DEPARTMENT OF
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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:

Many individuals around the world experience some form of superior limb loss. The most common treatment for these individuals is the use of a prosthetic limb. However, prosthetic limbs can be both very complex and expensive and are not always available to 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. A tradeoff of the affordability of the models, however,is that the gripping capability of the hands on small cylindrical objects can be lacking. The client, Ken Bice, has asked the team to modify the existing *Phoenix Reborn* model to increase the grip strength of the prosthetic hand. The team formed a solution revolving around the idea of increasing the length (and consequently surface area) of the fingers as well as incorporating an additional finger joint to the existing prosthetic. Resultantly, the frictional force between the prosthetic hand and an object of interest will be greater as a result of the increased surface area and greater ability to conform to curved contours. The proposed testing procedures involve subjecting the hand to a grip strength test to measure the maximum holding force that the hand can exert in a horizontal and vertical position. Data analysis of the testing will be used to highlight the areas where improvements were made relative to the existing model.The analysis will also be used to discover weaknesses for future improvement.

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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 exists 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].

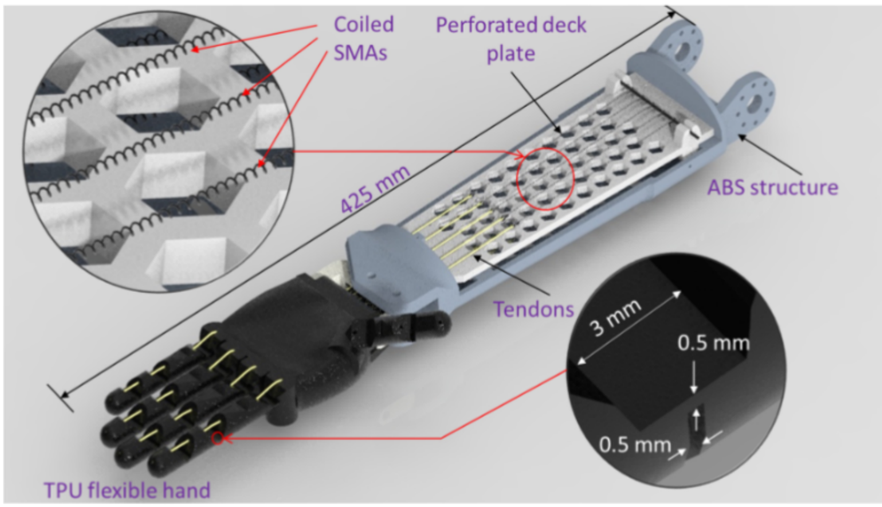

Figure 1. The Soft 3D-Printed Robotic Hand Actuated by Coiled SMA [6]

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.

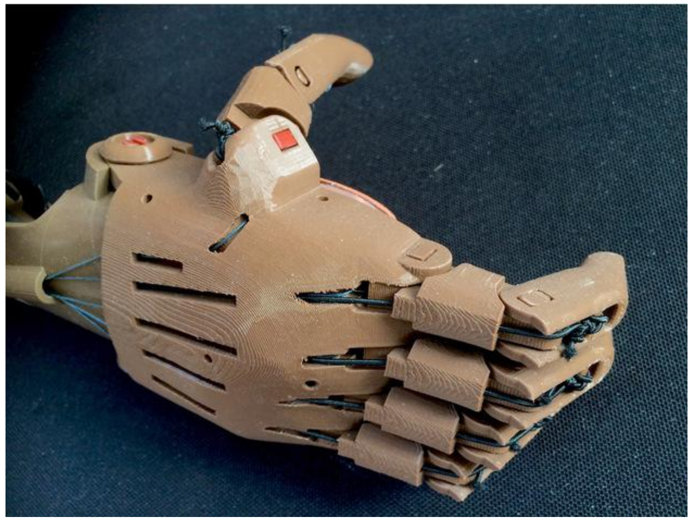

Figure 2. The Phoenix Reborn hand [9]

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 9.1)

3. Preliminary Designs

<u>3.1: Phalange Extension</u>

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 in 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.

