DEPARTMENT OF
Biomedical Engineering
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e-NABLE: Improved Prosthetic Grip Strength

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BME 200/300: Biomedical Engineering Design

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Abstract:

Upper limb loss affects a significant amount of people every year, with a common medical device for those individuals being a prosthetic. However, many prosthetic limbs can be both expensive and difficult to access for all groups of individuals in need. e-NABLE is a global community of volunteers that create affordable and effective 3D printed prosthetic hands for individuals in need from an Open Source library of models. The client, Ken Bice, has tasked the team with modifying the existing *Phoenix Reborn* prosthetic hand to increase the grip strength on cylindrical objects as this can be an area of struggle for existing models. The team fabricated a prototype to lengthen the fingers and add a degree of freedom to aid in cylindrical grip by allowing for a greater normal force to the palm of the hand. These changes theoretically improved grip via a more direct oppositional force vector to the palm and an increased ability to conform to cylindrical contours. The prototype was tested using a hand dynamometer alongside a series of qualitative tests to compare it to the original *Phoenix Reborn*. Qualitative testing was conducted using varying size and weight metallic cylinders to observe the capabilities of both the *Phoenix Reborn* and the prototype. The results from the quantitative testing were analyzed using MATLAB to calculate a p-value of 1.49e-09 showing a statistically significant improvement in the strength of the modified hand, with the qualitative testing showing an improvement to the overall capabilities of the prosthetic as well.

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1. Introduction

1.1: Motivation, Global and/or Societal Impact

It is estimated that in 2005, the United States had approximately 41,000 people with major upper limb loss and 500,000 with some sort of minor upper limb loss. This estimate climbed significantly, with the estimate for any type of limb loss reaching over 2.2 million in the United States in 2020 [1]. Of those with upper limb amputation or loss, approximately 56% of individuals use a prosthetic [2]. Keeping in mind that these statistics are for the United States alone, extrapolation of this data gives rise to a drastic global need for readily accessible prosthetic limbs.

e-NABLE is known for being a global community of volunteers who use an Open Source library of 3D models to print effective and affordable prostheses for those in need [3]. With chapters in over 100 countries globally e-NABLE has been able to provide between ten thousand and fifteen thousand upper limb prosthetics [3]. Widespread global efforts are possible as a result of not only the volunteers, but the prosthetics themselves. The nature of these prints is particularly beneficial as they can be constructed with "bubble gum and bailing wire" [4], a hyperbole drawn from the "at home" nature of the prints that allows for the accessibility of the models.

Our client, Ken Bice, believes that an improvement to the cylindrical grip strength of an existing e-NABLE would allow for the Tasks of Daily Living (TDLs) to be completed with much greater ease both practically and physically. By quantitatively and qualitatively increasing the capabilities of the hand, the team has the potential to improve quality of life for upper limb prosthetic users around the world with an accessible method at an affordable price.

1.2: Existing Devices/Current Methods

There currently exist many different types of prosthetic devices available for individuals in need, but they can be most generally classified into passive versus active prostheses [5]. Passive prostheses can be both static and adjustable, but do not possess the capability to mechanically function as a result of input from the user beyond that of influence from the sound hand. Active prosthetics possess a mechanical function often actuated by an elbow or wrist flexion of the user. An average value taken from a collection of studies states that approximately 34% of individuals who have the potential for a prosthetic hand use passive prostheses, most frequently as a hand analog that is primarily for aesthetic appearance [5]. This statistic helps explain why hand prosthetic devices similar in design to the anatomy of the hand have always been pursued to a greater degree than some alternate form of function for TDLs.

Current e-NABLE models function on a wrist or elbow actuated tensioning system that closes the prosthetic due to an increase in the arclength of the path when the actuating joint is flexed. More sophisticated models have a variety of mechanisms for prosthetic motor function. Some designs feature the use of Thermoplastic Polyurethane (TPU) to create flexion joints in the hand rather than use separate pieces for the fingers in combination with coiled shape memory actuators to flex the hand (Figure 1) [6]. Other models, such as the DEKA Hand [7], which is a highly capable robotic hand with six different powered grip configurations, show the vast complex capability of modern prosthetic technology. There also exist prosthetics with switch actuators that allow for more simple models to be capable of two different types of grip, namely a pinch grip and a cylindrical grip [8]. The wide range of functional capabilities of prosthetics comes as a natural consequence of technological advancements over time. The highly complex nature of these alternate hands also typically incurs a much greater price point, which leads to professional prosthetics in the range of $5,000-50,000, while e-NABLE can create an entire functioning hand for around $50 [4].

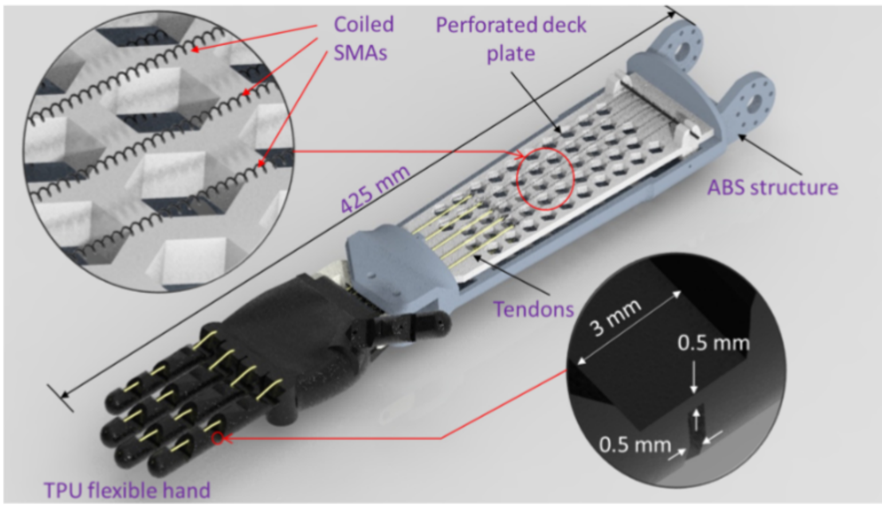

Figure 1. The Soft 3D-Printed Robotic Hand Actuated by Coiled SMA [6]

1.3: Problem Statement

The client has asked the team to modify an existing upper limb prosthetic to increase the cylindrical grip strength of the design. Currently, available professional prosthetic limbs are very expensive. On the contrary, less expensive hands are lacking in various areas. The team's client, Ken Bice, is associated with e-NABLE, a low cost provider of 3D printed prosthetics. e-NABLE is an online global community of volunteers who use 3D printers to make and distribute free/low-cost upper limb prosthetic devices for individuals in need. e-NABLE's open source design library allows users to access and modify existing designs to make improvements, allowing for frequent changes to the best designs recommended by the group. The goal for this project is to modify the existing *Phoenix Reborn* [9] model (Figure 2) currently offered by e-NABLE in order to improve at least two facets of the device's grip strength. The device must be made of materials found at local retailers that are low cost and accessible. Ideas for design modifications are limitless and should not be shelved for lack of anatomical resemblance, granted that they contribute towards the end goal of improving the overall grip strength.

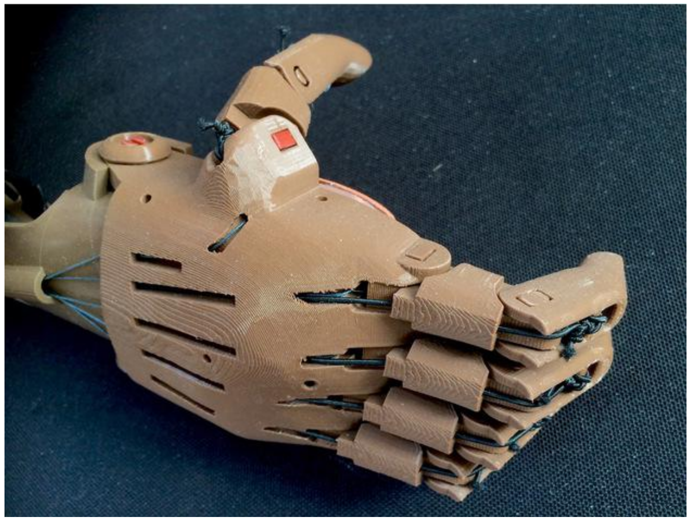

Figure 2. The Phoenix Reborn hand [9]

2. Background

2.1: Background Research

To further improve understanding of the hand and its flexion, the group looked into the biology of the hand. Thumb opposition is important for a stronger grip as it allows for the thumb to be placed directly opposite to the digits to wrap around an object and creates a greater degree of force between the object and the hand. The trapeziometacarpal joint [10] is what allows for the slight rotation of the thumb that does not limit it to one degree of freedom as in the *Phoenix Reborn*. By understanding the freedom that the thumb has, one of the team's preliminary designs was to reposition the thumb to allow for a variety of grips. The anatomy of the hand was studied closely to be able to understand how bone structure is applied to prosthetics. The current prosthetic model has two phalanx pieces and does not directly match the anatomically correct structure of the hand which has three [11]. The *Phoenix Reborn* model is lacking grip strength due to the inability to wrap the digits around cylindrical objects, so by extending the length of the digits by adding an extra phalanx, the prosthetic hand will have more surface area to grip the cylindrical object with. The team also looked into prosthetic tools rather than only making an adjustable prosthetic hand. Prosthetic tools are a prosthetic adaptation to an adjustable prosthetic hand [5]. Rather than building an anatomically accurate prosthetic hand, prosthetic tools take into account that anything can be built into a prosthetic to satisfy a user's needs. By thinking in this aspect, the team came up with the idea of adding a bar thumb. The bar thumb would allow for uniform pressure along the length of the cylindrical object it is picking up. To make sure that using the prosthetic stays easy, research was done to understand prosthetic training and the amount of time it takes a user to complete a task [12]. The team wants to keep the prosthetic at an affordable cost and at an easy usage for the user so as to not make the product inefficient in completing its task, even though the grip of the product might have been improved.

2.2: Design Research

The team decided to work with the phalange extension as a two stage improvement to the *Phoenix Reborn*. Returning to *Human Hand Anatomy-Based Prosthetic Hand* [11], there are a series of bands in the hands that allow for several different movements, but also improve the overall strength of the hand. Using Solidworks, the team edited one of the existing knuckles to be added as an extension to the digits. When adding the phalanx, the finger would have to close using one long chord which would cause the closing digit to lose strength in tension. In order to improve the strength, a second band was added to the design to improve the tension in adduction. The second band would be attached to the phalanx where the PIP joint would be on a biological hand. Studying the flexors in the hand, the team decided that it would be best to improve the intricacy of the tendons in the prosthetic model if a third phalanx were to be added. By adding the extra tendon and phalanx, the prosthetic has become a more accurate model of a biological hand.

2.3: Client Information

The client, Ken Bice, is e-NABLE's Madison Chapter Founder and has been a part of the e-NABLE community since 2017. He has created many designs and types of 3D printed prosthetic hands for those in the Madison area [13]. Ken Bice is also the owner of the BadgerHands.org facebook page "with the intent to offer support to STEM high school students, offering guidance and information for producing meaningful results from their projects" [13]. Mr. Bice has asked the team to create a design (or alter the current one) in hopes to increase the cylindrical grip strength of the already existing *Phoenix Reborn* e-NABLE hand.

2.4: Design Specifications

Currently, e-NABLE's *Phoenix Reborn* 3D printable prosthetic hand can only grip objects around the size of, or bigger than that of a soda can. The improved hand design must have specific requirements that will allow it to hold approximately a 6.6 cm diameter cylindrical bar that the client has provided. The overall design must also be created with the user's wrist flexion in mind. This is due to the fact that the main mechanism of opening and closing the hand is by extending or flexing the wrist joint, respectively. The design must not cause the user to exceed a normal motion of the wrist as part of the specifications regarding comfort and safety of the device. In regards to the cost and materials of the device, the team is limited to the average cost and availability of the current design, being that e-NABLE is a volunteer based group that must be able to provide quality but inexpensive devices to those in need. The material specifications are set to materials that would cost no more than the average cost of an e-NABLE hand, $50 [4]. The design must be user friendly and accessible to most 3D printers, as well as cautious of how much extra filament is used as supports. Finally, the design of the hand must be able to withstand day to day use. In past designs, there have been known flaws in the tension string systems that the team will be taking into consideration with the specification of shelf life.

