# e-NABLE: Create a hold and release mechanism for hand designs

University of Wisconsin-Madison
Biomedical Engineering Design 400
December 12th, 2018

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e-NABLE

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# Abstract

e-NABLE is an open source 3D printing volunteer community that provides low cost easily sourced prosthetics to individuals with an afflicted hand. The hand prosthetics provided by e-NABLE all operate by the same closing mechanism; the wrist is flexed causing strings to flex the fingers. This flexion of the wrist leads to muscle fatigue, especially while holding objects for an extended period of time. Currently, there is no way to keep the hand in a closed position without maintaining wrist flexion. The goal of this project is to create a mechanism for locking the fingers in a closed position, relieving muscle strain from wrist flexion during prolonged use of the device. The mechanism chosen is a clamp that is integrated onto the back of the palm of the original device. The clamp provides the ability to maintain tension in the strings without wrist flexion and allows the user to extend their wrist while keeping the fingers closed. The clamp design was tested using some proof of concept prototypes including: clamp material testing, distributed force testing, and EMG testing. Through these tests, the concept of the clamp design meets all current design specifications. The force gauge test indicate the hand is capable of holding the required weight of a 12oz soda can, and EMG data shows significantly less muscle activation using the new design.

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# Introduction

### *Motivation*

In war-torn nations around the world, the most common form of limb loss results from land mines, which cause 26,000 amputations each year [1]. In addition to limb loss due to violence such as land mines or terrorist attacks, lack of access to health services further compounds the number of amputees in developing nations. Prosthetic devices are both monetarily and geographically out of reach to amputees in these developing nations, with the average cost of a prosthetic in the United States ranging from \$5,000 to \$15,000 [1]. Unfortunately, the issue of access to prosthetics does not end once an individual manages to obtain one, because the average adult needs a new prosthetic every 3 to 5 years, and children need a replacement every 6 to 12 months [1]. Since amputees in developing nations typically belong to the working class, low-cost, durable, and operational prosthetics are desperately needed.

### *Existing Devices and Current Methods*

Prosthetic hands primarily serve either functional or cosmetic purposes. Of the functional prosthetics, these can either be powered via electric motors/batteries or body movements. Electric-powered prosthetics offer stronger grip force, since they aren't limited by the user's physical ability, and can be made to look more like an arm and hand. Myoelectric hands use electrical signals generated in the muscle and detected on the skin surface to control the prosthetic movements [3]. However, this type of prosthetic is expensive, ranging from \$20,000 to \$100,000 [4]. The bebionic myoelectric hand utilizes sensors and small motors to achieve fine hand movements with a weight comparable to a hand (Figure 1). In contrast, body-powered prosthetics tend to be lighter and cheaper [2]. An example of a body-powered prosthetic is the split-hook design (Figure 2). This type of design utilizes cables attached to the user's shoulders. By contracting muscles in the shoulder, the user creates tension in the cable to either open or close hook like pincers at the end of the prosthetic. While cheaper than a myoelectric hand, this design can cost up to \$10,000 and its grip force is limited by the user's physical ability [4].

**Figure 1: bebionic Myoelectric Hand Prosthetic**
The bebionic hand prosthetic has a similar weight and appearance to a biological hand, and operates using small motors which detect electrical signals in the skin.

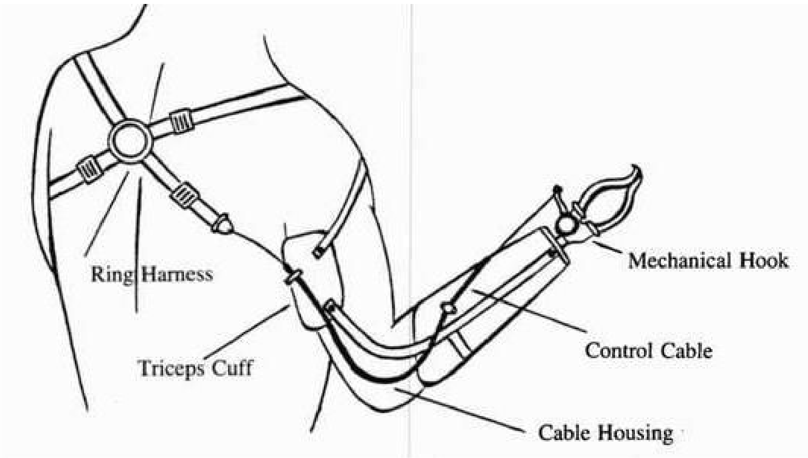


**Figure 2: Split-hook Hand Prosthetic**
The Split-hook hand prosthetic attaches at the shoulder. Using their muscles, the user applies tension to the cable to either open or close the hook at the terminal end of the prosthetic.

### ***Problem Statement***

e-NABLE is a large community of volunteers serving people in need of low-cost prosthetics. To date, over 10,000 volunteers have made and delivered 2,500 to 3,000 prosthetics to people in over 90 countries [5]. Currently, all e-NABLE hand designs operate by the same closing mechanism: the wrist is flexed, causing cables to clench the fist. If the user wants to continuously hold an object they must keep their wrist bent at an awkward angle (Figure 3). This fatigues the flexor carpi radialis muscle in the forearm, making it difficult to hold things for a prolonged time. The purpose of this project is to create a locking mechanism on the prosthetic so that objects can be held easily for a long period of time. To do this, the team must design a way to pull the contraction cables and lock them in place until the user wishes to release the item.

## Background

### *Client Information*

Mr. Ken Bice is the leader of BadgerHands, the Wisconsin chapter of e-NABLE. e-NABLE is an organization which provides open source 3D print files of prosthetic upper limbs. Using these files, e-NABLE's volunteer community of 10,000 volunteers assembles and delivers 3D printed prosthetics to over 90 countries around the world [5].

### *Product Design Specifications*

The team's prosthetic hand locking mechanism must enable the user to maintain the closed finger position without continuous wrist flexion. Additionally, the user must be able to perform the chosen task of holding a 12oz can of soda without failure. The optimal locking mechanism for this design would allow the user to lock or unlock the prosthetic using only the afflicted limb, however the team will first try to design a mechanism that requires the assistance of a non-afflicted hand. In other words, the team is using the assumption that the user of this new design has one fully functional hand.

Since prosthetics are often used in developing countries, the materials used in the new locking mechanism must also be easily sourceable. The current hand can be built with 3D printed parts and components one can buy from a craft store, so the locking mechanism must also be either printable or found in a craft store. Machined parts or expensive off-the-shelf items are prohibited in the design. Materials such as rubber bands and excessive metal in the hinges should also be avoided. This is because rubber bands tend to have a very short life expectancy on these hand prosthetics due to the hot, dry climate they are used in and metal parts in the hinges are considered a safety hazard to the user.

The assembly of the new device must be simple, like the current hand. A Youtube tutorial video is currently used for assembly of each of the hands, and the new locking mechanism will have to be conveyed to new users in the same way. Finally, maintaining a low device cost is essential for the e-NABLE community to thrive since each prosthetic is delivered for free by volunteers in the e-NABLE community, so the final device cost must stay between the current $12-$20.

## Preliminary Designs

Before brainstorming ideas for a clamp design, a base prosthetic was chosen to modify. The team decided to alter the Raptor Reloaded hand design. This design is meant for users who have no fingers but a partial palm. The fingers are closed by flexing the wrist, which increases tension in the flexor cables, which pull on the fingers thus closing the hand (Figure 3). By un-flexing the wrist, the elastic force in extensor cables located on the back of the hand and fingers open the hand back up.

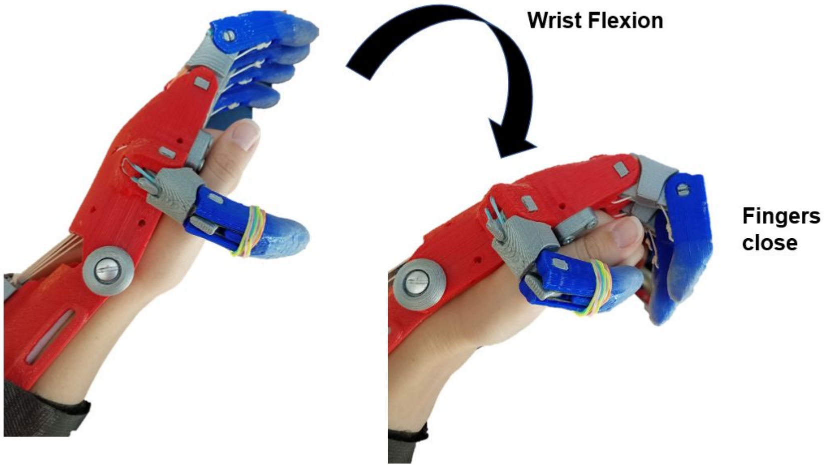


**Figure 3: e-NABLE Hand Closure Mechanism**
The hand is closed via flexion in the wrist. Wrist flexion tenses the flexor cables thus curling the fingers.

### *Pawl Ratchet Mechanism*

The locking mechanism for this design is located on the wrist joint (Figure 4). The 3D printed palm piece currently has two holes on the end that are connected by a pin to the forearm gauntlet. This joint could be redesigned to have a tooth-edge circle on the palm part, and a pawl ratchet on the gauntlet. The lock mechanism is a one hand with assist design. This means that closing the fist requires one hand (the injured one in this case), but opening the fingers of the prosthetic requires a second hand to release the ratchet. This design is easy to operate, but lacks a few features that would make is more user-friendly. It requires the user to always keep the wrist flexed during continuous use while holding an object. Even though the muscle doesn't apply force this whole time, the wrist is still bent at an uncomfortable angle. This design also does not allow for use of the prosthetic normally without activating the locking mechanism.

