THE UNIVERSITY *of* WISCONSIN MADISON

e-NABLE: Add lateral wrist movement to an e-NABLE standard hand design

Final Report

BME 200/300

Client: Mr. Ken Bice, Wisconsin Chapter of e-NABLE: BadgerHands

Advisor: Dr. Edward T. Bersu

Team Members:

Haley Yagodinski, Team Leader

Courtney Florin, Communicator

Kelly Starykowicz, BSAC

Claire Mitchell BPAG

Jack Metzger, BWIG

Liam Granlund, BWIG

December 7, 2018

BME Design

Abstract

The e-NABLE community is working to help kids in need of upper limb prosthetics, knowing they will grow out of them within 1-2 years. The solution is to 3D print hands that can be altered in size to fit the individual in need. Multiple designs have been created, including the *Raptor Reloaded.* With this, the user flexes the wrist to clench a fist, and extends the wrist to release the grip. From the anatomical position, flexion is the forward movement of the wrist that reduces the angle between the hand and the anterior part of the forearm; extension is the opposite movement. However, that is the only degree of freedom of the device. For those with sufficient ability to conduct lateral movement of their wrist, a means of unrestricting the prosthetic laterally would provide the benefit of a second degree of freedom. This second degree of freedom is currently not possible due to hinges on the side of device. By adding this motion, everyday tasks like twisting off a cap or taking a drink of water can be done. The final design replaced the hinges with an accordion style piece (made of TPU) at the wrist area, which allows for both degrees of freedom. After testing, it was noted that we accomplished full adduction and abduction capabilities, but lost some flexion capabilities. With this addition, the hand can transform the user from the kid with the "weird hand" to the kid with the cool hand.

Table of Contents

Introduction

Motivation

In the past decade, significant development has occurred in 3D-printing of upper limb prostheses. “All over the world people are designing and printing new devices that can easily fit a human arm. Scientific papers have been published regarding research in the field of 3D-printed upper limb prostheses. People are developing prostheses individually, and large communities have been established. Most of the development of 3D-printed prostheses began after the establishment of the global community e-NABLE. This community has grown into a worldwide movement of tinkerers, engineers, occupational therapists, university professors, designers, parents, families, students, teachers and people who have developed 3D-printed prostheses.” [2] The e-NABLE Community is a dedicated group of individuals from all over the world who are using their personal 3D printers to create free 3D printed hands and arms for those in need of an upper limb assistive device. They are people who have put aside their political, religious, cultural and personal differences to come together and collaborate on ways to help improve the open source 3D printable designs for those who were born missing fingers or who have lost them due to war, disease or natural disaster. The community started back in 2011, when Ivan Owen went to a steampunk convention wearing a homemade metal puppet hand. After posting a video of his hand online, a carpenter from South Africa contacted Ivan regarding fabricating him replacement fingers since he had lost his in an accident. Soon afterward, a mother reached out to them to see if they would take their designs to the next level, and design a hand for her 5-year old son. This lead to the creation of the first 3D printed e-NABLE hand, which was the inspiration for many designs to follow. Realizing the magnitude of the help this innovation could provide to people worldwide, Ivan decided against patenting his designs and instead published them as public domain, giving up all ability to profit from his invention. Worldwide people who owned 3D printers started improving the designs and printing them for friends, family, and strangers in need. A professor from RIT, Jon Schull, noticed this and started a Google+ group for individuals to share ideas and to connect people in need of a hand with people wanting to lend a hand. Within that first year, the e-NABLE community grew from 100 members to over 3000. They created over 750 hands for people around the world. In the next year, they more than doubled their members to nearly 7000. Approximately 2000 devices were created and gifted to individuals in over 45 countries. None of the designs are patented, but rather put out to communities to help those around them.[3] Currently, the commonly used e-NABLE prosthetic known as the *Raptor Reloaded* only has one degree of freedom. By completing the goal of adding a lateral wrist movement to the device, users will be able to do everyday tasks like drink water and twist off a bottle cap.

Current Design- Raptor Reloaded

The current e-NABLE design is the *Raptor Reloaded*. This device is 3D printed with PLA (polylactic acid), a hard and rigid plastic. It is constructed with an assembly kit that can be purchased online which includes items such as elastic string, super glue, velcro strips, grips for the fingers and foam pads. This device is used for an individual with a palm, but no fingers or thumb. The user places their forearm in the gauntlet where there is a strap to fasten their arm in. There is an additional strap for the palm to fit in the hand area. When the individual flexes their wrist, the fingers all close in the same motion. Ideally, the pointer finger and thumb will come together to allow the individual the ability to pinch or hold something like a piece of paper. The hinges on the side currently restrict any lateral movement due to the palm and gauntlet pieces being held together by a pin. To allow for more functionality of the hand, a second degree of freedom would be useful to implement. The ideal goal would be to allow the prosthetic to mimic the human motion of adduction and abduction of the wrist.

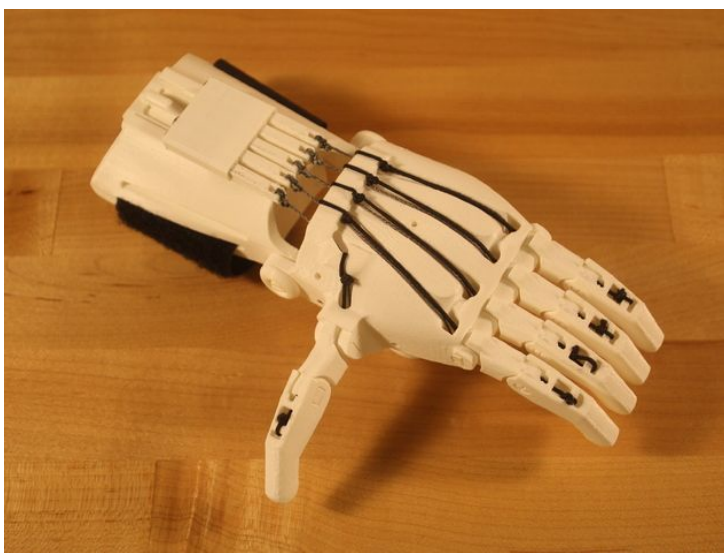

Figure 1. 3D printed and fully assembled *Raptor Reloaded* e-NABLE hand.

Problem Statement

The e-NABLE international community 3D prints ultra low-cost upper limb prosthetics and delivers them free to those in need. Members of this community have created a variety of prosthetic designs suited for various disabilities. The focus of this project is a design called the *Raptor Reloaded*, which is made for individuals with a palm, but no fingers. This device straps a gauntlet on the forearm, and the functional part of the prosthetic hand to the user’s palm. The individual then bends the wrist forward to clench a fist, and then back to release the grip. Unfortunately, that is the only degree of freedom of the device. For those with the ability to conduct sufficient movement of their wrist, a means of turning the prosthetic laterally would provide the benefit of a second degree of freedom. The current *Raptor Reloaded* design has hinges that fully restrict abduction and adduction. This lateral motion would allow for everyday movements, such as taking a drink of water or twisting off a bottle cap. The goal of this project is to design and test a modified e-NABLE design that adds lateral wrist movement without interfering with the current design capabilities of the *Raptor Reloaded*.