The design must be able to be used daily without infringement of the quality and strength of the hand itself. (See Appendix A)

3. Preliminary Designs

3.1: Phalange Extension

The first design that the team decided to move forward with was the Phalange Extension model. The term "phalange extension" coined by the team comes from a combination of traits of the model, which consists of an additional phalange piece on the hand that increases the degrees of freedom (DOF) and extends each finger (Figure 3). A current problem of the hand is that the fingers are unable to curl over a large enough area to actually hold a cylindrical object securely in the palm of the hand. This flaw drastically decreases the ability of the hand to safely and strongly hold an object for very short or extended periods of time. Thus an extension combined with an extra DOF would allow for cylindrical objects to be held more snugly in the prosthetic since a larger reach of each finger would wrap around and tuck the object more tightly into the hand. The addition of a new piece to the finger also allows for the addition of a secondary tensioning system on the hand through the pre-existing channels within the model. A secondary tensioning system would allow for increased mechanical advantage of the hand so that force can be dispersed effectively throughout the fingers when picking up objects of varying size and shape. The team believes that the combination of the extra range of the fingers in combination with the secondary tensioning system will allow for significant increases in grip strength of the model. The design would be constructed using the same materials already seen in e-NABLE models and as such would only result in a minor price increase to account for the additional printing filament.

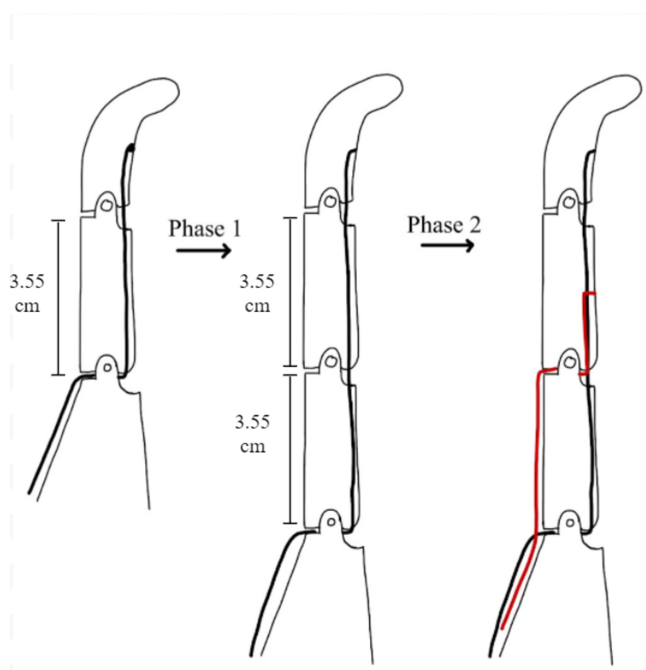

Figure 3. The Phalange Extension Design

3.2: Thumb Relocation

In the second design, a relocation of the thumbs orientation was considered. In the final concept of this design, the thumb was to be positioned parallel and facing the opposite direction of the rest of the fingers (Figure 4). When the user flexes their wrist, the fingers and thumb would contract to grasp a target object. This mechanism would work similar to a claw grabber and exert a larger force around the object than the standard prosthetic model. The main flaw within the original design that the relocation aims to deal with is the awkward angle/grip that the thumb offers. The original design results in much greater difficulty when attempting to get a firm grip on the object. This design would decrease user exertion as less force is wasted on an ineffective process of grabbing. Its position would allow for the thumb to wrap around the object itself, increasing the contact area, which solves the main issue presented with the original thumb orientation. New modeling and 3D printing of the palm would have had to be done to accommodate the new attachment. Along with that a new system of tensioners would also have to be designed to ensure that the thumb grasped correctly during flexion.

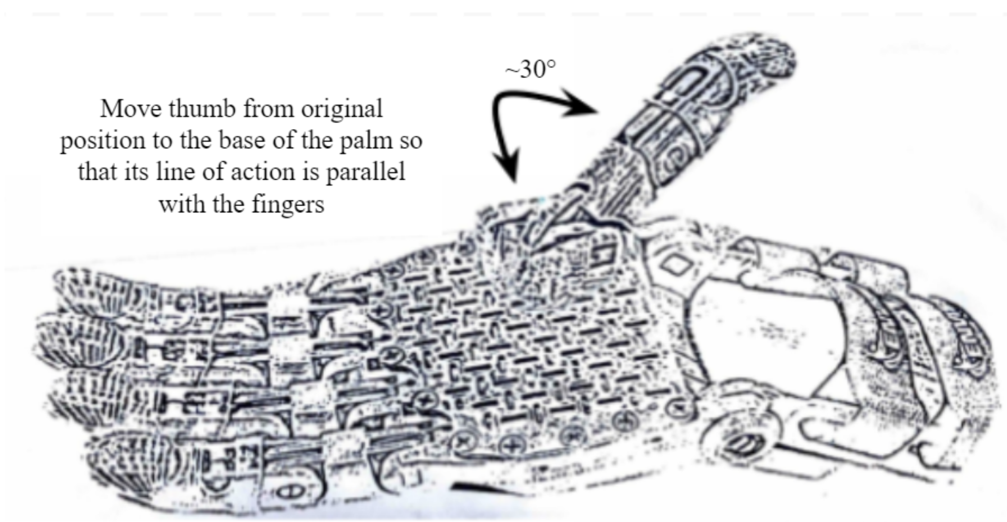

Figure 4. The Thumb Location Redesign

3.3: Bar Thumb

Design three aims to tackle the same inefficiency described in section 3.2. In this case the thumb is completely removed from the hand and is replaced with a rod that is perpendicular to the fingers (Figure 5). The bar design solves the ineffective grip of the thumb in the same manner as design two, but offers an even larger contact area with the object as the fingers and the whole length of the bar make contact with the object. It is possible that the bar itself could be made of, or coated in, a grippy material to increase grip further. This design also helps with grabbing smaller items as the bar creates a pinch point in between itself and the rest of the fingers. This redesign would likely take up the most time of the three presented ideas. A majority of the work would come from re-working the 3D model to accommodate the new attachment and the channels for the tension strings. Another large portion of the time would be assembling the new structure, which combined, decreases our overall time allocated for testing.

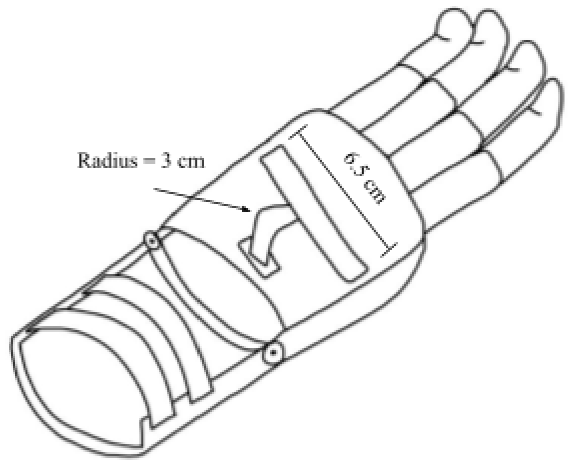

Figure 5. The Bar Thumb Configuration

4. Preliminary Design Evaluation

4.1: Design Matrix

Table 1. Design Matrix

Designs Criteria (*weight)	Design One Phalange Extension		Design Two Thumb Relocation		Design Three Bar Thumb	
Grip Versatility (30)	5/5	30	4/5	24	3/5	18
Safety (15)	4/5	12	5/5	15	3/5	9
Cost (15)	4/5	12	3/5	9	3/5	9
Ease of Fabrication (15)	4/5	12	3/5	9	3/5	9
Product Weight (15)	4/5	12	5/5	15	4/5	12
Aesthetics (10)	4/5	8	3/5	6	3/5	6
Total (100)	**86**		**78**		**63**	

*Note: When referring to weight it is always *x/100*

The design criterion weighed the three proposed designs based on grip versatility, safety, cost, ease of fabrication, product weight, and aesthetics (Table 1). Grip versatility is defined as the variations of grips and strength of the grips that the prosthetic allows. While the other factors are important, choosing a design with the strongest and most versatile grip is the main objective of this project. Grip versatility was weighted as the most important criteria at 30%. The second criteria evaluated was safety. Safety was weighted 15% due to the low chance of injury from fabricating and using the prosthetic. Along with safety, cost was weighted 15% as well. Cost was quantified as the total cost of the materials for the fabrication and complete development of the prosthetic. Next, ease of fabrication was weighted at 15%. The ease of fabrication criteria correlates to the difficulty of the fabrication process: obtaining materials or restrictions on fabrication. Product weight is defined as the size and weight of the prosthetic. This will likely determine comfort for the user. Product weight was weighted at 15%. Finally, aesthetics was weighted at 10%. Aesthetics were evaluated based on qualitative factors such as appearance and style of each design.

For grip versatility, the phalange extension design was ranked the highest. This is because the phalange extension design would allow for the strongest grip and have the most variety in the type of grip that needs to be applied.

For safety, the thumb relocation design was ranked the highest. This is because relocating the thumb would not change much from the existing design other than the exact placement of the thumb. Since the existing model is our baseline, the thumb relocation design would have a comparable safety to the existing e-NABLE model.

For cost, the phalange extension design was ranked the highest. This is because in the phalange extension design only the extra metacarpal for each finger would need to be 3D printed, however for the other designs a whole new hand would potentially have to be printed.

For ease of fabrication, the phalange extension design was ranked the highest. This is because the team will only need to 3D print additions to the hand, not the entire hand. Furthermore, the fabrication for this can be done in two phases to make sure the process can be attainable and create a high quality product.

For product weight, the thumb relocation design was ranked the highest. This is because the only aspect that will be changed from the existing design is the placement of the thumb and nothing extra will be added. Thus, the weight and size of the prosthetic will likely be similar to the existing model.

Finally, the phalange extension was ranked the highest in aesthetics. Adding a metacarpal to the existing prosthetic will make the design look more like an anatomically sound hand. The extension design will likely feel closer to an anthropomorphic hand.

4.2: Proposed Final Design

The final design selected for the project was the phalange extension design. This design was chosen based on the evaluation of the design matrix criteria: grip versatility, safety, cost, ease of fabrication, product weight, and aesthetics. Not only did the phalange extension design receive the highest score in the ease of fabrication and cost, it had the highest score in the highest ranked category which was grip versatility. The main objective of this prototype is to develop an affordable hand prosthetic with improved grip strength, which are all things that the phalange extension design aims to accomplish. The extension of the phalanges on the hand will allow the user to better wrap the prosthetic around an object. The extension will also increase surface area which in turn will improve the grip between the prosthetic and the object. Furthermore, this design is an addition to the current model, so the fabrication time will be achievable and cost will be kept low. Overall, the features of the phalange extension design that kept the cost low, kept the fabrication process straightforward, had good aesthetic appeal and increased grip versatility led to the decision of moving forward with the phalange extension design.

5. Fabrication/Development Process

5.1: Materials

There are a few key components that make up the design which are composed of different materials. Beyond the 3D printed components there are some parts which require different materials to be used. These include the retraction cables, which are used to open the hand, and the contraction cables, which are used to close the hand. For initial prototyping and design, the client has provided a fully assembled *Phoenix Reborn* hand to be modified with the intention of only producing a completely new hand at the very end of the design process if the design dictates. For the team's purposes, the materials received from the client as part of the hand will be excluded from the material analysis and cost breakdown at this point. Moving forward, they will become more defined upon producing a final design if a full new hand is produced. At this point these will simply be grouped into one category as the *Phoenix Reborn* hand which has an estimated cost of $40, according to the client [4].

When choosing materials, all items necessary to assemble the prosthetic hand are to be easily accessible "[the hand] should be able to be assembled using parts found at your local hardware store or craft store," the client, Ken Bice, explained [4]. This idea embodies one of the essential goals of eNABLE, to make prosthetic hands easily accessible to nearly anyone. The rationale behind choosing materials can be found below, however, this idea of easy accessibility was at the forefront of the decision making process.