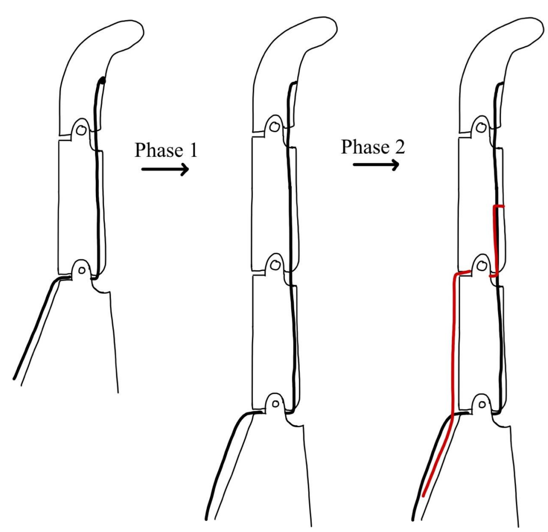

Figure 3. The Phalange Extension Design

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.

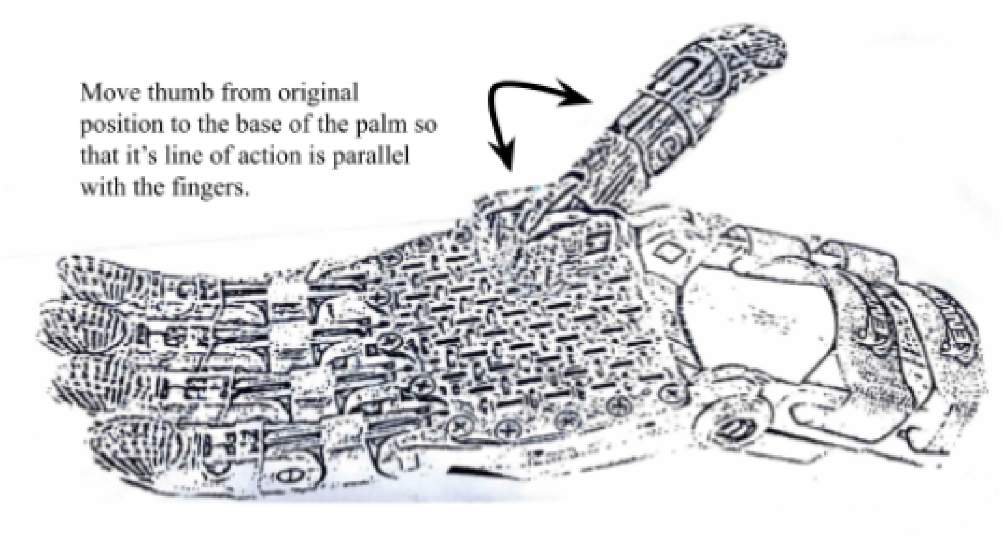

Figure 4. The Thumb Location Redesign

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.

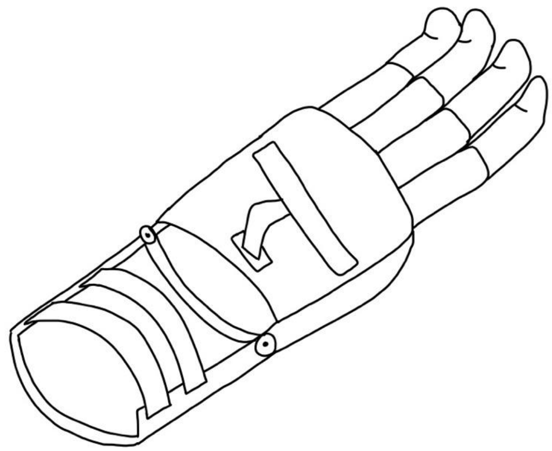

Figure 5. The Bar Tumb Configuration

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. 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. 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 in which 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 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 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. 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, 4 parts = 72 g	$5.76
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:	$47.12

5.2: Methods

The creation of the prototype began with the initial prototyping phase which is outlined in detail in the section below and has resulted in the creation of one new 3D printed component. The following is a brief outline of the projected plan for complete assembly.

Upon determination of satisfactory dimensioning and clearancing, a total of four phalanx components will be 3D printed. The current *Phoenix Reborn* hand will be disassembled and successively reassembled including the new, additional linkage in the fingers. The elastic thread and nylon thread will be strung through the intended channels and their tension will be set using the tensioning screws to ensure optimal performance.

5.3: Initial Prototyping

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 files, which proved to be incompatible 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 modelling 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 modelled based off of 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 1.4 in. This is approximately the same size as the other joints in each finger. This additional phalanx extends the length of the fingers by 1.4 in 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 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). In order to maximize efficiency in the production of these hands in the future, the part will 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, in the future, a soluble support material will be used if available. This would decrease the cleanup time necessary to remove the support material. 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 is preferred.