Background

Biology and Physiology

Symbrachydactyly is a congenital condition (a condition you are born with) in which the fingers are not formed properly.[10] This is a rare condition that occurs in 1 in every 32,000 live births. Although not confirmed, this is likely caused by a lack of blood flow to the tissues during development in the womb. Not only is symbrachydactyly affecting children, but nearly 10% of children are born with malformations to the hand.[3] The cause of these malformations is mostly unknown. Depending on the type and extent of the hand malformation, the child may have troubles adapting and functioning well. The child is likely to face various challenges as they grow and develop. They may have developmental problems such as delayed or deficient motor skills, as well as difficulties with activities of daily living and basic self-care skills. There will also be limitations on the types of exercises or sports they can participate in. Overall, there is potential for emotional and social hardship from children teasing them about their appearance. Some of these hand malformations can be fixed with surgery, therapy, or a prosthetic, but all of these options are extremely expensive.

e-NABLE has created many different 3D printed upper limb prosthetics, but we are looking to advance the *Raptor Reloaded.* This is a device used for a person with a palm, but no fingers. The current application of the *Raptor Reloaded* prosthetic is flexion and extension of the wrist. From the anatomical position, flexion is the forward movement of the wrist that reduces the angle between the hand and the anterior part of the forearm. Extension is the opposite movement in which one straightens his/her hand out to an approximate angle of 180 degrees. Anything beyond this 180 degree extension is known as hyperextension.[1] Another function of the wrist is lateral movement, which has two degrees of motion, abduction and adduction. A typical wrist has the ability of adducting 40 degrees and abducting 17 degrees.[6] An additional motion is rotation. While the wrist is able to rotate, this rotation occurs at the elbow. Two terms describing this motion are supination and pronation. Supination is rotating the forearm to a palm up position and pronation is rotating the wrist 180 degrees to a palm down position.[9] The purpose of our design is to allow for abduction and adduction of the individual, since wrist flexion and extension are already possible.

The strings on the model of the *Raptor Reloaded* mimic the work done by the muscles in the hand, specifically the flexors. Flexor digitorum profundus and Flexor digitorum superficialis are in charge of bending the fingers at the middle and tip joints of the fingers.[7] They do this by tightening, thus pulling the fingers forward. However, while the fingers mimic these particular muscles by also tightening and pulling the fingers close, the strings on the model hand do this process by tightening by extension rather than by tightening and shortening their length. In doing this, the *Raptor Reloaded* works contradictory to a typical human hand.

Client Information

e-NABLE is an international community that 3D prints inexpensive upper-limb prosthetics for children and adults in need. Our client is Mr. Ken Bice, who is a member of the Wisconsin statewide e-NABLE chapter called Badger Hands. The Badger Hands chapter is headquartered in Madison, Wisconsin. Mr. Bice lives in the Madison area and 3D prints these hands for people that need them in the community.

Design Specifications

The altered version of the *Raptor Reloaded* should maintain its current capabilities with the addition of a lateral movement to give the user another degree of freedom. The design must be usable by an individual with a palm, but no fingers. It must be 3D printed, ideally with materials that are easily obtainable, so that it can be 3D printed around the world. The design should be able to be reproduced onto several prostheses of different lengths and widths. The device must still maintain its original forceful grasp with the fingers and thumb. Because the prosthetic is typically used by children, it needs to last 1-2 years until they grow out of it. While wearing the prosthesis, the customer must be able to move their hand two degrees of freedom with ease. The weight or size of the device must be appropriate to the size of the user so it does not hinder them. The prosthesis must be easy to put on and off and should be easy to clean in between uses.

Preliminary Designs

Design 1- The Accordion

The first design is nicknamed “The Accordion” (Figure 2) due to the folded flexible TPU (thermoplastic polyurethane) material that connects the hand and wrist. This design removes the pins, which held the original model together at the wrist because they restricted the ability to adduct and abduct the wrist. TPU is used for the connection due to its ability to be 3D printed as well as its adjustable flexibility. This would allow the durability of the hand to be maintained, while allowing for optimal abduction and adduction. The design is compact and should not interfere with pre-existing mechanical elements. Additionally, it would require little maintenance and would be comfortable for the user. This design would require testing to observe if it can reach the desired range of motion. A drawback of this design is the requirement of more than one material for 3D printing.

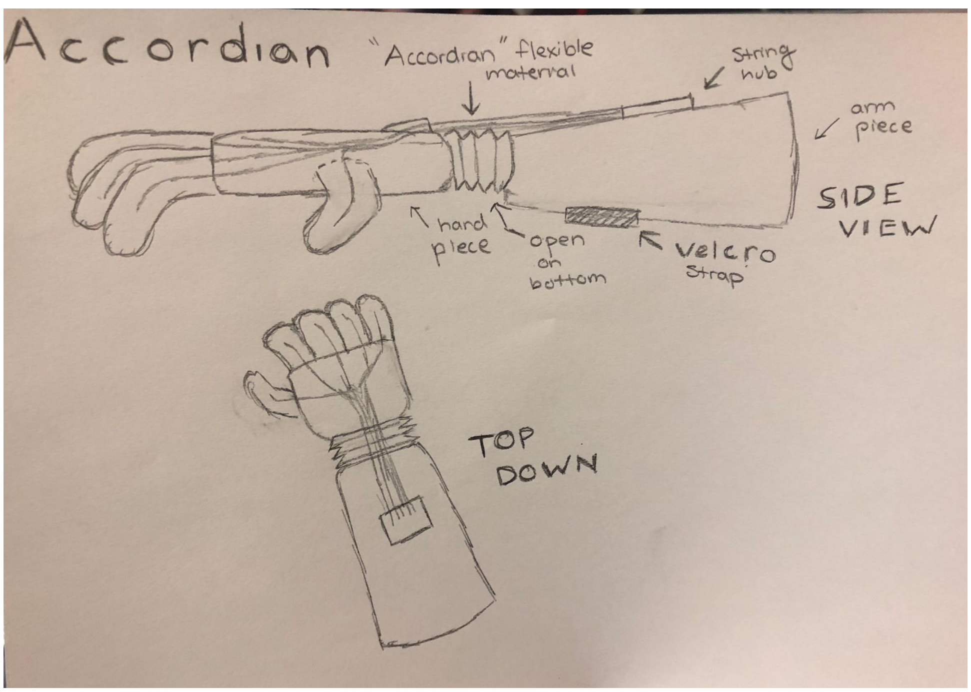

Figure 2. Drawing of The Accordion design with a side view and top down view.

Design 2- The FrizB

The second design is titled the "FrizB" (Figure 3), on account of the frisbee-like disc that exists on the back of the hand piece. There is a circle shaped case that is hinged onto the arm piece. This hinge allows for movement forward and back of the wrist, essentially taking the place of the old pins holding the pieces together. The palm piece would be designed to have a disc shaped protrusion on the back that fits into the circle case and sits in a track. As it sits in this track it should be allowed to spin and account for adduction and abduction of the wrist. This design does however require a movement of the strings in order to account for the addition of the casing and protrusion. This would require testing and refiguring in order to not interfere with the current capability of the hand, which is to close the fingers when the user brings their wrist forward.

