Mechanical Prosthetic Hand for Navy SEAL

Final Project Report

Cal Poly San Luis Obispo

Sponsor: Quality of Life Plus

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June 8th, 2015

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Statement of Disclaimer

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Executive Summary

Quality of Life Plus has been improving the lives of many wounded servicemen and first responders around the country. Its mission is to foster and generate innovations to aid and improve the quality of life for those injured in the line of duty. This project is the fifth iteration of designing a prosthetic hand for an active duty Navy SEAL. The first iterations have been myoelectric systems where sensors are attached to the user's muscles to actuate the prosthetic. However, the most recent has been a purely mechanical system, and was shoulder actuated. The design was more robust, it was lightweight compared to the first iterations, and it is also waterproof. This project is made out of Titanium 6AL-4V, which offers a great strength-to-weight ratio, is robust, reliable and easy to assemble.

This project took a different avenue of approach when manufacturing the prosthetic hand. The vast majority of the hand was 3D-printed using the latest technology of direct metal laser sintering. The material chosen for this device is Ti 6-4, where it was printed and donated by Lawrence Livermore National Laboratory located in Livermore, CA. Most of the hardware was made out of stainless steel and was purchased from McMaster Carr, and the Sure-Lok was obtained from a previous iteration. The prosthetic hand will include shock cord, non-flexible cable to withstand up to 200 lbs. per finger and a break cable that will interlock the fingers, palm and gantlet sub systems of the prosthetic. The device will also include a silicon sleeve with an embedded plate that will attach to the palm. The sleeve will attach via suction to the users residual and has been proven to work as he currently uses a similar device with a purely aesthetic hand.

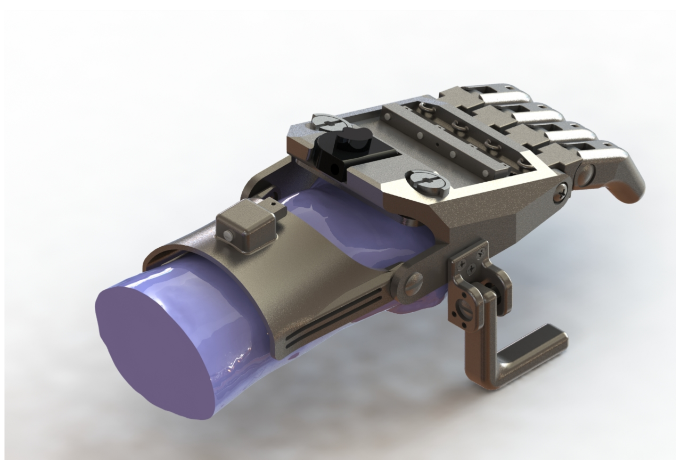

Figure 1: CAD model of the prosthetic hand.

This prosthetic was designed by analyzing the Raptor Hand created by e-Nable, an organization that helps small children by creating prosthetic hands that can be easily printed and assembled. In order to actuate our prosthetic, the user will need sufficient wrist movement and strength for proper function. Since our client has full mobility of his wrist, this will be the best method. The prosthetic uses a Sure-Lok to allow the user to maintain a grip without applying any excess force. The non-flexible cable will maintain a tension that will allow the user to grip and hold heavy items over a long period of time.

Once the Sure-Lok is not active, the flexible cord will spring the fingers back into the initial position. The thumb is not connected to any cables and is spring loaded to allow the user to manually place the thumb in three different positions.

During the initial inspection of the titanium parts received, the team noticed that the support material was still intact and needed to be removed. This will delay the assembly and testing of the titanium prototype. The support material will be removed via Electric Discharge Machining (EDM), which is a controlled process that is used to remove metal by electric spark erosion. The electric spark is used as the cutting tool to erode the work piece to the desired surface finish. Once completed, the hand will be assembled and tested and will be sent to the client's prosthetist to implement the silicon sleeve.

Figure 2: Final Prototype (not included are finger base and hardware)

Furthermore, our donor has agreed to reprint the prosthetic to allow any improvements of the design. This will be done towards the end of the summer. Several of our team members will remain in contact with the sponsor and LLNL to oversee the completion of this design.

Special Thanks

Quality of Life Plus, Lawrence Livermore National Labs, Aesthetic Prosthetics, Jon Monett, Scott Monett, Dr. Peter Schuster, Dr. Xuan Wang, BMED Department, Dr. Lily Laiho, David Laiho, Innovation Sandbox, Team Manus, Dom Doty, and Kelsey Dodge.

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1.0 Introduction

Prosthetic devices are designed to add functionality to the user's amputated limb, helping to restore some of the capabilities that the user previously had. The prosthetic industry is growing rapidly due to the advancement of electronics used in biomechanical devices; however, as prosthetic technologies advance, the devices become increasingly complex and expensive, increasing the difficulty of designing a robust product that provides simple functionality with limited hassle.

The goal of this project is to design a robust, mechanically actuated, open-source prosthetic hand that will enable an active Navy SEAL to increase his mobility. By June 2015, our Navy SEAL client will have an operating prosthetic that will attach to his residual, allow for an open and closed grip to be achieved and held firmly, and allow full, free, and comfortable movement of his arm and wrist.

This project also serves as a culminating capstone senior project in partial fulfillment of our undergraduate mechanical engineering degrees from California Polytechnic State University, San Luis Obispo.

Our supporter and sponsor is Quality of Life Plus (QL+), a 501(c)(3) not-for-profit organization whose mission is to foster and generate innovations to aid and improve the quality of life of those injured in the line of duty ("Introducing"). We will be interacting with Dr. Lily Laiho, Director of Interdisciplinary Projects, and Scott Monett, Executive Director and President of QL+. Though QL+ is the sponsor, this project is dedicated to an active-duty Navy SEAL who has continued to serve our country despite the loss of his hand in a training accident. It is an honor for us to spend this year creating a prosthetic hand; we hope to provide him with a reliable, durable, versatile hand in gratitude for his sacrifice in serving for our country.

2.0 Background

Extensive background research has been done on existing solutions and previous projects in order to gain insight into the design of a prosthetic hand that effectively replicates a human hand's functionality. Replication of the exact motion of a hand is nearly impossible; however, there are several prosthetics on the market that can drastically increase the abilities of the user.

The two main types of prosthetic hands are myoelectric, motor-powered prosthetics and cable-controlled, body-powered prosthetics ("Amputee Prosthetics", 2012). The most advanced and complicated are the myoelectric control systems since they use sensor pads that monitor the existing nerves in the arm to actuate motors that articulate the fingers movements. The problem with these designs is that they tend to be heavy, easily damaged, and contain overly-sensitive sensors that actuate the motors unintentionally.

The most common prosthetic is the body-powered prosthesis. Force is typically transmitted to the prosthesis through a cable system. The cable can be attached in different ways; one of the most common methods is to have the cable run from the prosthesis up the arm and across the back of the shoulders to a loop around the opposite shoulder ("Pursley"). Other methods feature a cable system that attaches to the wrist. With body-powered prostheses, the user has more control of when to actuate the hand because the body powered devices can be actuated in many different ways, including shrugging of the shoulders, flexion of the wrist, and abduction the shoulders.

There are two main types of body-powered prostheses: passive closed and passive open (Bolduc, James, et al, 2013). Passive closed devices are closed by default until the cable is tensioned, which opens the device. Passive open devices are open by default until tension is applied to the cable, which actuates the device to close. Our client has expressed interest in a passive open design.

2.1 Existing Products

Much of our research focused on analyzing what current prosthetics exist. Product categories emphasized in our research are open-source prosthetics, professional grade prosthetics, and past senior project iterations. A table summarizing our findings can be found at the end of this section, in Table 1.

2.1.1 Open-Source Prosthetics

Several open-source prosthetic hands currently exist and are proven to be useful. However, none of these hands are well-suited for military conditions. Open-source prosthetics are usually 3D printed so that anyone with access to a 3D printer can easily replicate the design. A common 3D printing method, Fused Deposition Modeling (FDM), and the materials used therein (ABS, PLA, etc.), result in part failure due to low strength and micro-fracturing caused by the layering process, where filament or wire is unwound to make a part. For the existing open-source products, there is little to no information regarding stress on the fingers or the maximum allowable load for the hand, for example. The open source prosthetic community is vibrant, with many designs and strong interest; however, there is a tremendous need for an engineering team to re-evaluate these designs to increase their durability and functionality.

One of the most common of the open-source prosthetic devices is the Raptor Hand, a project organized by e-Nabling The Future. It is a below-the-elbow prosthesis used for people with wrist mobility. It is actuated by flexion of the wrist, which creates a change in tension in strings, actuating a closing motion of the fingers and thumb as the tension is increased ("The Raptor Hand", 2014). The assembled hand is shown below in Figure 3.

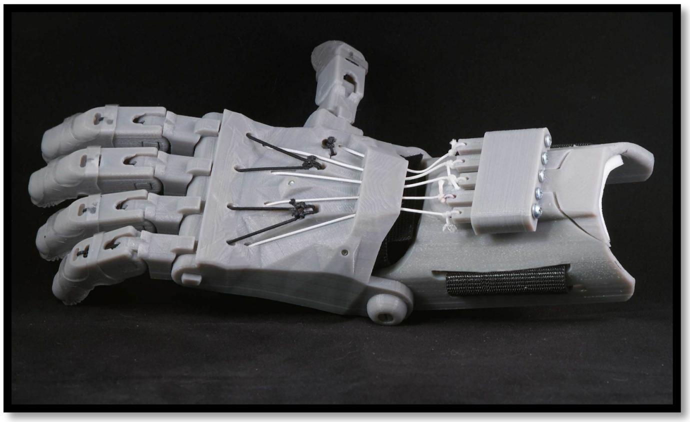


Figure 3: The Raptor Hand, a 3D-printed, wrist-actuated prosthetic hand from e-Nabling The Future ("Raptor Hand", 2014).

The Raptor Hand is fully mechanically actuated, meaning it can be used in water and contains no electronics. The assembly of the Raptor is simple, with the main mechanical components being 3D printed snap pins and elastic string, made from a material similar to that used in elastic waistbands. An exploded view of the Raptor Hand is shown below in Figure 4.

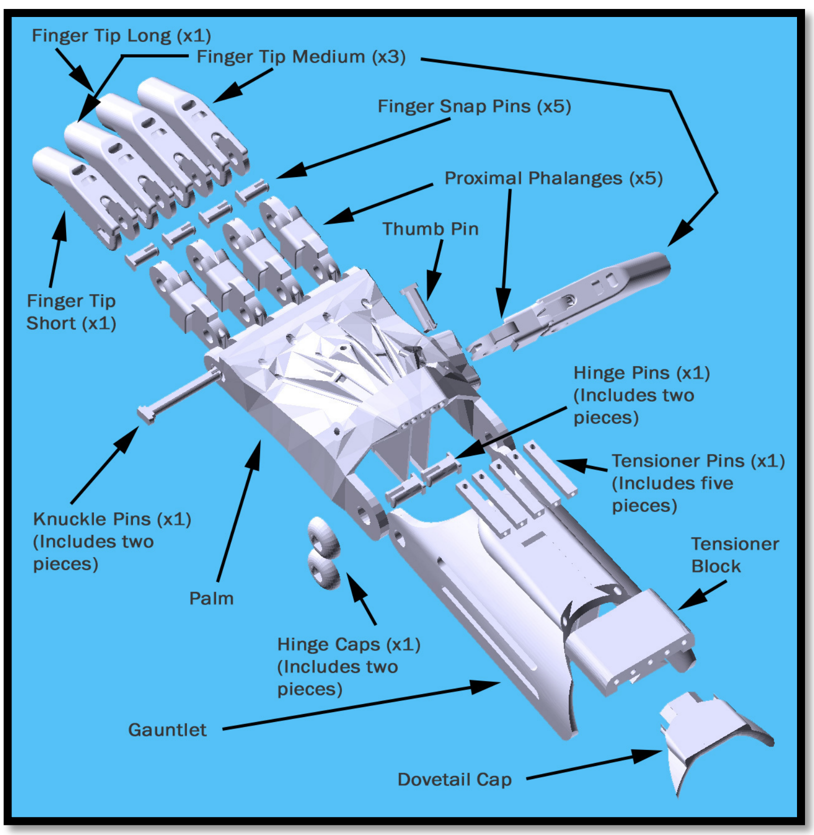


Figure 4: An exploded view of the Raptor Hand, a 3D-printed, wrist-actuated prosthetic hand from e-Nabling The Future ("Raptor Hand").

The simplicity of the device makes it easy to repair. Once assembled, the Raptor is secured to the arm with Velcro straps fixed to the gauntlet, as seen in Figure 4. The grasp of the Raptor does not extend far, limiting the usefulness of this hand in grasping large objects. The grasp, once achieved, can only be held so long as the user maintains flexion, or bending in his/her wrist; this is a significant disadvantage, meaning the user will not be able to hold objects of any weight for a long time.

Another disadvantage to this design is the weakness of small parts made with the FDM process. Thin parts like the tensioner pins and finger snaps will bend and are prone to permanent deformation, or even complete breakage. Parts made with a 3D printing process can be made stronger by choosing a process such as Selective Laser Sintering (SLS), which produces stronger parts since the powdered plastics are lasered together instead of layered together. With SLS, the plastic is fused together more strongly than in a layering process such as FDM. Another way to overcome the weak, small 3D printed parts is to replace them with off the shelf parts made from a metal or injection molded plastic. Overall, the Raptor is a great candidate as a design foundation upon which a more robust prosthetic can be designed and built.

Another example of an open-source prosthetic hand that is currently being used by many people is the wrist-actuated, 3D-printed Cyborg Beast hand, also from e-Nabling The Future, pictured below in Figure 5. This design is very similar to the Raptor, as it features cables running from the base of the hand to each individual finger; when the user tilts his/her wrist down, these cables are tensioned and the fingers are pulled down to a closed-hand grasping position (“Cyborg Beast” 2014).

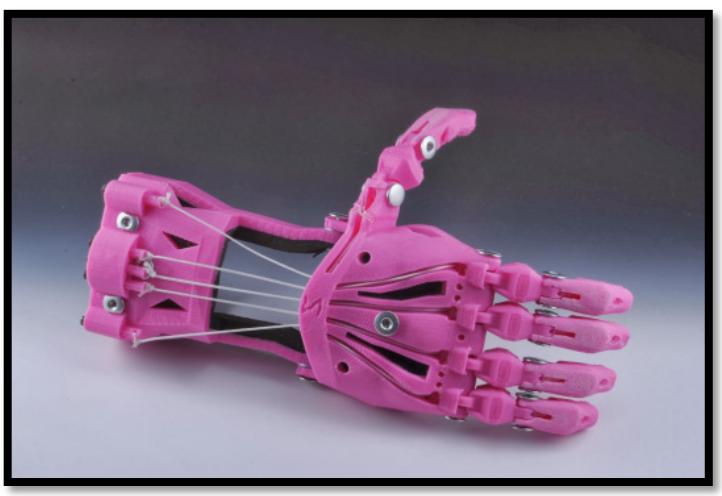


Figure 5: The Cyborg Beast, a 3D-printed, wrist-actuated prosthetic hand from e-Nabling The Future (“Cyborg Beast”, 2014).

The Cyborg Beast is simple and effective at lightweight tasks such as grabbing and handling small objects and performing tasks such as eating with a utensil. However, this hand does not meet our customer’s needs, as it is not strong enough to withstand more demanding military activities. Moreover, all fingers on this prosthetic, including the thumb, close in

unison as the cables are tensioned. This limits the variety of tasks the user can perform with the hand. The fingers also are not able to be locked into a closed-grip position, which means that the maximum weight of an object that is able to be carried with the hand is limited by the wrist strength of the user in keeping the cables tensioned ("Cyborg Beast", 2014). Despite these inadequacies, this product provides insight into the basic functionality of 3D-printed prosthetic hands; it also serves as a simple platform upon which our team will be able to add new features and functionality.

2.1.2 Professional Grade Prosthetics

A top professional-grade prosthetic on the market is the i-Limb Ultra, which is produced by Touch Bionics. It appears and functions similar to a human hand, and its motorized digits allow the fingers to naturally wrap around objects ("i-Limb"). i-Limb Ultra uses a myoelectric system that manually rotates the thumb into different positions, allowing for up to 14 automated grips and gestures. The pulsing and vari-grip feature lets the user vary the grip strength of an object. In addition, it has auto-grasp built-in to inhibit objects from slipping.

The i-Limb Ultra has a maximum load limit of 198 lbs, while the load limit per finger is 71 lb. The device takes 1.2 seconds to fully go from open to closed positions, and it weighs about 1 lb without the battery (Bolduc, James, et al, 2013). Since it is a myoelectric prosthetic, the i-Limb Ultra is not waterproof, and requires recharging every seven to eight hours. Many users of this product have experienced sensitivity issues, as the device can pick up electrical signals that cause the hand to move inadvertently.

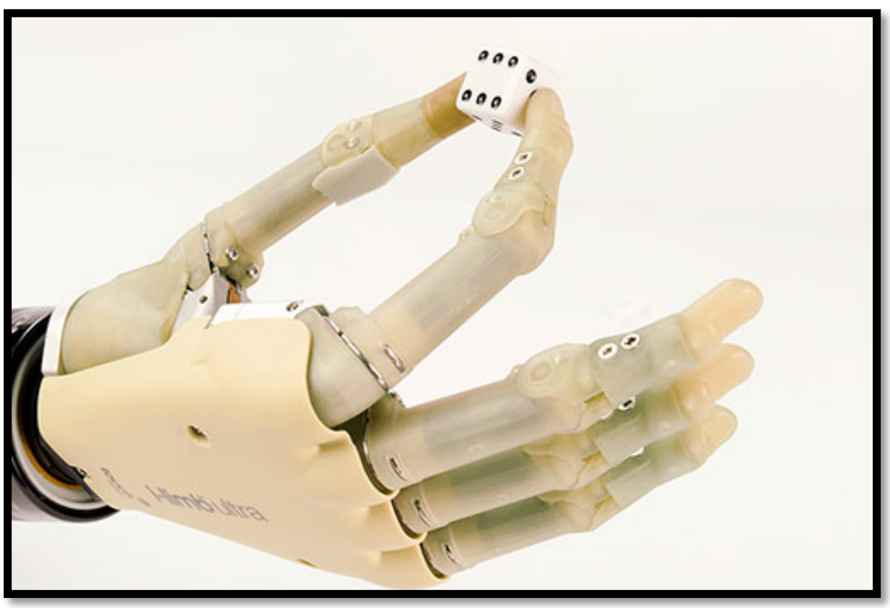


Figure 6: The i-Limb Ultra, a natural-looking prosthetic hand with motorized digits from Touch Bionics ("I-limb Ultra").

2.1.3 Current Solution

The solution that our customer currently uses is a fixed-hook strapped to a leather forearm brace, pictured below in Figure 7.

Figure 7: Fixed-hook prosthetic currently used by customer (Bolduc, James, et al, 2013).

This product is extremely simple, lightweight, durable, and reliable; however, it is also very limited in its functionality. In Figure 7, the user is shown using his hook pressed up against his residual to hold a magazine of ammunition (Bolduc, James, et al, 2013). To replace this simple design is difficult; we must design a hand that is as effective or better in every way at the tasks for which this current solution is used, while adding new functionality that will allow our customer to perform many new tasks. This fixed-hook design will therefore serve as a benchmark against which we will compare our final solution to ensure we are providing the customer with a product that meets and exceeds his needs.

2.1.4 Past Iterations

Several senior project teams at Cal Poly San Luis Obispo have designed products for previous iterations of this project. Although these projects had different customer requirements, the resulting designs can be built upon to meet the customer's current needs.

The last iteration of the Navy SEAL prosthetic hand, done by Team Manus, consisted of a more robust design than previous projects. The majority of the parts are made out of high-grade 7075 Aluminum, the cable connectors are made out of grade 5 titanium, and the cover is made out of carbon fiber (Bolduc, James, et al, 2013). The finger routing cable is made out of 200 lb test fishing line. Team Manus' design featured a two-member finger design to reduce possible breakage points. The base finger member contained two internal

compression springs, which enabled the hand to feature a default passive-open position. A fixed cable was attached to the base finger member to provide smooth motion.

The thumb system was designed to ensure that the thumb could be positioned so that when the fingers were in the closed position, the index finger and thumb would meet. This would allow for the hand to pick up smaller items if needed. The thumb system was designed to have a thumb, a spring detent, an indented pin, and a base (Bolduc, James, et al, 2013). In order to allow the thumb to be moved and snapped into different positions, the spring detent and indented pin work in cohesion. An advantage to this design is that it allows the user to move the thumb out of the way of the other fingers if needed.

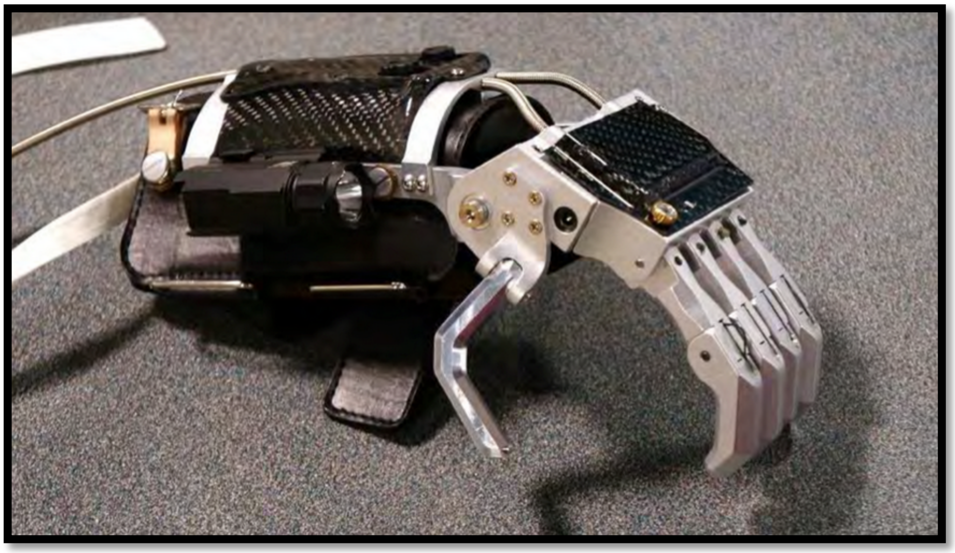


Figure 8: Complete assembly of Team Manus Hand (Bolduc, James, et al, 2013).

Using a single press fit pin allowed the fingers to connect to the finger mount, which was one solid piece that connected to the forearm cuff. The forearm cuff and the forearm base plate were connected through a bushing hinge. It was important to have the forearm base be as comfortable as possible for the user. Therefore, this iteration consisted of a forearm attachment with three layers: leather, aluminum, and a carbon fiber cover. At the time of the client fitting, the client requested changes on the forearm base. He requested a silicon sleeve to improve the conformability to avoid the base digging into his forearm.

In order to actuate the prosthetic hand, a shoulder-driven single pull-cable was used, as seen in Figure 10. This will allow the user to close the fingers with shoulder movement, which generates more power than wrist movements. The cable was attached to the user using a harness, which is one of the most common activation systems for prosthetic hands.

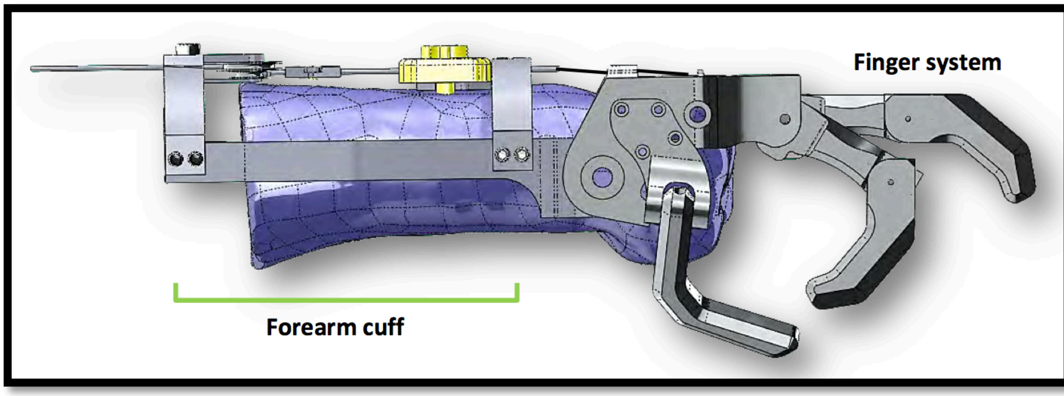


Figure 9: Side view of Team Manus design (Bolduc, James, et al, 2013).

As seen in Figure 10 below, Team Manus' cable routing system began at the harness and traveled down the arm connecting to the prosthetic hand. The cable passes through a stainless steel housing, which is connected to the bicep and elbow joint, and ends in a cable reduction system.

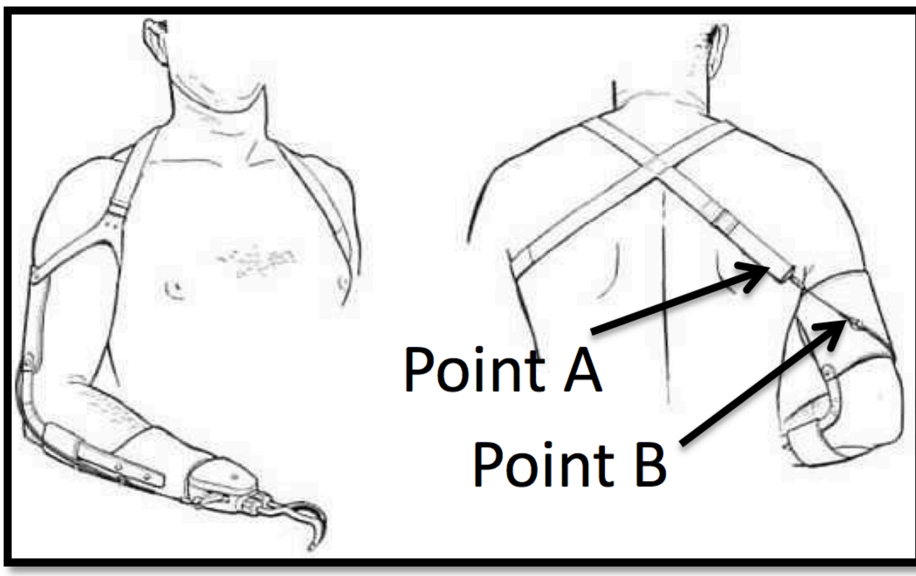


Figure 10: Shoulder harness of Manus Hand (Bolduc, James, et al, 2013).

Two other previous senior project teams created the Polygrasp and Polygrasp 2.0 prosthetic hands, which are pictured below in Figures 11 and 12.

Figure 11: Polygrasp hand created by previous senior project team at Cal Poly SLO (Bolduc, James, et al, 2013).

Figure 12: Polygrasp 2.0 hand: a fully mechanical, wrist-actuated solution that proved inadequate due to limited grip strength (Bolduc, James, et al, 2013).

The first Polygrasp design was myoelectric, featuring electronic sensors, batteries, and motors to operate the hand. This design proved light and dexterous, but the overall strength of the hand was low, the battery life was low, and the product was not very weatherproof; therefore, this was an inadequate solution.

Polygrasp 2.0 was fully mechanically and wrist-actuated, which meant that the grip strength was very limited, since the gripping force had to be generated entirely from wrist motion. This product was able to pick up and handle various objects, but the low grip strength and difficult operation made this solution inadequate for the customer.

2.2 Summary Table

The existing products we researched are summarized below in Table 1, weighing the pros and cons of each.

Table 1: Pros and cons for each existing product discussed in this paper.

							
	The Raptor Hand	**Cyborg Beast**	**I-Limb**	**Fixed Hook**	**Team Manus**	**Polygrasp**	**Polygrasp 2.0**
Pros	Simple, light, waterproof	Simple, light, replaceable	Realistic hand motion,	Simple, durable, low cost	Strong, durable, fully mechanical	Light, dexterous	Simple, light
Cons	Weak, all fingers move together, low grip strength	Weak, all fingers move together, low grip strength	Battery, expensive, overly sensitive	Not versatile	Machining, weight,	Not wearable, heavy, battery	Low grip strength , difficult to operate

2.3 Rapid Prototyping

Rapid Prototyping is a method of creating a model of a part or assembly using three-dimensional computer aided design (CAD) data. There are several techniques used in today's market that will produce a part quickly to allow the designer to visualize its design and make any improvements.

2.3.1 Selective Laser Sintering

Selective Laser Sintering (SLS) an additive rapid manufacturing process that consists of fine polymeric powder like polystyrene and polycarbonate. The material is spread on the surface using a roller, and just before the laser begins, the temperature is raised right below the melting point of the material by infrared heating in order to minimize thermal distortion (Chua, et al, 2000). By following this process, the fusion from layer to layer increases, and only grains in direct contact with the beam are affected. Once one layer is complete, the bed is lowered and the powder feed chamber is raised to allow a new layer of powder to be spread evenly over the build area. This process does not require support structures because the unsintered powder remains at the location where support is needed. Once the part is removed from the powder, the remaining powder is clean off and can be recycled. A similar process, Direct Metal Laser Sintering (DMLS), uses metal powders like titanium and aluminum, which provide even more strength if needed for rapid prototyped parts, and is described in further detail in the Final Design chapter.

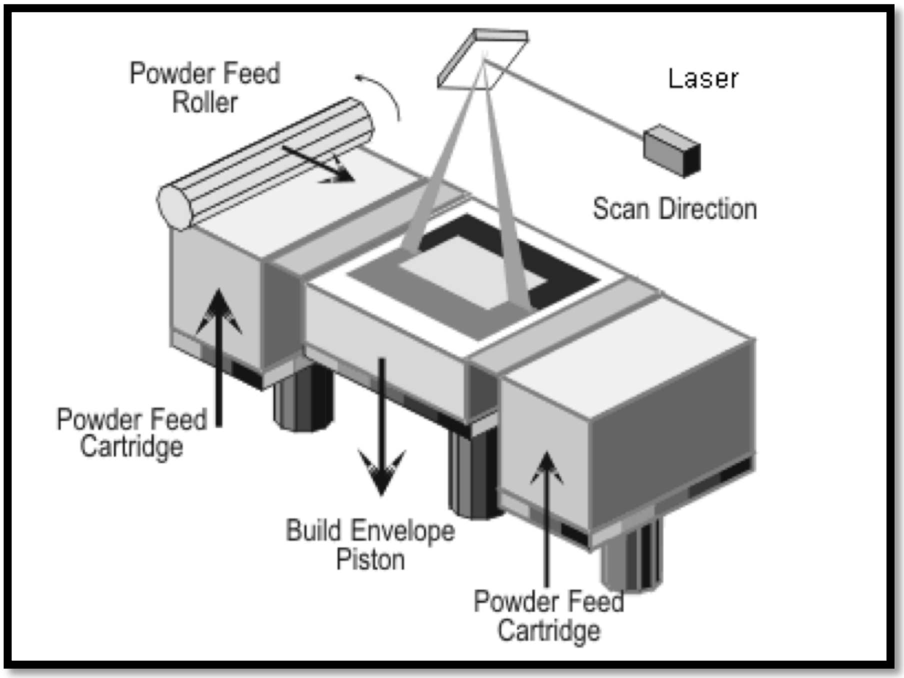


Figure 13: Selective Laser Sintering system (SLS) (Chua, et al, 2000).

2.3.2 Fused Deposition Modeling

In the Fused Deposition Modeling (FDM) process, a nozzle is able to move in the x and y directions as it deposits threads of molten polymeric material. The material is heated slightly above its melting temperature so that it solidifies moments after extrusion and cold-welds to the previous layer (Thrimurthullu, et al, 2004). Cold-welding is the process of joining two metal surfaces without heat, which forces the two layers together so that the oxide films are broken. There are several important factors to be considered using this process, which are steady nozzle and material extrusion rates, supporting structures for overhanging features, and the required nozzle head speed, which affects the layer thickness. The most recent FDM systems include two nozzles, one for part material, and another for support material. Also, water-soluble support structure materials are commonly used and can be deposited with lower densities by having air gaps between two layers.

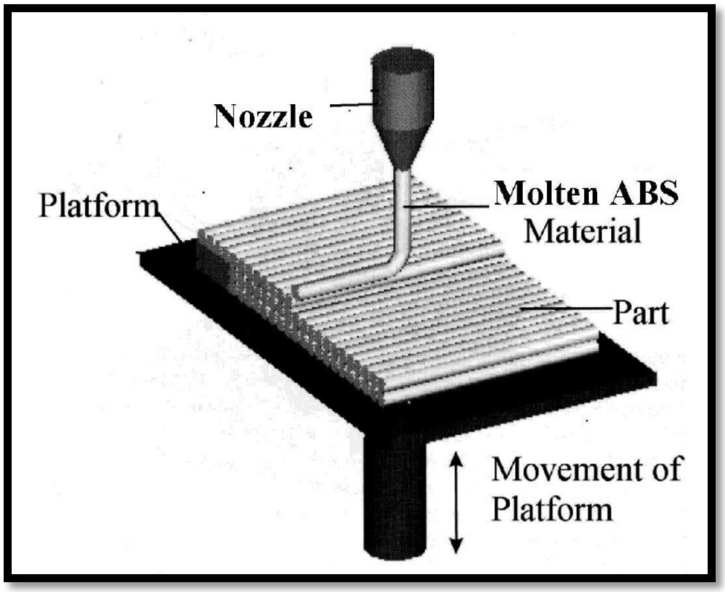


Figure 14: Fused Deposition Modeling system (FDM) (Thrimurthullu, et al, 2004).

2.3.3 Laminated Object Manufacturing

Laminated Object Manufacturing (LOM) is a process that uses a CO_2 laser to create consecutive passes of a 3D object from layers of paper with a polyethylene coating. The first step is to place a special tape down onto the platform, which is followed by a sheet of paper being fed through with the support of small rollers (Chua, et al, 2000). Next, a heated roller is used to melt the coating on the paper to allow each new layer to adhere to the previous layer. The laser then cuts the pattern into the top layer of paper, which allows the shape of the part to take form. This allows a boarder to be created around the part, which allows it to stay intact. After the border has been cut out, the laser creates hatch marks, or cubes within the border, which acts as supports to inhibit movement throughout the build.

Once the part is complete, a wire is used to cut the material from the metal platform. The part can then be removed from its border and supports. The supports can either be removed by shaking the part, or chisels might be used for certain parts. In order to prevent the part from falling apart, it is sanded and coated with lacquer to prevent any damage. The LOM process is very useful for manufacturing large parts rapidly.

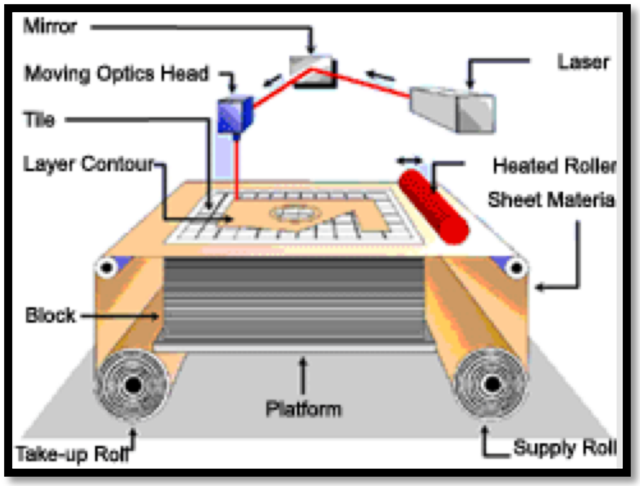


Figure 15: Laminated Object Manufacturing system (Chua, et al, 2000).

2.3.4 Stereolithography

Stereolithography (SLA) is considered the pioneer of the Rapid Prototyping industry; it was introduced in the late 1980's. The system consists of an ultra-violet laser, a vat of photo-curable liquid resin, and a controlling system (Williams, et al, 1996). The system lowers a platform into the resin, such that the distance lowered is a layer-thickness below the surface of the resin. Once the platform is in place, the laser beam traces the outline and fills in a two-dimensional cross section of the part, crystalizing the resin wherever it makes contact (Williams, et al, 1996). After a layer is complete, the platform lowers the same distance each time and proceeds with the next layer until the model is complete. The model is then removed and the excess resin is washed off and then placed in a UV oven for a final curing.

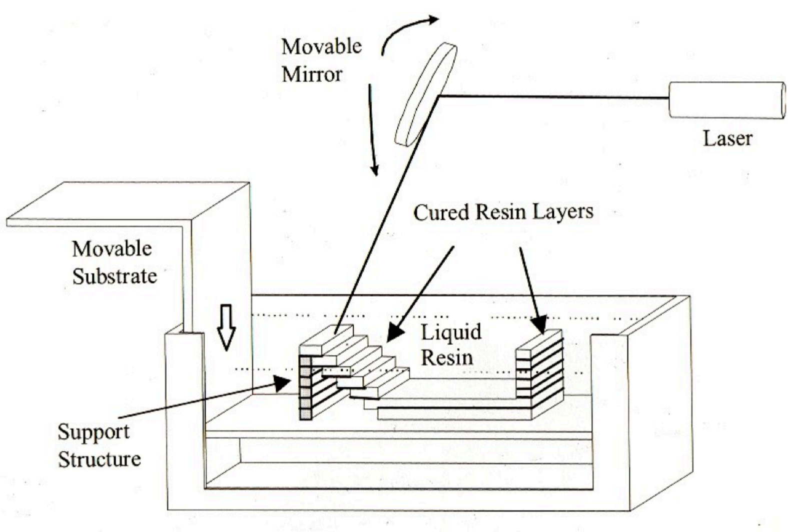


Figure 16: Stereolithography system (Williams, et al, 1996).

2.4 Metal Plating

Metal plating is one of the more common methods of increasing the strength of printed/machined parts of different materials. There are various different methods of metal plating; these are described in the following subsections.

2.4.1 Metal Plating of 3D-Printed Parts

Electroplating on plastic is a difficult technique due to the non-conducting surfaces, usually resulting in poor quality. However, the implementation of chemical processes for the surface preparation of acrylonitrile butadiene styrene (ABS) (Parkinson, et al, 1999) allowed good bonding between the plastic surface and the metallic coating. Plating on plastics has been improved in recent years and is an integral part of the manufacturing of automotive components. Most Nickel consumed in the plating of plastics is used for bright and decorative finishes, while only a small percentage is used for engineering applications. Polyimides are also a good selection for high performance materials with great mechanical properties, which are commonly required in rugged engineering applications (Parkinson, et al, 1999).

2.4.2 Electrodeposited/Electroplating

Electroplating (also known as electrodepositing) is used to modify the surface properties of a material by introducing a metal coating via electric current. An object is immersed into a solution that contains salt, which is positively charged and attracts to the object (Osaka, et al, 1995). The shape of the object also matters when immersing because the current flows more densely to prominent areas than to areas with minimal access. Therefore, the prominent areas will have thicker deposits and may affect the overall thickness of the layer.

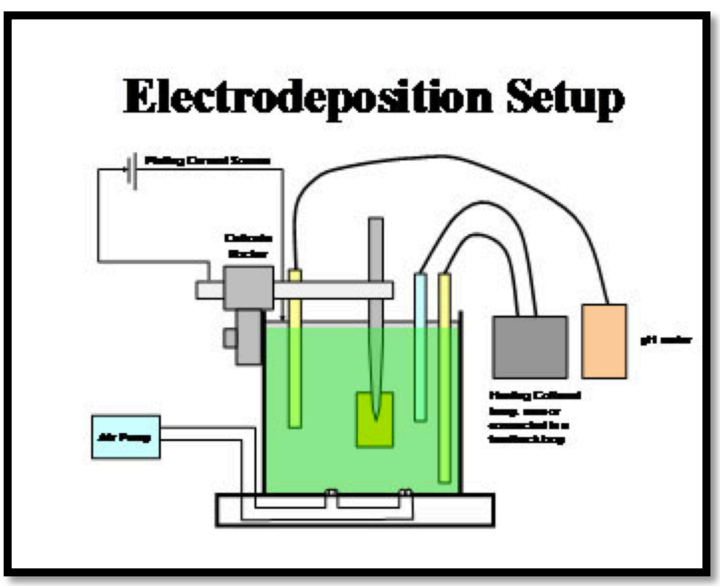


Figure 17: Diagram of electrodeposition process of metal plating metal parts (Osaka, et al, 1995).

There are many different materials that can be used in electroplating, for example, aluminum, brass, bronze, cadmium, copper, chromium, iron, lead, nickel and some precious metals such as gold, platinum, and silver. In addition, several different types of coatings can be achieved by controlling the voltage, amperage, temperature and the purity of the bath solutions (Osaka, et al, 1995). This process is inexpensive and simple and it is used in all aspect of optics, electronics and the automobile industry. For example, in the automobile industry, chrome plating is extensively used to enhance the corrosion resistance of many metal parts.

2.4.3 Electroless Nickel

Electroless nickel plating is a method that does not require electricity. This process is purely chemical and it's achieved through metal ion exchange using chemical reduction in a hot aqueous solution (Ridel, et al, 1991). Until electrodeposited, this method does not build up on corners. The thickness of the layer is uniform over the entire surface regardless of its shape. However, in order to use this method, the objects have to be heat-treated, and each material may have a different pre-heated process (Ridel, et al, 1991). An advantage for using this process is its excellent wear and corrosion resistance and for its ability to provide a uniform layer.

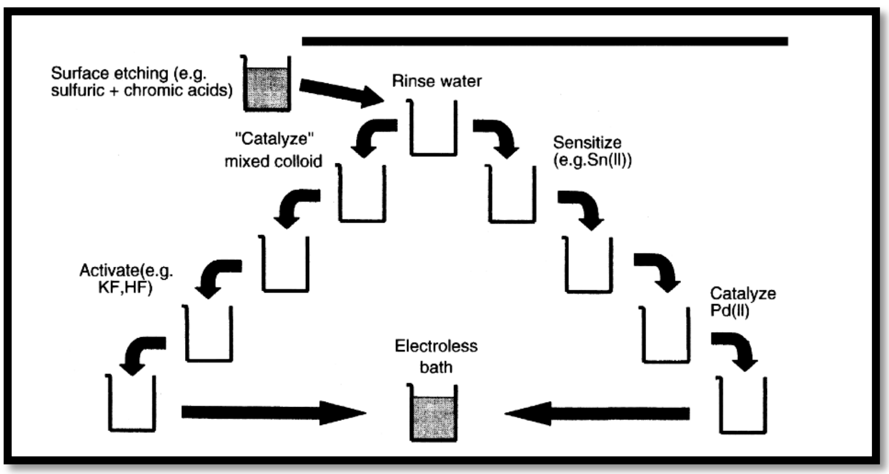


Figure 18: Schematic representation of the electroless deposition process (Ridel, et al, 1991).

2.4.4 Carburizing / Carbonizing

Carburizing is a process in when carbon is introduced to the surface layer of steel with low carbon content. The components need to be heated in a liquid or gaseous carbon-containing solution (Khusid, et al, 1983). The penetration of carbon into the surface of the object is controlled by time and temperature. There are many objects that can be carburized, but one must keep in mind the uniformity of the material. If there are different cross sections in the part, the cooling rate may vary, which can cause excessive stresses that can lead to failure (Khusid, et al, 1983). After the process is complete, the object is

either slow-cooled or quenched directly. The change in material properties include increased surface harness, increased wear resistance, and increased fatigue/tensile strengths.