The initial modeling performed and first prototype print have been successful and affirm that this design is a feasible option to move forward with through the design process.

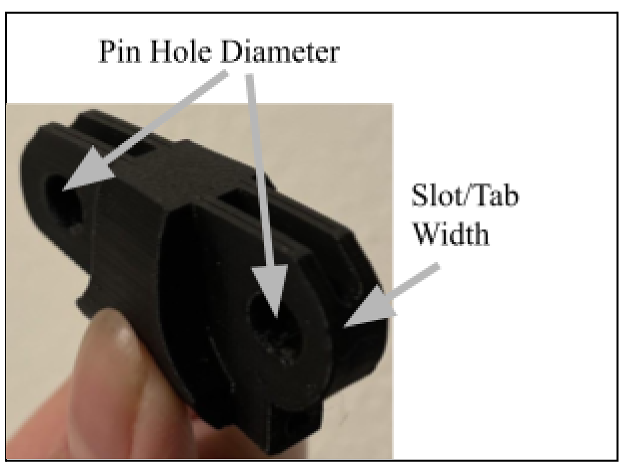

Figure 6a. One of the original parts of the *Phoenix Reborn* hand. The features which have been referenced in this report (i.e. Slot and tab) have been labeled for clarity.

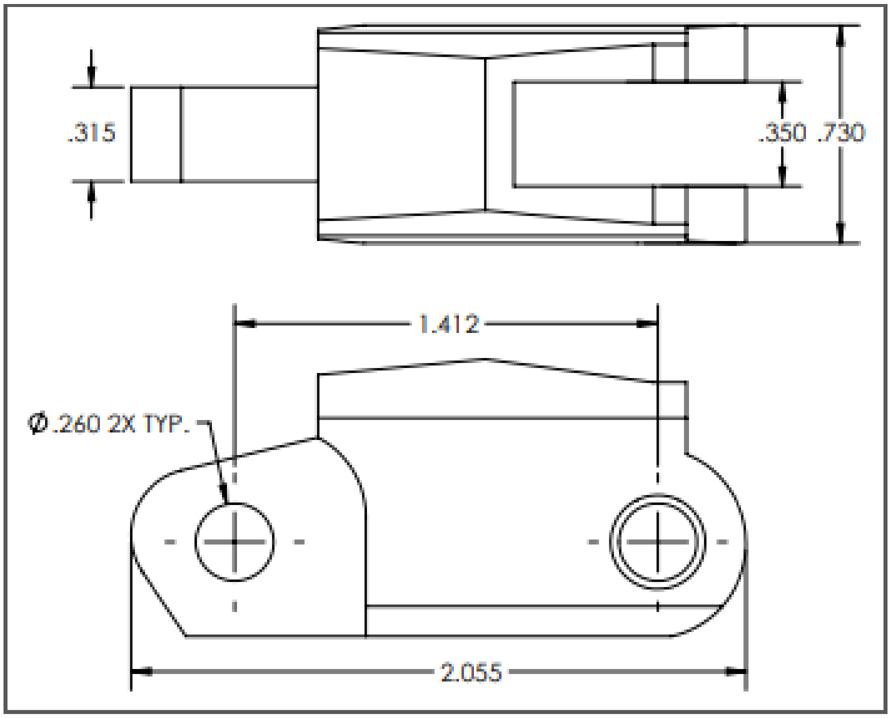

Figure 6b. Solidworks drawing highlighting the critical dimensions of the new part that was later 3D printed. These dimensions correspond with those on the existing parts.