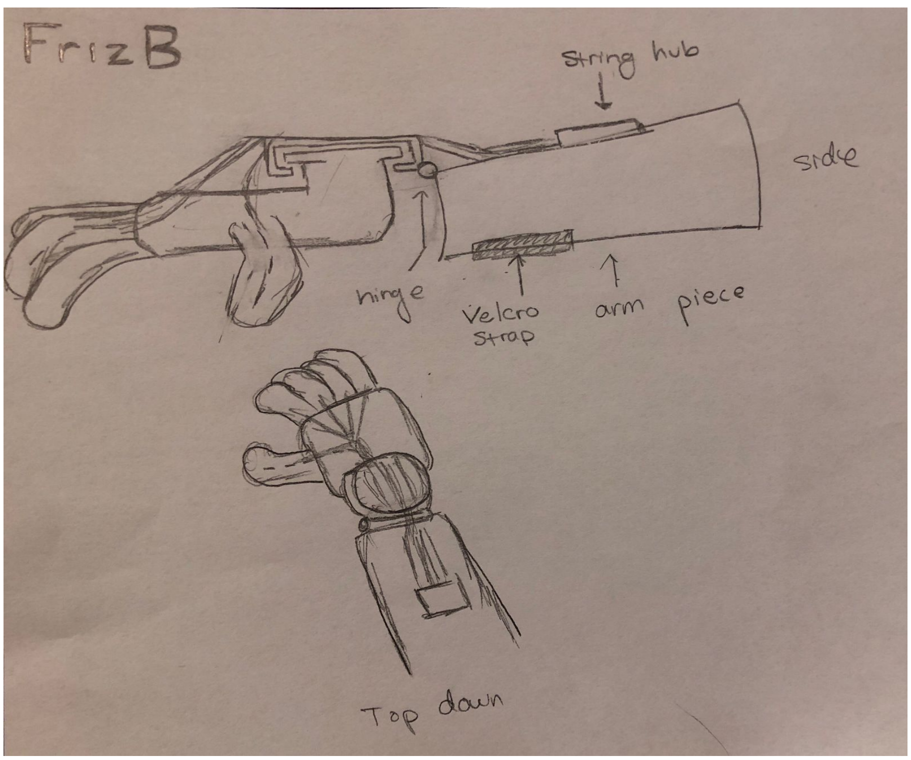

Figure 3. Drawing of the FrizB design with a side view and top down view.

Design 3- The Pulley

The third design was called “The Pulley” (Figure 4) because it consists of a pulley system to help move the wrist laterally. Like the other two designs, it does not have the pins covering the wrist joint, since these restrict the wrist laterally. The pulley is attached to the wrist, near where a watch face would sit. The string of the system is attached to the thumb and the pinky finger. The idea behind this design is that as the user adducts his/her wrist, the pulley pulls the pinky finger in the proper direction to assist the adduction and vice versa. However, it was unclear how the user would activate the pulley. If not created properly, the pulley string could end up restricting the lateral movement, which would be counterproductive. Though the design should maintain the capabilities of the current prosthetic, the strings of the pulley could potentially interfere with the strings of the hand. Also, this design would be easy to break and difficult to reproduce.

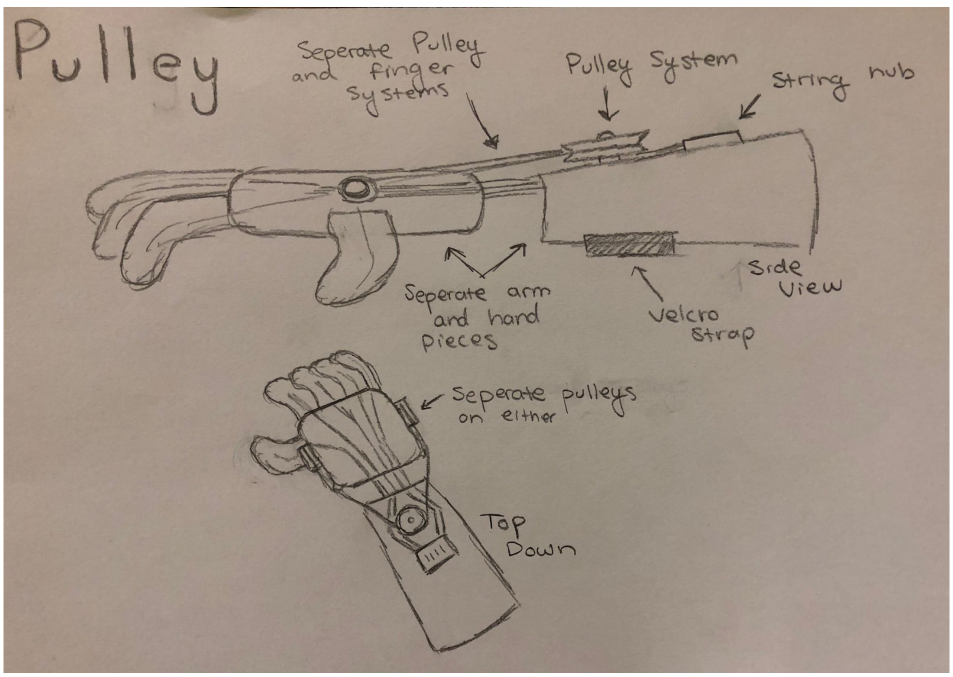

Figure 4. Drawing of the Pulley design with a side view and top down view.

Preliminary Design Evaluation

Design Matrix

Criteria	Weight	The Accordion		The FrizB		The Pulley	
Maintain Current Capabilities	25	(4/5)	20	(4/5)	20	**(5/5)**	**25**
Range of Motion	20	(3/5)	12	(3/5)	12	**(4/5)**	**16**
Patient Comfort	15	**(5/5)**	**15**	(2/5)	6	(3/5)	9
Functionality/Ease of Use	15	(3/5)	9	**(4/5)**	**12**	(2/5)	6
Durability	10	**(4/5)**	**8**	(3/5)	6	(2/5)	4
Reproducibility	10	**(3/5)**	**6**	(2/5)	4	(2/5)	4
Cost	5	**(5/5)**	**5**	**(5/5)**	**5**	**(5/5)**	**5**
Total	100		**75**		65		69

Table 1. The design matrix includes criteria used to evaluate the designs. The Accordion design scored the highest and was used for the final design.

Design Matrix Summary

The most important criteria, given a weight of 25, is that the design must maintain the current capabilities of the *Raptor Reloaded*. This means that it cannot interfere with the strings of the wrist flexion motion. The second most important criteria is the range of motion of the arm, with a weight of 20. Ideally, the prosthetic will have full range of motion in the wrist. Patient comfort is the next most important criteria. The individual will be wearing the prosthetic on a daily basis, so a high score is given to the design that will be the most comfortable. Functionality and ease of use is also a criteria that needs to be considered. It needs to be able to be put on the individual daily and function the same every time. A high score is given to the most reliable design. Durability and reproducibility are both given a weight of 10. The prosthetic needs to be durable enough to survive in all operating conditions without too much wear. It also must be able to be reproduced by people all over the world, so the material must be able to be 3D printed. Finally, cost is the last criteria. The design must fit within the $200 budget.

