone on the arm of a jogger. The arm band utilizes a magnetic strip, which is attached to the back of the battery and the Arduino case, as well as a clasp mechanism for secured placement on the arm. This alternative design has the benefit of removing weight from the forearm, which results in less torque required for the user to bend at the elbow joint.

3. Goals & Objectives [Unchanged]

3.1 Goal 1 – Processing the EMG signal input generated by muscle activation.
   a. **Objective 1a** – Limit the EMG sensor attachment to the forearm muscle area.
   b. **Objective 1b** – Design an algorithm in the Arduino IDE that will signal to flex the prosthesis when a minimum muscle activation threshold of 200 mV has been met until the patient relaxes their forearm.

3.2 Goal 2 – Creating a transradial prosthesis mechanism that uses the processed EMG data to allow amputees to mimic normal muscle movement and hand contraction.
   a. **Objective 2a** – Adjust placement of thumb piece from a 90° angle that was fully abducted and extended to a 135° angle that is fully extended and abducted in the open-source prosthesis design.
   b. **Objective 2b** – Use armband straps to attach the external battery and Arduino chip on the bicep area of the patient.
c. **Objective 2c** – Limit the max length of the actuator to 30 mm, a max gear ratio of 50:1 and a voltage of 6 volts.

**4. Methodology**

**4.1 EMG Sensor Placement and Testing**

The EMG sensor is one of the most important pieces for this device to work, therefore the sensor must be properly connected and functioning as needed. First, in order to ensure the EMG sensor works, the best muscle groups and attachment location must be found. After consulting with Dr. Hartstone-Rose at the USC School of Medicine, he recommends placing the sensor on the ventral side of the forearm and about 1 inch distal from the elbow because this group of muscles contain wrist and finger movement. For clearest results, the area the EMG will be attached to will be thoroughly cleaned with soap and water, abraded, and dried completely before attaching the sensor. Next, the EMG sensor must be connected to the Arduino micro-controlling computer. The sensor is connected to the micro-controlling chip ground and power leads in order to power the sensor as well as to an input lead where the chip will read in the data fed into that lead. Once this connection has been made, testing can be done to find out the proper muscle activation threshold as well as to ensure the sensor connection has been made appropriately. Testing will be conducted on each group member. Each group member will have the EMG sensor attached to themselves and will flex their forearm muscles for 2 s, relax their muscles for 2 s, then repeat for 20 seconds total. Each member will conduct 5 total testing trials; for 4 groups members that will be a total of 20 testing trials. After the proper threshold of muscle activation has been found, that value will be used in the software of this project to activate the linear actuator. It is understood that group members are adult males and will be able to output stronger muscle activation values than children are able to. Due to this, the threshold parameters in the software can be changed with initial testing on the patient. By attaching the EMG sensor to the patient and having them flex for 2 seconds then relax for 2 seconds for a total of 16 seconds; the software can output a list of values during the flexed and relaxed time period that can be analyzed to find the initial value of flexing. This value will be the patient's threshold. It is recommended that this initial testing process is done for every patient regardless of age or sex.

**4.2 Arduino Software Data Processing**

Next, once the EMG sensor has been connected to the Arduino chip, then the
necessary algorithm that will be able to decode the EMG data will be loaded onto the chip. This algorithm will be written in Arduino’s own IDE in order to simplify the process of loading the software onto the chip. The algorithm’s main function will be able to determine if the minimum muscle activation threshold has been reached or not. The Arduino chip will be continuously fed data from the EMG sensor and will constantly check each sensor value read by the chip to see if the threshold has been met. Then, if the threshold has been met, the algorithm must communicate to the linear actuator via one of the chip’s output pins to retract the actuator which tightens the strings on the prosthetic. Consequently, if the threshold has already been met and then the EMG values fall below the threshold value, the algorithm will then communicate to the actuator for it to extend and therefore relax the strings of the prosthetic. A screenshot of the current Arduino algorithm being developed is provided in Appendix A.

When tension is applied to the strings, the prosthetic moves in a grasping motion as to grab an object in front of the patient. However, it was noted that position of the thumb was somewhat problematic when trying to grasp a cylindrical object. The design of our device aims to rotate this thumb piece to 135° extended and abducted. Upon further research, a 3D CAD design was found that contains this preferred thumb placement and is called the Phoenix Hand V2 which can be seen in Figure 4.

