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Sand Foot

Sponsored by Quality of Life Plus

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Executive Summary

This critical design report describes the product development of a prosthesis for use on sand. Quality of Life Plus (QL+), a national non-profit organization aimed to develop prostheses for veterans and people with disabilities, introduced this project and its accompanying challenger, Sgt. Brady, to Cal Poly's Interdisciplinary Senior Project class in September 2018. After consulting with Sgt. Brady and QL+ and performing extensive research, the Sand Foot team defined customer requirements and engineering specifications to meet these requirements. Comfortability, durability, and sandproof were key customer requirements. Several conceptual models were brainstormed and a final design was selected based on the best design concepts of all considered models. The first prototype was composed of aluminum, carbon fiber, and polyurethane rubber -- all waterproof, sandproof, and non-corrosive materials -- and includes a curved toe design and rubber block used to mimic a flexing ankle and thus improve comfortability and functionality and several drains to waterproof and sandproof the prosthesis. Manufacturing occurred on the Cal Poly campus utilizing the Mustang 60 machine shop, the Cal Poly Composites Lab, and the QL+ lab. Funds were available to outsource parts if needed. The Sand Foot team manufactured the first prototype and sent it to Sgt. Brady for product testing and feedback. Unfortunately, the carbon fiber sole broke in transit to Sgt. Brady, and a thorough investigation determined the break was caused by impact. Poor manufacturing practices and unfamiliar materials resulted in a brittle sole. The team quickly pivoted and redesigned the sole using aluminum tubes, aluminum fittings, and canvas. The new design featured a curved toe and fit with the intended flexing ankle mechanism. A local amputee tested the final design. The amputee positively comments on the prosthesis' functionality and comfort, while weight, shape, and sand proofness were concerns. The feedback was helpful for the team as well as engineers and student who wish to adapt the design and improve others' quality of life.

Chapter I: Introduction

In September 2018, Sand Foot team members were tasked with designing and manufacturing a lower leg prosthesis for a trans-tibial amputee, Sgt. Craig Brady, that will allow him to walk more comfortably on sand. Sgt. Brady finds himself walking on the beach frequently, as he works for the New Hampshire Parks Department. The current prosthesis he uses causes him back pain after extended use due to its effect on his gait. The goal of the project is to develop an innovative lower limb prosthesis that will allow Sgt. Brady to comfortably walk on the beach for long periods of time. Requirements for this prosthesis are detailed in the objectives section of this document and include but are not limited to being comfortable, lightweight, and durable so that the product has a long lifetime.

The project was undertaken by four Cal Poly, San Luis Obispo undergraduates: fifth year biomedical engineering student Samantha Galicinao, fifth year student mechanical engineering student Daniel Dugan Dotson, fourth year manufacturing engineering student Christopher Urasaki, and fifth year mechanical engineering student John Dewing. The Quality of Life Plus National Foundation (QL+) will fund the project, and industrial engineering professor, Karla Carichner, and QL+ industry mentor, Alan Strasbaugh, will advise the team. Vanessa Salas served as the QL+ Project Manager and was vital to the communication between the team and the organization. While all of these individuals have a stake in the project, the main beneficiary will be Sgt. Brady, as he will be receiving the prosthesis for indefinite use at the end of the year.

Chapter II: Background

Relevance and Patents

In 2005, there were approximately 1.6 million amputees in the United States and of that population 65% underwent a lower limb amputation. Trauma is the leading cause of lower-limb amputations between the ages of 20 and 40 years of age accounting for 5.8% of total cases in the United States. For countries undergoing war and political distress, the number of lower-limb amputations jumps to 80% of all amputations. Although data for trans-tibial amputations in the United States and internationally is difficult to measure, there is clearly a market for limb prostheses and more specifically for specialized prostheses [5].

One of the earliest patents for a trans-tibial prosthesis was published on October 7, 1975 by Joseph G. Barredo. Previous trans-tibial prostheses expended the user's energy too quickly at the same comfortable walking speed of natural limbs thus resulting in discomfort and fatigue in the patient and pathological conditions due to the friction and pressure between the prosthesis and the tissue. Barredo was an amputee himself and aimed to improve its design therefore limiting these adverse events. The center of mass was shifted higher up the prosthesis to limit the its acceleration and deceleration forces and reduce the reaction forces on the residual nub. The foot was designed with a flexible yet robust material and with a curve foot acting as a fulcrum [2]. Other improvements to limit vertical displacement and improve comfort of the socket were included (Figure 1). Patents for electronic prostheses marketed for outdoor use are available, but inspired designs are outside the project scope and the proposed budget [1].

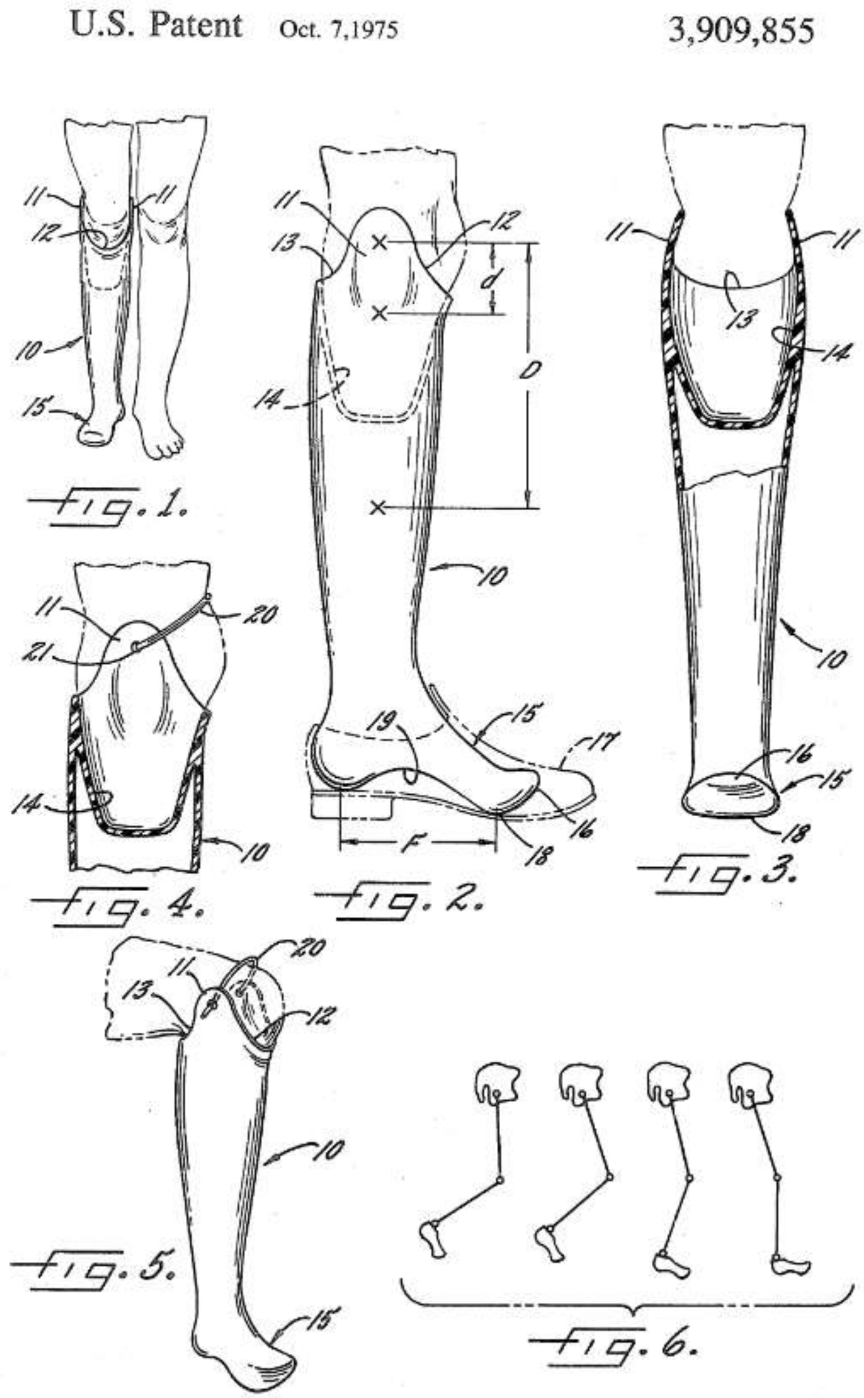


Figure 1: Sketches from Joseph G. Barredo's Below-the-Knee Prosthesis published on October 7, 1975

Current Market

A trans-tibial prosthesis is composed of a socket, a liner, a pylon, and a foot (Figure 2, Table I). The properties of the materials used to manufacture these components are dependent on the desired comfortability of the patient and distribution of the forces. Infinite Technologies, a leading prosthesis manufacturer, starts the manufacturing of a trans-tibial prosthesis with fitting their BK Shrinker to the residual nub. The function of their BK Shrinker is to shape and reduce edema on the residual nub and overall create a positive prosthesis experience for the patient. The patient is then fitted with a liner which is designed to absorb the forces acting on the residual nub while the patient is walking using the prosthesis. The liner keeps the tissue interfacing with the prosthesis healthy and increases the weartime of the prosthesis. The socket is initially built with plastic to allow for the residual nub to change shape and reduce in size. When the residual nub shape has stabilized, a laminated socket is fabricated with carbon fiber, a lighter and more durable material with high tensile strength. The socket is attached to the pylon, an upright structure that provides support and navigational guidance, and the pylon is attached to the foot. The foot's purpose is to transfer the forces to the ground and provide traction to move the patient [3]. TruLife Prosthetics manufacturers a trans-tibial prosthesis with non-corrosive materials and is marketed as the ideal prosthesis for outdoor use, especially near the coast. Sgt. Brady currently utilizes this prosthesis and will be the benchmark for this project [9]. Of the common trans-tibial prosthesis components, the team was required to build the pylon, with universal prosthesis connectors, and foot.

Figure 2: TruLife Kinetic Lower Limb System

Table I: TruLife Lower Limb System Components

A	Socket
B, C, D	Pylon
F	Foot

Physics of Walking on Sand

Research on the mechanical work and energy expenditure by trans-tibial amputees when walking on various terrains, specifically asphalt, mowed lawn, and high grass, have been performed and evaluated [10]. Little to no research has been done on the use of prostheses on soft surfaces, such as sand, hence the market for developing the sand foot. However, there have been studies on the biomechanics and energetics of walking and running on sand using natural limbs. A study published in 1998 showed that walking and running on sand using natural limbs required more mechanical work and energy expended than natural limbs walking or running on asphalt.

Walking on sand at the same speed as on asphalt requires 1.6-2.5 times more mechanical work, while running on sand requires 1.5 times more mechanical work. Mechanical work is the sum of external work W_{ext} and internal work W_{int}. External work W_{ext} is the sum of the positive work to move the body's center of mass forward relative to the body's surroundings W_{com} and the work done on the environment W_{env}. Internal work W_{int} is the positive work done to move the body's limbs forward relative to the center of mass (Appendix A). Energy expenditure is increased by a factor of 2.7 when walking on sand and by a factor of 1.6 when running on the sand. Walking on sand requires more energy because the kinetic energy waves causing horizontal motion and vertical motion are out of phase. It is therefore expected that walking and running with a prosthesis will require more mechanical work and expend more energy [8].

Chapter III: Design Development

Objectives

The project goal is to create a specialized trans-tibial prosthetic leg for the challenger, Sgt. Brady, that will allow him to walk for long periods of time in sand with less effort and pain. The new prosthetic limb created will attach to his current socket and provide a long-term solution to his sand walking difficulties. Lastly, the prosthesis will be easily maintained and operated by Sgt. Brady without further assistance from the team once the project is finished.

Customer Requirements

Below are the engineering requirements agreed upon by the team, the QL+ organization, and Sgt. Craig.

1. Lightweight
2. Waterproof
3. Sand-proof
4. Comfortable
5. Non-Corrosive
6. Matte Finish
7. Durable
8. Easily Maintained/Operated

9. Diffuses Weight

After deciding on custom requirements based on conversations with Sgt. Brady, each requirement was evaluated individually, and what were once qualitative attributes of a design became quantitative, measurable specifications. A test was designed for each requirement that produced a single value, and this single value was compared to tolerances decided by the team's judgement from previous experience or industry standards. Below are the extended explanations of the engineering requirements found in the House of Quality (Appendix B) and Requirement Table (Appendix C).

Engineering Requirements

Formulated by the customer requirement above, below are the engineering requirements, the method in which they will be tested, and the benchmark to meet.