2.4.5 Plasma Spray Coating

Plasma spray is a process where a high-speed flame is used to produce a dense, high-quality, machinable coating. Powders are injected into the plasma flow to melt the material (Fauchais, et al, 2004). One of the most common gases used in this process is argon. This process works by flowing argon between the electrode and nozzle, which is struck by a high voltage alternating electric arc, thus ionizing the gas stream.

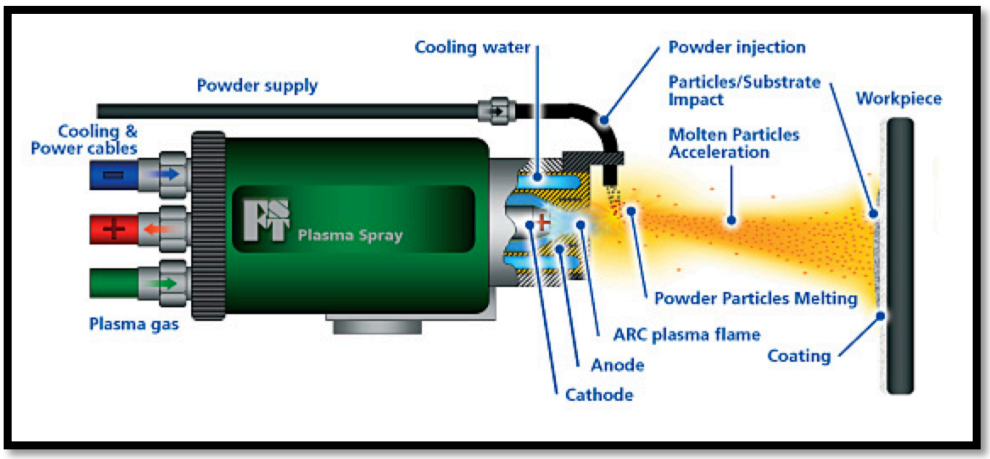


Figure 19: Diagram of the plasma spray metal plating process (Fauchais, et al, 2004).

2.5 Attachment Mechanisms

Stefan Knauss of Aesthetic Prosthetics, based in Pasadena, CA, is our Navy SEAL's prosthetist. Not only is Stefan an expert on prosthetic design, construction, fit, and functionality, but he is also knowledgeable on what our client requires from a prosthetic. Stefan will design the interconnect between our client's residual and the prosthetic, of which is depicted in Figure 20.

Among all prosthetic attachment methods, Stefan pointed out two that would be feasible for this project, the shuttle lock and the suction system.

A suction system consists of a soft liner, a one-way valve, and a sealing sleeve, pictured in Figure 20A. Inserting your liner-covered limb into the socket and applying body weight as you stand expels excess air through the valve. Suction provides uniform adhesion to the entire interior surface of the socket for security, stability, and reduced friction and shear. Depressing a button on the suction valve or unscrewing it can release the suction.

The shuttle lock is a two-part system with a padded liner pin at one end. The shuttle mates with a shuttle lock built into the bottom of your socket. Typically, a release button is found on the side of the prosthetic to aid in prosthetic removal. Refer to Figure 18B for a detailed image of a shuttle lock system. Figure 21 depicts a patient using a combination shuttle lock and suction hybrid prosthetic.

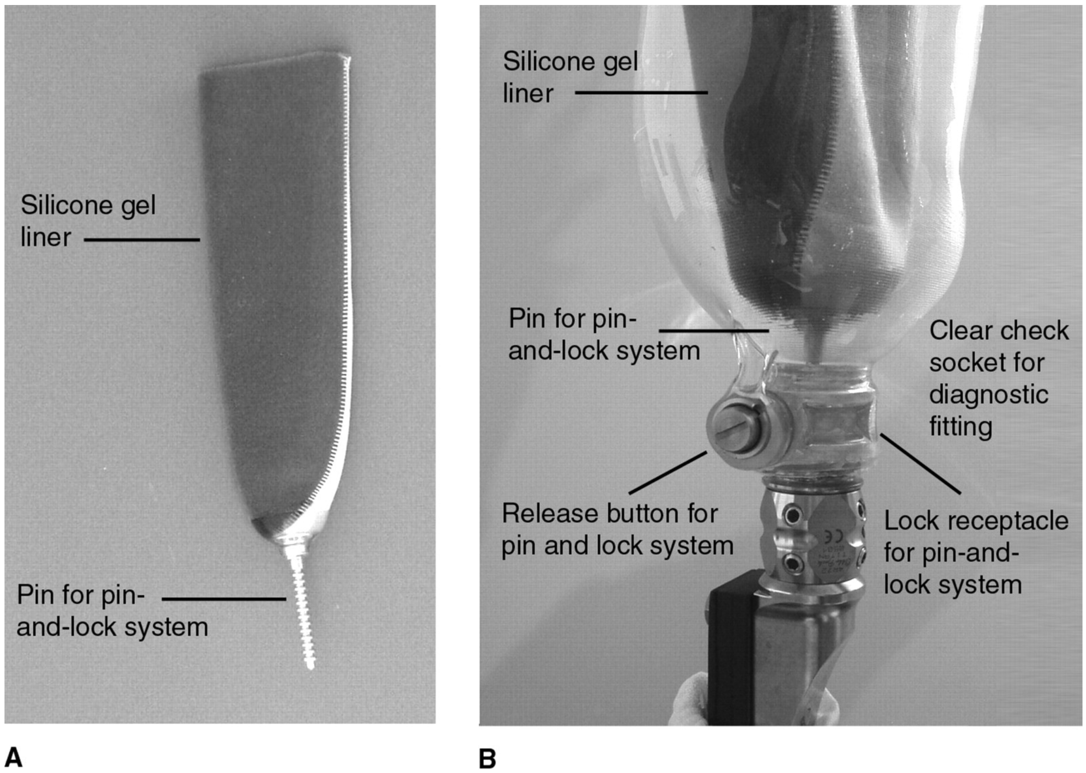


Figure 20: A, Liner with attached pin for shuttle lock mechanism. B, Shuttle lock mechanism in clear check socket (Journal of the American Academy of Orthopaedic Surgeons).

Figure 21: A patient putting on a suction and shuttle lock hybrid system (OANDP).

The suction system is ideal for a user with high activity level since the suction is not likely to remove unless intended to do so. The suction attachment method has a high degree of proprioception, that is, awareness of the movement and position of the body and it's parts relative to each other. Proprioception is, in a sense, a measure of control the user has over the prosthetic. Shuttle lock systems offer the least control of forces and a lesser degree of proprioception than the suction system. Shuttle lock attachments allow the most rubbing in the socket, which can cause calluses, blisters, and sores [Ottobock]. One drawback of the suction system is that discomfort can occur due to the high pressures acting on blood vessels, forcing blood flow to the areas of the limb under pressure.

The suction attachment method was highly recommended by Stefan. He stated the suction forces can support a heavy load, but not necessarily the client's own body weight.

The client has stated their preference for a suction based system as well. Because this system relies so heavily on a perfect fit, his prosthetist should be designing and creating this part of the system. Correct fit and an excellent attachment method are critical for the prosthetic to have proprioception.

Stefan has proposed an attachment method similar to a suction sleeve and shuttle lock hybrid. A urethane sleeve will be designed at varying durometers (30 to 80 durometer) to both hold the form and allow for uninhibited wrist motion. A plate-like metal part can be inlayed into the urethane sleeve as an attachment point from the sleeve to the prosthetic. This is similar to the shuttle lock method in that a metal part provides a connection point between the suction sleeve and the prosthetic.

3.0 Design Requirements and Specifications

After extensive research on the customer's needs and existing solutions, we have arrived at the design objectives described below.

3.1 Problem Statement

The user is an active duty Navy SEAL who has dedicated his entire career to defending our country. As a member of an elite unit, he has spent countless hours training for different combat scenarios. Several years ago, our customer lost his hand in a training accident; however, his dedication and perseverance has enabled him to remain in active duty.

Our customer has tried many prosthetic solutions ranging from a simple hook to the complex myoelectric i-Limb, but has not found a suitable device for his needs for various reasons. Our client has expressed interest in working with the open source community to build upon existing products and develop a more robust, versatile, and functional prosthetic hand for him and others who are interested in such a product. Our goal for this project is to develop a fully mechanical prosthetic hand that will allow our customer to improve his mobility and increase the range of tasks he is able to perform both as a Navy SEAL and at home, all while contributing to the progression of the open source prosthetics community.

3.2 Customer Requirements

The following requirements were derived from conversations with the sponsor, customer, and previous senior project teams. The conversation with the Navy SEAL was a recent development and these customer requirements have changed since the last proposal. Making the prosthetic appear like a human hand was removed from the list of requirements, and incorporating soft parts where needed was an added requirement. Also added to the list was the implementation of a silicone sleeve for attachment, something currently used by the customer. The intended activities of the prosthetic hand are further defined.

Table 2: Customer Requirements

Customer Requirements
Mechanically actuated
Prosthetic sustains a grabbing motion
Prosthetic locks grabbing motion
Durable to withstand military activity
Easily sanitized
Weather resistant: exposure to sun, high altitudes, deep salt water diving, sludge
Comfortable to wear
A modification of an existing, open source design
Must have soft parts where needed
Use current prosthetic attachment system which uses the properties of suction to stay on a residual
Ability to perform in daily activities
Ability to assist in using workout equipment

Above all, the device should be fully mechanically-actuated. The primary motions must include a grabbing and locking action for all fingers and ideally the thumb. The goal is for it to be durable enough to withstand the rigors of military duty, which means it must be corrosion and weather resistant. Ergonomics and comfort for our customer are important: if he does not feel good using it, he will not use it. For health reasons, it should be easily sanitized; furthermore, all component replacements must be accessible to the client for cleaning. The client has asked us to use an improved version of an open source prosthetic device. Actuation of the device should not inhibit the user's primary tasks as our customer still has a great deal of mobility in his wrist. The product must not fail under expected operating conditions. The product's appearance must be identifiable as a hand without drawing attention to the user. Ideally, the user can safely shoot and handle most common military firearms and equipment while using the product. These customer requirements were used in the QFD, Quality Function Development (see Appendix A).

3.3 Engineering Specifications

In order to give our customer the best possible product, we performed the QFD methodology to assess customer requirements and engineering specifications. First, we made a list of all parameters relevant to the effectiveness of a potential prosthetic hand. In addition, we made a list of customer requirements based on Team Manus's most recent meeting with our customer (Bolduc, James, et al, 2013). We then checked for correlations between the customer requirements and the engineering requirements with a weighting system. Cost and actuation sensitivity were linked to the most customer requirements. To evaluate the performance of similar products, we also used benchmark products to compare the requirements against. The fixed hook had the most correlations to important parameters, so we will attempt to design a device that will provide similar comfort and ease-of-use but with more versatility and robustness. See Appendix A for the House of Quality QFD chart.

The following specifications and targets in Table 3 were derived from QFD analysis of conversations with the sponsor, customer, and previous senior project teams.

Table 3: Descriptions of engineering specifications used in the QFD, targets and justifications for the parameters.

#	Parameter/Description	Targets	Tolerance	Risk	Compliance
1	**Weight**: The weight of the prosthetic device	1 lb.	Max	M	A, T, S
2	**Material strength**: The structural integrity of the material	7 ksi	Min	M	T
3	**Grip strength**: The amount of force that can be applied by the prosthetic device to a dynamometer of a given diameter	109 lbs.	Min	M	T, S
4	**Assembly time**: The amount of time to completely reassemble the prosthetic device with one hand	45 min.	Max	L	T, A
5	**Product life**: The number of actuation cycles sustained by the prosthetic device before failure	20k cycles	Min	M	T
6	**Drop impact test**: The prosthetic device will be repeatedly dropped from a specific height to assess durability	10 ft.	N/A	M	T
7	**Cost**: The amount of money needed to produce one prosthetic device (not to be confused with total project cost)	$1,000	Max	M	A
8	**Standard Off-the-Shelf (OTS) parts**: A rating on a scale of 1 to 5 indicating to what degree OTS parts were utilized (where 5 indicates all OTS parts used)	4/5	N/A	L	I
9	**Actuation sensitivity**: A rating on a scale of 1 to 5 indicating to what degree the device's response matches the intended action	3/5	N/A	H	T
10	**User comfort rating**: A rating on a scale of 1 to 5 indicating how comfortable the user feels wearing the prosthetic device	5/5	N/A	M	A

4.0 Design Development

Our team spent several weeks ideating a multitude of concepts for the different subsystems of our system in order to reach our design objectives. This process began with concept generation at the subsystem level, followed by concept evaluation and final design verification. This process is described in more detail in the subsections below.

4.1 Concepts

The concept generation phase of this project began with various ideation techniques performed for the main subsystems of the prosthesis, which include the arm attachment, fingers, actuation mechanism, and locking mechanism. Upon completion of ideation, Pugh matrices (see Appendix B) were completed in order to narrow down the list of concepts to the most feasible ideas. These ideas were then included in a decision matrix and evaluated on their ability to most effectively meet the engineering specifications and requirements of this project. The main concepts in this decision matrix are discussed below, followed by a description of the decision matrix and its outcomes.

4.1.1 Retracting Pin Attachment

This concept, pictured below in Figure 22, was related to the attachment of the palm of the prosthesis to the forearm of the user. It consisted of a spring-loaded button that could be depressed and slid into place; the button would slide and lock into place when it reached a hole in the forearm attachment sleeve. This is similar to the locking mechanism on the detachable handles of a Razor scooter.

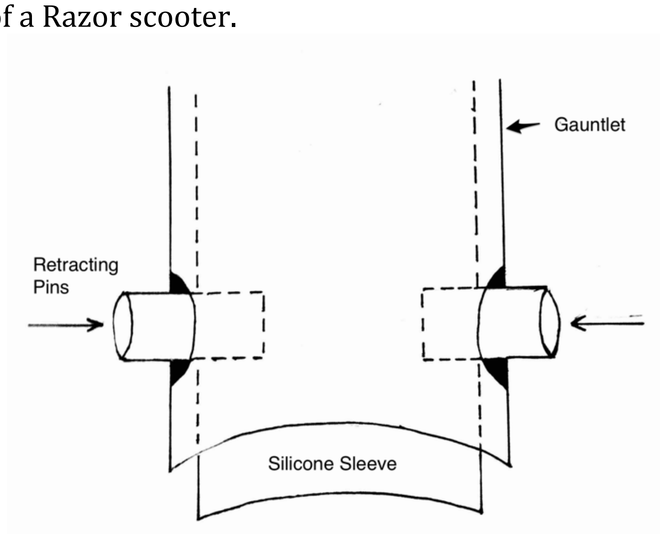


Figure 22: Sketch of the retracting pins attachment.

This attachment system would allow for a more easily disassemblable system for storage and cleaning and would be a durable and simple way to connect the palm of the prosthetic to any sleeve/gauntlet system that the final design would feature.

4.1.2 Finger-Locking System

One of the most significant design challenges for this prosthetic is the locking mechanism, which is needed for passive-open prostheses in order to maintain a closed-hand grip. There are many options for accomplishing this, and several concepts were generated, ranging from locks that "braked" the cable motion, to designs that blocked the structural members of the fingers. It was decided that the most feasible and most effective method of locking the grip would be a simple cam lock that acts on the actuation cables, which articulate the fingers. A quick sketch of this design is included below in Figure 23.

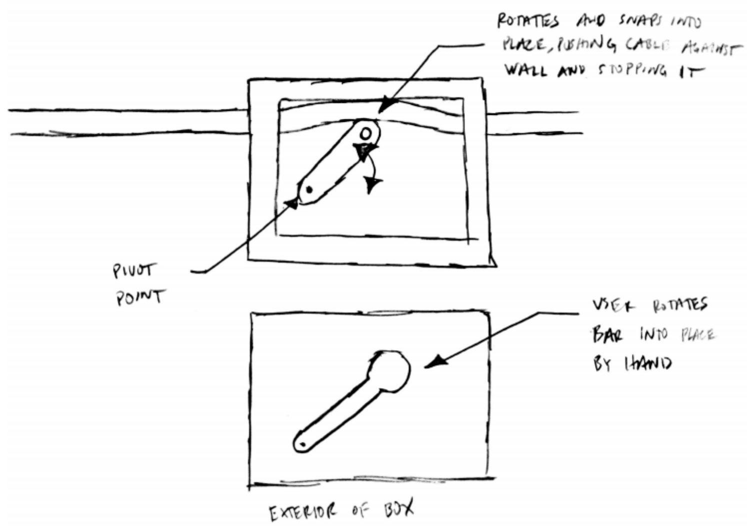


Figure 23: Sketch of the cable-locking mechanism concept to be integrated into the final design of the prosthetic hand. A bar rotates and jams into the cable, pushing it against the side wall of the enclosure and locking it in place until the bar is released.

This locking mechanism operates by rotating a small bar/cam into the cable, at which point it snaps into place and remains pressed against the cable, prohibiting motion of the cable and allowing the grip to be maintained until the lock is released. The user can grip an object, lock the hand, and then relax his/her wrist and forearm muscles while the object is still being gripped. The downside of this design is that the user has to use his/her other hand to lock and unlock the grip, which is a slight inconvenience for the user. However, the robustness, simplicity, and effectiveness of this design far outweigh the inconvenience.

It is important to note that a similar cable-locking mechanism, the TRS Sure-Lok, currently exists off-the-shelf. This mechanism is pictured below in Figure 24. It was used by previous senior project teams and is in common use among other mechanical prosthetic devices. It is expensive but robust, and proven to be effective; for these reasons, a Sure-Lok mechanism may be used in place of a custom-made locking mechanism in the final design of this product. The use of the Sure-Lok will depend on pricing, scheduling, and the company's willingness to collaborate; the details of this will be fleshed out in the near future.

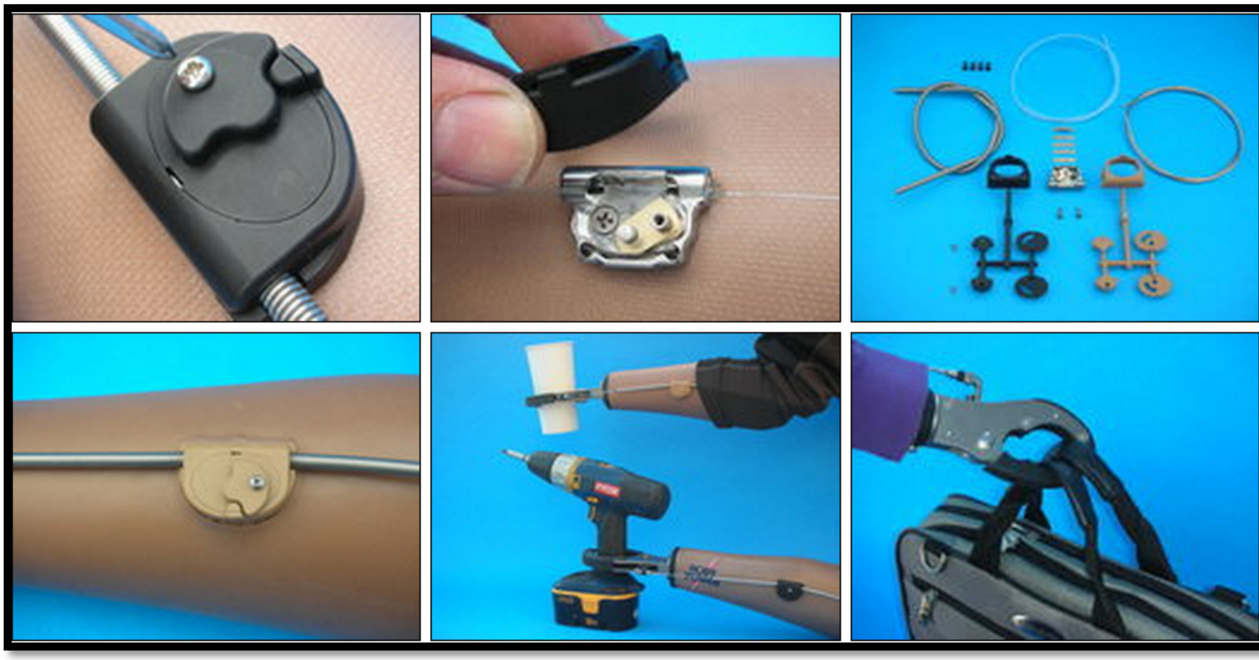


Figure 24: TRS Prosthetics "Sure-Lok" cable locking mechanism. Sure-Lok cable locks by TRS Prosthetics ("Sure-Lok", 2014).

4.1.3 Soft Parts on Fingertips and Palm

When we talked to our customer over the phone, he made it clear that an important requirement of our design is the inclusion of soft materials in locations where the hand should be more tender. This led to the idea to cover the fingertips and palm of the hand with soft, rubber/silicone materials; this would increase grip and the ergonomics of the hand, as it would make it more human-like in form. It would also increase the clean-ability and weatherproof extent of the hand.

Figure 25: Soft parts on fingertips and palm ("Sandia's Robot", 2012).

4.1.4 Guitar Tuning Tension System

Several ideas were generated to address the issue of string tensioning; each string needs to be tensioned so that the fingers move to their desired final gripping position when actuated. This idea is a simple mechanism similar to a guitar string tuning system, with pegs that are turned to rotate a bar around which the strings are wrapped, increasing the tension in them by the desired amount. This idea is sketched below in Figure 26.

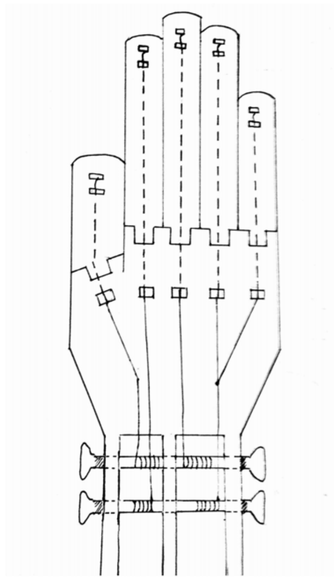


Figure 26: Sketch of guitar tuning tension system.

4.1.5 Screw and Block Tension System

Another string tensioning system concept that was included in our decision-making process was the current solution used in the e-Nable Raptor hand. This system is pictured below in Figure 27, and consists of tensioner pins that are inserted into holes in the main tensioner block, which are tightened by screws on the opposite side of the main block. Tightening the screws brings the tensioner pin closer to the screw and therefore increases tension in the strings.

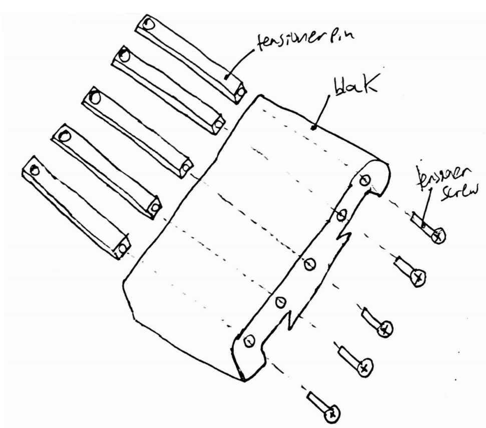


Figure 27: Sketch of screw and block tension system.

4.1.6 Winding Reel Crank System

This concept consisted of a winding reel tension system as seen in the figure below. The cable that is attached to fingers will be connected to a bolt system. The bolt system consists of a bolt and two threated nuts. This will allow the user to adjust the tension of the cable to enable the hand to be passive open or passive closed. An advantage to this system is that the user has the ability to change the tension without removing the cabling system and retying it. The bolt can be adjusted using a screwdriver or a coin.

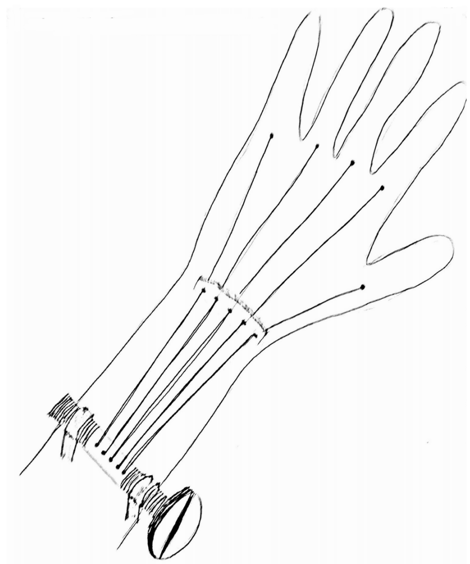


Figure 28: Sketch of winding reel crank system.

4.1.7 Non-Exposed Cables (Internal)

One of the most apparent weaknesses of the e-Nable Raptor hand is the exposed nature of all of the cables in the tensioning and finger return systems. These cables are not covered and there is an extreme likelihood that these strings will snag on objects and be weakened by the conditions of use, especially for a Navy SEAL. For these reasons, we came up with the idea of simply making all cable passages internal to the hand, eliminating the cable exposure to the elements, and thereby ruggedizing the hand dramatically.

4.1.8 Two-Joint Fingers with Cams

The finger design is one of the most important considerations in the design of a prosthetic hand; the fingers carry the load and require careful design in order to articulate smoothly and reliably. The human finger has three joints, one at the base connecting it to the palm, and two that enable the finger to wrap around objects. This is seen below in Figure 29.

Figure 29: Diagram of the joints and bones in a human finger ("Arthritis", 2014)

The topmost (distal inter-phalangeal) joint contributes least to the total mobility of the finger, and the presence of a third joint in a prosthetic finger only increases the complexity and potential for failure, and reduces the strength of the finger. For these reasons, we chose to increase the strength and reliability of our design by keeping the same finger design that is currently used in the e-Nable hands, as well as was used by the previous senior project team. The reduced complexity and increased strength far outweigh the minimal increase in dexterity that an extra articulating phalanx would provide the user.

A sketch of this finger design is included below. The fingers are designed so that they cannot be bent backwards any more than horizontal by including stopping blocks on the top of the finger members. The top member of the finger is fixed at a 30° angle with respect to the adjacent member.

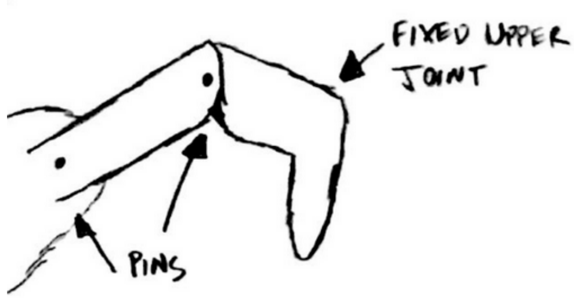


Figure 30: Sketch of the two-member, two-joint finger design that will be used in the final design of our prosthetic hand.

4.1.9 Individual Finger Articulation

One of our main goals for this design is to increase the dexterity of the hand to allow for a more broad range of tasks that can be completed by the user. For this reason, we included a complex finger design that would articulate individual fingers by integrating individual

cable locks and bypasses so that each finger could be actuated with the same motion, as preset mechanically by the user. This idea was not fully developed, but the basis existed in that it would be roughly four times as complex as the most common activation system. This complexity was an issue, but we wanted to include this as it would meet our requirements of increasing dexterity and range of tasks operable by the user. If this idea performed well in the decision matrix, it would be explored and developed more in-depth.

4.1.10 Shoulder Activation

Figure 31 below shows the shoulder activation concept, which increases the strength of the prosthetic since it provides the highest strength to weight ratio of most activation systems. This system is the design that was used by the previous senior project team; our customer expressed his discomfort while using these types of systems, but their sheer strength and robustness made them an automatic inclusion in our decision matrix.

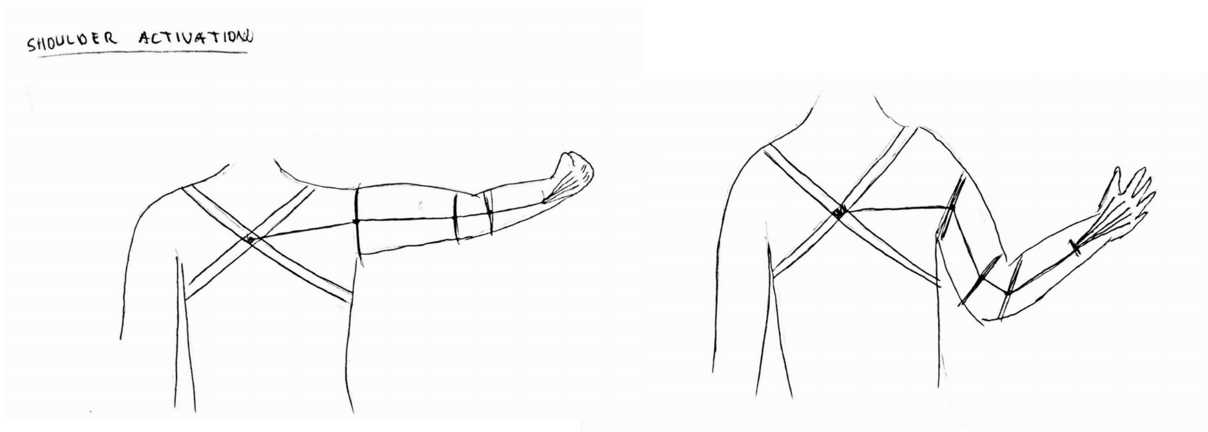


Figure 31: Sketches of typical shoulder activation system.

4.1.11 Wrist Actuation

Since the e-Nable prosthetics are all wrist-actuated, and since these systems are much simpler than shoulder actuated systems, we spent a considerable amount of time exploring methods of increasing the strength and durability of these systems. One of the main problems with wrist actuated prosthetic hands is the weak forearm attachment. For shoulder actuated prosthetics, the devices stay in place better since the harness, brace and sleeve all work in unison to keep the hand steady on the user. However, with wrist actuated prostheses, this is not the case. To remedy this, we aim to increase the wrist attachment strength by integrating a silicone sleeve that uses suction over the forearm to stay in place. The hand would then be wrist actuated and able to be locked in order to increase the strength of the prosthesis, while eliminating the complex cabling system and discomfort of the harness that is used in shoulder actuated prosthetic hands.

4.1.12 Plastic Fasteners Replaced with Metal OTS Parts

One of the weakest points of the current e-Nable Raptor design is the use of 3D-printed fasteners. These parts are low-strength, rough, low-tolerance, brittle, and pliable, making

them unsuitable for military conditions. This idea therefore consisted of increasing the overall strength and smoothness of operation by utilizing off-the-shelf metal fasteners for the pin joints throughout the hand. This would also increase the replicability, and ease of repair of the hand since the fasteners could be purchased off-the-shelf and installed easily.

4.1.13 Increased Wall Thickness

After printing the e-Nable Raptor hand and completing some simple testing, it was evident that the wall thickness of the palm was much too thin. If the hand is to withstand military conditions, the palm and attachment systems need to be much thicker and more durable. This idea was therefore to simply increase the wall thickness dimensions for our design.

4.2 Concept Selection

After solidifying our main contenders for modifying the e-Nable hand in order to most efficiently meet our design objectives, we completed a decision matrix to quantify the extent to which each concept would increase the durability and strength of the prosthesis. Constructing a weighted decision matrix for our design project posed an interesting challenge because most of our design decisions were modifications that were not necessarily interconnected. Specifications were selected from ones used in the Pugh matrices that were all-encompassing, and the list of concepts came predominantly from the top two or three choices from each Pugh matrix. Each specification was weighted in order to give favor to concepts that have more highly desired qualities (e.g. durability and functionality). The last row of the decision matrix displays the weighted score of each concept. The full decision matrix is included below in Table 4.

Table 4: Weighted Decision Matrix of Hand Modification Concepts with Specifications

Specifications	Weighting	Concepts												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Part replacability	6	8	4	3	5	7	5	7	5	4	5	5	9	5
Cleanability	7	6	6	4	4	5	4	4	5	6	5	5	5	5
Ergonomics	8	7	5	9	5	5	5	6	5	8	3	4	6	5
Manufacturability	8	8	4	4	6	8	5	8	7	4	5	7	9	6
Weight	7	7	6	7	6	6	5	8	6	5	5	6	6	6
Cost	7	8	5	4	7	8	5	9	6	4	3	6	8	7
Functionality	9	7	5	7	8	4	5	4	9	10	5	6	5	6
Durablity	10	6	4	7	8	3	6	8	0	0	5	3	10	8
Total Unweighted Score		57	39	45	49	46	40	54	43	41	36	42	58	48
Total Weighted Score		438	300	360	389	345	313	417	326	315	280	321	452	378

#	Concepts
1	Retracting pins attachment
2	Finger-locking system
3	Soft parts on fingertips and palm
4	Guitar tuning tension system
5	Screw and block tension system
6	Winding reel crank tension system
7	Non-exposed cables (internal)
8	Two-joint fingers w/cams
9	Individual finger articulation
10	Shoulder activation
11	Wrist activation
12	Plastic fasteners replaced w/OTS parts
13	Increased wall thickness

Concepts that fared well from this weighted system included replacing OTS fasteners, retracting pins attachment, non-exposed cables, guitar tuning tensioning system, and increasing wall thickness. This matrix, however, does not give the final say on what design decisions we make, since the entire process is subjective. As a group, we completed further analysis to determine which concepts would be included in our final design, while consulting this weighted decision matrix for insight.

5.0 Concept Design Analysis and Evaluation

The decision matrix results were verified through the use of engineering judgment and in some cases, analysis and testing of the prototype e-Nable Raptor hand. This analysis and testing is described in the sections below.

5.1 Pin Force/Stress Analysis

The most critical components in terms of the durability and strength of this design were determined to be the two pin joints in the finger. The current pins used in the e-Nable Raptor hand are small, 3D-printed snap-pins; these pins are weak and will be the first critical parts on the hand to break when subjected to the rigors of military use. For these reasons, the preliminary engineering analysis for this design consisted of stress calculations on the pins in order to determine the strengthening effects of changing the pin material, diameter, and width.

The detailed analysis can be found in Appendix C. The joints were analyzed with the hand in the open position with a perpendicular point load at the fingertip. This configuration was chosen because it would create the highest reaction loads at the finger base. The allowable force per finger was found to be related to the material yield strength, pin diameter, and width as follows:

$$F_{allowable,i} = \frac{K\sigma_{yield}d^3}{w}$$

Since both pins of each finger carry the same load and are of the same width, they can be assumed to be the same diameter as well and therefore the allowable applied load to each finger is equally dependent on both pins, despite the base pin being twice as long.

From the above equation, it is evident that increasing the diameter of the pins is much more effective than choosing a material of higher yield strength, since the diameter is raised to the third power. Pin width is dependent on the strength of the structural material of the fingers; therefore it is not analyzed in this optimization. It is also important to note that the larger the pin diameter, the larger the stress concentration on the finger, since a larger hole will be cut out of the structure. Based on these facts, it was decided that the diameter of the pins could be slightly increased in order to increase the load capacity, and a stronger, off-the shelf metal pin would also be used for various reasons beyond the increase in strength it would provide, namely decreased joint friction, increased robustness, and the use of off-the-shelf parts. Table 5 below includes a comparison of the increases in strength that a variety of different pin materials would provide under this load configuration, along with the relative cost of each material.

Table 5: Strength increase and cost of various pin materials for different standard pin sizes.

Material	Strength Increase	Approx. Mat'l Cost Increase	Strength-Cost Ratio
PLA	Nominal	Nominal	Nominal
Nylon	80%	190%	0.42
ABS Plastic	120%	250%	0.48
Steel	420%	70%	6.00
Aluminum	120%	120%	1.00
LS Titanium	1220%	1070%	1.14
Brass	460%	320%	1.44

From this table, it is clear that metal pins would be the most effective choice for our design. Titanium should only be chosen if the extreme strength is necessary despite the extreme cost. A high-strength steel pin would most likely be the most adequate choice due to its high strength-to-cost ratio. Moreover, since the structural material of the design is to be titanium, having a lower-strength pin material would make these parts the first to break in the hand, making them easily replaceable (since they are off-the-shelf) and eliminating major damage to the more intricate structural components of the hand.

5.2 Prototype Assembly

In order to more thoroughly and effectively evaluate our potential modifications to the e-Nable Raptor hand, we printed and assembled the e-Nable Raptor hand exactly as specified by the e-Nable community. This enabled us to get hands-on experience with the prosthesis so that we could see and experience firsthand the benefits and drawbacks of such a design and the potential effectiveness of our potential modifications. An image of this prototype is included below in Figure 32.

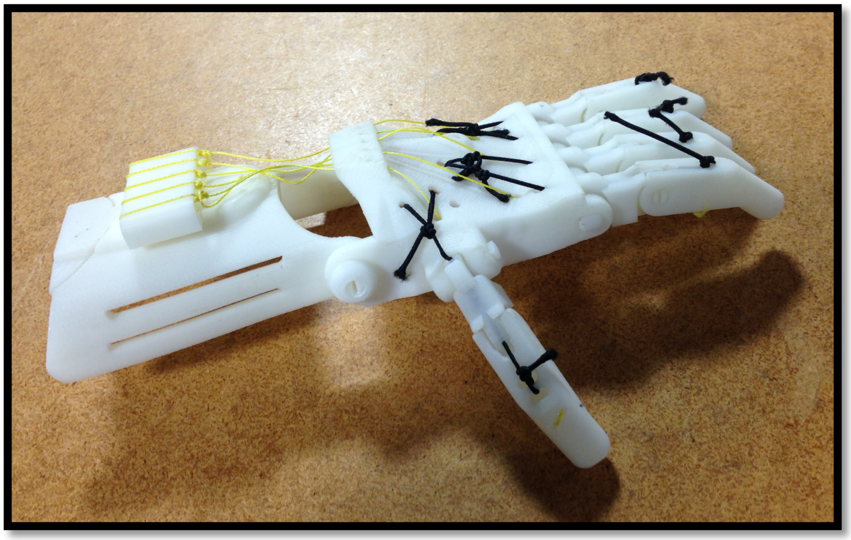


Figure 32: 3D printed prosthesis as designed by the e-Nable community.

This prototype of the Raptor hand was made using a fused deposition modeling process of rapid prototyped ABS plastic on a Stratasys machine. It was assembled according to e-Nable's instructions with the exception of the adjustable tension system. The tension blocks were too small to assemble without breaking and had to be omitted. This model was used to analyze the range of motion and effectiveness in picking up commonly sized objects, as discussed in the following sections.

5.3 Testing of Prosthesis

Two tests were completed for the printed prototype of the e-Nable Raptor prosthetic hand. These tests are described in the subsequent subsections.

5.3.1 Range of Motion

An important consideration in the construction of any cable-actuated prosthesis is the range of motion of the input that yields the desired output. It is important to keep the user's actuation motion in a comfortable range so that operation of the prosthesis does not inhibit the user's ability to complete the attempted tasks. Thus, the first test completed using the 3D-printed prototype of the e-Nable hand was a range of motion test. This was done by simply increasing the input (wrist angle) until a closed grip was achieved, as seen in the picture below in Figure 33 and is tabulated below in Table 6.

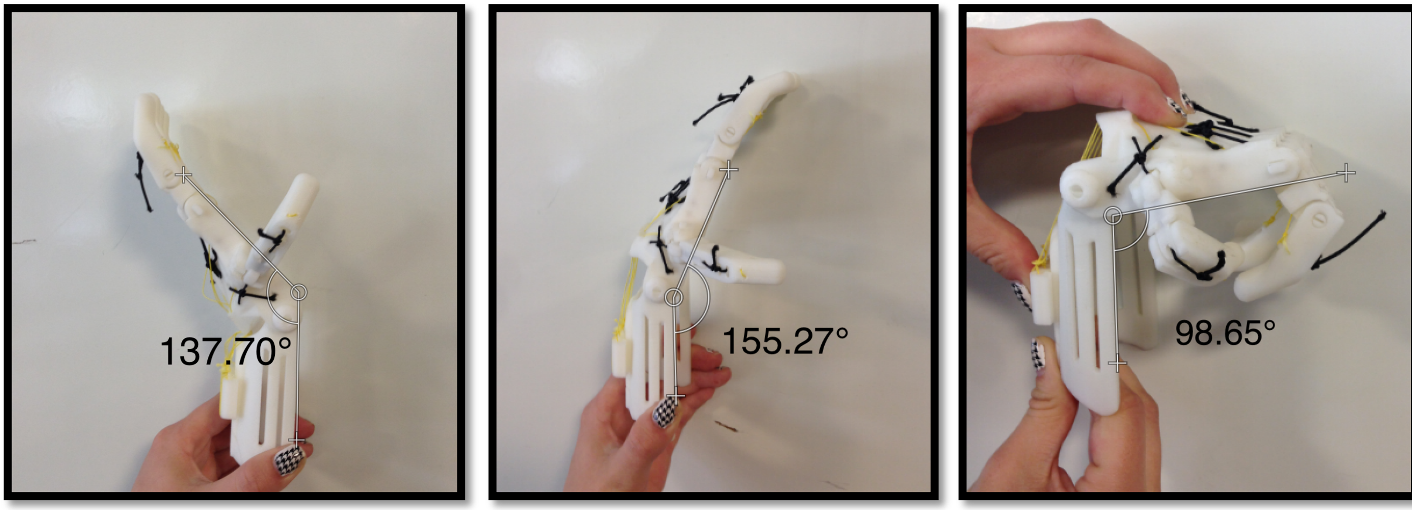


Figure 33: Raptor hand oriented in three different positions (left to right: open, neutral, and closed positions) with labeled angles to test range of motion.

Table 6: Hand Orientation and Angles

Hand Orientation	Angle
Open position	137.70°
Neutral position	155.27°
Closed position	98.65°
Full span	123.65°

The results of this test indicate that the user has to move his/her wrist by a total of about 130 degrees to go from a completely open to completely closed grip. This is a very large input range and could potentially be reduced in order to increase user comfort; however, a larger range of motion allows greater sensitivity for the user to perform dexterous tasks. The details of the range of motion will be fleshed out in the detail design portion of this project in the coming weeks.

5.3.2 Gripping Ability

Another test that was completed with the printed prototype was a simple qualitative test that consisted of attempting to pick up and hold several different objects. This was done to get an idea of how well the current prosthetic works. Pictures of this test are included below in Figures 34 - 37.

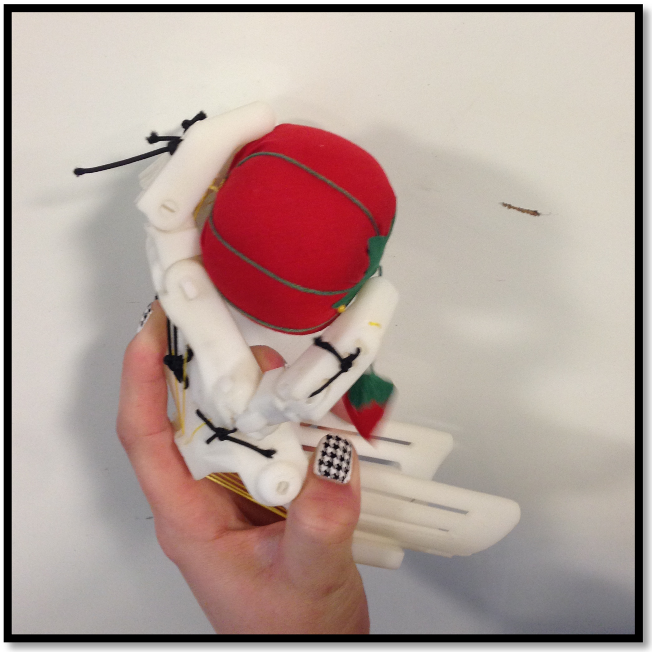


Figure 34: The prosthetic picked up and gripped this sewing pincushion the best of any object. The ease of picking up and gripping is likely due to the pincushions large size and soft, formable texture.