![Figure 4. Phoenix V2 Hand 3D printed model. This figure shows the Phoenix V2 Hand (A) and an illustration of how tension strings control the fingers (B).](image)

### 4.3 Linear Actuator Extension and Relaxation

The linear actuator, which will control the grasping motion of the prosthetic, will then be connected to the Arduino chip. The actuator will be connected directly to the gripper-box encasement into which the tension wires are embedded. These strings embedded in the gripper-box connect to the palmar side of the fingers of the prosthetic. When the strings are pulled, the fingers and thumb of the prosthetic curl inwards to perform a grasping motion. Therefore, the actuator must retract in order to pull on the
strings for the grasping motion and then extend to relax the strings and therein the fingers and thumbs of the prosthetic. Now the EMG to micro-controlling chip to actuator movement apparatus has been completed. This apparatus will be tested in a similar way to how the EMG sensor was initially tested. Each group member will wear the EMG sensor and then flex their forearm muscle until the actuator responds and retracts, then the group member will relax their forearm until the actuator responds and extends. This will be done continuously for 30 seconds and 5 trials will be conducted for each member for a total of 20 trials.

4.4 3D Printed Hardware Encasement Piece Design

Once the hardware pieces have been connected and tested, a 3D printed attachment piece will be designed to hold the EMG sensor, Arduino chip, linear actuator and all the wiring in place. This attachment piece will fit around the patient’s forearm and will attach directly to the prosthetic at the gauntlet portion of the 3D printed design as shown in Figure 4. This attachment piece will be designed using CAD software and printed with the use of HOPE’s 3D printer. As mentioned in the objectives, the maximum dimensions of this piece will be 18 cm in length and 8 cm in diameter. There must be enough space for all the hardware components to fit on the attachment, but this piece will be designed to weigh less than 5 pounds when all hardware pieces are attached. The weight of this attachment piece is becoming a limitation because there are multiple pieces being attached to the piece which contribute to its overall weight. Since this piece is going to be worn by the patient for long periods of time, the encumbrance that the patient will endure needs to be minimized, which will be done by limiting the overall piece’s weight to under 5 pounds. Padding and velcro- straps will also be added to this attachment piece in order to ensure the patient of the comfort as well as easy removal for when the patient decides to take the device off for the day.

4.5 Design Limitations

The main limitation that the company has run into with this project is the possibility of inaccurate data. The project sponsor, HOPE, builds prosthetics for children in need for free. Therefore, because all of our testing will be done on adult men, the data for EMG sensor readings may be inaccurate since the targeted user will be a child. However, this limitation is combated by making the design of the device as flexible and open to changes for specific patient needs. The attachment piece for the hardware components will be 3D printed and can be changed to fit the patient’s forearm length and geometry easily using CAD software. The software algorithms are developed in the Arduino IDE and can be changed to fit the patient i.e., the threshold value and extension
length of the actuator are changeable parameters based on the patient’s forearm muscle activity and overall length.

Another major limitation that has been found is the possibility of damage to the electrical components of the device, more specifically: water damage. It would be extremely difficult to make the design waterproof due to the fact that the EMG sensor needs to make direct contact with the skin in order to record the best and most clear data. The Arduino chip has a case in which it can be placed inside of in order to add protection to physical damage but due to the wiring, this case contains openings and therefore will not protect from water damage to the chip. In order to prevent any water damage, significant warnings in the form of labeling and direct verbal warnings during the consultation and fitting meetings will be required.

5. Results

5.1 Prosthetic Hand Design Results

5.1.1 Prosthetic Hand Overview

Using the online resources, “Enabling The Future” and “thingiverse.com”, the Phoenix Version 2 Hand was chosen as the most ideal prosthesis to help SenseTech achieve its goal. Not only does “thingiverse.com” have a CAD drawing of every piece of the Phoenix V2 Hand open source and available for manipulation on “thingiverse.com”, but it also is the most anatomically correct prosthetic hand on the website. A photo of the Phoenix V2 Hand is shown on the left side of Figure 4. The thumb of this protheses is positioned in more of a 135° angle instead of a 90° angle, a feature that the majority of other available options do not have. A total of 18 different pieces (at 102% scale) have been 3D printed and assembled to complete SenseTech's Phoenix V2 Hand. An assembly guide for the hand can be found in Appendix B.