The choice for 3D printer filament ultimately came down to availability. Polylactic Acid Filament, better known as PLA is a common low cost Fused Deposition Modeling (FDM) printing material that is the most reliable Ultimaker material. In addition to being one of the most common filaments, its properties are appropriate. With pressure tolerance of 65 MPa, service temperature tolerance of 52 ℃, and low thermal expansion (68 µm/m-℃) [14], it proves to be an adequate material. The support material used in the manufacturing process can also be PLA material, however, if available, PVA material is preferred as its water soluble characteristics make it much better suited for producing a clean final product as well as simplifying the post print processing.

The choice to use elastic cord as the material for the retraction cables was the result of various beneficial properties. Jewelry cord is particularly mildew resistant, and has high anti-abrasive properties. The blend chosen consists of a 70% spandex, 30% polyester mix with a unit weight of 0.68 g/m . The exterior polyester shroud provides high tensile strength. For pure polyester, the tensile strength at rupture is 27 MPa with a Young's modulus of 920 MPa [15]. Internally, the spandex has high dynamic elastic characteristics due to its quick work recovery which enhances the power of the performance [16].

Beading thread was chosen as the material for the contraction cables as it has a very high tensile strength, low weight, low cost, and high accessibility. One millimeter nylon beading thread has a tensile strength of 33.5 kg, assuming that a force is applied equally across all fingers during the action of holding an object, this would withstand a weight of 167.5 kg, far exceeding the force required by most users. This extreme strength is accomplished at a very low weight, only 0.94 g/m [17]. As with all materials this is easily accessible and relatively inexpensive (Table 2).

Table 2. Estimated cost breakdown of all components currently used for the prototype.

Component	Material	Unit Cost	Quantity	Total Cost
3D Printed Parts (Phalanx)	Polylactic Acid Filament (PLA)	$0.08 per gram	18 g/part, 8 parts = 97 g	$7.76
Elastic Retraction Cables	1 mm Elastic Jewelry Cord	$0.79 per meter	~ 0.92 m	$0.73
Nylon Thread Contraction Cables	1 mm Nylon Jewelry Thread	$0.69 per meter	~ 0.92 m	$0.63
Phoenix Reborn Hand	PLA, Bolts (3), Velcro, Foam	~ $40	1 Hand	$40
			Total Cost:	$49.12

5.2: Methods

Following completion of the design matrix, the “Phalange Extension” design displayed characteristics of high performance in all categories of the matrix and showed promising results for fulfilling the requirements of the PDS and problem statement.

The next step in pursuing this design involved exploring the currently available CAD parts for the *Phoenix Reborn* hand. Through the *Thingiverse* website and the e-NABLE website the team located files for the parts; however, these parts were only available in Stereolithography Mesh (.stl) files, which proved to be uneditable with Solidworks. The client, Ken Bice, provided a Solidworks parts file containing all of the components of the hand, however, the way in which these were converted left them unable to be recognized by Solidworks’ built in feature recognition system, and again, they proved to be uneditable.

The team decided to take a different approach to the modeling process, starting from scratch to produce unique, redesigned parts via reverse engineering. The phalange extension design involved the creation of one new component, a phalanx. This component was modeled based on the critical dimensions of the existing components measured with a caliper. These critical dimensions included the pin hole diameter and depth, slot and tab width and depth, and overall length and width (Figure 6a). Various other dimensions were taken to produce a part that matched the same anatomical appearance of the hand.

The distance from pin hole to pin hole on the new phalanx is 3.55 cm. This is approximately the same size as the other joints in each finger. This additional phalanx extends the length of the fingers by 3.55 cm and adds an additional joint, allowing the fingers to better match the contour of a curved object. All other major dimensions were kept the same, allowing this new part to be easily integrated into the original hand without making changes to the other components (Figure 6b). This maximizes the usefulness of the new component because not only can it be added into new prosthetic hands, but it can also be incorporated into existing hands.

The first prototype print of the new component went exceptionally well. The team used an *Ultimaker 3S* with a build volume of 230 x 190 x 200 mm. All features of the print were well defined and had no imperfections (Figure 6c). It was determined that in order to maximize efficiency in the production of these hands in the future, the part would be oriented in a different position to minimize the amount of construction material needed and speed up the printing process not only for the team, but for any customer who seeks to print this part. The PLA support material supplied by the *Ultimaker 3S* proved to be a viable option for support, however, it was decided that a soluble support material would be used if available. This decreases the cleanup time necessary to remove the support material and provides a cleaner finished product. The PLA support, however, will work, allowing consumers with less advanced 3D printer capabilities to still produce the part. If access to a resin based printer, or multifilament printer is available, that can also provide higher quality finishes at a greater cost.

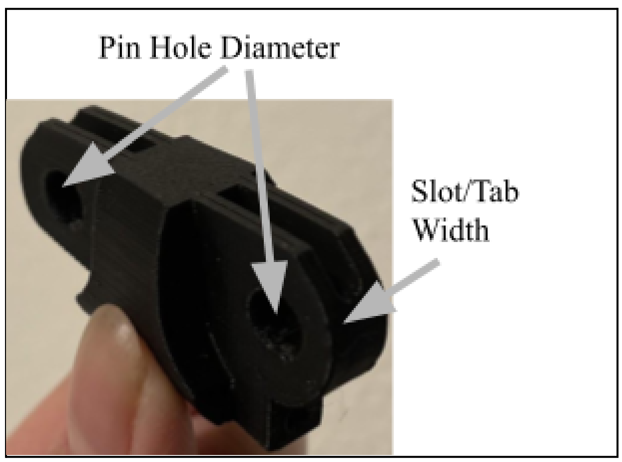

Figure 6a. One of the original parts of the Phoenix Reborn hand. The features which have been referenced in this report (i.e. Slot and tab) have been labeled for clarity.

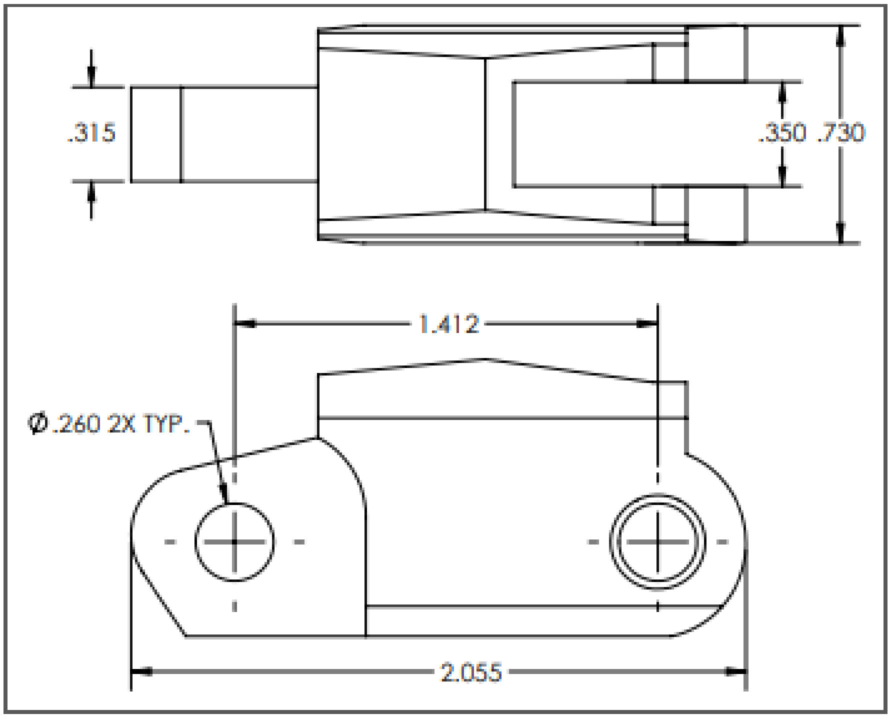

Figure 6b. Solidworks drawing highlighting the critical dimensions of the first iteration of the new part that was 3D printed. These dimensions correspond with those on the original parts.

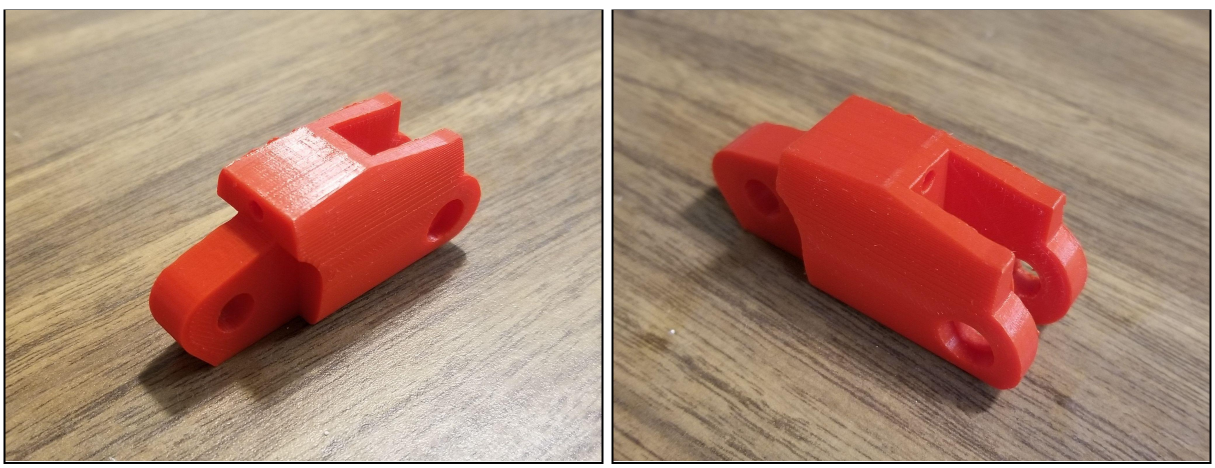

Figure 6c. The first iteration of the 3D printed phalange extension component. This prototype has both a male and female end to allow it to join with existing parts without adjustment of those components.

The initial modeling and first prototype print performed well with the assembly to the hand and were successful affirmations that this design was a feasible option to move forward with through the design process. With the first iteration complete, some places for possible improvement were identified to further improve the hand. Phase Two of the design upgrades was centered around improving the cable management and routing to maximize the tensioning system. This began with adding an additional cross-bar for string tie off at each phalanx located on the bottom of the piece, accessible via the lower tunnel. The original phalanx one component from the Phoenix Reborn hand was also recreated and modified to have this lower tunell cross-bar and extended channel (See Figure 7). Redesign of this component followed the same sort of modeling process as the other, beginning with reverse engineering in Solidworks followed by redesign.

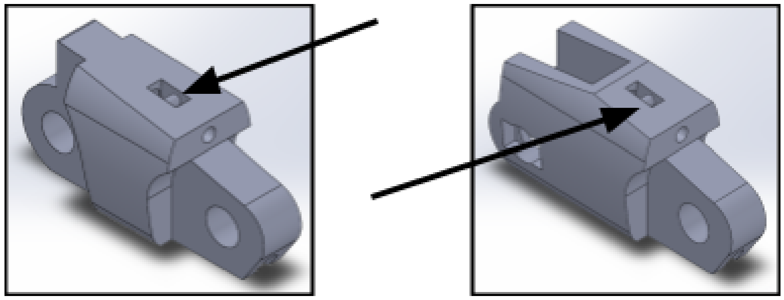

Figure 7. SolidWorks Drawing of the second iteration of parts with the additional crossbar tie off on both the old and new components (Phalanx One and Two).

Production of the first iteration of the part drew attention to the importance of a clean finished product that was not affected by the internal support material. With the addition of intricate channels and tunnels in the second iteration, it was evident that a better support material would be needed or else the part would be unusable. To account for time of support cleanup and the capabilities of PLA prints, the team chose to experiment with Formlabs Tough resin. Resin printing eliminated concerns about support material cleanup as the nature of the printing method allows it to be produced without need for support. The tough material has a tensile strength of 55.7 MPa, a tensile modulus of 2.7 GPa and a thermal expansion of 119.4 µm/m/°C [18]. The prototype produced using the resin printer had outstanding detail and a nearly perfect finish, however, in an attempt to stay true to e-NABLE's values, we determined that the increased cost ($175/L) was unreasonable for future production. It was ultimately decided to pursue all future designs by using PLA. This realization drew attention to another alternative material, PVA, which maintained some of the same high quality characteristics that the resin provided, while still maintaining low cost at only $0.19 per gram. This water soluble support maintained high print quality within the hidden channels, decreased post printing processing time, and maintained high quality parts. Another key issue was identified in this process that was important for the remaining print jobs of the project. The pin which was printed to attach the additional phalanx component did not scale correctly according to what we had expected (see Figure 8). During a client meeting, in which four new pins were provided, knowledge was also exchanged on how to properly work the Cura software to avoid future shortcomings in producing scaled parts.