Proposed Final Design

Overall, The Accordion design had the highest score. We concluded that this design would be used for our final design. The initial plan for the design was to print various accordion designs and test them one at a time by placing them in between the palm and gauntlet. At the time, we were unsure of how to attach the accordion piece. We knew we needed to edit the existing palm and gauntlet files to remove the hinges, as they restrict the lateral movement. One of our major concerns before fabricating was that the accordion would interfere with the strings. This would affect the flexion and extension of the wrist, which is one of the most important design criteria. Therefore, the design and attachment of the accordion centered around this concern.

Because of the compression and extension of the accordion, we hoped that the range of motion in the lateral direction would match that of a typical human wrist. However, we were unfamiliar with the material and therefore concerned about how much it would compress and extend. Since the Accordion was to be made from a soft, flexible material, we were confident that it would be comfortable for the patient to wear. Due to our concerns about the string interference and the lateral movement, we were uncertain as to how easy the device would be to use. If it worked as we imagined, it would be quite easy. However, we planned to encounter various problems throughout the design process, as improvement is always needed. We were confident that the Accordion would be reproducible because it is much simpler than many of our other design ideas. Also, the Accordion material that we were planning to use is very durable and we expected all of our designs to be rather inexpensive.

Fabrication/Development

Materials

To manufacture the prosthetic, Polylactic Acid (PLA) will be used to 3D print the parts at the Makerspace. Thermoplastic Polyurethane (TPU) will also be used to print the accordion part of the prosthetic because it can be adjusted for different flexibility. We were supplied an assembly kit by the client that includes: elastic string, normal string, super glue, velcro strips, hand files, grips for the fingers and foam pads. We decided to continue to work with PLA as our chosen material due to its prevalence, cost effectiveness, and ease of use.[8] Additionally, our client suggested that we use TPU as a material for the accordion part of the hand. He mentioned that it is readily available and can be 3D printed as well. TPU is a plastic with rubber-like characteristics. It can be stretched up to twice its original length, is resistant to abrasion and performs well, even at low temperatures. Additionally, it is resistant to oil, grease, and some solvents.[4] The density of TPU can also be altered to change the flexibility of the material, which will hopefully deliver the range of motion we desire through testing.

Methods

To begin fabrication, a full *Raptor Reloaded* prosthetic was printed at 135% at the UW Makerspace. To provide clean pieces that allowed the hand to function easily with minimal friction, PVA was used as support. PVA is soluble in water, allowing for support to easily fall off. With a hand being fully assembled, several ideas that would provide a second degree of motion were able to be visualized.

After finalizing a design, several accordion pieces were printed. The first 3 prints of the accordion failed. The first print was of a full cylinder accordion (30% infill, no support). This accordion had several folds that were not at an ideal angle of 45 degrees (from the center line, so 90 degrees in total) . This made the print become very stringy, because there was not enough time and space for the TPU to dry before being printed over. After this failed attempt to print, suggestions were given by Karl Williamson, the Shop Manager of the Makerspace, to change the speed of the print to 20mm/s and the temperature to 235 °C. This allowed the print to have time to set and the TPU would not be stringy. The second and third prints were of a half-cylinder accordion (20% infill, PLA support) with only 3 folds but at an angle of 90 degrees. These two prints failed because TPU is not able to printed with PLA support. The 4th print of the accordion (20% infill, TPU support) with 3 folds at 90 degrees and 1.5 mm thickness was successful. The suggestions by Williamson and printing with TPU support allowed this print to be successful, unlike the previous three. From here, more accordions were printed at different thicknesses and infill. One was with a thickness of 1 mm and 10% infill. Another was printed with a thickness of 0.7 mm and 10% infill. Both of these were successful.

To attach the accordion to the palm, a slit was drawn on the SolidWorks palm design that the other 200/300 e-NABLE group provided (this file has the other group's thumb attachment added to it). The palm was printed with PLA at 150% with the default printer settings. A gauntlet with a similar slit was then printed. The gauntlet was also printed at 150% in PLA. With these two pieces, the accordion could be attached to fully assemble a hand by sliding it through both the slit in the palm and gauntlet.

After a hand was fully assembled, the results from testing were not satisfactory. To improve this, the straight sections of the accordion were lengthened from 8 mm to 41 mm. This updated accordion design was printed at two thicknesses, 1 mm and 0.7 mm, both at 10% infill. They were then attached to the palm and gauntlet by being inserted into the slits.

On a further iteration of the hand, the slit in the palm was abandoned in favor of attaching the accordion to the palm through pins placed in holes at the bottom of the palm. Additionally the straight section of the accordion piece (0.7 mm, 10% infill) was lengthened by an additional 51 mm on the side that attaches to the palm (bringing the total length of that side to 92 mm). This allowed for more flexion to occur, allowing the long piece to slide under the palm as the wrist is flexed. The accordion piece was still attached to the gauntlet through the slit however.

The final prototype was printed at 150%.

Final Prototype

The final prototype consists of a redrawn palm attached to the accordion with pins, which is attached to the gauntlet through a track. The palm was redrawn without the hinges and with the addition of another group's current thumb design. It also has small holes on the edges for the accordion attachment. The accordion was printed at various thicknesses and lengths for testing. We cut holes into both sides of the accordion to attach to the palm using pins. The accordion was trimmed so it fit into the palm properly without folding. The gauntlet was edited to add a slit along the anterior portion. The purpose of this was for the accordion to slide into it for attachment. To secure this, we tied string through the accordion and gauntlet. This would be an attachment method that we would like to improve in the future.

The strings of the hand still attach the same way that they did in the *Raptor Reloaded* design. Upon use, we were pleased to see that the accordion does not interfere with the string movement. This, along with the pivoting of the accordion, allows for flexion and extension of the wrist. When the user flexes his/her wrist, the top part of the accordion slides partially out of the palm to allow for the full range of motion. The pins in the design secure the accordion, while still allowing it to pivot. The compression and extension of the accordion design should allow for sufficient abduction and adduction.