Figure 35: This rag was the smallest thickness of object the prosthetic could grab on to. The prosthetic had difficulty picking up the rag, due to the index and thumb misalignment, visible in this image. The soft texture of the rag helped the prosthetic hold on to the object with no slippage.

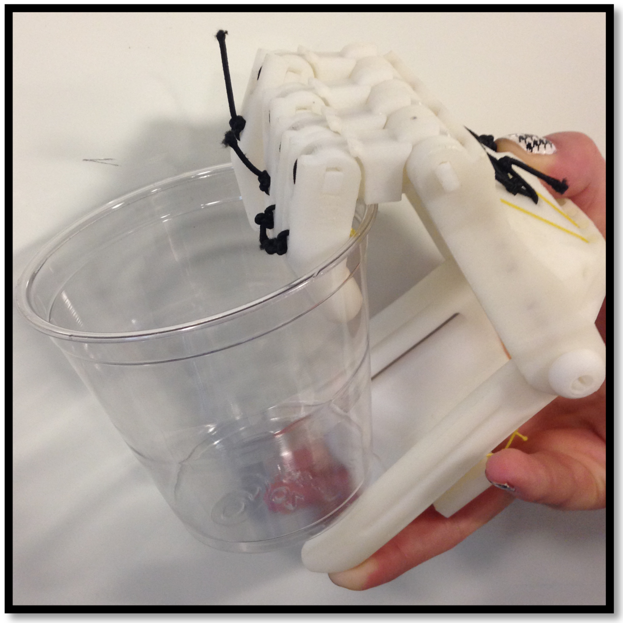


Figure 36: This plastic cup was too large for the prosthetic to hold and too thin in wall thickness for the thumb and index finger to pick up. The cup had to be placed near the prosthetic for it to be gripped at all, as it could not be picked up off of a table.

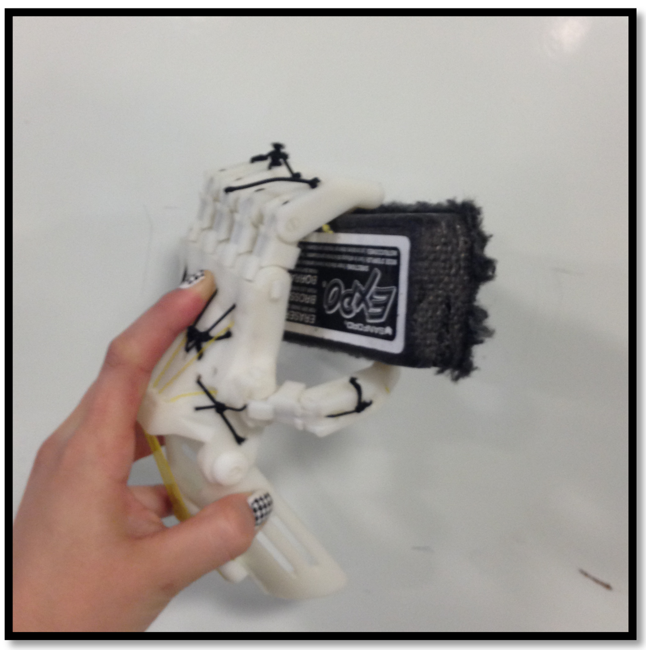


Figure 37: The prosthetic picked up this eraser well due to the object's large size. The thumb and index finger alignment in this figure looks more correct than when picking up the rag.

From this test, it was determined that the alignment of the index finger and thumb in unison were critical to picking up and holding objects. If the thumb and index finger did not align together when at the position required by the object size, it was very difficult to

pick up an object. The next iteration of the design should include an index and thumb position that will align when any distance from each other to accommodate most sized objects.

5.3.3 Finger Creepage Test

An additional experiment was done to determine how much the cables creeped after two hundred cycles of use. This is explained in detail in Appendix D. We determined that a significant amount of creepage exists in a Raptor hand that is assembled without the adjustable tensioning system. The index and pinky finger change 23.41° and 29.1°, respectively, when undergoing 200 cycles. It has been determined that the final design will need an adjustable tensioning system in order to align the finger position, otherwise the fingers will creep significantly. When finger misalignment is present, the quality of grip is also affected. Therefore, to optimize the quality of grip, an adjustable tension system is needed in the prosthetic design.

5.4 Plans for Future Testing

Plans for future validation and testing of customer requirements and engineering specifications of our subsequent prototypes and final design are shown below in Table 7. Along with these tests, finite element analysis will be done on the index finger in tension via device actuation to determine if any stress concentrations exist higher than 7 ksi, the stress level limit specified in the engineering specifications section.

Table 7: A description of test parameters, experimental methods and experiment targets performed on the final design.

Test #	Test Parameter and Experiment	Targets
1	**Weight**: The weight of the prosthetic device.	1 lb.
2	**Cord material strength:** Fracture load limit will be measured on a tensile testing machine for the flexible and non-flexible cord.	100 lb
3	**Structural material strength:** Ultimate tensile, yield, and fracture limit will be measured on a tensile testing machine.	7 ksi, UTS
4	**Grip strength**: The amount of force that can be applied by the prosthetic device to a dynamometer of a given diameter.	109 lbs.
5	**Assembly time**: The amount of time to completely reassemble the prosthetic device with one hand.	45 min.
6	**Product life**: The number of actuation cycles sustained by the prosthetic device before failure, repeated until failure or 20k cycles. One cycle is both the opening and closing of a grip.	20k cycles
7	**Drop impact test**: The prosthetic device will be repeatedly dropped from a specific height to assess durability. If the prosthetic changes in function due to the drop, the test is failed.	4 ft.

Test # (cont.)	Test Parameter and Experiment (cont.)	Targets (cont.)
8	**Cost**: The amount of money needed to produce one prosthetic device (not to be confused with total project cost).	$1,000
9	**Standard Off-the-Shelf (OTS) parts**: A rating on a scale of 1 to 5 indicating to what degree OTS parts were utilized (where 5 indicates all OTS parts used).	4
10	**Actuation sensitivity**: A rating on a scale of 1 to 5 indicating to what degree the device's response matches the intended action.	3
11	**User comfort rating**: A rating on a scale of 1 to 5 indicating how comfortable the user feels wearing the prosthetic device.	5
12	**Prosthetic locks grabbing motion:** Actuate the locking mechanism and rate the locking ability on a scale of 1 to 5, where 5 indicated the mechanism locks well without slippage.	5
13	**Weatherproof:** A rating of 1 to 5 indicating the ability of the prosthetic to function after being exposed to saltwater submersion, sun, dirt, mud, and sand, where are rating of 5 indicated all parts function as normal.	5
14	**Sanitization:** A 1 minute trial, where soap and water is used to clean dirt and bacteria away and indicated by a PASS or FAIL if all visible particles are removed.	PASS
15	**Open-source test:** A rating of 1 to 5, where 5 indicates the design is very well suited for the open source community.	3
16	**Soft parts grip test:** A rating of 1 to 5, where 5 indicates the soft parts add friction in the correct area to aid in gripping and 1 indicates poor friction.	4
18	**Ability to perform in daily activities:** The prosthetic is tested by picking up a pencil, opening a door handle, and pulling open a drawer while being rated on a scale of 1 to 5, where 5 indicates the action was completed without difficulty.	4 (avg)

6.0 1st Iteration Concept and Detailed Design

6.1 Concept Description

This iteration's concept is a product of the extensive ideation and concept evaluation that was completed throughout the past couple months. Concepts were evaluated first using Pugh Matrices to determine the most desirable designs for each function. Once the most effective designs for each function were determined, decision matrices were completed to select the designs that would most effectively meet the engineering specifications and customer requirements at an aggregate level. Lastly, engineering judgment, stress analysis and testing were performed to validate these choices.

A preliminary model of the concept design is pictured below in Figure 38. The main features are modeled, although they are simplified since the exact dimensions and forms are not currently known. This design borrows the structural design of the fingers and palm from the e-Nable Raptor ("The Raptor Hand", 2014). The material will be changed to either a stronger, more durable material such as PLA or nylon, or, if possible, a laser sintered titanium alloy. This will provide a stronger, more weatherproof and durable structure to withstand the rigors of military activity.

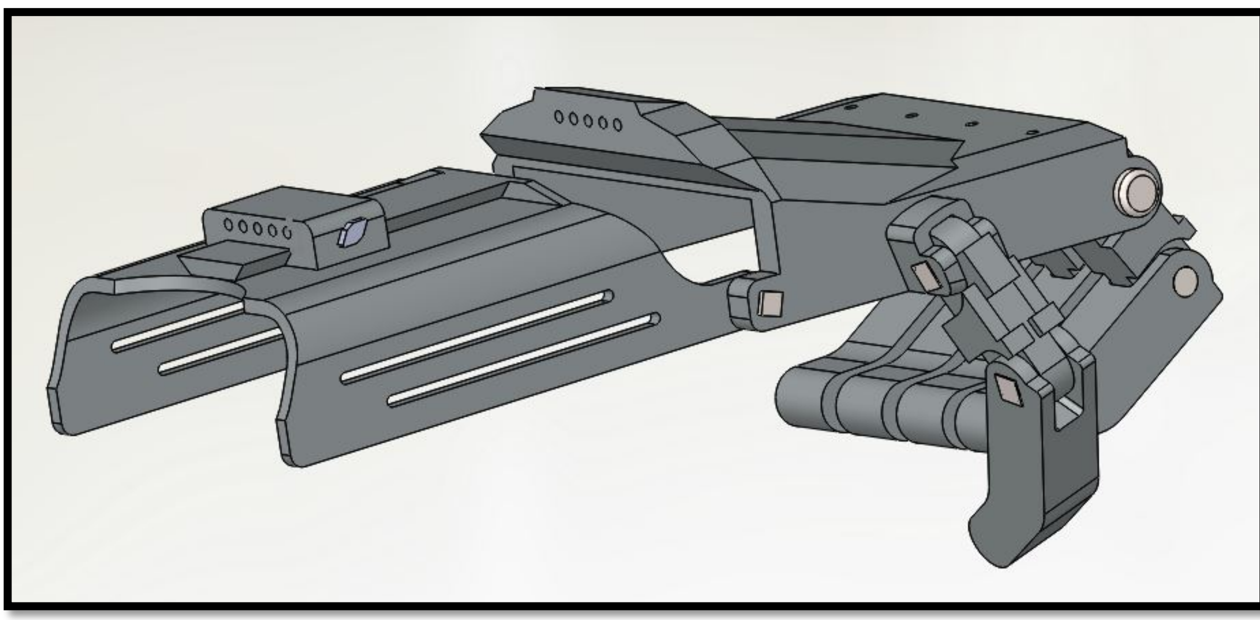


Figure 38: Isometric view of preliminary SolidWorks model of our concept design.

Based on structural analysis of the e-Nable hand (Appendix C), it became evident that the pins were one of the weakest aspects of the design. This will be remedied by utilizing off-the-shelf pins with larger diameters and a higher strength material than the current design, which uses small, weak rectangular snap-pins.

Per the customer's request, soft parts will be added in places at which the hand should be soft, such as fingertips, in the middle of the finger joints, and at the palm. The elimination of the user's interaction with unnecessarily hard, non-human-like parts will increase grip strength and increase the versatility and ergonomics of the hand. These soft spots are not included in the above model of the design; several materials and methods of achieving this are still being explored, especially one in particular, Plasti Dip, usually used for coating tools.

On the e-Nable Raptor hand, the elastic cables are made of weak materials and are exposed to the elements. This will be improved with our design through the use of a more durable cable material and internal passageways in the palm of the prosthetic within which the cables will reside. These changes will reduce the potential for failure due to the operating environment.

One of the most important aspects of our design is the cable locking and tensioning mechanism. The hand is passive-open, meaning it will be open by default until it is actuated, at which point it will close the grip, and it is actuated by downward wrist flexion. This design will feature a cable tensioning system similar to the current design (see section 4.1.5, "Screw in Block Tension System"), which will allow for pre-tensioning of cables and fine-tuning of individual cables. The locking mechanism is an innovative design that is similar to the locking mechanism of a scope on a rifle. Our design is pictured below in Figure 39.

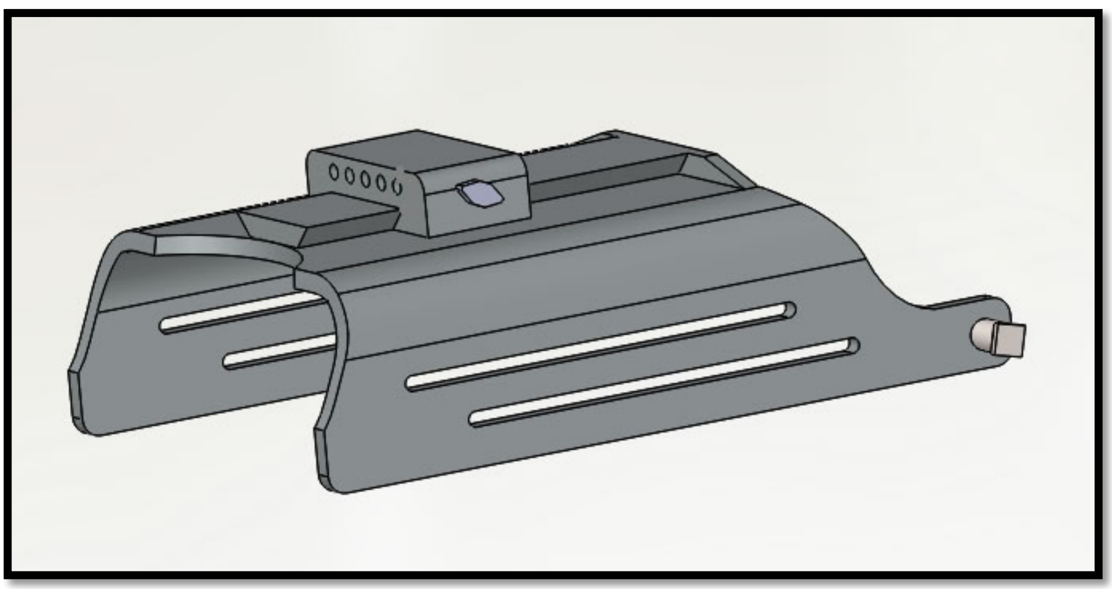


Figure 39: Block tensioning system atop the sliding lock-down grip pre-tensioning system. The block is split into two threaded pieces so that when a screw is loosened, the two block pieces are separated slightly and can be slid along the guide rail. When the screw is tightened, this gap is reduced until it is locked down securely in place.

This design consists of a sliding tensioning block; this block is adjusted to the desired position by loosening the clamp screw and moving until the desired grip is achieved. The screw is then tightened, and the block is fixed at the desired location. The block is then effectively fixed, and the grip will not slip, allowing the user to relax his/her wrist. This system is useful for tasks that require a closed-grip to be held for extended periods of time.

The major part of the design that is still incomplete is the forearm attachment. Our customer expressed a strong desire for us to work with the current maker of his prosthetic devices so that we could combine the silicone suction forearm sleeve from his current aesthetic/utility hands with the palm and finger design of the wrist-actuated prosthetic device. We have met with his prosthetic designer, and our findings are described in Section 2.5.

6.2 Manufacturing, Materials, and Assembly

Every component in this prosthetic will be made from laser sintered titanium, with the exception of the fasteners, cord, soft parts, and silicone sleeve. The direct metal laser sintering manufacturing method is ideal for this prosthetic because it allows us to have internal features, such as the string passageways, which would not be possible with a CNC or casting process. Titanium is the best material for this prosthetic because of its strength and low weight properties, even when in the powdered form used in the direct metal laser sintered process.

There are two types of cords, flexible and non-flexible. The flexible cord is made from an elastic band made of a similar material found in elastic waistbands. The non-flexible cord is made of 100 lb. tested Spectra fiber. The silicone sleeve is a part fitted specifically to our customer and will be provided by his prosthetist.

The joint pin fasteners will be off-the-shelf parts. Using widely available off the shelf parts will increase the reparability of the prosthetic. Anywhere where standard parts can replace titanium parts will be significant towards reducing the cost of the prosthetic. The powdered titanium used in this laser sintering process is incredibly expensive due to the small and uniform particle tolerance requirements. A faculty member has a connection with EOS, the major supplier of these direct metal laser sintering machines. The likelihood of making the prosthetic from laser sintered titanium will depend on this connection due to the high cost of this rapid prototyping process. We are prepared to instead choose a nylon powder laser sintered rapid prototyping process, where the machines are more readily available and the material is significantly less expensive. Laser sintered nylon is weaker than titanium, but also weighs less. Laser sintered nylon also has the undesirable effect of being flexible when cross-sections or wall thicknesses are small. Another option that is even more readily available is choosing to go with a PLA plastic fused deposition modeling process. This rapid prototyping process will likely hold less tolerance than the laser sintered processes; however, it will be much less expensive than laser sintered nylon. These processes are explored in detail in the Background section of this report.

This design is intended to be easy to assemble and disassemble. The small amount of parts used to create this prosthetic is the major contributing factor to this. Choosing an ergonomic way to insert and tie the cords in place is also critical when trying to reduce the overall assembly time.

6.3 Plans for Construction

To ensure that the final deliverable to our customer is of the highest quality and precision possible, we plan to produce several prototypes of our final design throughout the process. This will enable an iterative design process based on physical observations and test results of the prosthetic hand as the design progresses.

This process will entail first creating individual prototypes of major subsystems, such as the locking mechanism and the finger design. These prototypes will likely be 3D-Printed using one of the several printers available to students on campus at Cal Poly.

Once these individual subsystems are functioning as smoothly as possible, a prototype of the entire system will be created. With this prototype, we will test the interaction between all subsystems to ensure they work seamlessly to achieve the required performance for our Navy SEAL. This prototype will be 3D printed, but will include the actual arm attachment, metal fasteners, cabling system, and soft parts.

Based on the performances of these prototypes, the design will be adjusted and the final revised system will be manufactured.

6.4 Detailed Description of 1st Iteration Design

Once the initial concept design process was completed, this project transitioned into the detail design phase. This phase entailed fleshing out the fine details of the design, conducting analysis to ensure adequacy of design in meeting the engineering specifications, organizing all components, and preparing for manufacturing.

After intensive research and development, the resulting 1st iteration design of this prosthetic was arrived at and is pictured below in Figure 40. This is followed by descriptions of the three major subsystems: the forearm, palm, and fingers.

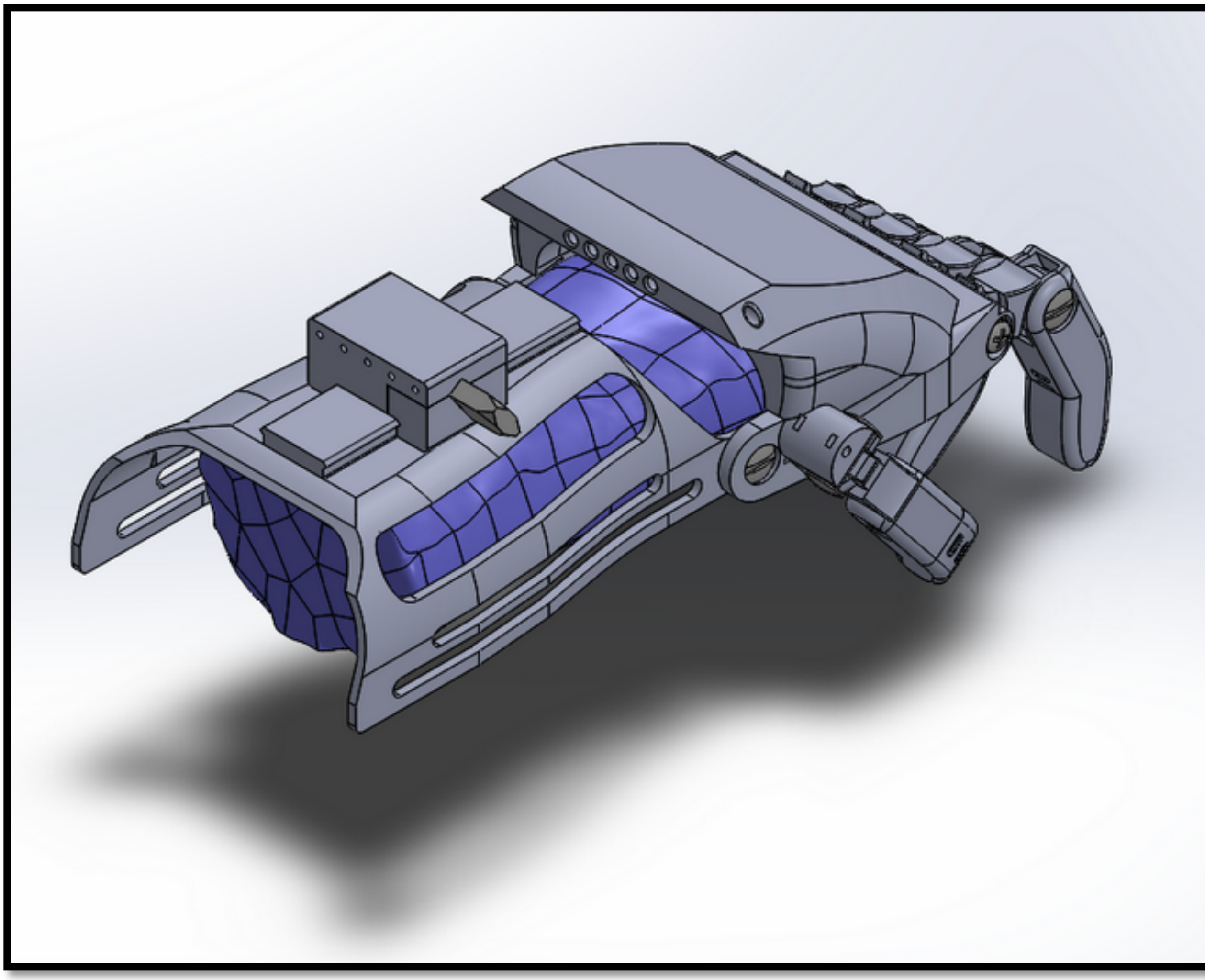


Figure 40: SolidWorks model of assembled prosthesis.

6.4.1 Forearm

The forearm subsystem of this design consists of a DMLS printed, thin-shelled "gauntlet" that is shaped to conform to the user's residual. It is pictured below in Figure 41. The user will be wearing a silicone-molded sleeve that will envelop his forearm and therefore provide a barrier between the flesh of the user's forearm and the titanium of the gauntlet. Slots on the bottom of the gauntlet allow for Velcro straps to be fastened around the user's forearm once it is securely positioned inside the gauntlet to provide an extra attachment point to the user and reduce wobbling of gauntlet around the user's forearm.

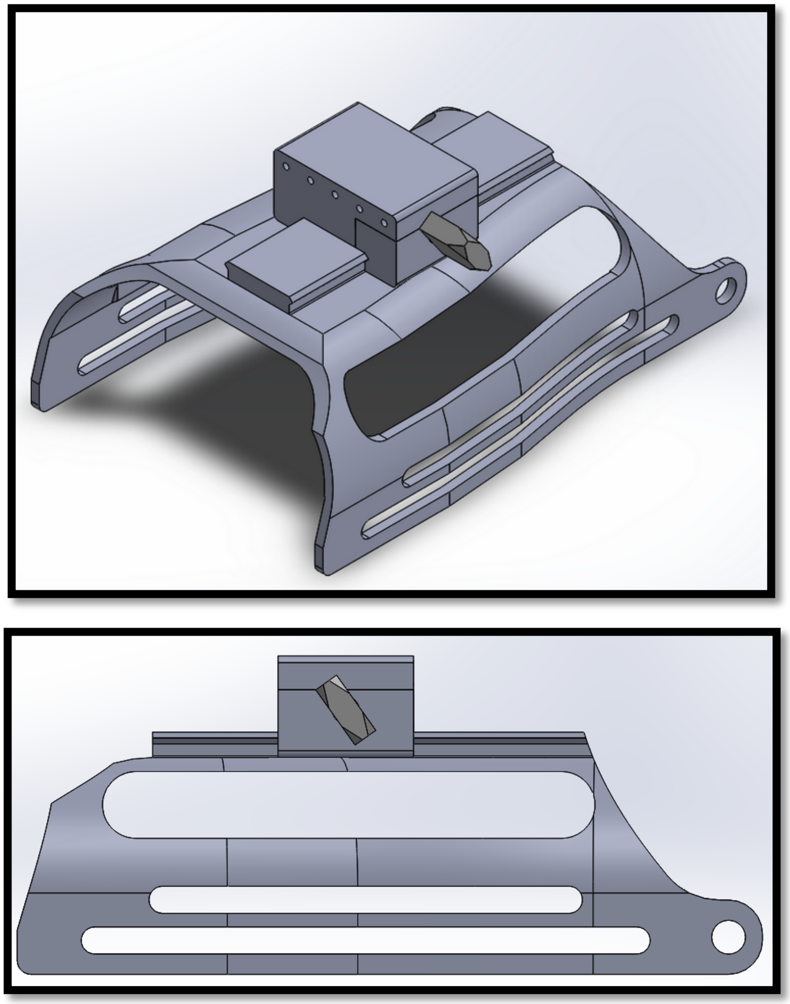


Figure 41: Model of forearm subsystem.

Atop the gauntlet sits a rail system on which the tensioner block sits. The tensioner block contains five small, square, internally-threaded inserts that slide inside holes in the block as the screws are tightened or loosened. Non-flexible cable is tied to these square inserts and passes through the palm to the fingers so that when the hand is actuated, the fingers are pulled down into a closed grip. The screws in the sliding inserts are adjusted to create equal tension in the strings and to allow the fingers to all close in the desired grip.

The tensioner block is split on one side and features a hole that runs through the width of the block. A hex nut is recessed into the far side of the large piece of the block. A thumb screw slides through the clearance hole in both pieces of the block and is secured into the hex nut. When the thumb screw is tightened, the two pieces of the block are brought together until they are secured tightly together around the rail; when the thumb screw is loosened slightly, the blocks are brought slightly apart, and the block is able to slide along the rail. This allows the user to slide the block into the desired position and lock it into place by tightening the thumb screw. By moving the block toward the palm on the rail, the

tension in the cables is reduced, and the wrist is able to move more while actuating the fingers less. When the block is moved further from the palm, the cable tension increases, and the hand is pre-tensioned into a grip. This allows for a grip to be achieved and locked into place when the thumb screw is locked down on the rail.

6.4.2 Palm

The palm subsystem consists of a DMLS printed titanium piece that is ergonomically shaped to feel most like a human hand while also accommodating the mechanical components that enable it to be actuated. There are internal passageways in the palm through which both elastic and non-elastic cables pass; the elastic cable passageways extend from the top of the middle of the palm, where they are tied off to prevent them being pulled through, to the top of the finger interface; the non-elastic cable passageways extend from the top of the palm, where the cables are received from the forearm subsystem, down to the bottom of the finger interface. These internal passageways are achieved by securing a plastic piece over the top of the palm; this reduces the risk of wear due to environmental effects and also eliminates the chance of the cables snagging on other objects and stretching or breaking. A picture of the palm is shown below in Figure 42.

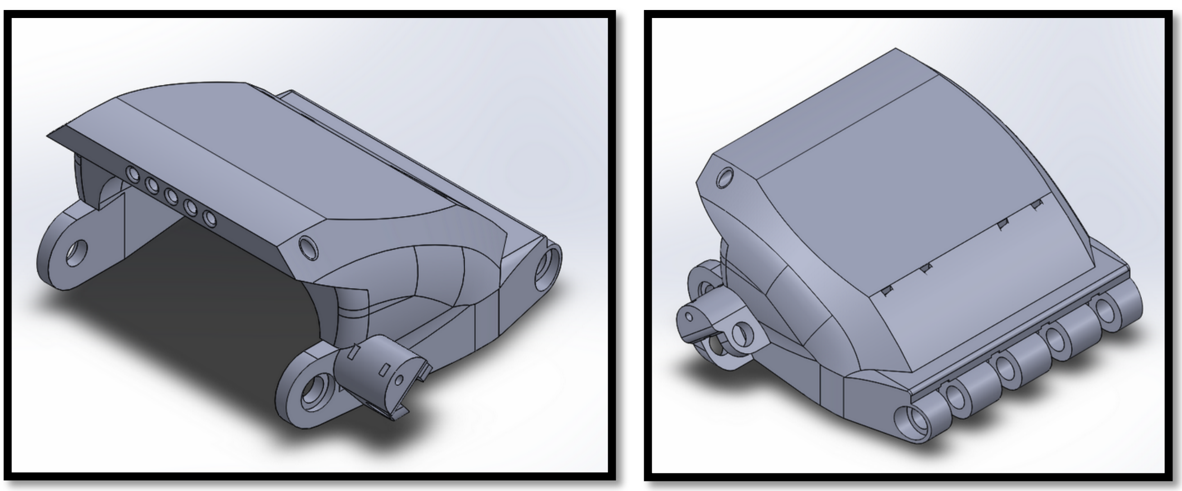


Figure 42: Model of palm subsystem, minus the silicone sleeve attachment mechanism.

The bottom of the palm features a hollowed-out portion that allows for the user's residual to be placed comfortably and snugly inside. The attachment point of the user to the prosthetic is at the tip of the hollowed-out portion, where an aluminum plate, which extends from the silicone-molded sleeve that surrounds the user's residual, is fastened by a series of bolts to the base of the titanium palm piece. The palm is fastened to the forearm subsystem by two Chicago screws.

Pending per our customer's desire is the inclusion of soft parts; a glove would be the ideal solution to encase the entire palm and all fingers; however, since the geometry and proportions of this hand are not like a human hand, off-the-shelf gloves would not work. A custom-made glove could be purchased if so desired, but it will most likely be expensive. Moreover, if a glove is not desired by the customer, the hand could be dipped and coated in a soft, tacky rubber material, like Plasti Dip.

6.4.3 Fingers

All five fingers of the prosthesis are identical, and can be seen below in Figure 43. The cables that pass through the palm are intercepted at the base of the fingers and directed through passageways that extend to the furthest member of the finger. The non-elastic cable is on the bottom of the finger members, so that when it is tensioned, the finger will be pulled down into a gripping position. The elastic cable is on the top of the finger so that when the tension in the non-elastic cable is released, the finger members will spring back up into a flat, open position. The fingers also feature stopping blocks on the tops of the members, so that the finger cannot be hyperextended past a flat position. The finger joints are comprised of steel Chicago screws that are smooth on the outside to allow for low friction operation. Silicone pads will be located on the fingers at critical locations to both increase the gripping ability of the hand and also to make the prosthesis more ergonomic by emulating the soft nature of a human hand.

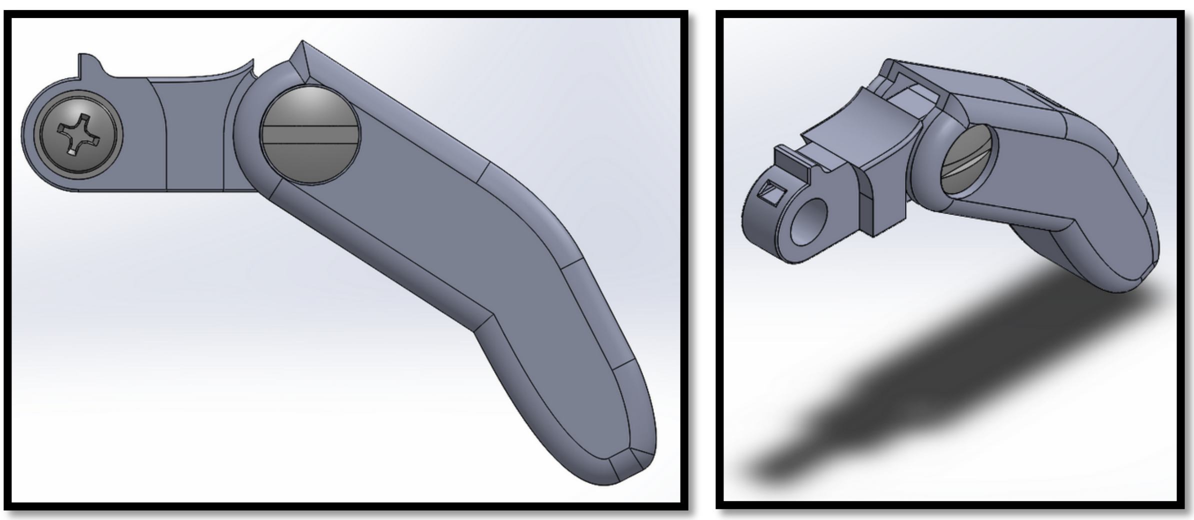


Figure 43: Model of finger used for all five digits in the final design

6.4.4 Operation

The operation of this hand is a fairly simple process. Extensive research has been carried out in order to determine the most ergonomic actuation methods; the most unobtrusive

method of actuation, wrist actuation, was chosen. More information on this decision can be found in the background section of this report.

The user operates this device by first placing it on his residual by following the instructions at the end of the "Assembly Instructions" section (6.2). Once the prosthesis is securely attached to the user's body and the tension in the actuation cables is fine-tuned, actuation is achieved by simply flexing the wrist downward. This creates tension in the cables, as the tensioning block will be locked down on the rail during actuation. The tension pulls the fingers together in a closed grip. When the user desires to open the grip again, he simply releases flexion of the wrist and the fingers will spring back up to the open position. This form of operation is desirous for completing simple, quick, dexterous tasks.

For more laborious and longer-lasting tasks, the user should take advantage of the grip-locking mechanism available on this prosthesis. This will allow the user to lock a grip and subsequently release flexion of his wrist, which is much more comfortable and allows for much heavier objects to be held for long periods of time. This locking mechanism is operated by first pre-tensioning the hand into a grip. This is done by loosening the thumb screw, sliding the tensioning block until the desired grip amount of grip is achieved, tightening the thumb screw to lock the tensioning system down on the rail.

6.5 Maintenance and Repair

This prosthesis was designed to be easily cleaned and serviced, while being as reliable and robust as possible. This was achieved through constant awareness of possible failure modes and the use of the FMEA (Failure Mode and Effects Analysis), with which we were able to identify the main causes and effects of failure and ways to prevent them. This FMEA table can be found in Appendix I.

Since the customer will be using this device in harsh, diverse conditions, fairly frequent maintenance should be performed in order to ensure its longevity. In addition to maintenance, deviations from design conditions may cause part failure. The results from these conditions are anticipated and addressed in the following sections.

6.5.1 Maintenance

The form of maintenance that will most likely be the most common is fine-tuning tensioning of the pins in the tensioning block. Over time and with increasing usage, the knots in the non-flexible cables will tend to loosen and the cables will tend to slacken. Therefore, the tensioning pins will likely need constant fine-tuning in order to ensure optimum gripping of the hand. Less frequently, but possibly necessary, will be the untying, tightening, and retying of knots due to extreme loosening.

Both the non-flexible, and more so the flexible cable, are prone to permanent stretching over time; exposure to water can accelerate this stretching effect. Adjusting the tensioner pins will alleviate this stretching effect, but only up until a certain point when the cord will

need to be replaced in order to perform as required. If the prosthetic does not hold a grasp as well as it used to, and adjustments to the tensioning system do not alleviate the problem, the cables should be replaced. This should be done by cutting or untying the knotted ends of the cables and removing the cables. The assembly instructions in Section 7.2 should be consulted when installing the fresh cables.

Since the user will be operating this device in harsh environments, the device most likely will require frequent, partial disassembly and cleaning to remove dirt/grime and any saltwater residue in crevices and hard-to-reach components. This will ensure smooth operation and reduce the risk of corrosion and degradation of the materials.

Lastly, the Chicago screws will need occasional re-tightening in order to ensure the smoothest operation possible. This can be done by simply tightening the bolts with a flat head (for the lower finger joint and wrist), or a Philips head (for the upper finger joint) screwdriver.

6.5.2 Repair Considerations

The most likely parts to fail and need repair are the cables. These cables operate under large loads with extreme cycling; the cables are also not incredibly durable and will be vulnerable to degradation in extreme weather conditions. In cases where the cables are snapped, repair simply entails the removal and replacement of the snapped cable, following the instructions in Section 6.2 above.

The device was designed to feature fasteners that are made of weaker materials than the structural members. Thus, given an unexpectedly large load, the fasteners would fail instead of the more expensive, intricate components. All fasteners are off-the shelf and standard sizes. Therefore, the most common parts to fail in this design are also the most easily and cheaply replaced. Repair of the prosthesis if a fastener fails entails simply replacing the fastener with a spare and ordering a new spare part.

More generally, if any component becomes loose, broken, or lost, the prosthetic should be removed and the Bill of Materials should be consulted to discover the part in question. Spare items can then be located in the provided Repair Kit, and the spare item should be ordered and replaced in inventory in case of future failure.

If a glove is used to encase the hand, it would be an off-the-shelf component as well, and is very prone to wear and tear. It will most likely require frequent replacement whenever it begins to stretch, rip, and wear down.

6.6 Safety Considerations

Since this prosthetic device will be used by a person, it is important that any safety hazards are made clear to the user to avoid unintentional harm. Additionally, the product was designed to take into account all possible modes of failure in order to make it as safe as

possible. Cable tension is an important factor, for excessive tension could cause the cable to snap and recoil the user. To prevent this from occurring, one end is fixed in place while the other end is attached to the tensioning block, which adjusts the length of the cable. This block is kept in place with a screw, and the cables will be covered with a special glove. While there are some small pinch points at the finger joints and the wrist joint, they are avoidable so long as the prosthetic hand is attached to the user's residual. In order to avoid the chance of overexerting the fingers, the parts will be made of direct metal laser-sintered titanium, so that the pins will break before the fingers.

6.7 Future Prototype Improvements

A prototype was made from ABS plastic and sourced off-the-shelf parts to conceptualize the final design. Specifically, the prototype was meant to test our dimensions and fit, appropriate selection of fasteners, the locking mechanism functionality, and overall function. The prototype is shown in Figure 44 below.

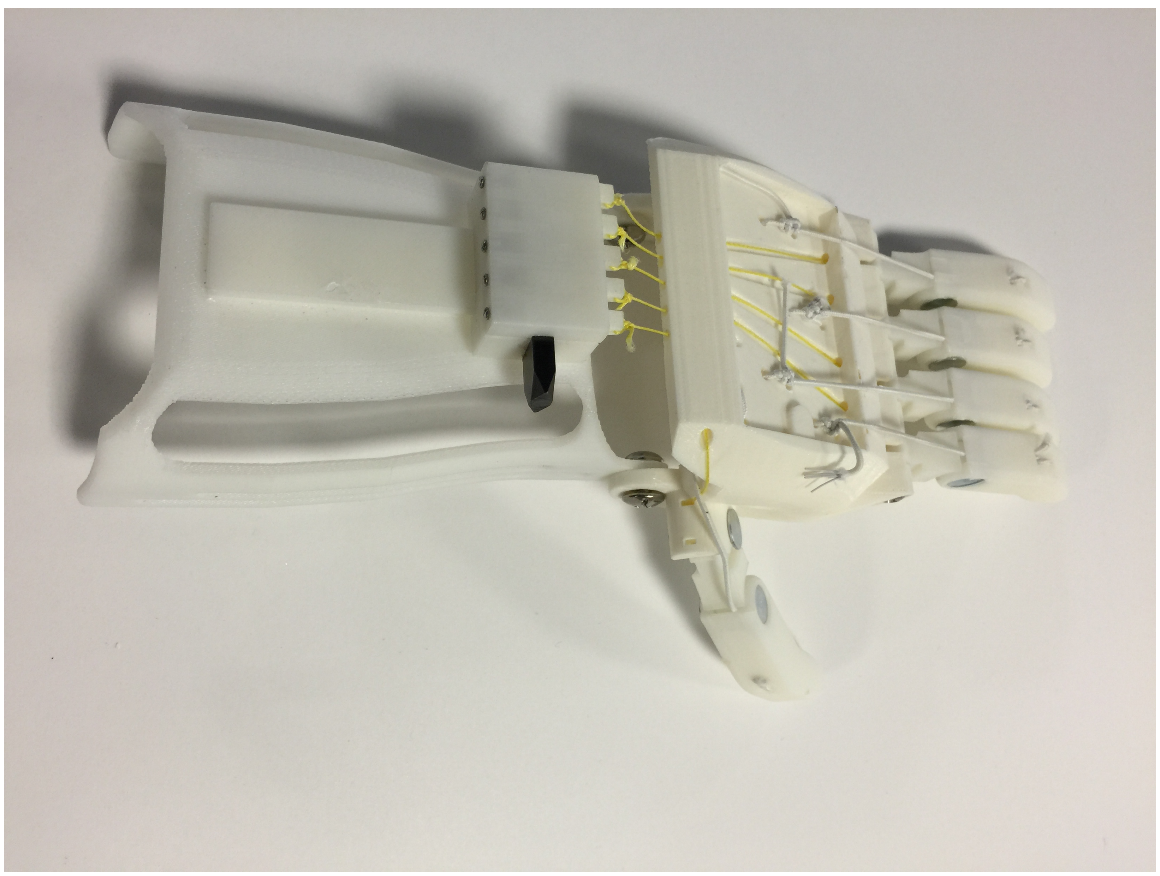


Figure 44: ABS Conceptual Prototype

The dimensions of the prototype are for the most part very good. All parts mate appropriately and with good clearance or interference where required. Fingers move easily about the hinges and all fasteners fit. The finger and palm passageways were built assuming a flexible cord diameter of 1/16 in. would theoretically fit. However, when

building the prototype, it became obvious that more clearance is needed to fit and thread a 1/16 in. diameter cord. In this design, space is at a premium, and large string passageways may not be possible in some areas such as the fingers. Some walls were made thin to accommodate the passageways, and upon one trial of actuation have already fractured. Designing appropriate string passageways in the fingers and palm will be critical in the next iteration. The wrist component fractured while being removed from the printing tray. In a way, this was a great misfortune; because it made it obvious to us there is a large stress concentration at the wrist. This stress concentration has since been removed from the part's design by increasing the cross sectional area along the wrist.

The locking mechanism was designed to lock a grip by unscrewing the main bolt, pulling back the tensioning system, and essentially putting the system into a passive-closed mode. The intention was for the user to have either a passive-open or passive-closed grip. With this prototype, we learned this was not likely to work as intended. If put in an active closed grip while the user is not wearing the prosthetic, the palm is flung backwards, making the prosthetic difficult to both actuate and place back on. If the user is wearing the prosthetic while put in passive closed mode, the user's wrist could fling back, making this a major safety concern. The grip locking mechanism will have to be redesigned for the next design iteration.

The fasteners were all selected alongside the design process, leading to a successful implementation during assembly. All fasteners perform and fit well. Even the threaded ABS plastic parts function well.

Overall, the prosthetic does complete a half actuation. The thumb actuation knocks into the palm, preventing further actuation on all fingers and causing an incomplete grip. The thumb position will have to be redesigned during the next iteration.