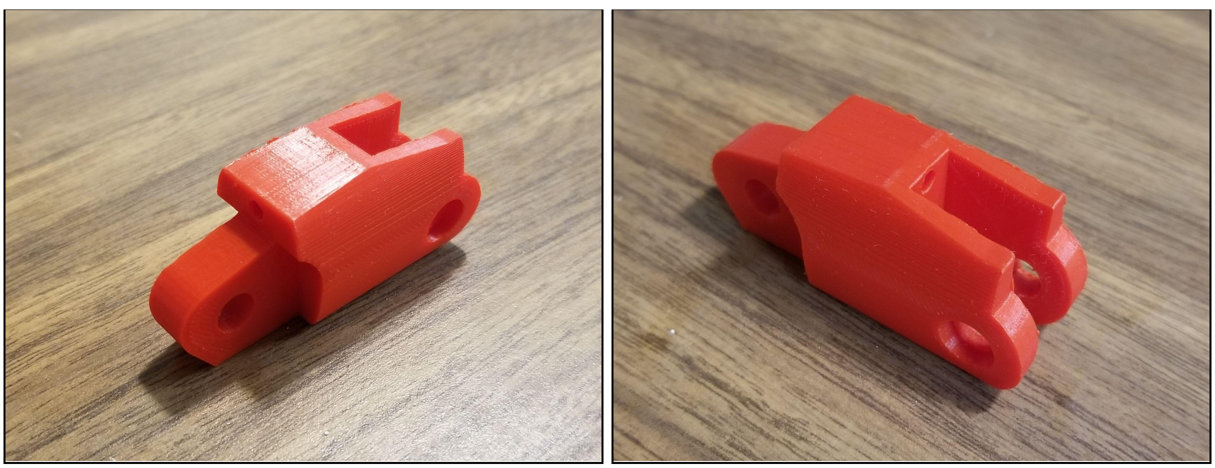

Figure 6c. 3D printed phalange extension component. This prototype has both a male and female end to allow it to join with existing parts without adjustment of those components.

6. Discussion

Given the weight criteria that the three design ideas were evaluated on and the results from the design matrix and initial prototyping, the team has decided to focus on the phalange extension design. This design shows the most promise in working towards the final goal of increasing grip strength for three main reasons: increased length of the fingers, larger surface area in contact with the object, and the extra DOF. With the phalanx addition, there are ethical considerations the team must keep in mind when implementing the design. 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” [18]. Given that this design idea is adding more weight to the prosthetic, it may affect the user’s center of gravity. This can cause an imbalance while doing daily activities which may lead to more frequent falling. In the event that the user does fall, the health and safety of the user as well as the integrity of the prosthetic are at risk if the prosthetic is used to catch the fall. This is another ethical issue that will need to be addressed when conducting research and testing of the device after the design implementation. By keeping these ethical considerations in mind when testing and evaluating the phalange extension design, the overall final product will be affordable, safe to use, and effective in grasping objects with a stronger force as opposed to other prosthetics on the market.

7. 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 has determined that the phalange extension will be the final design best suited to improve grip strength.

Adding an extra phalanx will improve the current design in three significant ways. First, each phalange of the prosthetic will be longer which will allow for a larger variety of objects that can be grasped. Additionally, the elongated phalanges ultimately increase the total surface area of the hand. This is useful for increasing grip strength because with the greater amount of surface area, more frictional forces can be distributed to more parts of the hand at a given moment. Lastly, the additional phalanx provides a place for another hinge joint in the finger giving a total of three DOF in each finger. The additional DOF from the implementation of this design would better match the anatomy of an able-bodied hand. Not only would it match better, but it would also allow for a smaller, more defined radius of curvature when grasping objects. This is advantageous for grip strength because the grip force applied to the object being grasped would increase in the normal direction (directed to the center of curvature). This is because normal force is inversely proportional to the radius of curvature, therefore with a smaller radius of curvature, there would be a larger normal force to the object.

In the future, the team will perform baseline testing of the current *Phoenix Reborn* model using a strain gauge in two different testing configurations. The first test will focus on cylindrical grip where the prosthetic will be secured in the same position as if the user would be holding a can. This simulates the effect gravity has on an object (weight) which shows how heavy of an object the prosthetic can hold. The second test will focus on the hook grip where the prosthetic will be secured in a vertical position as if holding a bag. This will give the team information about the strength and integrity of the fingers alone. After baseline testing of the current model, the team will then repeat the same tests with the phalange extension design and use data analysis to determine if there is a statistically significant difference for grip strength between the two designs.

The phalange extension is a proposed final design in which the first focus is proving that the additional phalanx is feasible in fabrication. From there, the design will then go through a two phased fabrication process with a second design matrix. With the extra DOF, there is an opportunity to change the tensioning system. With more research on tension systems dealing with curvature and normal force, the team will brainstorm three ideas for tensioning systems that will be beneficial for increasing the grip strength of the prosthetic. The tensioning system the team will move forward with will go through the same tests and data analysis mentioned above. The final design will be the result of the phalange extension with the changed tensioning system giving rise to an inexpensive upper limb prosthetic with an increased grip strength comparable to those currently on the market.

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9. Appendix

9.1: PDS

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 one inch 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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