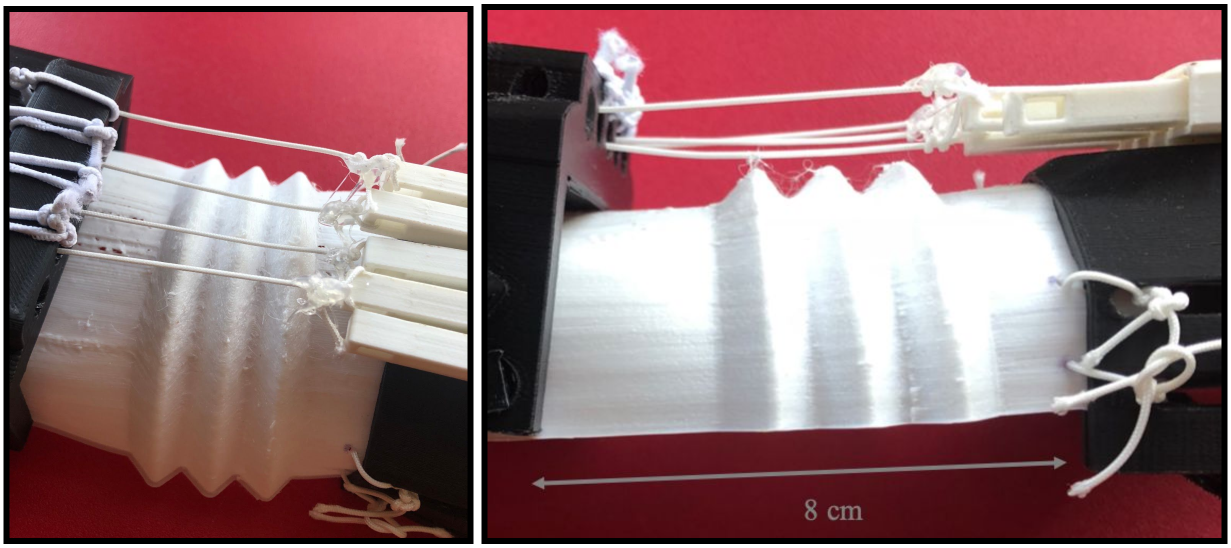

Figure 5. Close-up of Accordion piece attached to prototype through pins, a track in the gauntlet, and string.

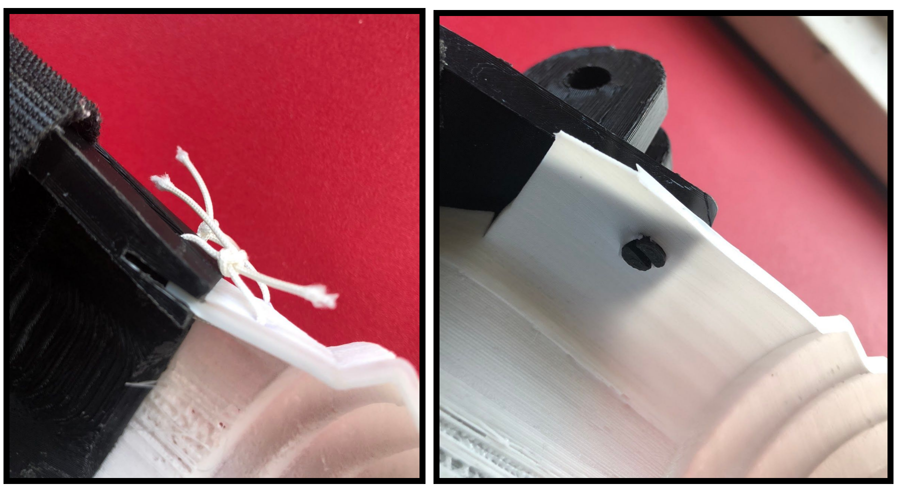

Figure 6. Close-up of attachments of accordion piece to gauntlet (left) and palm (right).

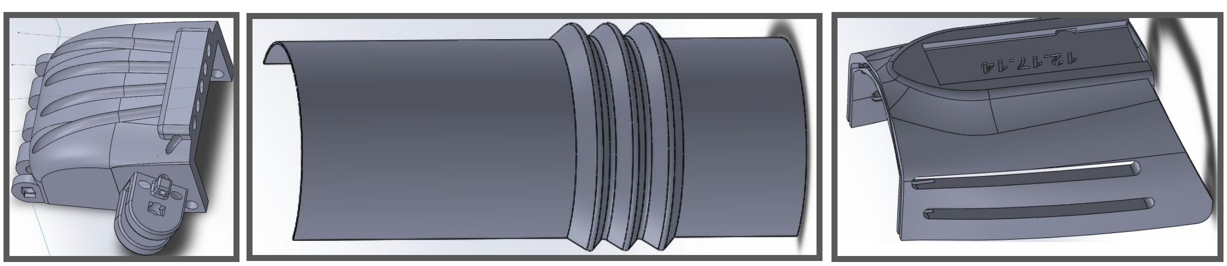

Figure 7. 3D printing Solidworks pieces used for assembly of final prototype.
(left) palm - (middle) accordion piece - (right) gauntlet

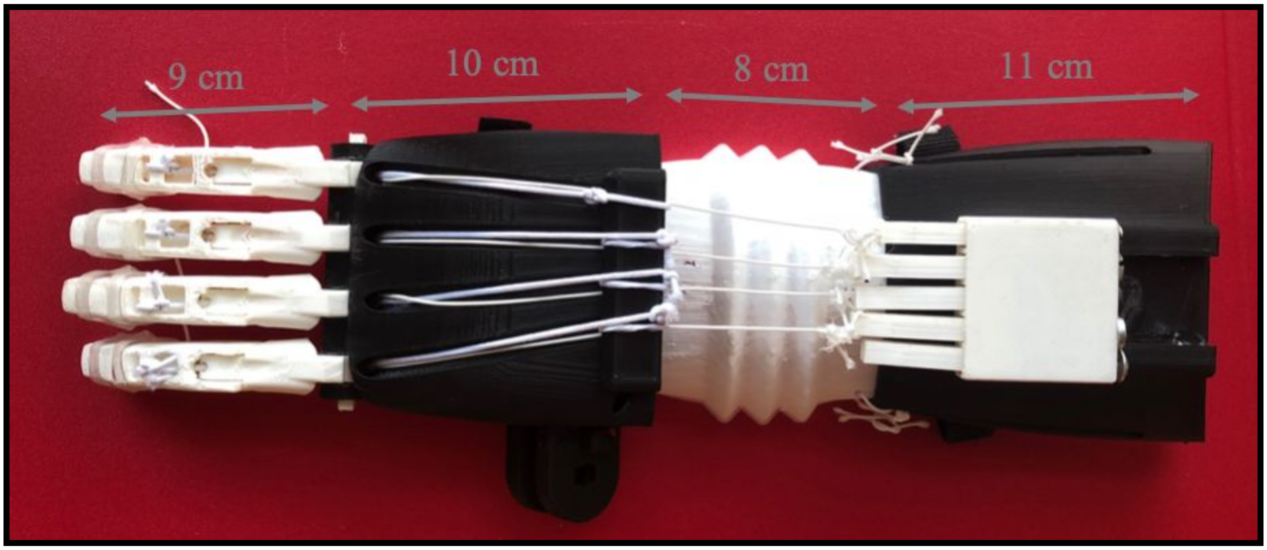

Figure 8. Fully assembled final prototype.

The final prototype, as seen in Figure 8, consisted of the palm, gauntlet, fingers (missing thumb), and accordion piece. The palm is the palm used by the other 200/300 e-NABLE group so it would be compatible with their thumb design (this is also why our design does not contain a thumb). For assembly, we used the assembly kit provided by our client, which included the strings and screws. The strings can be tightened or loosened as needed to create the most efficient use of the fingers.

