# Non-slip Prosthetic Surf Foot

## QL+
## Project 174a1 CP

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## Statement of Disclaimer

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## List of Nomenclature

CES database: Virtual library that contains important technical data on thousands of materials

COMSOL: Multiphysics simulation software

Dorsiflexion: Movement of raising the foot upward toward the shin

FEA: Finite element analysis

Liquid urethane: liquid material that becomes rubber (polyurethane) once cured

ksi – kilo pound per square inch

Plantar flexion: Movement of the foot when it is bent at the ankle away from the body

Socket: Connects the residual limb to the prosthetic

SolidWorks: Solid modeling computer-aided design (CAD) and computer-aided engineering (CAE) program

Transtibial: Below-the-knee

## Executive Summary

The Surf Foot project was created to resolve the challenges faced by Dana Cummings, a former Marine and transtibial left leg amputee, while surfing. Dana is a competitive surfer who first picked up the sport after he lost his leg. He currently utilizes a carbon fiber prosthetic leg when surfing. However, this prosthetic is not ideal for Dana as he often slips while standing up on his surfboard. As such, Dana would like a new non-slip prosthetic leg so that he can further pursue his passion of competitive surfing.

Our team, which consisted of four engineering students attending Cal Poly, San Luis Obispo, was sponsored by the QL+ organization. Over the course of three quarters, we worked to research, design, manufacture, and test a prototype that would meet Dana's requirements. After several months of brainstorming and conceptualizing, we designed a prosthetic leg made from five main components. These components include two pieces of carbon fiber which together serve as a leg, two rubber components intended to serve as a non-slip sole for the prosthetic, and an adapter that would allow Dana to attach the prosthetic to the socket he uses when surfing.

Unfortunately, due to the closure of on-campus facilities that resulted from the COVID-19 pandemic, our team was unable to complete the manufacturing and in-person testing of the prosthetic we designed. Instead, we compiled a list of in-depth instructions regarding the planned manufacturing process and testing of our design so that a future QL+ team could complete our project once campus facilities reopen.

Although we were unable to produce a final product, our team is confident that our design will eliminate Dana's problem of slipping while surfing, thus enabling him to further pursue surfing as a competitive sport.

## Introduction

Dana Cummings is a below-the-knee left leg amputee who lost his leg in a vehicle accident after serving in the United States Marine Corps. Dana didn't allow his circumstances to stop him from living an active lifestyle and following the accident he began to learn how to surf. As he progressed in surfing, he founded the organization AmpSurf in an effort to bring the joys of surfing to others with disabilities. AmpSurf aims to promote, inspire, educate, and rehabilitate disabled veterans, adults, and children by showing them what they are capable of doing as opposed to focusing on their disabilities. They offer surfing clinics to hundreds of these individuals "to bring the healing power of the ocean for an experience that is both mentally and physically one of the best forms of rehabilitation on the planet" [1].

The more advanced Dana's surfing became, the more he recognized the limitations of surfing with his prosthetic. He went to QL+, an organization committed to bettering the quality of life for those with physical disabilities, with an idea to minimize the challenges associated with surfing while utilizing a prosthetic leg. He requested a non-slip surfing foot that would allow him to stand up while catching a wave, prevent his foot from slipping toward the back of the board, and provide him with more points of contact with the surfboard to assist him in doing more complex maneuvers. Our team, appropriately named "Surf Foot", consists of two Biomedical Engineering students, Ryan Monjazeb and Sabrina Nelson, a General Engineering student, Luis Mata, and a Manufacturing Engineering student, Gerrit Sperling. As a team, and with the help of our advisor Jim Widmann, we plan to realize Dana's dream of a non-slip prosthetic surfing foot to enhance his surfing experience.