1. Weighs less than 4 pounds
    - The average trans-tibial prosthesis weighs about 4 lbs so that will be used that as an upper limit value when determining whether or not the design is **lightweight**. Sgt. Brady's current prosthesis weighs about 4 lbs.
2. Passes IPX7 Waterproof standards
    - After 30 minutes of being submerged 1.5 ft underwater, the prosthesis weighs a max of 20% more than its dry weight. This is a modified version of the way phones are tested for their IP rating (IEC 60529). This standardized process for testing water resistance with the modified criteria will be used to detect how the water affects the weight. For the team's purposes, it will define how **waterproof** the prosthesis must be [7]. How waterproof his prosthesis is determines how **heavy**, and therefore, how **comfortable** it is.
3. Passes IP6X Dust-proof standards
    - The moving parts of the prosthesis will be left in a chamber of circulating talcum powder for a total of 8 hours. If less than 100 grams of power is found within the parts, they will be considered **dust-proof** [7].
4. Passes custom Sand-proofing test

- To test the ability of the prosthesis to **keep out sand** on the beach specifically, a custom test has been created. After 1 hour of use in sand (wet and dry), the joint movement in the prosthesis will take no more than 10% more torque than originally required to move in order to meet the requirement.

5. 6 hour walk time
    - The **comfort** of the new prosthesis will be gauged by comparing it to the current prosthesis. Sgt. Brady wants to walk for at least 6 hours a day on sand. This will be the target time for the new design.
6. Corrosivity of all materials under 0.250 mil/year
    - If all load bearing components are made from materials falling under this level of corrosivity, it is reasonably assumed that the prosthesis is **non-corrosive**.
7. Matte Finish
    - Prosthesis will be visually inspected to have a matte finish so as to reduce glare.
8. Drop Test 1m, 20 times
    - After passing a drop test 20 times from 1 meter the prosthesis must not yield, fracture, or take more than 10% more torque to actuate any joint. It must also pass a fatigue simulation that will cycle any joint 100,000 times while loading the prosthesis with 4 times Sgt. Brady's weight.
9. Sinks into the sand and slips back less than 8 inches in dry sand with 350 lbs weight on it
    - In order to test the **displacement** of the prosthesis, it will be recorded being used in dry sand and measure the length the foot sinks into the sand (negative y direction) and the length it slips backwards (negative x direction). The team's goal is to match the same slip and sink of his anatomical foot, which is roughly 8 inches.

First in the design development process, preliminary testing was done to build empathy and better understand the problems Sgt. Craig endures at the beach. To simulate these conditions, a team member was equipped with an ankle brace and the bottom of the team member's foot was duct taped to a wooden plank to completely immobilize the ankle and toe bending, respectively. The team member then took this simulated prosthetic foot and tested it on wet and dry sand. Footage of walking without flexing limitations and with flexing limitations were recorded and observed. Side, front, and back profiles were also recorded and observed.

Figure 3 and Figure 4 are screenshots from the footage recorded and represent the quantitative results of the preliminary testing. The results of the dry sand testing is where most of the insight into the Sgt Brady's disposition on the beach was provided, seen in Figure 4. Shown by the orange outline of the heel, at the push off point (Figure 4.b) the "human" foot remains in contact with the sand via the toes bending. The simulated prosthesis, however, nose dives straight into the sand burying itself mainly due to the lack of surface area horizontal to the sand surface. This limiting factor of the current prosthesis also contributes to a large amount of sand collecting in the interior mechanisms which consequently adds weight to the prosthesis and to the user's discomfort.

Other factors determined to significantly contribute to Sgt. Craig's discomfort were the fixed ankle configuration and the slim profile of his current prosthesis. While performing the tests using the simulated prosthesis, the test subject noted that because their ankle could not bend, the team member must swing their leg slightly outward to initiate the next step in the sand. During the two hours of continuous testing, this outward swinging motion began to hurt the team member's back similar to how Sgt. Craig described. Lastly, the slim profile of the prosthesis did not distribute body weight sufficiently to prevent the prosthesis from sinking into the surface of the sand. This effect of the slim profile ultimately caused the user to swing their leg out to their side to prevent sinking into the sand, which added additional discomfort.

(a) **(b)** **(c)**

Figure 3: Walking on wet sand with and without a flexing ankle and toes

(a) **(b)** **(c)**

Figure 4: Walking on dry sand with and without a flexing ankle and toes

With these results in consideration, a new set of design requirements were formulated and different conceptual designs were brainstormed.

Bending Toe

The team's preliminary testing concluded that toe flexing optimizes the surface area of the sand foot's contact with the sand during the push off phase of walking. The bending toe design, as shown in Figure 5, includes a hinge at the end of the foot. The optimal torque would be determined during testing. However after a phone call with Sgt. Brady, the team decided that the slim profile was undesirable as surface area was lost on the sides of the foot and the hinge caused decreased stability in more heavy set individuals, such as Sgt. Brady. The hinge was also not the most sandproof design as sand particles could potentially enter the mechanism and reduce its function and longevity. During the same meeting, Sgt. Brady expressed strong preference for a simplistic and easy to maintain prosthesis.

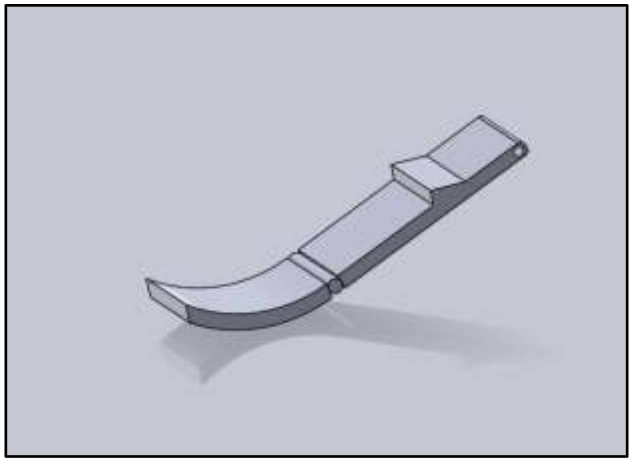
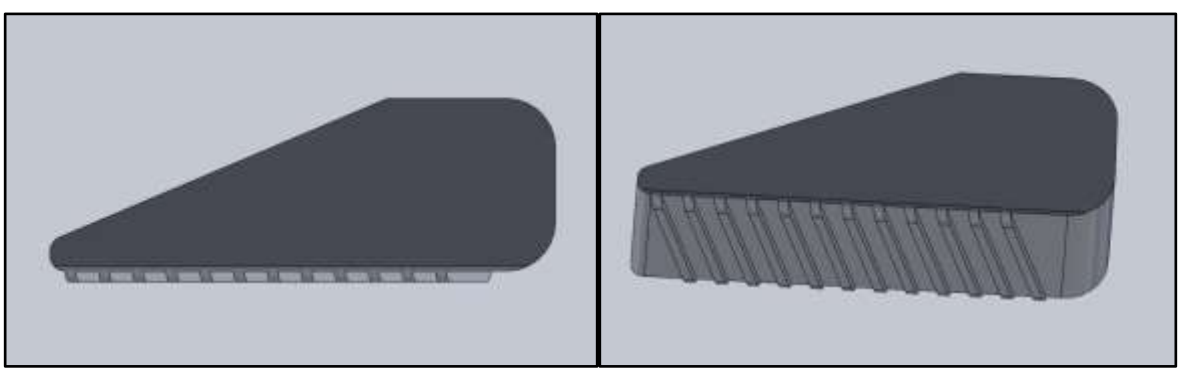


Figure 5: Bending Toe SolidWorks Model

Sock

The sock design, as shown in Figure 6, is the most lightweight of the conceptual designs because it was designed to be an addition to Sgt. Brady's current non-corrosive prosthesis. Rubber was the material of choice as it is non-corrosive, lightweight, and easy to form. Diagonal treads were included on the bottom of the sock to increase the surface area of the foot contacting the sand during all phases of walking. Because it is an addition to the current prosthesis, the sock is easy to remove and put on and is a desirable secondary function as Sgt. Brady expects to transition from asphalt or a harder surface to sand frequently. The design lacks in flexing ability because the foot remains flat-footed and the sock does not alter the design of the prosthesis ankle.



(a) **(b)**

Figure 6: Sock SolidWorks Model, **(a)** Side Profile of sock model **(b)** Bottom side includes a diagonal tread design

Carbon Fiber Bending

Carbon fiber is used widely in the prosthesis industry because it is a strong material with an adjustable spring constant. The material is also lightweight and non-corrosive. The carbon fiber bending design, as shown in Figure 7, was heavily inspired by the Pro-Flex prosthetic foot by Ossur and most closely resembles the design of Sgt. Brady's current everyday prosthesis. Both designs include a split toe which is designed to encourage inversion and eversion of the foot and a curved ankle to simulate ankle bending when force is applied. Because inversion and eversion are not desired movements, the split toe design was not a priority.

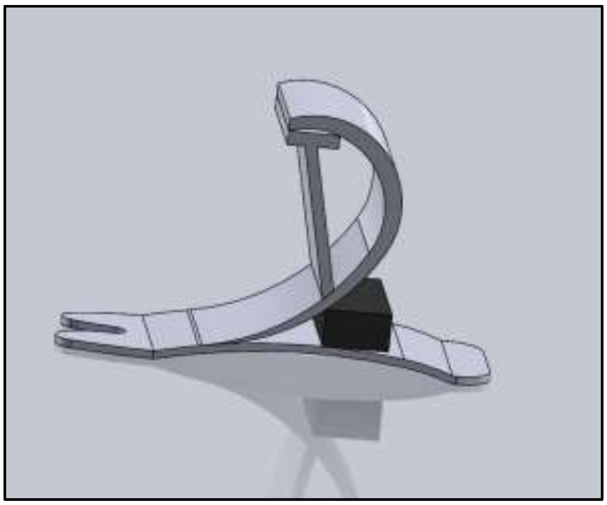


Figure 7: Carbon Fiber Bending SolidWorks Model

Snow Shoe

The snow shoe model, as shown in Figure 8, is the most robust and durable of the designs, and unlike the other models, it provides the largest surface area in contact with the sand. The benefits of a large surface area is weight is more evenly distributed and the push off phase is more effective since the foot does not sink into the sand. One large concern for this design is its size and therefore safety. The team will need to complete an investigation to maximize the width of the foot without interfering with Sgt. Brady's other foot during walking. The curved toe, similar to the bending toe and bending ankle model, ensures the optimal surface area of the foot is in contact with the ground during all phases of the walking cycle.

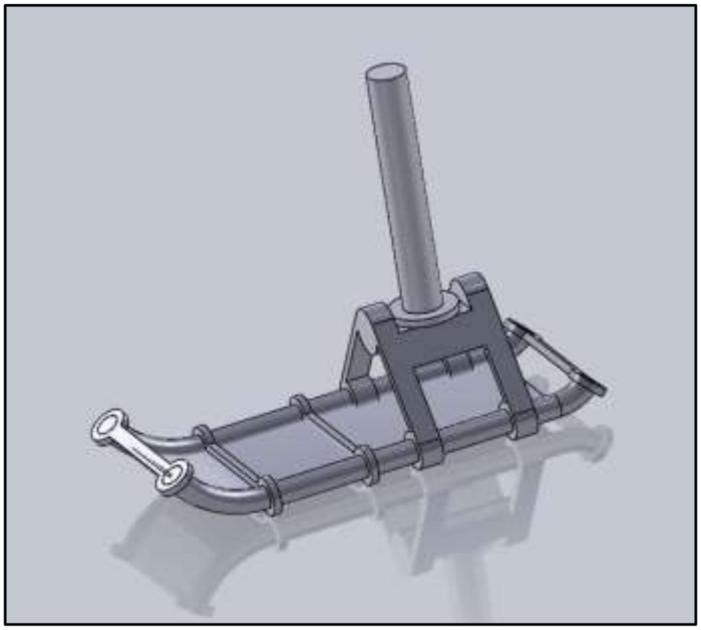


Figure 8: Snowshoe SolidWorks Model

Bending Ankle

The bending ankle model, as shown in Figure 9, is designed with a flexing ankle, a curved toe, and a slim profile. This design's flexing ankle is this design's the most novel component and is intentionally designed with rubber block which can vary in spring constants. The optimal spring constant of the rubber will be determined during testing. The curved toe, like other designs, increases surface area during push off. However, the slim profile poses concerns regarding stability and surface area.

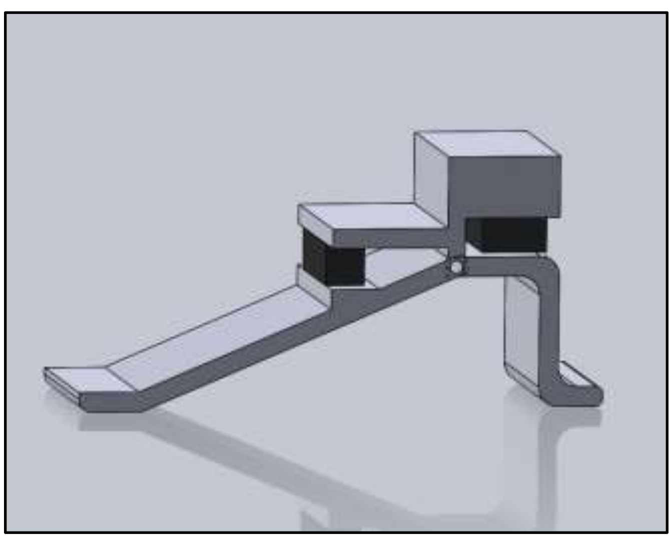


Figure 9: Bending Ankle SolidWorks Model

Pugh Chart

The team created a Pugh Chart (Table II) to compare the five conceptual models to Sgt. Brady's current sand foot prosthesis, the TruLife Kinetic Lower Limb System, and to determine the design choices. Ultimately, the team designed a final conceptual model that utilized the best design aspects of each conceptual model. The team made the following decisions:

1. The Snow Shoe and Bending Ankle models best satisfied Sgt. Brady's discomfort through increasing surface area by its wide profile and curved foot and increasing mobility of the ankle.
2. Carbon fiber is a desirable material because it is non-corrosive, strong, and flexible. *Update: Carbon fiber was no longer a desired material because it is difficult to manufacture.*
3. The treads on the sock model will increase surface area on the bottom of the foot.
4. The final conceptual design will be further sand proofed and waterproofed through strategic material selection and adding drainage areas.