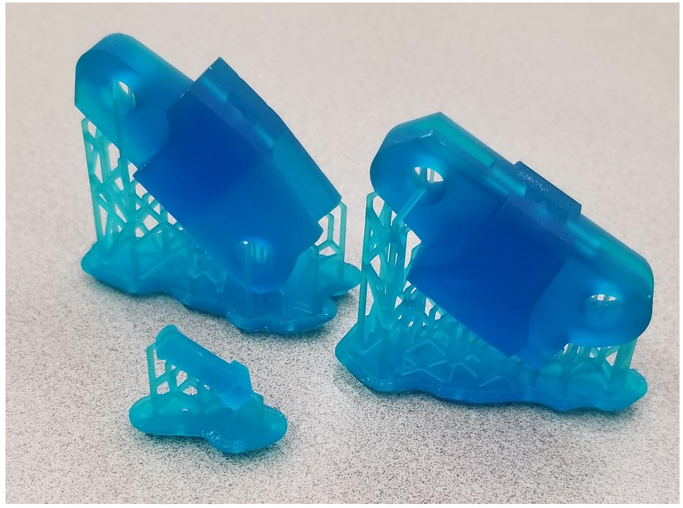

Figure 8a. Formlabs resin prints are seen above with the complex support structure still attached. This structure is easily separated to provide a high quality finish. These prints were the first to include the intricate tunnels running through the top and bottom of the part.

Figure 8b. The pin inside of the phalanx component is significantly smaller in diameter than expected, a key lesson moving forward in parts scaling. Note the very smooth, high quality finish of the part. This finish is achieved, at an increased price.

Following production of the resin prints, it was determined to resume production with PLA material, but use PVA support material for the reasons described above. The next iteration of prints did not have significant modifications as all components proved to fit well into the existing hand and function as intended. The only slight modification was to increase the clearance of the pinhole very slightly to decrease the friction at the joint allowing for a more fluid movement. An order for the third iteration of prints was placed at the UW Makerspace in which PLA build material would be used and supported by PVA. One of each component necessary for assembly of a single finger was printed as it was assumed that these would be the final prototype, but one more check of this exact configuration would be completed before printing the remaining parts. Unfortunately there was an error in printing and upon receival of the components, it was discovered that PLA support had been used. As seen in Figure 9 below, the build material and support material are all the same, making it nearly impossible to get the high quality finish that we wanted to create our prototype.

Figure 9. The prints above were intended to be the first set of final prototype prints, however, an error in printing led to the incorrect material being used and the prints were considered a failure.

In response to the failed prints in iteration three (Figure 10), the team needed to reprint the parts. This time, during setup, extreme focus was placed on ensuring that PVA material was used. The previous round of prints had appeared to be set up correctly in the eyes of the team as well as Makerspace staff, so during this round all checks were made to ensure a successful print. After a successful print of one of each component, the remaining finger components were printed as well as the palm base plate (Figure 11). The printing of the remaining finger components produced a couple pieces with deformations. These deformations could possibly stem from high moisture content in the build area which would negatively affect the performance of the sensitive PVA support material. Nevertheless, the components with blemishes were replaced with higher quality components. It was noted that printing in smaller quantities produced better results. Upon receival of this batch of prints, all necessary components for construction of the hand were completed.

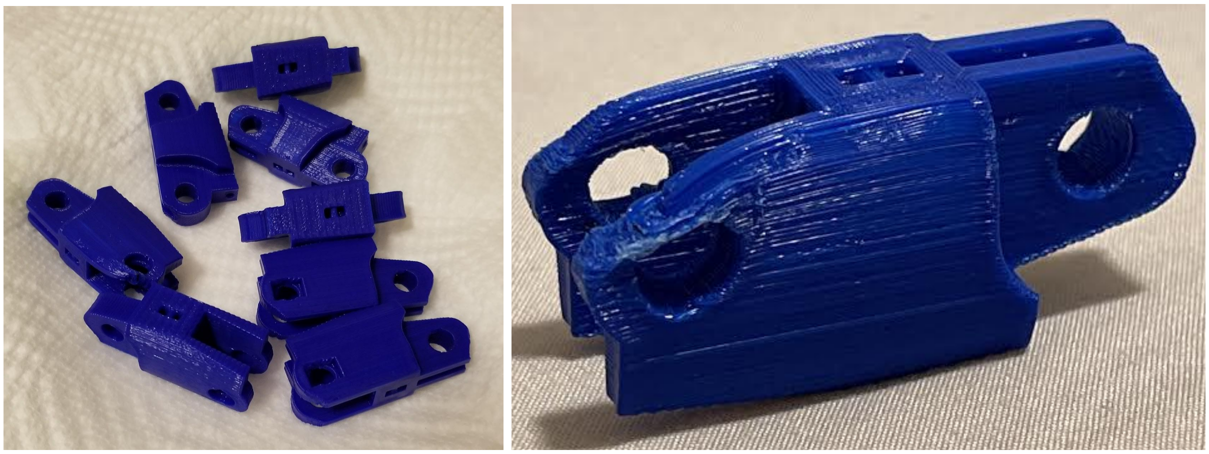

Figure 10. On the left are all eight of the components that were printed for assembly of all of the fingers out of PLA with PVA support material. Some of these prints were distorted as is seen in the picture on the right.

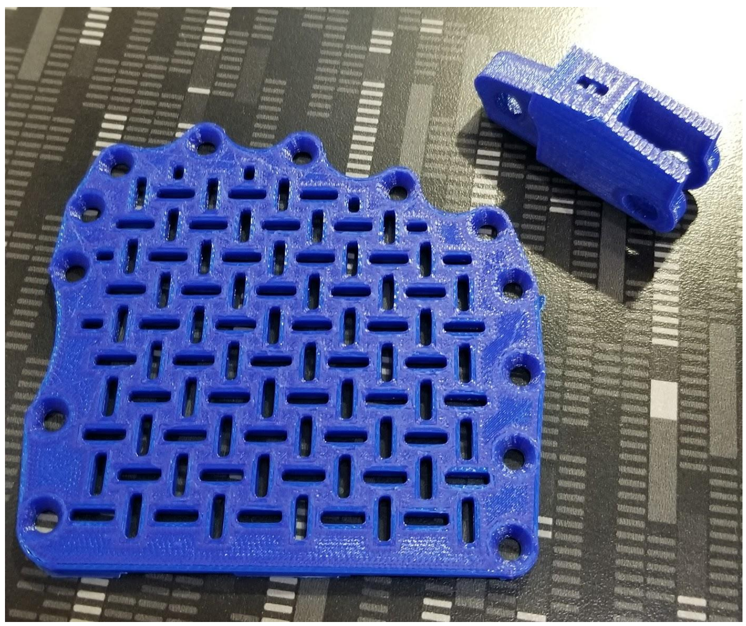

Figure 11. Seen here is the palm base plate as well as a reprinted PLA-PVA phalanx component with much better results.

All components were now successfully produced and this stage of design was complete. The parts were assembled and the hand was ready for testing. For a more in depth look at production and assembly of the hand, see appendix E.

5.3: Final Prototype

Upon determination of satisfactory dimensioning and clearancing, a total of eight phalanx components (4 male to male, 4 male to female) were 3D printed using PLA at 40% infill with PVA supports. In depth images of the dimensions of these parts can be found in appendix F. The current *Phoenix Reborn* hand was disassembled and successively reassembled including the new linkages in the fingers, as can be seen in Figure 12. The elastic thread and nylon thread was strung through the new intended channels and their tension was set using the tensioning screws and alternate tightness during the knot-tying process to ensure optimal performance.

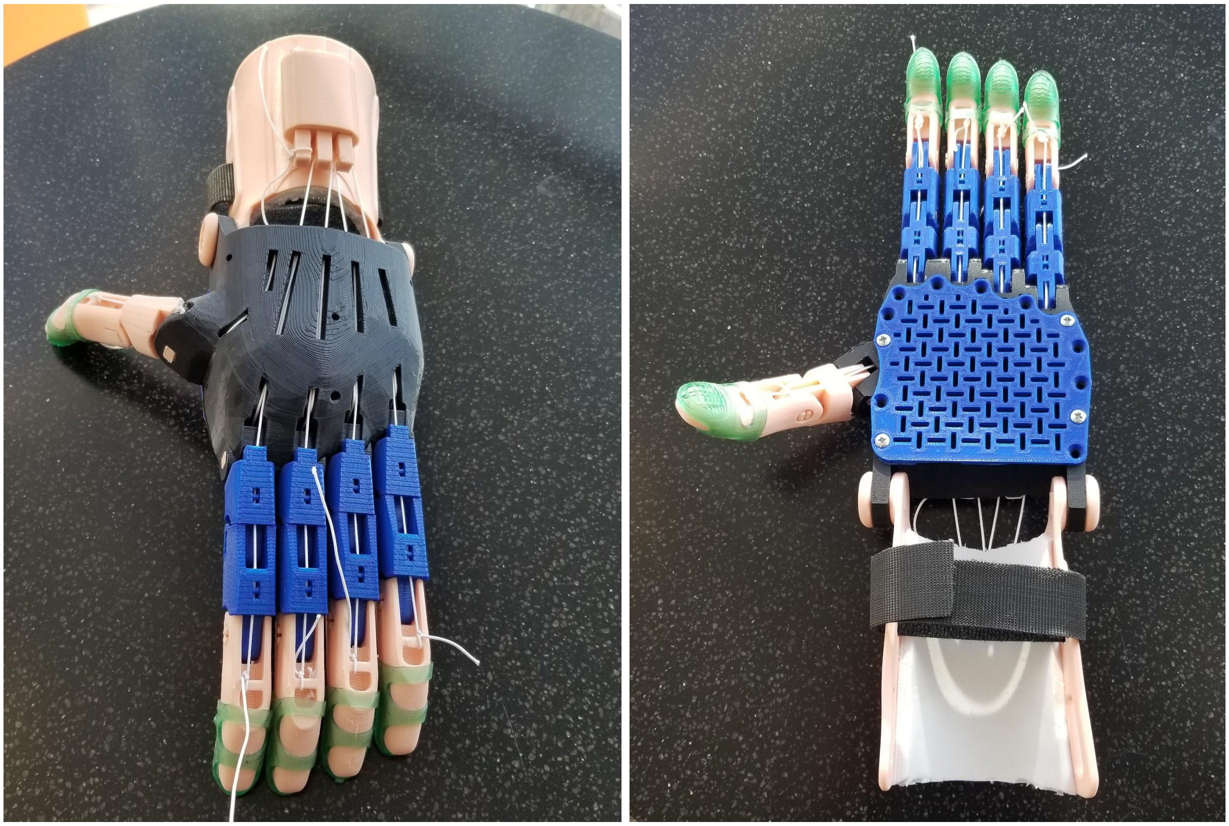

Figure 12. The assembled final prototype. For in depth images and dimensions, see appendix F.

The assembly process for the prototype takes longer than the *Phoenix Reborn* as a result of the increased amount of both nylon and elastic cord, which was already the most time consuming aspect of fabrication before the amounts were increased. Once the hand is constructed and the knots are super glued so that the user will not worry about grip failure on account of a string coming loose, the team anticipated that this prototype design would be capable of far more TDLs than previously seen and began to design testing to see if that was the case.

5.4: Testing

Two separate testing procedures were developed and conducted by the team, with each procedure set being catered to a specific criterion of the hand. The testing procedures became known simply as the "quantitative" and "qualitative" testing protocols and assessed the force values of the grip of the hand, and the capability of the hand to pick objects up, respectively.