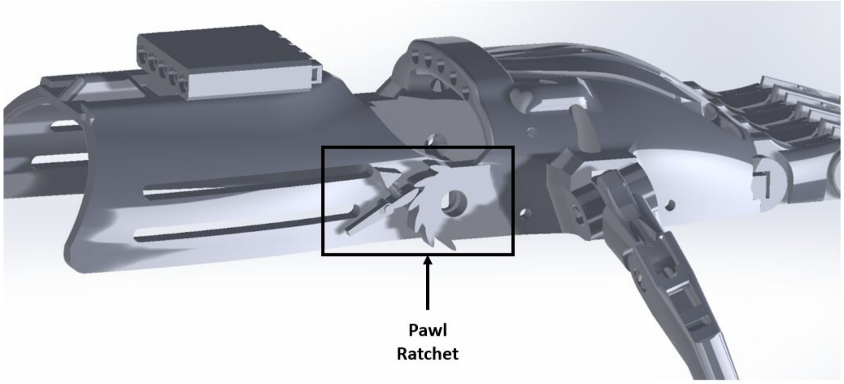


**Figure 4:** The pawl ratchet design looks the same as the current design, with the addition of a locking ratchet at the palm piece-gauntlet joint. This pawl ratchet (boxed above) allows tension to be taken off the wrist and moved to the joint during extended use of the prosthetic.

### *Gear Shift*

The gear shift design allows for normal use of the device when prolonged wrist flexion is not required. When the locking mechanism needs to be activated, the user then must use the un-afflicted hand to move the flexor cable box back on a track and lock it in place (Figure 5). This motion is similar to shifting gears in a car. Figure 5 below demonstrates how multiple slots can be created to flex the cables and fingers closed to different clench sizes of the hand.

This design does not require any extra parts to be bought, only an adjustment to the 3D printing of the forearm gauntlet. It would have to be lengthened and adapted to have slots rather than a single track as it currently does. The slots are a limitation to the design, because the device can only be as precise as the number of slots available to use. The more slots, the better finger precision available. However, due to 3D printing capabilities, the slots cannot be so thin that they would break when stresses are applied during continuous holding of an object. The other concern with this design is there would be stress applied via wrist extension to the users palm because the cables would pull back on the hand while pulling back the tensor box. There would have to be a design mechanism to stop it from extending too far back from what is comfortable.

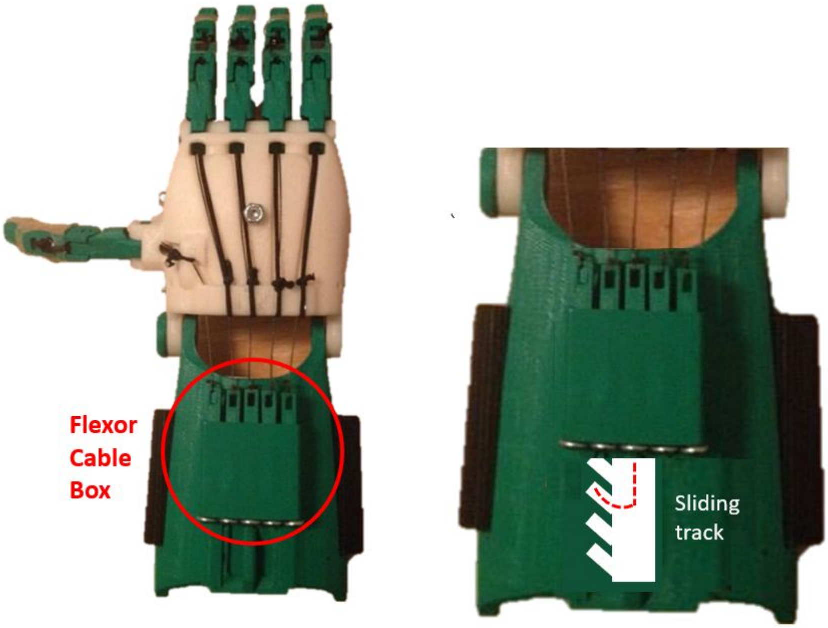


**Figure 5:** The gear shift design uses a sliding track with slots to adjust the cable tension. Adjusting tension will cause the fingers to close and the slot allows for continuous finger flexion without flexing the wrist the entire time.

### *Hand Clamp*

The hand clamp, like the gear shift, allows normal use of the prosthetic without needing to engage the locking mechanism. The locking mechanism in this design consists of a clamp that presses down on the flexor cables (Figure 6). To use this device the user must first flex their wrist, thereby adding tension to the flexor cables and closing the fingers. The clamp can then be lowered over each of the cables resting on the back of the palm. The location of the clamp is on the palm and not the forearm. This allows for the user to extend their wrist after locking the cables in place because the tension in the cables will be maintained. The hand clamp design is one-handed with assist, because it doesn't require two hands except to lock and unlock the continuous use mechanism.

With regards to design, a new palm piece, new clamp mechanism, and high friction materials would need to be made and sourced to complete the device. It may be difficult to source a high friction material that is also readily available. Another negative of this mechanism is the potential for the cables to slide loose of the clamp.

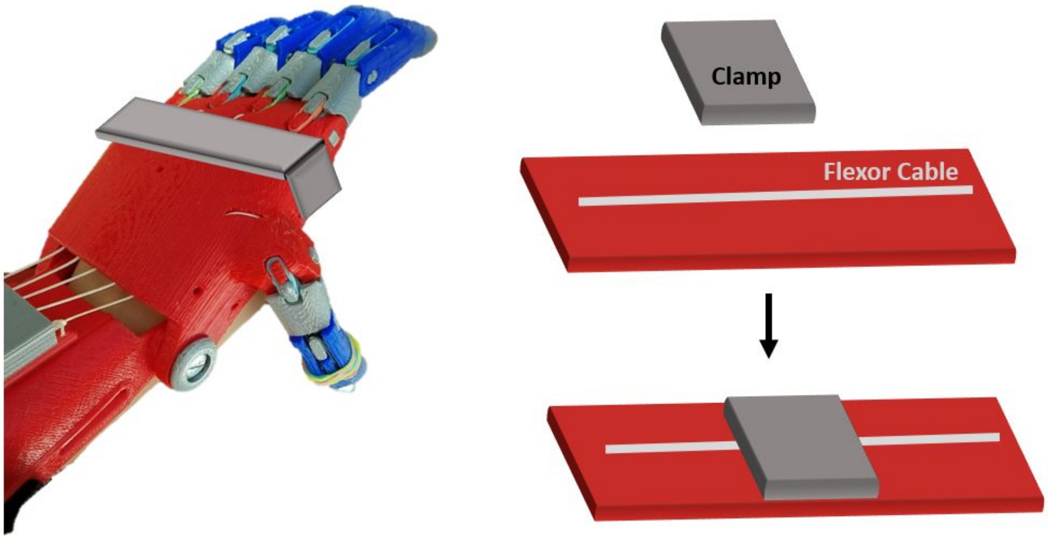


**Figure 6:** The hand clamp mechanism  preventing the movement of the flexor cables in order to lock the grip size in place.

### *Hand Ratchet*

The hand ratchet mechanism works with the same mechanics as the pawl ratchet, with the difference being that there is no longer a gauntlet that attaches to the user's arm. The entire fist closing mechanism is on the back of the hand, with a knob that turns to wind up the tension cables (Figure 7). The mobility of this design is beneficial because without the forearm gauntlet, the user now has a full range of wrist motion. The disadvantage is that the only way to use the fist closing mechanism is to twist the knob on the hand with the user's un-afflicted hand, so there is no way to have one-handed use. The release mechanism of this design is the same as the pawl ratchet, with a push button that allows the knob to spin and release the tension.

**Figure 7:** Hand Ratchet mechanism operating similar to that of the pawl ratchet mechanism however winding the flexor cable around a spool on the back of the hand to allow wrist freedom.

## Preliminary Design Evaluation

### *Design Matrix*

| | **Pawl ratchet Mechanism** | | **Gear Shift Mechanism** | | **Hand clamp - (put on the breaks)** | | **Knob - Hand Ratchet Mechanism** | |
|---|---|---|---|---|---|---|---|---|
| **Ease of use (30)** | 18 | 3/5 | 12 | 2/5 | 24 | **4/5** | 6 | 1/5 |
| **Hand precision (25)** | 15 | 3/5 | 10 | 2/5 | 25 | **5/5** | 20 | 4/5 |
| **Sourcing/ Cost (20)** | 16 | 4/5 | 20 | **5/5** | 8 | 2/5 | 16 | 4/5 |
| **Ease of assembly (15)** | 12 | 3/5 | 15 | **5/5** | 12 | 4/5 | 9 | 3/5 |
| **Safety (10)** | 8 | **4/5** | 8 | **4/5** | 4 | 2/5 | 8 | **4/5** |
| **Total (100)** | 69 | | 65 | | **73** | | 59 | |

**Table 1.** Design matrix evaluating each design on the criteria of: ease of use, hand precision, sourcing and cost, ease of assembly, and safety.

### *Summary of Design Matrix*

From the product design specifications, the user experience was weighted higher than the assembly requirements. Ease of use and hand precision were given the highest weight. Ease of use was determined by three things: the operation ability using only the afflicted limb, the amount of assistance from the functional hand, and the ergonomic use. Hand precision was rated by how many different grip sizes the hand could make while keeping a closed grip on what it was holding. Sourcing/cost were determined by how easily the materials can be acquired for the final design in a local craft store or by 3D printing capability. Ease of assembly was rated based on the criteria in the design specifications. The safety section was rated from an engineering perspective on how difficult it will be to design the prosthetic to lock a flexed fist and maintain the finger flexion over time.

Based on the design criteria, the hand clamp design was determined to be the best design by a narrow margin over the pawl ratchet mechanism (Table 1). The hand clamp design would be the easiest to use and more ergonomic than the other designs as it allows for normal one handed use of the device while also giving users the option to lock the grip and relax the wrist. It also would have the highest hand precision out of the designs considered because it does not rely on the hand grip to match up with a gear teeth or gear stops. The hand clamp may need a couple of new materials including some sort of rubber for the teeth and a specific type of cable- rather than fishing line which is sometimes used- to ensure the clamping mechanism does not break it. Other designs rated higher because there would be minimal, if any, extra materials required. Once the new parts are printed there will not be a significant increase in assembly difficulty because there are no springs or complex pieces in this design. Lastly, the hand clamp rated low in safety because of the anticipated potential for slippage failure was greater than that of other devices.

### *Proposed Final Design*

The design going forward is the hand clamp design, since it scored highest on the design matrix. The team anticipates it will be the most precise at locking the fingers in any given grip size. Another benefit of this design is that once the device is locked it frees up wrist movement after the clamp has been locked. Substantial testing is needed for the final prototype to ensure slippage will not occur during the client's provided task of holding a 12oz soda can.