Table II: Pugh Chart

	Bending Toe 	The Sock 	Carbon Fiber Bending 	Snow Shoe 	Bending Ankle 	Current Prosthesis 
Lightweight	+	+	S	-	+	D
Waterproof	S	S	S	S	-	
Sand-proof	+	+	S	+	-	A
Comfortable	-	-	S	+	+	
Non-Corrosive	S	S	S	S	S	T
Matte Finish	S	S	S	S	S	
Durable	-	-	+	+	-	U
Easily Maintained	S	S	S	S	-	
Diffuses Weight	-	-	S	+	+	M
$\sum +$	2	2	1	4	3	X
$\sum S$	4	4	8	4	2	X
$\sum -$	3	3	0	1	4	X

Design Change

In early May, the prosthesis arrived to Sgt. Brady broken -- a large crack propagated across the width of the carbon fiber sole, as shown in Figure 10. The team performed a drop test of previous carbon fiber foot sole iterations. The carbon fiber sole was dropped from approximately four feet with the bottom of the sole perpendicular to the ground. The test concluded that the carbon fiber sole could not withstand impact. Industry professional, Ryan Dunn, and Cal Poly Composites Professor, Eltahry Elghandour, informed the team that the materials used for manufacture was not carbon fiber, but a different mesh product and thus the fibers provided no strength. The resulting sole was essentially a block of resin which explained its brittle nature. Suggestions on next steps were to:

1. Outsource the carbon fiber foot
2. Wrap the carbon fiber foot with fiberglass
3. Manufacture the Snow Shoe design with several changes using aluminum tubing and canvas

Figure 10: Carbon Fiber Sole Longitudinal Crack

The team decided suggestion 3 was the best choice considering the timeline and the team's lack of composite expertise.

Chapter IV: Final Design

The finalized design, seen in Figure 11, uses a combination of the same ankle rotation and curved curved toes, but instead of a carbon fiber sole the team is implementing an aluminum frame wrapped in canvas for the base of the prostheses. The revised design features six main components, all featured in Figure 11 below, including the pylon, the rotation block, the rubber block, the aluminum support, the aluminum frame, and the canvas covering.. Each serves a vital role in the functionality of the prosthesis. An assembly drawing, excluding the redesigned sole, can be found in Appendix D.

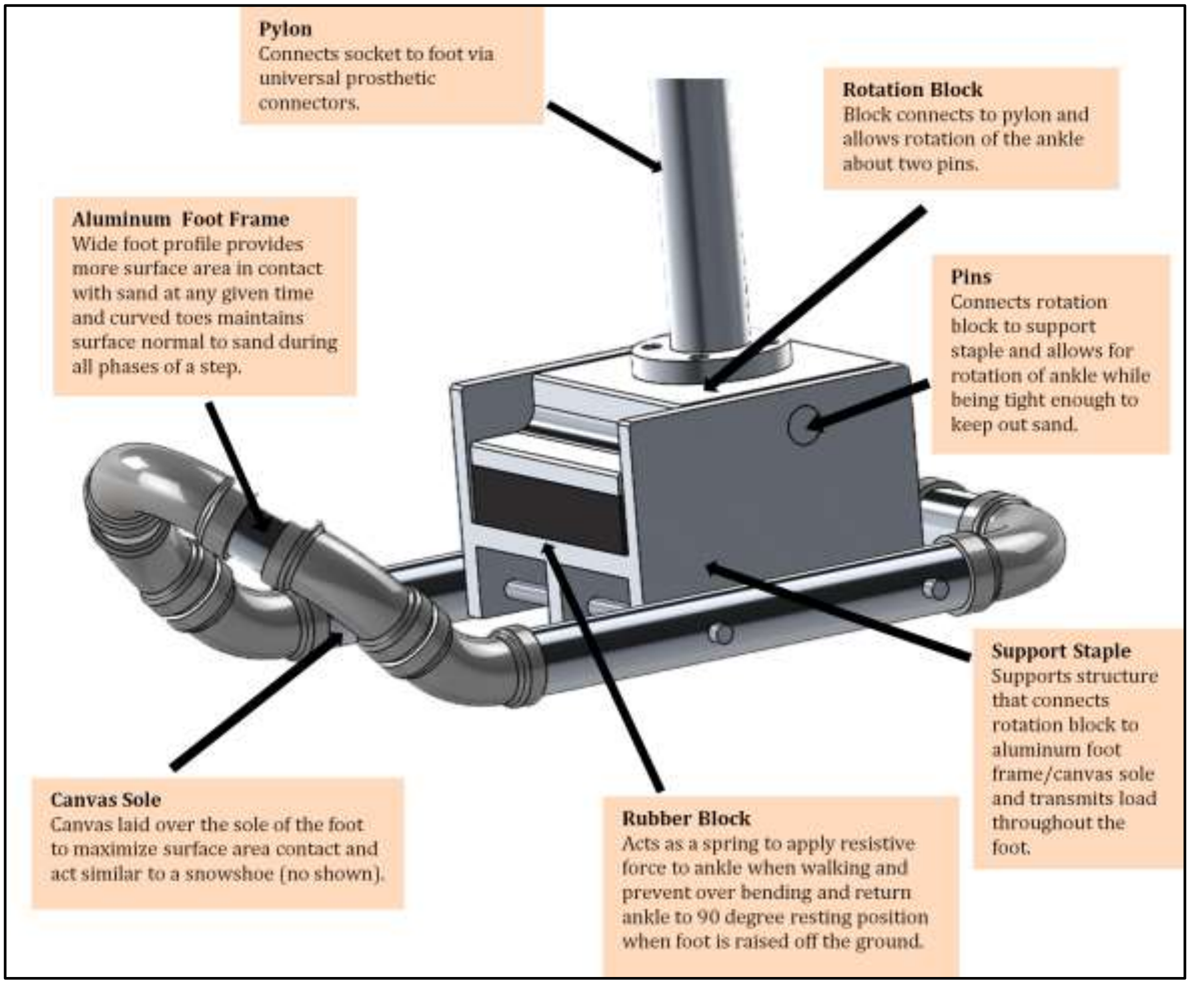


Figure 11: CAD Model (canvas overlay not pictured)

Pylon

The pylon, seen in Figure 11, anchors the foot to Sgt. Brady's already existing socket via a universal prosthetic adapted piece common to most prostheses on today's market. It will be made from aluminum due to its natural “resistance” to corrosion. Aluminum instantly forms a layer of aluminum oxide on its surface when exposed to oxygen, but aside from this very thin surface layer, aluminum corrodes slower than 0.250 mil/year, meeting the corrosivity specification specified in the requirements section of the report. The pylon is designed to take a load of at least 4 times Sgt. Brady’s weight. This benchmark was determined because when running on sand, one exerts about 2.5 times their weight as a force on their feet. Sgt. Brady weighs 245 lbs, so designing the pylon to take 1000 pounds of force gives a factor of safety of 1.6 in the pylon. The drawing for the pylon is not included in the Appendix because its specific height is not known because Sgt. Brady is going to use his spacer blocks to correct for any error in the height on the team’s end.

The pylon, pyramid insert, and pylon clamps were all purchased from Bulldog Prosthetics, a manufacturer of standard prosthesis parts. To reduce risk for corrosion, all parts were made from aluminum.

Rotation Block

The pylon is anchored to the rotation block via four screws. Screws were chosen over weldments because it provides Sgt. Brady the ability disassemble the prosthesis to clean it and QL+ the ability to easily send replacement parts should the challenger ever need them, without having to manufacture an entirely new prosthesis. The block itself is attached to the main foot body by two pins as featured in Figure 10 above. These pins are each press fit into both the support and the rotation block. They have rubber collars that go over them and create a buffer between the pins and the inside of the rotation block. This design prevents unnecessary wear on the pins as well as makes it easier for the block to rotate over the pins. These pins serve as the rotation point of the ankle, allowing the ankle to rotate in one plane to simulate the flexion and extension of a biological ankle. The ankle plate is machined on a CNC out of 6061 aluminum. The drawing can be found in Appendix D.

Rubber Block

The ankle plate is situated above a high-density rubber block. The block’s purpose is to act as a spring to dampen the free rotation of the ankle joint. It stabilizes the foot and allows the ankle to swing back into its 90 degrees resting position after Sgt. Brady has completed pushing off the ground and raised the prosthesis off the ground at the end of his step. Additionally, the rubber block is sized slightly taller than the space allotted for it so it is continuously in compression. This design feature causes the rubber to take significantly more of the load being sent down the pylon off of the pins anchored into the side of the aluminum support and significantly reduces the shear stress in the aluminum. The rubber block is connected to both the support below it and the ankle plate above it via an adhesive known as Household Goop. The drawing can be found in Appendix D.

Aluminum Support

The rubber block is situated atop the three-pronged support seen in Figure 10. This support serves to distribute the load through the rubber block down into the main foot body evenly and into the ground without creating any unacceptable stress concentrations. This will also be made out of aluminum for its non corrosive properties. It is connected to the rotation block via the press fit pins discussed in the rotation block subsection of the finalized design section of this report. The drawing can be found in Appendix D.

Carbon Fiber Sole

The carbon fiber base is manufactured primarily out of carbon fiber due to its high yield and tensile strength. The connection points between the main foot body and the rest of the prosthesis described above include the bottom and sides of the three-prong support, the sides of the rubber block, and the pins on the rotation block. The sides of the support and sides of the rubber block will both be attached to the main foot body by adhesives, one specific to rubber to carbon fiber and another specific to aluminum and carbon fiber. The carbon fiber base features curved toes and a curved heel. The curves serve to keep a large amount of surface area of the foot base in contact with the sand at all times, between just completing a step (heel coming in contact with the ground), standing flat, and beginning a new step (toes only pressing off the ground). This removes the possibility of any sharp edge that could dig into the sand and cause Sgt. Brady to slip and interfere with his gait. The heel also offers greater stability for when he is leaning backward. The drawing can be found in Appendix D. The carbon fiber sole was later removed from the final design due to breakage upon impact.

Feasibility Studies of Carbon Fiber Sole

The following FEA simulations were run in SolidWorks as feasibility studies to validate the design on a basic level. It is well understood within the team that these studies are not a substitution to the physical testing that must be done before a prototype can be sent to Sgt. Brady. However, that being said the results of these studies are very promising. Figure 12 shows the FEA model who standing upright load is applied.

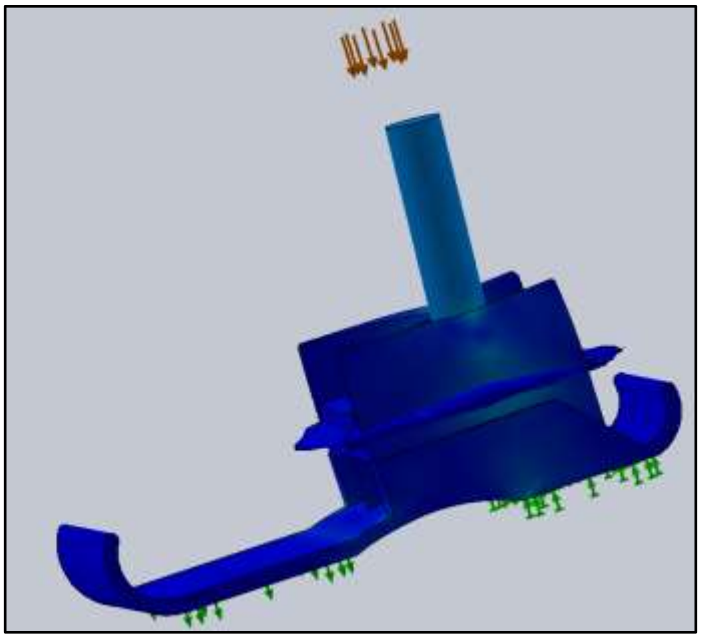


Figure 12: Standing Upright Load

This simulation runs 1000 lbs down the pylon of the prosthesis and results in a stress concentration at the base of the support and at the pin joint of 8.58 ksi. The components affected by this concentration, aluminum and carbon fiber, have yield strengths of 40 ksi and 500 ksi respectively. The aluminum support will be undergoing shear stress, and aluminum has a shear stress of 30 ksi, which gives wide margin between the expected stress and the maximum the material can handle. The 1000 lb load was based off of multiplying Sgt. Brady's 245 lb weight by 2.5 and then raising it for a factor of safety of 1.6.