The quantitative testing's primary objective was to observe whether or not the prototype had actually improved the physical gripping capabilities of the prosthetic. The team used the hand dynamometers from the UW Madison Anatomy and Physiology 335 Laboratory and the

BIOPAC software to test this. Trials were conducted over two second intervals alternating between hand flexion and hand relaxation for six flexions. The quantitative testing was able to provide the team with actual numbers for the grip force for both prosthetics, allowing for not only the prototype to be compared to the original, but for future models to be compared to the new control value as well. The team anticipated that the prototype would have a stronger grip force due to the increased radius of curvature and added degree of freedom allowing for a more direct oppositional normal force to the palm of the hand. However, also as a result of the extra degree of freedom and finger length, the team was conscious that these factors may actually cause an overall decrease in the force values since tension would be exerted over a greater distance with alternating force vectors and freely moving joints (See Figure 13).

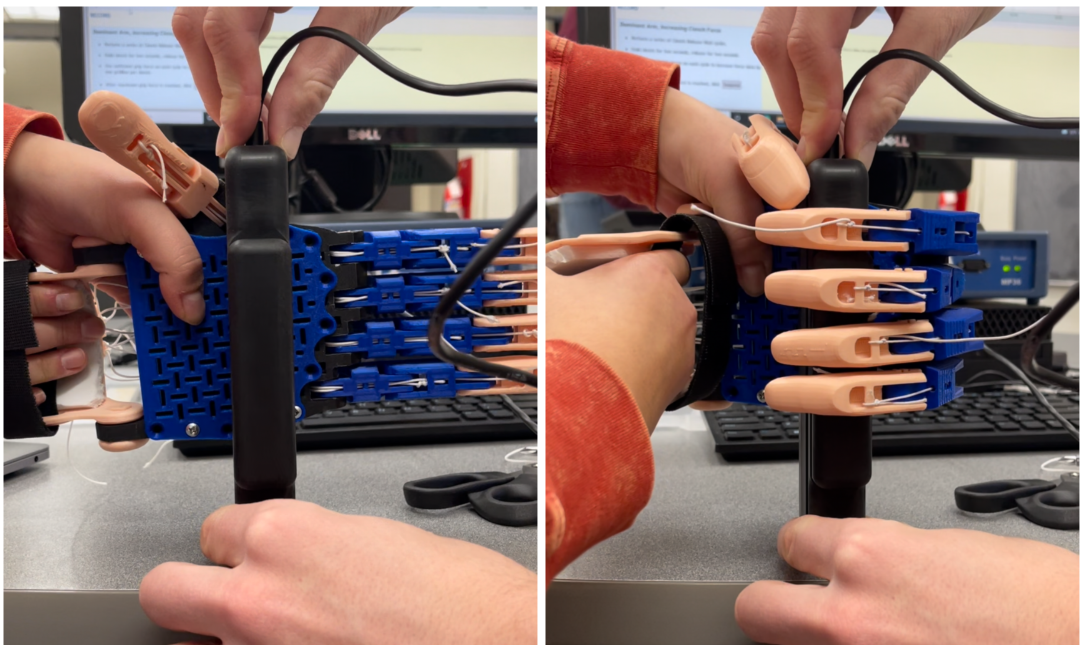

Figure 13: The setup for the quantitative testing involved a hand dynamometer being gripped by the hand in the arrangement seen above.

Qualitative testing involved a series of attempts to lift and hold cylindrical objects of varying size and weight with and without grip aids. Per the client, a common problem with most e-NABLE hands is that the PLA can be quite slippery and make it difficult to grip onto objects, so grip aids are used. The grip aids are micro-gel fingertip grips produced by "LEE Tippi" and can be found at Office Depot and Walmart, making them easily accessible [4]. The grips are traditionally used to help with page turning on individuals with sound hands and drastically improve the ability of the prosthetics to complete TDLs. Since TDL completion is a much better proxy for the capability of the prosthetic, the raw hand ability was tested alongside the use of grip aids. Three aluminum cans (245 mL Red Bull, 473 mL Bubly, 680 mL Arizona Iced Tea) of ascending diameter were used alongside one large cylinder composed of stainless steel (946 mL Hydro Flask). The large steel cylinder was used as a limiter for the testing and it was speculated that only the prototype with grips would be capable of picking the cylinder up if everything went as expected. The diameters tested were 52.55 mm, 65.60 mm, 72.75 mm, and 89.47 mm. Each cylinder was tested at its “empty” weight, which were 10 g, 17 g, 29 g, and 434 g, respectively. Each cylinder was also tested at its “full” weight, when the cylinders were filled with water to a weight of 281 g, 486 g, 713 g, and 1350 g, respectively. For every trial, the cylinder was placed on a flat surface and given three trial attempts to pick up the object for that trial and hold it steady without slipping (See Figure 14). The team anticipated that the prototype would outperform the original once heavier and larger cylinders were introduced to testing. See Appendix D for in depth testing protocols.

Figure 14: Seen above is the arrangement of components during the qualitative testing. A Redbull can and Hydroflask are seen being gripped here.

6. Results

Once testing was completed, data was digitized using Engauge Digitizer which uses pixel dimensions and user inputs to calculate accurate data points based on the graph given. This data was then exported as a .csv file which was then loaded into MATLAB. Once the team completed this, it was determined that the original Phoenix Reborn hand displayed a mean force of 5.58 N with a standard deviation of 0.773 N. The prototype displayed a mean force of 13.9 N with a standard deviation of 2.82 N (See Table 3).

Table 3. Basic statistical analysis values for the original vs. prototype hands.

Prosthetic	Mean Grip Force (N)	Standard Deviation (N)	Minimum Grip Force (N)	Maximum Grip Force (N)
Phoenix Reborn	5.58	0.773	4.71	6.78
Final Prototype	13.9	2.82	10.1	17.5

Once the data was collected and converted over to MATLAB and visualized, the team conducted a two sided t-test analysis on the force for the *Phoenix Reborn* hand and the prototype design (See Appendix C for in depth coding and data for the statistical analysis). The results from the testing were able to conclude with a p-value of 1.49e-09 that the data was statistically significant, allowing the null hypothesis, that the means are the same, to be rejected, showing that the mean grip strength was significantly larger in the prototype hand (See Figures 15 and 16).

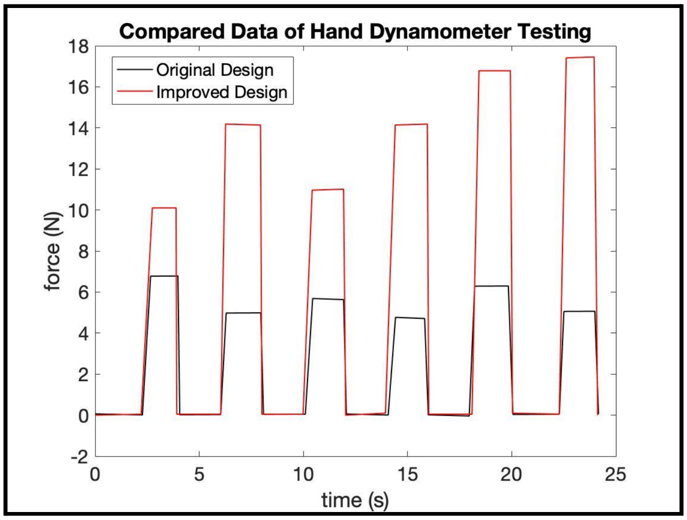

Figure 15: Line graph of grip force vs. time by both hands

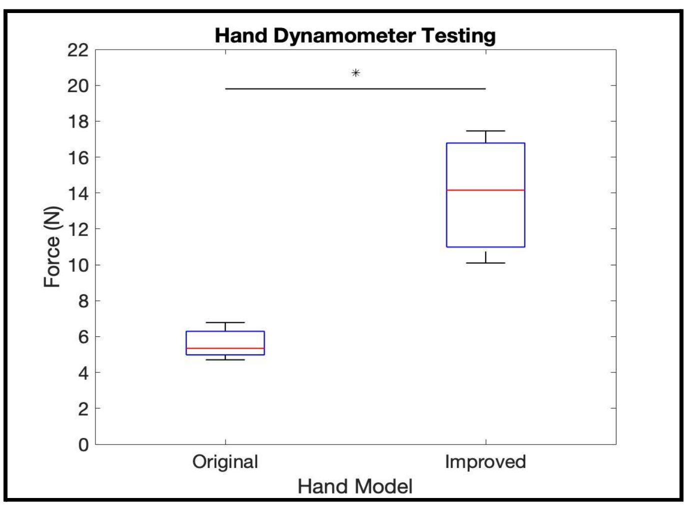

Figure 16: Box plot to show statistical significance of the difference between grip strength

The data the team collected for the qualitative testing was visualized to make inferential conclusions using histogram graphs to show the significance in the gripping capabilities of the *Phoenix Reborn* hand and the prototype design (See Figure 17). The prototype showed a very clear improvement when compared to the *Phoenix Reborn* in the ability to grip different sized objects as the cylindrical object's radii increased. The clearest observations came when viewing the results of the tests with the Hydroflask. Although there was no success for either design without grip assistance, the prototype with grip aids was able to complete the task of picking up the Hydroflask as hypothesized.

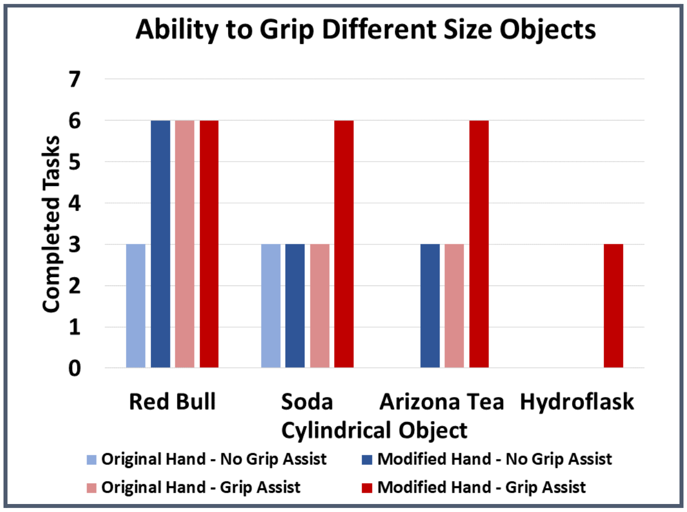

Figure 17: Histogram of qualitative performance by size

Comparing the data that was collected for the ability of weighted objects, there are a few significant data points that should be mentioned. (See Figure 18) At an arbitrarily light weight of the object without any additional weight, or "empty", we can see there is a peak at the modified hand with grip assist, completing the most tasks than that of any other variable. A similar outcome was observed for the "full" weight testing. The original hand without grips failed to pick up a cylinder, whereas the modified hand with grip assist was able to pick the cylinder up in nine of the twelve trials at the four different weight ranges.

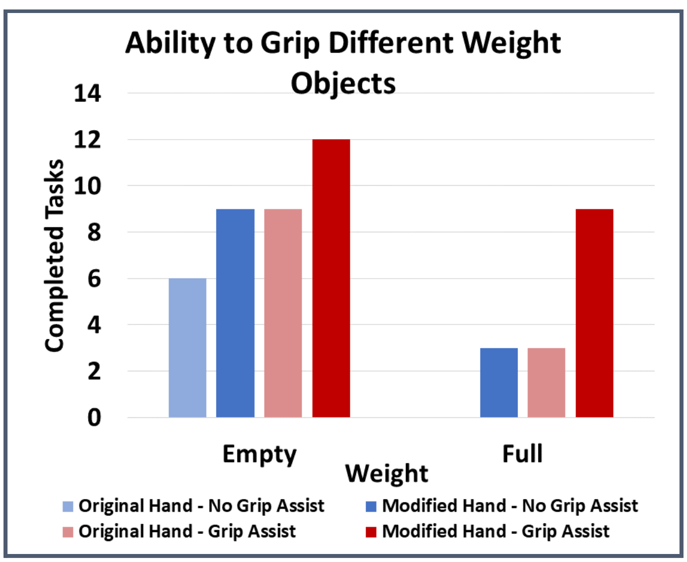

Figure 18. Histogram of qualitative performance by weight

7. Discussion

The testing data that was collected from both the qualitative and quantitative testing proved that the design the team moved forward with was successful in improving the grip strength and versatility of the prosthetic. Since e-NABLE is a non-profit organization, the prosthetics that are being dispersed across the world do not have any testing standards. Due to the lack of testing standards, there was little to no guidance for testing the prototype. This could give rise to implications of the results that the team collected because the testing criteria the team made may not have been accurately tested for. In addition, some potential sources of error that are worth mentioning from quantitative testing are: insufficient grip around the dynamometer, slight variability in the assembly between configuration in regards to the tensioning and retraction system, and variability in user force input.