6.8 Material Selection and Justification

The material selected for this mechanical prosthesis has to be durable, lightweight, and non-corrosive due to the extreme conditions in which it will be used. The material that we selected will be a titanium alloy because of its strength to weight ratio and favorable material properties. Many different materials can be selected for the structural components, ranging from ABS plastic to other DMLS-printed metals. This choice depends on the monetary resources and strength requirements of the user. Titanium was by far the most advantageous choice for our customer, for the aforementioned reasons; however, different end customers might have different justifications for the use of different structural materials.

Since our prosthetic hand will be made from a strong alloy, we decided to implement some off the shelf parts in our finger and wrist joints; these parts will be made out of steel, which will allow our customer to replace any pins that might fail. Since the finger joints have high concentrated stresses, we choose a material that is not as strong as titanium. Further

supporting our choice of steel joints is the fact that steel and titanium do not exhibit galvanic corrosion when in close contact and in corrosion-conducive environments.

The cable used for the spring-back of the fingers is an elastic stretch cord that is resistant to abrasion, mildew, and UV sunlight. The cord used to actuate the hand and hold a grip needs to be very strong, as the tension in the cable is more than 10 times larger than the inputted force per finger due to a much smaller moment arm around the pivot points in the fingers. Therefore, a strong cable is necessary. 100 lb. test spectra fiber is used in the prototype, but a stronger cable will need to be used for the final design. This cable will likely be made of a similar material, just thicker and more robust.

The silicone attachment sleeve was chosen because of its great comfort and suction abilities, as well as its unobtrusive nature in allowing the user to maintain full range of motion of his wrist.

6.9 Engineering Analysis

During the design process, engineering analysis was completed in order to ensure that this design would adequately handle the rigors of military activity. The analysis was focused on determining the stress in the load-bearing members, including the pins, finger members, and palm, as well as the tension in the cables, under various loading conditions. The analysis was simplified to reduce unknowns and accelerate trade-studies; however, all simplifications that were made were chosen so that they would represent worse cases than would actually be encountered during normal use.

As the analysis was extensive and equation-heavy, it will not be included in this report. However, the results will be discussed to prove the robustness of this design.

The first analysis that was completed consisted of determining the loading on the pins and in the non-flexible, load bearing cable. This was computed with a vertical load with respect to the ground at the fingertip (which is a simplification that yields a worst-case result), and at intervals ranging from an open grip (angle of zero degrees) to a closed grip (angle of ninety degrees). The input load that was deemed worst-case was a load of 250 pounds, to account for the full body weight of the user plus any equipment he might be wearing. Assuming evenly distributed loads across the four fingers, the fingertip load would be 62.5 pounds. Since the applied load on the hand was simplified as a point load at the very tip of the hand, this creates much larger reaction forces in the hand components as the moment arm of the load is much greater in this scenario. The resulting loads in the pins and cable are graphed over grip angle, as shown in Figure 45 below. The grip angle that causes the maximum reaction forces in the cable and pins was then chosen to be the worst-case load.

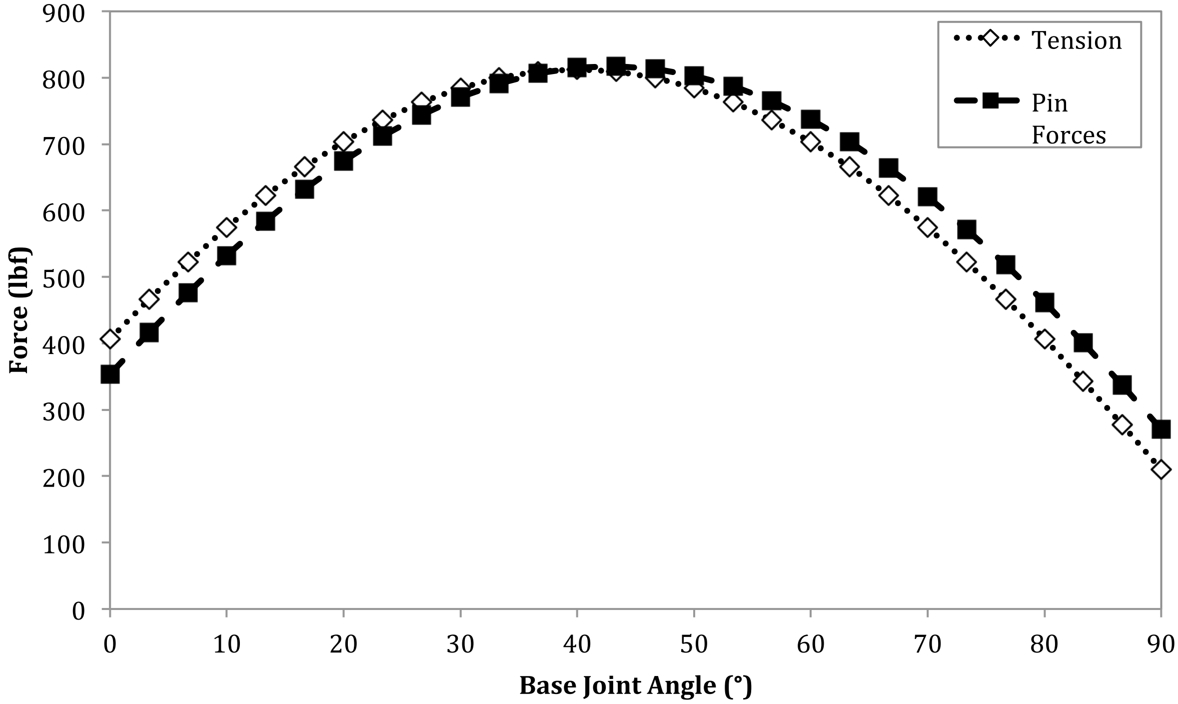


Figure 45: Plot of the tension in the non-flexible cable and the forces in both pin joints in one finger, as a result of the worst-case loading condition described in the text above.

With these calculated forces, the stresses in the pins were calculated to ensure that they would be able to withstand the worst-case loading condition. The stresses were compared to the material strength, and the factors of safety were computed. Next, the stresses in the structural finger members and palm interface were calculated based on the pin forces, cross-sectional area, and stress concentrations. The resulting factors of safety for the pin joints in the finger and hand are included below in Table 8. All factors of safety were in an acceptable range, especially considering the overestimation of the loading conditions.

Table 8: Factors of safety for the simplified, exaggerated loading conditions. All factors are above 1, meaning that there are stresses lower than the material's strength limits.

Analysis	Result
Pin Stress	16,650 psi
Pin Factor of Safety	3.60
Base Member Stress	8,380 psi
Base Member Factor of Safety	7.52
Tip Member Stress	28,683 psi
Tip Member Factor of Safety	2.20

Another loading case that was examined in this analysis was if the hand was subjected to impact loads perpendicular to the fingers when in passive-open position. This would be experienced, for example, if the user smacked his hand inadvertently on the table with the

four parallel fingers. This design features stopping blocks at the top of the finger members so that the fingers do not rotate backwards past a completely flat position. These members therefore counteract the moments caused by the impact load, which means that the pin joints themselves only experience the same load as the impact forces. Thus, the pin joints will definitely be able to withstand any reasonable impact loads in this configuration to which the user subjects it; moreover, the user will likely be cautious of even subjecting the hand to high impact loads because of psychological reasons. Regardless, analysis was carried out to determine the allowable impact load on the hand; this force is dependent on the area of the stopping features that react to the applied force by jamming together. This force came out to be approximately 600 pounds, which is very high and not likely to be reached or exceeded.

The third and final loading case that was analyzed was if the finger was subjected to lateral forces; such as if a finger got snared on an object during rapid hand movement. This is important because the fingers were designed to mainly support loads in the plane coincident with the forearm, which is where most loads are encountered. However, we want this prosthetic to be able to withstand more demanding military activities, so we needed to ensure that the hand could withstand unexpected loads in unexpected orientations. This load was analyzed as a point load at the fingertip with the finger in an open position, again contributing to a worst-case scenario as the moment arm is at its greatest in this orientation. The weakest part in the finger in this loading scenario was determined to be the tabs that interface with the two members and the pin. The maximum allowable impact force was calculated using the material strength of the titanium; this value ended up being around 1500 pounds, an incredibly high impact force that is extremely unlikely to ever be encountered. Given that this loading condition was worst-case, it is safe to say that this hand will not yield when exposed to reasonable lateral loading.

The analysis on this design confirmed the feasibility of this design. Slight adjustments to dimensions might be made to further improve the strength of the structural components, and stronger cable will likely be chosen due to the high tension it will experience. Hand calculations for this analysis can be found in Appendix J.

6.10 Cost Analysis

Cost is an important consideration for this project, not only for the sponsor who will be providing the funds to complete the prosthesis, but also for future parties who wish to duplicate this design, as this design will be provided to the open source community upon completion. It is important to note that this prosthesis can be produced in many different materials, ranging from plastic to vinyl to titanium, using any rapid prototyping process. Therefore, the cost will vary significantly depending on the process used. The cost analysis completed for this project was conducted for the prosthesis that will be built directly for our customer, and therefore reflects solely the design that is proposed in this paper and is not indicative of all options that are available in future prototypes of the design.

It is also important to note that the main cost of this design is associated with the DMLS-printed titanium parts; however, this cost will not need to be paid by our sponsor as we have received a generous grant from Solar Turbines, who have offered to donate their time and resources to provide us with DMLS-printed titanium parts free of charge. Table 9 below shows the cost analysis for this design; the costs for the DMLS-printed parts were determined via quotes from a prominent company who offers DMLS-printing titanium services.

Table 9: Cost analysis for the production of our final design.

Items	Proposed Cost	Actual Cost
Tensioning System Components	$2,836.00	$0.00
Palm	$4,708.00	$0.00
Forearm	$4,970.00	$0.00
Finger Components	$5,380.00	$0.00
Fasteners, Cords, and Taps	$57.60	$57.60
Suction Sleeve and Interconnect	$700.00	$700.00
Total	**$18,651.60**	**$757.60**

It should also be noted that, as the dimensions of this design should be changed for each individual user, and the cost of rapid prototyping does not necessarily reduce drastically with increased volume of production, a mass-produced cost estimate is not feasible for this product. It is done on a customer-by-customer basis, depending on size and strength requirements and the desired end cost, as many different materials can be used.

A prototype was made from ABS plastic; a cost breakdown of the design is included below in Table 10. The "Fasteners, Cords, and Taps" cost is listed as zero for the actual cost because these components will be removed from the prototype and installed on the final design when completed. The proposed cost was based on quotes from Shapeways, a company that offers 3D-printing services at a fairly steep cost. Much cheaper options are available for users who wish to make this hand out of plastic, as we found a resource on campus at Cal Poly who built it at material cost, which was only $27. This cost analysis is representative of the cost that a user would have to pay in order to make a simplified version of this design, without the silicone sleeve attachment mechanism.

Table 10: Cost analysis of ABS prototype.

Items	Proposed Cost	Actual Cost
Tensioning System Components	$871.00	$0.00
Palm	$493.00	$27.23
Forearm	$294.00	$0.00
Finger Components	$1,420.00	$0.00
Fasteners, Cords, and Taps	$57.60	$0.00
Total	**$3,135.60**	**$27.23**

7.0 Final Design

The design process used in this project was highly iterative, due to the nature of creating functional prosthetic devices that are unique to the individual for which the prosthetic is created. Many design elements were designed, built, tested, and modified several times in order to ensure that the final design would be both ergonomic as well as mechanically sound. The evolution of the design is evident through the development of this report. The final deliverable to our customer is pictured in Figure 46 below and is described in the section below.

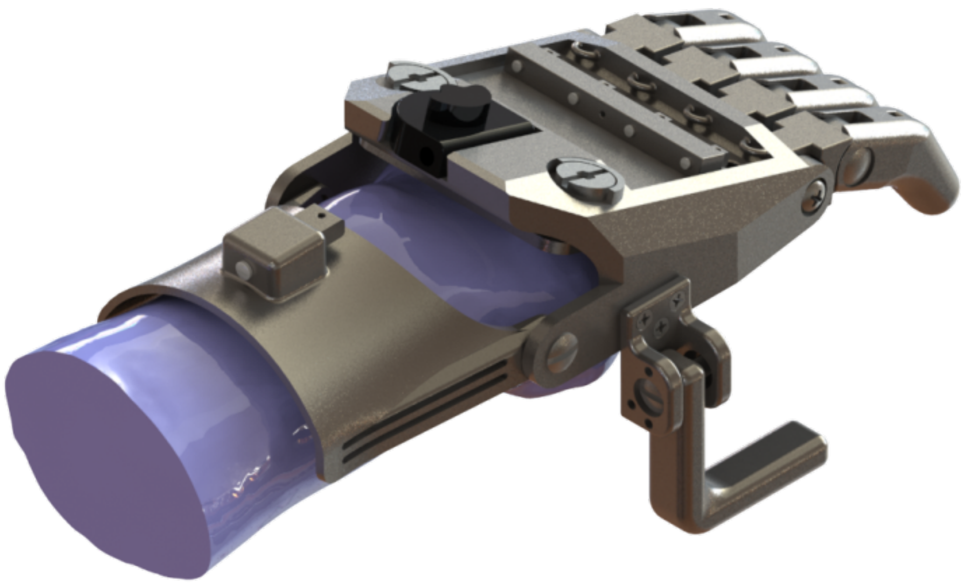


Figure 46: Digital rendering of the final design as delivered to the customer, without actuation cables attached.

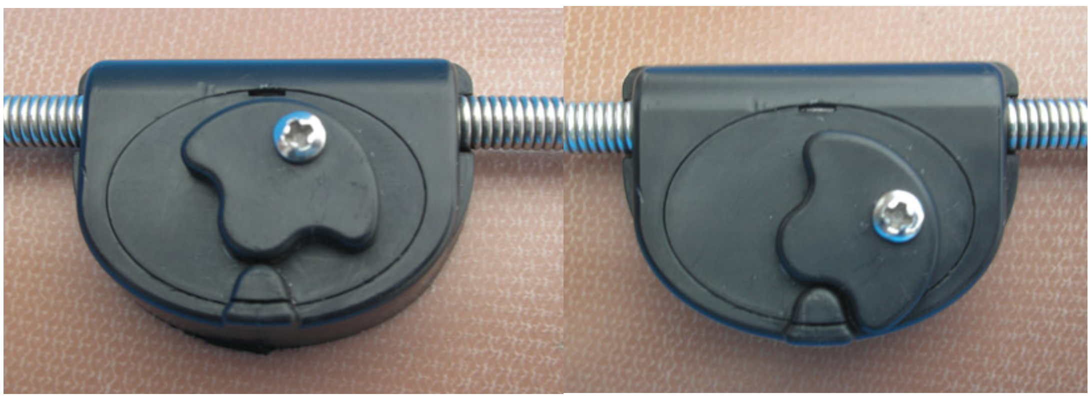
The final design operates under the same principles that were decided upon at the first iteration stage. The prosthesis is wrist-actuated, with wrist flexion creating tension in cables which pull the fingers to a closed grip. The prosthesis features a locking mechanism that enables the user to release wrist flexion while still maintaining a firm, closed grip; this enables the user to carry heavy objects for long periods of time. The hand attaches to the user's residual via a silicone suction sleeve molded specifically to the customer's arm. All of the fasteners are standard and off-the-shelf for maximum part replace-ability and strength, and the strengths of all manufactured parts were maximized using a DMLS Titanium manufacturing process.

The main deviations of this final iteration from the previous are the exact locking mechanism employed, the cable routing, the attachment mechanism to the user's residual, the fingers, and the thumb. These are described in the sections below.

7.1 Detailed Description of Final Design

Locking Mechanism:
After several iterations of self-designed and manufactured locking mechanisms, the locking mechanism found in the final iteration of this prosthesis is an off-the-shelf product made by TRS Prosthetics called the "Sure-Lok". This increases not only the part replace-ability in the design, but also ensures that a well-tested, proven product is used in our prosthesis that is certain to withstand the customer's demands.

The locking mechanism is very simple; it consists of a housing through which a single cable passes (in this design, a bicycle brake cable is used). Inside of the housing is a spring-loaded cam, which rotates about a fixed point. A picture of the Sure-Lok mechanism is found below in Figure 47.



(a)
Locked Position

(b)
Unlocked Position

Figure 47: Picture of the Sure-Lok from TRS Prosthetics, used in this iteration to lock the main actuation cable and allow for a grip to be maintained without maintaining wrist-flexion.

When the user wishes to lock a grip, he/she rotates the cam into the "lock" position, which rotates the cam until it jams the cable against the inner wall of the housing. The spring-loaded cam then locks itself in place when the cable is jammed tightly against the housing wall, maintaining tension in the cable ahead of the cam and allowing for tension to be relaxed in the cable behind the cam. This enables the user to release wrist flexion once the desired grip is achieved and locked. An additional feature of this locking mechanism is the ability to initiate the locking feature before the grip is achieved. This allows the user to rotate the cam into the "lock" position, then actuate the hand until the desired grip is achieved, then release wrist flexion while the lock maintains tension.

Cable Routing:
Because the Sure-Lok locking mechanism operates with a single cable, the cable routing system for the prosthesis had to be redesigned. A bar was designed that would transfer the actuation input from the single cable that extends from the gauntlet and through the Sure-

Lok, to the individual cables that are needed to actuate the four fingers of the hand. The bar contains four miniature sliding-block tensioning systems that allow for the user to fine-tune the tension in the four individual actuation cables and allow for a uniform closed grip to be achieved. A computer rendering of the cable bar mechanism is found below in Figure 48.

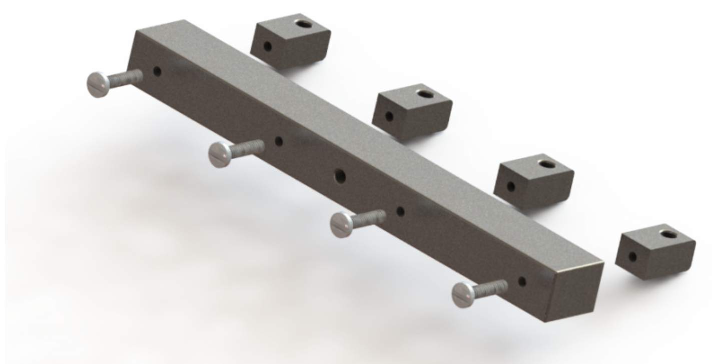


Figure 48: Exploded view of the cable bar used to transfer actuation tension from the single cable that extends to the forearm of the system to the individual fingers.

Attachment Mechanism:

One of the main goals for this project was to create a prosthetic device was not only functional, but one that was comfortable and ergonomic for the user to wear. It was decided early on that a silicone-molded suction sleeve would be the best method of creating a uniformly-distributed, rigid attachment to the user's residual, as opposed to the Velcro straps used by previous project. A rigid attachment to the user's arm allows for a higher degree of proprioception for the user, meaning that he will feel like the prosthesis is actually a part of his body as it will not be wobbling around on his arm during use.

The silicone attachment sleeve will be designed and custom-molded by our customer's current prosthetist upon the completion and assembly of the rest of our design; however, an additional rigid attachment method was needed to secure the sleeve to the prosthesis. A simple plate was designed that would include cylindrical, internally-threaded bars that extend vertically from the plate base. This plate will be embedded in the silicone material of the sleeve, allowing the bars to extend up and into cavities in the palm structure, where threaded thumb-screws are to be tightened down on the threaded bars until the sleeve is secured rigidly to the palm. This mechanism is depicted below in Figure 49. The screws used are off-the-shelf fasteners with a low thread count and large head for easy tightening.

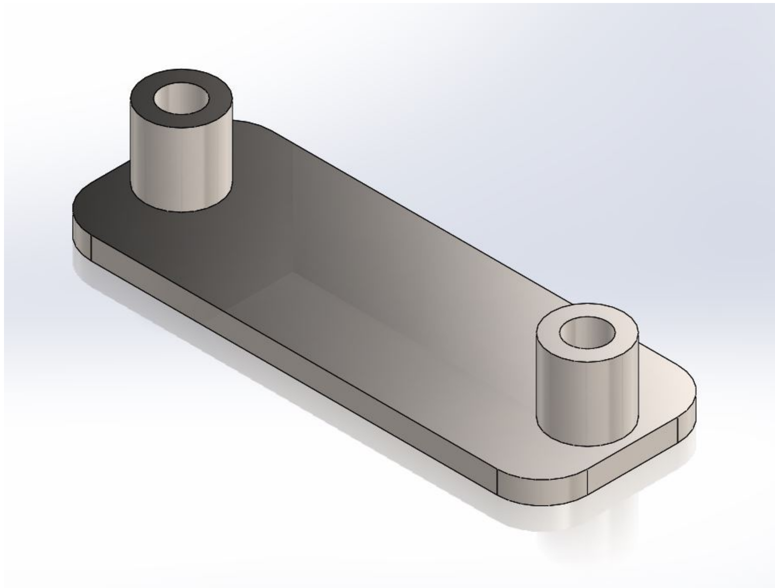


Figure 49: Rendering of the plate that is to be embedded in the silicone suction sleeve that encases the user's residual, providing a rigid attachment and thereby increasing proprioception of the prosthetic device.

Fingers:

The fingers in this final iteration are very similar to the previous iterations, with the exception of a few modifications to ensure smooth actuation and increased strength. After testing the fingers from previous prototypes, it was determined the actuation of the topmost member was too excessive while the lower-most member was not inclined to rotate as much. For this reason, the fingers were modified by making their default, open positions to be slightly angled downward, giving them a "head start" in actuation so that both members are equally inclined to rotate downward.

Additionally, the cable passageways were optimized based on test results from previous prototypes, and the finger members were opened up in critical locations to reduce pinch points and increase the smoothness of actuation. These modifications and attributes are seen in Figure 50 below.

Figure 50: Computer rendering of finger assembly, featuring the modifications and improvements mentioned in the text above.

Thumb:
The thumb in this final iteration is one of the most drastic deviations from the previous iterations. Previously, the thumb was actuated along with the fingers and was identical to the finger members aside from its placement on the hand. However, testing of this prototype revealed many problems with this design, as it contributed to an unnatural and unfeasible gripping motion.

The new thumb design is much more robust and useable, consisting of a single rigid thumb member that rotates about a Chicago screw in a base member. The thumb rotates along an axis parallel to the user's arm, allowing for much more realistic grip achievability. The thumb is able to be rotated into three different positions through a simple spring-loaded mechanism that pushes a peg on the thumb member into one of three corresponding holes in the base member. In order to move the thumb to a new position, the user has to push the thumb (compress the spring) in a direction opposite the loads that would be encountered by the user, drastically reducing the propensity for inadvertent thumb adjustments. This mechanism also allows for the thumb to be rotated completely out of the way, allowing for just the fingers to open and close in case an oddly-shaped object is to be carried, or exercises such as pull-ups are desired to be completed by the user. This mechanism is shown in a computer rendering below in Figure 51.

Figure 51: Computer rendering of the thumb mechanism found in the final iteration of this design. This rendering does not depict the compressed spring, which is concentric with, and located around, the Chicago screw pin of the assembly.

7.2 Geometry, Material, and Component Selection

Geometry:
Early in the design process, it was decided to define the prosthetic as a reflection of a human hand instead of a realistic interpretation of a hand. Our prosthetist informed us that hyper-realistic prosthetics tend to appear eerie if not emulated accurately. The geometry of the palm, fingers, gauntlet and joint all appear and move as human-inspired features. The closed grip is performed by four gripping fingers and a stationary thumb,

similar to the way a human hand grasps. Another geometric consideration was to include fillets and rounds where possible to avoid sharp edges.

The prosthetic is modeled around the user. The gauntlet and palm inner-geometry is based on a three-dimensional image scan of the user's residual. The silicone sleeve, made by the prosthetist, is formed from the inside of the gauntlet and palm. The prosthetic is essentially formed around the user.

Material:

The final product is made from direct metal laser sintered (DMLS) titanium, specifically from a powdered Ti6AlV4 alloy. This material has an ultimate tensile strength of 166 ksi and a yield strength of 150 ksi. Titanium is an excellent material for high strength design requirements where minimizing weight is of great importance. Not only is the titanium itself a low-density metal, in addition the DMLS process can print at a specified density, resulting in an overall lightweight and high-strength finished product.

The non-flexible cable is Spectra 400, a type of Spectra made specifically for prosthetic use with a high load capacity of 400 lb. Spectra 400 is an excellent material for this application because of it's high strength and weather resistance. Most cabling with a small diameter tend to deform plastically with a small load, though Spectra tends to remain unstretched with high loads.

The sleeve interfacing the prosthetic with the user is casted by the prosthetist from silicone. Silicone allows for suction between an organic surface, such as a residual, and the silicone itself. This creates the vacuum effect required for attachment. Silicone is often chosen for medical applications because of it's ability to resist bacteria growth.

The flexible cable is made from an elastic material wrapped around a nylon core. This cable is not load bearing, therefore high strength properties are not required when selecting this cable. From trial and error, it has been determined that most bungee-type cabling bought from a standard craft store works for this prosthetic.

Component Selection:

Chicago screws were selected as the finger and base pin joints because of their smooth outer surface and ease of replacement. A typical screw cannot be used for pin joint applications since sharp threads can shear away material. Press-fit pins could be used, however this would require special tooling to remove and replace.

The Navy SEAL has sensitive nerves in his right thumb. The fastener connecting the residual to the palm is used each time the user attaches and detaches the prosthetic.

Therefore, for comfort and convenience, a hinged D-ring pull-tab fastener was selected. The hinged ring is easy to pick up and turn, especially since it requires no extra tools. The hinge is low profile, minimizing the potential safety risk of getting caught on something.

The Sure-Lok is a lightweight, small footprint, cam locking mechanism that allows for the user to lock a grip, without needing to strain their wrist. The Sure-Lok was chosen based on its effectiveness and reliability in prosthetic use. Team Manus also implemented a Sure-Lok in their design.

Since the prototype is made primarily of a titanium alloy, galvanic corrosion had to be considered when selected fasteners. Titanium is a cathodic metal, therefore it had to be paired carefully with non-anodic metals. An anodic metal would tend to corrode the titanium. Most fasteners were selected from grades of stainless steel on the more cathodic side of the galvanic corrosion scale (see Figure 52) rather than anodic to prevent this issue.

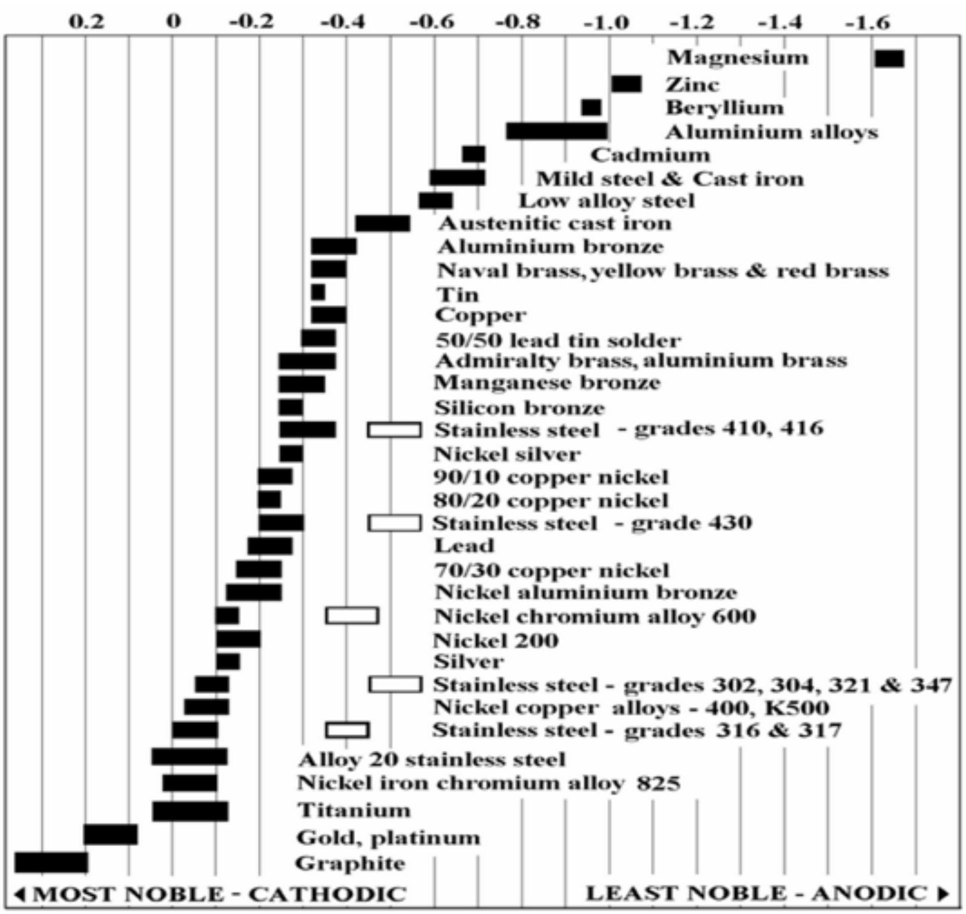


Figure 52: Galvanic Corrosion Scale
[http://www.corrosionist.com/galvanic_corrosion_chart.htm]

7.3 Manufacturing

A majority of component in the prosthetic hand assembly are made from direct metal laser sintering titanium, a resource provided by Lawrence Livermore National Laboratory.

Direct metal laser sintering (DMLS) is a net-shape and additive manufacturing process which fuses metal powder together via a high power laser, layer-by-layer, into a shape specified by a.stl file. The term "sintering" is a misnomer, as the laser fuses the metal powder locally. Metals typically used in this process include alloys of titanium, steel, and aluminum.

The manufacturing process starts with having a metal build plate placed into the print bed. A device brushes over one layer of powder onto the heated build plate, then the laser begins fusing the geometric slice specified for that layer (z=0). The powder brushing and laser process repeats in each z-slice until the part is complete. Powder is removed from the part within the machine to be recycled. The parts (still attached to the build plate) are removed from the machine. Typically, these parts are machined, electric discharge machined (EDM) or sawed off the build plate, then finished with a machine or EDM machine until the correct shape is achieved. The surface finish is rough, thus an abrasive finishing process may be desired, depending on the design's intended use.

The strength and accuracy of the parts depends on the parts orientation within the machine. Layers made relative to the X-Y plane are stronger than layers relative to the Z plane as the fusion of powder particles is more concentrated in the X-Y plane. Parts built in the center of the build plate tend to be stronger than parts near the edges of the build plate because of the laser focusing geometry, though this effect varies by machine. DMLS can product a part with high strength, thus it is emerging as a production-ready additive manufacturing process. Part resolution is more accurate relative to the X-Y plane than in the Z plane. A support structure is built along with the object to insure part accuracy in areas where overhangs are present. The support material must be cut away with a machining or EDM process.

The ability to make unique geometric features and strong parts, rapidly, without special tooling are the main advantages while considering the use of DMLS for this project. Features such as hollowed out finger parts, lattice low-density structures, or string passageways that are possible with DMLS are difficult or impossible to achieve with standard manufacturing methods (i.e. milling or casting). DMLS machines are expensive. The perfectly sphered powdered metal itself is a precise and expensive commodity. Thus, DMLS is often a cost prohibitive process.

7.4 Prototype Differences from Planned Design

The final prototype that is to be submitted to our customer is slightly different from what was originally desired, due to time constraints and unforeseen complications. The main

deviations from the final prototype of this design and the planned design are simply the lack of soft parts in the finger and palm, as well as the lack of a fitting with our customer and therefore the possible need for slight adjustments of dimensions for an optimum fit. Due to the iterative approach of our design and the outsourcing of the DMLS Titanium manufacturing process, we were able to include many of our final design elements into our final prototype submitted at the conclusion of this project. Notwithstanding, there are several recommendations for future work outside the scope of our project that are discussed in the following section.

7.5 Final Cost Analysis

Below in Table 11, the cost is broken down by system. The only costs associated with this project are those of the fasteners, cord, taps, miscellaneous supplies, as well as the anticipated expense of the silicone sleeve and interconnect from the prosthetist. We were extremely fortunate to have such a cutting-edge resource provided by LLNL, for we easily saved over $10,000 from this partnership.

Items	Cost
Sure-Lok	$0.00*
Palm, Forearm, Fingers, Cable Bar	$0.00†
Fasteners, Cords, Taps, and Supplies	$384.11
Suction Sleeve and Interconnect	700.00^{\Delta}$
Total Cost	**$1,084.11**

Table 11: Final Cost Breakdown

*Used from Team Manus supplies
†DMLS parts donated by Lawrence Livermore National Labs
$^{\Delta}$Parts from prosthetist will be made once titanium assembly is complete

8.0 Design Verification

When it came to perform testing, it became apparent that we would not be able to do so with the titanium prototype due to the delays by LLNL. As a result, we decided to take data using our most recent prototype to at least get an approximate assessment of the design and functionality. Also, due to time constraints, we prioritized tests that we deemed to be most feasible and meaningful. The tests we narrowed down, along with descriptions and acceptance criteria, can be seen below in Table 12.

Item No	Specification or Clause Reference	Test Description	Acceptance Criteria
1	Grip Strength Test	Measure load capacity of grip with weight increments of 25 lb	150 lb.
2	Actuation Cycle Time	Measure period of time to actuate from a closed grip to an open grip, back to a closed grip again for a full cycle	< 2 seconds
3	Actuation Sensitivity	Measure input angle required for user to achieve a full grip closure output	25°-35° wrist flex per grip closure
4	Repair Assembly Time	Time to complete common repair assemblies of the prosthetic hand, including: cord replacement, fastener replacement, tension realignment	< 20 min. per repair
5	Weight	Measure the weight of the prototype on a scale	< 2 lb.
6	OTS Parts	Measure proportion of non-DMLS parts that are OTS	> 75% of non-DMLS parts

Table 12: Test descriptions and acceptance criteria.

On the following page, Table 13 displays the test date, the contingency plan, what equipment is required for testing, as well as the test results.

Item No	Specification or Clause Reference	Test Date	Contingency Plan	Equipment Required	Results
1	Grip Strength Test	5/29/15	realign the string placement with respect to the Sure-Lok, reevaluate locking mechanism	Weights, various	25.9 lb. before grip-locking
2	Actuation Cycle Time	5/29/15	tighten the flexible cord, remove debris from passageways	Timer	1.2 sec.
3	Actuation Sensitivity	5/29/15	reroute and realign cables and passageways, reorient tensioner system, use a lesser durometer at sleeve to prevent motion inhibition	Camera, photo editing software	18.57° input for full grip closure
4	Repair Assembly Time	5/29/15	pre-assemble sub-assemblies, provide pictorial instructions	Timer	cord replacement: 12 min fastener replacement: 2 min tension alignment: 14 min
5	Weight	5/29/15	hollow out more part sections, design less bulky geometries	Scale	0.6 lb.
6	OTS Parts	5/29/15	use more OTS parts	N/A	100%

Table 13: Test date, contingency plan, equipment required, and results.

The grip strength test of the prototype (Item No. 1 in Tables 12 and 13) is detailed in Appendix E. This test identified that Sure-Lok jamming begins to occur when the applied load is at or greater than 25.9 lb. Sure-Lok Jamming is an easily fixable occurrence, though it requires a special procedure to unjam, thus it is valuable for the user to know when to expect jamming. The finger repositioning effect is lessened in the titanium model because of stoppers built into the finger and base joints. Due to not having the titanium parts finished in time, testing had to be done with a PLA plastic and titanium hybrid prototype. The testing was limited in order to not break the prototype. To gain insight on the ability of the prosthetic to sustain a grip under a load, further testing with all titanium parts is required.

The actuation cycle time measures how long it takes to actuate and grip, let go, and bring the prosthetic back to the original position. Delays in actuation can be caused by friction in the string passageways or friction at the interfacing joints. The actuation cycle time was

measured with a stopwatch to be 1.2 seconds, less than the goal of 2 seconds. A smaller time is better, and can be achieved by sanding down the interfacing components to get rid of rough surfaces.

The actuation sensitivity test is detailed in Appendix F. The input angle for a full grip closure was measured to be 18.57°, under the ideal range of 25° to 35° input. The test results indicate this prosthetic is too sensitive. The titanium model has a tensioning system for the Sur-Lok cable to make the input angle adjustable, thus sensitivity is not expected to be an issue.

The repair assembly time test measures how long it takes to perform repairs common with this prosthetic: cord replacement, fastener replacement, and tension realignment. The cord replacement of a flexible and non-flexible cord on one finger was timed at 12 minutes. Adding super glue to the ends of the cabling help to thread the cord into the passageways. Replacing a chicago screw was timed at 2 minutes, well under the 20 minute goal. The adjusting of tension was performed on an earlier prosthetic and timed to take 14 minutes. The tension adjustment is a fine tuning process, therefore can take the longest of all repairs.

The weight of the PLA and titanium hybrid used for testing was 0.6 lb. Similar fasteners were used in this prototype that will be used in the final design. However, the PLA is lighter than titanium, thus we expect the final prototype will be heavier, at approximately 1.9 lb., depending on the density of titanium specified in the final DMLS parts. This estimation lies under the 2 lb. limit. If further weight reduction is required, the titanium parts can be specified to print at a lower density (incorporating lattice structures) and more parts can be hollowed out. The weight requirement goal of 2 lb. is to reflect the weight of a human hand in order to keep the prosthetic comfortable for long periods of wear.

The ratio of OTS parts to non-OTS parts for non-titanium parts was 100%. A goal of 75% was set to keep the prosthetic repairable with easy to find, store bought fasteners in case replacement was necessary. All non-DMLS parts were OTS, therefore our goal was met.

9.0 Project Management

The following roles listed below have been assigned to the members of Team ProstheTech and will ensure that the team has a fair division of labor, effective use of time and resources, and an overall successful senior project experience.

Project Manager and Design Engineer: Michael Friedman
- In charge of scheduling, organizing, tracking, and communicating all project logistics
- Treasurer, responsible for managing project budget
- Creates presentations and expo poster, compiles and edits reports

Manufacturing Engineer and Human Interaction Designer: Heather Martin
- Optimize design for manufacturability and assembly
- Oversees that all designs are intuitive and optimized for human interaction
- Keeping in contact with the project sponsor

Mechanical Engineer and Military Expert: Jose Lemus
- In charge of prosthetic mechanism design
- Provides military expertise when making project decisions
- Creates detail drawings

Design Engineer and CAD Manager: Ryan Burke
- Responsible for the overall design
- Oversees SolidWorks modeling
- Tracks design revisions
- Performs engineering analysis

In order to maintain appropriate progress throughout our senior project, a Gantt Chart was developed in Microsoft Project. Major milestones, which are listed below in Table 14 were mapped out as diamonds, and tasks were planned out to ensure deadlines are met.

The remainder of Fall Quarter and the first couple weeks of Winter Quarter will be spent on detailed design work, which will involve material selection and subsystem analysis. From there, a SolidWorks model will be created based on the results of the design analysis. The manufacturing time for the silicon sleeve we plan to design could be very long, so planning ahead with preparing the design and ordering the part is essential. Detail drawings and a Bill of Materials will be created to document the SolidWorks design and product components. In addition, a Final Design Report will be compiled halfway through Winter Quarter to summarize the work up until that point, along with a corresponding presentation to the senior project class and our sponsor. Once we receive feedback from our project advisor and sponsor, we will make further design modifications that will be reflected in the next iteration of the SolidWorks model. The last couple weeks will involve manufacturing and assembly the next prototype iteration.

Once we have a built prototype by the start of Spring Quarter, modifications will be made prior to sending files to LLNL for manufacturing. The remainder of Spring Quarter will be spent making design modifications, testing to verify design requirements, putting together the Final Project Report and preparing to display our findings for the Senior Design Expo, which will happen at the end of May.

Table 14: Project milestones and dates.

Milestone	Date
Meeting with Customer	Week of Monday, November 10th
Preliminary Design Report	Friday, November 14th
PDR Presentation	Week of Monday, November 17th
Meeting with Prosthetist	Friday, January 9th
Final Design Report	Tuesday, February 3rd
CDR Presentation	Week of Monday, February 2nd
Senior Design Expo	Friday, May 29th
Final Project Report	Monday, June 8th

10.0 Conclusions

Although our design met most of the requirements we established at the beginning of this project, there are several aspects that can be improved for future manufacturing of our design. Firstly, weight-relieving measures should be taken to make this prosthetic as light as possible without greatly impacting the structural integrity of the hand. Throughout the project, we were unsure of the final material and corresponding material properties that our final prototype would feature. Therefore, we were hesitant to remove too much material in case we had to settle for a weaker material, which would compromise the strength of the hand. Since we are now certain that our design will be produced out of Titanium, despite the relatively low density of the material, the weight should still be reduced to increase the ergonomics of the hand. Locations for possible weight reduction are the hollowing out of the finger tips and overall slimming of the palm structure, especially at the inside tip of the residual cavity, near the cable passageways. Additionally, there are several post-DMLS production measures that should be conducted in order to ensure the best possible strength and surface finish of the parts. The final prototype that we are submitting to our customer features DMLS Titanium parts that went straight from the DMLS machine to the machine shop for rough finishing and then to the assembly. However, the DMLS process leaves a significant amount of residual stresses in the printed parts; for the final production of this hand, the parts should be annealed to reduce these residual stresses. The manufacturer of our hand, Lawrence Livermore National Laboratory, has agreed to carry out this process for the final production of the hand. Sandblasting or bead blasting should also be done on the parts to ensure the optimum surface finish for aesthetics, comfort, and safety of the hand.

One of the main aspects of our design that might need to be adjusted for future work is the overall fit for our Navy SEAL. Since all of our work was based off a 3D scan of his residual, which was taken several years ago, we are not entirely sure if our parts will fit as comfortably as possible. We left room for the Navy SEAL's prosthetist to mold the silicone sleeve to interface as closely as possible with his residual, but it is highly unlikely that this first prototype will fit him perfectly. In the event that there is a significant issue with the fit of this device to our customer, some final dimension adjustment will likely be needed. The locking mechanism used on this hand (Sure-Lok by TRS Prosthetics) is only able to lock one single cable, meaning that the only grip that can be locked and held is a grip with all of the fingers closed. This was selected for many reasons, namely simplicity, part replace-ability, and reduction of failure modes associated with multiple complex mechanisms. We wanted to make sure our customer was able to complete the most rigorous tasks as well as possible. However, this is fairly limiting design if the user has a desire to hold many different grip orientations; if single-finger articulation and locking is requested, a similar locking mechanism can be replicated and modified to allow for this kind of operation. This is an area that can be explored in the future after the final prototype is demonstrated to work properly and durably.

Lastly, the final design that we completed in this project should be modified and submitted to the open-source community for the benefit of others with similar disabilities as our Navy

SEAL customer. This was an initial request by our customer and sponsor; as our project progressed, we realized that the most important focus of our project should be that our design works for our specific customer before we worry about designing for others. This requires many significant modifications to our design as the open-source community will not likely have access to a DMLS machine and will likely print out of ABS or PLA plastic. As an addendum to this project, team member Ryan Burke has completed a design that will be submitted to the open-source community based on the operation principles of our final design. This open-source design is discussed in detail in Appendix O.