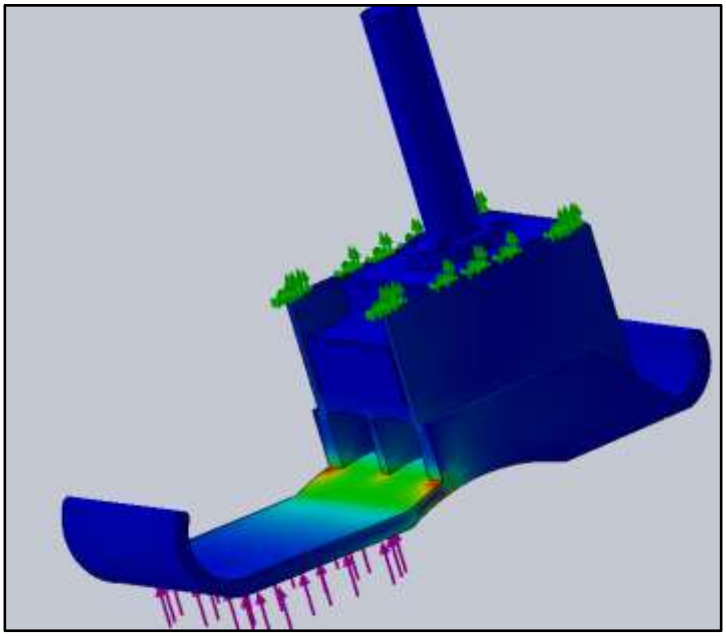


Figure 13: Load Beginning of step

This next study shows that same 1000 lb load being applied to the end of the toes, simulating the push off at the beginning of a step while walking, as shown in Figure 13. This results in a stress concentration of 75 ksi in the main foot body, but as noted before, carbon fiber has a yield strength of 500 ksi.

Again, these simulations are only being used for feasibility studies and only serve to validate the concept, not as a substitute for testing. That being said, the results are very promising and make it appear as though the design will be able to take heavier loads without yielding.

Due to poor manufacturing practices and materials, the carbon fiber sole did not uphold the expected material properties determined in the FEA above and the carbon fiber sole broke upon impact. A revised sole design come composed of aluminum and canvas was manufactured. The team decided a curved toe must be included in the revised design.

Sealant

The pin connection point is sealed to keep sand and salt water out of the foot. This practice is done using an O-ring on the inside of the main foot body and a liquid sealant on the outside. In addition to the O-ring and sealants, the nature of the press fits, in general, will work to keep sand from becoming trapped inside the rotation block or aluminum support.

Specifications Met

Table III below details the final conceptual design satisfaction of all of the engineering specifications. Using material properties analyzed in SolidWorks, the current design fulfills the lightweight, displacement, non-corrosive, and matte finish requirements set at the beginning of this process.

Table III: Engineering Specifications

Engineering Spec.	**Explanation**	**Satisfied**
Light Weight	Prosthesis must weigh less than 4 lbs.	Yes
Displacement	Prosthesis must slip back less than 8 inches and sink less than 4 inches when loaded with 350 lbs.	Likely
Waterproof*	Must pass IPX7 waterproofing standards	Likely
Sandproof*	After being completely buried, ankle joint may require no more than 10% more torque to actuate than initially	Likely
Dust Proof	Must pass IP6X dust proofing standards	Likely
Non-Corrosive	Must not include materials known to corrode more than 0.250 mil/year when in contact with salt water or salt air	Yes
Matte Finish	Must have a matte finish	Yes
Durable*	Must be able to pass fatigue simulation loading 980 lbs on pylon 100,000 times and be dropped from a height of 1 meter 20 times without yielding, fracturing, or adding 10% more torque to required	Likely

	to actuate ankle joint	
Comfortability*	Sgt. Craig must be able to walk comfortably for 6 hours in the sand	Likely

Note: Engineering Requirements with a (*) are further explained below.

The waterproof and dustproof requirements are two of the most important design factors. Because of their level of importance, testing procedures typically used to test the level of water and dust proof aspects of electrical systems will be used to test this prosthesis. More details on these specifications and their testing protocol can be found below.

1. *Waterproof*: After being submerged for 20 minutes, the product will not weight more than 1.2 times its original weight. There are no internal air pockets or spaces capable of holding enough water to add .72 lbs. to the weight of the foot, therefore it cannot weigh more than 20% of what it originally weighed.
2. *Sand Proof*: Minimal moving parts, all moving parts effectively sealed from outside elements. This prosthesis will feature only one rotating part, and said part will be effectively sealed by O-rings and a liquid sealant.
3. *Durable*: The design must be able to support Sgt. Brady's weight, pass the drop test mentioned in the "Objectives" section of the report, and show that it will pass a fully fleshed out FEA fatigue test of 100,000 cycles. Based on feasibility studies and material selection in the prosthesis, it seems likely that this will pass the durability requirements. in fact did not pass the durability test. *Update: Upon shipping the prosthesis to Sgt. Brady the carbon fiber sole was subject to an impulse force causing fracture. With this information, the team performed a drop test which repeated the fracture during shipping. Refer to the next section for further design updates.*
4. *Comfortability*: The ultimate test for this design is if it eases the lower back pain Sgt. Craig feels while walking on the beach. This will most likely be the last test performed on the prototype and will take place when the team ships a working model to Sgt. Brady to utilize at the beach. To gain a little insight on the design before that final step however,

members of Operation Surf have been contacted to test the design locally and provide feedback on how the prosthesis works for them.

In addition to these tests, the team has also decided to perform additional tests for reliability. Reliability testing is different from the fatigue testing as it pertains mostly to the longevity of the prosthesis regarding the adhesives joining the materials and the pin connections holding parts together, both of which do not get analyzed in the fatigue model.

Snow Shoe Aluminum/Canvas Frame

A snow shoe metal frame with a canvas overlay was designed after the team's carbon fiber sole fractured and they investigated the difficulties and limitations of manufacturing carbon fiber. Aluminum and canvas are both non-corrosive and waterproof materials. The canvas overlay stretches from the bottom of the metal frame, folds over the frame, and is back stitched together using a wax coated thread. The support block sits in between the inner sides of the metal frame, and the metal frame and support block are bolted twice on both sides. Bolts and stitched were used for easy canvas replacement, if needed. The size of the aluminum tubing was chosen to ensure high yield and tensile strengths.

Feasibility Studies on Aluminum/Canvas Sole

A SolidWorks FEA study seen in Figure 14 determined that when 700 lbs, 2.5 times the weight of Sgt. Brady, was loaded at the top end of the foot, a maximum stress was 17000 psi. Aluminum yields at 45000 psi, and thus the design's factor of safety is 2.65. The predicted displacement was less than 1 mm. Based on these results, the team was comfortable manufacturing the revised sole.

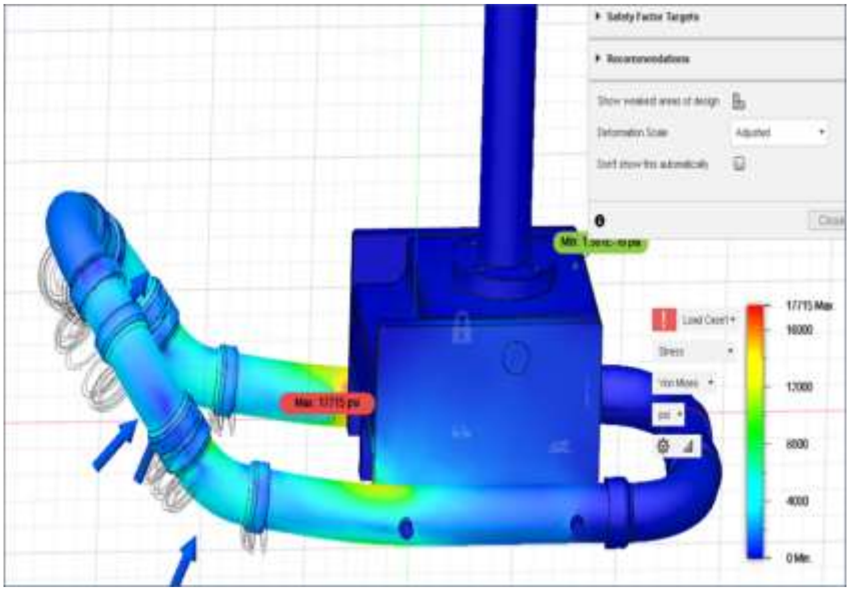


Figure 14: FEA of Aluminum/Canvas

Volunteer Testing

Due to the redesign, the new prosthesis was first tested by a local tran-tibial amputee who was approximately half the weight of Sgt. Brady. Upon wearing the prosthesis, the subject was asked to comment on the size and shape of the prosthesis. Afterwards, the prosthesis was used on dry and wet sand, as shown in Figures 15 and 16. Sand proofness was measured by a shake off test after burying the foot in approximately an inch in sand.

Figure 15: Prosthesis during toe off stage

Figure 16: Prosthesis during heel strike stage

Table IV shows the results of the test and the specifications met. The team has greater confidence in these test results than in the feasibility study results discussed in the previous section.

Table IV: Specifications Met Based on Subject Testing

Spec. #	Parameter Description	Results	Pass/Fail
1	Weight	4.5 lbs	Fail
2	Waterproof	Aluminum and canvas are waterproof	Pass
3	Dustproof	---	Pending
4	Sandproof	Accumulation	Pass
5	Comfortability	Subject Approved	Pass
6	Corrosivity	Aluminum and canvas are non-corrosive	Pass
7	Matte Finish	Aluminum has a shiny finish	Fail
8	Durability	No significant damage	Pass
9	Sand Displacement (x,y)	No significant displacement	Pass

The most concerning feedback was the prosthesis weight and sand proofness, especially since sand accumulation increased weight. Based on the results, the team decided to mill out the aluminum surrounding the four threaded holes in the rotational block and brainstormed several sand drain designs. Also, with the redesign, the matte finish test failed due to material selection.

However, the team decided this specification was the lowest priority and is confident that the prosthetic will function accordingly without this met specification.

Chapter V: Manufacturing Plan

A significant amount of effort has been put into establishing a good prototype manufacturing plan. Sgt. Brady already has a functioning prosthetic socket and the universal connectors that attach the carbon fiber socket to the prototype ankle and foot. Therefore, the plan is to design from the ankle pylon down. From that connection point, there are only four unique parts needed, the aluminum rotation and support blocks, the rubber ankle block, and the carbon fiber foot.

Carbon Fiber Foot

The team elected to manufacture the custom carbon fiber foot in-house. The organic shape of the design as seen in Figure 17 would result in a costly and time-consuming outsourcing process. The fabrication of the custom shape was done in the Cal Poly Composites Lab as they have all the necessary equipment for the process. The material of choice was a fibrous cloth and an epoxy resin, and the manufacturing process is known as a wet lay-up. An advantage to using the wet lay-up practice is fibers are oriented in multiple directions thus optimizing strength, but excess resin is a concern. Excess resin results in increased brittleness, a less uniform material, a shorter curing time, and a general reduction of overall properties.

Laying down and curing straight prepreg carbon fiber sheets, as seen in Figure 18, was an alternative material. The straight grain means that the carbon fibers are all aligned in a single orientation. The orientation of the layered sheets then allows for a fiber orientation that is entirely customized to the direction the forces that are put into the foot. See Figure 19 for examples of different fiber orientation. Prepreg means that the carbon fiber is impregnated with resin. Prepreg carbon fiber has on average 15% less resin than normal hand lamination. Despite this advantage, prepreg carbon fiber sheets were not used since the team was not experienced with laying down the sheets to optimize strength in all directions.