## Fabrication and Development Process

### *Materials*

Hand pieces including the fingers, joint pins, palm, gauntlet and flexor cable box were all 3D printed using an ultimaker 3 with PLA filament. The elastic cables can be obtained from a craft store and are non-brand-specific to the proposed design. The flexor finger cables were comprised of 60 lb fishing line or a slightly thicker nylon rope but this choice may depend on the volunteer assembling the device. The bolts used for the flexor cable box are dependent upon the scale of the print but are also non-specific as the plastic is not threaded. The design is meant for maximum flexibility for the assembler.

### *Final Prototype*

The final prototype (Figure 9) is a modification of the original raptor reloaded palm piece with the clamp integrated onto the proximal side of the part. The extensor cable attachment sites were moved distally in order to make room for the grooves of the clamp, tensor cable guides were rerouted a little bit in order to run through the clamp, and attachment sites for the other clamp parts were added along with other minor modifications to the original palm piece. This prototype uses bolts as pins sourced after 3D printing. The clamp itself uses the ‘smooth’ teeth geometry discussed below in preliminary clamp testing and operates via a mechanism similar to a draw latch in which the geometry of linkages within the clamp hold the clamp in position. For Assembly drawings see Appendix V.

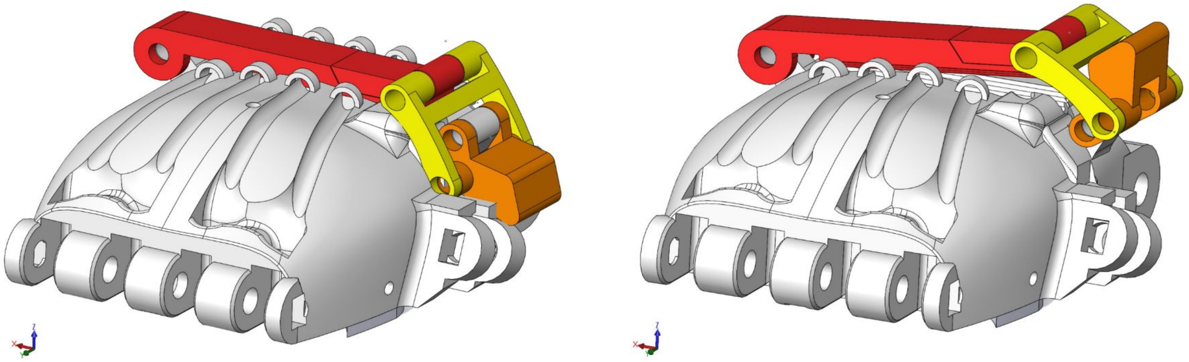


**Figure 9:** SolidWorks model of right handed final prototype. The clamp is pictured in color, in both the closed (left) and open (right) positions. To open or close the clamp, the user operates the lever (orange).

## *Testing*

### Clamp Teeth Geometry Testing

Before designing the clamp, test models of the clamp’s teeth were made with two different surface profiles. The team compared smooth waves and jagged edges to determine which tooth geometry would hold the strings the best. An image of the test piece’s base, with smooth and jagged tooth geometries is shown below (Figure 10). The test piece’s base consisted of PLA, while the material of the matching upper piece was varied in order to determine an ideal material combination for the clamp teeth. Four sets of upper pieces were made, with each set containing one smooth and one jagged piece. One set was made from PLA, while three other sets consisted of thermoplastic polyethylene (TPU), a flexible thermopolymer, at various infills. 10%, 20%, and 50% were chosen as the TPU infills for testing.

A string was placed between the base of the test piece and either a PLA or TPU upper piece whose geometry matched the geometry of the base (smooth or jagged). A c-clamp was then tightened until contact was made with the upper piece, followed by an additional ¾ turn to add a small amount of torque. To maintain consistency between trials, the same person adjusted the c-clamp each trial. After the clamp and string were secure, a force gauge was used to pull on the string and evaluate the force at which slippage occured. An image of the test setup is shown below (figure 11). The string was repositioned between trials to prevent it from carving out a groove between the edges of the clamp, thereby reducing the total friction holding it in place. Additional trials also help account for the human error involved in tightening the clamp. There were three trials done for each of the clamp top piece, and an additional set of trials with the flat side of PLA on the flat side of the PLA base piece. All of the data was tabulated into a table for analysis. The raw data can be found in Appendix II and graphical representation of the results as well as a discussion can be found in the results section (See Figure 15).

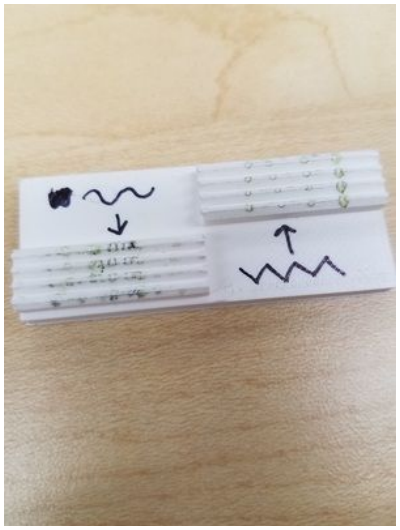


**Figure 10:** Base of the test piece (made of PLA) with wavy and jagged edges on the left and right, respectively. The green streaks are marks left behind by the string after slippage.

**Figure 11:** Testing setup. A corresponding upper piece made of either PLA or TPU was placed on either wavy or jagged side of the base for testing. String attached to a force gauge sits in between the upper and lower pieces, while the c-clamp was used to keep constant pressure on the two test pieces throughout testing.

## Distributed Force Testing

Upon completion of material geometry testing the team designed and 3D printed a standalone clamp (Figure 12). This clamp was not incorporated into the hand to save on printing costs if multiple prototypes were needed. The team hypothesized there might be an inherent force distribution across this type of clamp, so three sites were tested, depicted in (Figure 12). The string was positioned at each site, and a similar testing protocol to the clamp teeth geometry testing was used while replacing the c-clamp with the prototype clamp. Similarly, a force gauge was used in order to determine the force required to make the string slip. Each location was tested twice. Additionally, the team tested the idea of using knots in the string to increase the force of failure. Two knots were tied and placed into the clamp at each site. Again, each location was tested twice.

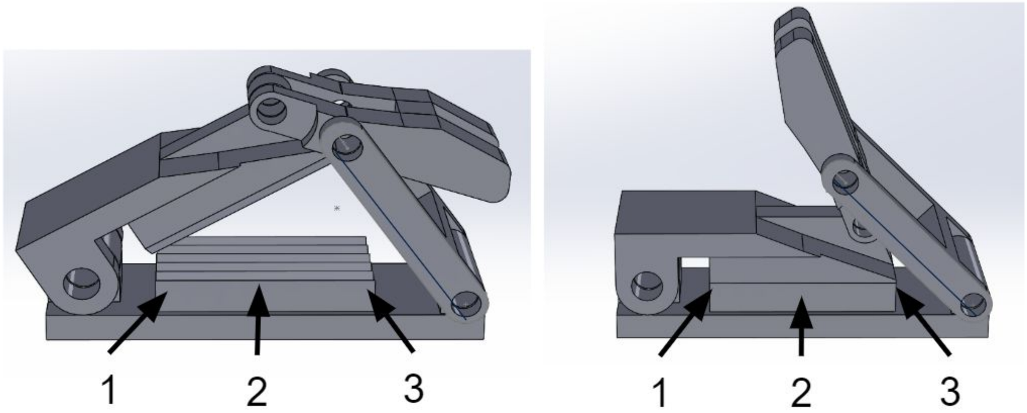


**Figure 12:** SolidWorks drawing of standalone clamp shown in the open (left) and closed (right) positions. Locations 1, 2, and 3 represent sites of string placement used for distribution testing.

## EMG testing

To directly test if a clamp design could reduce the amount of forearm fatigue, EMG measurements were taken on the wrist flexor and extensor muscles (Figure 13). The experiment was done using a 20 oz. Pepsi bottle and compared muscle activation between a total 4 variations of bottle hold: flexed vs unflexed wrist position and holding the bottle parallel vs perpendicular with the ground (Figure 14). Also note that a handle was added to the soda bottle to allow the hand to hold the bottle. This handle was needed because the location of the prosthetic thumb prevented a stable hold on the soda bottle.

The flexed wrist position used the original prosthetic hand which was modified to include a testing bar that the tester grasped to approximate an amputee's use of the prosthetic. Muscle activation with the flexed grasp position was then measured in the two hold positions: soda bottle parallel or perpendicular to the ground. Contrastly, testing of the team's clamp design was approximated by taping the prosthetic fingers closed (essentially the same as clamping the tensor cables) which allowed the tester to maintain grip on the soda bottle with an un-flexed wrist. Finally, a control test was measured where the tester used their own hand and gripped the bottle with an un-flexed wrist with the bottle perpendicular to the ground.

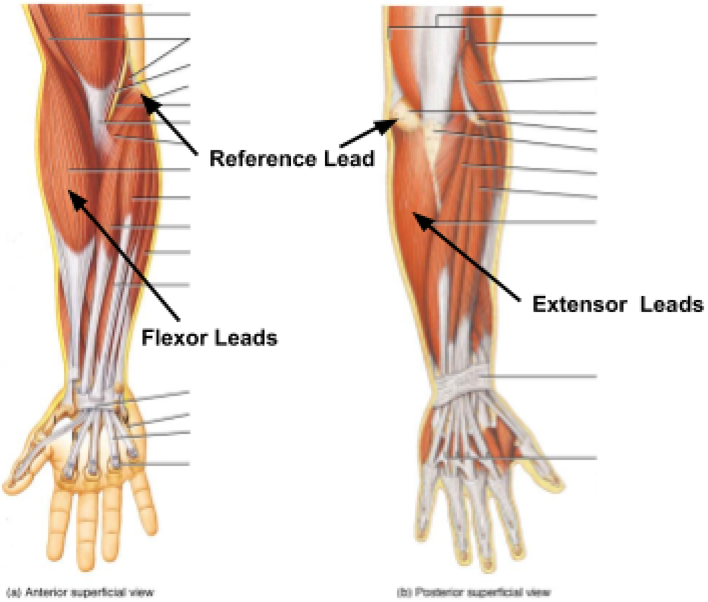


**Figure 13:** Location of leads during EMG testing. One reference lead was placed on the medial epicondyle of the Humerus, with two leads each on the wrist flexor and extensor muscles in the forearm.