After evaluating the first fully printed prototype once it was completed and put together, the team noticed a difference in the hyperextension of the phalanges along with the snugness of fit for each rotating joint. Changes to the pin hole dimensions were made to the prototype to fix these problems to ensure the prototype was operating in the same fashion as the original *Pheonix Reborn* model during final testing. Moreover, the fingertip grips that were used in the qualitative testing were to replicate how the hand would most likely be used in daily living. The testing with the grips is not repeatable and would be an area of the prototype that would need to be changed in order to make this testing repeatable and accurate.

With the final prototype, an additional phalanx was added and therefore increased the total weight of the prosthetic. Cross sectional studies have shown that there is an increased prevalence of falling with upper limb loss due to “reduced balance confidence, use of upper limb prostheses, and reduced physical capabilities” [19]. This could be due to the user’s center of gravity being affected leading them to fall. This ethical consideration should also be addressed in additional testing of the prosthetic’s integrity if it were to undergo a fall or impact.

8. Conclusions

Given the abundance of upper limb prosthetic users, e-NABLE’s goal is to provide affordable, easily accessible prosthetics to those who want or need an alternative to those already on the market. The current e-NABLE *Phoenix Reborn* model has a functional, working design; however, it is lacking the strength and versatility to grasp a wide variety of objects. This led to the client tasking the team in modifying the current *Phoenix Reborn* model to improve grip strength. After brainstorming different designs and utilizing a design matrix for choosing one design to move forward with, the team determined that the phalange extension was the final design best suited to improve grip strength.

The prosthetic hand grip that e-NABLE provided did not have enough degrees of freedom or surface area to grip cylindrical or heavy objects. The final design resolved this problem by adding a phalanx joint to create greater surface area and a better grip around cylindrical objects. By adding the third joint, the fingers were able to wrap around cylindrical objects such as the different sized cans used in testing. The final design also featured a new tensioning system that allowed the phalanges to effortlessly close with the newly added joint. Without the tensioning system the phalanges would have trouble closing and would lose strength in grip due to the added joint.

The team found that adding the third phalanx improved upon crush force as well as surface grip as it was able to grip heavier objects, as well as objects wider in diameter. By increasing the surface area the hand could create more friction between the object and the hand and therefore allowed for better grip around heavier objects. The tensioning system also improved upon the closure of the phalanges around a cylindrical object by closing each joint starting with the distal phalanx and closing to the proximal, whereas the original design would close starting with the proximal and would not allow for an arched flexion of the phalanges. By reducing the radius of curvature between the fingers and the cylindrical object, the normal force was increased, allowing for a better grip on the testing object.

Some things that did not work were the composition of the phalanx and the joint holes where they were supposed to attach to the existing phalanx pieces. The pieces needed to be individually filed in order to fit with the existing phalanx pieces. Due to the pieces being the wrong size, we needed to make a second rendition of the piece. Another problem was that the wrong material was used in the second print of the second rendition of the phalanx piece. The material was not PVA and the supports and entire back surface of the piece were warped. The team came across the issue of the phalanx pieces not closing in the right order when flexing the hand. This was due to using the old tensioning system while adding a phalanx piece, which uses more energy to close and does not close in the proper order. When closing an anatomically correct hand, the distal phalanx flexes first but in our first model the proximal phalanx would flex first and would not wrap around a cylindrical object properly. To fix this, the team made a new tensioning system that was threaded through a new path between the phalanx joints. Lastly, it was troublesome coming up with qualitative and quantitative tests as qualitative testing proved difficult to do when measuring grip and crushing force. What the team might do differently is establish an improvement that can be easily tested quantitatively and accurately as measuring the crushing force has a lot of room for error. Another thing the team might do differently is establish what requirements the client wants through thorough questioning rather than having a general instruction to improve the overall product; the team would like to know what specifically about the product needs to be improved.

For future testing the group hopes to do more thorough testing such as using a marking paint/ink on the fingers of the prosthetic hand to mark the specific location of the phalanges and their pressure distribution on the surface of an object. Another idea to measure pressure distribution is to use a series of force sensitive resistors that can sense different pressures to a certain extent when pressed. By utilizing these resistors the team could see what parts of the prosthetic are utilized in grip more than others so that the team can improve upon the lower pressure areas of the prosthetic. This would allow the team to improve upon the curvature of the palm and the fingers if any of the fingers are being utilized more than the others.

For future work, the team hopes to work on the existing thumb as its position is not beneficial to the grip of the prosthetic hand overall. Its placement makes it difficult to grip cylindrical objects. One of the original ideas was to make the thumb opposable and adjustable as to accommodate for the different hand grips needed for daily use by the user. Making the thumb adjustable, as well as adjusting it with just the hand alone posed as a challenge that the group hopes to resolve in the future. More future work involves integrating a pulley system that will increase the total crushing force in the tensioning system of the hand. Integrating a pulley system would also be difficult as it would be bulky and require a lot of moving parts that would need to be constantly maintained whereas the goal of the prosthetic is to be long term and usable with minimal maintenance. One last bit of future work would be to make the contour of the palm pliable so that different objects can mold into the surface of the palm. The pliable material would create a better seal of friction with the object being grabbed and allow for a greater grip force.

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10. Appendix

A: Product Design Specifications

e-Nable Prosthetic Grip Strength - BME 300/200

Product Design Specifications
September 24, 2021
Section 306

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Function: The client, Ken Bice, has requested that the function of the e-Nable *Phoenix Reborn* 3D printable prosthetic hand be altered to achieve an increased capability of cylindrical grip strength. Current models of prosthetic hands provided by e-Nable are very limited in their ability to grasp cylindrical objects smaller than a soda can, approximately 6.6 cm in diameter. The improved open cylindrical grip strength prototype should be able to hold a textured cylinder approximately 2.54 cm in diameter with significant mass for an extended period of time. Functionalities seen in the new product should remain largely the same if not improved when compared to the existing *Phoenix Reborn* model, minimizing substandard functionality sacrifices. Level of comfort should also be considered when developing the prototype to not have overexertion or harm to the user by straying too far from current standards. Simplicity and ease of use should also be considered so that users will not have to go through an overly intense learning curve prior to efficient and effective use.

Client requirements:

- Develop a prosthetic hand that is capable of an improved strength cylindrical grip
- Device must be able to pick up and hold a textured cylinder that will be supplied by the client
- Include a mechanism that limits overexertion of the user while using the prosthetic
- Ensure that the low-cost nature of the initial product is maintained with the prototype
- Possess equivalent or more accessible manufacturing intensity when compared to existing e-Nable models

Design requirements:

1. Physical and Operational Characteristics

a. *Performance requirements:* The prosthetic will be used daily by an individual of any age. Thus, the prosthetic must be able to withstand daily activities such as picking up and holding objects as well as general reinforcement and stability. The prosthetic is removable, but must be sized appropriately to the individual prior to use. The prosthetic will perform the cylindrical grip adequately.

b. *Safety:* Our design will be tested to ensure function without potentially dangerous failure at a given range. Any identified hazards will be reworked to prevent any injury wherever possible and proper use of the design will be conveyed to the user.

c. *Accuracy and Reliability:* The design will mimic the anatomy of a human hand with equivalent anthropometric sizes to that of the individual user. Elementary movements will be performed by the hand, with goal closure speeds of the fingers to be nearing that of functioning fingers, approximately 170-200 degrees/second [1]. The design will also be able to repeat these movements with minimal change in performance throughout its lifespan due to elastic deformation.

d. *Life in Service:* Per the client, 3D printed e-Nable prosthetic hands are currently designed to endure a lifespan of approximately two to three years of daily use with little maintenance or repairs. All changes to the design must meet or exceed this same life span.

e. *Shelf Life:* The final design will not use rubber bands as they break within days when exposed to high humidity areas, most frequently users who reside in tropical climates. The shelf life of the prototype will match the life in service of the current models, approximately two to three years. To account for the inability of rubber band use, elastic string is to be incorporated. Adolescent consumers are expected to upgrade to a different prosthetic size to accommodate growth after shelf life period and fully grown users can make repairs or reconstruction as necessary.

f. *Operating Environment:* The components of the prototype must withstand direct contact with surfaces of 37 ℃ (human body temperature), but also must withstand use in a variety of climates ranging in temperature from -25 ℃ to 40 ℃ and 40 - 80% humidity [2]. Proper function must also occur under mild daily accumulation of dirt and grime, but is expected to have a level of cleaning and maintenance given significant dirt build up.

The device must be able to operate without deterioration in aquatic conditions. The noise level should not increase beyond the current levels, which are not measured, but are not particularly jarring or disturbing in any given environment. Any modification to the design should not significantly interfere with the overall toughness or the peak/ultimate stress of the design from significant loading.

g. *Ergonomics:* The redesigned hand will not be designed for activities beyond that of standard activities of daily living. The product will act to be an improvement on the existing cylindrical grip to grasp objects like a door handle, soda can, or garden hose.

h. *Size:* The size of the hand should not be less than a print of 125% model size per the client, for ease of construction. The size of the model hand provided to the team is 140% upscaled. Scaling the *Reborn Hand* [3] parts at 124% would result in: palm width (widest) of 80 mm, wrist joint (outer radius) of 75 mm, and a wrist joint (inner radius) of 64 mm.

i. *Weight:* The design should not exceed a weight of 400 g [4] to ensure ease of use and limit muscular strain on the user. It should also be noted that this weight is especially important to adhere to since the prosthetic stresses muscular structure rather than skeletal and thus can be perceived as heavier than it really is by the user [4].

j. *Materials:* Metals should not be used as they are heavy and expensive. Plastic filaments are easier to print and allow for the prosthetic to be worn in conjunction with electromagnetic devices. All plastic components must be an affordable 3D printable filament that is also a recognized safe material when under consideration as a biomaterial. Per the client's request, any additional components must be easily accessible and affordable, such as being available at most hardware and craft stores.

k. *Aesthetics, Appearance, and Finish:* Changes made to the design of the *Phoenix Reborn* hand should match the current characteristics of the hand wherever possible and only change to improve grip strength/function. The texture of the hand should be smooth with an absence of any sharp edges. The color is negligible as this is up to the consumer to choose their printer filament and make aesthetic choices as they please.

2. Production Characteristics

a. *Quantity:* The client requires one 140% upscaled size final prototype as a proof of concept with full functionality. Other prototypes should be constructed at a smaller scale for initial concept testing and design but in as minimal quantity as possible in order to keep overall cost down.

b. *Target Product Cost:* Final product cost should remain between current standards of $30-$45 for e-Nable models. Price increases innately result from greater percent upscale of the print requiring more material and thus being more expensive for the user.

3. Miscellaneous

a. Standards and Specifications: Due to the "at home" nature of the prosthetic's design and construction, there are not many ASTM standards that directly apply to the product. However, the team still needs to be mindful of ASTM D4964, Standard Test Method for Tension and Elongation of Elastic Fabrics (Constant-Rate-of-Extension Type Tensile Testing Machine) [5].

b. *Customer:* The client prefers whichever style would be the most suitable to increase the grip strength. There is no preference as to if the product has to be in the form of an addition to the design or an implementation into the current design. The client also does not require that the prototype be passive or active in nature.

c. *User-related concerns*: The main concerns regarding patient use of this device is overexertion. Extended use of muscles in the arm and wrist can lead to fatigue and the inability to complete various tasks. The design must be comfortable for long term usage for the user.

d. *Competition:* There are currently four e-NABLE hand designs that are on the market so the prototype has competition within the realm of the client. There are also many other designs such as the *Pisa/IIT SoftHand* [6] which uses adaptive synergies and friction based transmission to perform daily activities, as well as the *DEKA* arm [7] which has six powered hand grips.