Testing

The main purpose of this project was to add lateral movement to the *Raptor Reloaded* design. Our original goal was for the Accordion design to meet the range of motion of a typical human wrist: 17 degrees in abduction and 40 degrees in adduction. To test this, one team member held the gauntlet down on a table while another moved the palm laterally, marking the distance it was able to travel. The angles were measured with a protractor and recorded. Three trials were performed in each direction for three different accordions. The different accordion types varied based on thickness and length: 0.7-mm thick (long), 0.7-mm thick (short), and 1.0-mm thick (short). The .7 and 1 mm values were the thickness of the accordions, the short accordion was 118.55 mm in length and the long was 169.28 mm in length. (these values are from the solidworks files) When 3D printed, these values were enlarged by 150%. Once the data was collected, it was clear that the 0.7-mm long accordion was the most successful. In fact, it was able to laterally move slightly more than a typical human wrist, with a final abduction of 23 degrees and an adduction of 43.3 degrees.

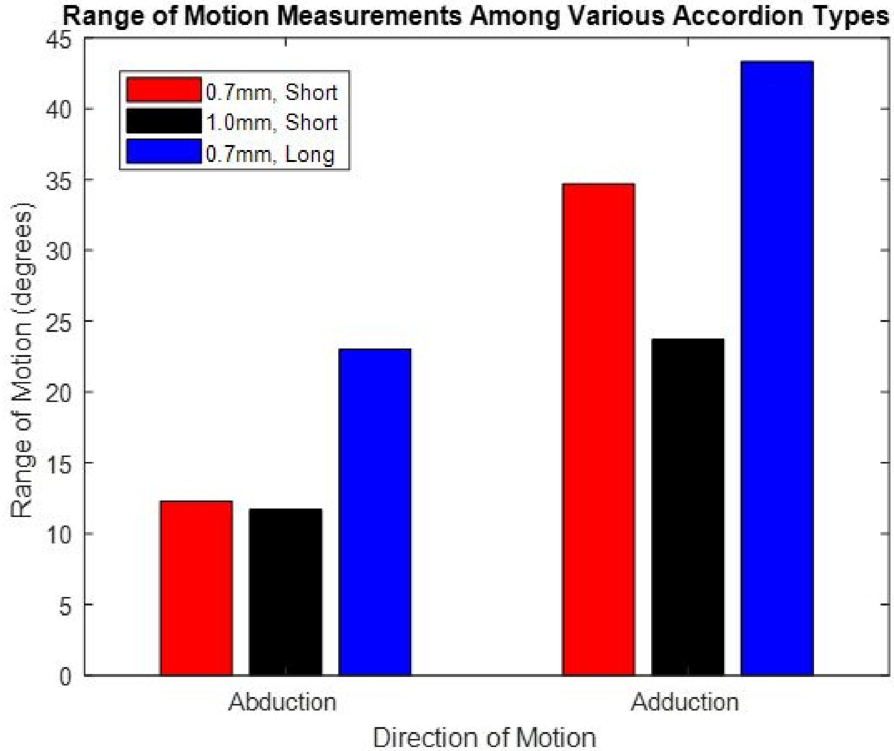

Figure 9. The above graph displays the adduction and abduction capabilities of three different accordions. The 0.7-mm long accordion was the most successful.

One of our most important design criteria was for the hand to maintain the flexion and extension capabilities seen in the *Raptor Reloaded*. To test this, we had a group member wear the final design of the hand while another marked the path that it took during flexion and extension. We did three trials in each direction and compared the data to the *Raptor Reloaded* and a typical human wrist.

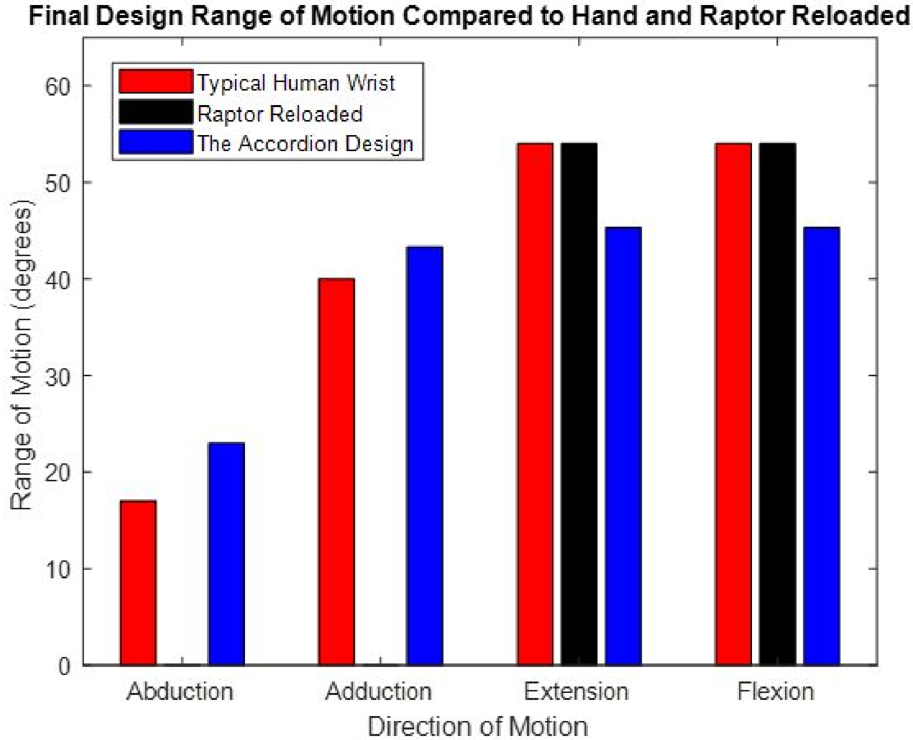

Figure 10. The graph shown above compares range of motion among the final Accordion design, the *Raptor Reloaded*, and a typical human wrist.

Although the Accordion design of the hand was able to flex and extend, it did not quite meet the capabilities of a typical human wrist. This is most likely due to the attachment of the accordion piece impeding the ability to fully flex without some constraint. Due to the *Raptor Reloaded* having no means of abduction and adduction before the introduction of the accordion piece, it is valued at zero on the bar graph. It should be noted that although the accordion design exceeds the degrees of adduction and abduction of a typical human wrist, it will only be able to perform to the abilities of the human using the prosthesis (i.e. a human cannot exceed the wrist's fixed range of motion).

Results

To properly analyze the testing results, we performed two one-sample t-tests against a significance level, alpha, of 0.05. We used a null hypothesis stating that the mean range of motion of the accordion was equal to that of a typical human wrist. From observing the data, we chose an alternative hypothesis stating that the mean range of motion of the accordion was greater than that of a typical human wrist. The t-test for abduction resulted in a p-value of 0.00457, which led us to reject the null hypothesis and conclude that the Accordion design has an abduction range of motion greater than that of a typical human wrist. The t-test for adduction resulted in a p-value of 0.2196, which led us to fail to reject the null hypothesis and conclude that the Accordion design has an adduction range of motion equal to that of a typical human wrist. Based off of our analysis, we determined that we were successful in attaining the lateral movement of the wrist.