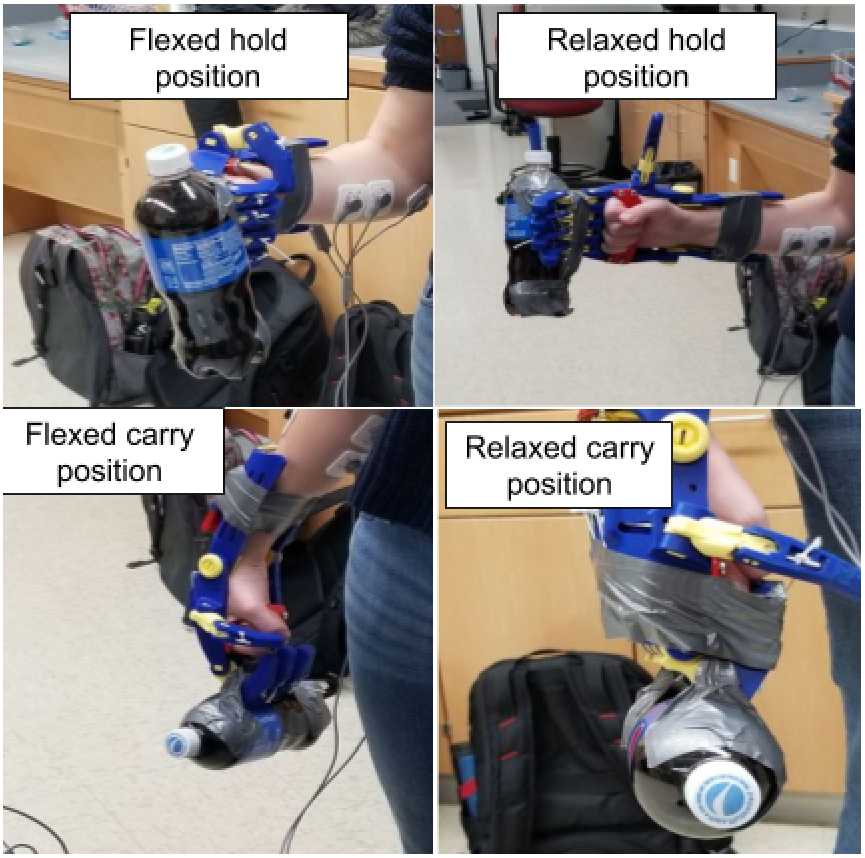


**Figure 14:** Different arm positions for EMG testing. Flexed wrist position (left column) vs. relaxed wrist position (right column) and hold position/bottle perpendicular with ground (top row) vs carry position/ bottle parallel with ground (bottom row).

# Results

### *Clamp Teeth Geometry Testing Results*

In terms of geometry comparisons, both the wavy and jagged conditions crimped the fishing line, which could eventually cause the line to snap, while the flat condition flattened the line. When the line did slip, it caused more shearing in the peaks of the jagged condition compared to the wavy. Overall, the jagged condition caused more plastic shearing and fishing line wear than the wavy condition. Strength-wise, the flat condition performed as well as the wavy, however the team preferred the wavy because it was believed it would perform better if the print was not quite perfect. Therefore, the team chose the wavy conformation over the jagged and flat.

For material comparison, there were mixed results. The PLA/PLA condition had the highest force of failure, while the PLA/TPU conditions caused the least deformation in PLA. When shearing did occur, it was more noticeable in the PLA than TPU. However, due to the greater accessibility of PLA, as well as the reduced deformation of the wavy condition (in contrast with the jagged) the team preferred PLA to TPU.

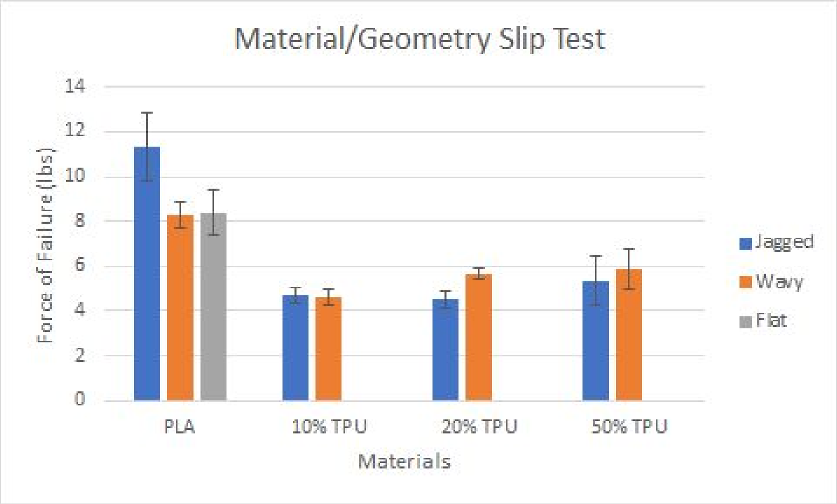


**Figure 15:** Test data for different clamp geometries using test piece from Figure 10.

### *Distributed Force Testing Results*

Our results indicate there is a force distribution across the clamp, with the highest clamping force at position 1 (closest to the hinge) and lowest clamping force at position 3 (farthest from the hinge) (See figure 12). Adding knots to the string increased the force of failure up to 70%. The graph in (Figure 16) shows the difference in clamping force across the clamp surface. These results indicate that when this clamp is incorporated into the hand design, the clamping force will be larger at the thump than the pinky. Also, if a greater clamping force is required, adding knots into the strings may be a solution.

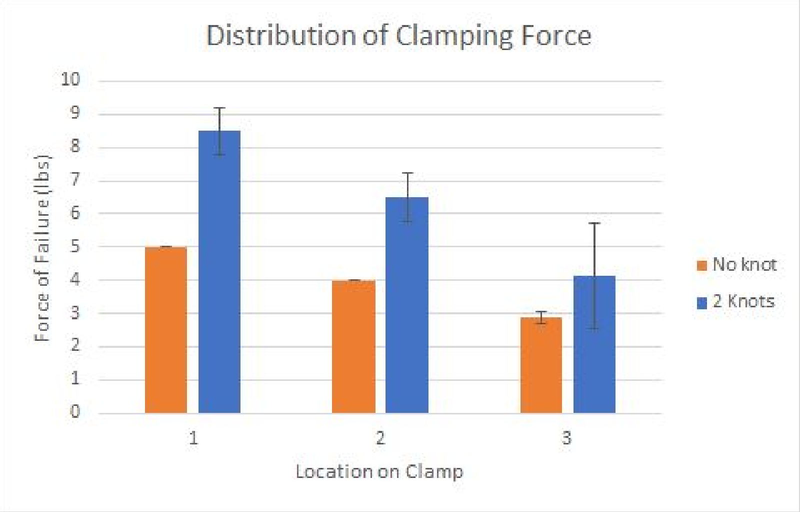
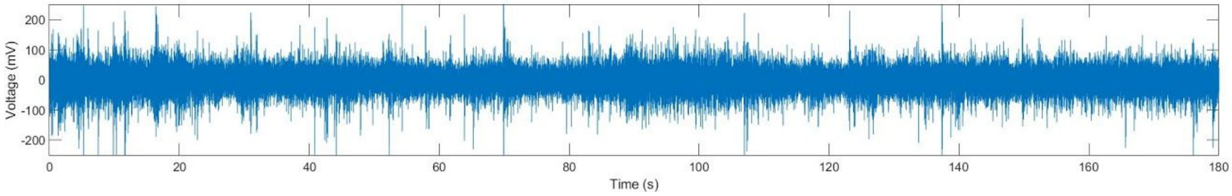


**Figure 16:** Test data for the clamp prototype.

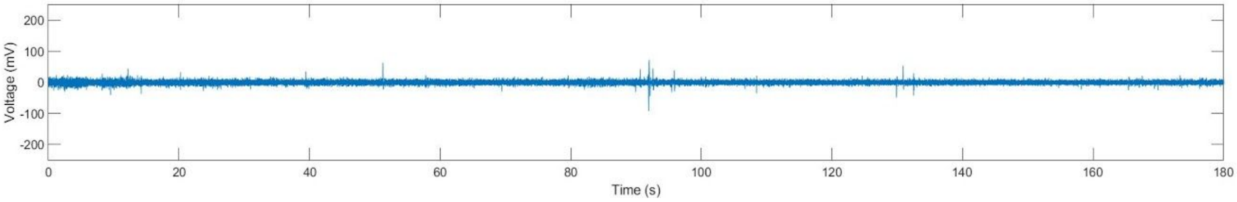
### *EMG Testing Results*

The extensor muscles did not show a significant change regardless of grasping method and can be ignored because that is not the part of the arm being fatigued. The flexor muscle on the other hand showed a substantial 85.75% muscle activation reduction by using a the prototype representation in the carrying position and a 52.78% muscle activation reduction in the holding position.

Original Prosthetic - Carry



Final Prototype Representation - Carry



Control - Carry

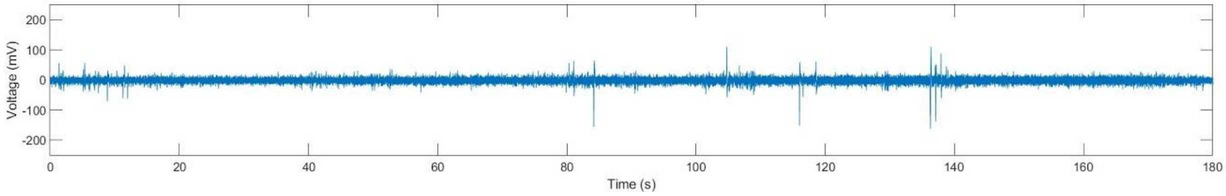


**Figure 17:** Raw EMG data showing the muscle activation for three different grasping techniques in the carrying position: Using the original prosthetic, using a prototype representation, and not using the prosthetic (control).

## Discussion

Looking at the data from the material geometry testing and distributed force testing the choice was made to make the clamp lever closer to the thumb. This was an ergonomic decision as well as a mechanical decision. Ergonomically, it is much easier to use the free hand to activate the clamp when it is near the thumb. If it were the other direction the user would have to awkwardly reach around their hand to use the device. Mechanically, it is better this way as well. This is due to the slight distributed force created by this type of clamp. When the prosthetic hand is holding an object, most of the grip contact and friction comes from the thumb, index, and middle fingers. Because these fingers are used more often, or used more when holding a heavy object, it is beneficial to have those strings in higher tension. The higher possible tension before failure increases the lifting capacity prior to failure of the whole hand.