## Background

There are four main phases that occur while a person is surfing: paddling out, standing up, paddling into a wave, and riding the wave. Paddling out and paddling into a wave typically do not require much use of the lower body because the surfer is laying on top of their surfboard. Surfboards come in many different sizes however, and very small “shortboards” can have an effect on the use of the lower body while paddling into waves. On a shortboard the lower half of the surfer’s body is submerged in water and because of the lack of floatation of the board, a kicking motion is often required to generate enough speed to paddle into a wave. “Longboards” are typically long enough and allow enough floatation for the user to be out of the water as they paddle. This necessitates the use of only the upper body to paddle into a wave as the user does not have the ability to kick their feet if their feet are not submerged in water. However, standing up on both types of boards and riding waves require the same essential physical skills associated with the lower body, such as balance, agility, flexibility, and strength. When initially standing, critical maneuvers must be performed in the ankles, knees, and hips to ensure stability on the board [3]. The upper body is used to push the surfer’s body up and provide clearance for the feet of the user to be swung around and underneath the center of gravity of the surfer. Being a physically demanding sport, it is even more challenging with limited use of the lower leg. From reviewing footage of Dana standing up on his surfboard and comparing it with the typical standing of a non-amputee, it can be seen that because of his prosthetic, Dana has to maneuver his body slightly differently to account for the limited mobility of his prosthetic. As he leans forward, with nearly all of his weight on his front foot, his legs form an approximate right triangle with the surfboard, rather than his rear leg coming to a standing position simultaneously with his front foot. This limited mobility that is caused by having a prosthetic is where Dana’s slipping occurs and can be seen in Figure 1. The flat sole of his foot is not able to contact the surfboard and the edge of his foot that does contact does not provide adequate friction to prevent his body weight from slipping out from underneath him.

**Figure 1. Photo of where Dana’s slipping problem occurs**

Numerous surfers who deal with below-the-knee amputations have designed their own prosthetics to improve their surfing quality. However, there is such a small market for these types of prosthetics that they are typically made as personal projects and little information about the specifics of the prosthetics are available. Many previous designs have dealt with ankle mobility. In fact, there is a commercially available SwimAnkle. The design uses a unidirectional hinge system, which achieves a 70 degree plantar flexion, to assist in the optimization of swimming performance [7]. The success of this ankle implies that ankle mobility is a feasible design option. It could potentially be able to assist in the reduction of drag while paddling out beyond waves. Furthermore, it could also help to increase speed while paddling into waves, particularly on a short board, when swimming and kicking motions are used to generate speed. Another important design consideration implemented in the SwimAnkle is a protective cover to keep debris out, which is critical for use in the ocean and while walking through beach sand.

Another interesting design concept that was found is the Rush Foot Rogue, seen in Figure 2. The foot uses a flexible fiberglass design to allow for a limited range of plantar and dorsiflexion. Some potential benefits of this competitor’s design are the increased mobility that the flexible foot provides as well as its waterproof capabilities and lack of physically moving parts. Using the properties of the fiberglass to provide mobility is an intelligent design choice for a product that can be taken through sand, immersed in salt water and exposed to other harsh conditions because the mobility does not come from a moving, rubbing part that is subject to greater wear under such conditions. However, one drawback of the design in regard to Dana’s problem is the sharpness of the edges on the bottom of the foot. Because of this issue, the Rush Foot cannot solve the main issue of slipping while standing up on a surfboard.

**Figure 2. Rush Foot Rogue, available for purchase**

A Cal Poly senior project group last year developed a prototype that focused on ankle mobility as well. The ankle was made with a baseplate bonded to the foot, which acted as a washer to distribute force from the assembly. There were also two rubber components that served as bushings to allow constrained motion and assist in returning the ankle to the neutral position. The bottom rubber allows the post to dig in, while the cross at the bottom of the post prevents the post from over rotating when a torque is applied. The top rubber served as the main source of resistance for the ankle and provided the movement necessary for surfing. It permitted motion and contributed the proper resistance needed to maintain control and return the leg to the proper position. Both rubber bushings were encased in an aluminum shell to hold the whole assembly together [5]. Figure 3 shows an image of the assembly.