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12.0 Appendices

12.1 Appendix A – QFD

Customers: Active Duty Navy SEAL, QL+

Engineering Requirements	Benchmarks: Fixed Hook	Benchmarks: Touch Bionics: i-Limb Ultra	Benchmarks: e-Nable Cyborg Beast	Benchmarks: e-Nable Raptor Hand	Benchmarks: Team Manus Hand	Targets	Units	Total	Ability to shoot and handle firearms	Durable to withstand military activity	Cleanable	Operable in water / weather resistant	Fully mechanically actuated	Device does not inhibit motion	Ergonomic	Human-like appearance	Comfort	Actuate thumb	Maintain a closed-hand grip	Open and close hand	Part replaceability	Repairability
Weighting								100%	1	3	3	3	9	9	9	1	3	3	9	9	3	9
Weight	+	+	+	+	-	1	lbf	74.3%	9	9			3	9	9	1	9		3	3		
Structural material strength	+	-	-	-	+	7	ksi	18.9%		9		3	1			1						
Grip strength	-	+	-	-	+	109	lbf	64.9%	9	9			9					3	9	9		
One-handed assembly time	+	-	-	-	-	45	min	56.8%		9			3		9	3					9	9
Product life (cycles)	+	-	-	-		20k	#	67.6%	3	9	3	9	9		3	1		3	1	9		
Drop impact test	+	-	+	+	+	4	ft	36.5%	9	9	1	1	1	1	1	1	1		1	1		
Cost	+	-	+	+	-	1k	$	86.5%	9	9	3	3	9	3	9	3	3	3	1	9		
Standard OTS Parts	+	-	-	-	-	4	1/5	64.9%	3	9	3		9					3		3	9	9
Actuation sensitivity	-	-			+	3	1/5	94.6%	9	9		1	9	9	9		9	9	3	3		
User comfort rating	+	+			-	5	1/5	81.1%	9	3	9		3	9	9	9	9					
Benchmarks: Team Manus Hand									1	3		3	9	1	1	1	1	1	9	3		
Benchmarks: e-Nable Raptor Hand										1	1	3	9	9	3	3	3	1	1	3	3	3
Benchmarks: e-Nable Cyborg Beast										1	1	3	9	9	3	3	3	1	1	3	3	3
Benchmarks: Touch Bionics: i-Limb Ultra									1	1	3			9	3	9	3	3	9	9		
Benchmarks: Fixed Hook										9	9	9	9	9			9				9	9

Legend

Correlation		Benchmarks	
9	High	+	Performs well
3	Medium	-	Does not perform well
1	Low		
Blank	None		

12.2 Appendix B – Pugh Matrices for Four Major Functions

12.2.1. Hand Activation

Criteria \ Concept	1	2	3	4	5	6
Ease of use	DATUM	-	S	S	+	S
Ease of attachment		-	S	+	+	S
Ease of detachment		-	S	+	+	S
Response time		+	+	+	+	S
Complexity		-	S	+	+	-
Support		-	S	-	-	S
Weight		-	S	+	+	-
Size		S	-	+	+	S
Manufacature cost		-	-	+	+	+
Adjustability		-	S	+	-	S
Reliability		-	S	+	S	+
Range of motion		S	S	-	-	+
Σ+		1	1	9	8	3
Σ−		9	2	2	3	2
ΣS		2	9	1	1	7

#	Concept
1	Team Manus Hand
2	Sensor harness
3	Above elbow harness
4	Fixed hook harness
5	Raptor, wrist activation
6	Adjustable harness, 2 settings

12.2.2 Finger Design

Criteria \ Concept	1	2	3	4	5	6
Number of Joints	DATUM	-	-	S	S	S
Ease of Assembly		-	-	S	+	+
Dexterity		+	+	S	-	-
Ability to Conform		+	+	S	-	-
Lock Ability		-	-	S	S	-
Joint Strength		S	+	-	+	-
Appearance		-	+	S	-	-
Weatherproof		-	S	S	S	+
Weight		S	+	+	+	+
Cost (total)		-	-	S	+	+
Cleanable		-	-	+	+	+
Hold & Release		+	+	S	-	-
Σ+		3	6	2	5	5
Σ−		7	5	1	4	6
ΣS		2	1	8	3	1

#	Concept
1	Team Manus Hand
2	Cascading Finger
3	3-Joint w/ Cams
4	2-Joint w/ Cams
5	Tentacles
6	Toy Grabber

12.2.3 Integration of Soft Parts

Criteria \ Concept		1	2	3	4	5	6
Part replacability	DATUM: Utili-Hand	S	+	-	+	+	-
Operation in water		S	-	-	-	-	-
Cleanability		S	-	-	-	-	s
Comfort		+	+	-	-	-	s
Integration does not inhibit motion		-	+	+	+	+	-
Ease of initial attachement		S	-	-	-	+	-
Ease of disattachement		S	-	-	-	+	-
Perminancy of attachement		S	S	S	S	S	-
Durability		-	-	-	-	-	-
Manufacturability		S	+	+	+	+	+
Σ+		1	4	2	3	5	1
Σ–		2	5	7	6	4	7
ΣS		7	1	1	1	1	2

#	Concept: Integration of Soft Parts
1	Slip a silicone casing over the mechanical skeleton
2	Tension a velcro strap around a silicone sleeve
3	Tension a knob around a silicone sleeve
4	Bolt the silicone to a reduced-size gauntlet
5	Use retracting pins to interact with holes in silicone sleeve
6	Use adhesion for permanent attachement

12.2.4 Strengthening Options

Criteria \ Concept	1	2	3	4	5	6	7	8	9	10	11	12	13
Repairability	DATUM	S	-	-	-	-	S	S	S	S	S	S	S
Part replacability		-	-	-	-	-	S	S	+	+	S	S	-
Comfort		S	S	+	S	S	S	S	S	S	S	S	S
Ergonomic		S	S	+	S	S	S	S	S	S	S	S	S
Weather resistant		S	S	+	S	S	S	S	S	S	S	S	+
Cleanable		S	S	-	S	S	S	S	S	S	S	S	S
Military ruggedness		+	+	+	S	+	S	S	-	S	S	S	S
Σ+		1	1	4	0	1	0	0	1	1	0	0	1
Σ−		1	2	3	2	2	0	0	1	0	0	0	1
ΣS		5	4	0	5	4	7	7	5	6	7	7	5

#	Concept
1	Team Manus Hand
2	Laser sintering
3	Metal plating
4	Silicon sleeve dampener
5	Casting
6	Carbon fiber
7	Cross-section/stress concentration optimization
8	Intended fracture point
9	Stronger plastic (e.g. nylon)
10	Replace printed fasterners w/ OTS metal
11	Steel insert into fastener holes
12	Increased wall thickness
13	Heat treating steel parts

12.3 Appendix C – Pin Analysis

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STATIC ANALYSIS OF FINGERS (OPEN GRIP):

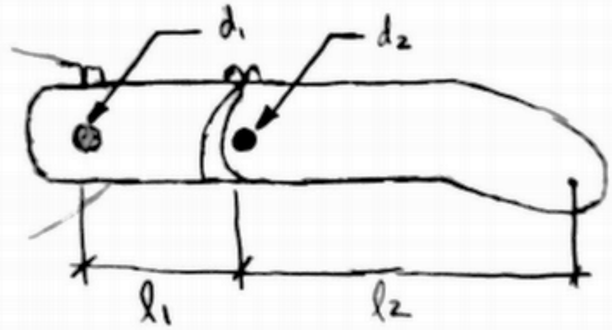
OBJECTIVE: CALCULATE LOADS ON PIN JOINTS OF FINGER AT OPEN GRIP CONFIGURATION.

RESULTS: $P_1, P_2 = (\sigma_{allowable})\frac{\pi d^3}{16 w}$

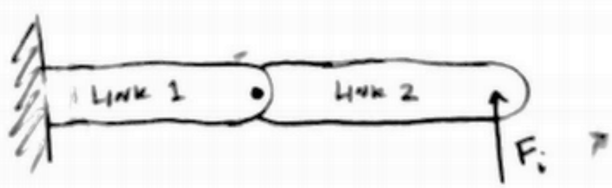
METHOD: STATICS

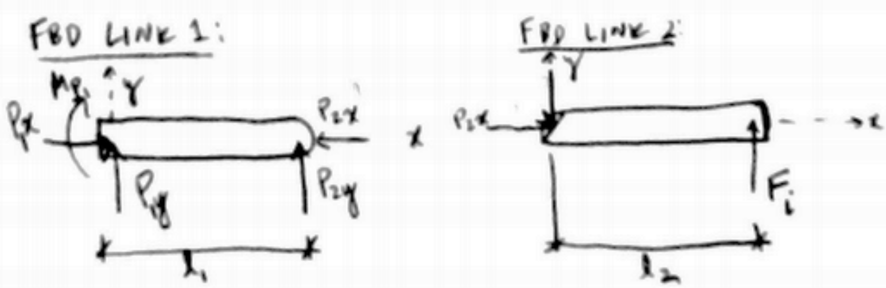
ASSUMPTIONS:
1) RIGID STRUCTURAL MATERIAL
2) NEGLIGIBLE FRICTION
3) EQUAL DISTRIBUTION OF LOAD ACROSS 4 FINGERS
4) 2-D FORCES

ANALYSIS: SKETCH OF FINGER IN OPEN CONFIGURATION:



SIMPLIFIED MODEL:





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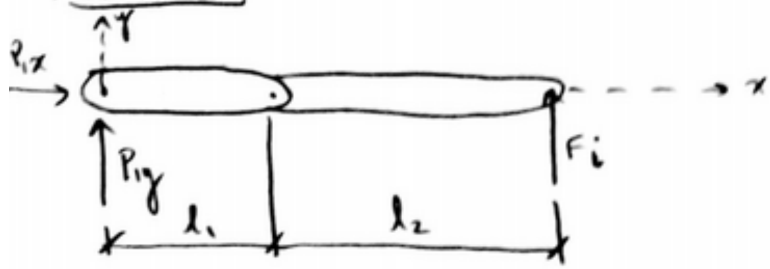
FBD SYSTEM:



$\Sigma F_y = 0$:

$$P_{1y} + F_i = 0$$

$$\boxed{P_{1y} = -F_i}$$

$\Sigma M_{P_1} = 0$:

$$M_{P_1} - F_i(l_1 + l_2) = 0$$

$$M_{P_1} = F_i(l_1 + l_2)$$

↑ THIS MOMENT IS SUPPORTED BY THE BASE "STOPPERS"

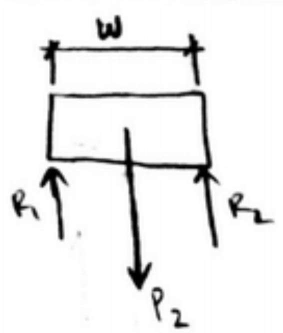
ΣF_y (FBD LINK 2) $= 0$

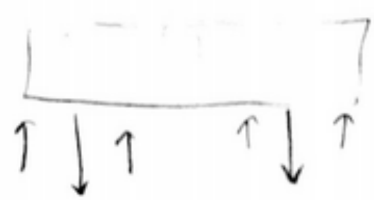
$$\boxed{P_{1y} = -P_{2y}}$$

THE PINS HAVE EQUAL REACTION FORCES IN THE OPEN CONFIGURATION

ALLOWABLE FORCE AT PIN 2 (SHORT)

FBD:





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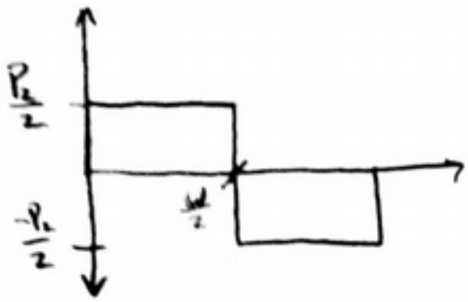
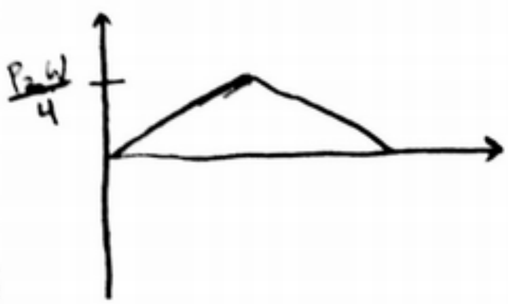
SHEAR DIAGRAM OF PIN:



MOMENT DIAGRAM OF PIN:



MAX STRESS ON PIN 2 IS AT CENTER, BENDING, NO SHEAR SINCE $V(x)=0$ AT CENTER.

$$\hookrightarrow \sigma_{max} = \frac{Mc}{I} = \frac{\left(\frac{P_2 W}{4}\right) \cdot d}{\frac{\pi}{64} d^4}$$

$$\sigma_{max} = \frac{16 P_2 W}{\pi d^3}$$

IN TERMS OF σ_{max},

$$\boxed{P_2 = (\sigma_{max}) \frac{\pi d^3}{16 W}}$$

ALLOWABLE FORCE AT PIN 1:

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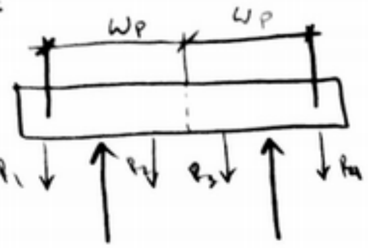
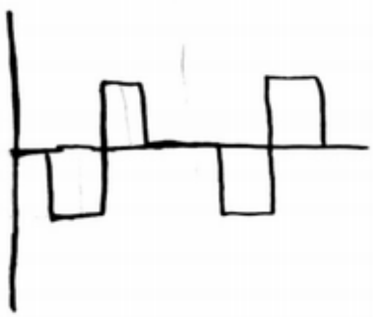
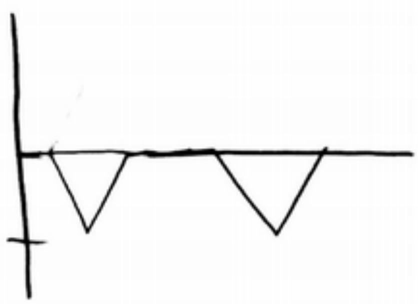
FBD:



SHEAR DIAGRAM:





SINCE IT IS ASSUMED THAT THE LOAD IS UNIFORM ACROSS ALL FINGERS, THE FORCES AT EACH PIN LOCATION ARE THEREFORE EQUAL AND THE MAX STRESS IS EQUAL TO THE MAX STRESS ON PIN 2:

$$\therefore \; P_1 = (\sigma_{max}) \frac{\pi d^3}{16 w}$$

MATERIAL PROPERTIES (σ_{max}) AND GEOMETRIES (d, w) CAN BE CHANGED IN ORDER TO OPTIMIZE P_1.

THIS WILL BE DONE IN EXCEL...

12.4 Appendix D – Finger Creepage Test

Introduction:

On the Raptor hand, a tensioning system is made to adjust the tension of the non-flexible cord on each finger separately. This allows each finger to align exactly how the user intends. The current prototype, a scaled down model of the Raptor made with ABS plastic, was assembled without this tensioning system. We assume finger alignment is important for the function of the entire prosthetic. The goal of this experiment is to determine if an adjustable tensioning system is critical to keep the fingers aligned.

Procedure:

The change in finger position relative to the gauntlet position before and after 200 cycles was measured. One cycle is defined as a continuous open and close grasping motion of the hand. The position was determined with an angle-measuring tool on photograph editing software.

By inspection, it was determined the index and pinky finger were changing in position more than other fingers. In the interest of determining the maximum possible change in angle, these fingers were chosen as a basis for measurement.

Also measured was the time per cycle, in case this information is useful to us in the future.

Results:

The photographs of the index and pinky finger at 0, 100, and 200 cycles are shown below. See Table D-1 below for a summary of the results.

Table D-1: The index and pinky finger position measured at different cycle times and the overall change in position from 0 to 200 cycles.

Number of Cycles	Time per Cycle (s)	Index Finger Position	Pinky Finger Position	Change of Angle from 0 to 200 Cycles-Index	Change of Angle from 0 to 200 Cycles-Pinky
0	-	120.37°	104.93°	23.41°	29.1°
100	1.075	126.67°	106.44°		
200	1.234	96.95°	75.83°		

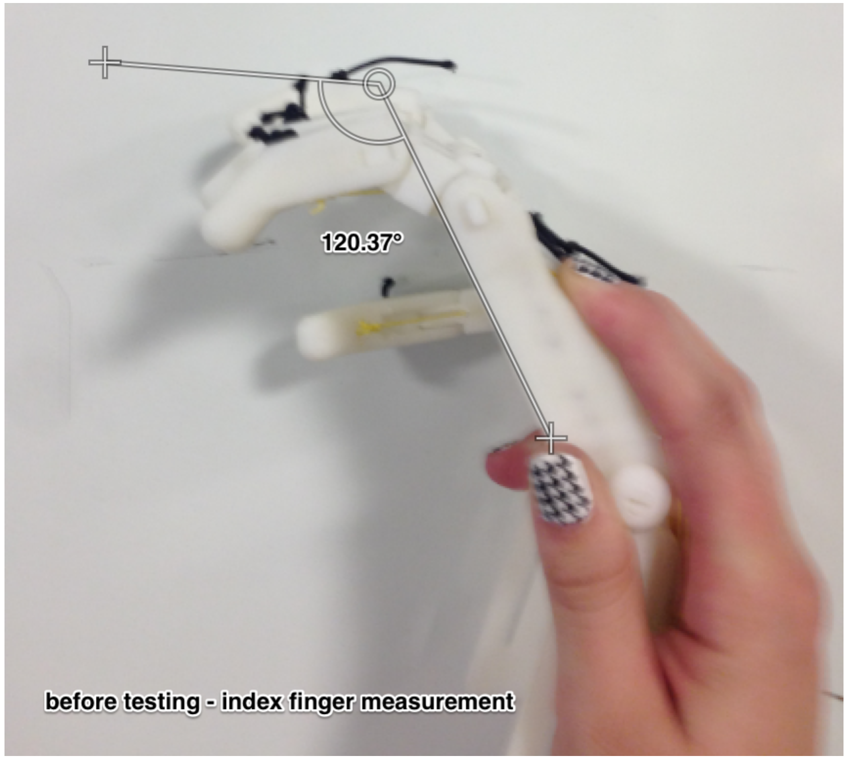


Figure D-1: The index finger position at 0 cycles relative to the gauntlet position.

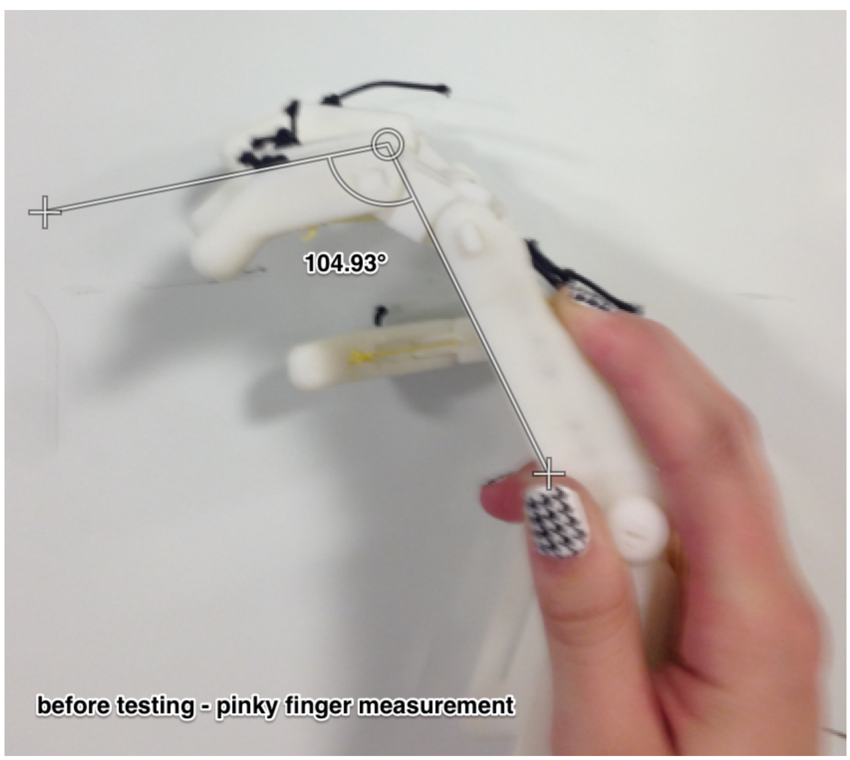


Figure D-2: The pinky finger position at 0 cycles relative to the gauntlet position.

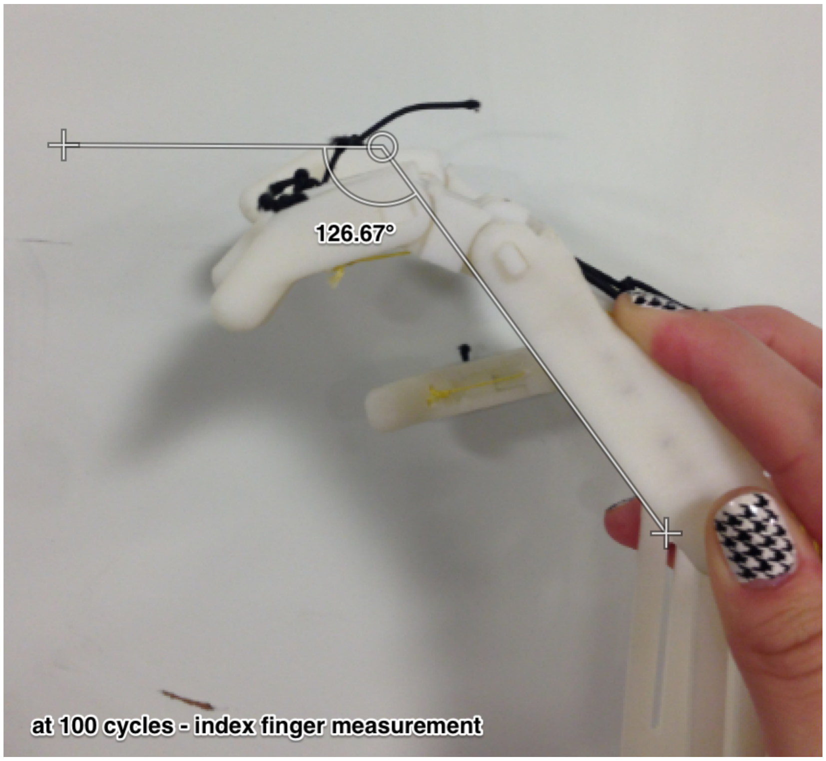


Figure D-3: The index finger position at 100 cycles relative to the gauntlet position.

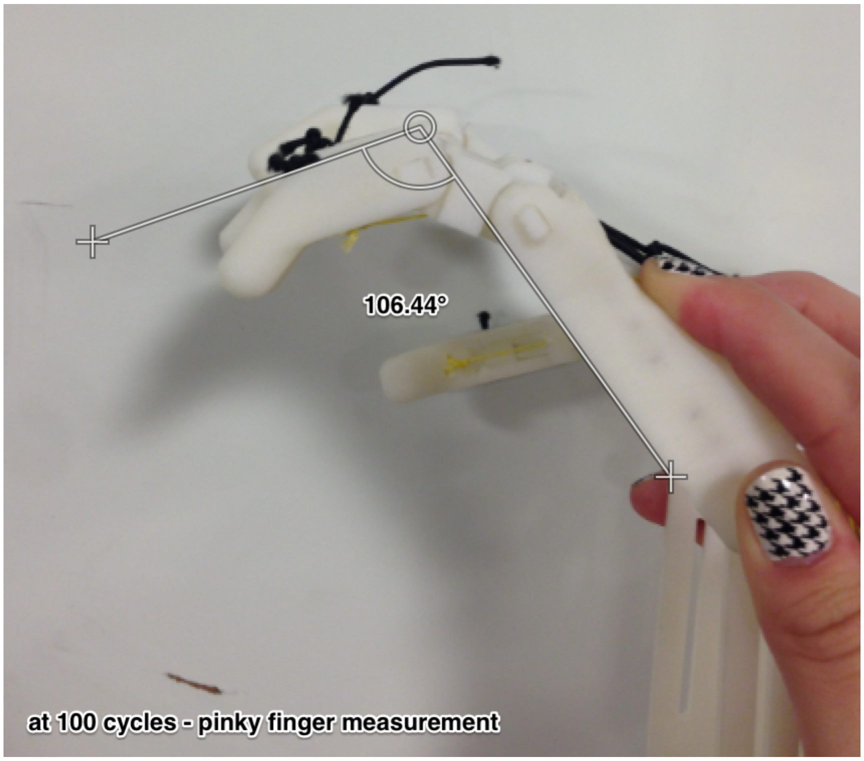


Figure D-4: The pinky finger position at 100 cycles relative to the gauntlet position.

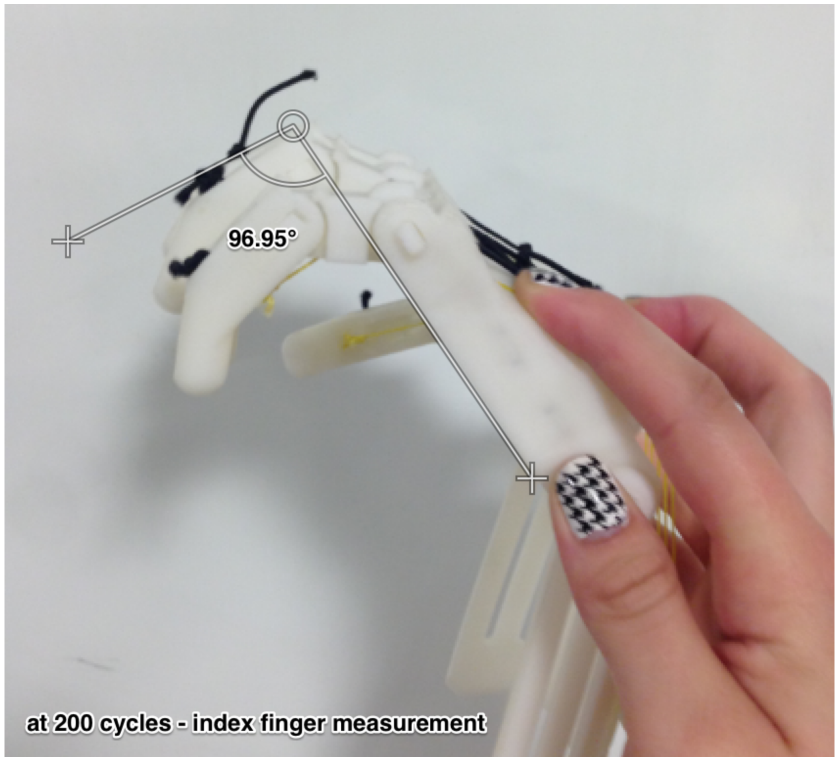


Figure D-5 The index finger position at 200 cycles relative to the gauntlet position.

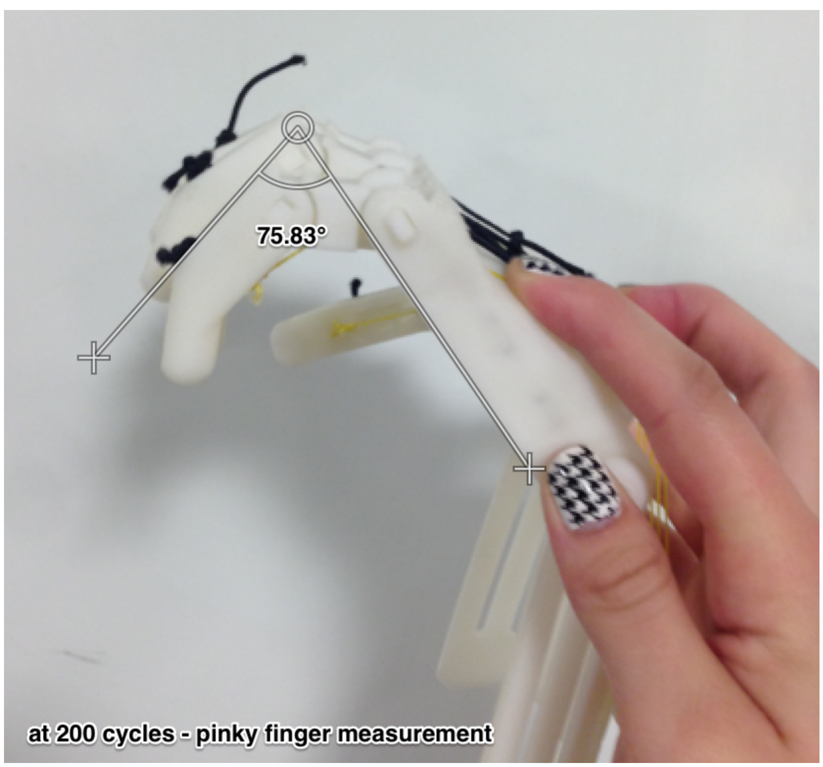


Figure D-6: The pinky finger position at 200 cycles relative to the gauntlet position.

Conclusion:

A significant amount of creepage exists in the Raptor Hand assembled without the adjustable tensioning system. The index and pinky fingers change 23.41° and 29.1°, respectively, when undergoing 200 cycles. It has been determined that the final design will need an adjustable tensioning system in order to align the finger position, otherwise the fingers will creep significantly. When finger misalignment is present, the quality of grip is also affected. Therefore, to optimize the quality of grip, an adjustable tension system is needed in the prosthetic design.

12.5 Appendix E – Grip Strength Test

Introduction:
The intended purpose of the grip strength test was to determine how much load the prosthetic may carry with an actuated, locked grip, before grip slippage occurs. Grip slippage can be caused by finger realignment or Sure-Lok failure. The cable bar, which carries a large amount of the load, is made from DMLS titanium. However, the rest of the prototype components (not including cable) are made from fused deposition modeled (FDM) PLA plastic. Catastrophic failure (components breaking) is a possibility in this test because the components made from plastic do not have the design's intended strength that titanium provides. As to not break the prototype, the load applied was limited, preventing the failure of the plastic components.

Procedure:
The prototype was placed in a locked grip. Objects were weighed, placed in a bag with a carry handle, and hung on the fingers of the locked hand (see Figure E-1). The ability of the grip to hold position was observed. The bag was then unloaded, and the hand was unlocked to check for potential jamming in the Sure-Lok. The prototype was then relocked, reloaded with a higher weight, and the process was repeated with larger weights incrementally until the load reached 25.9 lb.

Figure E-1: A locked grip with a load applied.

Results:
With a limited load to prevent prototype damage, there are no results on the ability of the prosthetic to sustain a grip when loaded and locked. However, important observations

were made. It was observed that fingers will reposition themselves when placed under a load. The non-flexible cable is a fixed distance regardless of position, thus even when locked, the fingers have the ability to move. Realignment was noted when the load was applied to 7.6 lb. (see Table E-1)

At a load of 25.9 lb, the Sure-Lok jammed. The Sure-Lok's internal lever wedges itself into the device when a heavy load is applied. A user can tell the Sure-Lok is jammed when the prosthetic seems to be unable to unlock. The lever can be dislodged by having the user re-initiate a locking grip. This corrects the issue and the Sure-Lok can now unlock.

During testing, one string knot become imbedded in a string passageway, requiring restringing. All non-flexible cable was then tightened. This caused less fingers to reposition themselves. Using judgment, it was decided to stop the testing at 25.9 lb. to avoid damage to the prototype. It became clear the Sure-Lok was not going to fail under high loads, only jam.

Table E-1: Load applied and effect on grip.

Load applied (lb.)	Effect on Grip	Notes
4.1	None	
6.8	None	
7.6	Realignment	
11.0	None	
12.4	None	
13.3	None	
15.1	None	Replaced string
20.6	None	
25.9	Sure-Lok jam	

Conclusion:

To make a conclusion regarding the grip sustaining ability would require further testing once the titanium parts are complete. Discovering when exactly Sure-Lok jamming occurs is useful information for the user, and has since been included in the operator manual. The finger repositioning is corrected in the titanium model with having positioning stoppers at the base of the finger and finger joint. Though Sure-Lok failure nor part failure was not achieved in this test, it provided a basis for judgment that the PLA plastic parts would fail before the Sure-Lok would.

12.6 Appendix F – Actuation Sensitivity Test

Introduction:
The actuation sensitivity test measures the change in angle of the gauntlet required for a full grip closure, actuated by the user. A 25°-35° angle change per grip closure has been determined to be the ideal user input. This is a test for user comfort.

Procedure:
The prototype was photographed before (Figure F-1) and after (Figure F-2) actuation. Photo editing software was used to analyze the angle of the gauntlet relative to the palm. The difference of these two angles is the overall input angle.

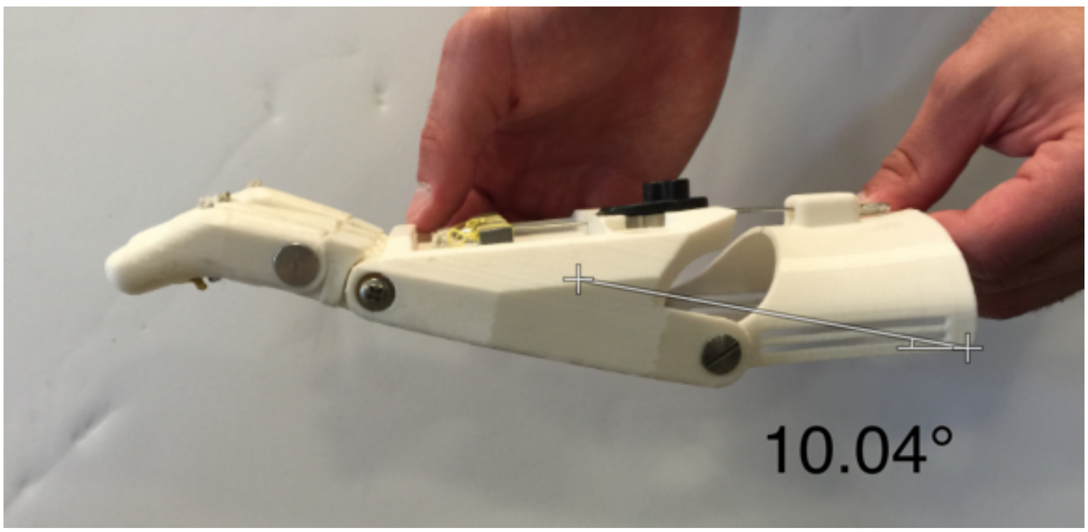


Figure F-1: The angle of the gauntlet relative to the palm before actuation.

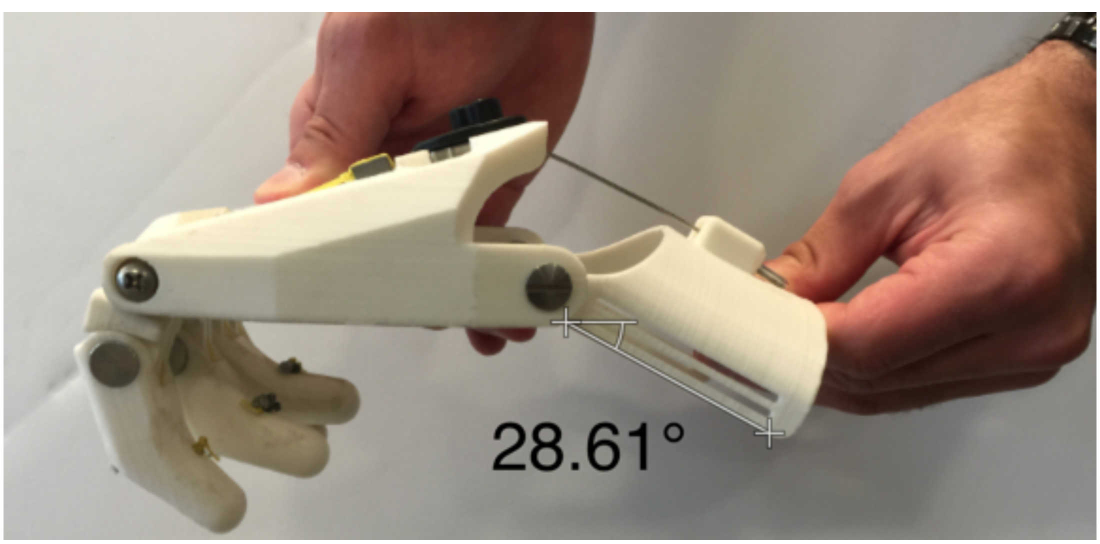


Figure F-2: The angle of the gauntlet relative to the palm after a full grip closure.

Results:

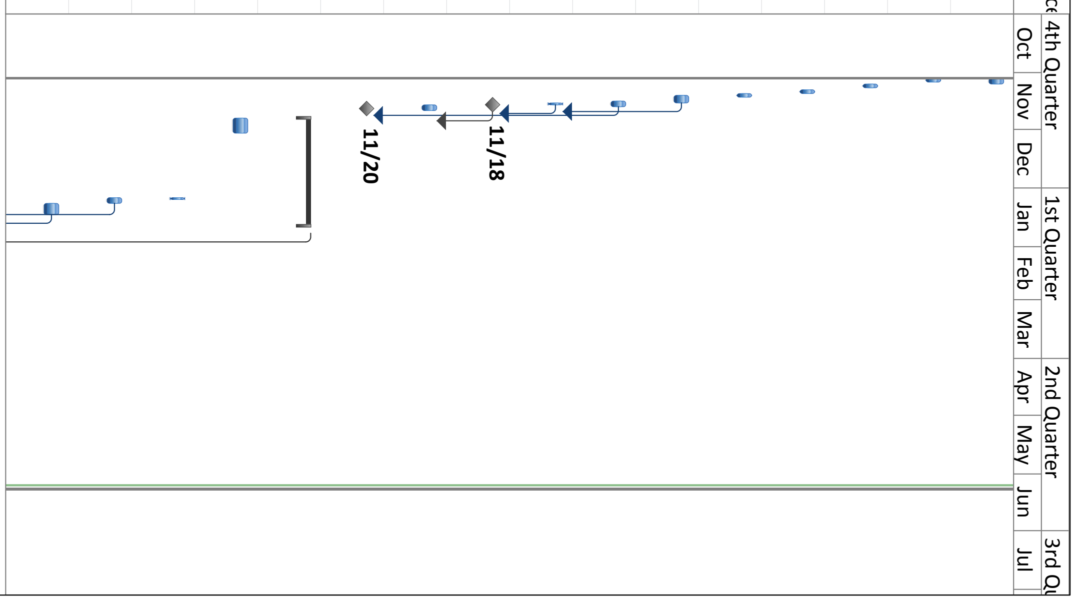
The overall input angle for this prototype is 18.57°. This is on the lower end of the 25° to 35° range, therefore the prosthetic is too sensitive.

Conclusion:

This prototype is overly sensitive because the input angle lies outside the lower end of the ideal range. The titanium model has an adjusting Sure-Lok cable position to allow the user to adjust this actuation sensitivity, therefore more customization and comfort is possible.