Ultimately, the team was unable to create a prototype of a modified eNABLE Raptor Reloaded with an optional clamping mechanism. This was due to unforeseen 3D printing complications. The team was able to theoretically collect muscle activation data using an EMG and a current model Raptor Reloaded. This data shows that the new clamping mechanism reduces muscle activation in the forearm, hopefully leading to less strain in the flexor muscles during prolonged use.

During the EMG testing, an impromptu handle was created for the soda bottle. This is important to note because the stress induced by current designs is caused by the force required to keep the fingers locked around a device. Adding a handle eliminated this stress, making it so the forearm muscle activation was only indicative of wrist flexion. This difference arises from the lack of friction with the tape handle. During ideal use, the prosthetic would require enough tension in the strings to create enough friction on the bottle to hold it in place. The string tension would ultimately be higher than the final frictional forces on the bottle. This added force required for wrist flexion is considerably higher than those during the EMG test, which just required the user to flex their wrist. This disparity between required wrist flexion forces should be resolved when a full hand with clamp is assembled and fully tested.

Perhaps the biggest source of error in this process was in the 3D printed parts. The final prototype was printed twice at the Makerspace. On one print, the clamp fit perfectly; on the other, the clamp would not close properly, causing the anchor pin to break due to extra stress. Other parts can at times come out warped. Another problem with 3D printing is hole size resolution. The printer may attempt to print a hole with nominal diameter of 3mm, but the actual size can be up to 0.5mm smaller. This discrepancy must be solved so the team can design appropriate sized pins to connect the clamp parts together. For testing purposes metal screws were used, however the product design specifications call for the pins to be 3D printed like the rest of the prosthetic.

## Future Work

The first task of next semester will be to assemble and test the final prototype. Important tests include failure loading to determine the max weight the device can hold and clamp activation with the strings in tension and relaxation. So far, all of the testing has enabled the clamp with relaxed strings. It is possible that loading with the strings in tension could shear the fishing line, ultimately snapping it.

The bulk of next semester will be focused on reproducibility. As mentioned in the discussion, prints at the Makerspace had varied accuracy throughout the semester. The team will test printing of the clamp at multiple other 3D printing sites to ensure it can be printed accurately at different locations and at different sizes. This testing will be extremely important because e-NABLE users will print this design from various models of 3D printers all around the world.

The team would also like to repeat EMG testing with the final prototype. This is because, as mentioned in the discussion, the EMG testing grip did not match the grip will be used to hold items since a handle had to be added to the soda bottle. For future testing it is important to find an object the hand can hold via its closed grip (without a handle). Additionally, the team would like to try to measure muscle fatigue directly in a second round of testing, rather than simply muscle activation.To do this, longer hold durations of objects may be required.

Finally, if time permits, the team will attempt to incorporate some of the other e-NABLE designs from this semester into the final design. These designs could add lateral wrist movement and better thumb positioning for grip to this design.

## Conclusion

There is high demand for low-cost, easily sourced hand prosthetics and e-NABLE is a community of volunteers dedicated to creating 3D prosthetics to fill this demand. Current e-NABLE devices are limited because constant wrist flexion is required to continuously hold objects, which causes forearm fatigue over time. After thorough brainstorming, the team proposed and tested the addition of a clamp locking mechanism to the existing e-NABLE Raptor Reloaded device. The team's clamp design is printed within the palm of the Raptor Reloaded hand model and functions by holding down the flexor cables, thereby preventing the fingers from uncurling. As usage of the clamp is optional, the device may be operated as normal or in the clamped position if desired. Due to time constraints and inconsistent printing at the Makerspace, a final prototype with the incorporated clamp was not printed in time for full testing. However, proof of concept testing of a clamp design revealed that it can be used to hold strings in place without failure well above the specified holding weight of 1 12 oz soda can (< 1lb). EMG testing, in turn, showed that muscle activation in the forearm is reduced. This is because the user is able to relax their wrist while using the new clamp design. Future work needs to be done next semester to fully test the incorporated design.

## References

[1] E. Strait, Prosthetics in Developing Countries. 2006.

[2] R. Bowers, "Prosthetic Devices for Upper-Extremity Amputees", Amputee-coalition.org, 2014. [Online]. Available: http://www.amputee-coalition.org/military-instep/prosthetic-devices-upper.html. [Accessed: 02-Oct- 2018].

[3] "Myoelectric prosthetics 101", Ottobockus.com, 2018. [Online]. Available: https://www.ottobockus.com/prosthetics/info-for-new-amputees/prosthetics-101/myoelectric-prosthetics-101/. [Accessed: 08- Oct- 2018].

[4] “How Much Does a Prosthetic Arm Cost? - CostHelper.com,” CostHelper. [Online]. Available: https://health.costhelper.com/prosthetic-arms.html. [Accessed: 02-Oct-2018].

[5] e-NABLE, "ABOUT", Enabling The Future, 2018. [Online]. Available: http://enablingthefuture.org/about/. [Accessed: 02- Oct- 2018].

# Appendix

## *I. Product Design Specifications*

**Client Requirements:**

- The device fingers should be able to close and stay closed without continuous wrist flexion.
- Materials should easily be sourced in developing countries.
- The new design should be relatively simple to assemble.
- The final product should cost $12-$20.

**Design Requirements:**

1. **Physical and Operational Characteristics**

- *Performance requirements:*
    - User should be able to hold simple objects such as a water bottle without fatiguing the wrist.
    - Comparable gripping abilities compared to current designs available.
- *Safety:*
    - The device should have rounded corners and dull edges where possible to avoid injuring the user.
    - Metal hinge components should be avoided to allow for a shearing break of the prosthetic joints in the case of a fall, avoiding potential harm to the user being caught in the device being bent at an awkward angle.
- *Accuracy and Reliability:*
    - The device's grip mechanism should allow for comparable or improved hold maneuverability to the existing Raptor Reloaded prosthetic.
- *Life in Service:*
    - The plastic parts should outlast the strings, rubber bands, Velcro straps, etc. On a Raptor Reloaded, in a high heat region, such as Africa or southeast Asia.
    - The Velcro straps and flexor cord should last one year and the extensor stretchy cord should last 3 months.
    - If the part is destined for use in the USA, the extensor cord should last closer to a year.
- *Shelf Life:*
    - The device should be able to be printed and sit in a box put together without degrading or falling apart.
    - In terms of durability, the limiting factor will be rubber bands or elastic strings shelf lives.

- *Operating Environment:*
    - These devices are often sent to war-torn developing countries, where the climate is hot and humid.
- *Ergonomics:*
    - The device must comfortably fit on the user.
- *Size:*
    - The gauntlet of the device will fit snugly around the wrist and/or forearm of the user, being large enough to provide mechanical stability to the user.
    - The device can be scaled to match the size of the user.
    - The size will be more constrained by the final weight of the device.
- *Weight:*
    - The device should be as light as possible while maintaining mechanical strength.
    - It has the potential to be used my small children so keeping the materials light and keeping a weight/material reducing design should be considered.
    - The typical weight of existing e-NABLE devices is ~1lb, so the design should be as close to that as possible.
- *Materials:*
    - Materials must be able to withstand the specified environmental conditions and be resistant to degradation due to chemical and temperature exposure.
- *Aesthetics, Appearance, Finish:*
    - The final product shall be aesthetically pleasing to look at as it will be in plain view on the user.
    - The product shall have no burs or sharp edges that can possibly harm the user or snag on clothing.
    - There is no finish needed as 3D printed plastic is ready to use once cured.

2. **Production Characteristics**

- *Quantity:*
    - Device part files will be available online for volunteers to 3D print and assemble.
- *Target Product Cost:*
    - Current e-NABLE designs typically cost between \$12-\$20. Therefore, to maintain affordability, this device should not exceed \$20.

3. **Miscellaneous**

- *Standards and Specifications:*
    - N/A
- *Target Population*
    - The target group for this device is a user who has one working hand and one hand that is missing all digits (palm intact).

    - Users of the device range in age from children to adults, so the design must be scalable in size.
- *Patient Related concerns:*
    - Materials must be easily found and replaced.
- *Competition:*
    - The Bebionic prosthetic hand utilizes motors and sensors to achieve precise hand movements.
    - Prosthetic hands which are solely cosmetic range from $3,000 to $5,000 [2].
    - Prosthetic hands which operate using elastic cables, typically cost about $10,000.
    - Cosmetically realistic myoelectric hands may cost $20,000 to $30,000 or more. These contain processors that can tell how much pressure the user is putting on a held object and whether it is hot or cold.