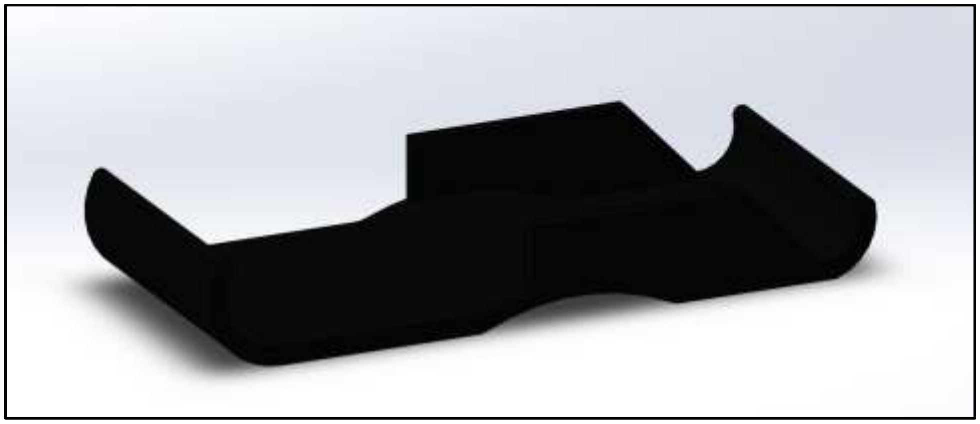


Figure 17: Carbon Fiber Foot

Figure 18: Prepreg Unidirectional Carbon Fiber

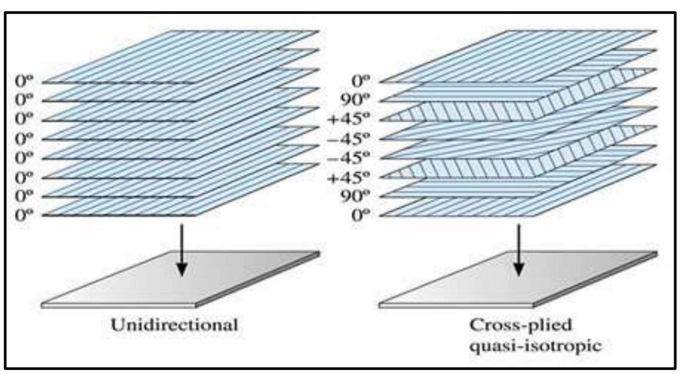


Figure 19: Fiber Orientations Example

The custom shape of the prosthesis' foot was achieved by machining a 3D printed negative, see Figure 20, and positive, not shown, of the shape and molding the three layers carbon fiber sheets and epoxy resin onto it. Once the general shape was created, the positive and negative molds were clamped together and was flipped upside down to drain extra resin. Despite the use of mold release and plastic wrap, the 3D printed negative was completely destroyed to release the carbon fiber sole. The carbon fiber sole was then sand to fit the aluminum block and improve aesthetics.

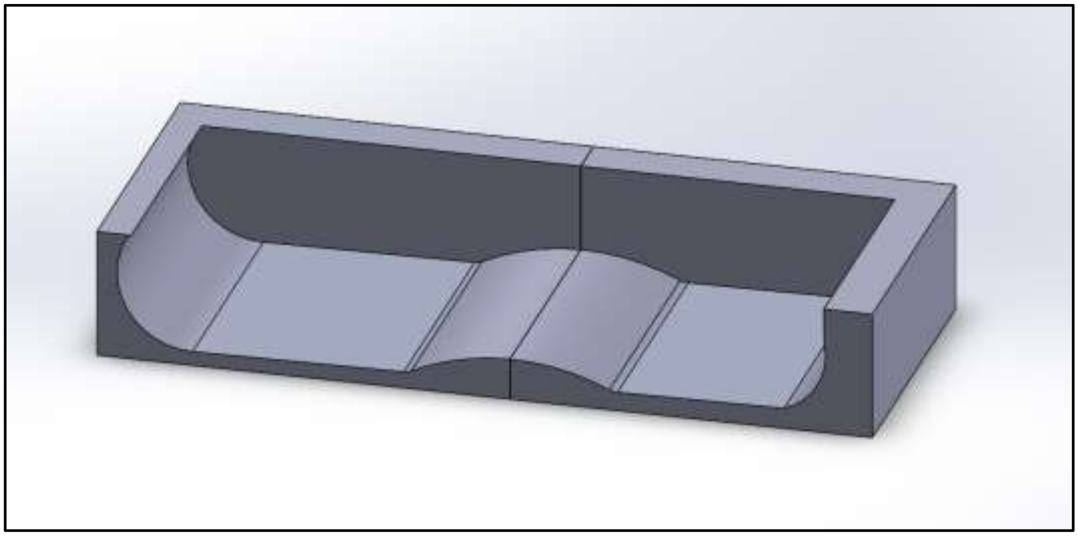


Figure 20: Carbon Fiber Foot Mold

A lack of resources and manufacturing experience resulted in a brittle carbon fiber sole. The manufacture practice did not involve excessive amounts of heat and pressure to properly cure the resin and optimize the fiber to matrix ratio. The team conversed with several composite companies, but time and money were the greatest limitations on moving forward. Refer to the following section for manufacturing details of the aluminum/canvas sole.

Aluminum/Canvas Sole

Architectural 60-63 aluminum tubing with an OD of ⅞” and a wall thickness of 0.219” was lathed to fit in the 90 degree and 45 degree aluminum connectors of 0.860” ID and 0.375” socket depth, cut into sections, and assembled as seen in Figure 11. J-B weld specific to aluminum to aluminum contact was used to adhere the pieces. Canvas was then cut to size, fitted onto the aluminum frame, and stitched using a backstitch and wax-coated polyester thread. The aluminum support block was bolted to the aluminum frame at two points on both sides of the prosthesis.

Aluminum Ankle Blocks

The main support structure of the prosthesis shown in Figure 21 was made of custom aluminum parts. These parts were designed to be manufactured relatively easily by a Haas CNC machine. The basic CAM work for one of the aluminum parts can be seen below in Figure 22 as an example of how the custom parts are to be cut from a stock block of aluminum. Both the rotation block and support block was cut from solid billets of aluminum stock. Using a 3-axis mill, the parts were programmed so they can be cut in only 2 operations. Each part only needed to be flipped in the vice once to minimize the chance of any out of tolerance features. Because both parts are relatively square, no soft jaws or special fixturing will be required to machine the parts and this will cut down on their fabrication time.

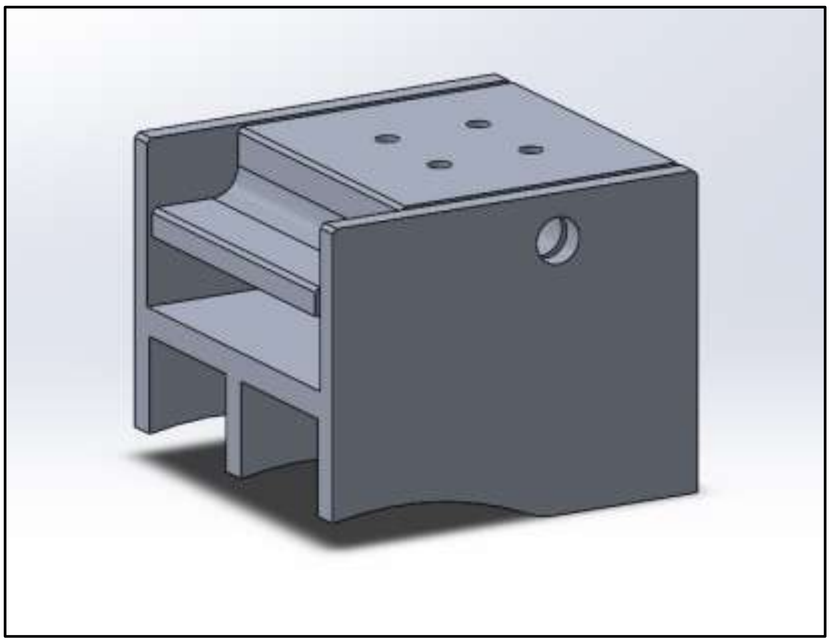


Figure 21: Aluminum Ankle

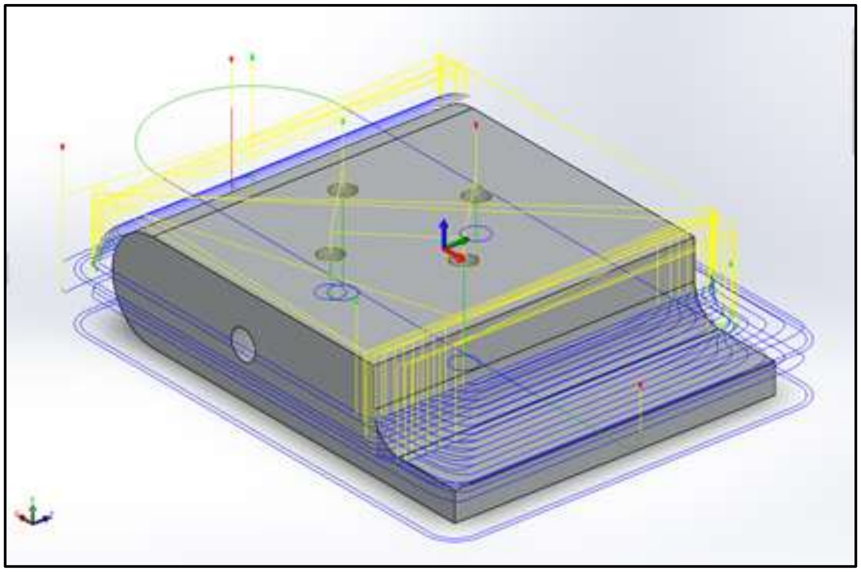


Figure 22: Example CAM

Rubber and Assembly Materials

The density of the rubber block is very important to the design as it directly determines how much the ankle can bend. The rubbers are all polyurethane compounds that were mixed and casted into rectangular block molds. Testing different densities and types of rubber helped but ultimately, the team plans on giving Sgt. Brady multiple densities of rubber blocks to try out when the prototype is sent to him. The shore harnesses of the rubber sent to Sgt. Brady range from 30 to 50. This way, he can fine tune the design to what is most comfortable for him. For Sgt. Brady to easily test the rubber densities, a slightly modified version of the design was manufactured and sent to him. Instead of press-fit pins holding the aluminum ankle assembly together, repositionable bolts were used. The rubber blocks was also not be glued into place but rather held in place by the pressure of the two surrounding aluminum blocks.

The team used exclusively adhesives to join the different materials described above to each other. Connecting rubber and carbon fiber to aluminum using fasteners can cause stress concentration and splintering issues in the nonmetallic materials. The adhesives went through extensive corrosion resistance and stress testing to determine the correct adhesives to be used on this prosthesis. The press fit pins to be used in the final prosthesis will be bought at a nominal size of 3/8” diameter. The side of the pins that were attached to the support block, as shown in Figure 23, were dipped in a rubber sealant that will protect the hinge from wear and corrosion.

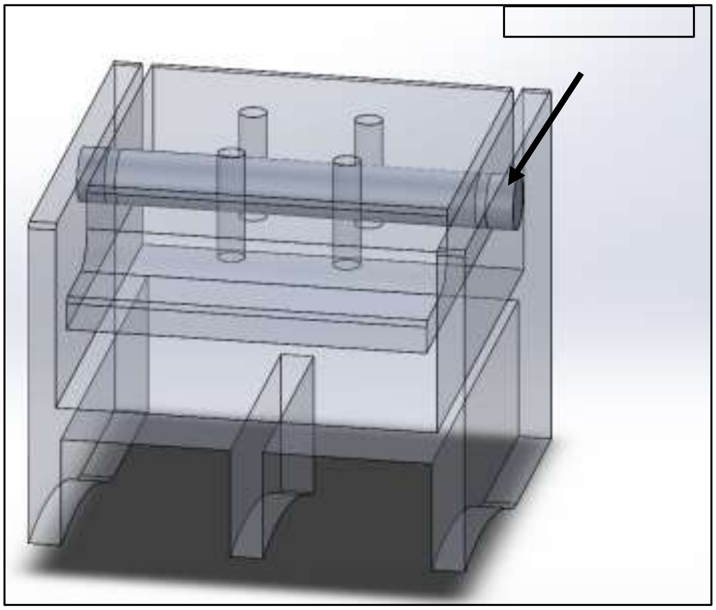


Figure 23: Translucent to Show Hinge Point

Good Manufacturing Practices

A table with the technical data sheets and safety data sheets for each adhesive and polyurethane rubber is in Appendix F. Many of the adhesives and polyurethane rubbers may inflict damage if inhaled by, consumed by, or contacted with the human body. In accordance to the technical data sheets, all mixing and curing occured in the QL+ lab, a static environment compared to the unpredictable conditions of the outside. Following the safety data sheets, all manufacturing utilizing adhesives and polyurethane rubber was performed in a fume hood, and team members wore gloves, safety classes, closed-toe shoes, and jeans.

A significant amount of machining in the Mustang 60 machine shop was required for the aluminum parts and carbon fiber fabrication in the Cal Poly Composites Lab. Safety precautions were taken to prevent any injuries -- wearing protective clothing (i.e., safety glasses, jeans, closed-toe shoes, etc.), utilizing safety guards, working with a machine shop or lab staff present, etc.

Safety Considerations

Sgt. Brady will use this prosthesis to support his weight daily. Therefore, safety is the priority. The team has been testing the safety of the design at multiple points in the prototyping process. The first check was done at the 3D modeling stage by running an in-depth FEA simulation on the finalized solid model to determine any large stress concentrations. None higher than acceptable were detected, with a wide margin. In the near future, the strength of the fully constructed prototype will be tested before it is sent to Sgt. Brady to use. A test weight of 1000 lbs will be used, considering a safety factor of 2.65 as mentioned previously in the final concept design section.