5.1.2 Gauntlet Piece

The Gauntlet piece of the Phoenix V2 Hand is shown below in Figure 5. The location of this piece is proximal (above) the wrist and connects to the palm of the hand. This piece is thermoformable to the arm of the patient for a customized fit and provides the track (can be seen protruding on the top of the Gauntlet) that the Gripper Box shown in Figure 6 fits into. The modification of this piece required us to stretch the ‘track’ further up the arm so that the actuator can be mounted onto the prosthesis. Figure 2 shows the planned
placement of the actuator. The dimensions of the original gauntlet piece (A) was 120 mm x 106 mm x 8 mm and the dimensions of our modified gauntlet design with the extended track (B) are 222 mm x 106 mm x 8 mm. The manipulation was a 102 mm extension of the gauntlet track on the x-axis.

![Figure 5. Gauntlet 3D Print Model. This figure shows the CAD drawings of the unmodified version of the gauntlet piece (A) and the new, modified version of the gauntlet (B).](image)

5.1.3 Gripper Box

The Gripper Box piece of the Phoenix V2 Hand is shown below in Figure 6. This piece functions as the structure that all of the tension wires feed into. More specifically, inside of the Gripper Box is the location of very important functional pieces of the hand; the whippletree (Figure 7), the swivel pin (Figure 8), and the thumb tensioner (Figure 9). The whippletree, in short, distributes the load of the object being grasped by the hand throughout all of the fingers and tension wires. The swivel pin and the thumb tensioner are pieces that help the whippletree perform its function. Additional information regarding the whippletree can be found in Appendix C. The manipulation that was required for the Gripper Box was to reduce the overall size of the piece by a 2% scale and print it at 100% scale. By doing this, it allowed for the Gripper Box to slide up and down the track of the Gauntlet, a function needed to make the hand grasp while keeping the functionality of the whippletree. The Gripper Box will attach directly to the linear actuator. As previously mentioned, the goal of this is to directly pull the gripper box up
the track of the prosthetic to perform the hand grasp function as well as keeping the functionality of the whippletree.

In order to attach the linear actuator to the box, another manipulation was made. As seen in the bottom picture of Figure 6 below, two small protrusions are on the back of the box that will allow connection to the actuator. The dimensions of the original gripper box (A & B) is 33 mm x 35 mm x 18 mm and the dimensions of the manipulated gripper box with the protrusions (C) is 41 mm x 35 mm x 18 mm. The manipulation was two 8 mm protrusions on the back side of the x-axis. These two protrusions contain holes that will allow screws to feed through. The actuator is placed in between these protrusions and a screw is fed through one protrusion, through a hole at the end of the actuator then through the second actuator and being capped off. This allows the actuator to pull and push the gripper box in order to create bio-mimetic functionality.

![Gripper Box 3D Model Design](image)

*Figure 6. Gripper Box 3D Model Design.* This figure shows the CAD drawings unmodified gripper box (A and B) as well as the modified gripper box (C).

### 5.1.4 Whippletree Piece

As previously mentioned, the whippletree is shown below in Figure 7 and is located inside of the gripper Box. The manipulation of the whippletree required was a 2% scale reduction of the piece overall so that it will fit into the reduced gripper box (100% scale).
Figure 7. Whippletree 3D Print Model. This figure shows the CAD drawing of the whippletree of the Phoenix V₂ Hand.

5.1.5 Swivel Pin Piece

Figure 8 below shows the swivel pin. This piece holds the whippletree inside of the gripper box. Again, all that was needed was a 2% scale reduction and print at a 100% scale.

Figure 8. Swivel Pin 3D Print Model. This figure shows the CAD drawing of the swivel pin piece.

5.1.6 Thumb Tensioner Piece

Figure 9 below shows the thumb tensioner piece. This piece is for the tension wire for the thumb and also received a 2% reduction in scaling to fit inside of the gripper box.
Figure 9. *Thumb Tensioner Piece 3D Print Model.* This figure shows the CAD drawing of the thumb tensioner piece.

### 5.2 EMG Sensor Data Readings

The EMG sensor testing trials for each group member have been completed and a sample screenshot of the data printout has been provided in Figure 10. Once the patient being tested on activated their muscle for 1 second, the data was recorded for the next 1 second to ensure complete muscle activation. The minimum value during this time of muscle activation will be taken as the threshold to be met to activate the actuator because during this activation time this value represents what minimum value occurs during muscle activity. After the testing trials were completed the average value was 200 mV. In Figure 10 the muscle activation alternates between 30 and 31; this is a baseline value when no muscle activity is being recorded. Once these values reach 200 or greater, the software will signal to the actuator to tense.

Figure 10. *A trial run of the EMG Myoware sensor.* Sensor placement was located on the ventral side of the right forearm. A repeated cycle of sustained grasp-relax muscle activations was performed. Grasp muscle activations that exceeded the set threshold of 200 are denoted with an asterisk.
5.3 EMG to Actuator Connection Results

The EMG testing trials have been concluded and the threshold value has been determined. The final tensile state for the actuator has been set to 1% of functional length, or 0.3 mm, and the relaxed state has been set to 60% of functional length, or 18 mm. Testing the actuator-to-EMG sensor connection has been completed. Testing was done using a similar testing protocol outlined in section 5.2. Each group member had the EMG sensor attached to them and the EMG sensor was connected to the Arduino chip and actuator. The group member would flex for a period of 2-5 seconds and the actuator would retract or do nothing; this is considered one trial. If the actuator retracted the trial is marked as a success, if the actuator does nothing the trial is considered a failure. Ten flexing trials were done for each group member. A 90% success rate was reported for the flexing trials. During the flexing trials, if the trial was a success the actuator should extend once the group member relaxes. Therefore, for every successful flexing trial, we can observe whether or not the actuator extends due to muscle relaxation. A 94.4% success rate of relaxation was reported. Overall the actuator responds to muscle activity a majority of the time which is vital to the success of the project.

5.4 Finished Fully-Integrated Prosthesis

All components of the design have been printed, built and integrated into one functioning prosthesis. The gauntlet piece, with its modification, has been attached to the hand; the gripper box component has been attached to the gauntlet piece; and all these pieces have been connected via strings. The actuator has been attached to the gauntlet piece and gripper box and has been connected to the Arduino chip. The EMG sensor has been attached to the Arduino chip as well. Both the Arduino chip and battery pack have been attached to an iPhone arm band that will be worn around the bicep of the client. The battery is able to supply enough power to the Arduino chip and actuator that they can operate autonomously while being controlled by the forearm muscle of the client. When the battery pack is turned on and the EMG sensor is attached to the forearm, the prosthesis grasps when the forearm tenses and relaxes when the forearm relaxes. This fully-integrated prosthesis has been attached to all four group members and has been tested for at least 10 minutes on each group member. A full view of the completed prosthesis is shown below in Figure 11.
6. Conclusions

6.1 Goal 1 - Processing the signal generated by muscle contraction.

Goal 1 can be analyzed by the two objectives that were set to complete it. The first objective set for Goal 1 is to limit the EMG sensor attachment to the forearm muscle area. It can be concluded by looking at Figure 10 above that the sensor can accurately and continuously measure the muscle activations on the forearm muscle on a healthy adult male. Also, during final testing of all of the integrated components, the actuator accurately responds to muscle activation. However, a current limitation for this objective is that the EMG sensor has not been tested on someone that doesn’t have a hand. So, there is no data available from anybody that we are making this product for. With that being said, the EMG sensor has an adjustable gain if it is harder to pick up muscle activation on a patient without a hand. Also, if the forearm muscle region does not have strong enough muscle signal, the EMG can easily be moved to the bicep muscle or any other muscle on the body.

The second objective for Goal 1 was to design an algorithm using the Arduino IDE that will keep the prosthesis flexed when the primary EMG sensor is activated until the patient relaxes the forearm muscles. SenseTech can say with confidence that this
objective has been achieved. The code for this objective can be found in Appendix A. This objective has been achieved and verified through preliminary testing; the software does everything that is required without failing. However, a limitation to this objective is that a patient with smaller muscle activation signals (a child without a hand) would have to change the maximum and minimum threshold values inside of the code for it to be tailored for the patient. This limitation does not seem to be major issue, as the code is fairly easy to modify.

6.2 Goal 2 - Creating a transradial prosthesis mechanism that uses the EMG sensor in order to allow amputees to mimic normal muscular movements and hand contraction.

Goal 2 can be analyzed by the three objectives that were set to complete it. The first objective for Goal 2 was to adjust the placement of the thumb. This objective was originally set because SenseTech was initially working with the Raptor Reloaded hand – probably the most common hand used by HOPE. After further research, the Phoenix V2 Hand was discovered. Not only did this prosthetic look better, but it had a better anatomically placed thumb (first objective) and had the function of the whippletree (explained in the results section). This objective is 100% complete and there are no limitations.

The second objective for Goal 2 is to use armband straps to attach the external battery and Arduino microcontroller on the bicep area of the patient. This objective was also achieved. A visual of this objective can be seen in Figure 11. The only limitations to this objective is the comfortability of these straps and any damage that could occur with a more active client. The battery and the Arduino can be moved around the armband to be in the most comfortable location possible but may get in the way at times. This limitation can also be visualized in Figure 11.