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B: Materials and Expenses

Item	Description	Manufacturer	Date	QTY	Cost Each	Total	Link
Prototyping							
First Print	2 M/F new phalanx 20% infill	Makerspace	10/12	1	$1.44	$1.44	n/a
Second Print	Improved phalange (two phalanx components, one pin) Formlabs tough resin	Makerspace	11/1	1	$7.58	$7.58	n/a
Third Print	1 male-male phalanx 1 male-female phalanx 80% infill, intended PLA/PVA	Makerspace	11/5	1	$2.32	$2.32	n/a
Fabrication							
Fourth Print	4 male-male phalanx pieces (40% infill PLA with PVA Support) 4 male-female phalanx pieces (40% infill PLA with PVA Support)	MakerSpace	11/12	1	$7.76	$7.76	n/a

Fifth Print	Palm cover (PLA no support) 1 M/F phalanx reprint (PLA/PVA)	Makerspace	11/17	1	$3.22	$3.22	n/a
TOTAL:							**$22.32**

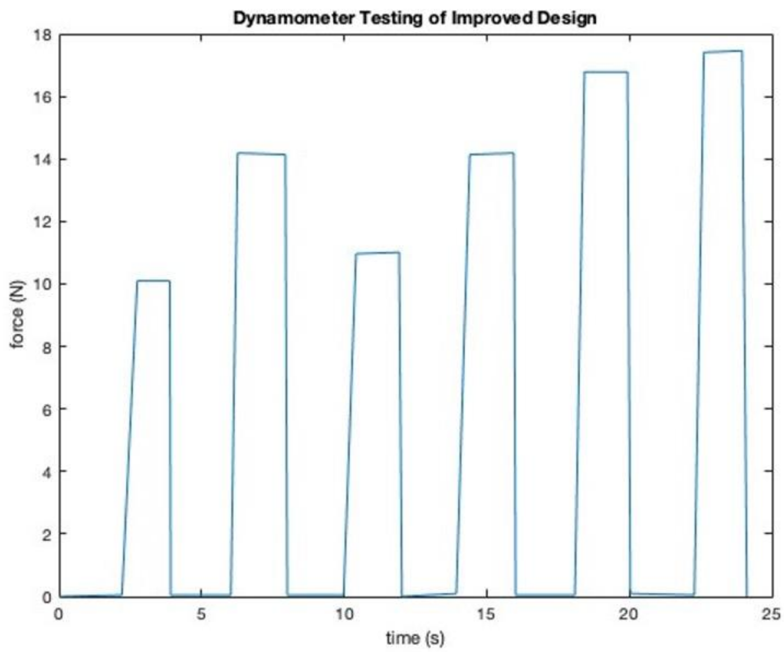
Zero-Expense components from client:

Component	Material	Unit Cost	Quantity	Total Cost
Elastic Retraction Cables	1 mm Elastic Jewelry Cord	$0.79 per meter	~ 0.92 m	$0.73
Nylon Thread Contraction Cables	1 mm Nylon Jewelry Thread	$0.69 per meter	~ 0.92 m	$0.63
Phoenix Reborn Hand	PLA, Bolts (3), Velcro, Foam	~ $40	1 Hand	$40
			Total Cost:	$41.36

C: Coding/Data Analysis

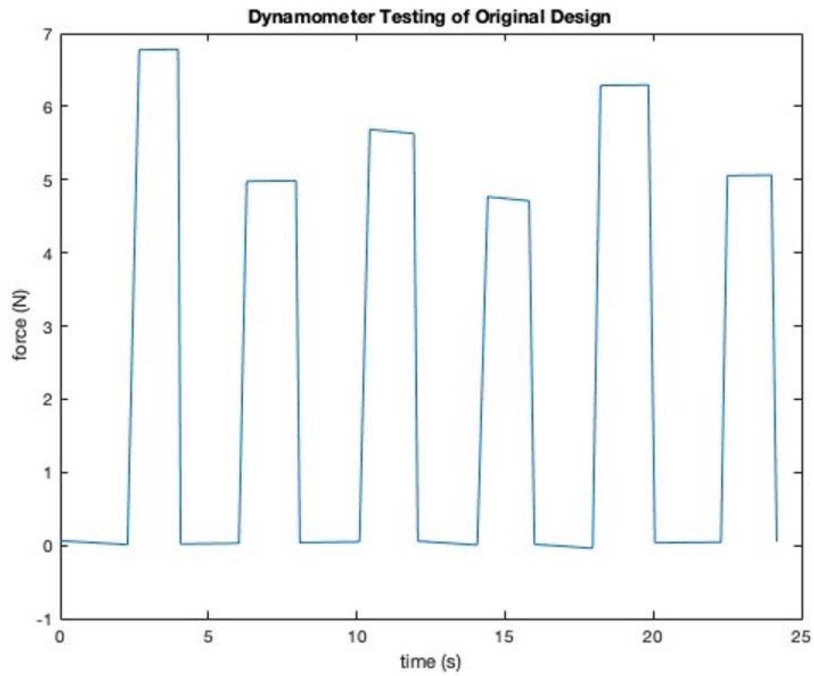
Dynamometer Testing of Improved Design

```
close all; clear all;

[file, path] = uigetfile('/Users/kenziehurt/Documents/MATLAB/BME300/Improved.csv','/Users/kenziehurt/Documents/MATLAB/BME300'); data = importdata([path,filesep,file]); time = data.data(:,1); kg_force = data.data(:,2); force = kg_force*9.81;

figure(1); plot(time, force); title('Dynamometer Testing of Improved Design'); xlabel('time (s)'); ylabel('force (N)');
```



Dynamometer Testing of Original Design

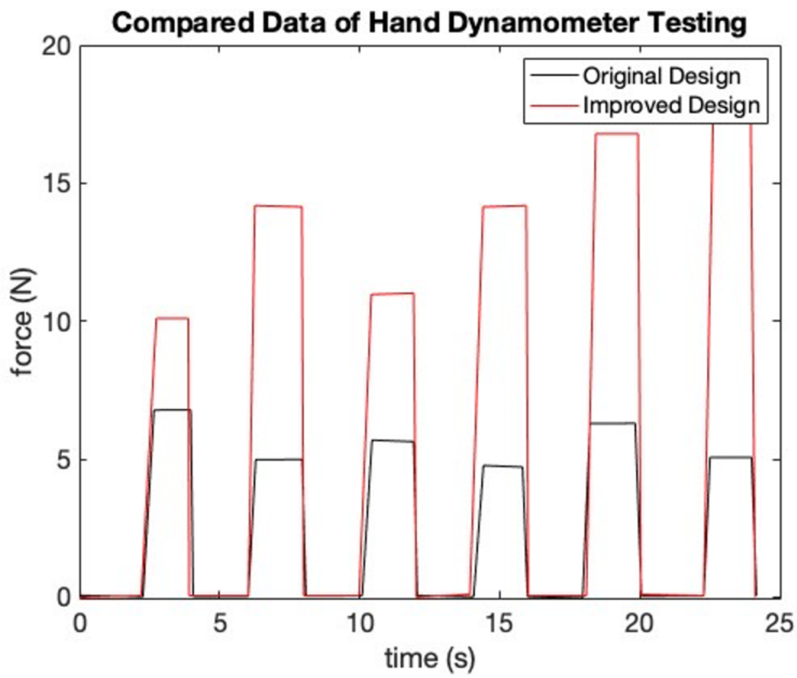
```
close all; clear all;

[file, path] = uigetfile('/Users/kenziehurt/Documents/MATLAB/BME300/Original.csv','/Users/kenziehurt/Documents/MATLAB/BME300'); data = importdata([path,filesep,file]); time = data.data(:,1); kg_force = data.data(:,2); force = kg_force*9.81;

figure(1); plot(time, force); title('Dynamometer Testing of Original Design'); xlabel('time (s)'); ylabel('force (N)');
```

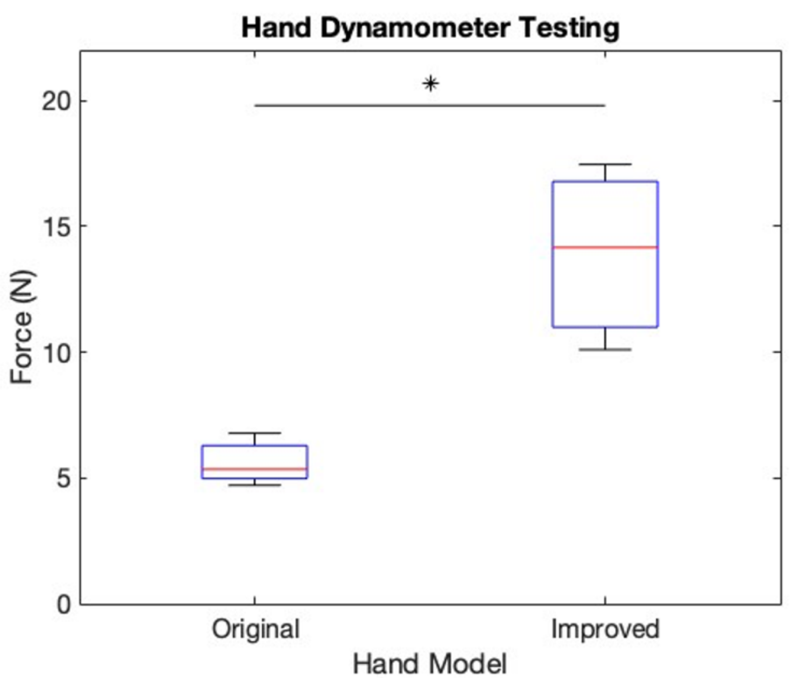


Comparison

```
close all; clear all;

[file, path] = uigetfile('/Users/kenziehurt/Documents/MATLAB/BME300/
Original.csv','/Users/kenziehurt/Documents/MATLAB/BME300');
original = importdata([path,filesep,file]); o_time =
original.data(:,1); o_kg_force = original.data(:,2); o_force
= o_kg_force*9.81;

[file, path] = uigetfile('/Users/kenziehurt/Documents/MATLAB/BME300/
Improved.csv','/Users/kenziehurt/Documents/MATLAB/BME300'); improved =
importdata([path,filesep,file]); i_time = improved.data(:,1); i_kg_force =
improved.data(:,2); i_force = i_kg_force*9.81;

figure(1); p = plot(o_time, o_force, 'k', i_time, i_force, 'r');
p(1).LineWidth = 1; p(2).LineWidth = 1; ax = gca; ax.FontSize = 16;
title('Compared Data of Hand Dynamometer Testing'); xlabel('time
(s)'); ylabel('force (N)'); legend('Original Design', 'Improved Design');

o_maxes = sort(o_force, 'descend'); Original =
o_maxes(1:12); i_maxes = sort(i_force,
'descend'); Improved = i_maxes(1:12); [h,p] =
ttest2(Original, Improved)

figure (2); bp = boxplot([Original, Improved], 'labels', {'Original', 'Improved'});
set(bp,{'linew'},{1}) ax = gca; ax.FontSize = 16; title('Hand Dynamometer
```

```
Testing'); xlabel('Hand Model'); ylabel('Force (N)'); yt = get(gca, 'YTick');
axis([xlim 0 ceil(max(yt)*1.2)]); xt = get(gca, 'XTick'); hold on; b = plot(xt([1
2]), [1 1]*max(yt)*1.1, '-k', mean(xt([1 2])), max(yt)*1.15, '*k'); b(1).LineWidth =
1; hold off;

avg_o = mean(Original) std_o =
std(Original) avg_i =
mean(Improved) std_i =
std(Improved) max_o =
max(Original) min_o =
min(Original) max_i =
max(Improved) min_i =
min(Improved)


h =

1


p =     1.490260528447388e-09


avg_o =    5.584162650000001


std_o =    0.773342471518545


avg_i =   13.937573849999998


std_i =    2.823481490773167


max_o =    6.781751100000000


min_o =    4.709879100000000


max_i =   17.456012099999999


min_i =

  10.098512100000001
```