As seen in Appendix G, the Hazard Identification Checklist, the prosthesis has no obvious safety hazards aside from is buckling under Sgt. Brady's weight, which is why it is designed with a factor of safety of 2.65. And according to the FEA studies already ran, it would likely be able to support far more than 700 lbs since the current max stress concentrations in aluminum and carbon fiber are 8.5 ksi and 75 ksi respectively, and aluminum has a shear strength of 30 ksi while carbon fiber has a yield strength of 500 ksi. Other than buckling, the only safety concerns are the pinch point around the pin joint, and the prosthesis potentially falling off a shelf and onto someone. Both of these will be easy to avoid after properly briefing Sgt. Brady on how to safely handle the device.

Testing Descriptions

To verify that the design it will undergo eleven tests to determine if it meets all of the customer requirements. Appendix H shows the complete DVP&R for the project which is briefly summarized below.

The prosthesis was weighed to ensure that it is under the required 4 lbs designated by Sgt. Craig. The whole assembly was then subjected to a durability test which entailed a series of repeated drop tests from one meter combined with a fatigue model. The prosthesis was held to the same waterproofing standards that cell phone manufacturers use to ensure that no salt water can corrode the inner mechanisms of the design.

The team has determined that being sand proof is the most important feature to guarantee a long last prosthetic. To make this possible, the team conducted both sand and dust proof tests. The sand proofness was measured by measuring the torque needed to bend the ankle after an hour of use in both wet and dry sand. The torque required cannot increase by 10% over this time frame of the design will be considered not sand proof. The dust test will be conducted by placing the moving parts of our prosthesis will be left in a chamber of circulating talcum powder for a total of 8 hours and will be considered to pass if it collects less than 100 grams in that time frame. At the time of the project's completion, a dust test was not performed.

Maintenance

The prosthetic has been designed to require no maintenance, apart from rinsing the salt water off occasionally. Any foreseeable maintenance will be due to the adhesives wearing and eroding over time, which again is extremely unlikely. Several tests were performed to determine what type of adhesive will resist the corrosive power of the ocean, but nonetheless, the problem may still arise. Sgt. Brady will receive a supply of the adhesives used in the production of the prosthetic in the case that he would need to "touch up" any spots that appear to be weakening.

Cost Estimate

The cost estimate is calculated below in Table IV.. It also does not shipping and handling costs of the prosthesis to and from Sgt. Brady. However, these costs are not significant to the overall cost. The team spent $358.26 on testing materials. A significant amount of funds was put into testing materials, specifically adhesives and differing polyurethane rubber, because durability and comfortability of the final prosthesis are key requirements according to Sgt. Brady. Testing of these materials is an investment the team is comfortable making. The final prototype cost is about $506.46. The higher cost is attributed to the increased amount of aluminum and carbon fiber materials. The total project cost is $918.95. Because the prosthesis is not bound for the market, a mass manufacturing cost is not required although predicted below. After many conversations, with QL+, the project budget is undefined. Funds will be allocated on a need basis.

Table IV: Cost Estimate

Part Description	P/N	Qty	Total Cost
Thicker CF Strips	87365K24	4" X 1/8" X 3'	$31.30
Aluminum Sheet Stock	8975K514	.25" X 4" X 2'	$19.73
Aluminum Bar Stock	8975K242	1' X 4" X 1"	$34.42
Epoxy Resin and Hardener	----	1	$84.46
Polyurethane Rubber	PMC-121/30 Dry	Trial Size	$27.78
Polyurethane Rubber	PMC-744	Trial Size	$34.08
Polyurethane Rubber	PMC-746	Trial Size	$34.08
Epoxy Adhesive	19TT82	1	$21.29
e120-HP	6430A24	1.69 oz	$16.89
Adhesive Assortment	7538A16	1 (8 in set)	$19.02
SikaFlex 252	----	1	$11.50
araldite 2015 (adhesive)	----	1	$23.71
Testing Total			$358.26
Carbon Fiber Foot	87365K24	4" X 1/8" X 25'	$250
Epoxy Resin and Hardener	----	1	$84.46
Aluminum Bar Stock (support)	9008K68	4" X 4" X 6"	$66
Aluminum Bar Stock (hinge)	9008K68	1" X 4" X 1'	$34
Press Fit Pins	97395A363	10	$7
Rubber Block	PMC-------	1	$35
Mounting Screws	NA	10	$10
Epoxy Adhesive	NA	1	$20
Prototype Total			$506.46
Project Total			$918.95

The manufacturing cost, excluding the labor cost, is approximately $300. The team's prosthesis is a low-cost solution for walking on sand and other soft surfaces.

Final Prototype

The final prototype was manufactured using the practices explained above. Upon receiving feedback from the amputee test subject and from QL+, weight was reduced from the rotational block top decreasing the prosthesis weight to approximately 4 lbs, the weight of Sgt. Craig's current prosthesis and the engineering specification target. The team is satisfied with the final prototype considering the obstacles they faced in the weeks before the project expo and presentation to Sgt. Brady. Views of the final prototype are in Figure 24 through Figure 29.

Figure 24: Isometric View

Figure 25: Front View

Figure 26: Back View

Figure 27: Bottom View

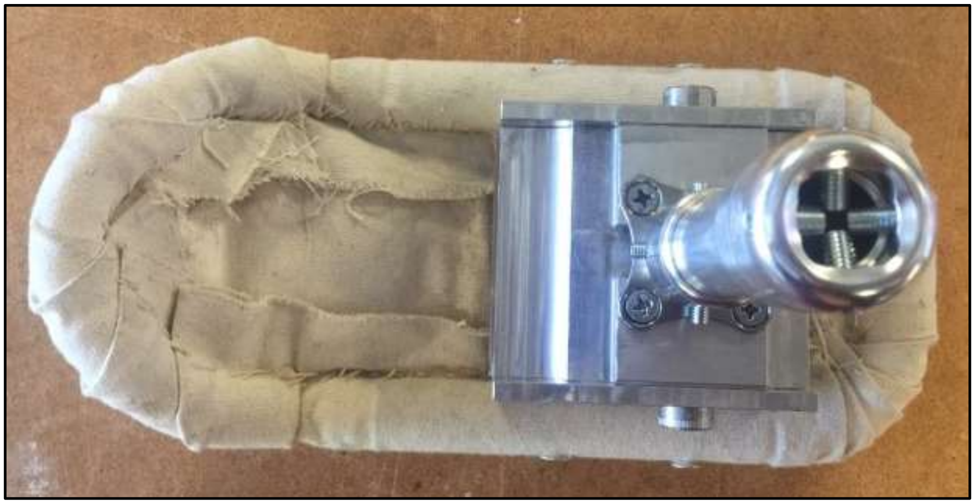


Figure 28: Top View

Figure 29: Side View

Chapter VI: Project Management Plan

To ensure the team could produce a quality prosthesis for Sgt. Brady, a management plan was devised to lay out the design, build, test process. Per the team contract, each member of the team was required to make time to meet at least one-time outside of the pre-organized class time each week. An estimated 15-20 hours per week was spent planning, building, or otherwise working on the project by each team member to ensure deadlines were consistently met.

Team Roles

Although the team worked in unison on most of the aspects of the project, each team member was assigned a primary role with preset requirements for this project. The roles are as follows:

- **Dugan** - Primary meeting lead and head of operations
- **Samantha** - Point of contact for QL+ representatives
- **John** - Design lead
- **Chris** - Manufacturing lead

These roles act as a basis to guide the team in the right direction but were not binding. It was expected that each team member be responsible for contributing to all of the aspects of the project. Due to the slightly simplistic nature of the project (the prosthesis being knee down and the fact that a working socket is available) the team expected an accelerated design, build, test process. The team's main goal this year was to have a working model of the prosthesis able be shipped to Sgt. Brady before the beginning of spring quarter, so the team can get user feedback and adjust accordingly. A detailed budget was also be created after an official design is approved. It was the expectation to design, test, and build the prosthesis with a rough budget of $2,500 based off of past projects.

Gantt Chart

A Gantt Chart, shown Appendix E, was created early into the project to guide the team and to surface any unforeseen events and considerations the team would face. At the time of its generation, the most unforeseen events and considerations the team will face are sending the prosthesis to Sgt. Brady in New Hampshire and the time to outsource machined titanium and carbon fiber parts. The Gantt Chart was not well followed because the unforeseen events did occur, and the team quickly investigated the issues and created a sound contingency plan.

At the conclusion of the project, the team is looking into receiving feedback from Sgt. Brady and making this feedback available to future students and engineers who wish to redesign and manufacture the sand foot.

Chapter VII: Recommendations and Conclusions

Recommendations

Regarding the overall design, the team recommends that future teams brainstorm new designs that reduce the weight and improves the sand proofness of the prosthesis. Several ideas the team has brainstormed includes adding a drain to the canvas or removing the canvas overlay and welding an aluminum mesh to the aluminum frame. In addition, the team recommends revisiting the carbon fiber sole design or possibly using fiberglass instead due to this higher Young's Modulus and easier manufacturing process. Future teams will also have the time and funds to outsource these composite parts.

Due to budgetary reasons, the team elected to make the metal portions of the prosthesis out of aluminum. Aluminum served the necessary functions of the parts it is constructed out of, but if a future iteration of this project was to be done, with a higher budget, titanium would be a better option. It corrodes even less than aluminum and also has a higher strength to weight ratio, which would allow Stg. Brady to use the foot long before it wears out.

Additionally, the team completed a fatigue study in SolidWorks to ensure the longevity of the prosthesis. This decision was made because Cal Poly does not have the equipment necessary to run an actual fatigue study, so it must be computer simulated. While the simulation will give accurate results, it would be better to run the fatigue study on the actual parts in the future instead of a 3D model.

Conclusions

The team has sent the final prototype and has scheduled a meeting with Sgt. Brady to receive feedback. Further design concepts can be made by future QL+ participants to reduce the overall weight and sand proofness of the design. QL+ will check in with Sgt. Brady in the next few months to check in with the feasibility and the longevity of the design. Since the local amputee who tested the design was not a good representation of Sgt. Craig's build, the team is eagerly awaiting his feedback on this new design. The team will make the design available on the QL+ website so other engineers and students can adapt the design and improve the quality of life of amputees with similar struggles as Sgt. Brady. In addition, the materials are accessible and inexpensive making it a low cost alternative to prostheses on the market.

Acknowledgements

The Sand Foot team is honored to acknowledge the following groups and individuals:

- *Sgt. Craig Brady*, for the opportunity exercise our creativity and technical skills to build a unique prosthesis and welcoming the team into his world
- *Jon Monett and The QL+ Foundation*, for their guidance, support, and funding to complete this project
- *Karla Carichner*, for being an honest and supportive senior project advisor
- *The Hangar Clinic of San Luis Obispo*, for their assistance in prosthesis parts
- *Eltahry Elghandour and the Cal Poly Composites Lab*, for welcoming us into his composites lab and for providing their composites expertise
- *Ryan Dunn*, for providing his composites expertise
- *Karen Aydelott*, for volunteering to test the final prototype and providing her honest feedback

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Appendix A: Total Mechanical Work Equation

$$W_{\text{tot}} = W_{\text{ext}} + W_{\text{int}} = W_{\text{com}} + W_{\text{env}} + W_{\text{int}} .$$

Appendix B: House of Quality

Customer Requirements (Whats)		Engineering Requirements (HOWS): Weighting (1 to 5)	Weight	IP6X Dustproof	IPX7 Waterproof	Sand-proof test	40% increase in comfortable walk time	Corrosivity	Matte finish	Drop test survival	Displacement (x,y)	Benchmark: Current Prosthesis
Customer Requirements	Lightweight	15	●			Δ	○					5
	Waterproof	13			●		○					2
	Dustproof	9	Δ	●		Δ						3
	Sandproof	13	Δ	Δ		●	○					2
	Comfortable	17					●				●	1
	Non-corrosive	12			Δ		Δ	●				5
	No Glare	9							●			4
	Durability	12				Δ		○		●		4
	Units		lbs	grams	lbs	in*lbs	hr	mil/year	GU	Yes/No	in	
	Targets		4	100	<20%	<10%	6	<.250	<40	Yes	<6	
	Current Prosthesis		4	300	40%	N/A	0	<.250	<40	Yes	>9	
	Importance Scoring		157	94	117	153	288	144	81	108	153	
	Importance Rating (%)		12.1	7.3	9.0	11.8	22.2	11.1	6.3	8.3	11.8	