Lastly, the third objective for Goal 2 is to limit the actuator to a max stroke length of 30 mm, a max gear ratio of 50:1, and a voltage of 6 volts. The linear actuator that has been integrated into the prosthesis has the capability of pulling and pushing a total of 30 mm, has a gear ratio of 50:1, and a maximum voltage of 6 volts. This was chosen so that it could fit onto the prosthetic comfortably, actuate as fast as possible (make hand grip as fast as possible), and have a low voltage that the battery and Arduino can handle.

Overall, SenseTech believes that this final product works as intended and can easily be improved on by future design groups.
7. Future Plans [Unchanged]

7.1 Ideas for Improved Solution Design

Design and completion of our sensor-integrated prosthetic has gone in a timely manner; however, the area which we, as a group, share the least combined experience in is with the 3D modeling software. Because of pressure to stay on pace with the completion of the project, we were unable to allocate the time to taking CAD modeling courses or otherwise being trained in functional use of these programs. As a result, our electrical components remain exposed and susceptible to water infiltration. A highly improved design modification in the future would be to have a team with more CAD experience put forth 3D printed extensions of the gauntlet which include a safe and secure encasement in which the actuator, microcontroller, and battery may all reside. In this way, our device would be maximally protected from any kind of electrical hazard, and thus, minimize risk of injury to the user.

Shifting to the software-end of our solution design, the grasp function control algorithm we have implemented in response to muscle activations is extremely simplified. The microcontroller reads in the EMG data, and if threshold is achieved, it outputs to the actuator the signal to retract, thus effecting a grasp motion of the prosthetic. Currently this is a binary solution: retract or extend back to rest. An improved design would program the microcontroller in such a way that the user is provided more fluid, continuous control of the extent of grasp. Resultantly, the user could be capable of making grasps that selectively determine the degree to which the hand should close, instead of flipping between either fully closed or fully relaxed grasping states.

7.2 Future Groups Work

Future groups may continue to build off our existing sensor-integrated prosthetic design by including the aforementioned solution improvements to maximize functionality and minimize risk associated with daily, all-condition use. Time must certainly be allotted for group members to learn how to use Autodesk Inventor or another CAD modeling program, unless they already bring extensive CAD modeling experience with them to the table. Dimensions must be precise and form-fitting to the individual electrical components, thus ensuring minimal exposure to the elements. Furthermore, thorough testing of the EMG sensor readings should be conducted in future studies. This would provide necessary information for designing a more complex software component which facilitates the degree of grasp function on a more continuous level. We believe having
collaborative interaction across students of different engineering backgrounds – especially mechanical, electrical, and computer science – would enhance the quality of the finalized solution, as there are simply skill-sets that we as biomedical engineers do not have as robust knowledge or experience in. This collaboration should ideally be sought in the Hands On Prosthetic Engineering (HOPE) organization as it pulls from students across many different majors, though primarily still in the College of Engineering and Computing.

8. Budget

8.1 Funding Sources

The University of South Carolina Biomedical Engineering Program has provided $1,000 towards the budget of this project. A budget of $1000 was allocated towards necessary materials. Table I below outlines a comprehensive review of all of the materials necessary to complete the project. A total of $601.08 is final amount of money spent at the conclusion of the project. If SenseTech, or any future group wanted to create another hand, Table II outlines the required materials and money necessary for that budget, totaling $339.23.
Table I. *SenseTech Budget*. The estimated budget for the development of an EMG sensory driven attachment that integrates into a HOPE 3D printed prostheses for hand grasp function.

<table>
<thead>
<tr>
<th>Acquired Item</th>
<th>Cost</th>
<th>Total Spent</th>
<th>Remaining Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Raspberry Pi Zero W Starter Kit</td>
<td>$47.70</td>
<td></td>
<td>($1000 - $601.08) = $398.92</td>
</tr>
<tr>
<td>2 GPIO Header &amp; Jumper Wires</td>
<td>$21.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Arduino Microcontroller Starter Kit &amp; Case</td>
<td>$108.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 iPhone Armband Holder</td>
<td>$27.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Linear Actuator</td>
<td>$110.67</td>
<td>$601.08</td>
<td></td>
</tr>
<tr>
<td>6 Myoware EMG Sensor Development Kit</td>
<td>$86.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 EMG Electrode Pads</td>
<td>$48.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 USB Battery Pack</td>
<td>$36.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Linear Actuator</td>
<td>$104.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Dental Rubber Bands</td>
<td>$10.74</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table II. SenseTech Budget for future hands. The estimated budget for the creation of a SenseTech customized EMG hand.