12.7 Appendix G – Project Gantt Chart

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		Project Proposal Revision	3 days	Tue 11/4/14	Thu 11/6/14	
2		Pugh Matrices and Decision Matrix	2 days	Tue 11/4/14	Wed 11/5/14	
3		Assembly of Raptor Hand	2 days	Fri 11/7/14	Sat 11/8/14	
4		Initial SolidWorks model	2 days	Mon 11/10/14	Tue 11/11/14	
5		Design Validation Testing	2 days	Wed 11/12/14	Thu 11/13/14	
6		PDR Rough Draft	4 days	Thu 11/13/14	Sun 11/16/14	
7		PDR PowerPoint	3 days	Sun 11/16/14	Tue 11/18/14	
8		PDR Edit	1 day	Mon 11/17/14	Mon 11/17/14	6
9		Preliminary Design Report	0 days	Tue 11/18/14	Tue 11/18/14	8
10		PDR Revision	3 days	Tue 11/18/14	Thu 11/20/14	9
11		PDR Presentation (Class/Sponsor)	0 days	Thu 11/20/14	Thu 11/20/14	7
12		**Design Analysis**	**22 days**	**Tue 11/25/14**	**Tue 1/20/15**	
13		DFMEA/DVP/Analysis Plan	3 days	Tue 11/25/14	Tue 12/2/14	
14		Select materials for hand, joints, fingers, cable, etc.	1 day	Tue 1/6/15	Tue 1/6/15	
15		Modify Team Manus finger CAD files	3 days	Tue 1/6/15	Thu 1/8/15	
16		Design palm structure	6 days	Fri 1/9/15	Wed 1/14/15	



Project: Senior Project Gantt Char
Date: Sun 6/7/15

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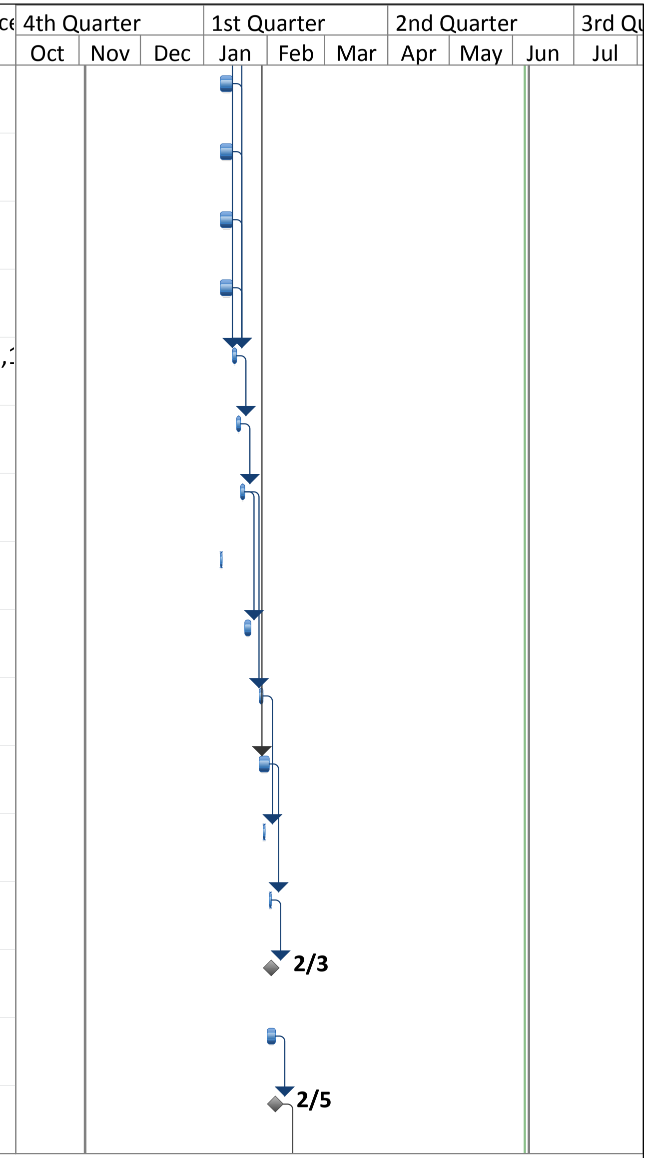
ID	Task Name	Duration	Start	Finish	Predece
17	Design locking mechanism	6 days	Fri 1/9/15	Wed 1/14/15	
18	Design tensioning mechanism	6 days	Fri 1/9/15	Wed 1/14/15	
19	Design gauntlet attachment	6 days	Fri 1/9/15	Wed 1/14/15	
20	Design cable routing	6 days	Fri 1/9/15	Wed 1/14/15	
21	Create SolidWorks models of newly designed components	2 days	Thu 1/15/15	Fri 1/16/15	15,16,:
22	Modify initial component designs	2 days	Sat 1/17/15	Sun 1/18/15	21
23	Make changes to SolidWorks model to reflect new design	2 days	Mon 1/19/15	Tue 1/20/15	22
24	Meeting with Stefan (Aesthetic Prosthetics) in Pasadena	1 day	Fri 1/9/15	Fri 1/9/15	
25	Detail Drawings and BOM	3 days	Wed 1/21/15	Fri 1/23/15	23
26	Print new prototype	2 days	Wed 1/28/15	Thu 1/29/15	23
27	FDR Rough Draft	5 days	Wed 1/28/15	Sun 2/1/15	12
28	Qualitative prototype testing	1 day	Fri 1/30/15	Fri 1/30/15	26
29	FDR Edit	1 day	Mon 2/2/15	Mon 2/2/15	27
30	Final Design Report	0 days	Tue 2/3/15	Tue 2/3/15	29
31	CDR Powerpoint	4 days	Sun 2/1/15	Wed 2/4/15	
32	CDR Presentation (Class/Sponsor)	0 days	Thu 2/5/15	Thu 2/5/15	31



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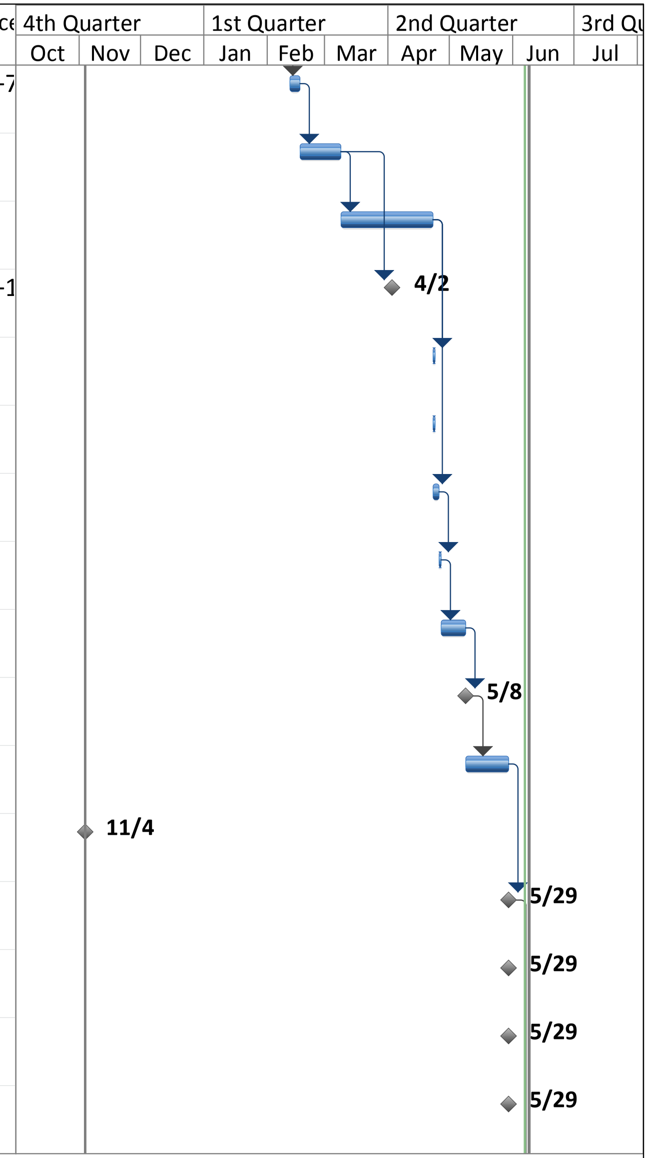
ID		Task Mode	Task Name	Duration	Start	Finish	Predece
33	✓		FDR Revision	5 days	Thu 2/12/15	Mon 2/16/15	32FS+7
34	✓		Ideate design modifications	20 days	Tue 2/17/15	Sun 3/8/15	33
35	✓		Modify SolidWorks model	32 days	Mon 3/9/15	Wed 4/22/15	34
36	✓		Visit Lawrence Livermore Labs	0 days	Thu 4/2/15	Thu 4/2/15	34FS+1
37	✓		Order any remaining parts	1 day	Thu 4/23/15	Thu 4/23/15	35
38	✓		Project Hardware/Safety Demo	1 day	Thu 4/23/15	Thu 4/23/15	
39	✓		Print Prototype 3.0	3 days	Thu 4/23/15	Sat 4/25/15	35
40	✓		Build Protype 3.0	1 day	Sun 4/26/15	Sun 4/26/15	39
41	✓		Further Ideation and CAD Modifications	12 days	Mon 4/27/15	Fri 5/8/15	40
42	✓		DMLS Titanium File Submission	0 days	Fri 5/8/15	Fri 5/8/15	41
43	✓		Expo Prep	21 days	Sat 5/9/15	Fri 5/29/15	42
44	✓		Senior Design Expo	0 days	Tue 11/4/14	Tue 11/4/14	
45	✓		**Prototype Testing**	**0 days**	**Fri 5/29/15**	**Fri 5/29/15**	**43**
46	✓		Grip Strength Test	0 days	Fri 5/29/15	Fri 5/29/15	
47	✓		Actuation Cycle Time	0 days	Fri 5/29/15	Fri 5/29/15	
48	✓		Actuation Sensitivity	0 days	Fri 5/29/15	Fri 5/29/15	



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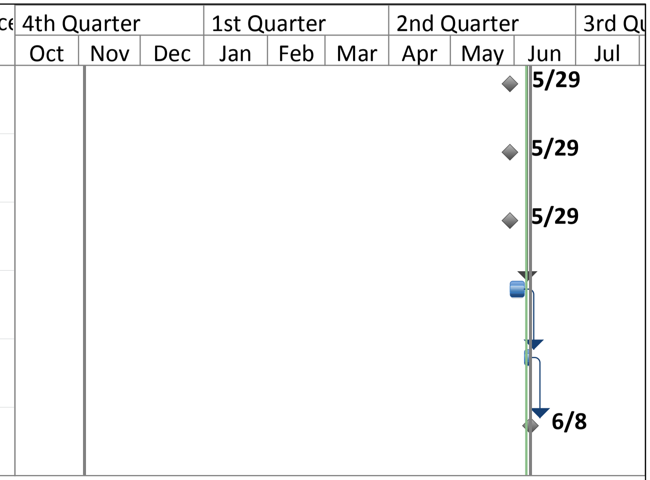
ID	Indicators	Task Mode	Task Name	Duration	Start	Finish	Predecessors
49	✓		Repair Assembly Time	0 days	Fri 5/29/15	Fri 5/29/15	
50	✓		Weight	0 days	Fri 5/29/15	Fri 5/29/15	
51	✓		Off-The-Shelf (OTS) Parts	0 days	Fri 5/29/15	Fri 5/29/15	
52	✓		FPR Rough Draft	7 days	Sat 5/30/15	Fri 6/5/15	45
53	✓		FPR Edit	3 days	Sat 6/6/15	Mon 6/8/15	52
54	✓		Final Project Report	0 days	Mon 6/8/15	Mon 6/8/15	53



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12.8 Appendix H – Hazard Identification

ME428/429/430 Senior Design Project 2014-2015

SENIOR PROJECT CONCEPT DESIGN HAZARD IDENTIFICATION CHECKLIST

Team: ProstheTech Advisor: Dr. Peter Schuster

Y	N	
☑	☐	Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☑	Can any part of the design undergo high accelerations/decelerations?
☐	☑	Will the system have any large moving masses or large forces?
☐	☑	Will the system produce a projectile?
☐	☑	Would it be possible for the system to fall under gravity creating injury?
☐	☑	Will a user be exposed to overhanging weights as part of the design?
☐	☑	Will the system have any sharp edges?
☐	☑	Will any part of the electrical systems not be grounded?
☐	☑	Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?
☑	☐	Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☑	Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☑	☐	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☑	☐	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☑	Can the system generate high levels of noise?
☑	☐	Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☑	☐	Is it possible for the system to be used in an unsafe manner?
☑	☐	Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add a complete description, list of corrective actions to be taken, and dates to be completed on the reverse side.

Description of Hazard	Corrective Actions to be Taken	Planned Completion Date	Actual Completion Date
If the cables break due to excessive tension, there is a chance that they might recoil the user.	The cables will tensioned as least as possible and they will be embedded within the prosthetic.	4/6/15	
Cables, flexible and non-flexible, have the possibility of being pinched or cut off.	Cables will be embedded into the prosthetic to prevent the exposure which causes these circumstances.	4/6/15	
It is possible that objects may become stuck in pinch points at the finger joints.	The finger design will have high tolerances, and cushioned padding will be installed where necessary.	4/6/15	
The user of the design will be required to exert an abnormal physical posture during use of the design due to wrist actuation.	Make the motion sensitivity appropriate for an ergonomic response.	4/6/15	
Acid is used to dissolve support material in the 3D-printing process.	Eye and hand protection must be worn when initially handling 3D-printed parts.	4/6/15	
Device will be exposed to extreme environmental conditions.	Testing will be performed, and a robust material will be selected.	4/6/15	
It is possible for the user to overexert the fingers to cause the product to break, which can make parts fly off.	Communicate with the user to explain the product's limitations to avoid unsafe use.	4/6/15	

12.9 Appendix I – Failure Mode and Effects Analysis

Function and Performance Requirement	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Occurrence %	Criticality	Recommended Action(s)	Responsibility & Target Completion Date
Locking Mechanism	Slip	grip disengage (total functional failure), derail	9	Excess tension, insufficient clamping force, enviromental conditions, derailing, bolt loosening	3	27	Structural material strength test, weatherproofing test, test load applied on cord before slippage caused, impact test	Jose, 12/3/14
	Derail	grip disengage (total functional failure)	9	bolt loosening, structural failure of lock or gauntlet	1	9	Structural material strength test, weatherproofing test, test load applied on cord before derailing caused, impact test	Jose, 12/3/14
	Bolt breaking	grip disengage (total functional failure)	9	user error on bolt torque, impact force or interaction with other object, excessive and unintended stress case	3	27	Design for bolt strength, impact test	Heather, 12/4/14
	Bolt loosen	slip	7	Vibration, user error on bolt torque, impact force or interaction with other object, thread strippage	6	42	Design for bolt strength, impact test	Heather, 12/4/14
	Rail break	grip disengage (total functional failure)	9	Impact force with other object, prosthetic is dropped, excessive and unintended stress case	3	27	Structural material strength test, weatherproofing test, test load applied on cord before rail break caused, impact test	Michael, 12/5/14
Finger Members	Fracture	potential for grip disengage (total functional failure)	8	Impact force or interaction with other object, excessive and unintended stress case	5	40	Structural material strength test, design for strength, impact test	Ryan, 1/5/14
	Elastic Deformation	Melting of plastic materials, inaccurate finger alignment, wear caused by missalignment	4	Extreme temperature environment, excessive and unintended stress case	4	16	Structural material strength test, design for strength, impact test	Ryan, 1/6/14
	Corrode	Joint friction, rough surfaces	3	Operation in high humidity conditions or in water	4	12	Laboratory accelerated corrosion testing	Heather, 1/7/14
	Melt	Melting of plastic materials, missalignemnt of joints and fingers	7	High temperature environment	2	14	Ensure operating temperature conditions do not exceed melting point of material	Heather, 1/8/14
Pin Joints	Plastic deformation leading to fracture	Ineffective finger joint (severity depends on number of joints fractured and where fractured), joint resistance, joint missalignment	9	High impact force, excessive and unintended stress case	5	45	Structural material strength test, design for strength, impact test	Michael, 1/9/14
	Elastic Deformation	Joint resistance, joint missalignment	4	High impact force, excessive and unintended stress case	6	24	Structural material strength test, design for strength, impact test	Jose, 1/10/14
	Melting	Missaligned joint	5	Extreme temperature environments, material properties	2	10	Ensure operating temperature conditions do not exceed melting point of material	Jose, 1/10/14
	Particle buildup	Joint resistance	4	Operation in wet/muddy/dusty conditions	9	36	Test exposure to dirt and sand	Heather, 1/11/14
	Friction	Joint resistance	7	Surface roughness of material	1	7	Grind all parts which interact with the joint to a high surface finish	Ryan, 1/12/14
	Joint Failure	Finger fall apart, non-operable fingers	9	Fatigue failure, hole in members too large, pin too small, pin shrinkage, broken pins	4	36	Check clearance toleranes	Ryan, 1/12/14

FMEA (cont.)

Function and Performance Requirement	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Occurrence %	Criticality	Recommended Action(s)	Responsibility & Target Completion Date
Cable	Snap	Inarticulable fingers	7	Too much pre-tension, excessive and unintended stress case, snagging on external objects which cause tear	4	28	Cord material strength test, train user to tension correctly, internalize cords	Heather, 1/13/14
	Plastic deformation	Finger misalignment, weakened cable strength, fingers unable to actuate without correct cable length	8	Too much pre-tension, too heavy of a load, snagging on external objects	8	64	Cord material strength test, design for strength, impact test, internalize cords	Michael, 1/13/14
Retracting Pins	Jam	Total failure of attachment system, user unable to take off prosthetic	8	Fatigue failure, excessive and unintended stress case	1	8	Material strength test, design for strength, fatigue test, impact test, internalize cords	Michael, 1/14/14
	Inadvertent Actuation	Disattachment of hand to user	6	Bumping pins on external objects	3	18	Internalize pins to prevent actuation when unintended	Heather, 1/14/14
Gauntlet	Fracture	Disattachment of hand to user depending on severity	7	Impact force, excessive and unintended stress case	5	35	Material strength test, design for strength, impact test	Jose, 1/15/14
	Deform	Hand misalignment, awkward arm attachment	6	Extreme temperature environment, unexpected load placement	2	12	Material strength test, design for strength, impact test	Ryan, 1/15/14
	Corrode	Rough surface	3	Operation in high humidity conditions or in water	4	12	Laboratory accelerated corrosion testing	Heather, 1/16/14
	Melt	Deformed/dysfunctional hand	8	Extreme temperatuare environment	2	16	Ensure operating temperature conditions do not exceed melting point of material	Jose, 1/16/14
Silicone Sleeve	Suction released	Prosthetic falls off of user	9	Seal between user and silcone is broken by strenious activity or foriegn object	2	18	Work with prosthetisist to insure good fit	Michael, 1/17/14
	Rip	Suction is lost	7	Tear caused by fatigue failure or excessive and unintended stress case	1	7	Work with prosthetisist to insure good fit, choose material for strength	Heather, 1/17/14
Soft Parts	Wear	Decreased grip ability	4	High usage, dirty operating conditions	9	36	Perform weatherproofing tests, fatigue tests	Ryan, 1/18/14
	Rip	Decreased grip ability if soft parts fall off	3	Handling sharp objects	5	15	Make soft parts replacable	Ryan, 1/18/14
Anchor Points of Cord	Fracture	Non-flexible cord is non-operable which renders entire finger to be inoperable	8	Extreme cable pre-tension/loading, cross section of part, material selection	6	48	Design achor point for strength, material strength test, design for strength, impact test	Michael, 1/19/14
	Deform	Non-flexible cord is missaligned	4	Extreme cable pre-tension/loading, cross section of part, material selection	5	20	Design achor point for strength, material strength test, design for strength, impact test	Michael, 1/19/14
Palm	Fracture	Disattachment of hand to user	7	Impact force, unexpected load placement, stress concentrations	6	42	Material strength test, design for strength, impact test	Jose, 1/20/14
	Deform	Hand misalignment, awkward arm attachment	6	Extreme temperature environment, unexpected load placement	5	30	Design for strength, material strength test, design for strength, impact test	Heather, 1/20/14
	Corrode	Joint friction, rough surfaces	3	Operation in wet conditions	4	12	Laboratory accelerated corrosion testing	Ryan, 1/21/14
	Melt	Deformed/dysfunctional hand	8	Extreme temperatuare environment	2	16	Ensure operating temperature conditions do not exceed melting point of material	Ryan, 1/21/14
Tensioner System for Individual Cords	Bolt breaking	grip disengage (total functional failure) depending on number of bolts broken	9	user error on bolt torque, impact force or interaction with other object, excessive and unintended stress case	3	27	Design for bolt strength, impact test	Michael ,1/22/14
	Bolt loosen	slip	7	Vibration, user error on bolt torque, impact force or interaction with other object, thread strippage	6	42	Design for bolt strength, impact test	Heather, 1/22/14

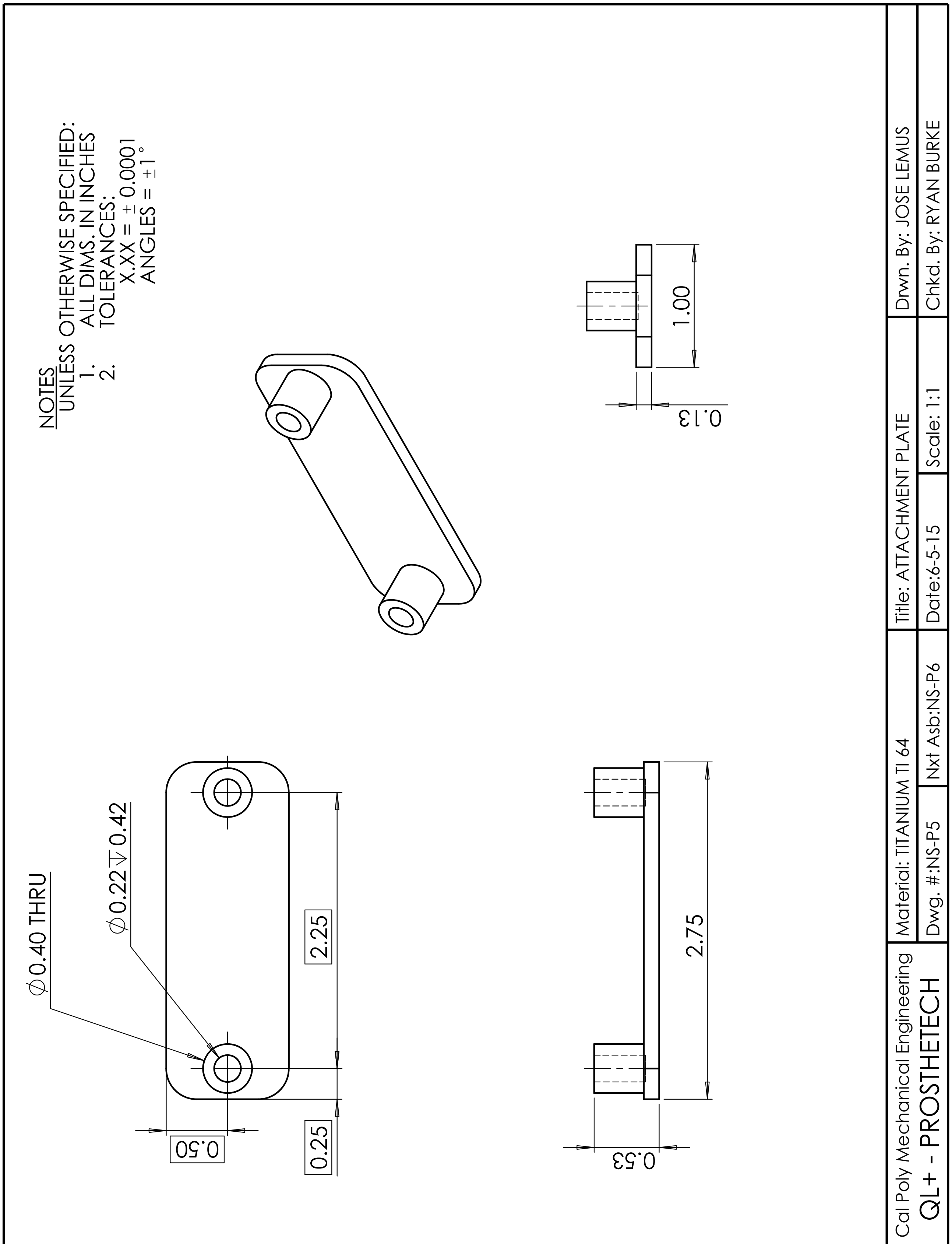
12.10 Appendix J – Bill of Materials

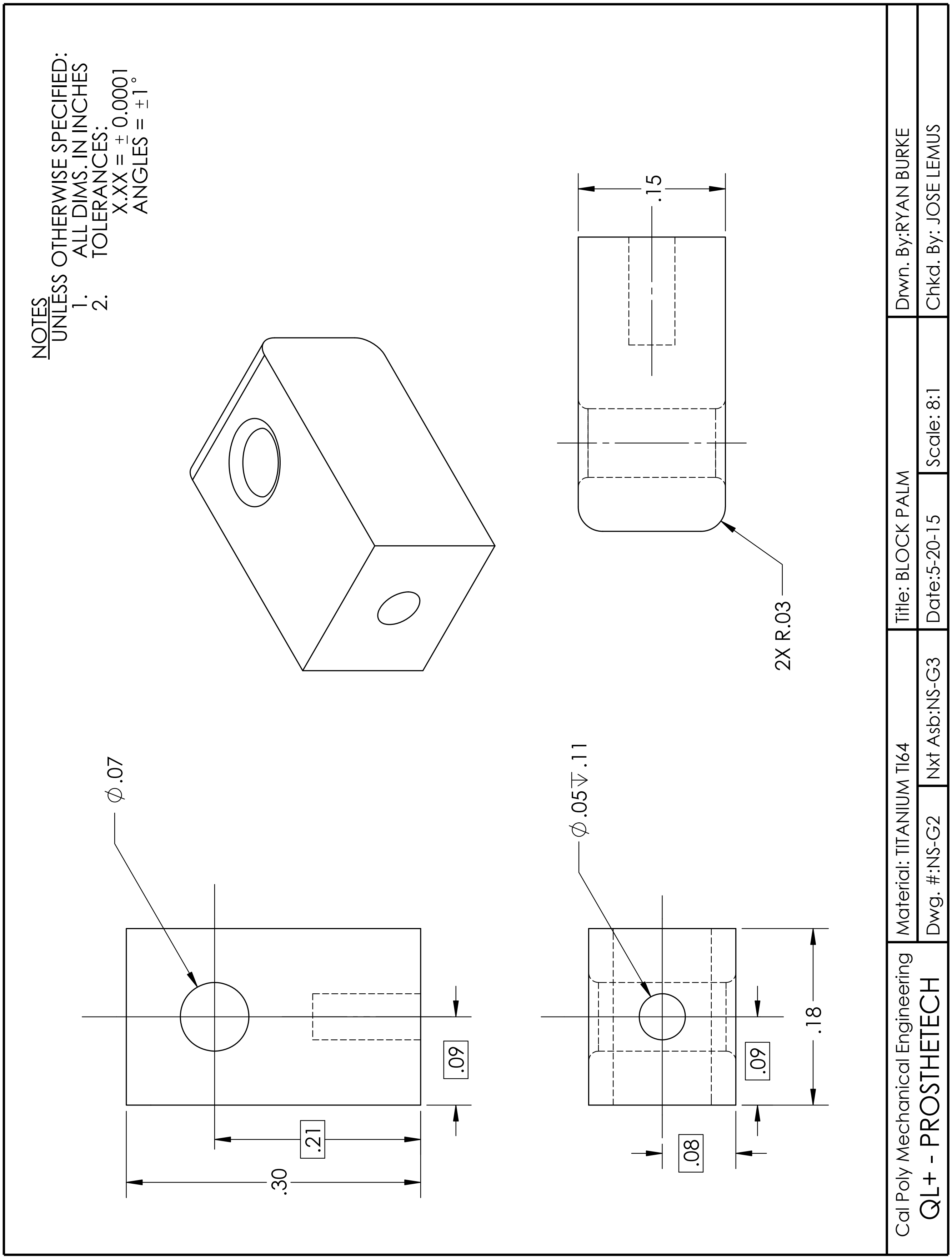
System / Categories	Part	Item No.	Description	Qty.	Material
Fingers	Base Finger	8A2-DF1	Finger member closest to the palm	4	Titanium Ti64
	Finger	8A2-DF2	Finger member farthest to the palm	4	Titanium Ti64
	Finger Plate	8A2-DF3	Plate to prevent foreign material from entering	4	Titanium Ti65
	Pin Joint	8A2-DF4	Chicago screws for fingers and thumb	4 (25 pack)	Steel Zinc-Plated
Thumb	Thumb	8A2-T1	Positionable thumb	1	Titanium Ti64
	Thumb Frame	8A2-T2	Attaches thumb to palm	1	Titanium Ti64
	Thumb Joint	8A2-T3	Flat head phillips machine screw	1 (Pack of 100)	Stainless Steel
	Thumb Bolt	8A2-T4	Thumb chicago screw	1 (10 pack)	Stainless Steel
	Spring	8A2-T5	Compression spring	1 (Pack of 12)	Stainless Steel
Palm	Palm	8A2-P1	Connects fingers and gauntlet	1	Titanium Ti64
	Palm Joint	8A2-P2	Connects base finger to palm	1 (Pack of 50)	Stainless Steel
	Washer	8A2-P3	Military spec steel flat washer	2 (Pack of 100)	Cadmium-Plated Steel
	Assembly Bolt	8A2-P4	Bolt with handle	2	
	Assembly Plate	8A2-P5	Assembles sleeve to palm	1	Titanium Ti64
	Palm Standoff	8A2-P6	Female threated round standoff	1	Stainless Steel
Gauntlet	Forearm	8A2-DG1	Connects to palm with chicago screws	1	Titanium Ti64
	Tension Block	8A2-DG2	Adjust cable position from gauntlet to mux	1	Titanium Ti64
	Tension Bolt	8A2-DG3	Bolt for adjustment	1 (pack of 100)	Stainless Steel
	Wrist Joint	8A2-DG4	Chicago screws for wrist	1	Stainless Steel

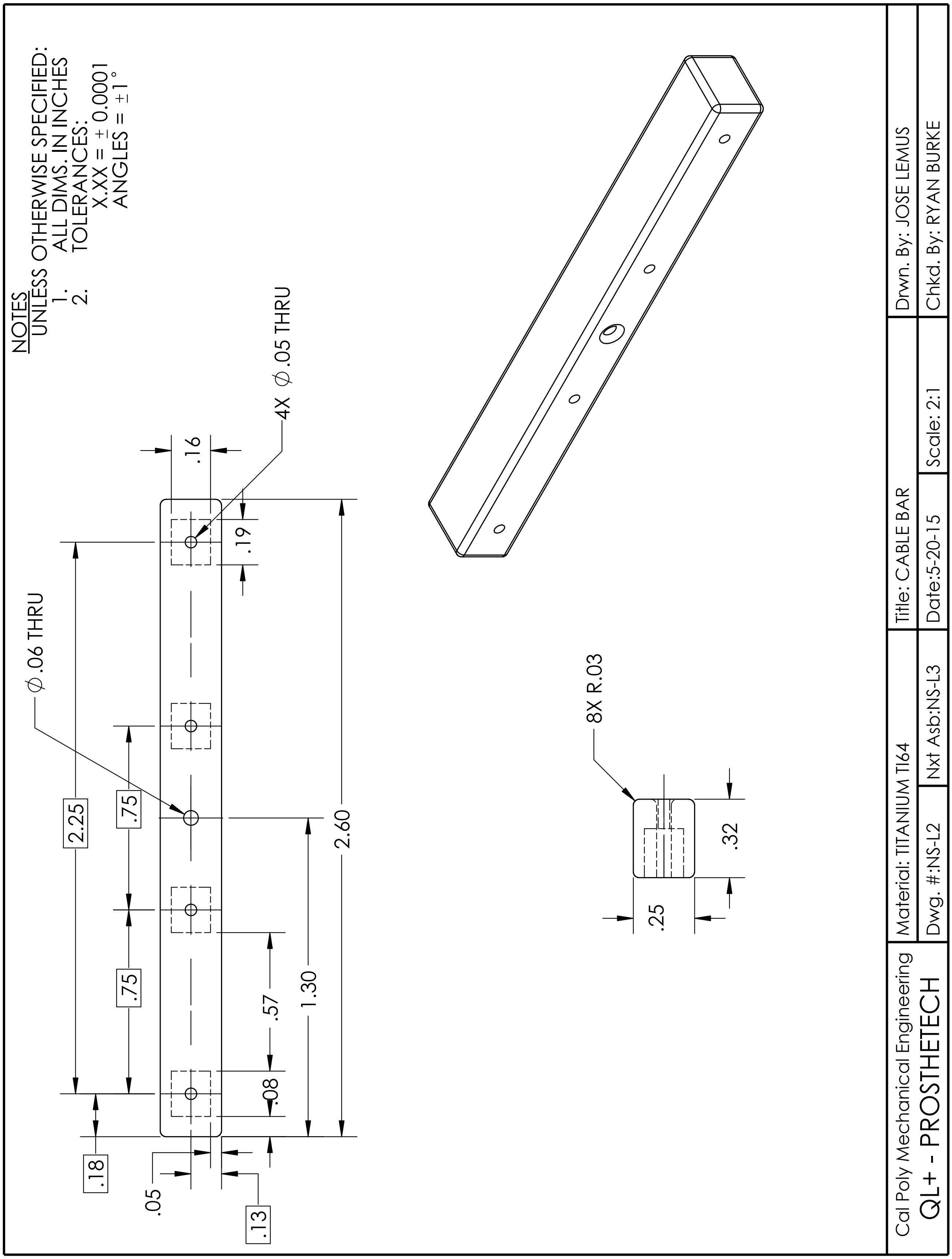
BOM (cont.)

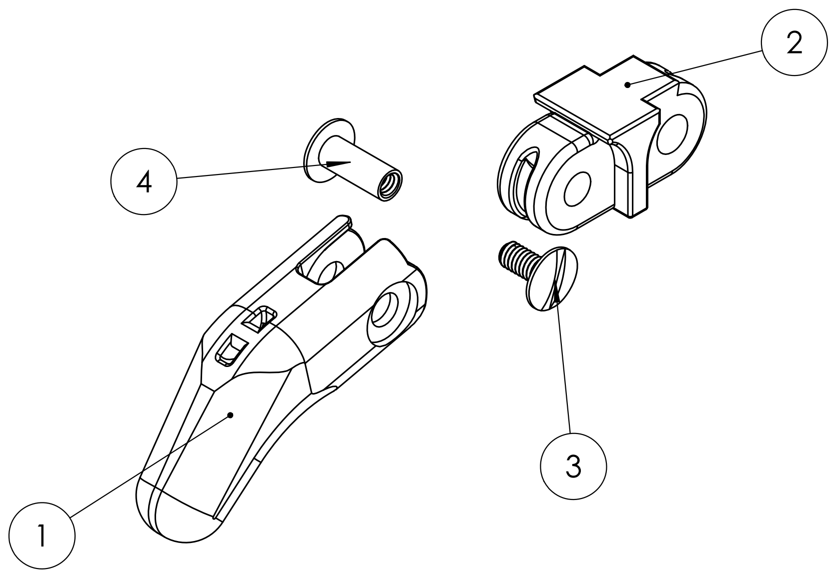
System / Categories	Part	Item No.	Description	Qty.	Material
Locking System	Sure-Lok	8A2-L1	Enclosed locking mechanism	1	Steel and plastic
	Mux	8A2-L2	Aligns cable along variable position bar	1	Titanium Ti64
	Mux Tension Blocks	8A2-L3	Adjust cable position from mux to finger	4	Titanium Ti64
	Mux Tension Bolts	8A2-L4	Adjusts tension in gauntlet cable	1 (Pack of 100)	Stainless Steel
Cable	Shock Cord	8A2-C1	1/32 Shock cord	1 (10ft)	Nylon sleeve, elastic core
	Non-flex Cable	8A2-C2	200 lb. cord	1 (150 yd)	Spectra
	Break Cable	8A2-C3	Break cable	1 coil	Stainless Steel
	Crimp Sleeve	8A2-C4	Stopper for break cable	1	Aluminum

12.11 Appendix K – Detail Drawings



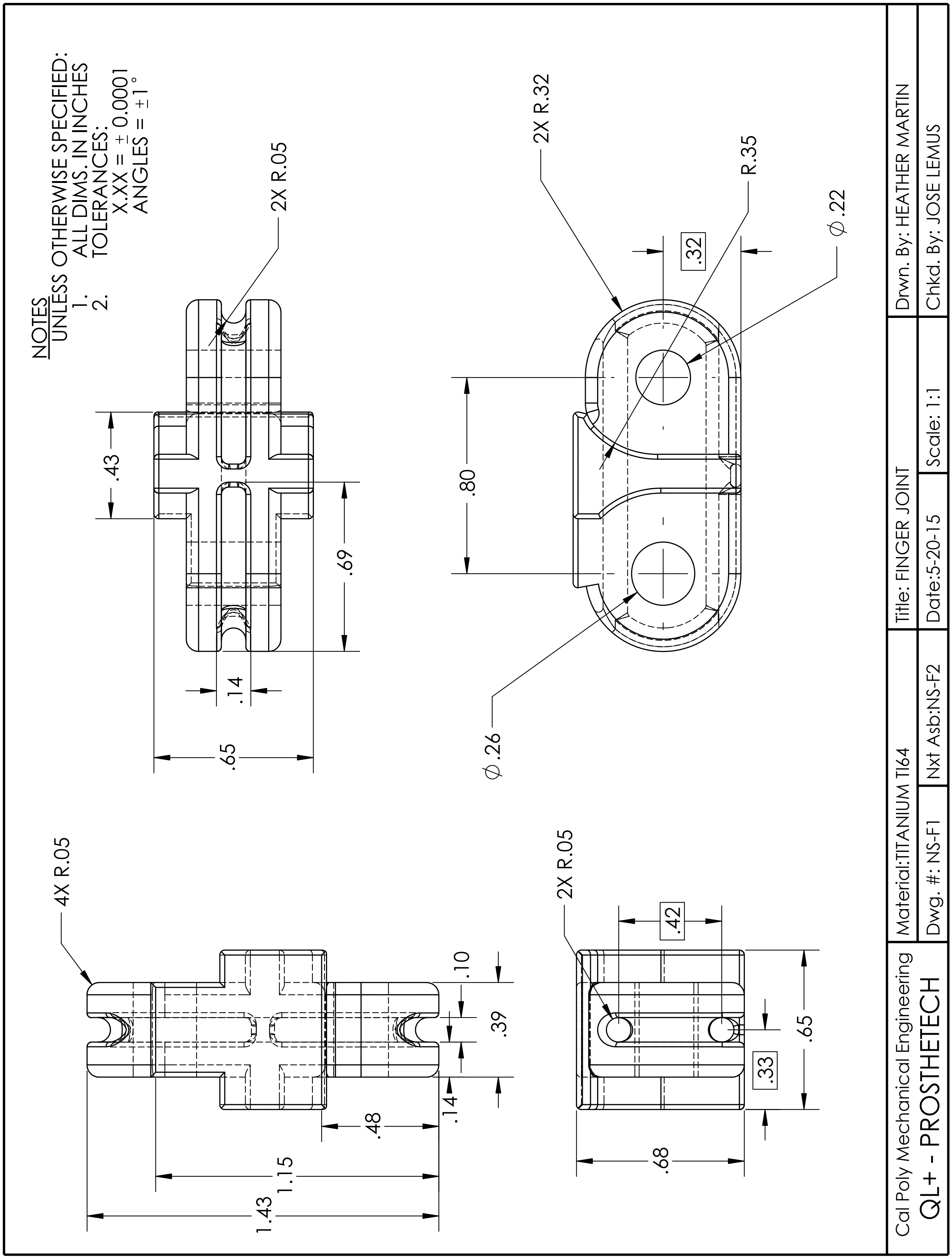

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
.15
2X R.03
Ø.07
Ø.05 ↧ .11
.09
.21
.30
.09
.08
.18
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material: TITANIUM TI64
Dwg. #:NS-G2
Nxt Asb:NS-G3
Title: BLOCK PALM
Date:5-20-15
Scale: 8:1
Drwn. By:RYAN BURKE
Chkd. By: JOSE LEMUS

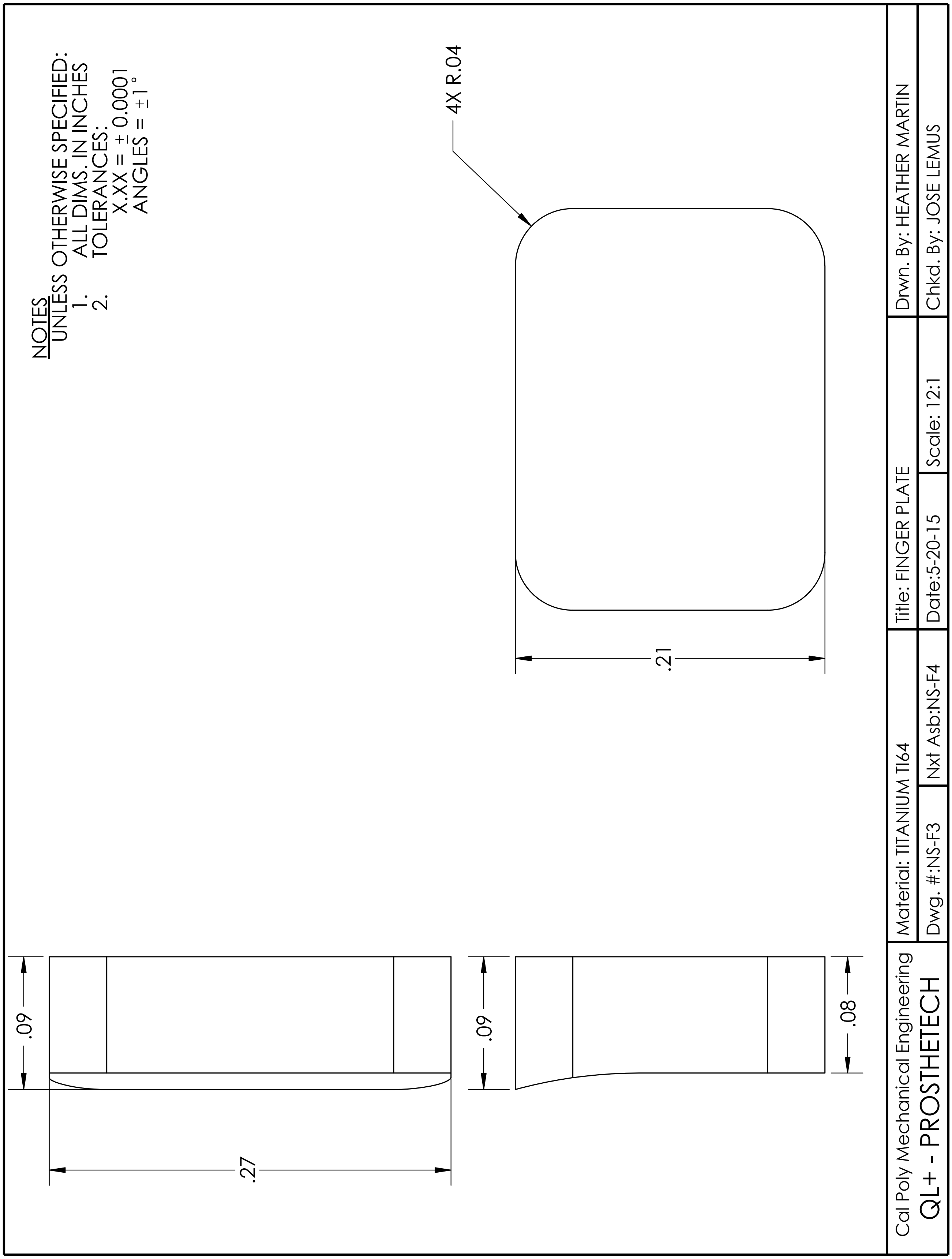

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
4X Ø.05 THRU
Ø.06 THRU
.16
.19
2.25
.75
.75
2.60
1.30
.57
.08
.18
.05
.13
8X R.03
.32
.25
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material: TITANIUM TI64
Dwg. #:NS-L2
Nxt Asb:NS-L3
Title: CABLE BAR
Date:5-20-15
Scale: 2:1
Drwn. By: JOSE LEMUS
Chkd. By: RYAN BURKE



ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	FINGER	TITANIUM TI64
2	1	FINGER_JOINT	TITANIUM TI64
3	1	FINGER SCREW- M	STAINLESS STEEL
4	1	FINGER SCREW- F	STAINLESS STEEL

Cal Poly Mechanical Engineering QL+ - PROSTHETECH			Title: FINGER ASSEMBLY		Drwn. By: JOSE LEMUS
	Dwg. #:NS-A2	Nxt Asb:NS-A3	Date: 6/6/15	Scale:	Chkd. By: RYAN BURKE