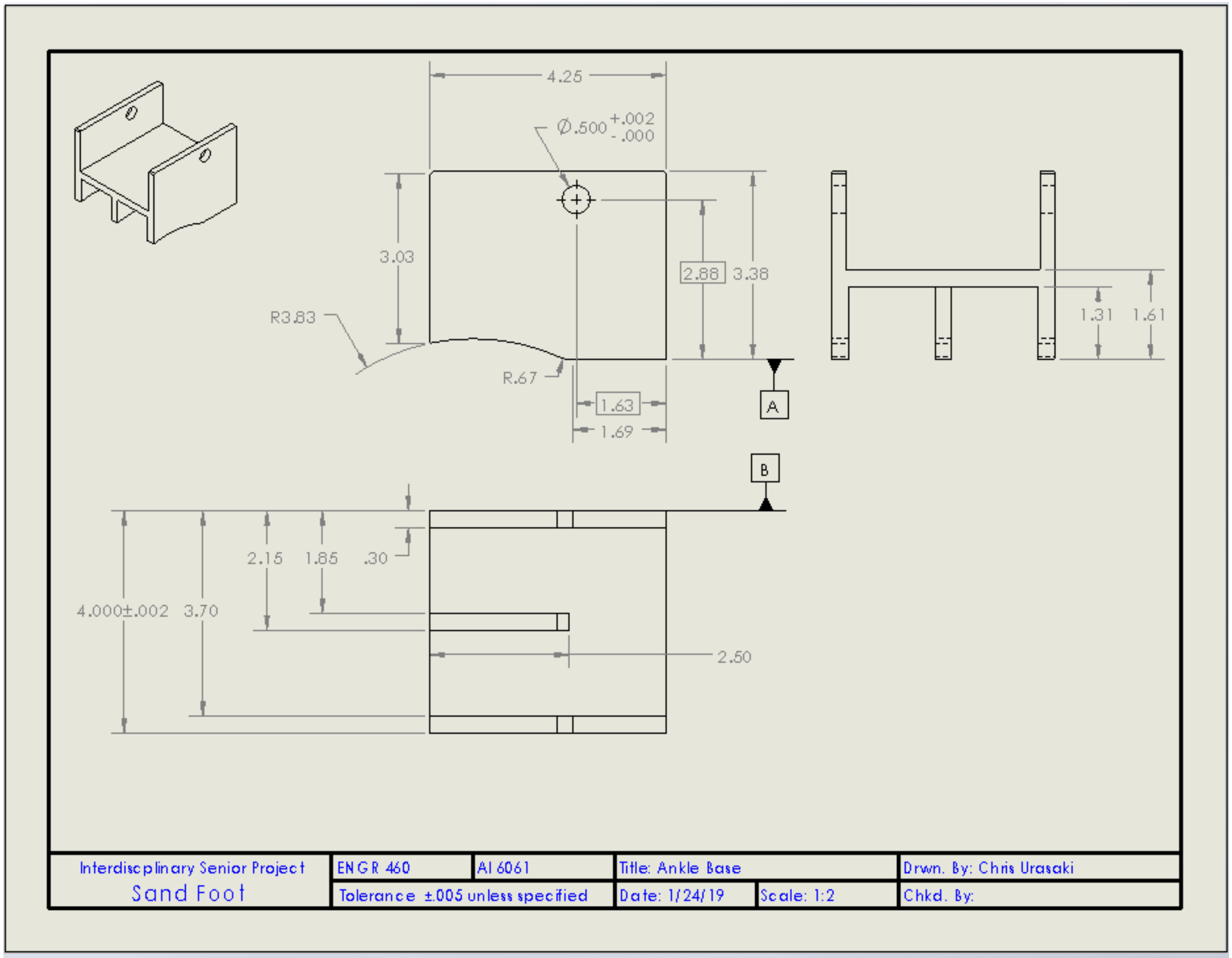
● = 9	Srong Correlation
○ = 3	Medium Correlation
Δ = 1	Small Correlation
Blank	No Correlation

Appendix C: Requirements Table

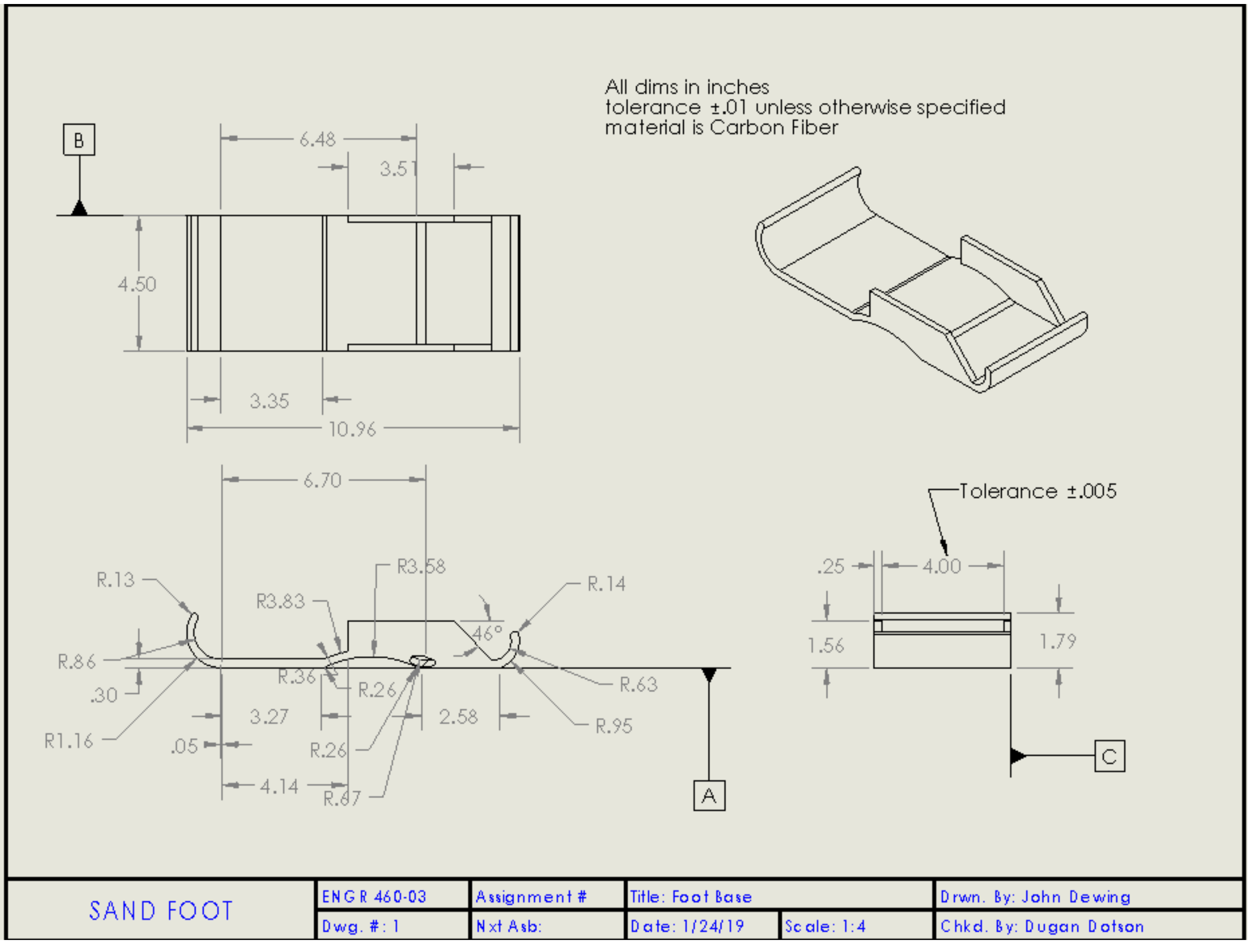
Spec. #	Parameter Description	Requirement or Target (Units)	Tolerance	Risk	Compliance
1	Weight	4 lbs	max	M	T
2	Waterproof	wet weight < 120% dry weight	max	H	T, I
3	Dustproof	100 grams of powder	max	M	T
4	Sandproof	post joint torque < 110% pre joint torque	max	H	T, I
5	Walk Time	40% longer min)	± 5%	H	T, S
6	Corrosivity	0.250 mil/year	max	M	A
7	Matte Finish	40 Gloss Units	max	L	I
8	Durability	1m, 20 times	min	M	T, A, I
9	Sand Displacement (x,y)	(x,y) 6 in, 6in	± 2in	H	A, T