Discussion

The success of the accordion piece in achieving the full lateral range of motion allows for future uses of the *Raptor Reloaded*. The files can be spread around the e-NABLE community, which in turn could lead to a product that can be used worldwide, and allow users missing part of a hand to gain more freedom with their new prosthetic. Because symbrachydactyly occurs at birth, there is a need for cheap prosthetics as the child will grow out of it quickly. e-NABLE has created a device to meet this need by 3D printing prosthetics.

Overall, analysing the ethical effects of 3D printing shows it is a fairly environmentally friendly process. It can make things lighter and less materially exhaustive, saving resources. PLA is also a material that is able to be recycled. However, 3D printers in general use a lot of energy which can still be hurtful to the environment.[11] The entire environmental impact is currently being researched at institutions such as Yale. On another note, the act of 3D printing leads to a lot of excess in the attached support material, which adds to the world's overall plastic waste.

Initially, for attachment of the accordian to the gauntlet and palm pieces, the team had decided to go through with a track that the accordion would slide into and be capped off. However, this restricted movement in flexion and both lateral directions. Due to this, the change was made to a pin attachment at the palm instead of the previously established gauntlet. After a final prototype was fully fabricated and an evaluation of it was made, there are several changes that could be done to improve the design. One of these is to improve the accordion attachment to both the palm and gauntlet to make the full prosthetic more easy to reproduce as this was a major design criteria. By finding a better way to attach these pieces, there is also a possibility of gaining back the flexion/extension that we previously lost. Another change would be to see what adding more folds to the accordion would do. Lastly, changing the pins that are used to attach the accordion to the gauntlet would be a necessary modification in hopes of increasing patient comfort.

One possible source of error is how we tested the degrees of motion. For both the testing of abduction/adduction and flexion/extension, group members were used to bend the prosthetic to see what degrees could be attained. Ideally, some sort of machine to carry out these testing procedures would reduce the chance of possible human error. Another source of error would be the quality of the TPU prints from the Makerspace. The TPU printer near the end of the project timeline began to not work quite as well as it previously did. This made the prints become not fully complete as there were several holes in the accordion. This could have affected the results from testing.

Conclusion

e-NABLE, an online community whose purpose is to design and fabricate 3D printed prosthetics inexpensively, had a hand design called *Raptor Reloaded*. Although this was a popular prosthetic for people with a palm and no fingers, it was lacking in many ways functionally. Our project this semester was to add lateral movement to the hand to add functionality but without losing the abilities it already had. To do so our group designed an accordion-design inspired wrist piece that attaches between the palm and the gauntlet. The attachment would allow for extension, flexion, abduction, and adduction, all without losing grip strength since the strings which pull the fingers into a grip could continue to function normally and slide over the top of the attachment with no interference. After testing of the final design, we were able to meet our design criteria by fully reaching the adduction and abduction degrees of a typical human. We unfortunately lost a couple degrees in flexion, which should be fixed if more time was allotted.

One of our biggest struggles was 3D printing, as it is time consuming and resulted in many failed prints. If we were given a chance to start this project again, we would allow for more time to print accordion pieces. It would be beneficial to have a different number of folds in the accordion to test. In the future there is still more testing we would like to do on TPU. By printing more accordion pieces at different infills it would give us a better idea of what the perfect balance between range of motion and durability is. To test durability we would use the tensile test with the MTS machine and, after significant force had been put on the accordion for an extended period of time, we would measure the range of motion again. Combining that information with how the accordion was visibly holding up under the conditions we could determine the infill which allowed the wrist to function best for a significant period of time.

Also, if given more time we would ideally like to collaborate further with the other e-NABLE design groups to add increased grip strength and thumb function to our laterally moving wrist to create a more fully functioning hand on multiple fronts. As far as the accordion pieces in specific, we would like to see how adding more folds to the accordion would alter the tensile ability and improve how the wrist was attached at the palm and gauntlet to increase patient comfort, create a design that is easily reproducible, and one that does not limit the flexion and extension. The progress we made this semester, and the improvements to be done in the future, work to provide a hand to transform the kid with the “weird hand” to the kid with the cool hand.

References

[1] Dr. Ed Bersu, accomplished anatomist

[2] G. Smit, “3D-printed upper limb prostheses: a review,” *Taylor and Francis Online*, 02-Feb-2017. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/17483107.2016.1253117. [Accessed: 18-Sep-2018].

[3] HealthyChildren.org. (2018). *Children with Congenital Hand Anomalies & Malformations*. [online] Available at: https://www.healthychildren.org/English/health-issues/conditions/Cleft-Craniofacial/Pages/Children-with-Congenital-Hand-Anomalies-Malformations.aspx [Accessed 11 Dec. 2018].

[4] J. FlyntI, “TPU Filament: Properties, How to Use It, and Best Brands,” *3D Insider*, 29-Mar-2018. [Online]. Available: https://3dinsider.com/tpu-filament/. [Accessed: 16-Oct-2018].

[5] J. Owen, “ABOUT US,” Enabling The Future, 01-Oct-2017. [Online]. Available: http://enablingthefuture.org/about/. [Accessed: 02-Dec-2018].

[6] J. Ryu, A. K. Palmer, and W. P. Cooney, “Wrist Joint Motion,” *Biomechanics of the Wrist Joint*, pp. 37–60, 1991.

[7] N. Yurtoğlu, “http://www.historystudies.net/dergi//birinci-dunya-savasinda-bir-asayis-sorunu-sebinkarahisar-ermeni-isyani20181092a4a8f.pdf,”*History Studies International Journal of History*, vol. 10, no. 7, pp. 241–264, 2018.

[8] “PLA vs ABS Filament: Plastic Strength, Flexibility Compared! Which Is Better For 3D Printing?,” *All That 3D*, 27-Jan-2018. [Online]. Available: https://www.allthat3d.com/pla-vs-abs/. [Accessed: 27-Sep-2018].

[9] Stride, B. (2018). *Wrist Movements*. [online] Ergovancouver.net. Available at: http://www.ergovancouver.net/wrist_movements.htm [Accessed 9 Oct. 2018].

[10] Texaschildrens.org. (2018). *Symbrachydactyly | Texas Children's Hospital*. [online] Available at: https://www.texaschildrens.org/health/symbrachydactyly [Accessed 10 Dec. 2018].

[11] “Valued Figure 2f from: Irimia R, Gottschling M (2016) Taxonomic revision of Rochefortia Sw. (Ehretiaceae, Boraginales). Biodiversity Data Journal 4: e7720. https://doi.org/10.3897/BDJ.4.e7720.”