## *II. Clamp teeth geometry testing*

Raw data

| Wavy Trial 1 | Wavy Trial 2 | Wavy Trial 3 | Average | Stdev | |
|---|---|---|---|---|---|
| PLA | 9 | 8 | 7.9 | 8.3 | 0.608276 |
| 10% TPU | 4.1 | 5 | 4.8 | 4.633333 | 0.360555 |
| 20% TPU | 5.8 | 5.4 | 5.8 | 5.666667 | 0.23094 |
| 50% TPU | 5.9 | 5 | 6.8 | 5.9 | 0.9 |
| | | | | | |
| | Jagged Trial 1 | Jagged Trial 2 | Jagged Trial 3 | Average | Stdev |
| PLA | 11 | 13 | 10 | 11.33333 | 1.527525 |
| 10% TPU | 5 | 4.8 | 4.3 | 4.7 | 0.360555 |
| 20% TPU | 4.1 | 4.8 | 4.6 | 4.5 | 0.360555 |
| 50% TPU | 6.2 | 5.7 | 4.1 | 5.333333 | 1.096966 |
| | | | | | |
| | Flat 1 | Flat 2 | Flat 3 | Average | Stdev |
| PLA | 9 | 9 | 7.2 | 8.4 | 1.03923 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 10% TPU |  |  |  | #DIV/0! | #DIV/0! |
| 20% TPU |  |  |  | #DIV/0! | #DIV/0! |
| 50% TPU |  |  |  | #DIV/0! | #DIV/0! |
|  |  |  |  |  |  |
|  | Knot Wavy 1 | Knot Wavy 2 | Knot Wavy 3 | Average | Stdev |
| PLA | 15 | 15 |  | 15 | 0 |
| 10% TPU |  |  |  | #DIV/0! | #DIV/0! |
| 20% TPU |  |  |  | #DIV/0! | #DIV/0! |
| 50% TPU | 12 | 10.5 | 8.8 | 10.43333 | 1.601041 |
| 50% TPU (Slippage) |  | 8.8 | 7.8 | 8.3 | 0.707107 |
|  |  |  |  |  |  |
|  | Knot Jagged 1 | Knot Jagged 2 | Knot Jagged 3 | Average | Stdev |
| PLA |  |  |  | #DIV/0! | #DIV/0! |
| 10% TPU |  |  |  | #DIV/0! | #DIV/0! |
| 20% TPU |  |  |  | #DIV/0! | #DIV/0! |
| 50% TPU | 12 | 10 | 11.2 | 11.06667 | 1.006645 |
| 50% TPU (Slippage) | 10 | 10 | 10.4 | 10.13333 | 0.23094 |

### *III. Clamp Force Distribution*

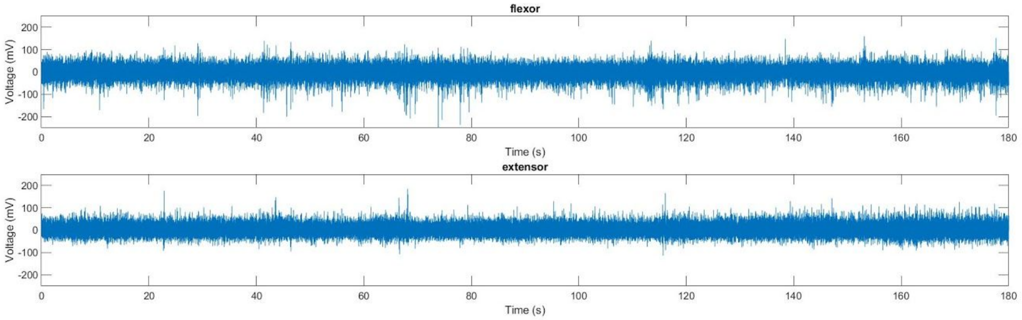
Raw Data

| No knot | Clamp side | Middle | Far side |
|---|---|---|---|
| Trial 1 | 5 | 4 | 3 |
| Trial 2 | 5 | 4 | 2.75 |
| Average | 5 | 4 | 2.875 |
| Stdev | 0 | 0 | 0.176777 |

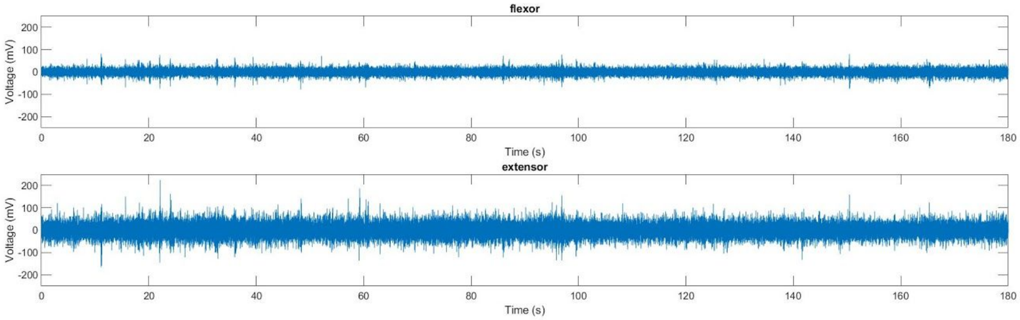
| 2 knots | Clamp side | Middle | Far side |
|---|---|---|---|
| Trial 1 | 9 | 7 | 3 |
| Trial 2 | 8 | 6 | 5.25 |
| Average | 8.5 | 6.5 | 4.125 |
| Stdev | 0.7071068 | 0.707107 | 1.59099 |