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
2X R.05
.43
.69
.14
.65
2X R.32
R.35
.32
∅.22
.80
∅.26
4X R.05
.10
.39
.14
.48
1.15
1.43
2X R.05
.42
.33
.65
.68
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material:TITANIUM TI64
Dwg. #: NS-F1
Nxt Asb:NS-F2
Title: FINGER JOINT
Date:5-20-15
Scale: 1:1
Drwn. By: HEATHER MARTIN
Chkd. By: JOSE LEMUS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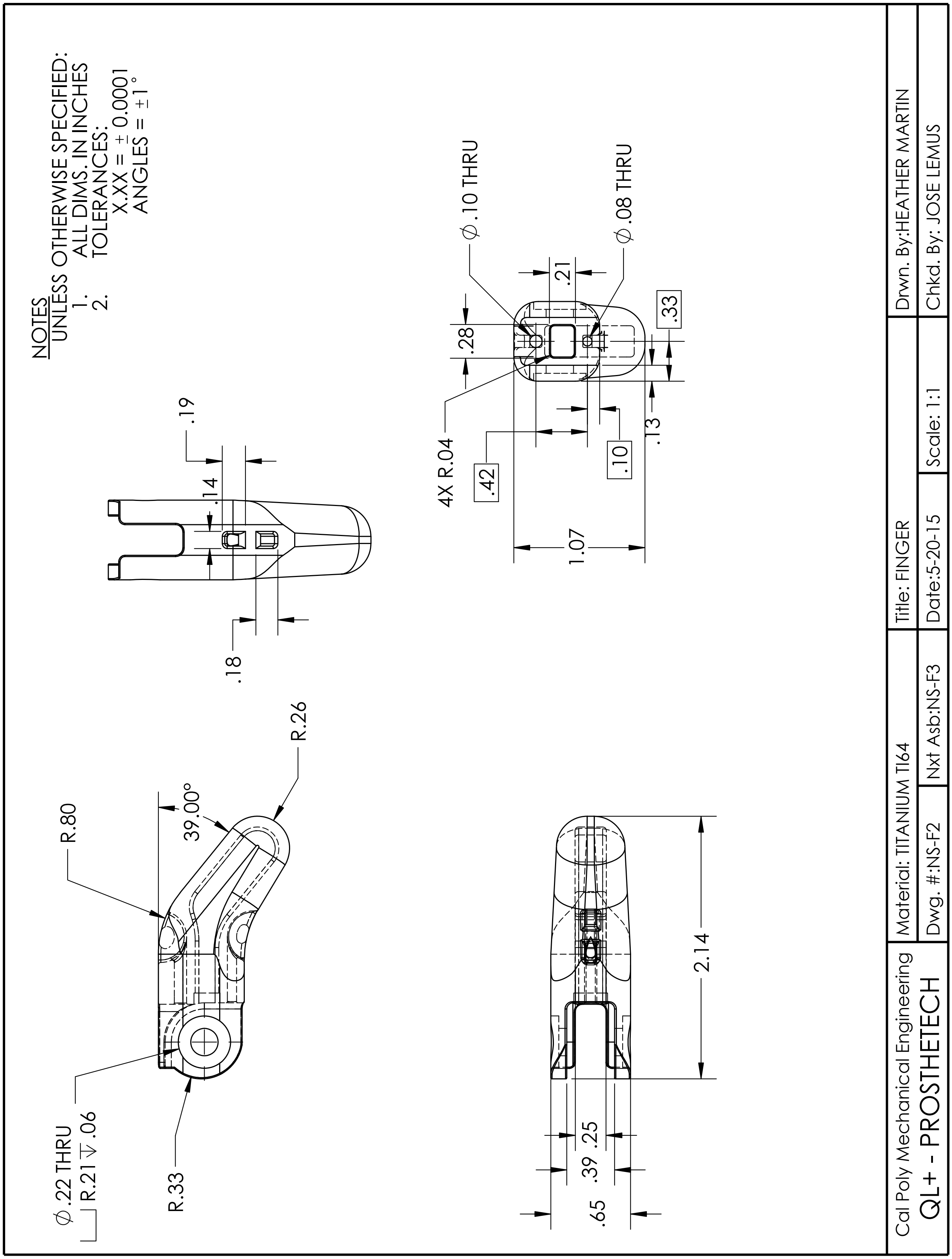
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
4X R.04
.21
.09
.09
.08
.27
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material: TITANIUM TI64
Dwg. #:NS-F3
Nxt Asb:NS-F4
Title: FINGER PLATE
Date:5-20-15
Scale: 12:1
Drwn. By: HEATHER MARTIN
Chkd. By: JOSE LEMUS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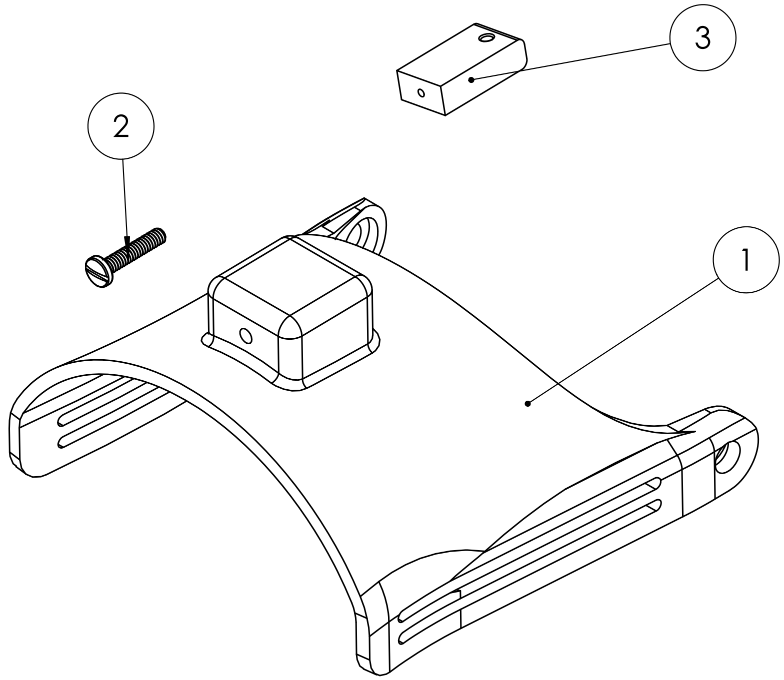
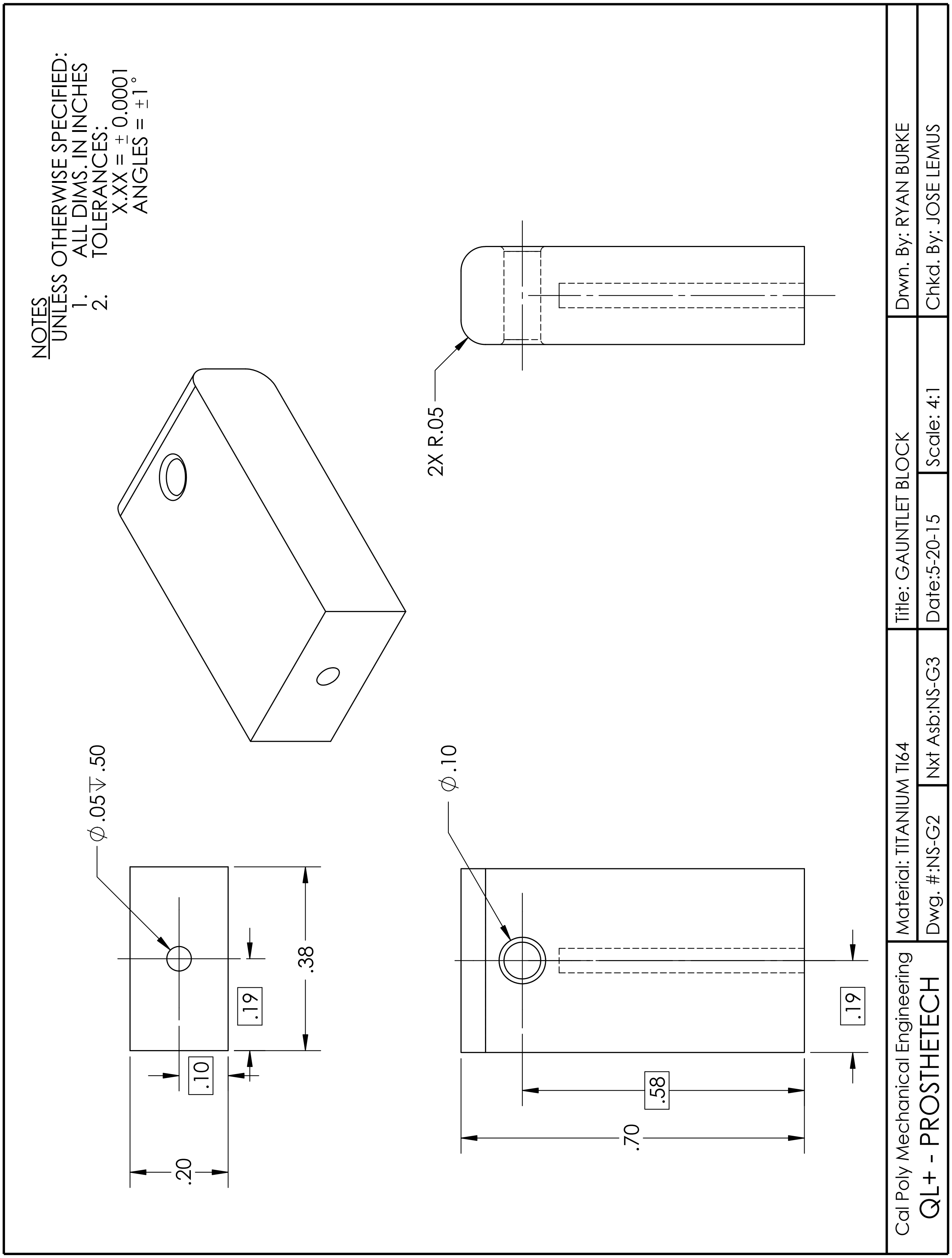
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
Ø.22 THRU
R.21 ↧.06
R.33
R.80
39.00°
R.26
.65
.39
.25
2.14
.18
.14
.19
4X R.04
.42
1.07
.28
Ø.10 THRU
.21
Ø.08 THRU
.33
.13
.10
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material: TITANIUM TI64
Dwg. #:NS-F2
Nxt Asb:NS-F3
Title: FINGER
Date:5-20-15
Scale: 1:1
Drwn. By:HEATHER MARTIN
Chkd. By: JOSE LEMUS



ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	Gauntlet-Straight	TITANIUM TI64
2	1	BLOCK SCREW	STAINLESS STEEL
3	1	GauntletBlock	TITANIUM TI64

Cal Poly Mechanical Engineering			Title: GAUNTLET ASSEMBLY		Drwn. By: JOSE LEMUS
QL+ - PROSTHETECH	Dwg. #:NS-A3	Nxt Asb:	Date: 6/6/15	Scale: 1:1	Chkd. By: RYAN BURKE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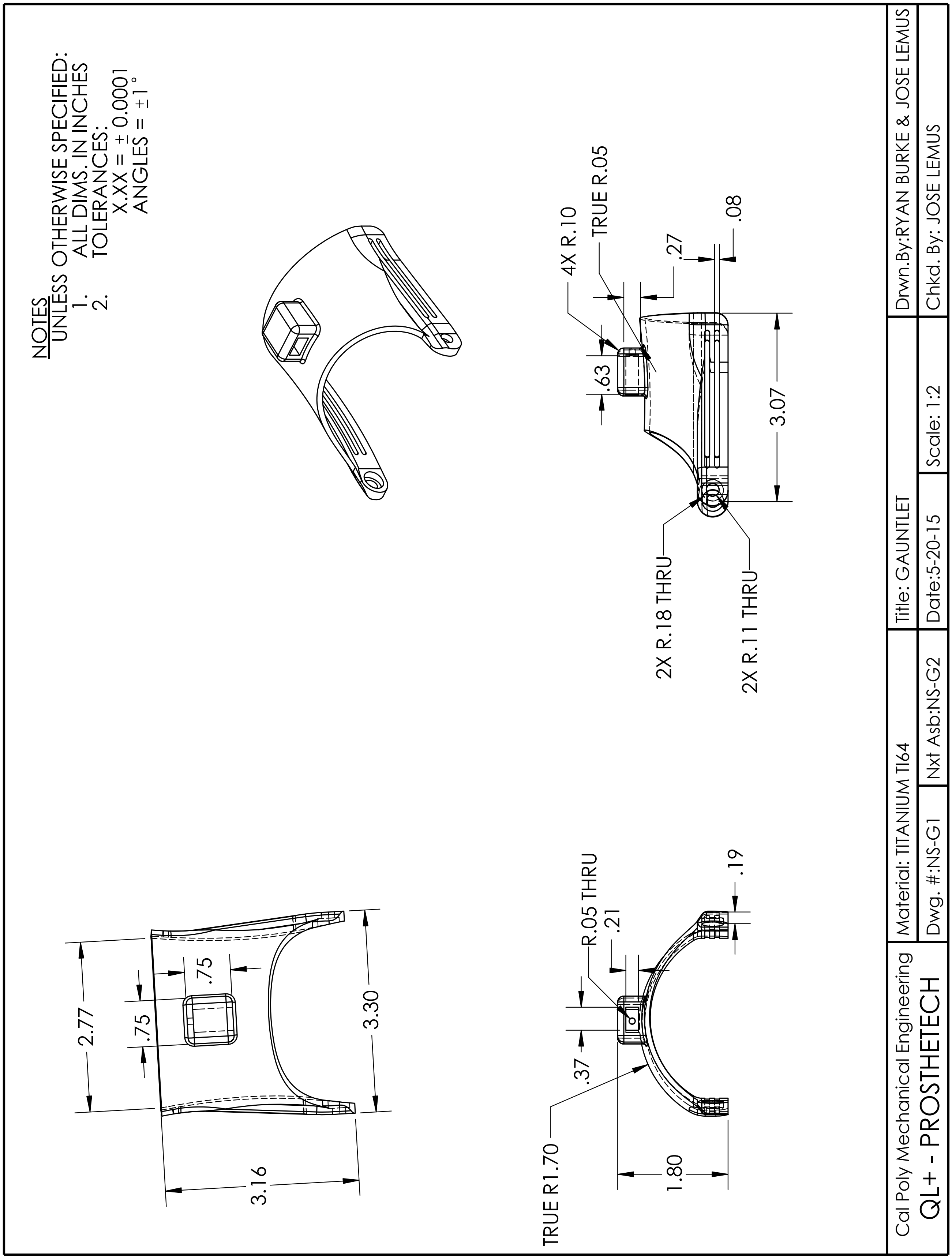
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
2X R.05
Ø.05 ▽ .50
Ø.10
.19
.38
.10
.20
.19
.58
.70
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material: TITANIUM TI64
Dwg. #:NS-G2
Nxt Asb:NS-G3
Title: GAUNTLET BLOCK
Date:5-20-15
Scale: 4:1
Drwn. By: RYAN BURKE
Chkd. By: JOSE LEMUS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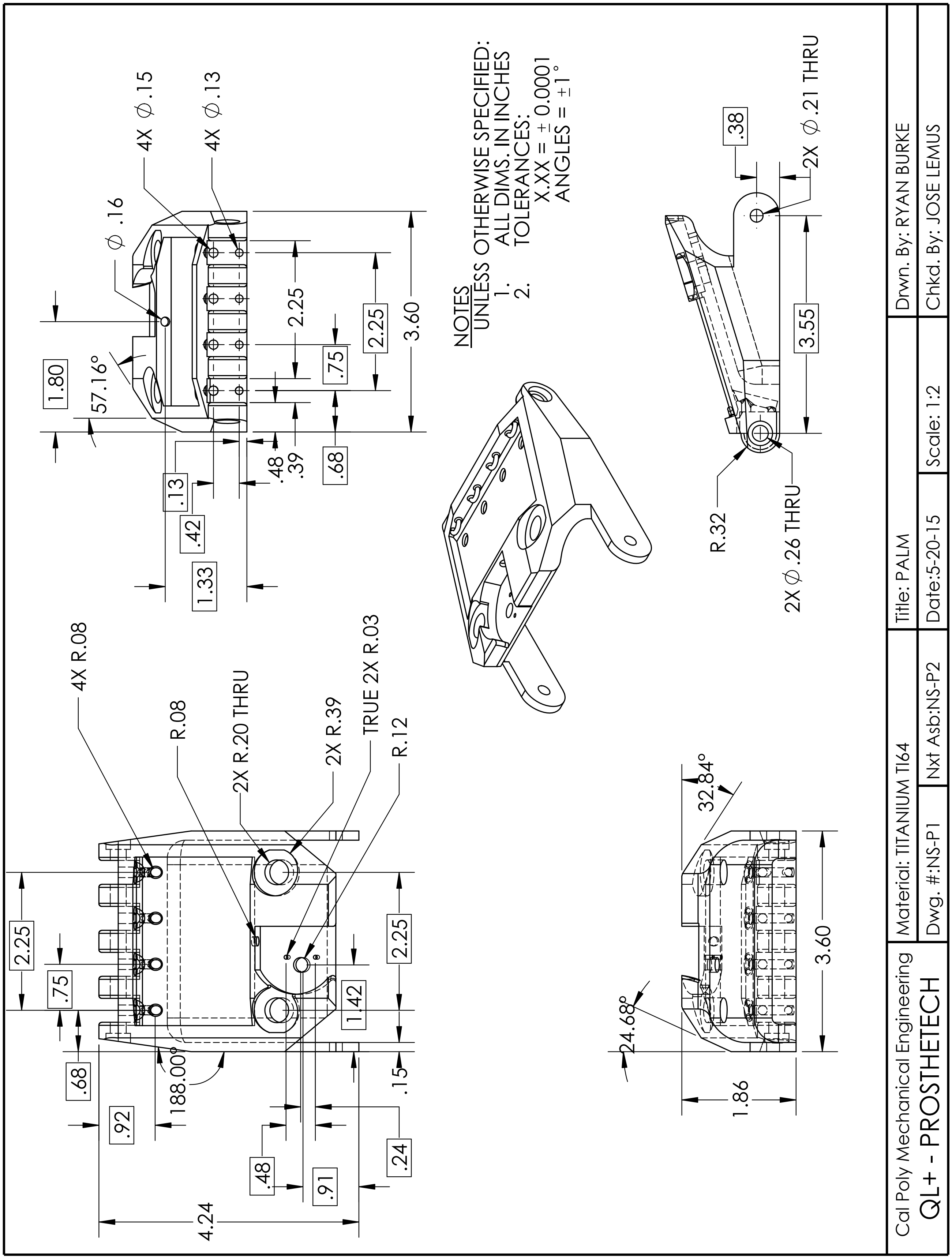
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
4X R.10
TRUE R.05
.27
.08
.63
3.07
2X R.18 THRU
2X R.11 THRU
2.77
.75
.75
3.30
3.16
R.05 THRU
.21
.19
.37
TRUE R1.70
1.80
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material: TITANIUM TI64
Dwg. #:NS-G1
Nxt Asb:NS-G2
Title: GAUNTLET
Date:5-20-15
Scale: 1:2
Drwn.By:RYAN BURKE & JOSE LEMUS
Chkd. By: JOSE LEMUS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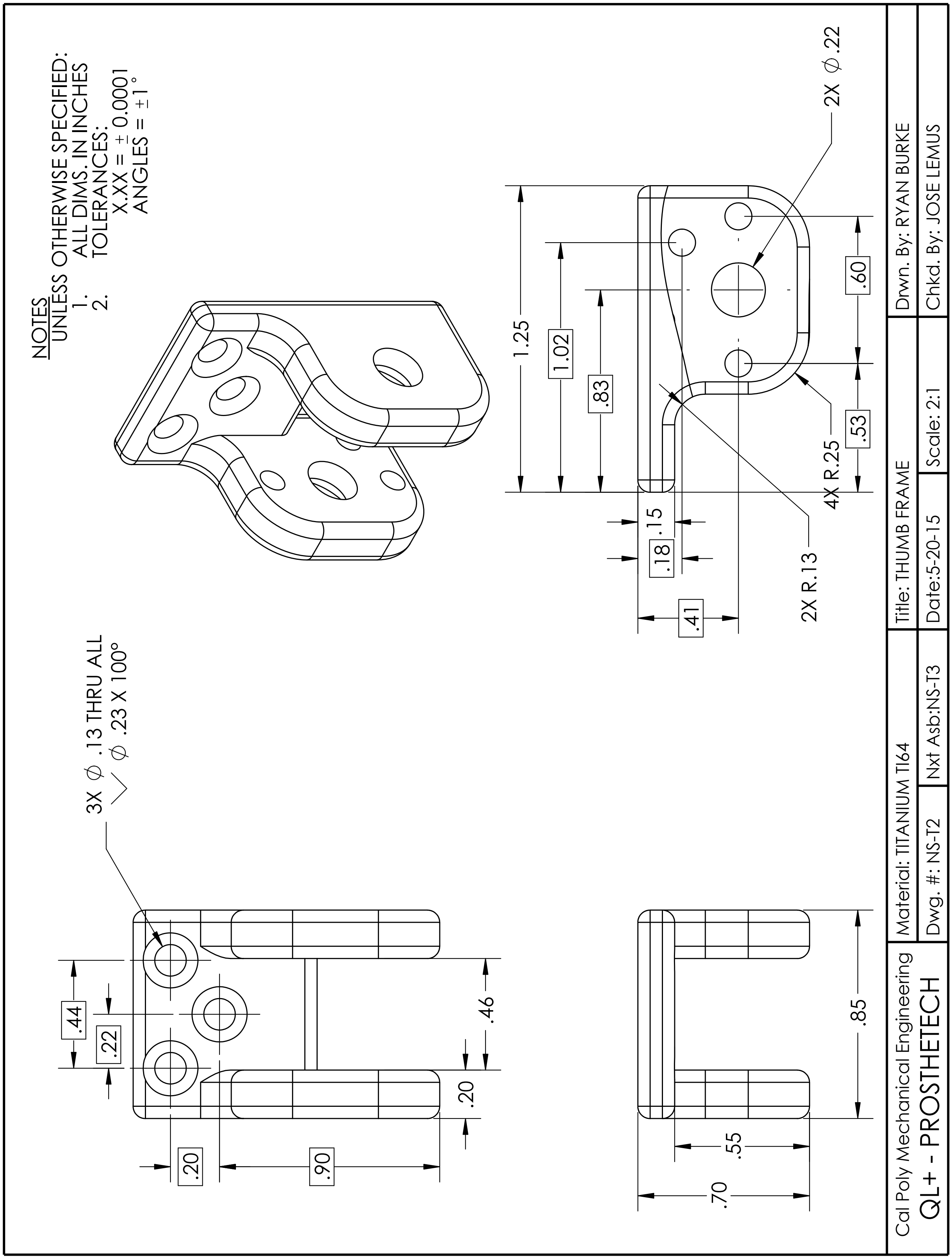
1. ALL DIMS. IN INCHES
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
4X R.08
R.08
2X R.20 THRU
2X R.39
TRUE 2X R.03
R.12
4X ⌀.15
4X ⌀.13
⌀.16
57.16°
188.00°
24.68°
32.84°
R.32
2X ⌀.26 THRU
2X ⌀.21 THRU
1.80
2.25
.75
3.60
.68
.39
.48
.13
.42
1.33
1.42
.15
.92
.24
.91
4.24
1.86
3.55
.38
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material: TITANIUM TI64
Dwg. #:NS-P1
Nxt Asb:NS-P2
Title: PALM
Date:5-20-15
Scale: 1:2
Drwn. By: RYAN BURKE
Chkd. By: JOSE LEMUS


NOTES
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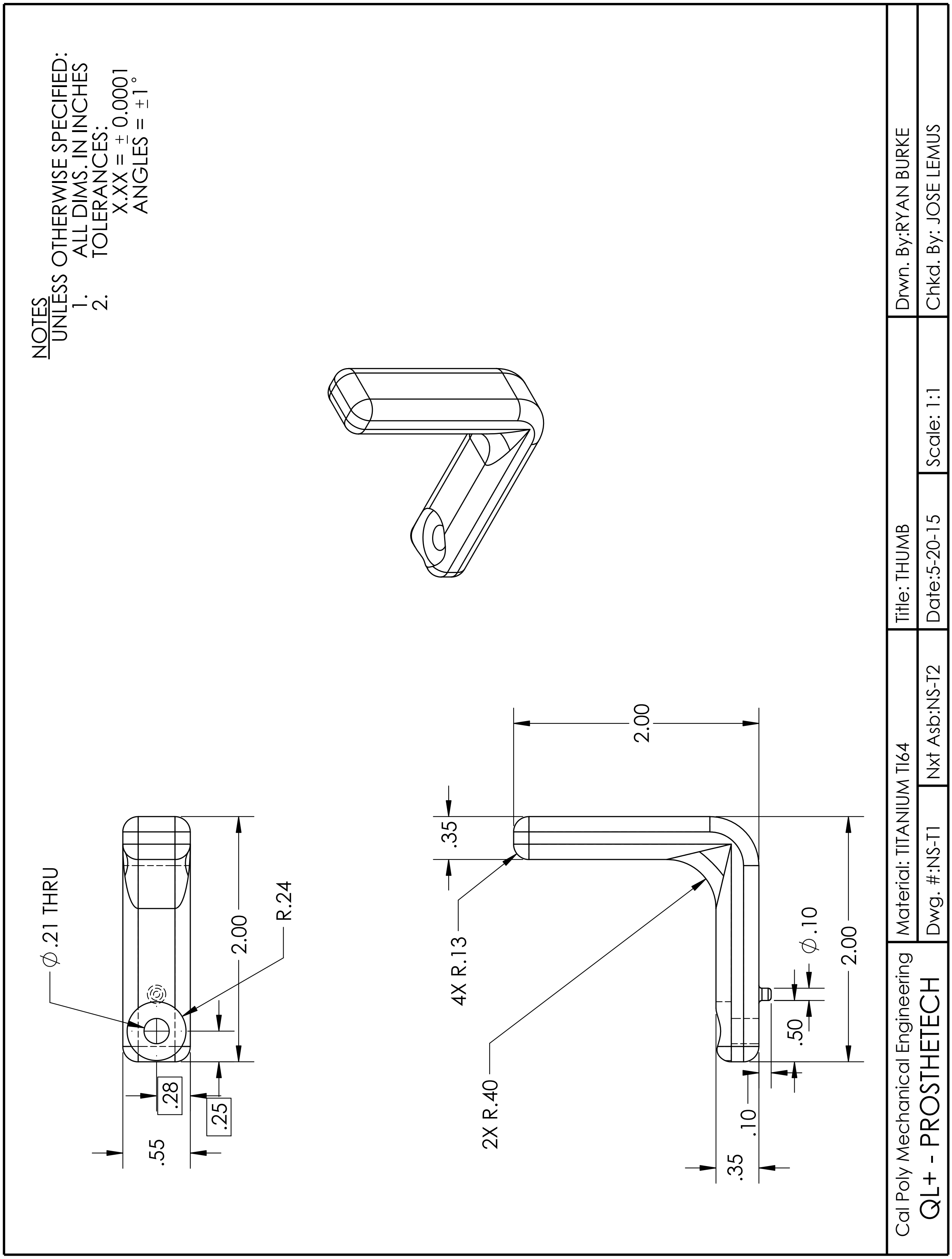
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
3X ⌀ .13 THRU ALL
⌵ ⌀ .23 X 100°
2X ⌀ .22
4X R.25
2X R.13
1.25
1.02
.83
.60
.53
.15
.18
.41
.44
.22
.46
.20
.20
.90
.85
.55
.70
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material: TITANIUM TI64
Dwg. #: NS-T2
Nxt Asb:NS-T3
Title: THUMB FRAME
Date:5-20-15
Scale: 2:1
Drwn. By: RYAN BURKE
Chkd. By: JOSE LEMUS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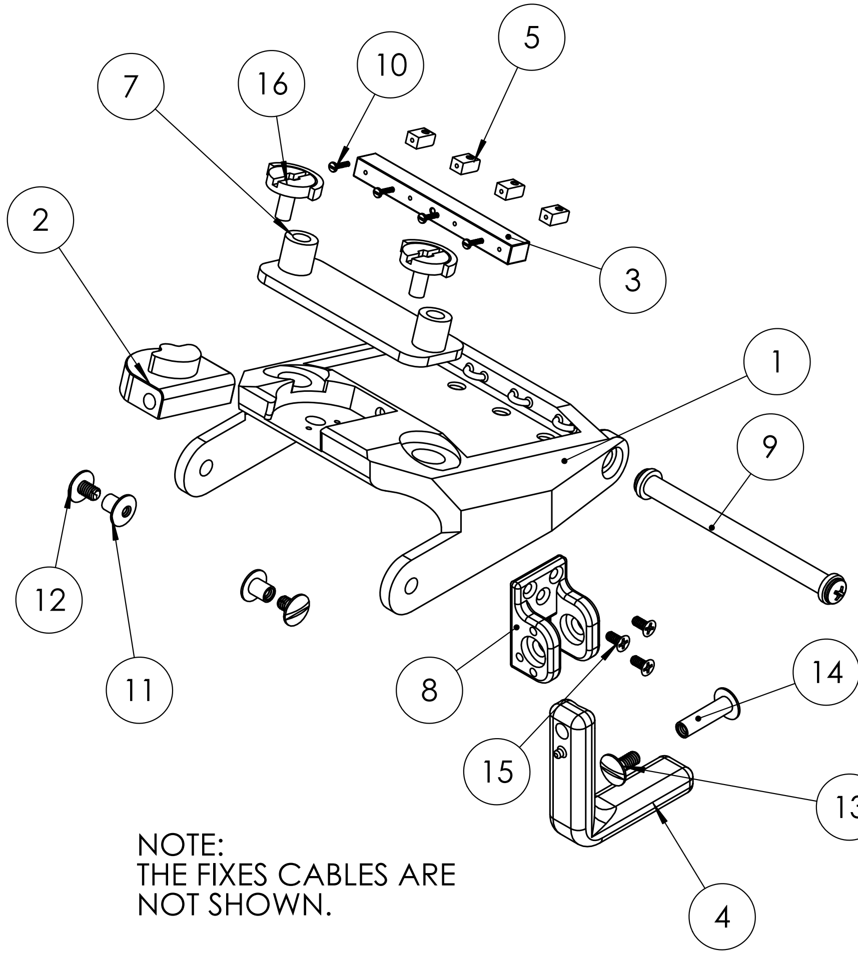
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
X.XX = ± 0.0001
ANGLES = ±1°
Ø.21 THRU
R.24
2.00
.55
.28
.25
4X R.13
.35
2.00
2X R.40
Ø.10
.50
2.00
.10
.35
Cal Poly Mechanical Engineering
QL+ - PROSTHETECH
Material: TITANIUM TI64
Dwg. #:NS-T1
Nxt Asb:NS-T2
Title: THUMB
Date:5-20-15
Scale: 1:1
Drwn. By:RYAN BURKE
Chkd. By: JOSE LEMUS



NOTE:
THE FIXES CABLES ARE
NOT SHOWN.

ITEM NO.	QTY.	DESCRIPTION	MATERIAL
1	1	Palm	TITANIUM TI64
2	1	Sure-Lock	STEEL & PLASTIC
3	1	Cable Mux	TITANIUM TI64
4	1	Thumb	TITANIUM TI64
5	4	Block Palm	TITANIUM TI64
7	1	Attachment Plate	TITANIUM TI64
8	1	Thumb Tab	TITANIUM TI64
9	1	Palm Standoff	STAINLESS STEEL
10	4	Tension Bolts	STAINLESS STEEL
11	2	Gauntlet Screws-F	STAINLESS STEEL
12	2	Gauntlet Screws-M	STAINLESS STEEL
13	1	Thumb Bolt-M	STAINLESS STEEL
14	1	Thumb Bolt-F	STAINLESS STEEL
15	3	Thumb Joint	STAINLESS STEEL
16	2	D-Screw	STAINLESS STEEL

Cal Poly Mechanical Engineering			Title: PALM ASSEMBLY		Drwn. By: JOSE LEMUS
QL+ -PROSTHETECH	Dwg. #:NS-A1	Nxt Asb:NS-A2	Date:6/6/15	Scale:1:2	Chkd. By: RYAN BURKE

12.12 Appendix L – List of Vendors

Vendor	Description	Cost	Vendor Contacts
Amazon	Elastic cord	$5.98	(888) 280-3321
Amazon	Nitrile gloves	$8.92	(888) 280-3321
Amazon	ABS Filament	$27.23	(888) 280-3321
Amazon	Teflon spray	$13.82	(888) 280-3321
Amazon	Fasteners	$6.99	(888) 280-3321
Betty's Fabrics	Elastic cord	$5.98	(805) 543-1990
Betty's Fabrics	Elastic cord/velcro	$4.84	(805) 543-1990
Dick's Sporting Goods	Fishing line	$26.98	(805) 545-0740
Foothilll Cyclery	Brake cable	$4.31	(805) 541-4101
Lee Spring	Springs	$26.69	(888) 777-4647
McMaster-Carr	Fasteners	$58.94	(562) 692-5911
McMaster-Carr	Fasteners	$15.17	(562) 692-5911
McMaster-Carr	Fasteners	$70.60	(562) 692-5911
McMaster-Carr	Fasteners	$53.51	(562) 692-5911
Miner's Ace Hardware	Fasteners	$3.13	(805) 543-2191
TRS, Inc.	Spectra cable	$59.50	(800) 279-1865

12.13 Appendix M – Operator's Manual

This manual includes guidelines for the assembly process, operation, and safety concerns.

12.13.1 Assembly

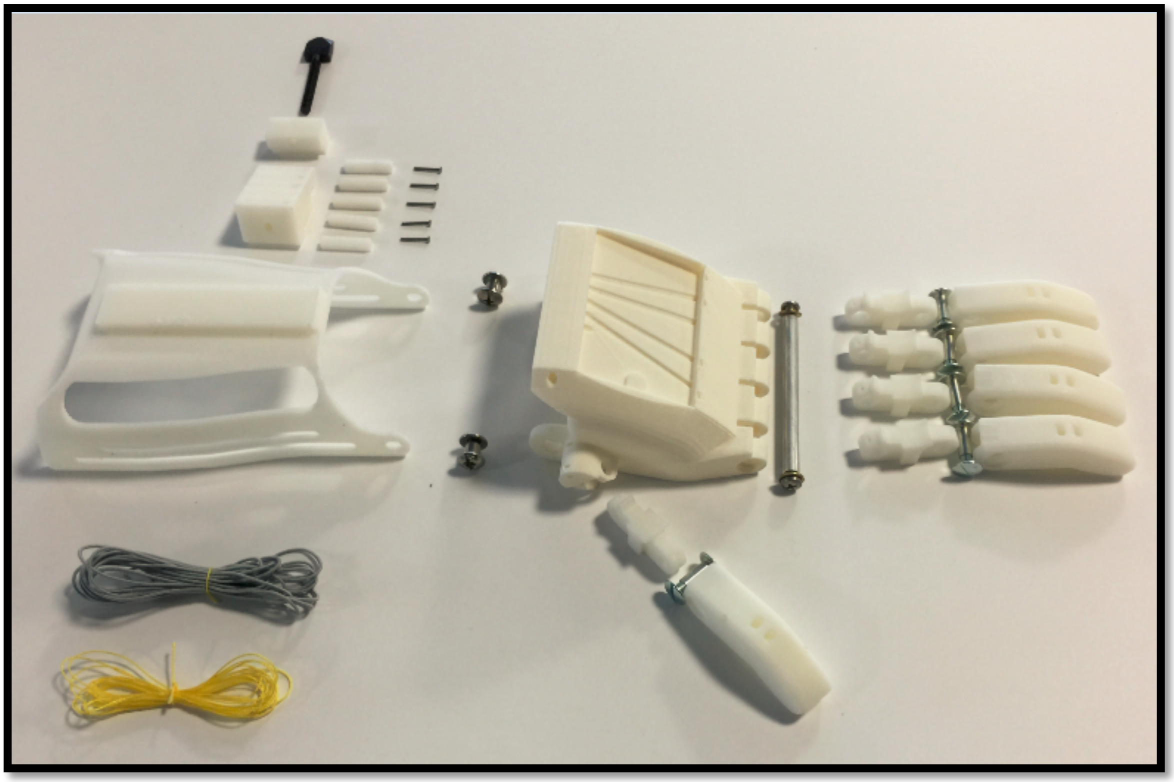


Figure M-1: Most major components of prosthesis ready for assembly.

First, the Sure-Lok mechanism should be secured into place on the palm. After the Sure-Lok is fastened down, the assembly will continue with the finger tips. The non-flexible cable should be inserted into the bottom hole of the fingertip member starting at the tip and sliding through the passageway toward the knuckle joint. A thick and sturdy knot should be tied at the end of the string to ensure that it will not be pulled into the passageway. The same should be done for the flexible cable in the passageways located on the top of the fingertip member.

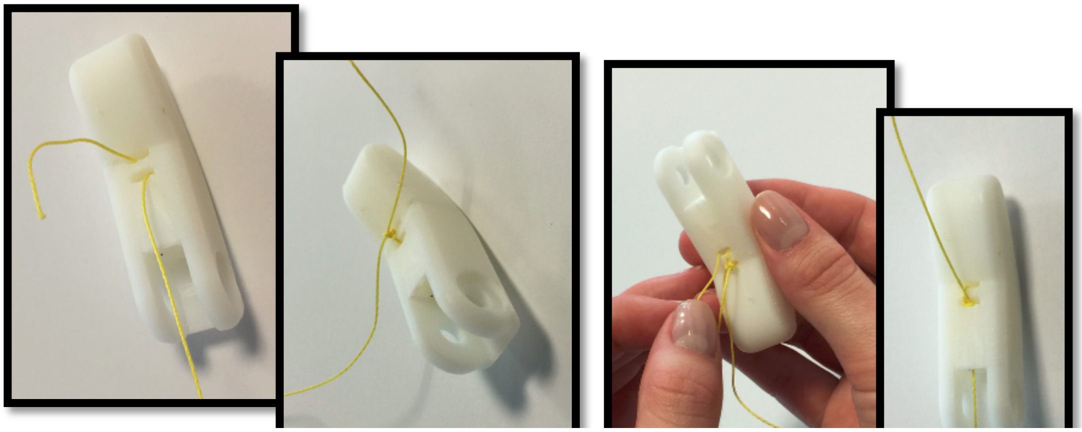


Figure M-2: Tying and threading the non-flexible cable through the passageways in fingertip joint.

Once the cables are tied, the fingertip and base members should be slid together and the Chicago screw for the knuckle joint should be inserted into its holes and tightened down. The cables should then be routed through their respective passageways on the base member. This should be done for all four members of the hand.

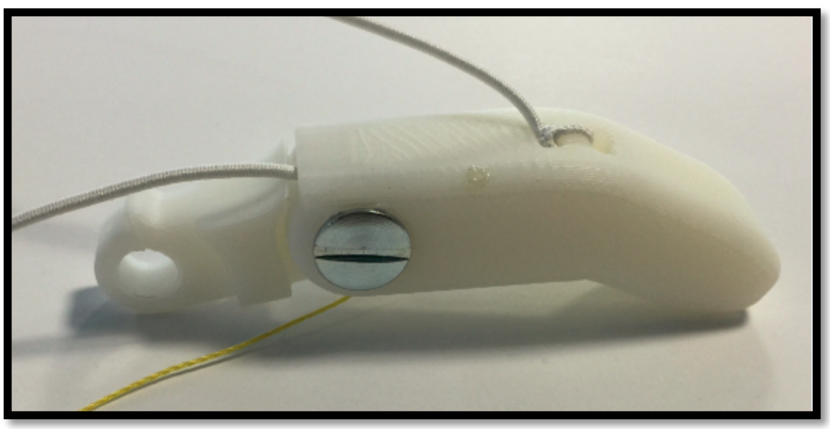


Figure M-3: Connected tip and base members of finger assembly, with cables threaded completely through.

The fingers should then be laid out neatly in front of their slots on the palm (all fingers are identical so the order does not matter). Once laid out, the flexible (top) cable should be inserted into its passageway on the base of the palm and pushed through until it protrudes through the hole on the top of the palm. Next, the flexible cable should be pushed through its passageway until it protrudes through the hole on the top of the palm in the same manner. This should be done for all four fingers; the cables can be taped or tied down to ensure that they are not pulled back through during the next steps.

Once the cables are routed, the index finger should be inserted into its slot on the palm and the long stainless steel shaft should be inserted into the hole on the base of the palm until

the index finger can rotate freely around the shaft, seen below in Figure M-4 The same procedure should be executed for the remaining three fingers so that all are secured on the palm. The screws and washers for the stainless steel shaft should be applied and tightened down on the shaft ends to secure the shaft in place.

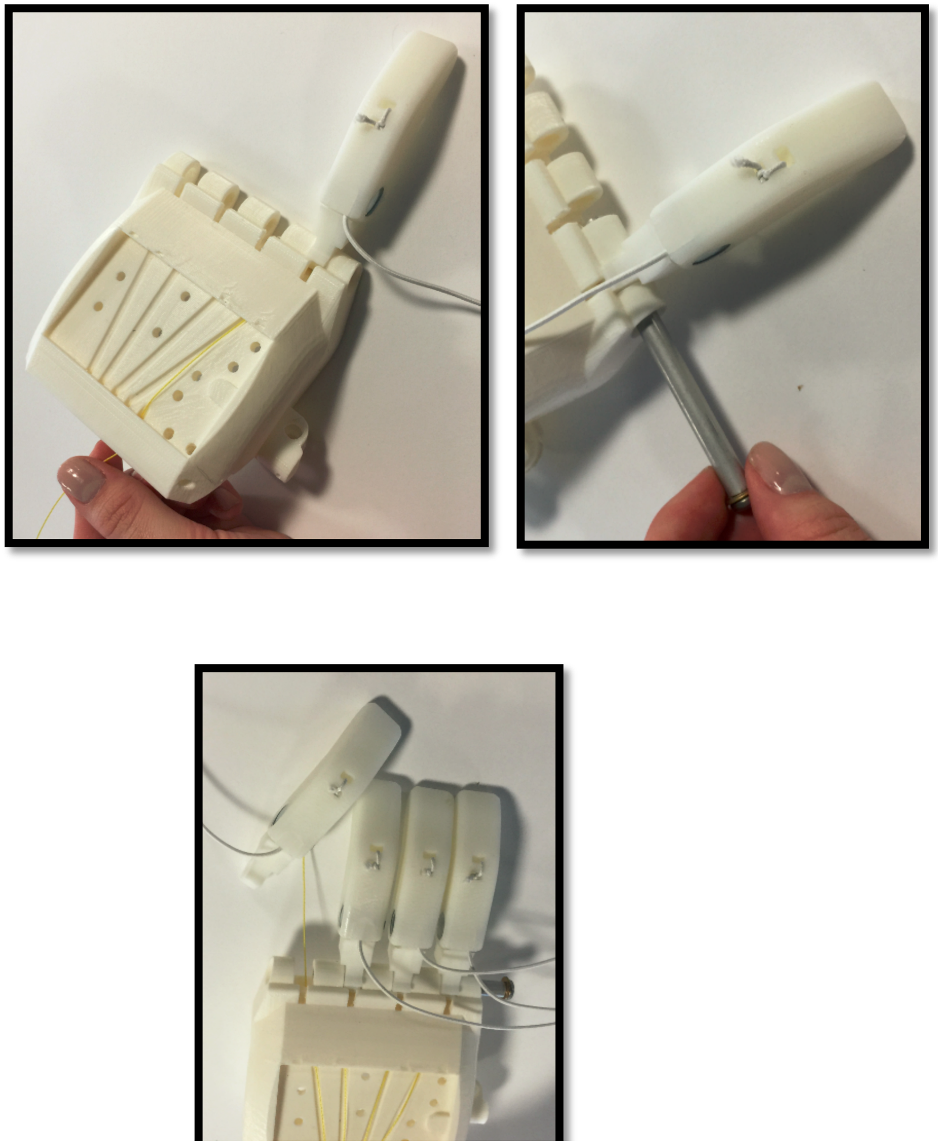


Figure M-4: Connecting the fingers to the palm by inserting the base rod through the holes in the palm and finger base joint one by one.

With the fingers secured in place, the flexible cables should be looped through their tie-down bars on the palm one by one, pulled tightly, and then secured with a knot. Next, the four small cable bar blocks should be obtained and slid into their respective holes on the Cable Bar. One by one, the small cable bar screws should be inserted into their holes on the Cable Bar and tightened until the threads are engaged.

The non-flexible cables should then be slid through the holes on the ends of these blocks. The Cable Bar should then be positioned so that the holes for the cables are directly over the passageway hole in the palm. This will allow for the bar to have maximum room to slide and therefore maximum range of motion for the grip. With the Cable Bar in this position, the four non-flexible cables should be tied securely around the cable bar blocks. Next, the Gauntlet should be placed in its correct position inside of the tabs protruding from the palm. The associated Chicago screws should then be inserted and tightened down. The bicycle brake cable should then be inserted through the center hole in the Cable Bar, continuing up through the Sure-Lok hole (making sure that the Sure-Lok is in the "unlocked" position). The gauntlet sliding block should then be obtained, slid into its hole in the gauntlet, tightened down with the small screw, all in a similar manner to how the smaller blocks were assembled in the Cable Bar.

With the Gauntlet Block in place, the bicycle brake cable should be threaded through the hole in the end of the block. The bicycle cable should be pulled tightly (but not so tight that the Cable Bar slides back), and the Gauntlet should be rotated until the desired default angle is achieved. The cable should be cut to size and a crimp-able cable stopper should be slid over the free end of the cable and crimped down with a set of pliers.