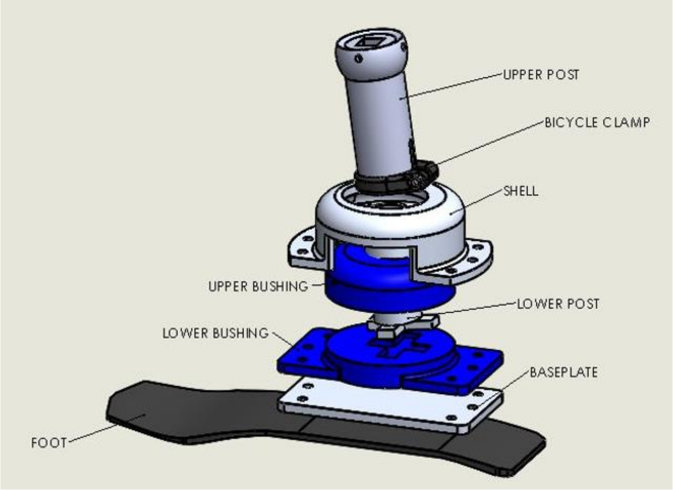


**Figure 3. Assembly of last year's Senior Project design for Surf Leg**

The biggest issues with the design were the weak elasticity of the top rubber, the attachment of the foot to the ankle, and the size of the foot. The baseplate was glued to the foot, which could not withstand the shear force that was applied to it. Also, the foot was too large. This made it hard to maneuver while getting up and standing on the board and created more drag when paddling out or into a wave.

Dana currently uses an everyday prosthetic leg that he has modified for surfing. Figure 4 shows an image of his current prosthetic.

**Figure 4. Current modified prosthetic leg used by Dana Cummings while surfing**

A vacuum system is used to secure his leg to the socket of the prosthetic. Dana has shaved down the four hole pyramid adapter between the socket and pylon on his leg so that he could be lower to the board while surfing and has attached a rubber sole to the bottom of his Fillauer All

Pro Direct Mount foot (of which the unmodified version is shown in Figure 5) to improve surface area, but these are the only minor adjustments he has made. The flat foot design does not provide adequate surface contact between his foot and the surfboard when he is standing up to catch a wave.

**Figure 5. Fillauer All Pro Foot, the prosthetic Dana currently has**

**Objective:**

The overarching goal of this project is to improve Dana’s surfing experience. In order to accomplish this, our team has designed and will manufacture a custom prosthetic foot that allows for multiple points of contact while increasing traction of the foot on a surfboard. The foot needs to be able to prevent Dana’s rear leg from sliding when he stands up on the board to catch a wave, and also increase the number of positions that his foot can be placed. In order to prevent sliding, Dana would like the prosthetic foot to have multiple points of contact that can mimic the big toe and inside of a human foot. Furthermore, he desires that it be made out of a material that has a high coefficient of friction to minimize slippage. He would also like the overall height of the prosthesis to be as short as reasonably possible so that he can keep his center of gravity low while he’s riding a wave. Due to the fact that Dana will be utilizing this product to surf, he also requires it to be corrosion resistant, sand resistant, waterproof, durable, and requests that it generates minimal drag in water while he’s paddling out. The design also has to be comfortable to wear and enable easy maneuvering while surfing. Our team has taken the customer requirements provided by Dana and converted them into engineering requirements.

This process is shown in the Quality Function Deployment Table (Table V) in Appendix B. The importance of each customer requirement is weighted on a scale of one to five with five being highly important and one being of little importance. We then determined what engineering requirements would satisfy each customer requirement. After researching the coefficient of friction of various surfboard wax brands, we found that many brands have a coefficient of friction around 0.2 if the normal force applied is 2.5 psi or greater. After doing a friction test, we determined that 0.65 would be sufficient for our design based on Figure 21 [6] (see appendix A), surfing knowledge, and engineering judgment. Our goal for the weight of the design is 3.0 pounds or less in order to keep it lightweight and comfortable to wear. Furthermore, we don’t want the prosthesis to retain any water or sand, so this weight must stay consistent before and after use. While the length and surface area of the foot are very important in the comfort level and ease of use, they also play a role in the resistance created while paddling out. Consequently, these requirements need to be large enough to provide stability and comfort but small enough that they don’t hinder Dana’s surfing experience. Once manufactured, we will test the drag created by the prosthesis by measuring the force required to pull it through water. The exact height of the prosthesis will be dependent on what Dana feels most comfortable with, but our initial target is 7.5 inches from the ground to the top of the prosthesis. We plan to give Dana a few choices on what material he prefers for the base of the foot, but the shore hardness of the materials will fall within a range of 20A-60A. This will provide Dana comfort, ease of use, and durability.