### *IV. EMG testing*

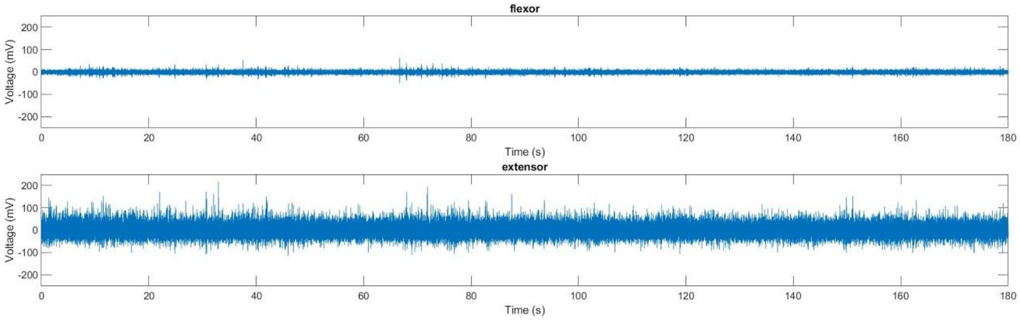
Original Prosthetic - Hold



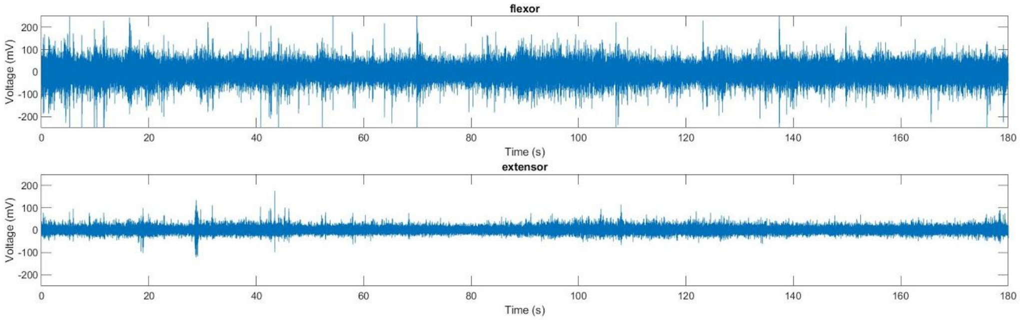
Final Prototype Representation - Hold



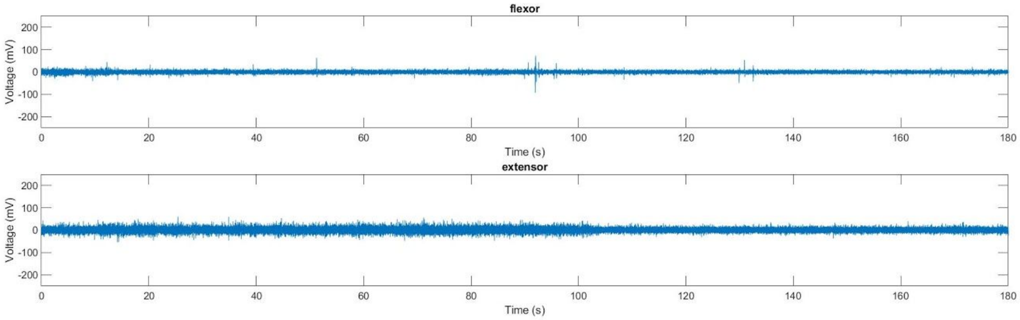
Control - Hold



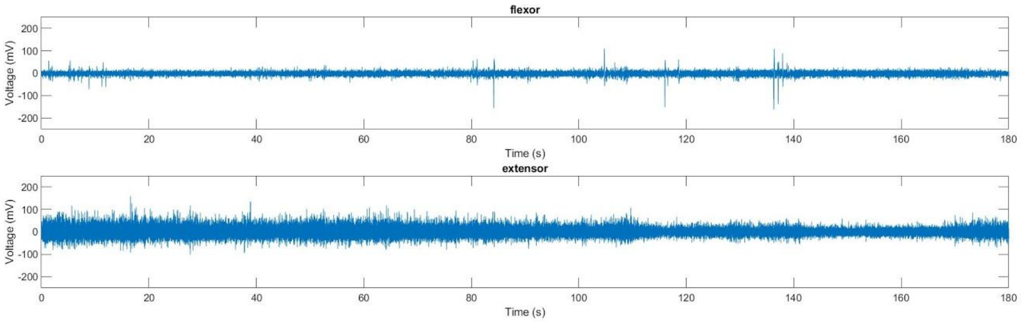
Original Prosthetic - Carry



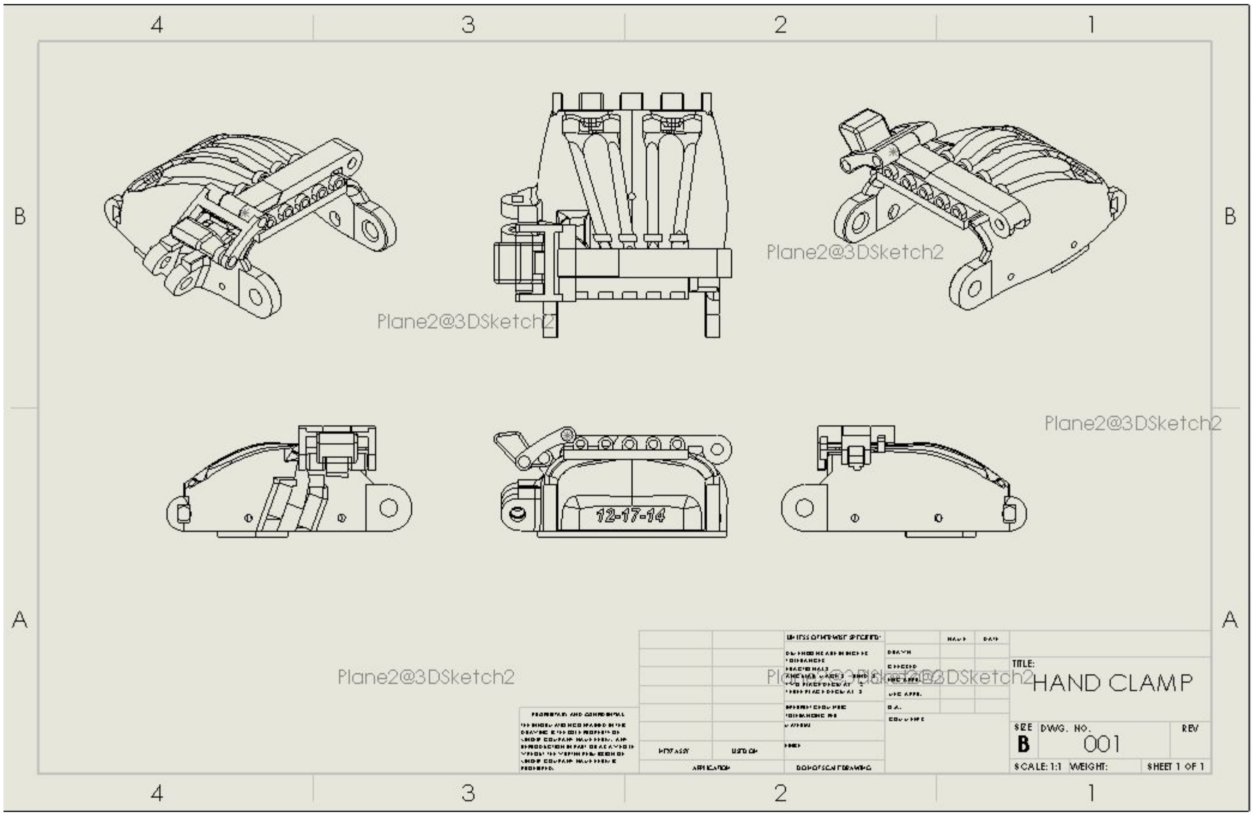
Final Prototype representation - Carry

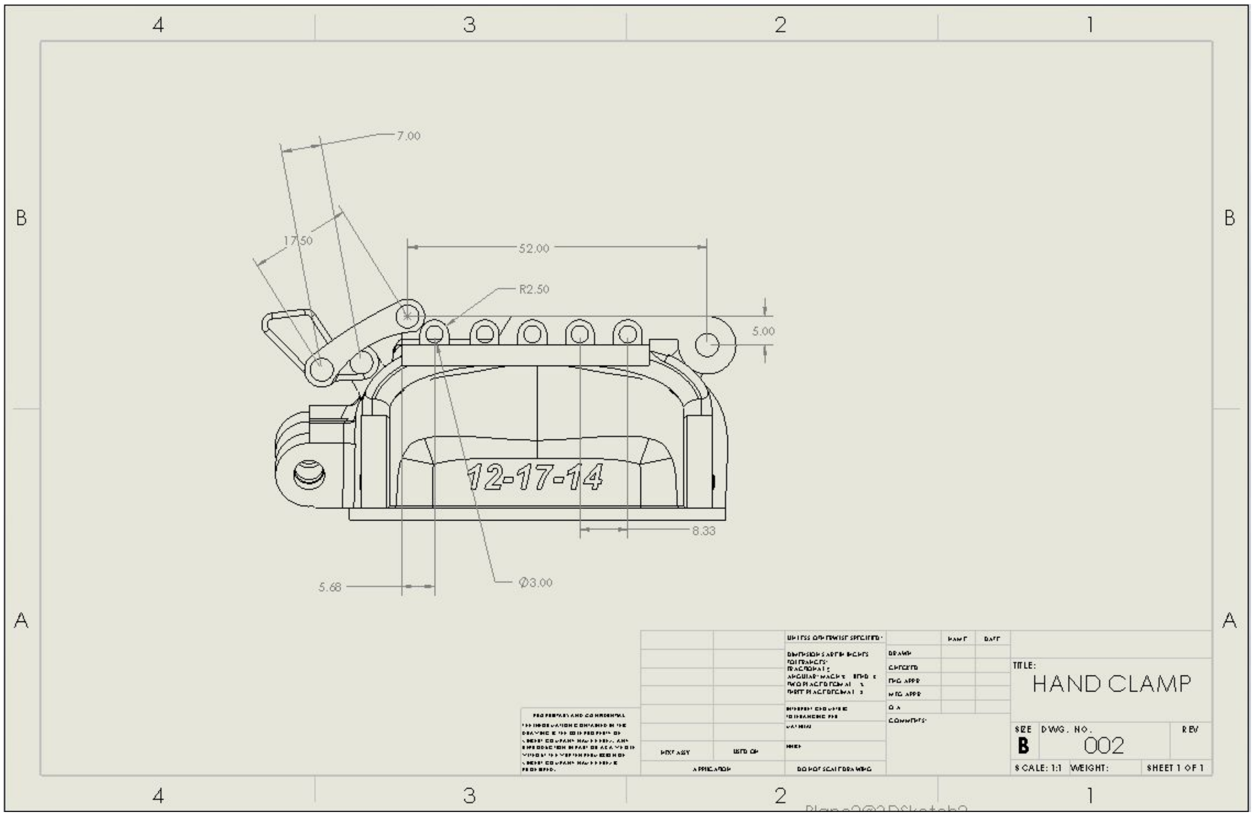


Control - Carry



## *V. Final Design Drawings*





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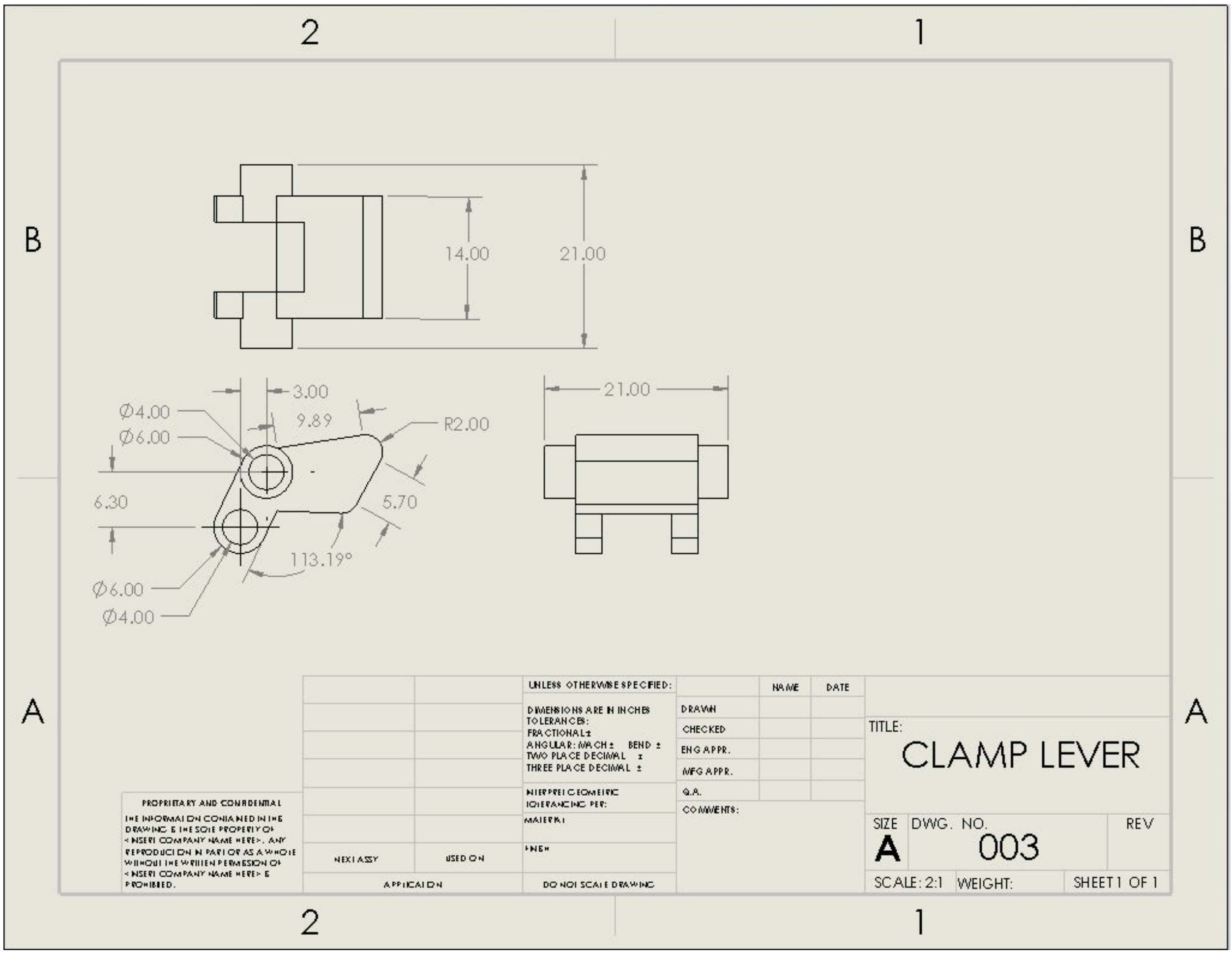
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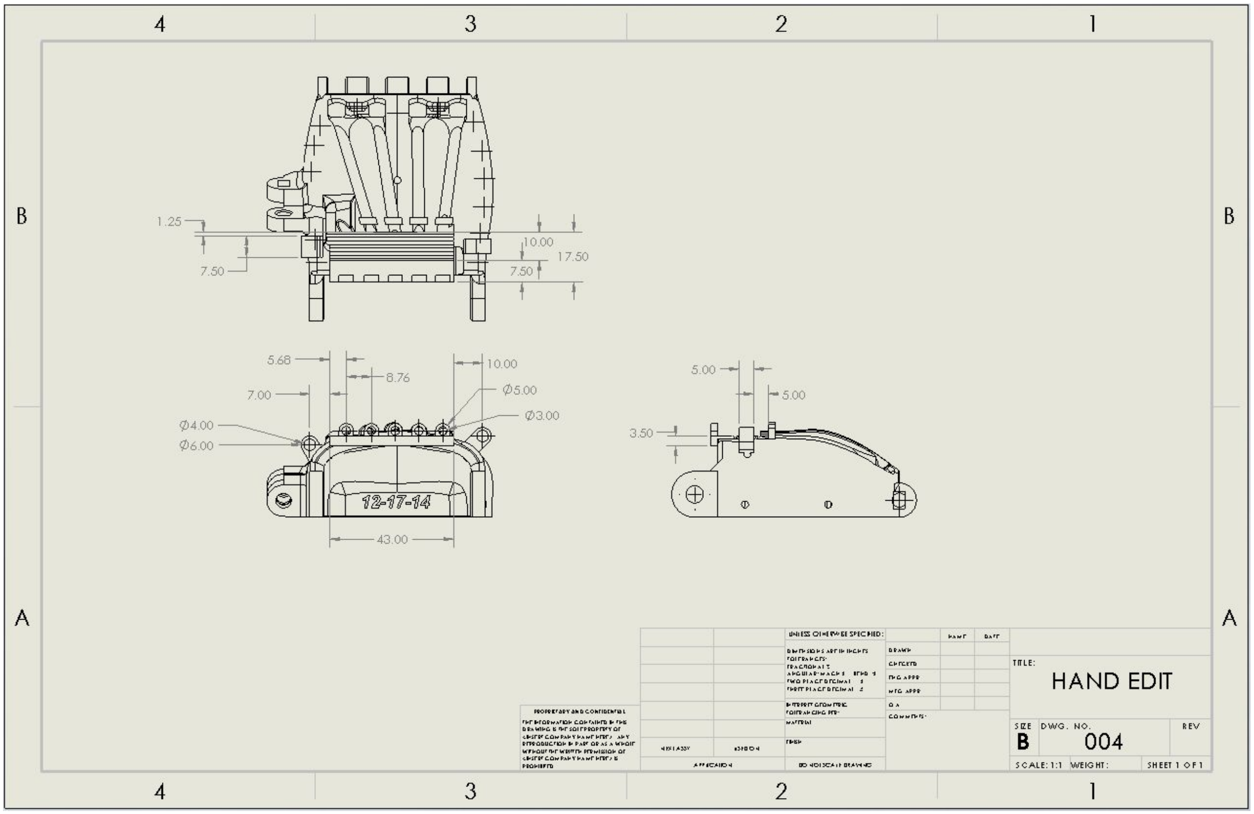
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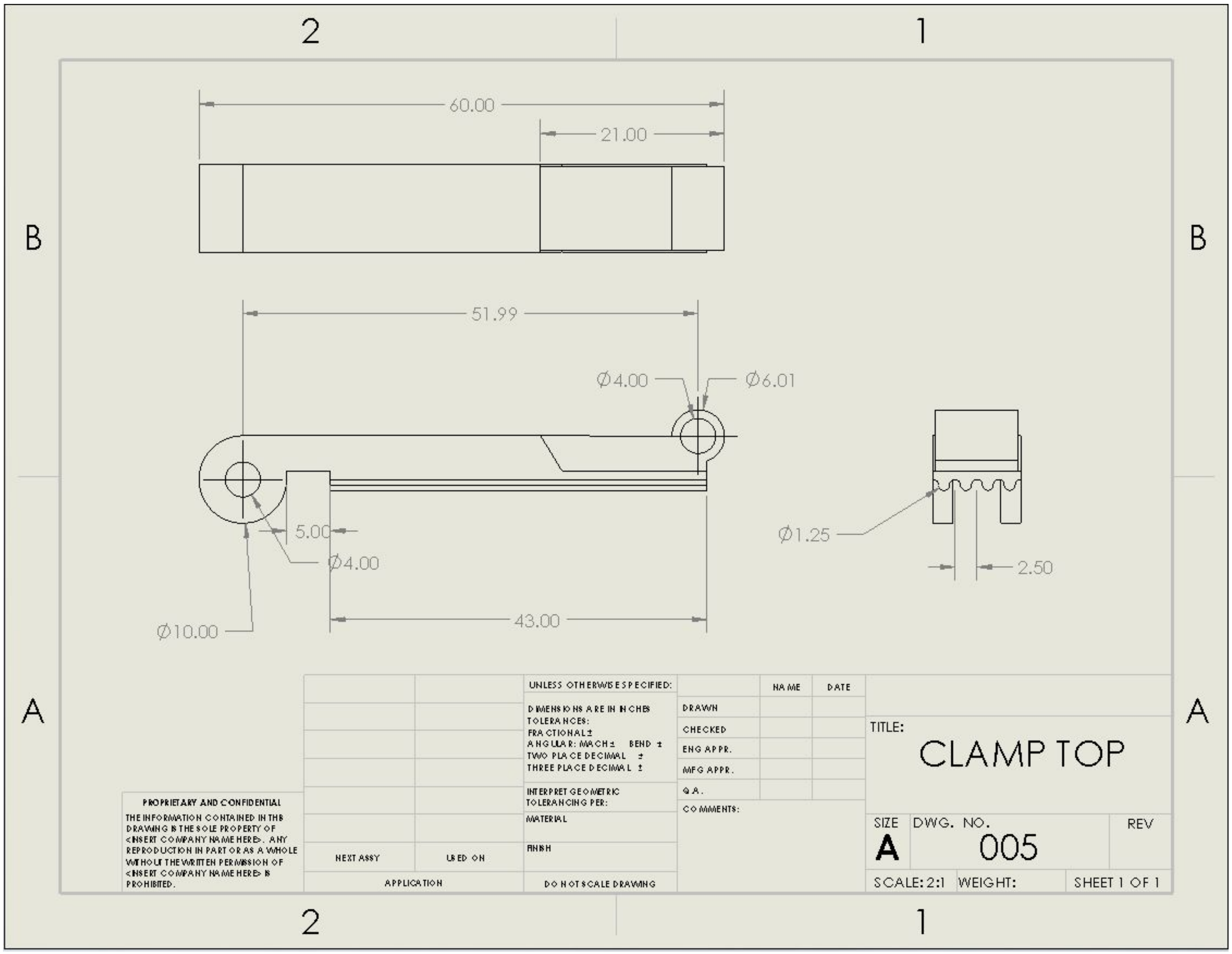