Next, the thumb needs to be assembled. This is done by first sliding the shaft end of the Chicago screw into the end of the thumb frame that faces the tip of the hand (non-counterbored hole). The spring should then be slid over the shaft of the Chicago screw, until it is recessed into its bore in the inside of the thumb frame. Next, the thumb member should be inserted into the slot and the Chicago screw shaft should be slid through the hole in the thumb so that the spring is seated inside the counterbores in both the thumb and frame members. The thumb should be positioned so that the pin protruding from the thumb member aligns with one of the holes located in a circular pattern around the Chicago screw hole on the body-facing end of the thumb frame. The other end of the Chicago screw should then be inserted into the opposite end of the frame and tightened securely. Lastly, the thumb subsystem should be positioned over the three associated screw holes and the three flathead screws should be tightened down, securing the thumb subsystem and the palm together.

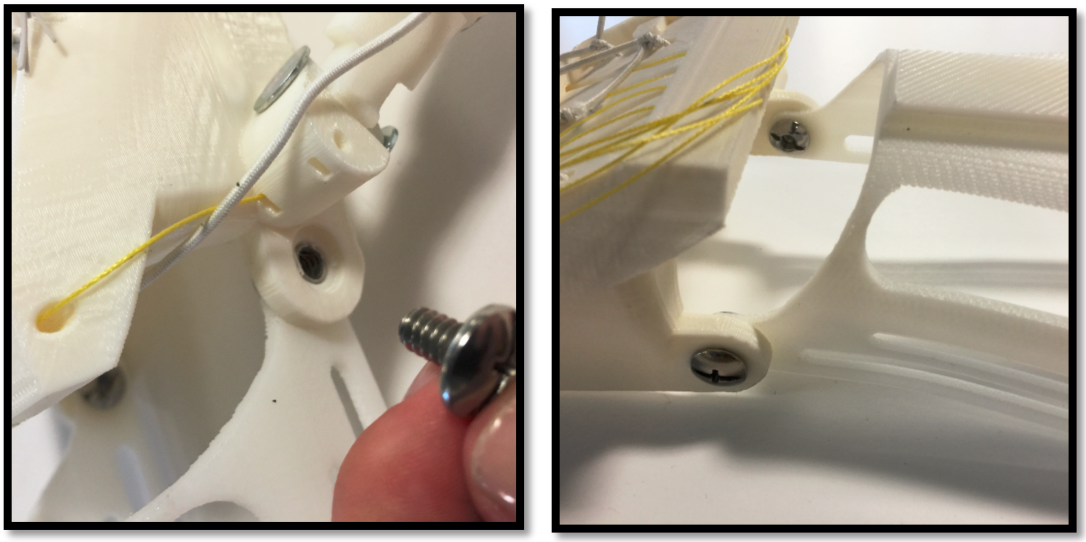


Figure M-5: Attaching the palm to the forearm subsystem with Chicago screws.

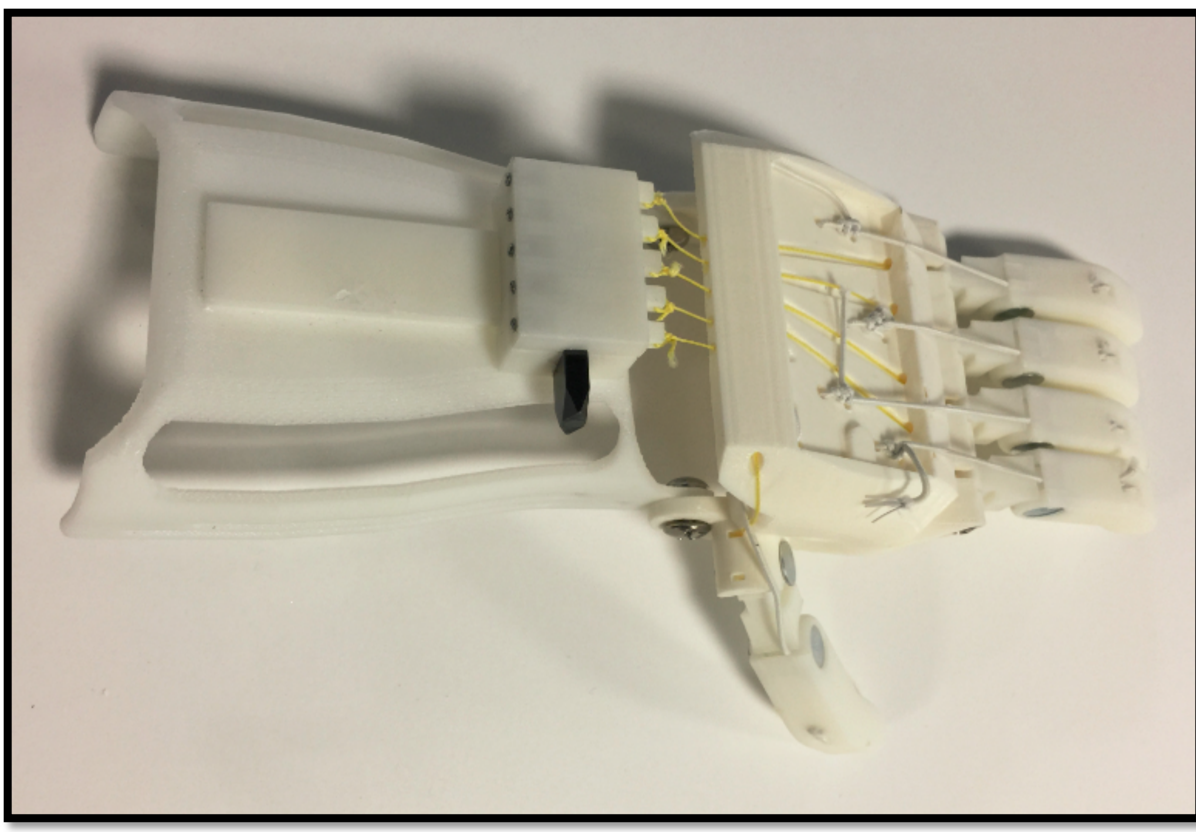


Figure M-6: Fully assembled prosthesis, without plate cover for internal passageways, glove, or Velcro straps. These features were not available in time for the first prototype assembly.

The user will wear the prosthesis by first sliding his residual through the provided silicone sleeve, until a tight suction is achieved at the inside tip. He will then place the end of the silicone sleeve near the inside tip of the prosthesis cavity, where he will slide the metal plate protruding from the silicone sleeve into the titanium block on the palm, ensuring that the holes of the protruding plate are aligned with the holes in the block. He will then tighten two thumb screws through these holes so that the silicone sleeve is effectively attached to the palm of the prosthesis. The user will then place his forearm in the gauntlet and wrap the Velcro around his forearm for added rigidity.

This concludes the main assembly of the prosthesis. Fine tuning of the tensioning blocks (achieved by tightening or loosening the adjustment screws) will be necessary once the user wears the device for the first time.

12.13.2 Operation

Below is a description of how the user will set up the device for use, how it is operated, and how it is removed. To wear the device, the user must first obtain the custom-molded silicone sleeve and slide it over his residual. The user will then place his sleeve-encased residual into the prosthesis and insert the two protruding pins into the corresponding holes in the palm. The user will then tighten down the two provided thumb-screws until the device is secured rigidly to the sleeve. The user will then secure the gauntlet over the forearm portion of the sleeve and tighten down the provided Velcro straps until the gauntlet is secured rigidly over the forearm. The device is now secured rigidly to the user's body.

Operation of the device begins with setup and fine-tuning of the tensioning systems. With the device in place, the user will actuate the device by flexing his wrist downward, thereby creating tension in the cables and bringing them to a closed-grip position. The tensioning blocks in the palm should then be moved forward/backward by loosening/tightening the adjustment screws on the opposite side of the cable bar. The tension should be adjusted until all four fingers close uniformly throughout the actuation of the device.
If the user wishes to adjust the default angle of the device with respect to his residual, he can simply adjust the tension in the block on the gauntlet via the adjustment screw. Tightening the screw will bring the block closer to the end of the cavity in the gauntlet and increase the default angle of the device.

To operate the thumb, the user pushes the thumb member in the direction toward the finger tips, compressing the spring and enabling the thumb to be locked into one of the three available positions by lining up the pin on the thumb with the pin holes on the thumb frame.

As mentioned above, the user will achieve a grip by simply rotating his wrist downward, which increases tension in the cables and brings the fingers downward into a closed-grip position. If the user wishes to lock a grip (useful for carrying heavy objects for long periods of time), he simply rotates the cam on top of the Sure-Lok counterclockwise into the "lock"

position. The user then achieves the desired grip by actuating the device as usual. When the desired grip is achieved, the user can then release wrist flexion and the locking mechanism will maintain this grip. When the user wishes to return the hand to the default position, he increases the actuation slightly (to un-jam the inner mechanism of the Sure-Lok against the cable) and rotates the cam clockwise into the "unlocked" position.
When the user wishes to remove the prosthetic from his body after use, he simply removes the Velcro straps, loosens the screws on the palm and removes the sleeve from the device, and finally removes the silicone suction sleeve.

12.13.3 Safety Concerns

Safety is of utmost importance in this design and has been a major consideration throughout the design process. As the prosthesis is attached to the users body at all times during use, it is important that the device will not cause any harm to the user or increase the user's chance of being harmed while operating it during military activities. However, there are several safety concerns that need to be addressed before the user works with this device.

The cables used in this design, although strong, are prone to breaking, especially if the hand is subjected to extreme mechanical, thermal, or chemical loads. In the event that the cable is overloaded, it might snap and injure the user; moreover, this would disengage any grip that the user might have locked, causing him to lose the grip in that finger and drop any object he might be carrying. To prevent this, the user must evaluate the loads the hand will be subjected to; anything weighing more than the user's bodyweight should be carried with extreme caution. Additionally, any extreme temperature environments should be avoided to reduce the chance of the cables weakening.

The suction sleeve used in this design might also provide a couple safety concerns. If the device is to be used over long periods of time, the continuous suction on the tip of the user's residual might cause discomfort and possibly pain. To prevent this, the user should remove the device when not needed to allow his residual to be relieved from the constant suction, especially if heavy loads are being encountered by the hand. The prosthetic device is only as strong as the suction achievable in the sleeve. If the sleeve loses suction, the prosthesis will separate from the user's residual; this presents the chance for injury of the user depending on the application of the hand. This also might cause the prosthesis to be damaged if it tumbles to the ground. The user should pay close attention to the feel of the suction sleeve; if he feels it might be losing suction, he should stop using it immediately and adjust it or cease operating it under the current application. The user's prosthetist can be consulted for more information regarding the suction sleeve as he is much more knowledgeable on the subject and on ways to improve the suction of the sleeve to prevent this occurrence. The Velcro straps should provide a temporary failsafe if separation of the sleeve from the device due to suction loss is encountered.

Additionally, there are several pinch points that should be avoided when operating the hand, especially between in the finger members. The user should be aware of these points

and attempt to achieve grips before coming in contact with either his own or another person's hand or body in order to eliminate the chance of pinching them when a grip is actuated.

12.14 Appendix N – Stress Analysis

LOAD ANALYSIS:

OBJECTIVE: DETERMINE FORCES IN PIN JOINTS AND TENSION IN CABLE AS FUNCTION OF FINGER ANGLE AND INPUT LOAD.

RESULTS: $P_t = \sqrt{(T\cos(\theta_2 - 90))^2 + (F + T\sin(\theta_2 - 90))^2}$;

$P_b = P_t$; $T = \frac{F l_2}{r_c} \sin(180 - \theta_2)$

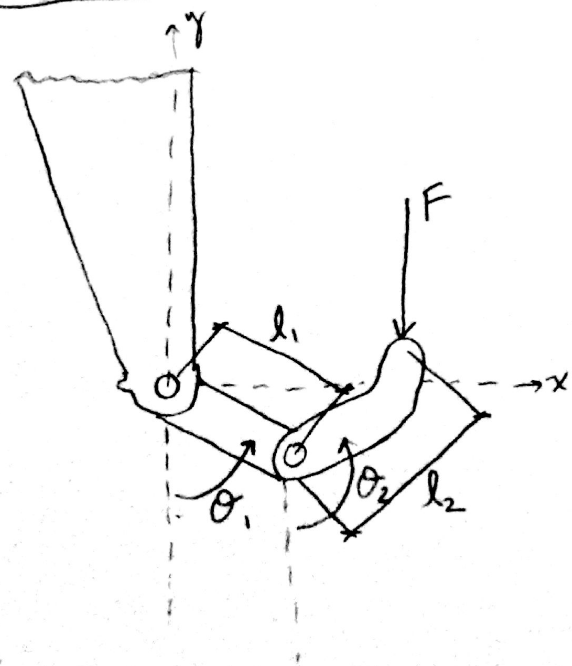
METHOD: STATICS

ASSUMPTIONS:
1) RIGID BODIES & CABLE
2) POINT LOAD AT FINGERTIP
3) PALM PARALLEL TO GAUNTLET
4) LOAD DISTRIBUTED EVENLY ACROSS 4 FINGERS

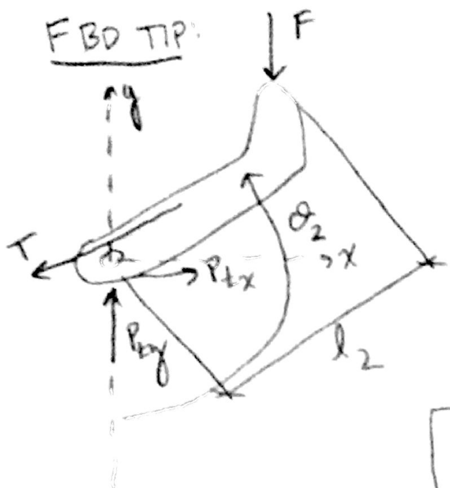
KNOWN: $l_2 = 1.95$ in; $r_c = 0.15$ in ; $F = 250$ lb/4

ANALYSIS:

SCHEMATIC:



FBD TIP:



- $\Sigma M_p = 0$

$$T r_c = F l_2 \sin(180 - \theta_2)$$

$$\boxed{T = \frac{F l_2}{r_c} \sin(180 - \theta_2)}$$

- $\Sigma F_x = 0$

$$P_{tx} = T\cos(\theta_2 - 90)$$

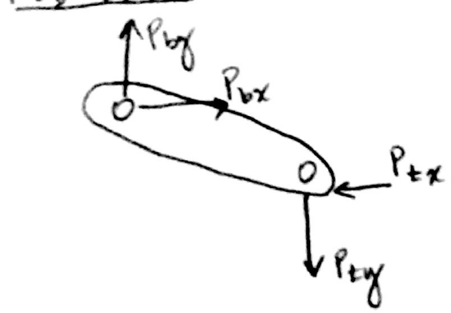
- $\Sigma F_y = 0$

$$P_{ty} = F + T\sin(\theta_2 - 90)$$

$$\boxed{P_t = \sqrt{\left(T\cos(\theta_2 - 90)\right)^2 + \left(F + T\sin(\theta_2 - 90)\right)^2}}$$

PIN FORCE IN TIP PIN

FBD BASE:



$\Sigma F_y = 0$: $P_{by} = P_{ty}$

$\Sigma F_x = 0$: $P_{bx} = P_{tx}$

$$\boxed{P_b = P_t}$$

PIN STRESS ANALYSIS

OBJECTIVE: DETERMINE PIN STRESSES AND ASSOCIATED FACTOR OF SAFETIES.

RESULT: $\sigma_{PIN} = 16,650$ psi

$n_f = 3.60$

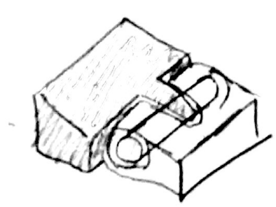
METHOD: $\sigma = \frac{MC}{I}$

ASSUMPTIONS:
1) CHICAGO SCREW MODELED AS SOLID PIN
2) LOADS EQUAL TO MAX'S AS CALCULATED PREVIOUSLY
3)

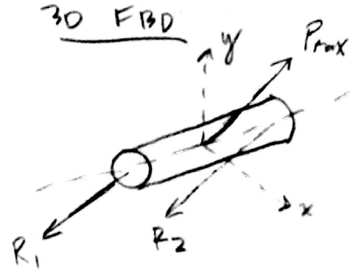
KNOWN: $P_{max} = 817.23$ lbf ; $d = 1/4''$; $l = 1/4''$; $\sigma_{all} = 60,000$ psi (STEEL)

ANALYSIS:

ISO VIEW OF PIN JOINT:



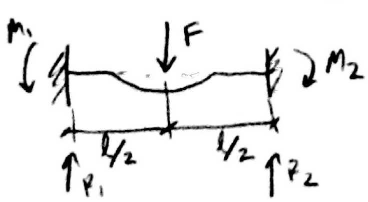
3D FBD



FORCES ARE ALL IN ONE PLANE;

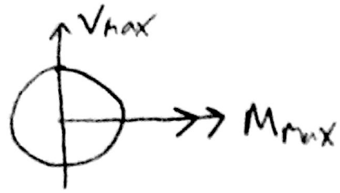
↓

PIN CAN BE MODELED AS FIXED SUPPORTS W/ CENTER LOAD:



$\Rightarrow M_{max} = \frac{Fl}{8}$; $V_{max} = \frac{F}{2}$

STRESS DIAGRAM:



σ_{max} @ TOP IN BENDING;

$$\sigma_{max} = \frac{M_{max} c}{I}$$

$$= \frac{\frac{P_{max} l}{2} \cdot \frac{d}{2}}{\frac{\pi}{16} d^4}$$

$$\boxed{\sigma_{max} = \frac{4 P_{max} l}{\pi d^3}}$$

$$= \frac{4(817.23 \text{ lbf})(0.25 \text{ in})}{\pi (0.25 \text{ in})^3}$$

$$\boxed{\sigma_{max} = 16{,}650 \text{ psi}}$$

$$n_f = \frac{\sigma_{all}}{\sigma_{max}}$$

$$= \frac{60{,}000 \text{ psi}}{16{,}650 \text{ psi}} \longrightarrow \boxed{n_f = 3.60}$$

PIN WILL NOT SNAP IN WORST-CASE LOADING

MEMBER STRESS ANALYSIS:

OBJECTIVE: DETERMINE STRESSES IN MEMBERS HELD TOGETHER BY PIN JOINT.

RESULT: $\sigma_{MID} = 8,379.40$ psi ; $n_f = 7.52$

$\sigma_{OUT} = 28,683$ psi ; $n_f = 2.20$

METHOD: $\tau = \frac{V}{A}$

ASSUMPTIONS: 1)
2)

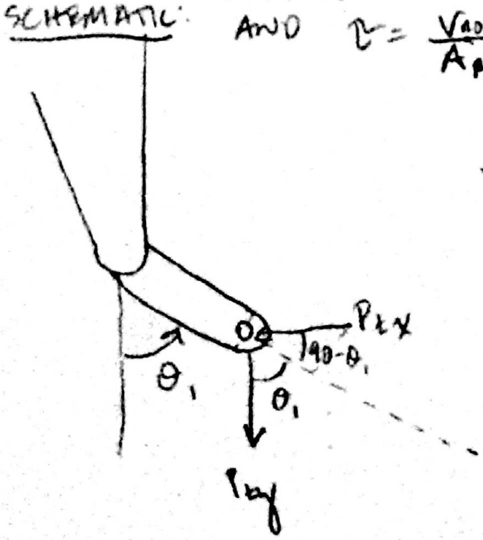
KNOWN: • $V_{max} = \frac{P_{max}}{2}$ (FROM FIX-SUPPORT BEAM SUPERPOSITION EQ. IN PIN ANALYSIS SECTION)

• $l = 0.25''$ • $\theta_1 = 45°$ • $\sigma_{AR} = 63,000$ psi

• $w = 0.5''$ • $\theta_2 = 95°$

ANALYSIS: SHEARING OCCURS AT MINIMUM AREA. FORCES ARE RESOLVED INTO COMPONENTS NORMAL TO MIN. AREA AND $\tau = \frac{V_{norm}}{A_{min}}$

SCHEMATIC:



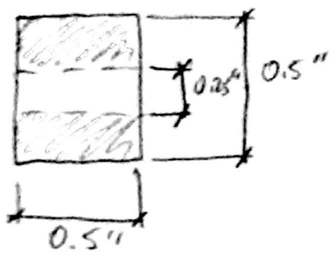
$$V_{norm} = -P_{tx}\cos(90-\theta_1) + P_{ty}\cos(\theta_1)$$

PLUGGING IN NUMBERS...

$$V_{norm} = -806.33\ \text{lbf}\cos(90-45°) + 133.04\ \text{lbf}\cos(45°)$$

$$= -476.10\ \text{lbf}$$

AREA DIAGRAM:



$$A_{min} = (0.5\,in)^2 - (0.5)(0.25)\,in^2$$

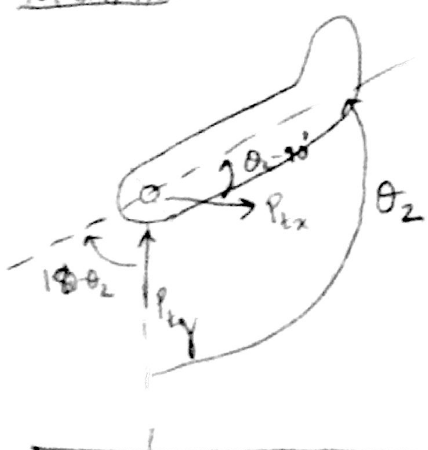
$$A_{min} = 0.125\ in^2$$

STRESS CONCENTRATION FACTOR

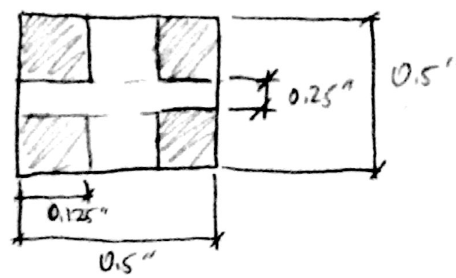
$$\tau = \left(\frac{476.10\ lbf}{0.125\ in^2}\right) 2.2$$

$$\boxed{\tau_{MID} = 8{,}379.40\ psi}$$

SCHEMATIC:



AREA:



$$\boxed{V_{norm} = P_{ty}\cos(180-\theta_2) + P_{tx}\cos(\theta_2 - 90^\circ)}$$

PLUGGING IN NUMBERS

$$= 133.04\ lbf \cos(180-95^\circ) + 806.33\ lbf \cos(95-90^\circ)$$

$$\boxed{V_{norm} = 814.86\ lbf}$$

STRESS IS ANALYZED ON ONE SIDE.

$$\tau = \frac{V}{A} k_f$$

$$= \frac{(814.86\ lbf)(2.2)/2}{(0.25")(0.125")}$$

$$\boxed{\tau_{out} = 28683\ psi}$$

CALCULATING FACTORS OF SAFETY FOR TITANIUM MEMBERS

$$n_{f_{MID}} = \frac{63,000 \text{ psi}}{8,379.40 \text{ psi}}$$

$$\boxed{n_{f_{MID}} = 7.52}$$

$$n_{f_{OUT}} = \frac{63,000 \text{ psi}}{28683 \text{ psi}}$$

$$\boxed{n_{f_{OUT}} = 2.20}$$

TRANSVERSE IMPACT ANALYSIS:

OBJECTIVE: DETERMINE STRENGTH OF HAND WHEN IMPACT LOADS ARE EXPERIENCED TRANSVERSE TO HAND.

RESULTS: $F_{allowable} = 603$ lbf IMPACT

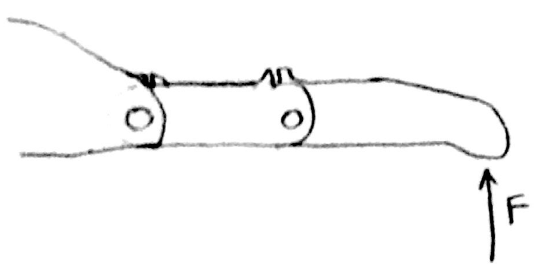
METHOD: $\sigma = \frac{P}{A}$

ASSUMPTIONS: 1) $n_f = 2$
2)

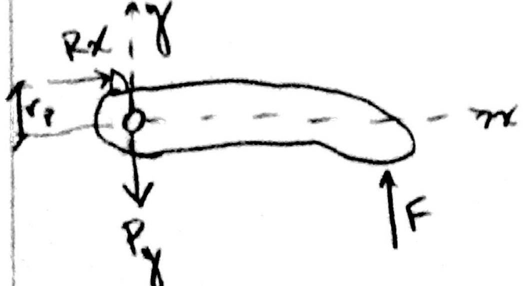
KNOWN:
- $h = 0.46$ in
- $A_b = .008$ in^2
- $b = 0.17$ in
- $r_p = 0.32$ in
- $l_2 = 1.95$ in
- $\sigma_{yield} = 141{,}000$ psi
- $\sigma_{TS} = 63{,}000$ psi
- $n_f = 2$

ANALYSIS:

SCHEMATIC:



FBD TIP:

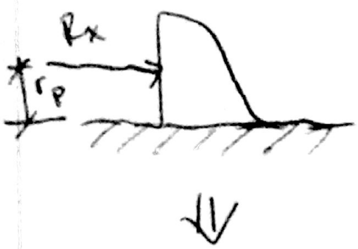


$\Sigma M_p = 0$:

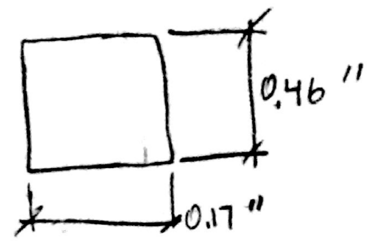
$$F l_2 = R_x r_p$$

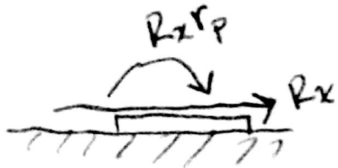
$$R_x = \frac{F l_2}{r_p}$$

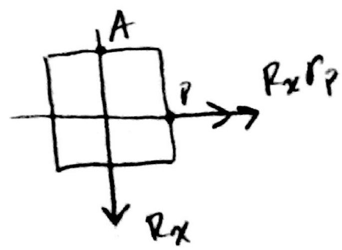
STOPPING BLOCKS IDENTICAL ON MIDDLE AND TIP MEMBERS... FORCES ANALYZED AT BASE OF STOPPER, WHERE IT WILL FAIL



BASE AREA







- $\sigma_A = \frac{Mc}{I} = \frac{R_x r_p}{\frac{1}{12} b h^3}$

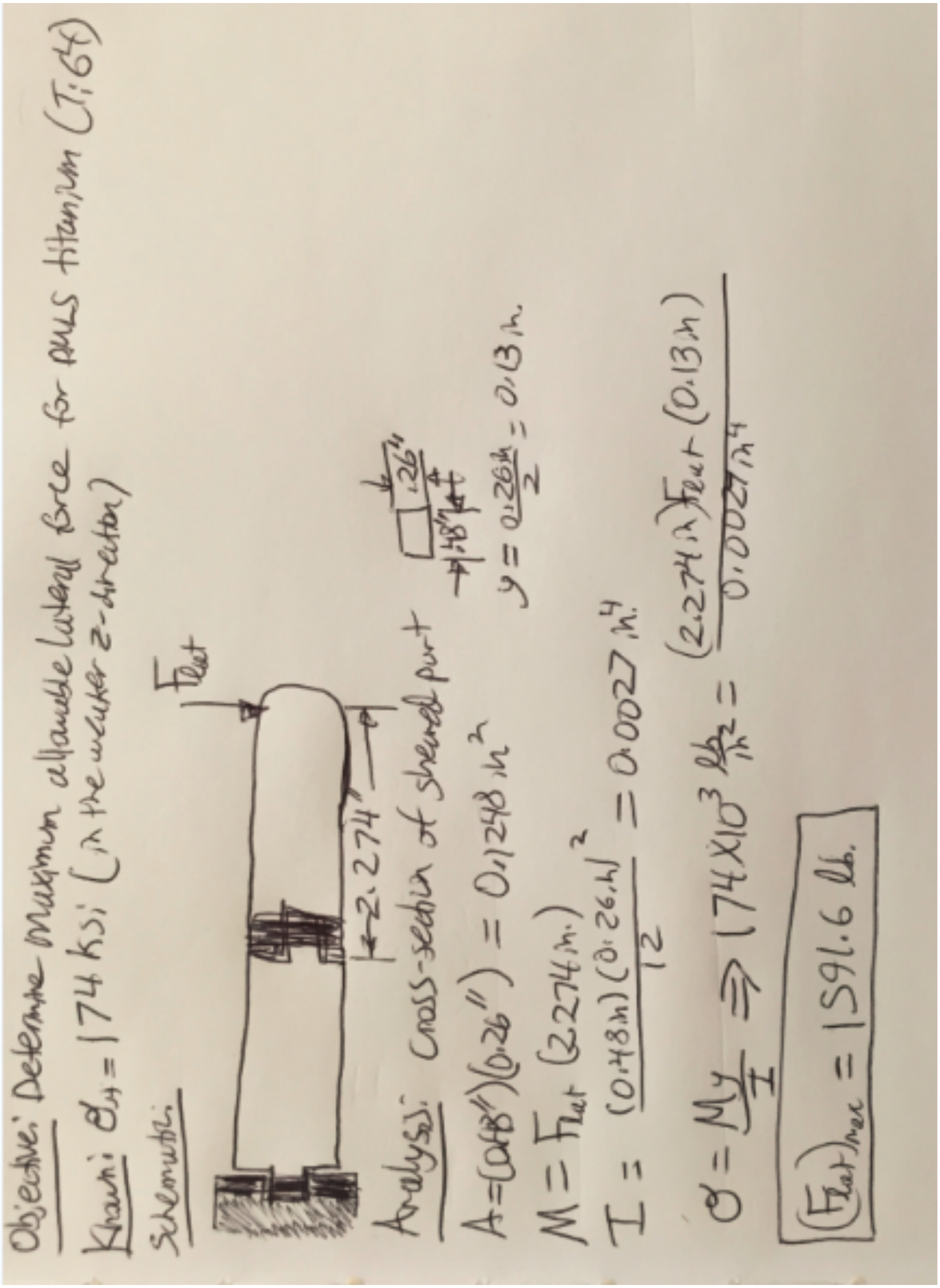
$$\left(\frac{63{,}000\ psi}{2}\right) = \frac{F(3 \times 1.95\ in)}{\frac{1}{12}(0.46'')(0.17\ in)^3}$$

$F =$

- $\tau_B = \frac{VQ}{It} = \frac{R_x \frac{bh^2}{8}}{\frac{1}{12} bh^3 b} = \frac{3 R_x}{2bh}$

$$\left(\frac{141{,}000\ psi}{2}\right) = \frac{F\left(\frac{3 \cdot 1.95\ in}{0.32\ in}\right)}{2(0.46\ in)(0.17\ in)}$$

$$\boxed{F = 603.14\ lbf}$$



Objective: Determine maximum allowable lateral force for DMLS titanium (Ti64)

Known: $\sigma_y = 174$ ksi (in the weaker z-direction)

Schematic:

Analysis: cross-section of sheared part

$A = (0.48'')(0.26'') = 0.1248 \text{ in}^2$

$y = \frac{0.26 \text{ in}}{2} = 0.13 \text{ in.}$

$M = F_{lat}(2.274 \text{ in.})$

$I = \frac{(0.48 \text{ in})(0.26 \text{ in})^2}{12} = 0.0027 \text{ in}^4$

$\sigma = \frac{My}{I} \Rightarrow 174 \times 10^3 \frac{lb}{in^2} = \frac{(2.274 \text{ in})F_{lat}(0.13 \text{ in})}{0.0027 \text{ in}^4}$

$(F_{lat})_{max} = 1591.6$ lb.

12.15 Appendix O – Open-Source Design

As an addendum to this senior project, team member Ryan Burke created an alternate design of a prosthetic hand that retains the main principles of operation as the final design by Team ProstheTech, but is compatible with the open-source community. This was an initial goal at the outset of the project, but was eventually deemed outside the scope of the project since the main focus was to ensure an operational prosthesis for the specific Navy SEAL.

Before discussing the changes made from the final design, it is important to understand why these changes are necessary. There are many requirements that prove a unique challenge to designing an open-source prosthesis. These challenges arise from several fundamental characteristics of open-source prostheses.

The main challenge is due to the fact that, although prostheses are traditionally highly dependent on the individual customer as people's bodies vary greatly from person to person, open-source prostheses are designed so that they work for as many different people as possible while requiring a minimal amount of adjustment. Additional challenges include cost and material limitations, as the most commonly available 3D-printer materials are not very strong and have many inconvenient material properties for devices that are supposed to be as rugged and reliable as prosthetic hands.

Based on these limitations, an open-source prosthesis was designed that maintained the same operational principles as the final hand delivered to the Navy SEAL. This design is pictured below in Figure O-1 and the main differences from the Team ProstheTech design are described in detail in the following sections.

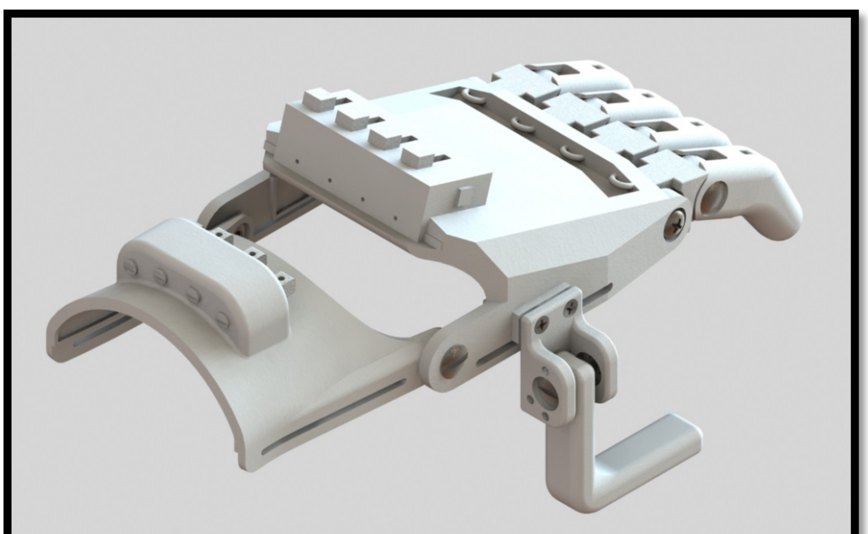


Figure O-1: SolidWorks rendering of the open-source design based on the operation principles of the Team ProstheTech hand, but more compatible with the open-source community.

Locking Mechanism

The most glaringly obvious and operationally different feature in this open-source design as opposed to the final design by Team ProstheTech is the actuation system. Although the main actuation principles are the same (wrist-operated by cable tension), the cable routing, tensioning, and locking systems are markedly different. The reason for altering the locking system was due to the fact that the Sure-Lok by TRS Prosthetics is extremely expensive (around $700) and only works on cables of 1/16" diameter. A new locking system was designed based on the locking mechanism concepts featured in the Sure-Lok, but simplified and adapted to allow for thinner cables and simpler materials to be used. Because this locking mechanism is 3D-printable and extremely inexpensive, it was designed to be able to lock all four fingers individually if so desired, allowing for more complex grips to be achieved. The locking mechanism is seen above in Figure O-1 located on the back of the palm.

The operational concepts of this locking mechanism are very simple and similar to the Sure-Lok. The system features four individual cams, all rotating about a common shaft and enclosed in a frame-like structure. The cams feature protruding eccentric pins on one side of each cam. Elastic cables (rubber bands or flexible cord) are fastened around these protruding pins and around an L-shaped bar actuator that sits below the frame and extends to the side and above the frame top, with which the user is able to activate the locking mechanism by pushing the bar forward. When the bar is all the way to the back of the system, it is unlocked, since the elastic cable rotates the cam away from the actuation cable. When the bar is all the way forward, the system locks, since the cam is pulled into and jammed against the actuation cable. A diagram of this mechanism is found below in Figure O-2.

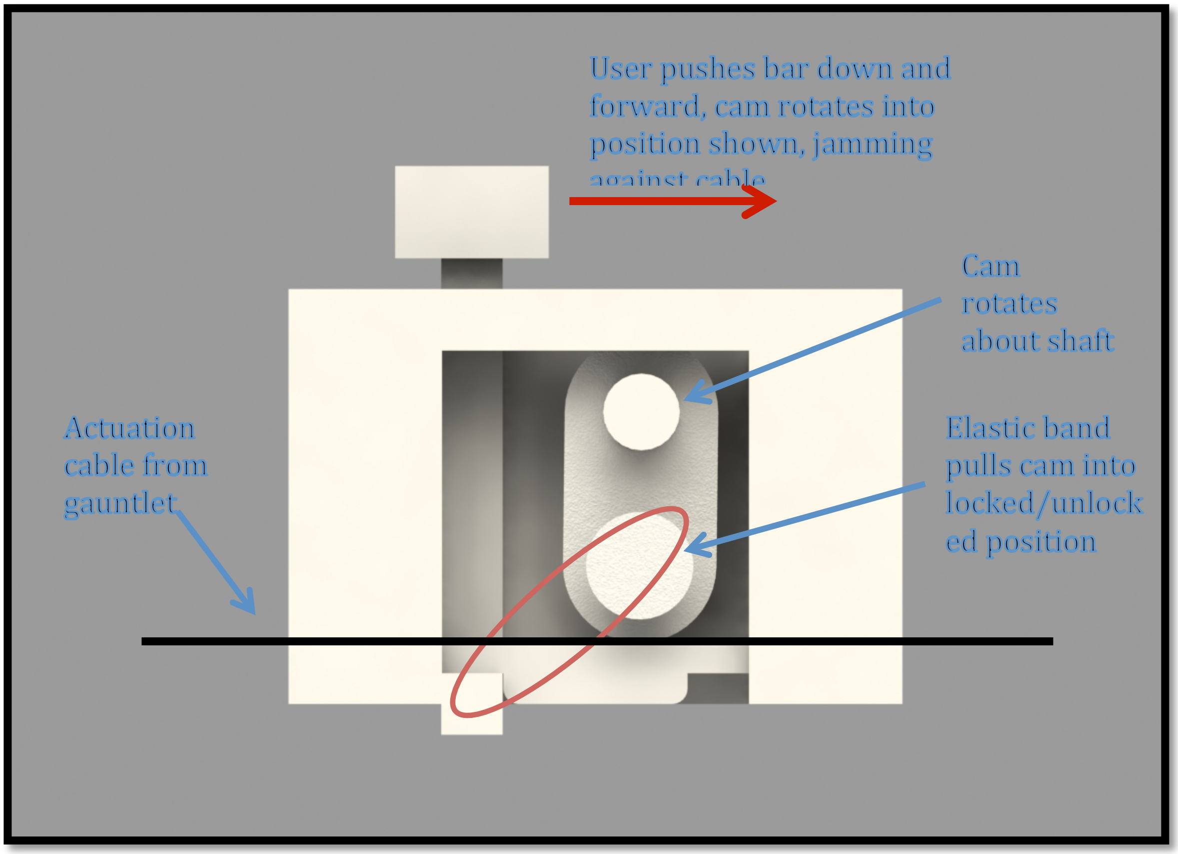


Figure 0-2: Diagram of one of the cam modules in the locking mechanism used in the open-source prosthetic hand design.

When the user wishes to lock a grip, he simply moves the bars of the desired gripping fingers forward into the "locked" position, actuates the grip, and releases wrist flexion in the same manner as with the Sure-Lok-equipped hand. The internal flexible cable tension forces the cams to jam against the actuation cable. Any further actuation counteracts this force and allows the grip to be increased; any loading will cause the cam to jam further into the actuation cable, making the grip-lock even more intense.

Attachment System

The system used to secure the user's residual in the final design proposed in this project is very complex and expensive. Most people do not have dedicated prosthetists or funds to purchase custom-fitted silicone suction sleeves (which cost a minimum of $700 each), so the open-source version of our final design needed an alternate attachment system.

The main requirements of the attachment system were that it needs to be rigid and comfortable, contributing to a high degree of proprioception for the user. To achieve this on a low budget with readily available and versatile materials, an alternate attachment system was designed that consists of a foam-lined and Velcro-strapped gauntlet and palm. The gauntlet and palm structures were altered to accommodate the strips of foam to

ensure they are embossed to eliminate any chance of sliding. Any foam of reasonable thickness can be used; however, a closed-cell material such as neoprene or memory-foam is suggested to eliminate moisture accumulation and bacterial growth. A sheet of 1/4" thick, adhesive-backed neoprene is suggested, packages of sufficient material to outfit the entire prosthesis are readily available for around $25 online. Furthermore, Velcro strap slots were added to the palm so that the user's residual can fit snugly inside.

Scalability

One of the main challenges with making open-source prostheses is making the device easily scalable for the diverse customer base. The diversity in arm size and shape is extremely high, and the diversity in residual size and shape is even higher. One of the measures taken to alleviate any size incompatibilities when scaling this prosthesis was the use of foam in the palm and gauntlet to more closely encase the residual, as mentioned in the section above. There is more work to be done in this aspect of this design; however, painstaking measures were taken during the design phase of the prosthesis to ensure dimensions are easily changed due to our highly iterative design process. This will prove useful in future scaling of this design.

This entire prosthesis was designed around a 3D-scan of the specific customer's residual. Although the process of dimensioning the device was conducted manually, there is hope that this process can be programmed to autonomously generate a prosthesis that is custom sized for each individual customer. The process would be roughly as follows: the user takes many pictures in many different angles around his/her residual, uploads them to a program that stitches these files into an STL file; the STL file is read by a piece of software that then communicates with SolidWorks to create a part that closely follows the arm contours, resulting in a new part that interfaces with the rest of the parts in the design. Preliminary research confirms the feasibility of such a system thus far. With more time and programming practice, it is hoped that this code can be generated and tested sometime in the near future. When executed, this plan would greatly improve the scalability of this design.

Cost

A proper cost analysis of this open-source design is difficult, as almost all components are 3D-printed, and the costs of manufacturing will vary greatly depending on the material and vendor. Assuming the user is able to find someone to print the parts for him/her, and using all the same metal off-the-shelf fasteners where applicable as the final Team ProstheTech design, the user can expect to pay about $100 for the prosthesis. This cost can be driven down significantly if the user wishes to sacrifice strength by using 3D-printed fasteners. In short, the cost to produce this prosthesis will be very close to the cost of the E-Nable open-source hands that are currently on the market.

Conclusion

This open source prosthetic hand design takes all the best aspects from the final design by Team ProstheTech and combines them with the versatility and frugality of the open-source community. Although this design is not nearly as strong as the DMLS Titanium hand, it shares the same operational principles as developed and honed over the course of Team ProstheTech's yearlong project. The main differences between these two designs are the locking mechanism and the attachment systems. As this design has yet to be printed and tested, there is room for iteration and fine-tuning of the design. A prototype of the locking mechanism will be printed and tested shortly to ensure proper operation before a full hand is produced. In addition to the iteration required for optimization of this open-source design, the most significant work that still needs to be completed is the coordination and programming of the scaling system to ensure that accurate and adequate prostheses are able to be generated for a multitude of very diverse users.

The sponsor for this project, Scott Monett, was recently able to contact and briefly converse with one of the heads of the "Enabling the Future" project, who was very interested in hearing about the work that Team ProstheTech has done on our mechanically actuated prosthetic hand. It is our hope that we will be able to meet with the people from "Enabling the Future" and discuss the opportunity to partner with them both to learn of ways to improve our design and to potentially bring our design to a broader base of physically disabled people whom this open-source, mechanically actuated prosthetic hand can benefit.