<table>
<thead>
<tr>
<th>Acquired Item</th>
<th>Cost</th>
<th>Total Spent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MyoWare EMG Muscle Sensor</td>
<td>$44.12</td>
<td></td>
</tr>
<tr>
<td>2 Arduino UNO Microcontroller</td>
<td>$25.24</td>
<td></td>
</tr>
<tr>
<td>3 Linear Actuator</td>
<td>$104.11</td>
<td></td>
</tr>
<tr>
<td>4 USB Battery Pack</td>
<td>$36.10</td>
<td></td>
</tr>
<tr>
<td>5 iPhone Armband Holder (x2)</td>
<td>$27.73</td>
<td></td>
</tr>
<tr>
<td>6 Jumper Wires</td>
<td>$5.24</td>
<td></td>
</tr>
<tr>
<td>7 EMG Electrode Pads (50-pack)</td>
<td>$36.69</td>
<td></td>
</tr>
<tr>
<td>8 Phoenix V2 Hand Assembly Kit</td>
<td>$30.00</td>
<td></td>
</tr>
<tr>
<td>9 Estimated PLA filament cost (3D printing)</td>
<td>$30.00</td>
<td></td>
</tr>
</tbody>
</table>

$339.23

8.2 Links to Purchased Materials

b. https://www.amazon.com/Foxnovo-Breadboard-Jumper-Wires-Female/dp/B00PBZMN7C/ref=sr_1_3?ie=UTF8&qid=1509562694&sr=1-3&keywords=female+to+male+jumper+wires
c. https://www.amazon.com/Phantom-YoYo-Dupont-Cable-Female/dp/B00KOL5BCC/ref=sr_1_5?ie=UTF8&qid=1509562742&sr=8-5&keywords=female+to+female+jumper+wires
e. https://www.amazon.com/Reserwa-Armband-Adjustable-ReflectiveiPhone6s/dp/B072F2Q84S/ref=sr_1_26?ie=UTF8&qid=1516717814&sr=8-%2026&keywords=iphone+running+armband
f. https://store.arduino.cc/usa/arduino-starter-kit

g. https://store.arduino.cc/usa/arduino-uno-case


i. https://www.sparkfun.com/products/14409

j. https://www.sparkfun.com/products/12969

k. https://www.adafruit.com/product/1565

l. https://www.thingiverse.com/thing:1453190


o. https://www.amazon.com/Clear-X-Heavy-Orthodontic-Elastic-Braces/dp/B01MUC97XM/ref=pd_sim_121_11?encoding=UTF8&pd_rd_i=B01MUC97XM&pd_rd_r=STFM8PBG5W7VH213PCP2&pd_rd_w=neVFp&pd_rd_wg=8l6cS&psc=1&refRID=STFM8PBG5W7VH213PCP2
9. References


10. Appendices

Appendix A. Current Arduino Software Code

```c
proshstompove
#include <Servo.h>

Servo myServo;
#define PIN_SERVO (2)

void SetStrokePerc(float strokePercentage)
{
    if (strokePercentage >= 1.0 && strokePercentage <= 99.0)
    {
        int usec = 1000 + strokePercentage * (2000 - 1000) / 100.0;
        myServo.writeMicroseconds(usec);
    }
}

void SetStrokeMM(int strokeReq, int strokeMax)
{
    SetStrokePerc(((float)strokeReq) / strokeMax);
}

// If EMG has reached threshold and CurrentPosit
if (sensorValue >= 200 && CurrPos == 60) {
    // start actuator to tensile state
    SetStrokePerc(1);
    CurrPos = 1;
}

// If EMG has released below threshold and Curr
else if (sensorValue < 200 && CurrPos == 1) {
    // set actuator to relaxed state
    SetStrokePerc(60);
    CurrPos = 60;
}

delay(700);
```

This appendix is the printout of the current Arduino software code that has been developed. The software includes positions controls for the linear actuator as well as a continuous loop to check if the minimum threshold of muscle activity has been met.

Appendix B: Link to Phoenix V2 Hand Assembly Guide

https://cdn.thingiverse.com/assets/dd/6b/45/30/fc/Phoenix_v2_assembly_guide.pdf

Appendix C: Additional Whippletree Information

https://www.youtube.com/watch?v=dW5B_CeJtd8&feature=youtu.be