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D: Testing Protocols

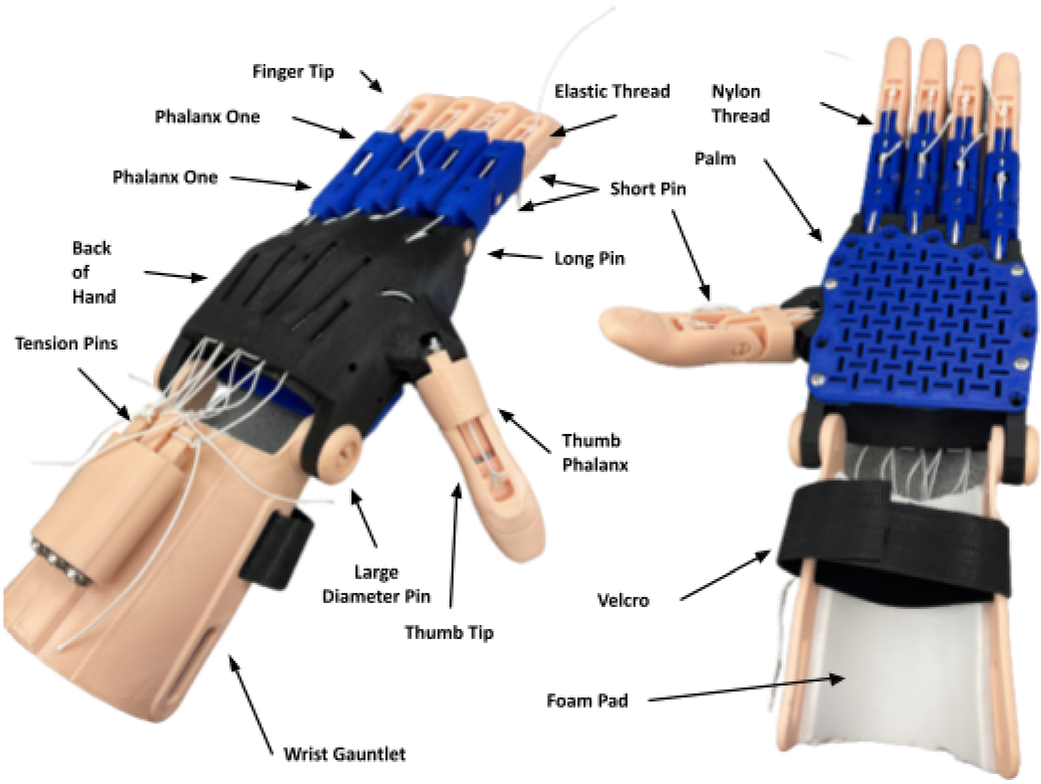
Qualitative testing protocol:

1. Start with a fully assembled version of the phoenix reborn hand and the various testing objects (Red Bull can, Bubly can, Arizona Iced Tea can, Hydro Flask) on a level surface.
2. Begin with the objects at full volume. Use the testing rod on the prosthetic hand and attempt to lift the object completely off the level surface. This should be completed with every object. Record a yes if it successfully lifted the object off the surface with no support and no if it was not able to lift the object.
3. Complete this testing with each object filled to its full volume.
4. Now add rubber fingertip grip additions to the pinky, ring, middle and index fingers. Repeat testing with the full volume and empty volume for each of the objects and record results.
5. Now to test the new prototype, disassemble the hand and reassemble it with the phalanx addition.
6. Complete testing of the new prosthetic using the empty and filled weights for each of the 4 objects.
7. Repeat steps of adding "page turner" additions to the pinky, ring, middle and index fingers on the prototype.
8. Complete testing again using filled and empty volumes and record data.

Quantitative (Hand dynamometer) testing protocol:

1. Connect the hand dynamometer and open up the BIOPAC Student Lab Software
2. Calibrate the dynamometer and prepare the file for data collection
3. Hold the dynamometer vertically and position the prosthetic hand in a position such that the fingers will close directly onto the sensor, steadying the hand on the table top
4. Start the recording and wait two seconds
5. Close the hand as far it will go for two seconds
6. Relax the hand for two seconds
7. Repeat steps 5 and 6 for five more hand flexions (closures)
8. Stop the recording and end collection
9. Go to the data analysis section on the BIOPAC software and export the graph as an image
10. Repeat the testing for all prototypes to be tested and analyzed

E: Assembly Guidelines

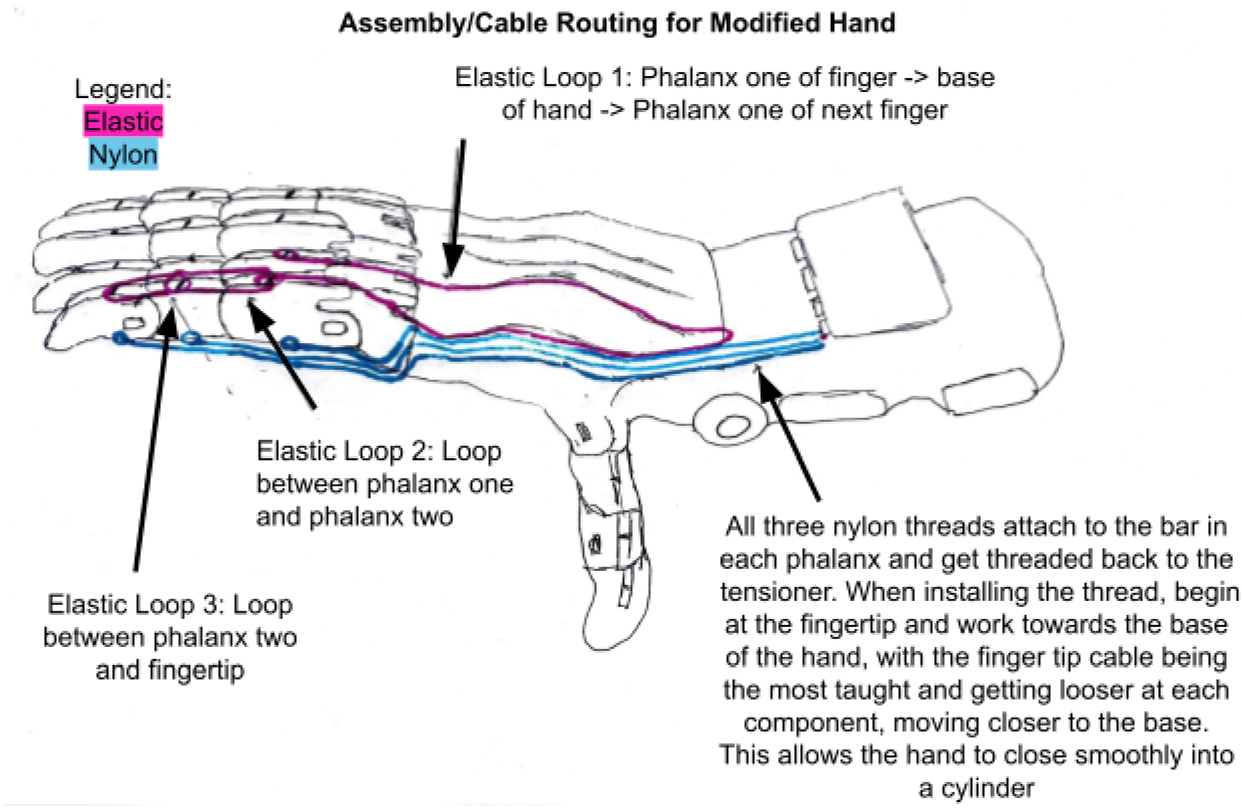


Materials		
(3) Tension Pins	(4) Phalanx Two	Velcro
(1) Wrist Gauntlet	(4) Finger Tip	Foam Pad
(1) Back of Hand	(10) Short Pin	Nylon Thread
(1) Palm	(2) Long Pin	Elastic Thread
(1) Thumb Phalanx	(2) Large Diameter Pin	Screws
(1) Thumb Tip	(4) Phalanx One	

Instructions

1. **Print Components:** Access the stl. files for the assembly through thingiverse and print the parts in the quantities outlined above in the materials table. PLA build material is recommended. If available, PVA support material is best for ease of assembly, however, PLA support material is acceptable

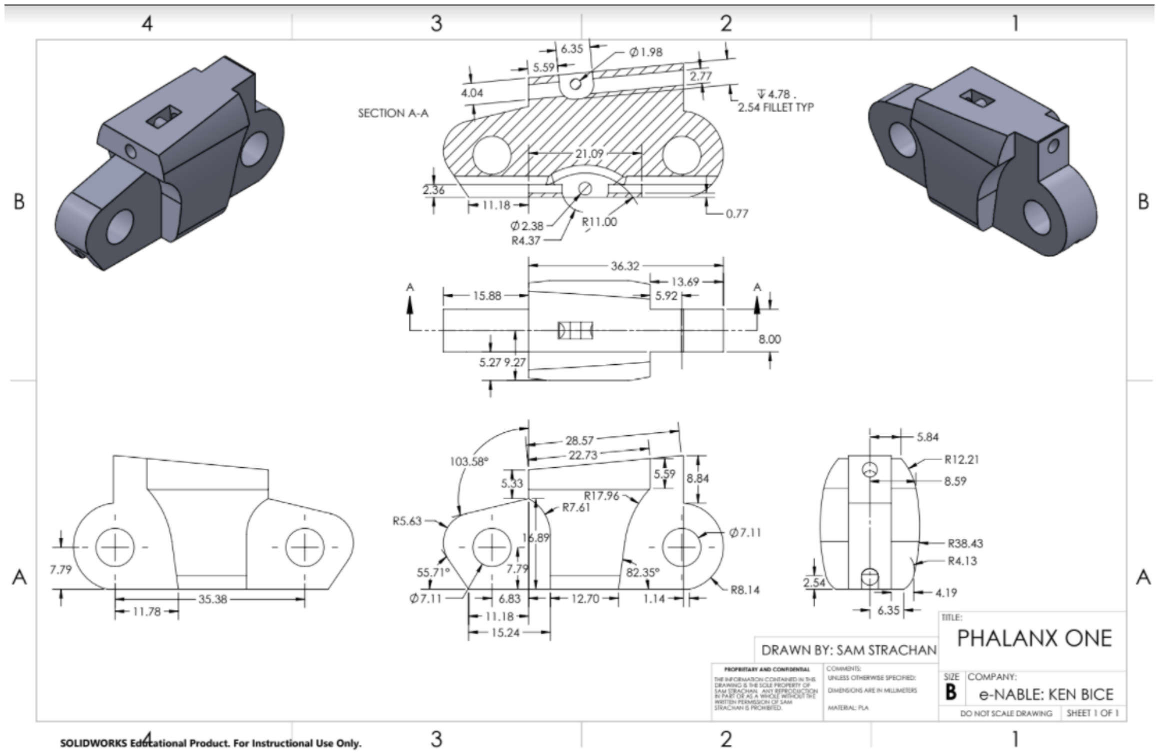
2. **Clean Parts:** Remove all support materials from the parts, ensuring all channels and holes are free and clear. If PVA support is used, it can be dissolved in warm water for the best finish.
3. **Acquire materials:** Some additional materials (all found in the materials table above) are needed beyond the 3D printed parts, however these are not extremely specific, the most available resources will suffice.
4. **Assemble 3D Printed Components:**
    a. Attach the wrist gauntlet to the back of the hand using two large diameter pins. Press the pins firmly into the corresponding holes until they snap into place.
    b. Install the three tension pins into their corresponding tracks on the back of the wrist gauntlet and thread the tension pin bolts into the back of the tension pins.
    c. Assemble the four fingers
        i. Connect phalanx one to the back of the hand using a long pin. Note, two phalanx one components must be attached to the back of the hand at one time, using one long pin. Firmly press the pin in until it snaps into place.
        ii. Connect the second phalanx (male to female component) to the end of phalanx one using a short pin.
        iii. Connect the finger tip to phalanx two using a short pin. Ensure that the pin is firmly seated in place.
        iv. Repeat steps i-iii for the remaining fingers.
    d. Assemble thumb
        i. Attach thumb phalanx to the back of the hand using a short pin
        ii. Attach the thumb tip to the hand using the remaining short pin.
    e. Install the palm by threading four screws into the corresponding holes in the palm.
5. **Thread cables and elastic retraction cables according to the cable routing guide below:**



6. **Apply finishing touches**
    a. Wrist cushion: Cut the foam to size according to the size of the gauntlet and glue in place
    b. Velcro wrist strap: Cut velcro to the correct size for the user's wrist size and install in the velcro slot on the gauntlet

F: Solidworks Drawings

Modified Phalanx One Component:



Modified Phalanx Two Component: