Accessible Children's Prosthetics Created Using 3D Printing Technologies

Ryan Carroll[1], Brian Carrozza[1], Juan Lopez[1], Yardley Ordonez[1], Edgar Sanchez[1], Daniel Kim[2], Andres Lee[2], and Dr. Kwok Siong Teh[2]

[1]Cañada College, Redwood City, CA 94061
[2]School of Engineering, San Francisco State University, San Francisco, CA 94132

Abstract

It is estimated that about 1,500 babies are born each year in the United States with upper limb reduction defects, which may create significant functional limitations for the child. In addition to birth defects, the most common cause of partial hand loss occurs through trauma. The research conducted for this paper focuses primarily on devices which have been fabricated for children with partial hand defects or amputations, specifically for those children whose wrists are still fully functional. Technologically advanced and commercially available prosthetics are expensive, costing upwards of four thousand dollars. In addition, because of their utilization of advanced electronics, durability for use by children is a concern. Alternatively, purely mechanical and body-actuated prosthetics are also available but only perform basic single-grip functionality. With these two categories of prosthetics, users are forced to choose between high cost and limited functionality. This research seeks to bridge that gap by providing a low-cost, 3D printable prosthetic hand with improved functionality. In order to enhance prosthetic functionality, increasing grip diversity was a primary focus. This was done by adding a mechanism which enables the ability to control fingers individually, thus allowing the user to handle smaller items with a more precise, two or three-finger grip. A grip lock has also been implemented in order to reduce fatigue during extended use. Multiple tests were devised in order to test the effectiveness of the design modifications made, with results showing marked improvements over a standard prosthetic in certain use cases. Our goal with these modifications is to increase the number of children with upper limb loss to be able to use 3D printed prosthetics and pass a series of tests to show the improvements.

Introduction

The *"Accelerated STEM Pathways through Internships, Research, Engagement, and Support"* (ASPIRES**)** program is a collaboration between Cañada College's Engineering Department, San Francisco State University School of Engineering, and UC Merced. The project is supported by a grant from the US Department of Education through the Minority Science and Engineering Improvement Program (MSEIP), Grant No. P120A150014.[1] For the ASPIRES 2017 Summer program, we were assigned to be the mechanical engineering group. Our group was led by SFSU Mechanical Engineering Professor, Dr. Teh with the help of two senior year students from SFSU as our mentors, Daniel Kim and Andres Lee. Our group was assigned to provide qualitative research on child prosthetics and to design our own prosthetic hand by means of 3D printing.

Children in the US have a significant risk of either being born with an upper body limb deficiency, such as congenital limb deficiency, or suffering from a traumatic hand amputation. In a study conducted by the Centers for Disease Control and Prevention (CDC), around 4 out of 10,000 births will suffer from upper body limb deficiency each year.[2] Upper body limb deficiency will range from having missing fingers to missing an arm. Besides upper body limb deficiency, traumatic hand amputations are devastating injuries that cause permanent physical damage. In a study done by the National Traumatic Databank (NTDB), there were 2,238 patients that suffered a related hand amputation due to trauma. The majority of amputations occurred in the age group of 0 to 5 years and 54% of 2,238 patients had a hand related trauma amputations.[3] From both studies, we recognized that children in the age group of 0 to 5 years had the highest risk of having the stump of the wrist with either a partial hand or no hand.

Figure 1: M-fingers[4]

Our group recognized that children who suffered a hand amputation or were born with a hand deficiency, have expensive options in hand prosthesis. It is reported that an electronically powered prosthetic hand will range in cost of $25,000 to $75,000.[5] Body powered prosthesis are a less expensive option, with costs ranging from $2,000 to $10,000.[5] Observing the price ranges from both types of prosthesis, our group recognized that body-powered prosthetics are the most reasonable choice for growing children. Some of the popular choices in prosthesis include having a body-powered hook or a wrist-actuated prosthetic, such as the M-fingers in Figure 1. M-fingers consist of wrist-driven, cable-actuated mechanical fingers with a multiposition thumb as an option. is one of many wrist actuated prosthetic hand options that are available on the market. Observing the prices of medically available prostheses, our group noted that annual prosthetic services can range in cost from $500 to $3,000.[6] Body actuated prosthetics required less therapy than myoelectric prosthetics, and remain popular in the US. Body prosthetics have less wear and tear than the myoelectric ones, but one of the most common defects of a body powered prosthetic hand is the maintenance on the cables.

Approach

In regards to the stated problems with medically available prosthetics, our objective was to design and 3D print a prosthetic hand that will be cost efficient and more accessible for a growing child. We are currently printing with the Ultimaker 2+ provided by the San Francisco State University Engineering Department. We used polylactic acid (PLA) as the main material to 3D print our design. The cost of polylactic acid is around $0.075 per meter and our design will require about 17.2 meters of PLA. The cost for our prosthetic hand will be about 0.22 % of a lower range prosthetic hand which costs about $2,000. Since the cost is at a much lower price to produce, we will also be focused on having our design be available as open-source for anyone to access. The benefits to having our design open-source through a website like www.instructables.com is that we will be giving anyone access around the US and other countries who need something like our prosthetic hand. When someone accesses the design files, they will be able to download it and modify the size of the parts depending on the child through an STL reader such as Cura. One of the easiest ways for us to modify the sizes of our design and print is through Cura, which is an STL reading software that will translate the design specifications into G code. G code is used mainly in computer-aided manufacturing to control automated machine tools. Since a child is constantly growing, and there may be a need to replace various parts on this system, a reprint of the design will be inexpensive and easy to create.

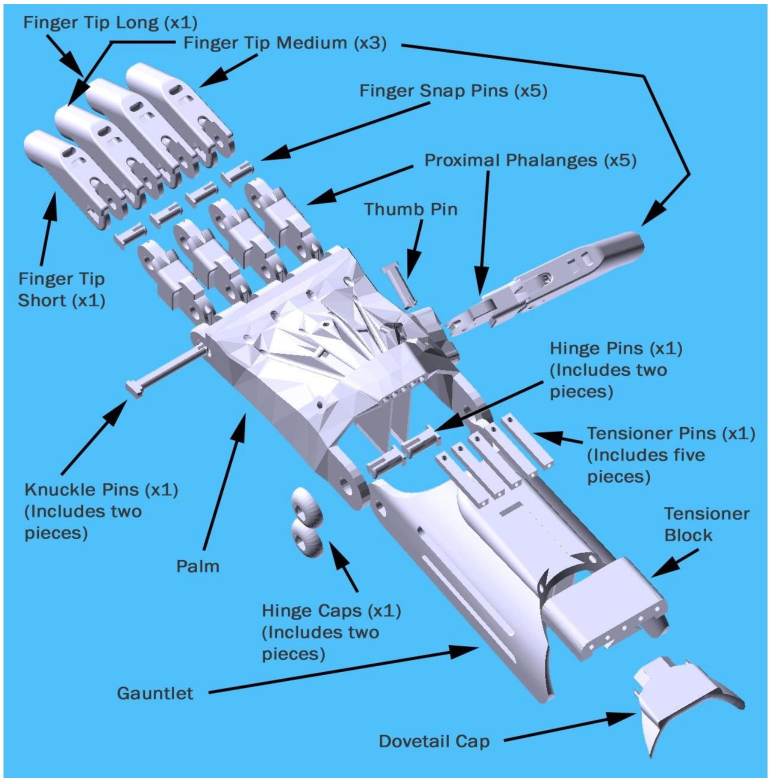

Figure 2: The Raptor Hand[7]

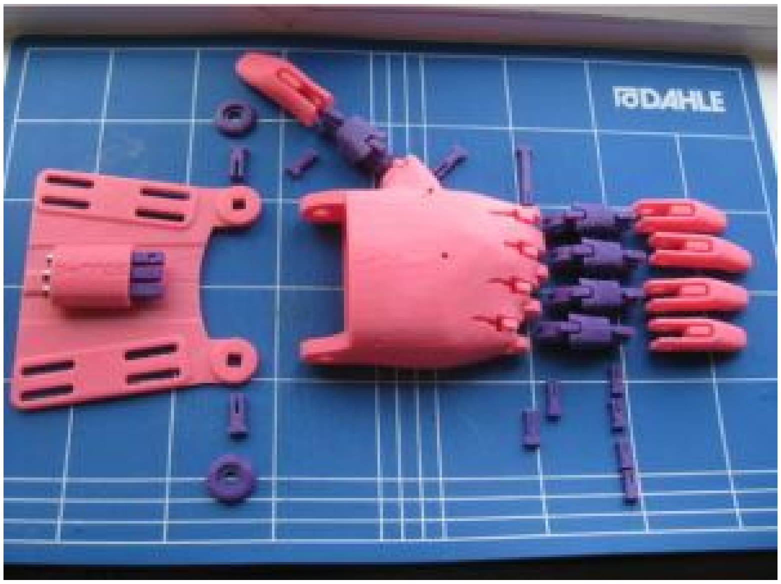

Figure 3: The Phoenix Hand[8]

In terms of the 3D printed models, our group looked at several designs that were open-source and decided to implement different mechanical features for a better functioning prosthetic hand. Two of the models we looked at were the Raptor and Phoenix, which can be seen in Figures 2 and 3. These two models are similar in design and were some of the most popular prosthetic models that were open-source. In Figure 2 and Figure 3, we can see that there is a tensioner block for both the Raptor hand and the Phoenix hand. We noticed that both models and the M-fingers model, only had a wrist-actuated mechanism. Wrist-actuation allows the user to grip onto something through the use of tension on the strings. When the wrist portion of the hand flexes then the tension of the strings attached to the fingers will cause the fingers to bend and close into a fist. Our group decided to build a locking mechanism for better grip and have individual finger control instead of just having the wrist actuation act upon all the fingers simultaneously for gripping. The grip locking mechanism would allow kids to grip an object for an extensive period of time. The individual finger control would allow the use of individual fingers for precision.

<u>Mechanical Design</u>

In the following section we will talk about the mechanical features that we have come up with for our prosthetic hand. We will first talk about the individual finger control then the grip locking mechanism that we implemented into our palm design.

Individual Finger Control:

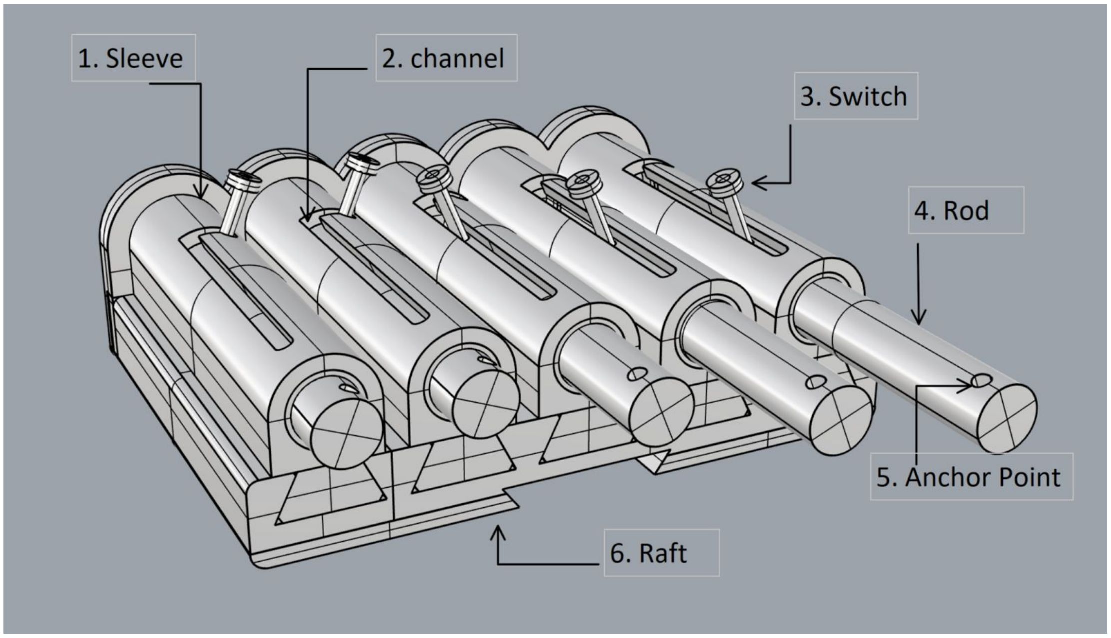

Figure 4: Individual Finger Control (IFC) Design with labels

Figure 4 shows the Individual Finger Control (IFC) mechanism with labeled parts of the design. The IFC raft and sleeve are both stationary parts to create tension on the string used for each finger tied with the string material. This design serves as a modified tensioner that most wrist actuated prosthetic hands use to anchor the string material and create tension. Observing Figure 4, we see each sleeve attached to the raft so they can be easily replaced individually instead of replacing the whole IFC mechanism. The Rod our group designed implemented a switch feature that moved along the channel of the sleeve to create less tension on each string material used to implement the individual finger control, as we can see on the right side of the figure. The notch on the end of the rod is referred to as the anchor point, where we tie the end of a string that will create tension. Features like the rod, sleeve, and raft are important to easily fix or replace parts of the individual finger control

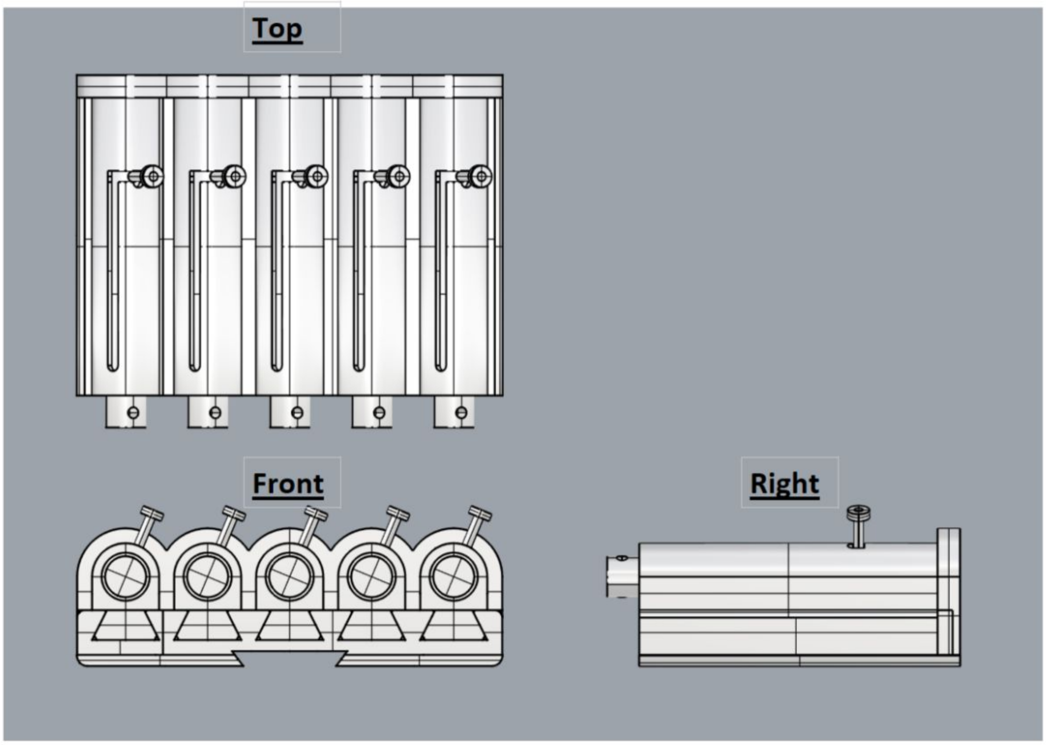

Figure 5: Top, Front, Right Views of Individual Finger Control (IFC) mechanism

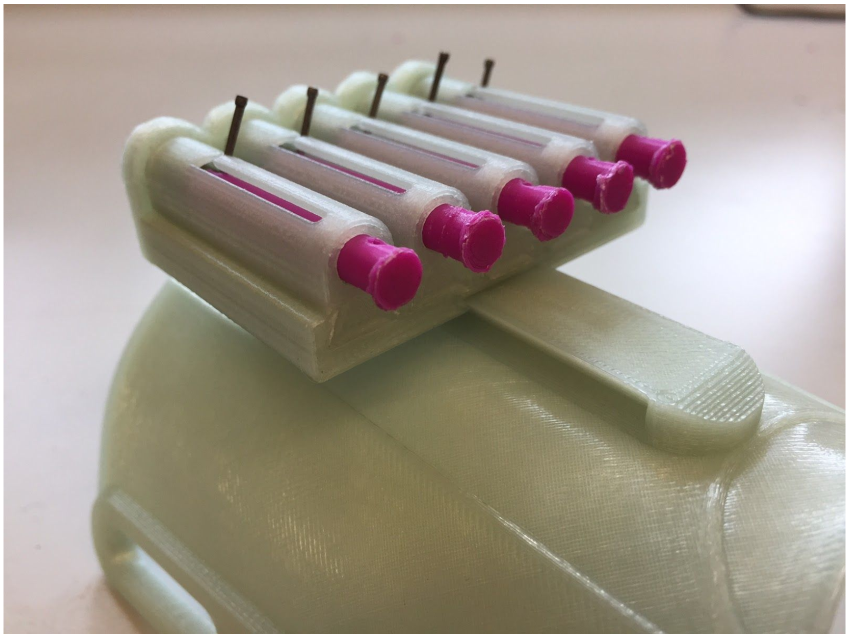

Figure 6: 3D printed IFC mechanism attached to gauntlet

Figures 5 and 6 show different views of the final individual finger control design and we should refer back to Figure 4 for the details of each part of the IFC mechanism. We see in figure 6 our modified tensioner attached to the gauntlet portion of the prosthetic hand design. The gauntlet serves as an anchor for the whole prosthetic to strap onto the forearm portion of a human arm.

Grip Locking Mechanism:

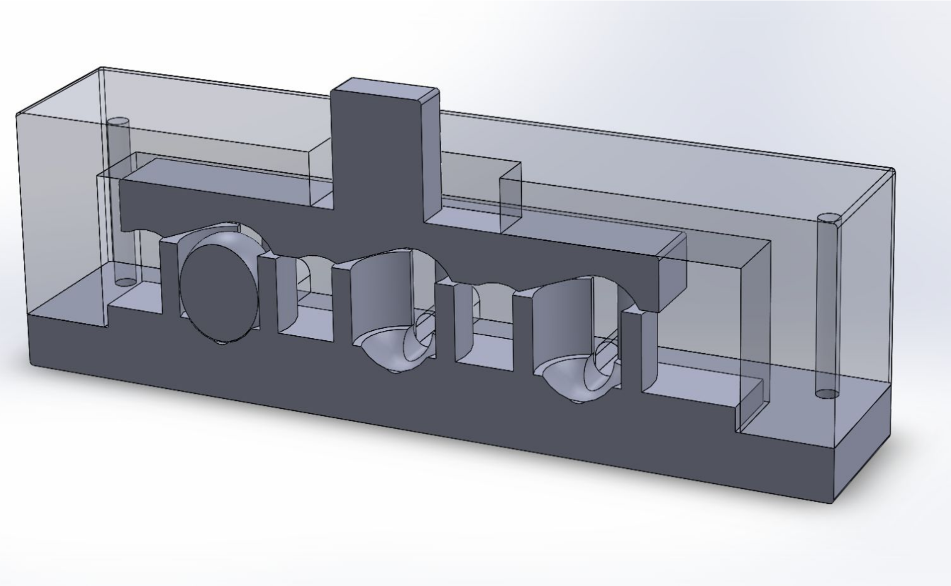

Figure 7: Early stage of the grip locking mechanism

Figure 7 is an older design of the grip lock mechanism that we had to modify. The location of the mechanism was to placed on top of the palm of the prosthetic hand. The mechanism itself consists of two locks, one being the top and the other being the bottom. The bottom block has 5mm ball bearings. The way this mechanism works is that each channel has a string going through it. When the switch is moved to the right, the bottom portion of the switch presses down on the the ball bearing. The ball bearing being pressed down will clamp down onto the string creating a grip locking mechanism on the string.

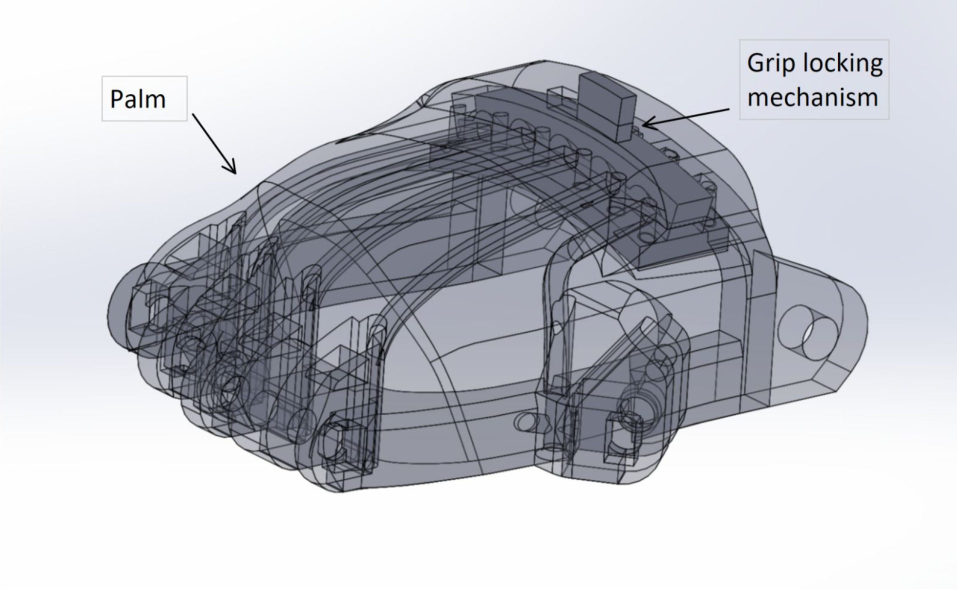

Figure 8: Grip Lock Mechanism embedded in the palm design

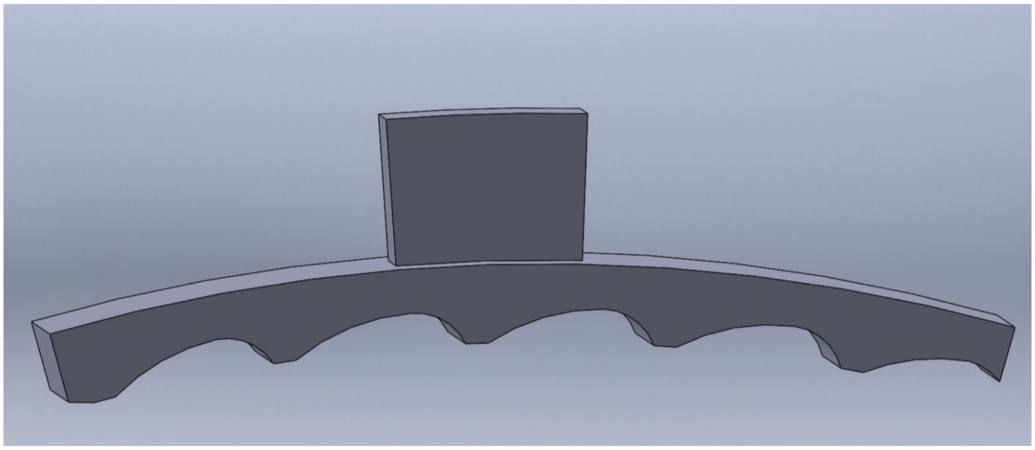

Figure 9: Switch

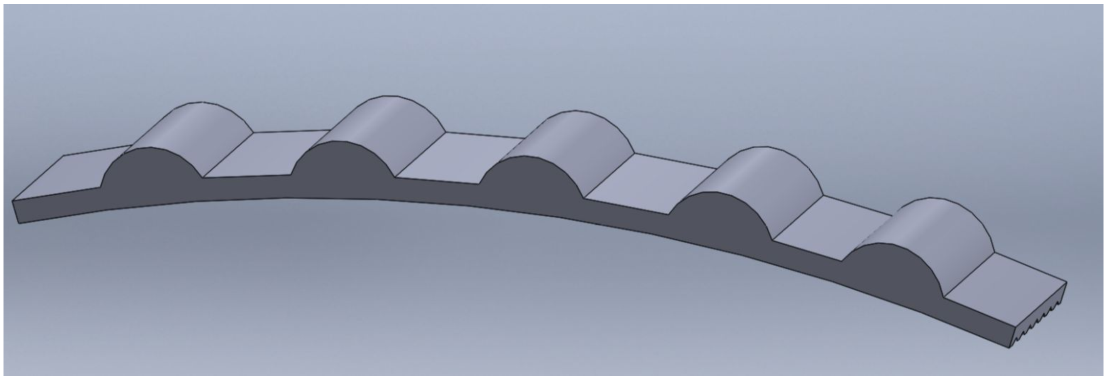

Figure 10: Shim

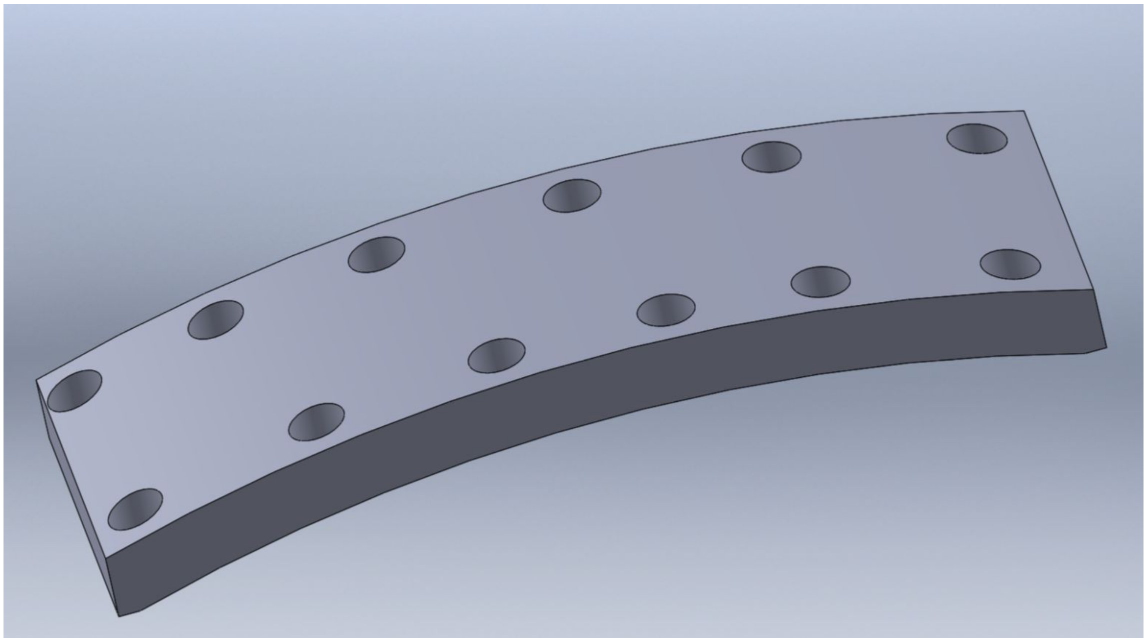

Figure 11: Bottom Plate

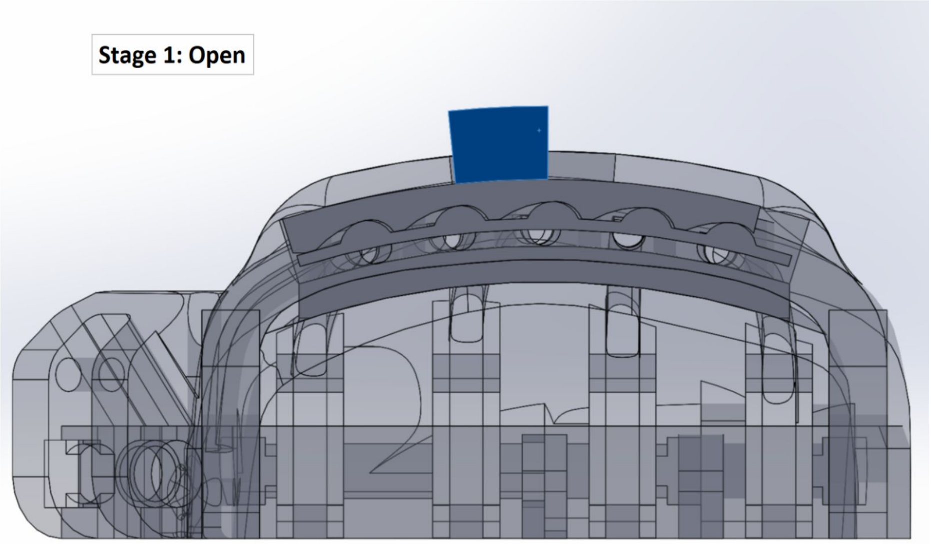

Figure 12: Grip Locking Mechanism open (unlocked)

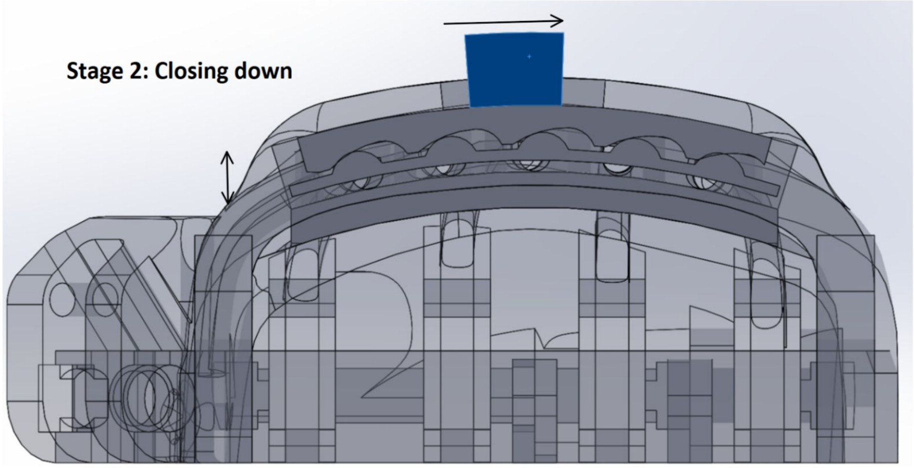

Figure 13: Grip locking mechanism in transition from unlocked to locked

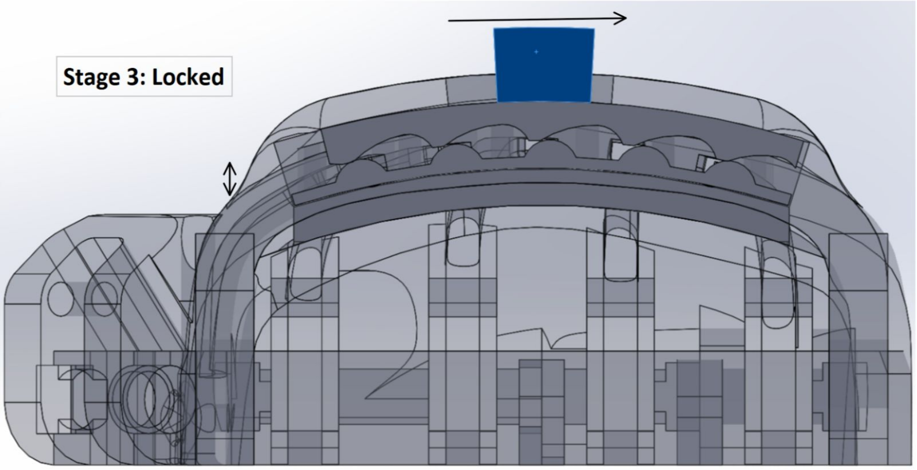

Figure 14: Grip locking mechanism locked

The Grip locking Mechanism consists of three parts, which are the switch, the shim, and the bottom plate, shown individually in Figures 9-11. In Figure 8, we can see that our locking mechanism is meant to serve as a low profile attachment. In order to explain how our mechanism works, we will have to look at Figure 12-14. In the first stage, our locking mechanism is not active yet and we can see the channels where the string comes out are still visible. In the second stage, as we move the switch from the left (grip lock off position) to the right (grip lock on position), the bottom portion of the switch interacts with the shim and begins to clamp down. At this stage we can see that our channels are starting to be less visible. By the time we reach the last stage, we can see that the shim part is completely touching the bottom plate clamping down on the string material that will create a grip lock. This mechanism will help the user make a tight grip on an object that will be held for a long time instead of relying on the wrist actuation movement needed in order to grip onto something for a longer period of time.

Testing:

In order to measure the effectiveness of the modifications made to the prosthetic hand design, three tests were devised and conducted: two separate precision tests, and a grip strength test. Each test was conducted using both a standard Reborn hand assembly as well as our modified Reborn hand with Individual finger control and grip lock. The first grip precision test is intended to evaluate the effectiveness of the individual finger control for tasks requiring a precise grip. This test consists of a pile of 15 washers (25.25mm Dia. x 1.25mm thick) which the tester picks up one at a time and places to form a second pile approximately 7 inches away. With the modified reborn hand, the individual finger control is set to permit only the thumb and forefinger to perform the task. Each prosthetic was allowed 60 seconds to perform each trial. The second precision test is to evaluate both hands' ability to accurately make button selections, such as on a telephone or microwave oven. This test consists of a self-made four-button device assembled using a breadboard, arduino, and four off-the-shelf push buttons attached to four multicolor LEDs. With the buttons numbered 1-4, a human tester was tasked with using each prosthetic to accurately push the buttons in a predetermined pattern at a fast pace. As they pressed the buttons, a second person watched the LEDs and recorded any incorrect button presses. The third and final test was designed to measure the advantage of a prosthetic having silicon fingertips installed, and the effect of this on the grip strength of the prosthetic. For this test, a length of fishing line was attached to the bottom of a 1 inch diameter carbon-fiber rod of negligible weight. Each prosthetic then held the rod as weight was hung from the bottom of the fishing line. Weight was added until the rod slipped from the hand's grip, with special attention paid to how much weight was present when slippage began.

Table 1: Grip Precision Test 1 - Stacking Washers
(Modified Prosthetic Hand [w/ thumb and index finger active])

	Washers moved from A to B	Washers Dropped	Washers failed to pick up
Trial 1	10	2	3
Trial 2	8	4	3

Trial 3	8	4	3
Trial 4	10	2	3
Trial 5	11	1	3

Table 2: Grip Precision Test 1 - Stacking Washers
(Standard Prosthetic Hand)

	Washers moved from A to B	Washers Dropped	Washers failed to pick up
Trial 1	9	3	3
Trial 2	10	2	3
Trial 3	10	2	3
Trial 4	9	3	3
Trial 5	8	4	3

Table 3: Grip Precision Test 2 - Patterned Button Pressing
(Standard Prosthetic Hand)

	Correct Input	Incorrect Input
Trial 1	3	11
Trial 2	6	8
Trial 3	4	10

Table 4: Grip Precision Test 2 - Patterned Button Pressing
(Modified Prosthetic Hand [w/ thumb and index finger active])

	Correct Input	Incorrect Input
Trial 1	13	1
Trial 2	14	0
Trial 3	14	0

Table 5: Grip strength Test - Weighted Rod
(Standard Prosthetic Hand [w/o silicone fingertips])

	Weight when slippage began	Weight when full slippage occurred
Trial 1	550 g	550 g
Trial 2	500 g	500 g
Trial 3	490 g	490 g
Trial 4	700 g	700 g
Trial 5	600 g	600 g

Table 6: Grip strength Test - Weighted Rod
(Modified Prosthetic Hand [w/ silicone fingertips])

	Weight when slippage began	Weight when full slippage occurred
Trial 1	1600 g	--
Trial 2	1464 g	--
Trial 3	1565 g	--
Trial 4	1500 g	--
Trial 5	1565 g	2240 g

Analysis:

Stacking Washers Test:
For all trials of this test, conducted with both prosthetics, the palm of the prosthetic was held as close to parallel to the tabletop as possible. Both prosthetics had silicone fingertips installed on at least their thumbs and index fingers. For trials involving the unmodified, standard prosthetic, effort was made to use only the thumb and index finger when grasping washers. In terms of each prosthetic's ability to pick up the washers, the advantage had by the modified prosthetic, with only it's thumb and index finger active, was negligible. However, with its unused fingers (middle, ring, and pinky) out of the way, the modified prosthetic proved less likely to knock down the stacks of washers, as it moved them from stack A to stack B.

Patterned Button Pressing Test:
For all trials of this test, conducted with both prosthetics, the palm of the prosthetic was held as close to parallel to the tabletop as possible. Both prosthetics had silicone fingertips installed on at

least their thumbs and index fingers. “Incorrect input” for this test includes both a press of the wrong button and the pressing of more than one button at a time, even if the intended button was one of the buttons pressed. For this test the advantage had by the modified prosthetic, with only it’s thumb and index finger active, was significant. In the three trials performed using the modified hand only a single errant button press occurred outside of the predetermined pattern. This is in contrast to the repeated errors made using the standard prosthetic. With the standard prosthetic’s four fingers falling in a straight line, presses of the first three buttons were consistently inaccurate, with unintended presses of the buttons to the right and left of the intended one. Only the rightmost button was consistently pressed correctly.

Weighted Rod Test

Analysis of Cost

Table 7: Bill of Materials

Item	**Quantity**	**Price**
PLA	1 roll (~111m)	$25.00
Braided fishing wire	1 roll (137m)	$10.72
Nylon String	1 roll (~91m)	$7.79
Springs	12-pk	$ 5.43
Sheet metal screws #6 x 3/8	16-pk	$ 1.18
Total Cost: $50.12		

Table 8: Estimated Cost to Produce our Prosthetic Hand Breakdown of Materials Used

Material Used	**Quantity Used**	**Unit Cost**	**Total Price of Material Used**
PLA	~17.2m	$0.225/m	$3.87
Braided fishing wire	~3.66m	$0.078/m	$0.29
Nylon String	~1.83m	$0.086/m	$0.16
Sheet metal screws	5 screws	$0.074/screw	$0.37
springs	5 springs	$0.452/spring	$2.26
Estimated Total Cost to Produce our Prosthetic Hand: $6.95			

Table 7 shows the materials used to create our prosthetic hand design. PLA was a major factor since our hand was 3D printed. In Table 8 we calculated the estimated total price of material used by multiplying the unit cost by quantity used of each material. We then took the sum of all the total prices of materials used.

Conclusion and Recommendation

In conclusion we found a big problem in the industry of prosthetic hands for children. The problem was that prosthetic hands were either high function and high price or low functionality and lower price. With our individual finger control and grip lock features we hoped to have a third option for families in need of a hand where it will be a durable, high functionality, and at a low cost. Through all of our research we concluded that the changes we made to the existing hand would have the most change in function to replicate a real hand.

References

1. ASPIRES. (n.d.). Retrieved August 07, 2017, from http://www.canadacollege.edu/stemcenter/aspires.php
2. C. (Ed.). (2016, November 14). Birth Defects. Retrieved July 26, 2017, from https://www.cdc.gov/ncbddd/birthdefects/ul-limbreductiondefects.html
3. Borne, A., Porter, A., Recicar, J., Maxson, T., & Montgomery, C. (2017). Pediatric Traumatic Amputations in the United States. *Journal of Pediatric Orthopaedics, 37*(2). doi:10.1097/bpo.0000000000000693
4. Internet Medicine Admin. (December 13, 2014). *M-fingers* [Infographic]. Retrieved from:http://internetmedicine.com/2014/12/13/theres-a-new-touch-in-prosthetics-have-you-considered-silicone-lately/
5. Carey, S. L., Lura, D. J., & Highsmith, M. J. (2015). Differences in myoelectric and body-powered upper-limb prostheses: Systematic literature review. *Journal of Rehabilitation Research and Development, 52*(3), 247-262. doi:10.1682/jrrd.2014.08.0192
6. Resnik, L., Meucci, M. R., Lieberman-Klinger, S., Fantini, C., Kelty, D. L., Disla, R., & Sasson, N. (2012). Advanced Upper Limb Prosthetic Devices: Implications for Upper Limb Prosthetic Rehabilitation. *Archives of Physical Medicine and Rehabilitation, 93*(4), 710-717. doi:10.1016/j.apmr.2011.11.010
7. Owen, J., *The Raptor Hand* [Infographic]. Retrieved from: http://enablingthefuture.org/upper-limb-prosthetics/the-raptor-hand/
8. Enabling the Future, The Phoenix Hand [Infographic]. Retrieved from: http://enablingthefuture.org/phoenix-hand/

Appendix:

Figure 1: M-fingers[4]

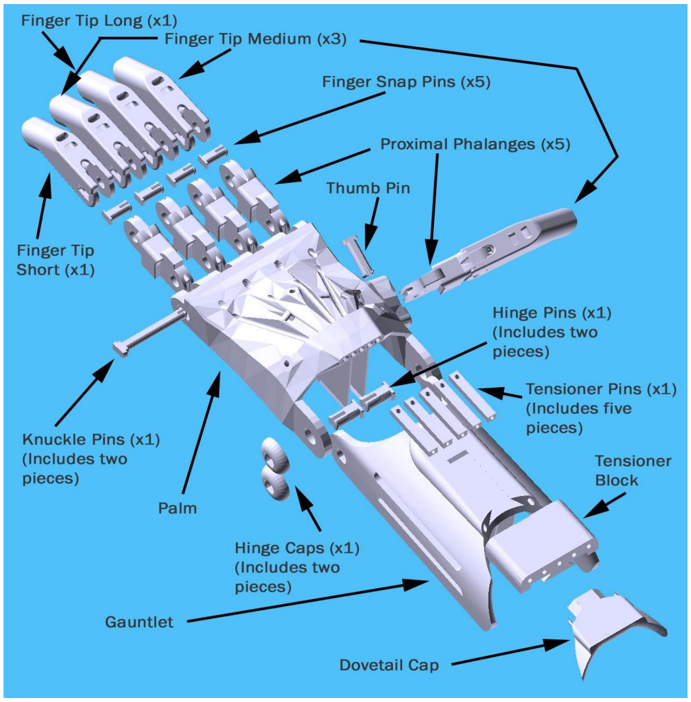

Figure 2: The Raptor Hand[7]

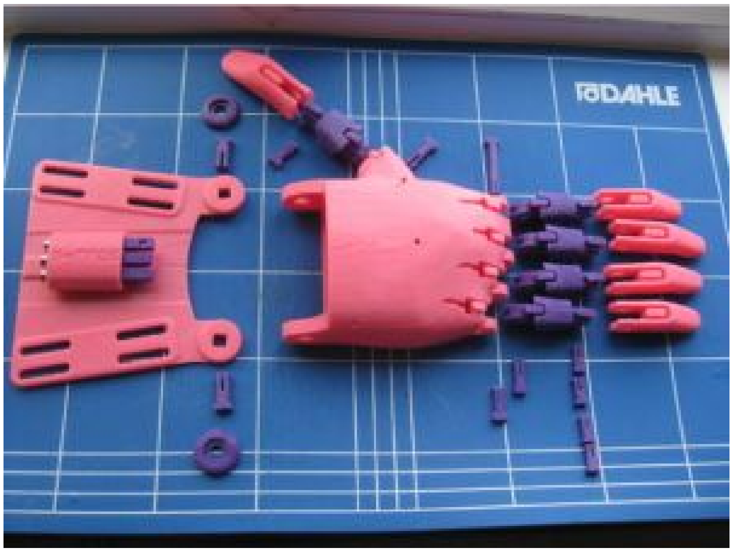

Figure 3: The Phoenix Hand[8]

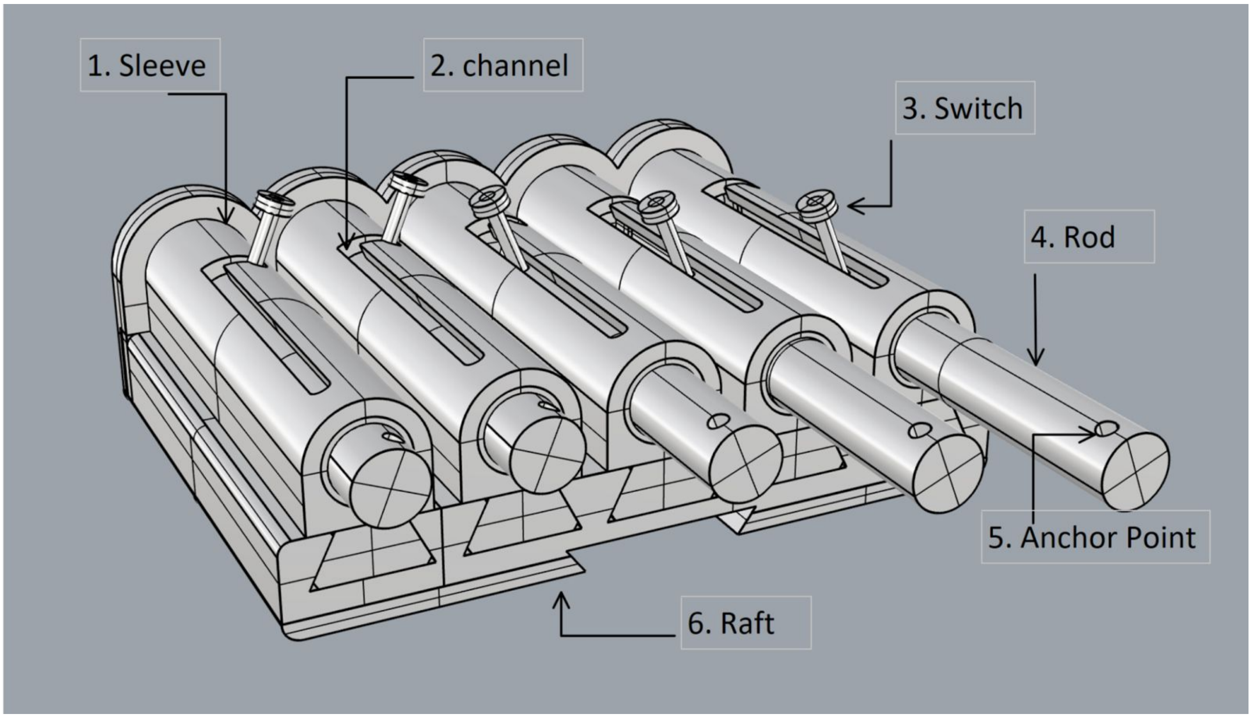

Figure 4: Individual Finger Control (IFC) Design with labels

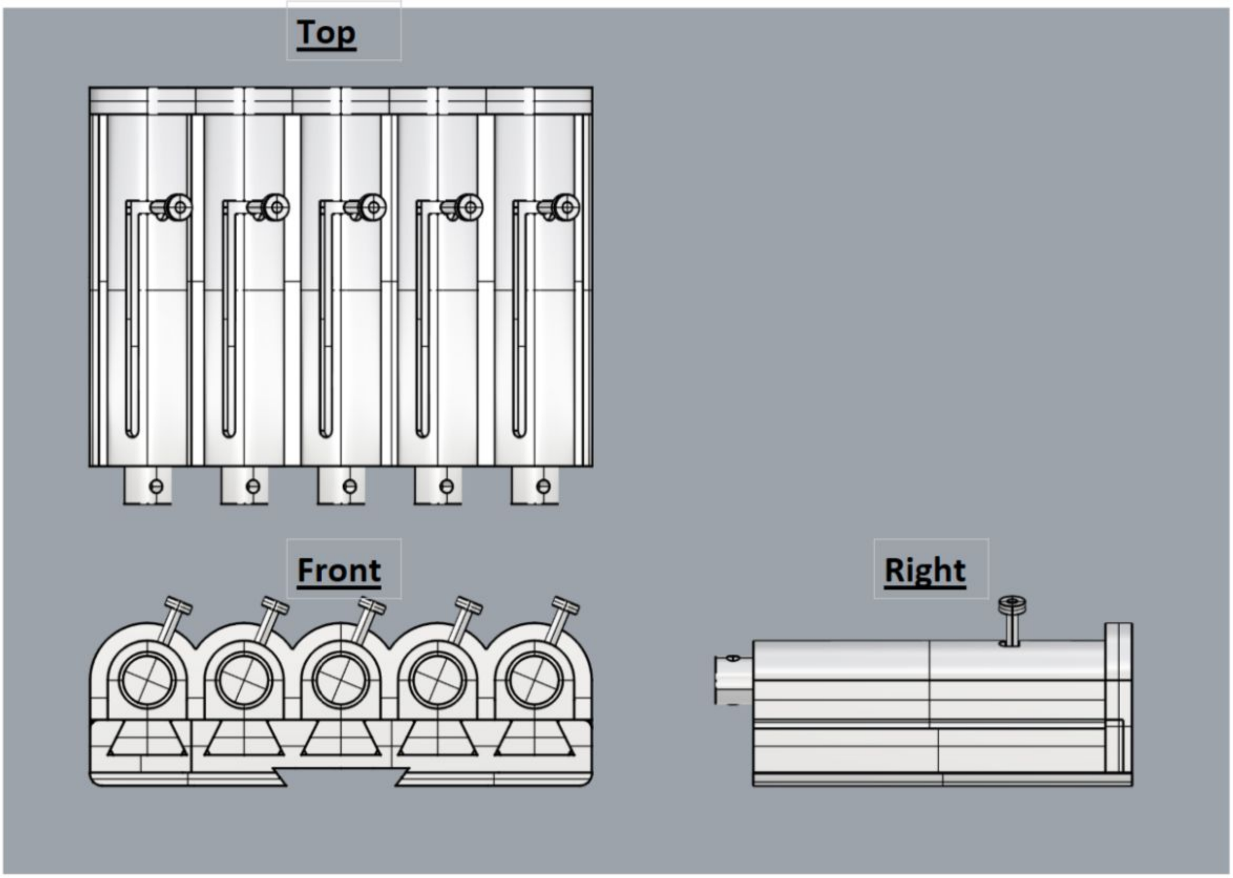

Figure 5: Top, Front, Right View of Individual Finger Control (IFC) mechanism

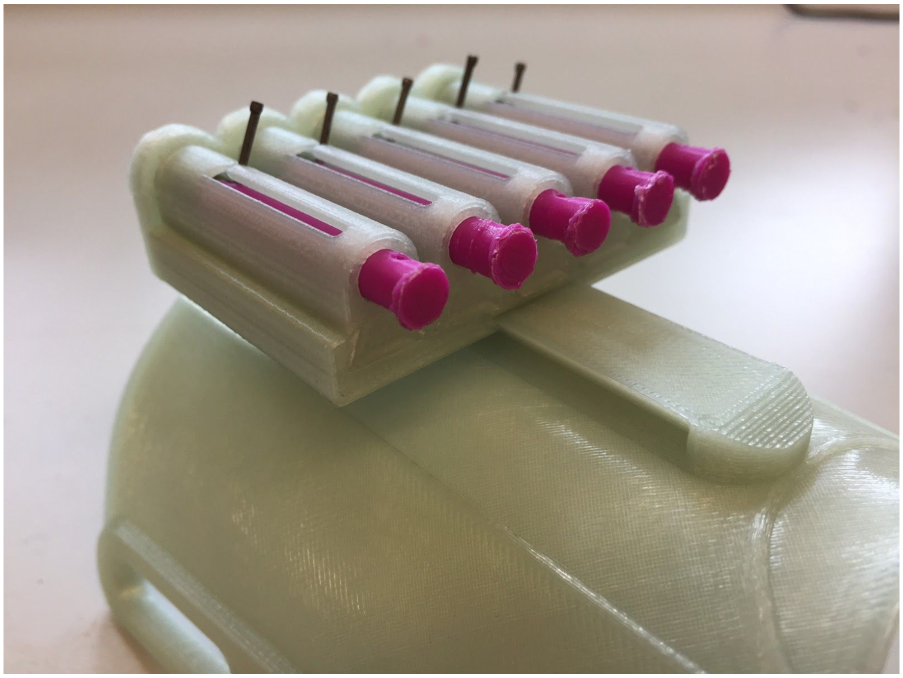

Figure 6: 3D printed IFC mechanism attached to gauntlet

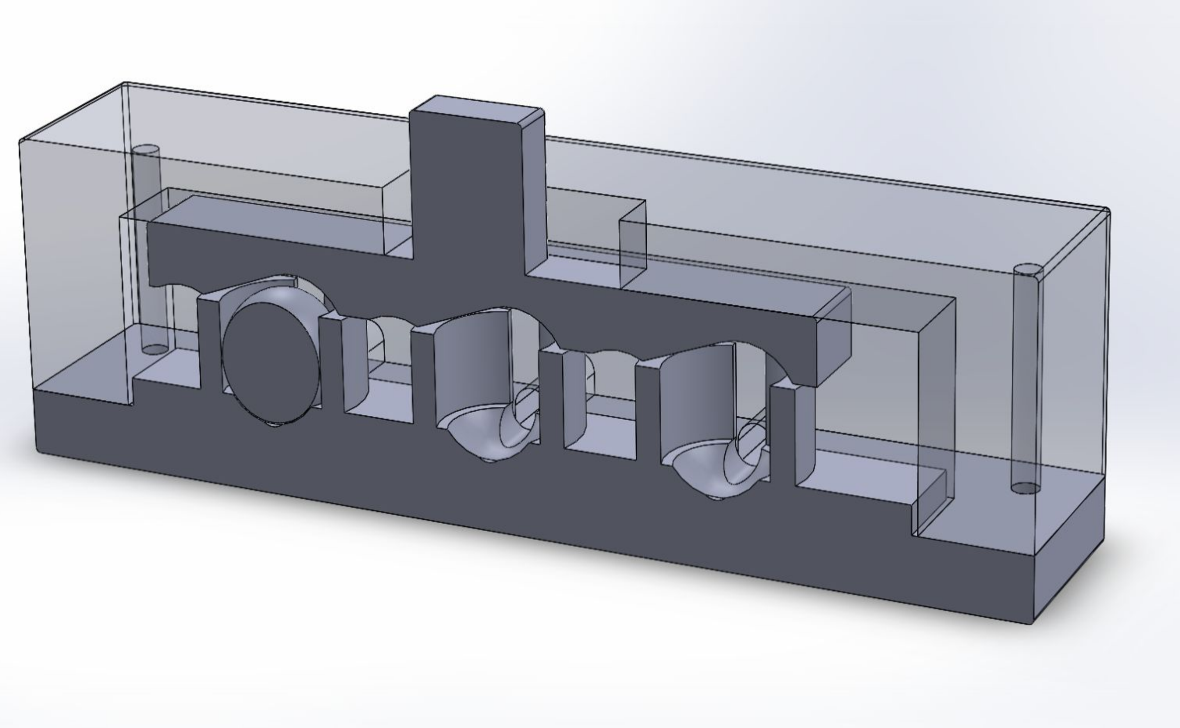

Figure 7: Early stage of the grip locking mechanism

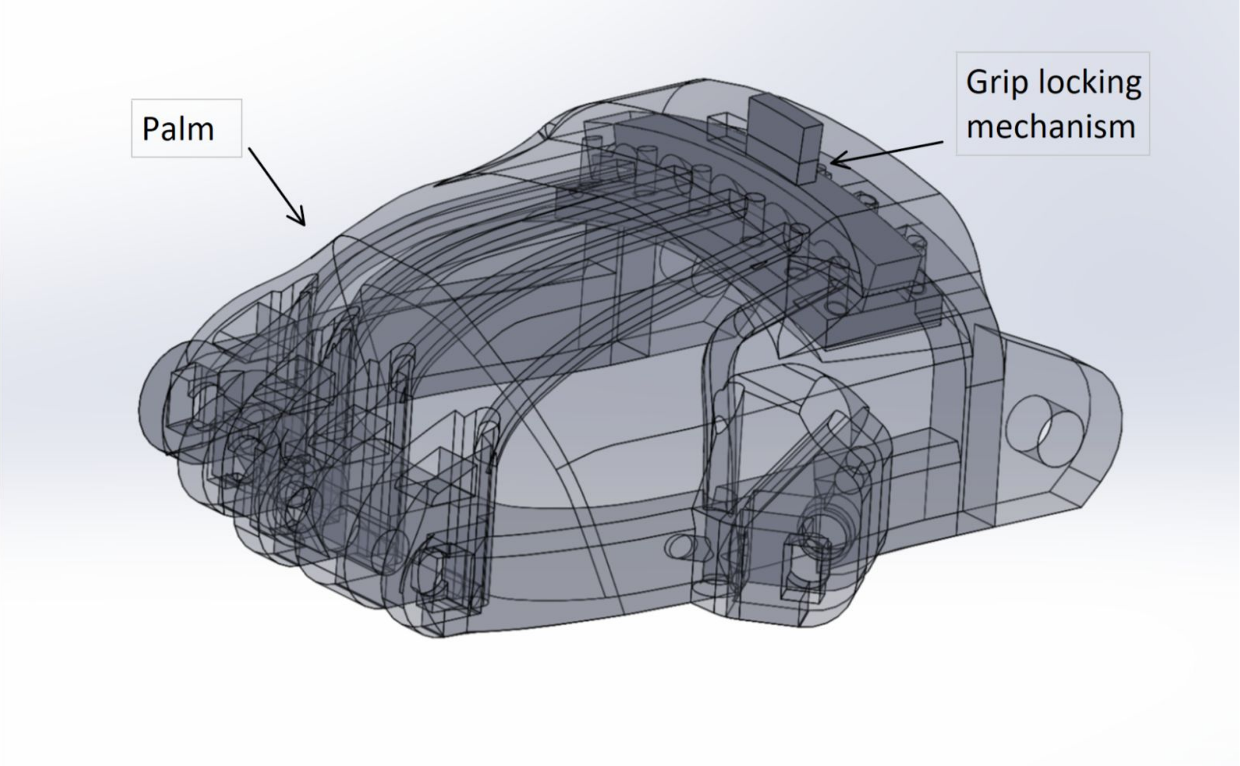

Figure 8: Grip Lock Mechanism embedded in the palm design

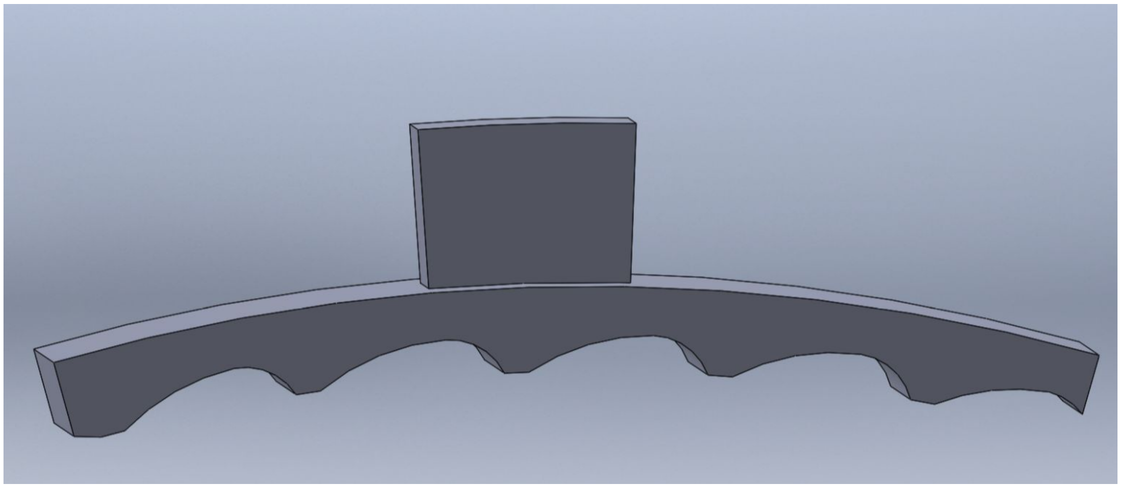

Figure 9: Switch

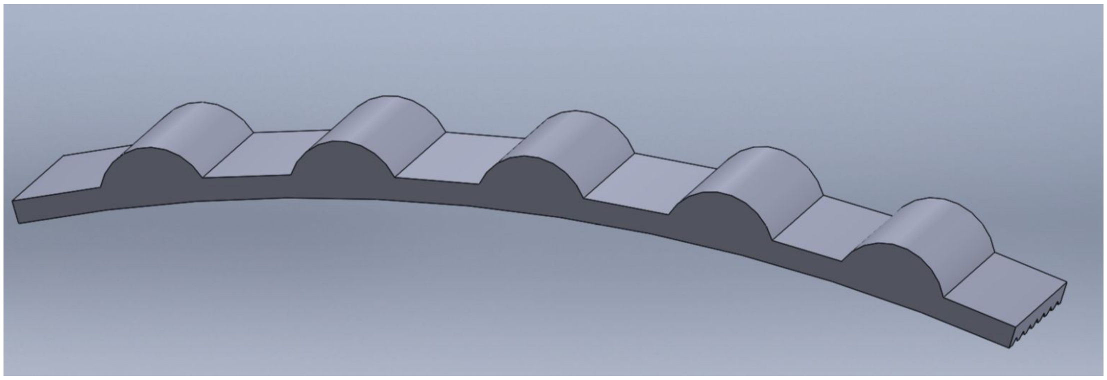

Figure 10: Shim

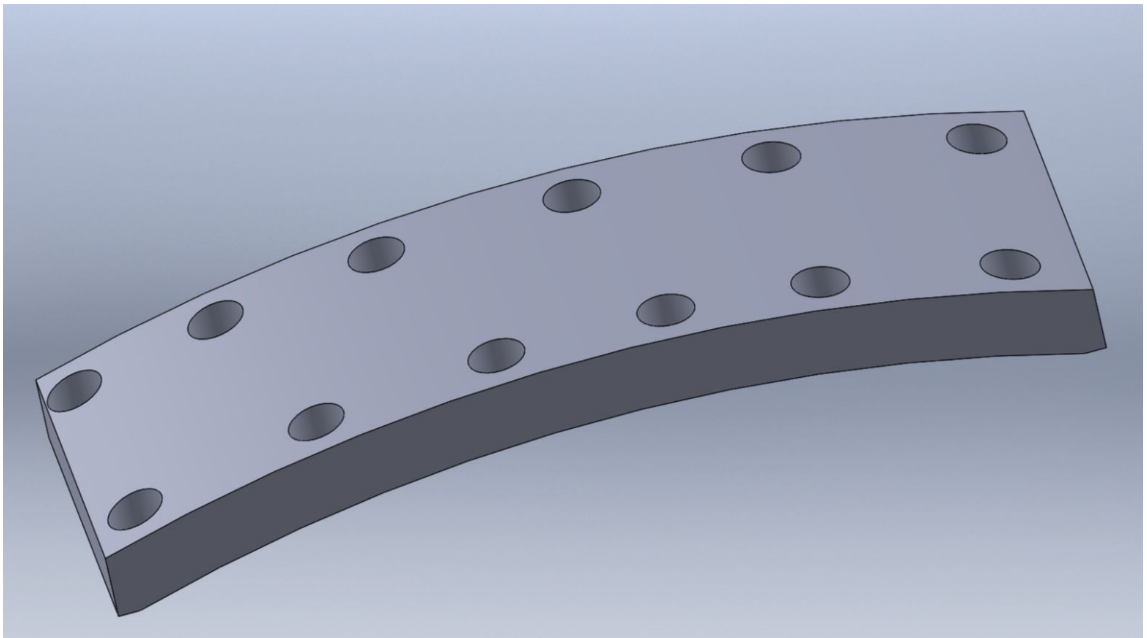

Figure 11: Bottom Plate

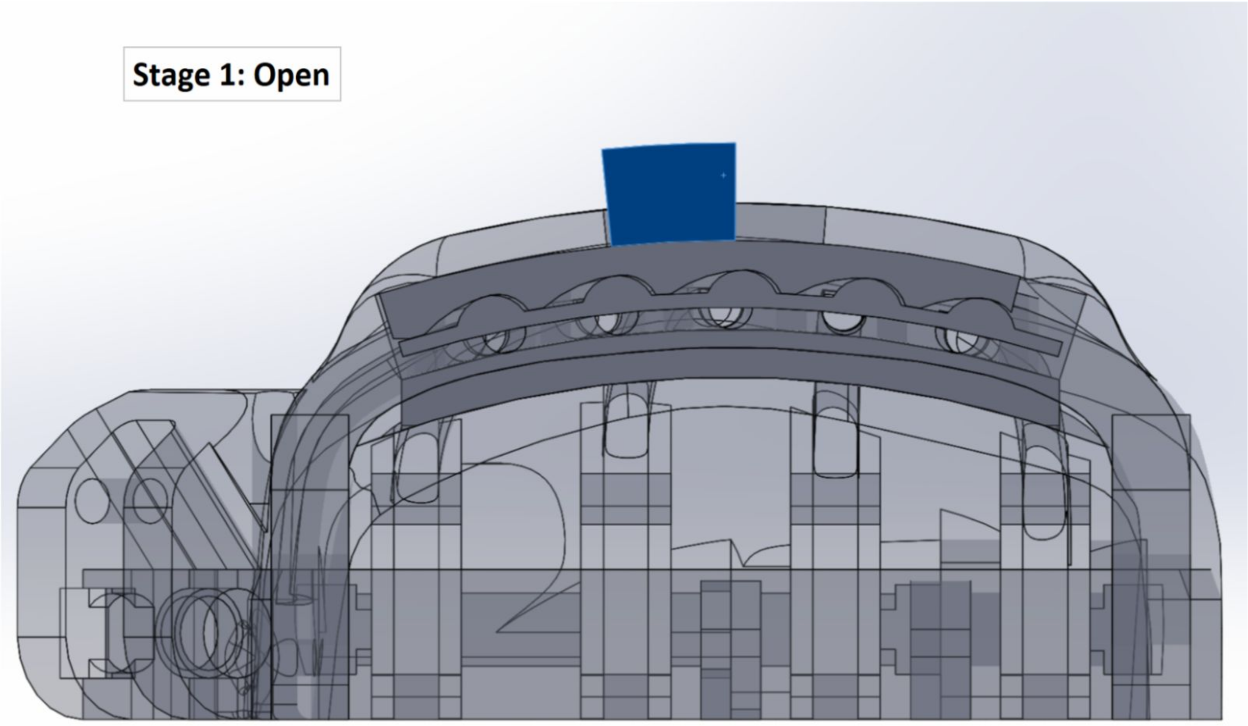

Figure 12: Grip Locking Mechanism open

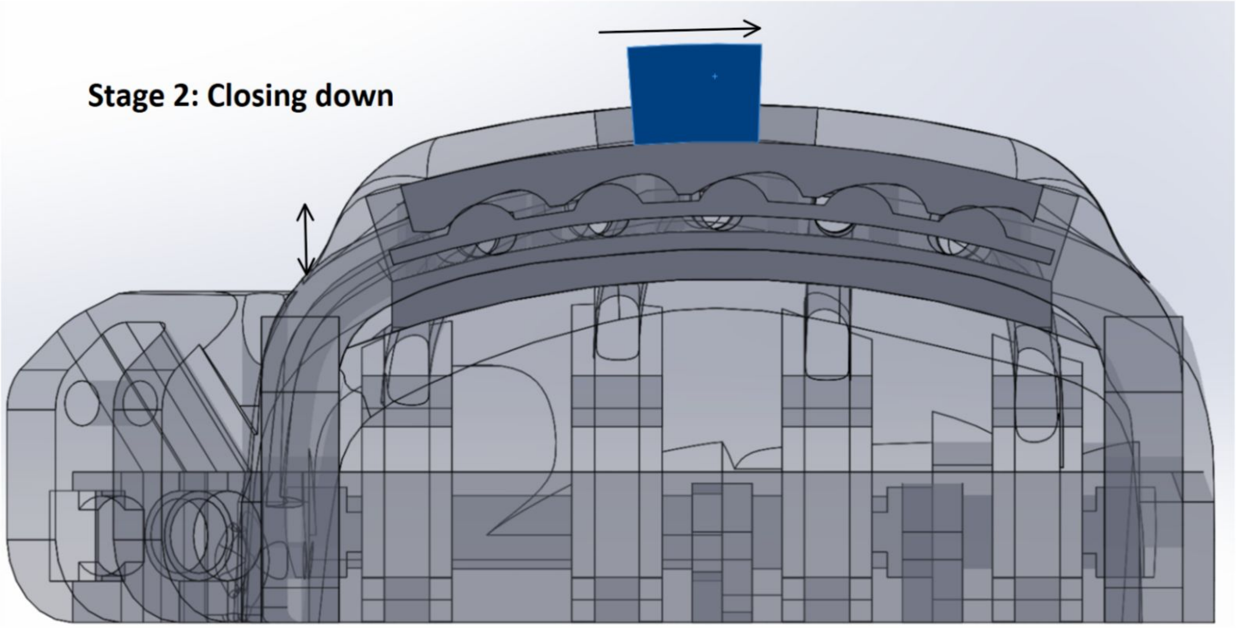

Figure 13: Grip locking mechanism active

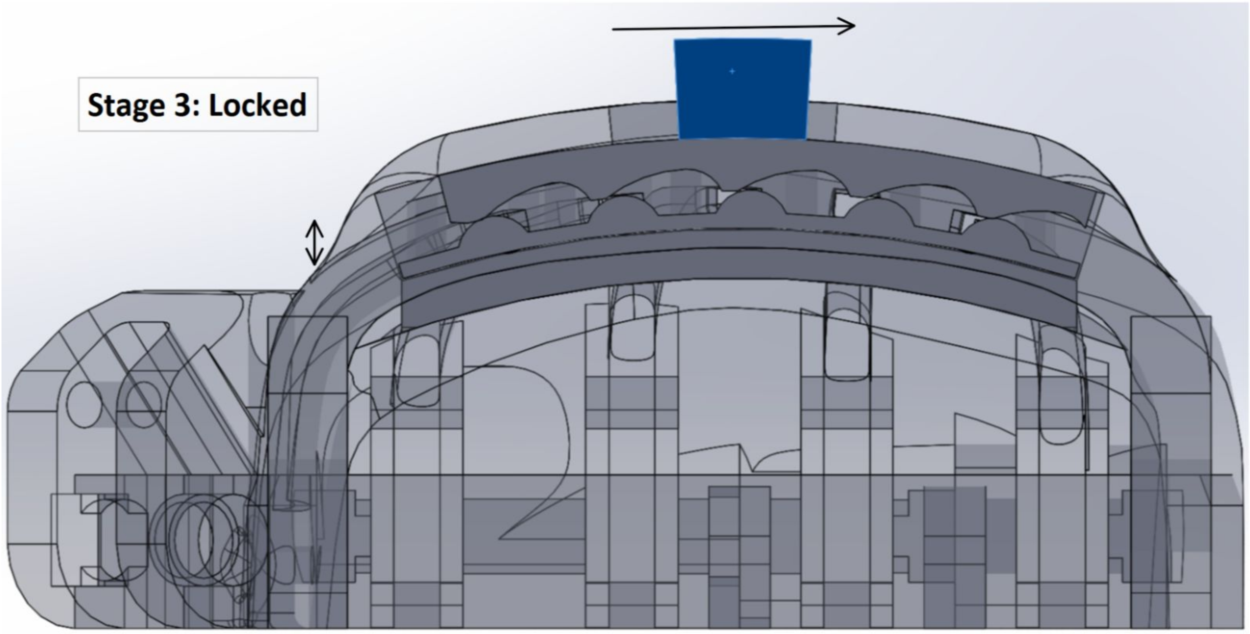

Figure 14: Grip locking mechanism locked

Table 1: Grip Precision Test 1 - Stacking Washers
(Modified Prosthetic Hand [w/ thumb and index finger active])

	Washers moved from A to B	Washers Dropped	Washers failed to pick up
Trial 1	10	2	3
Trial 2	8	4	3
Trial 3	8	4	3
Trial 4	10	2	3
Trial 5	11	1	3

Table 2: Grip Precision Test 1 - Stacking Washers
(Standard Prosthetic Hand)

	Washers moved from A to B	Washers Dropped	Washers failed to pick up
Trial 1	9	3	3
Trial 2	10	2	3
Trial 3	10	2	3

Trial 4	9	3	3
Trial 5	8	4	3

Table 3: Grip Precision Test 2 - Patterned Button Pressing
(Standard Prosthetic Hand)

	Correct Input	Incorrect Input
Trial 1	3	11
Trial 2	6	8
Trial 3	4	10

Table 4: Grip Precision Test 2 - Patterned Button Pressing
(Modified Prosthetic Hand [w/ thumb and index finger active])

	Correct Input	Incorrect Input
Trial 1	13	1
Trial 2	14	0
Trial 3	14	0

Table 5: Grip strength Test - Weighted Rod
(Standard Prosthetic Hand [w/o silicone fingertips])

	Weight when slippage began	Weight when full slippage occurred
Trial 1	550 g	550 g