Appendix D: Drawings

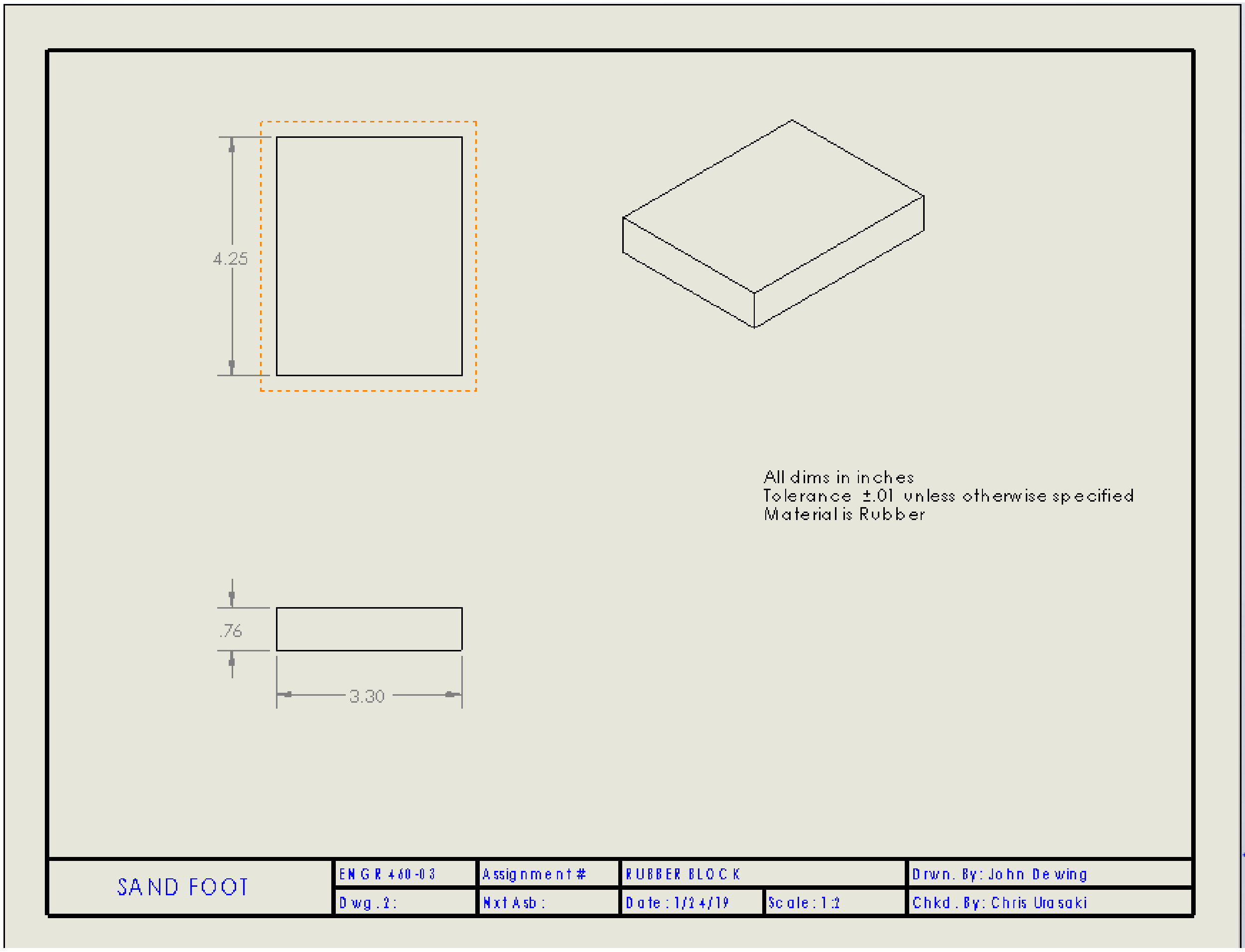
Aluminum Support



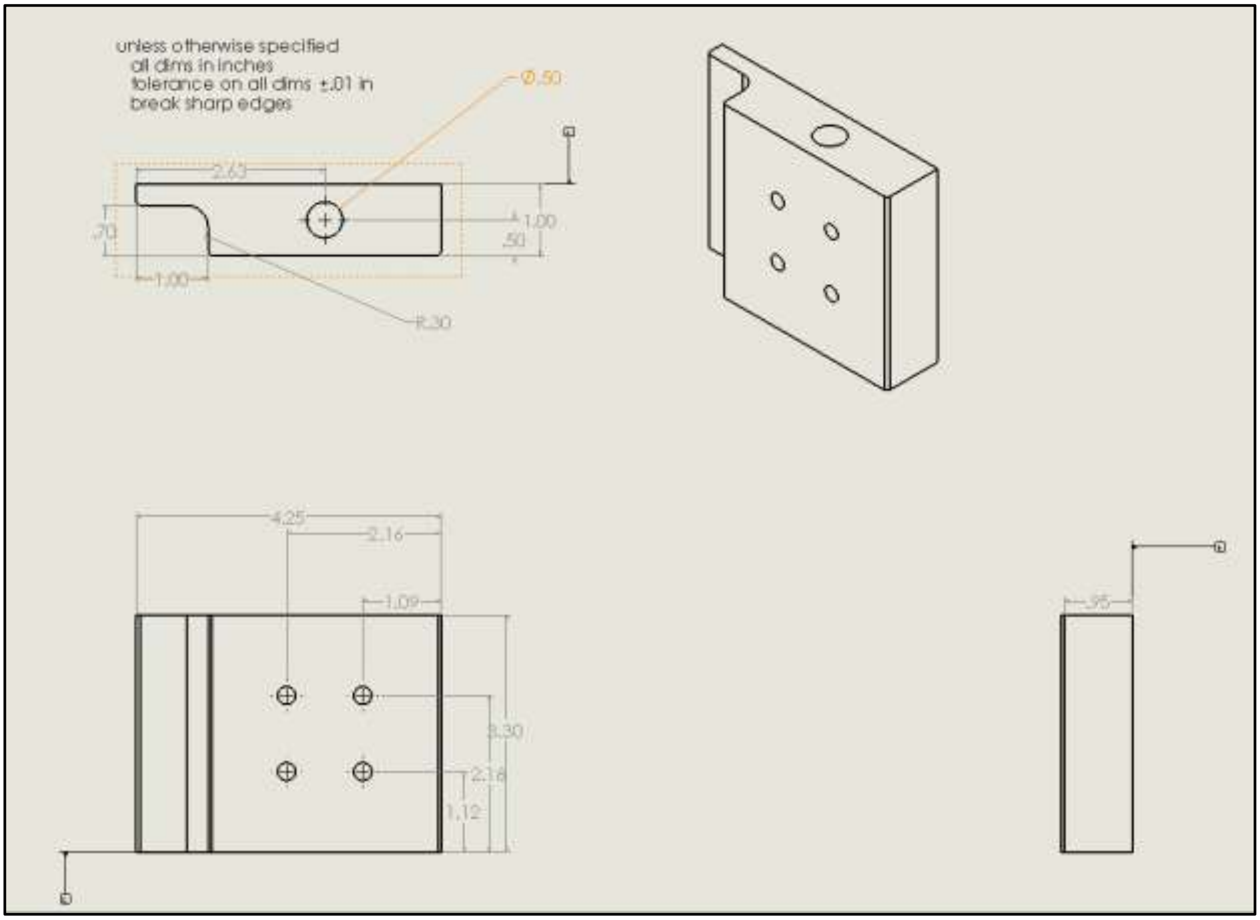
Carbon Fiber Base



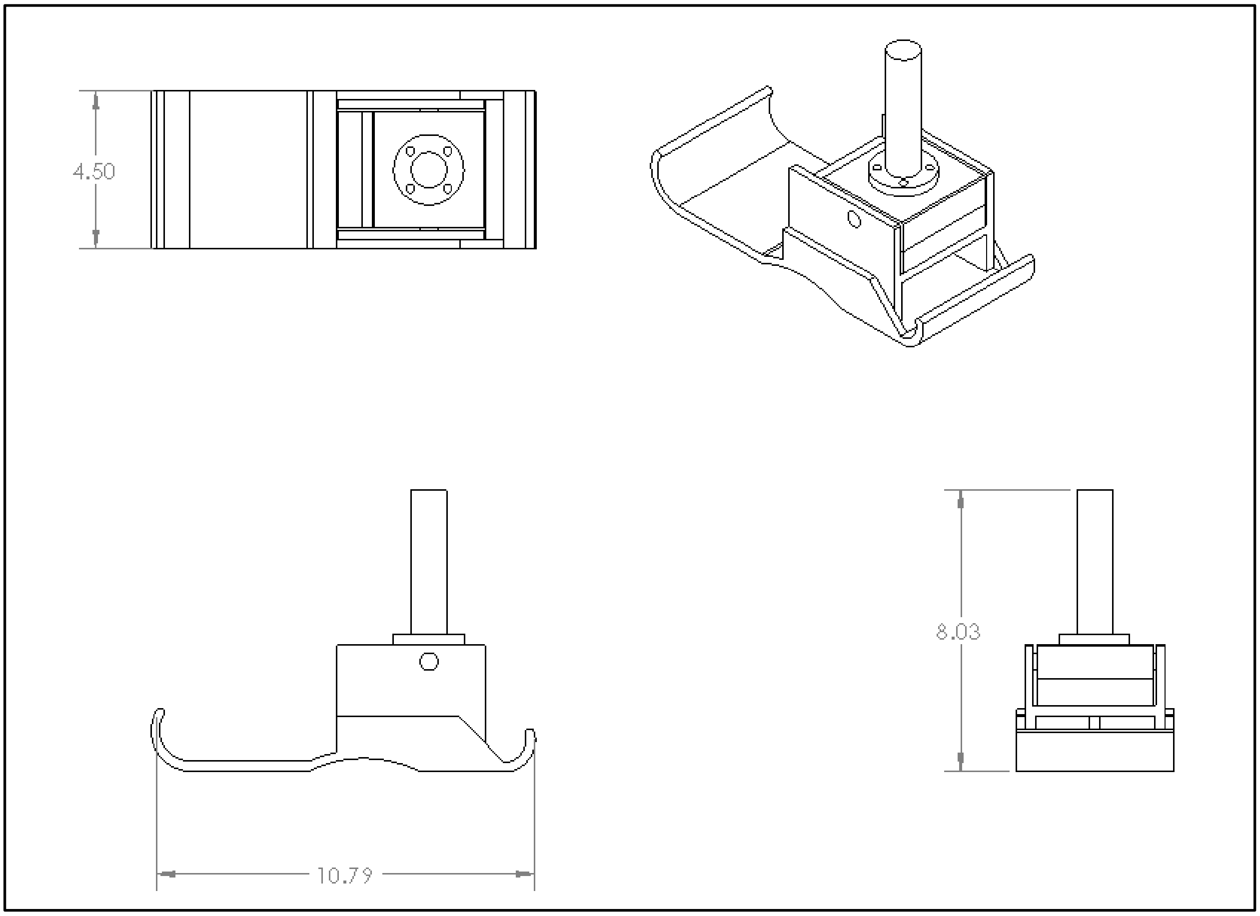
Rubber Block



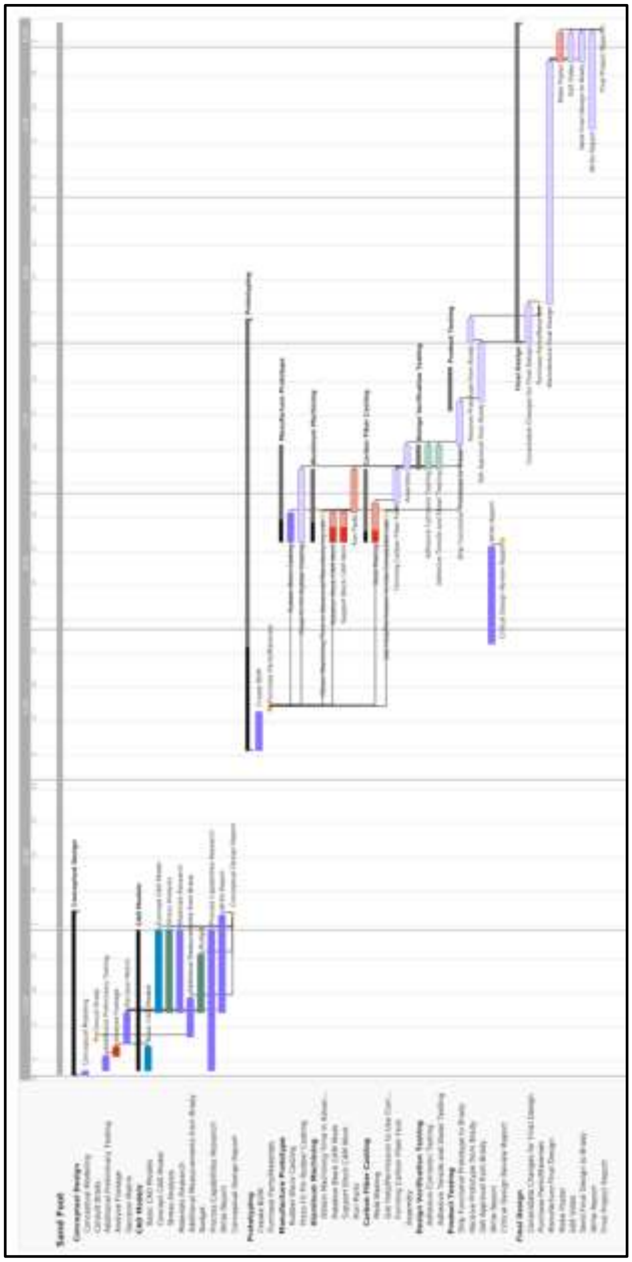
Rotation Block



Assembly Drawing



Appendix E: Project Gantt Chart



Appendix F: Technical Data Sheet and Safety Data Sheet Links

Part	**Technical Data Sheet**	**Safety Data Sheet**
WEST SYSTEMS 105 Epoxy Resin	https://www.westsystem.com/wp-content/uploads/105-205-Epoxy-Resin.pdf	https://www.westsystem.com/wp-content/uploads/105-SDS.pdf
WEST SYSTEMS 205 Fast Hardener	https://www.westsystem.com/wp-content/uploads/105-205-Epoxy-Resin.pdf	https://www.westsystem.com/wp-content/uploads/205-SDS.pdf
PMC 121-30 Dry	https://www.smooth-on.com/tb/files/PMC-121_SERIES.pdf	https://www.smooth-on.com/msds/files/642A_1-642B_1.pdf
PMC-744	https://www.smooth-on.com/tb/files/PMC-744.pdf	https://www.smooth-on.com/msds/files/644A_1-644B_1.pdf
PMC-746	https://www.smooth-on.com/tb/files/PMC-746.pdf	https://www.smooth-on.com/msds/files/646A_1-646B_1.pdf
Loctite EA 0151	https://www.grainger.com/product/LOCTITE-Epoxy-Adhesive-19TT82	http://complyplus.grainger.com/grainger/msds.asp?sheetid=4093469
Loctite E-120hp	https://www.mcmaster.com/6430a24	https://www.mcmaster.com/379nmna
Epoxy Structural Adhesive Assortment	https://www.mcmaster.com/7538a16	https://www.mcmaster.com/815pneg
SikaFlex 252	https://usa.sika.com/dms/getdocument.get/8a7a425c.../pds-ipd-sikaflex252-us.pdf	https://usa.sika.com/dms/getdocument.get/0e603baf.../ipd-msds-Sikaflex252-us.pdf
Araldite 2015	https://krayden.com/technical-data-sheet/hunts_araldite_2015_tds/	https://www.freemansupply.com/MSDS/Combined/adhesives/Araldite/Araldite2015ENG.pdf
Structural Adhesive Epoxy, J-B Weld Marineweld	https://www.mcmaster.com/7605A7	https://www.mcmaster.com/7605A7

Appendix G: Senior Project Conceptual Design Review Hazard Identification Checklist

SENIOR PROJECT CONCEPTUAL DESIGN REVIEW HAZARD IDENTIFICATION CHECKLIST

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 all the electrical systems properly grounded? Not applicable.
☐	☐	Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC? Not applicable.
☐	☐	Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids? Not applicable.
☐	☑	Will there be any explosive or flammable liquids, gases, dust fuel 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…?
☑	☐	Will the system easier to use safely than unsafely?
☐	☑	Will there be any other potential hazards not listed above? If yes, please explain below?

Appendix H: DVP&R

DVP&R

Report Date		1/22/2019	Sponsor	Quality of Life Plus								
TEST PLAN										TEST REPOR		
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS		
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail
1	Weight	Weigh using a scale	4 lbs	Samantha	PV	1	C					0
2	Waterproof	Must pass IPX7 waterproofing standards	wet weight < 120% dry weight	Chris	DV	1	B					0
3	Dustproof	The moving parts of our prosthesis will be left in a chamber of circulating talcum powder for a total of 8 hours.	100 grams of powder	All	DV	1	B					0
4	Sandproof	1 hour of use in sand (wet and dry)	post joint torque < 110% pre joint torque	John	DV	1	B					0
5	Walk Time	Challenger must remain a comfortable walking gait for an increased amount of time	Comfortable for 6 hours of usage	Samantha	PV	1	C					0
6	Corrosivity	Bond aluminum and carbon fiber with chosen adhesive. Place in saltwater for 1 hour, 2 hours, 3 hours, and 6 hours.	0.250 mil/year	Chris	CV	10	B					0
7	Matte Finish	Visual Inspection	Visible Matte Finish	John	DV	1	B					0
8	Durability	Drop 1m, 20 times	Supports 1000 lbs without fracturing and if all joints still have full range of motion, using no more than 10% more torque that what was required before the drop	Dugan	DV	1	B					0
9	Durability (Adhesive)	Shear stress testing of aluminum/carbon fiber and aluminum/rubber adhesives	max shear stress	Samantha	DV	15	B					0
10	Sand Diplacement	Prosthesis must slip back less than 6 inches and sink less than 6 inches when loaded with 350 lbs.	(x,y) 6 in, 6in	Dugan	DV	1	B					0
11	Fatigue	Simulate repeated use using FEA simulation	Can take 600,000 steps without significant impact to functionality	John	DV	1	B					0