**Table I. Surf Foot Formal Engineering Requirements**

| **Specification Number** | **Parameter Description** | **Requirement or Target (units)** | **Tolerance** | **Risk**<br>L = Low<br>M = Medium<br>H = High | **Compliance**<br>A = Analysis<br>T = Test<br>S = Similarity to Existing Designs<br>I = Inspection |
|---|---|---|---|---|---|
| **1** | **Friction** | **0.65** | **± 0.3** | **L** | **A, T** |
| **2** | **Weight** | **3 lbs** | **± 0.5** | **M** | **A, T, S** |
| **3** | **Consistency in weight (before and after submersion)** | **0 lbs** | **+ 0.1** | **M** | **A, T** |
| **4** | **Length of Foot** | **9 in** | **± 0.15** | **L** | **A, T, S, I** |
| **5** | **Anti-rust** | **0 mm/year** | **Max** | **M** | **A, T** |
| **6** | **Surface Area of Foot** | **31.5 $in^2$** | **± 2.5** | **L** | **A, T, S, I** |
| **7** | **Drag While Swimming or Paddling** | **2 $lb_f$** | **Max** | **M** | **A, T, S, I** |
| **8** | **Height** | **7.5 in** | **± 0.05** | **M** | **A, T, S, I** |
| **9** | **Shore Hardness of Material Used for Base of Foot** | **40A** | **± 20** | **M** | **A, I** |

## Design Development:

Design development was primarily done in a team setting. A major idea generation process the team used was brainstorming. As a group we created conceptual prototypes that would solve Dana’s slipping problem. The best ideas to come from the idea generation processes were the Curved Edge, Modified Rush Foot, Spring Design, and Ankle Adapter.

In our initial discussion with Dana, he told us he wanted a foot with an edge that could increase the surface contact between his foot and the surfboard when his foot is at an angle, so we came up with the Flat Edge Design (Figure 6). This design is similar to what Dana uses now, but with a flat, angled edge on the inside edge of the foot and toe area to increase surface contact when his foot is at an angle. The drawback with this design was its inability to adjust to the various angles Dana requires while surfing; Dana would have to stand up the same way every time, which is impossible given that every wave is different. Early on, we decided to rule this design out because it didn’t adequately solve Dana’s non-slip problem.

**Figure 6. Flat edge design**

The Curved Edge Design (Figure 7) is similar to what Dana has now as well as the Flat Edge Design, but with a curve along the inside edge of the foot and toe area to mimic the edges of a human foot and allow Dana more surface contact at whatever angle he puts his foot at.

**Figure 7. Curved edge design**

The Modified Rush Foot (Figure 8) is an adaptation of a non-slip prosthetic foot, the Rush Foot Rogue, that is already on the market. As mentioned earlier, the issue with the Rush Foot Rogue that is on the market is that it only has a flat sole, so it would put Dana in the same position he is in now, where he doesn’t have enough contact when his foot is at an angle, resulting in slipping. This design would require us to add a curved edge modification in order to improve the amount of contact he has on the inside of his foot and the toe area.

**Figure 8. Modified Rush Foot design**

Our Spring Design (Figure 9) consists of a flat sole with edges on the inside of the foot and toe areas that can move up as Dana bends his foot inward or up at the toes. The yellow pieces on the conceptual prototype represent torsional springs that would make the edges return to a flat position when they’re not being actively bent. This would allow Dana to have good surface contact at whatever angle he positions his foot at, which would help prevent slipping.

**Figure 9. Spring design**

The ankle adapter piece of the Ankle Adapter Design (Figure 10) is typically attached in a way that allows plantar and dorsiflexion, but since Dana needs to bend his ankle to the side when he stands up on his board, we came up with this design which turns the ankle adapter 90 degrees to allow side to side movement, but not forward and backward movement. With this design, we would also have to add a spring system that would make the sole of the foot return to a flat position when it’s not actively being bent.