Appendix

Appendix A: PDS

Function: e-NABLE international community 3D prints ultra low cost upper limb prosthetics and delivers them free to those in need. Almost all the hand designs (used for those missing fingers but still have a palm) strap a gauntlet on the forearm, and the functional part of the prosthetic hand to the remaining palm. The user then bends the wrist forward to clench a fist, and backward to release the grip. But that is the only degree of freedom of the device. For those with sufficient lateral movement of their wrist, a means of turning the prosthetic wrist laterally would provide the benefit of a second degree of freedom. The project is to design and test a modified e-NABLE design that incorporates abduction and adduction to the wrist movement.

Client Requirements:

- Need to add a second degree of freedom to existing prosthesis.
- Current prosthesis design is for individuals with a palm but no fingers.
- Advancing *Raptor Reloaded* design
- Cannot lose any of the functions already implemented with the first degree of freedom.
- Must be 3D printed

Design Requirements:

1. **Physical and Operational Characteristics:**

   a. *Performance requirements:* The prosthesis should maintain its current capabilities with the addition of a lateral movement to give the user another degree of freedom. It needs to be able to withstand everyday use.

   b. *Safety:* The prosthesis needs to add a lateral motion without overusing the user's wrist or palm. The motion needs to be a simple motion that will not put strain on the user's residual limb. It needs to fit and be fully controlled by each individual user.

   c. *Accuracy and Reliability:* The precision and accuracy of this design depend on each individual user. Overall, it should have two degrees of freedom. The radial flexion should approach 17 degrees and the ulnar flexion should approach 40 degrees.

   d. *Life in Service:* The prosthetic will typically need to last 1-2 years, or until the child grows out of it. The material and strings should not be damaged with daily use.

e. *Shelf Life:* The device will be given to the recipient within a couple weeks of being printed and assembled.

f. *Operating Environment:* The device will most likely be used in room temperatures(68-77 degrees Fahrenheit). Noise level will not affect the prosthesis. The device needs to be able to withstand subtle debris, such as dust, but the materials previously used for the prosthesis will be sufficient. Because children will most likely be operating this device, all the pieces must be well secured to ensure nothing is lost or damaged.

g. *Ergonomics:* The patient for this prosthesis must have a palm to be able to wear the *Raptor Reloaded* design. The device must be accurately measured to fit the patient comfortably. However, the design will be able to be repeated onto several prosthesis of different lengths and widths. The device must still maintain its original forceful grasp with the fingers and thumb.

h. *Size:* The device will be designed and printed specifically for each patient. The e-NABLE prostheses range from fitting kids to adults. The *Raptor Reloaded* prosthesis is just the wrist and hand so the length and size of the forearm will not be needed. A kid's(5-8yr) hand is between 5 and 7 inches and an adult's hand ranges from 7 to 10 inches.

i. *Weight:* The weight of the finished product should be anywhere from around 100-280g depending on the age and size of the user. (values from the similar 3D prosthesis *Cyborg Beast*) This means that the hand is generally lightweight so the user is relatively unhindered, even in the case of small children.

j. *Materials*: Current common materials are ABS, PLA, and Nylon. Nylon is not recommended because Nylon filament must be kept desiccated when not in use. ABS and PLA materials result in durable parts that rarely change with respect to mechanical characteristics over time.

k. *Aesthetics, Appearance, and Finish:* The prosthetic will be 3D printed. Aesthetics are not as important as function. New additions will fit the aesthetics of the current model.

2. Production Characteristics:

a. *Quantity:* There is a need for one altered prosthesis that can then be replicated.

b. *Target Product Cost:* The budget for this project is $200.

3. **Miscellaneous:**

a. *Standards and Specifications:* In order to maintain quality prints across many different types of printers, e-NABLE asks for volunteer fabricators to target the following quality specifications:

- No large gaps in between shells. The print must be “water-tight”.
- Layer height between 0.1mm and 0.25mm.
- No experimental, scented, or chemically-treated filament.
- Printer must be properly calibrated to achieve the dimensional tolerances necessary for functioning hands.

b. *Customer:* While wearing the prosthesis, the customer must be able to move their hand two degrees of freedom with ease. The weight or size of the device must be appropriate to the size of the user so it does not hinder them. The prosthesis must be easy to put on and off and should be easy to clean in between uses.

c. *Patient-related concerns:* Each prosthetic is made unique to each patient, therefore sterilization is not necessary and since the design is general, sizing will be adjusted for each specific person, and there will be no patient data to store.

Appendix B: MATLAB Code

Graph 1:

```
c = categorical ({'Abduction','Adduction'});
y = [12.3 11.7 23; 34.7 23.7 43.3];
bar(c,y, 'Facecolor' , 'Flat');
ax = gca;
ax.FontSize = 11;
bar_handle = bar(c,y,'grouped');
set(bar_handle(1),'Facecolor','r') ;
set(bar_handle(2),'Facecolor','k') ;
set(bar_handle(3),'Facecolor','b') ;
ylabel('Range of Motion (degrees)');
xlabel('Direction of Motion');
legend({'0.7mm, Short', '1.0mm, Short' , '0.7mm, Long'});
```

```
title ('Range of Motion Measurements Among Various Accordion Types')
```

Graph 2:

```
c = categorical ({'Flexion', 'Extension' , 'Abduction' , 'Adduction'});
y = [54 54 45.3; 54 54 45.3; 17 0 23; 40 0 43.3];
bar(c,y,'Facecolor' , 'Flat');
ax = gca;
ax.FontSize = 25;
bar_handle = bar(c,y,'grouped');
set(bar_handle(1),'Facecolor','r') ;
set(bar_handle(2),'Facecolor','k') ;
set(bar_handle(3),'Facecolor','b') ;
ylim([0 65])
legend({'Typical Human Wrist','Raptor Reloaded','The Accordion Design'});
ylabel('Range of Motion (degrees)');
xlabel('Direction of Motion');
title ('Final Design Range of Motion Compared to Hand and Raptor Reloaded')
```

Appendix C: Material Costs

Description	Supplier	Quantity	Date	Price	Total
Full hand assembly(100%)	Makerspace	1	9/24/2018	$12.93	$12.93
Hand palm and gauntlet(135%)	Makerspace	1	9/29/2018	$11.39	$11.39
Fingers and joints(135%)	Makerspace	1	10/2/2018	$10.83	$10.83
Fingers and joints(150%)	Makerspace	1	10/18/2018	$7.64	$7.64
One joint(150%)	Makerspace	1	10/20/2018	$0.40	$0.40
TPU half cylinder(150%) no folds	Makerspace	1	11/2/2018	$0.88	$0.88
TPU half Accordion(150%) 1.5mm	Makerspace	1	11/7/2018	$2.94	$2.94
TPU half Accordion(150%,10%infill) 1mm	Makerspace	1	11/19/2018	$2.97	$2.97
TPU half Accordion(150%, 10%infill) 0.7mm	Makerspace	1	11/28/2018	$3.19	$3.19

Palm with Slit(150%)	Makerspace	1	11/28/2018	$8.04	$8.04
Palm, Gauntlet, and Pins(150%)	Makerspace	1	11/30/2018	$14.74	$14.74
2 Accordions (1 long(0.7mm), 1 short(1mm))	Makerspace	1	12/3/2018	$15.51	$15.51
					TOTAL: $91.46