Trial 2	500 g	500 g
Trial 3	490 g	490 g
Trial 4	700 g	700 g
Trial 5	600 g	600 g

Table 6: Grip strength Test - Weighted Rod
(Modified Prosthetic Hand [w/ silicone fingertips])

	Weight when slippage began	Weight when full slippage occurred
Trial 1	1600 g	
Trial 2	1464 g	
Trial 3	1565 g	
Trial 4	1500 g	2240 g
Trial 5	1565 g	

Table 7: Bill of Materials

Item	**Quantity**	**Price**
PLA	1 roll (~333m)	$25.00
Braided fishing wire	1 roll (137m)	$10.72
Nylon String	1 roll (~91m)	$7.79
Springs	12-pk	$ 5.43
Sheet metal screws #6 x 3/8	16-pk	$ 1.18
Total Cost: $50.12		

Table 8: Estimated Cost to Produce our Prosthetic Hand Breakdown of Materials Used

Material Used	**Quantity Used**	**Unit Cost**	**Total Price of Material Used**
PLA	~17.2m	$0.075/m	$1.29
Braided fishing wire	~3.66m	$0.078/m	$0.29

Nylon String	~1.83m	$0.086/m	$0.16
Sheet metal screws	5 screws	$0.074/screw	$0.37
springs	5 springs	$0.452/spring	$2.26
Estimated Total Cost to Produce our Prosthetic Hand: $4.37			