**Figure 10. Ankle adapter design**

When evaluating these last four designs, we looked at how they met the most important requirements from our QFD (Table V), which were non-slip functionality, durability, and corrosion resistance. Since we designed all of these to solve Dana’s slipping problem, they all meet the non-slip requirement. When looking at durability, we decided that moving parts would most likely decrease the overall lifespan of the product. Because the spring design and ankle adapter both have moving parts, we concluded that those had a higher likelihood of breaking before the simpler designs that don’t have moving parts. The Rush Foot Modification, although it doesn’t have any moving parts specifically, does have flexibility, which we worried could cause it to break sooner than our simplest design, the Curved Edge. The Rush Foot Modification would also require us to change Dana’s current pylon, which we are trying to avoid. As far as corrosion resistance, the ocean poses a threat to any metal that is exposed on our designs, which is why the Spring Design and Ankle Adapter Design both failed in that category. The only design that achieved non-slip functionality, durability, and corrosion resistance was the Curved Edge Design.

The final decision was made with a Pugh Matrix visible in Table VI in Appendix B. While looking at the customer requirements and all generated concepts, a datum of the Flat Edge Design was selected to compare how the other designs would be expected to perform relative to it. The Flat Edge Design was chosen as the datum because this design is what Dana described as what he thought the solution to his problem would look like. When specifically comparing the Curved Edge Design to the datum as a group, the team determined that the design would outperform the datum in four major customer requirements while underperforming for zero requirements. The other three designs scored worse than the datum on two to seven requirements, many of which we considered crucial to meet in the final design. We decided that the Curved Edge Design was the best option because of our confidence that it will meet all of the requirements desired by the customer.

After presenting the Curved Edge Design to Dana in December (shown in Figure 11), he provided us with some feedback. He generally liked the idea, but he was worried this design would not allow enough flexion with his carbon fiber foot. The Fillauer All Pro foot he uses now has an arch in the middle, similar to an exaggerated arch of a human foot, that provides some give as the user puts their weight onto the foot. It also has a split down the middle of the carbon fiber pylon piece which allows the user to lean a small degree from side to side easier than if it were a solid piece of carbon fiber. After presenting this idea, we were also told by our sponsor that we should be designing and manufacturing the entire prosthetic, not solely the foot. Because Dana likes so many features on his current prosthetic, we decided to go with a very similar design that would provide Dana with all the features he likes and would not require him to have to relearn how to surf on a completely new prosthetic design.

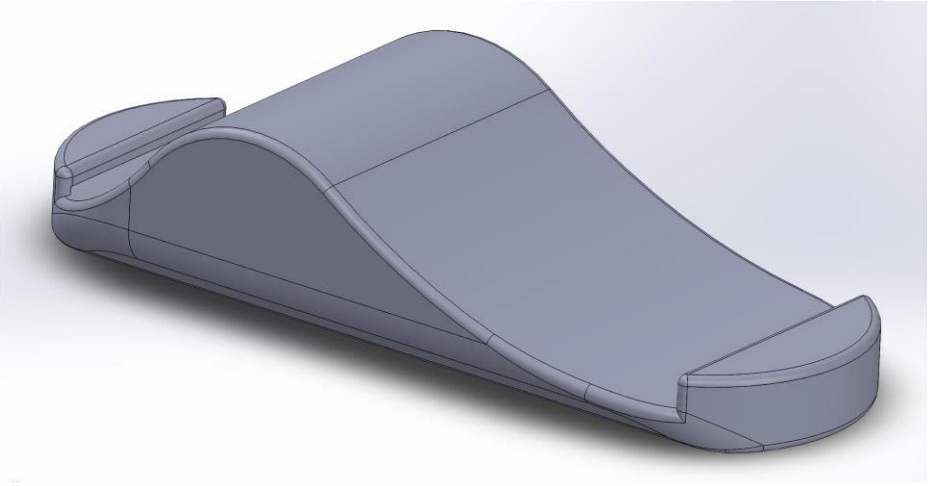


**Figure 11. SolidWorks model of design presented to Dana (curved edge)**

**Final Design Concept:**

Taking both Dana's and our sponsor's feedback, we redesigned the prosthetic, this time focusing on making the entire prosthetic and including the features Dana mentioned. To incorporate these ideas, we decided to design a pylon and foot with the same curvature and material as the Fillauer All Pro Dana currently uses. We also decided to split the rubber foot piece into two pieces (a toe piece and a heel piece) which will allow the foot a bit of flexion as Dana puts his weight on it. We plan to keep the curves on the edges of the rubber pieces to provide Dana with multiple points of contact at any angle he chooses to put his foot at, which will make standing up on the board much easier for him. This curve will also provide him with more maneuverability while surfing as he will be able to place his foot at multiple angles. This design is simple in that it has no moving parts which will make it more durable and require little to no maintenance. At most, he will have to rinse off his foot with freshwater to try and minimize corrosion. Salt and sand would pose a threat to any design we pursue. Other design ideas involving moving parts would be more affected by salt and sand than this design because there would be more spaces for sand and saltwater to get caught, resulting in corrosion and wear and therefore a decreased longevity of the foot. This design will also be easy to manufacture based on its simplicity. A detailed description is laid out in the following sections, and detailed manufacturing plans are laid out in Appendix H.

In terms of safety, we plan for this prosthetic to have a factor of safety of three. To do this, we must verify that our design can withstand a load of 600 pounds without yielding. We have completed finite element analysis (FEA) with an expected load of 600 pounds and our model was well below the yielding point. This supporting analysis is explained further in the following chapter as well as Appendix F. Once our prosthetic is manufactured and assembled, it will need to undergo physical testing to further verify that our product is safe for Dana to use. A Safety Checklist can be viewed in Appendix L.

## Detailed Description of Final Design

The following figures show the model of our final design. Due to the fact that Dana likes all of the features on his current Fillauer All Pro prosthetic, we decided to mimic this design. After getting his exact dimensions, we decided to make the carbon fiber foot and pylon a similar height to what he currently has. Because of the similarity in design, this prosthesis can be attached to his current socket with the use of a pyramid adapter, shown in Figure 12.

**Figure 12. Titanium Foot Pyramid Adapter**

Figure 13 shows the labeled isometric view of our design. The pylon and foot have curves similar to Dana's current prosthetic and will provide a bit of flexion as he puts weight on it. They will be fastened together with three 316 stainless steel binding barrels in the shape of a triangle. Originally we only had two binding barrels, but we added a third to prevent the pylon from pivoting about the axis of the original two which would add additional stress where the bolt holes are and could potentially lead to a fracture in the pylon or foot. We will purchase a Titanium Foot Pyramid (Figure 12) to add to the top of the pylon in order to connect it to Dana's socket. The rubber components will be fastened to the front and back of the foot using two 316 stainless steel binding barrels each as well as an adhesive to ensure that they will not slip off or move around on the foot. The curved edge on the rubber components can be seen in the front view of the model in Figure 14. An assembly drawing with Bill of Materials along with detailed drawings of each part and mold components can be viewed in Appendix C.