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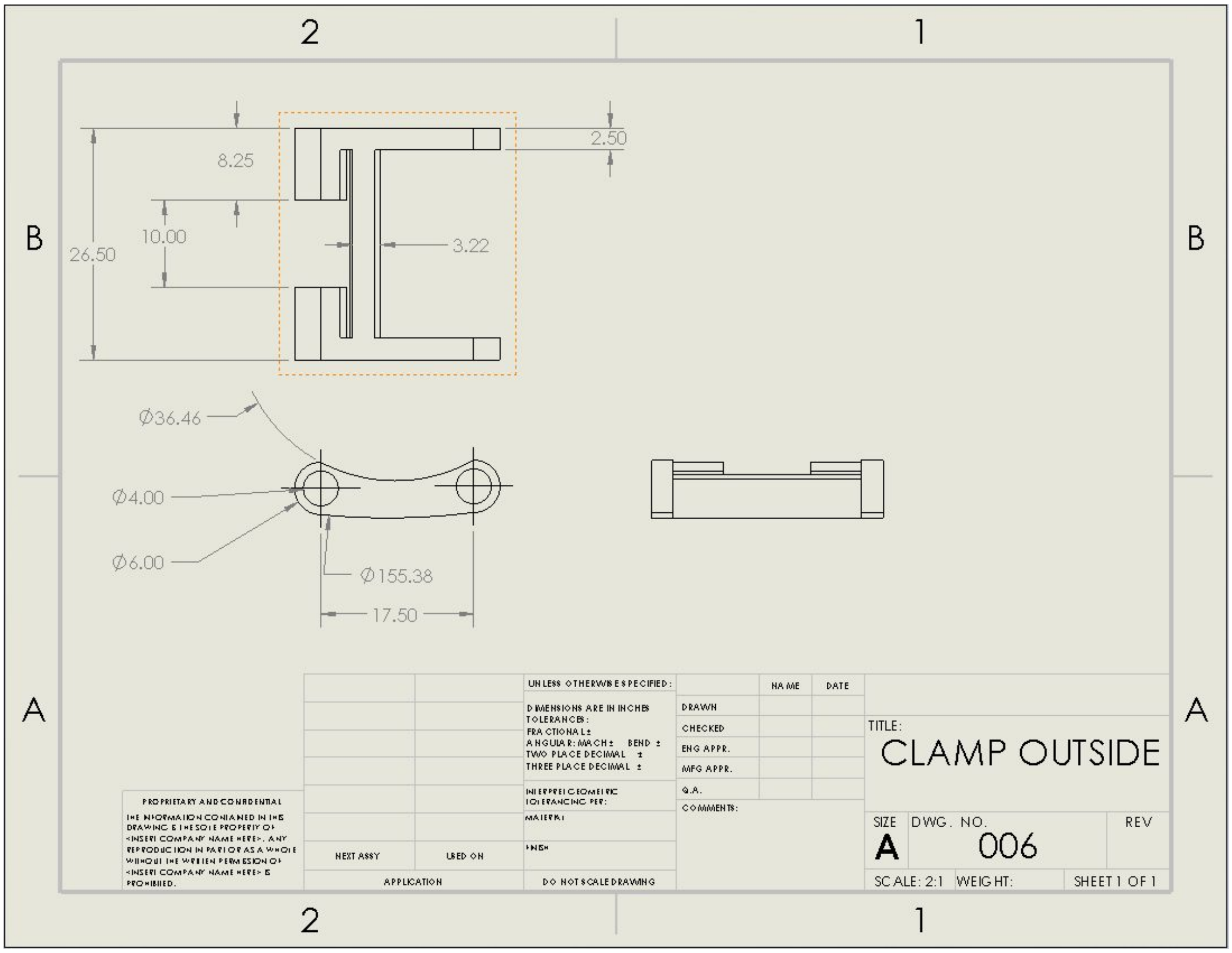

## *VI. Semester Budget*

| **Expenses** | | | |
|---|---|---|---|
| **Item** | **Date** | **Cost** | **Notes** |
| Raptor Reloaded full size 3D print | 09/17/2018 | 30.75 | To use as a model for brainstorming, testing, and for presentation. |
| Material and Geometry Testing | 10/22/2018<br>10/23/2018 | 0.22<br>0.34<br>0.40 | We printed materials to test clamp material/geometry failure |
| Ethan’s clamp | 11/1/18 | 1.07 | |

| | | | |
|---|---|---|---|
| Ryan’s clamp print 1 | 11/8/18 | 0.60 | Print too small, need to reprint. |
| Ryan’s clamp print 2 | 11/9/18 | 1.01 | |
| Clamp palm piece | 12/2/18 | 9.45 | |
| **Semester Total** | | **$43.84** | |