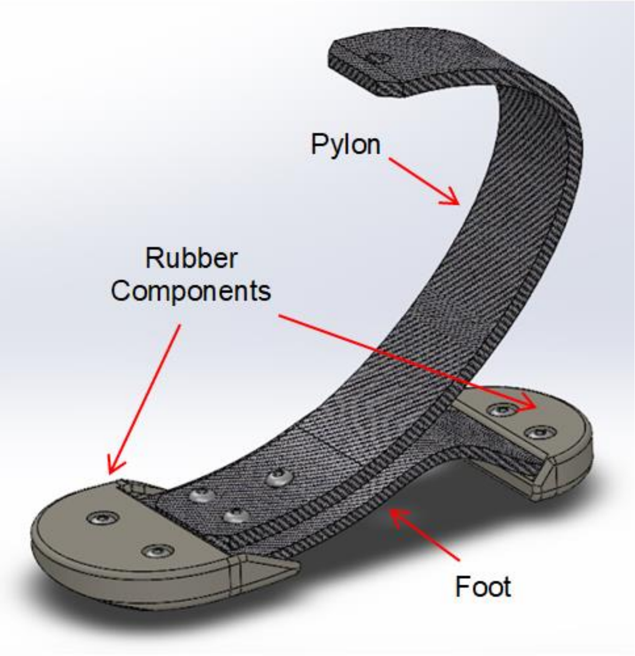


**Figure 13. Isometric view of prosthetic design**

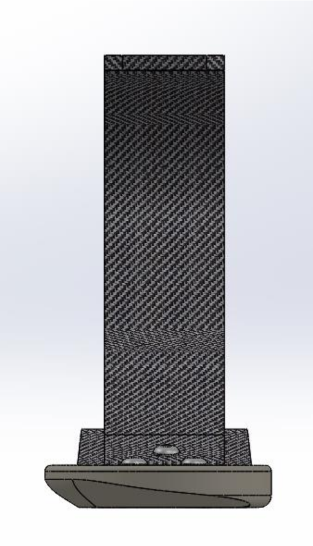


**Figure 14. Front view of prosthetic**

## Material Selection:

There were three main components that materials had to be considered for: the foot sleeves, the foot and pylon, and the adapters. All materials selected must withstand ocean conditions.

1) Foot Sleeves - After conducting initial background research on what type of material to use for the foot sleeves, it was decided that some type of elastomer would be the best material. Our team then gained access to the CES database in the MATE Department to compare various elastomers. A decision matrix was then assembled to select the best elastomer; please refer to Table VII in Appendix B to see the foot sleeve material decision matrix. It was determined that polyurethane would be the best elastomer to use due to its high tensile strength, fatigue strength, and hardness compared to other elastomers. After deciding on our material, we obtained polyurethane samples from Smooth-On. Furthermore, the manufacturer provided a shore hardness for each polyurethane sample. The samples we selected have varying levels of shore hardness: 20A, 40A, and 60A. 20A is about the hardness of a rubber band, 40A is about the hardness of an eraser, and 60A is almost as hard as car tires. We chose such a wide range of shore hardnesses to allow Dana to get a feel for the types of polyurethane available. Once we have a better idea of what shore hardness Dana prefers, we will order more samples closer to that range if necessary.
2) Foot and Pylon - The foot and pylon will both be made out of carbon fiber reinforced polymers (which we have been referring to as simply carbon fiber). Dana's current prosthetic is made out of carbon fiber, as well as many other prosthetics on the market. Carbon fiber is a good material to use due to its weight, specific strength, and resistance to corrosion, fatigue, and creep. Dr. Eltahry Elghandour is allowing our group to use carbon fiber sheets available in the Cal Poly Composites Lab.
3) Adapter - There are two main materials used for adapters: titanium and stainless steel. Titanium has a maximum weight limit of 300 pounds, and stainless steel has a maximum weight limit of 265 lb. We believe that the higher load criteria of titanium is worth paying a bit more, so the adapter will be made out of titanium.

## Coefficients of Friction Test for Polyurethane Samples:

To find the coefficients of friction for each potential foot sleeve material, we gained access to samples of each polyurethane type. Each sample was placed flat on a dry waxed surfboard, and the board was tilted until the polyurethane sample began to slip. At this point, the angle of the board was measured. This process was repeated 15 times for each sample, and we were able to obtain the average angle at which the sample would slip. The static's calculations were run to see what the static coefficient of friction would be to have the friction forces overcome at the specified angles. A summary of the results can be seen below in Table II.

**Table II. Measured Coefficients of Friction**

| Polyurethane Sample | Average Angle (deg) | Coefficient of Friction |
|---|---|---|
| VytaFlex 20 | 48 | 1.125 |
| VytaFlex 40 | 41 | 0.876 |
| VytaFlex 60 | 32 | 0.634 |

As seen from the table, the smaller the shore hardness, the higher the average angle until slippage and the higher the coefficient of friction. The results of the tests seem realistic because a lower shore hardness corresponds to a softer material, which we anticipated to have a higher coefficient of friction. The VytaFlex 60 polyurethane sample was closest to our engineering specifications. That being said, we would still like to test each sample to see if Dana prefers a softer or harder polyurethane.

## FEA Analysis Results:

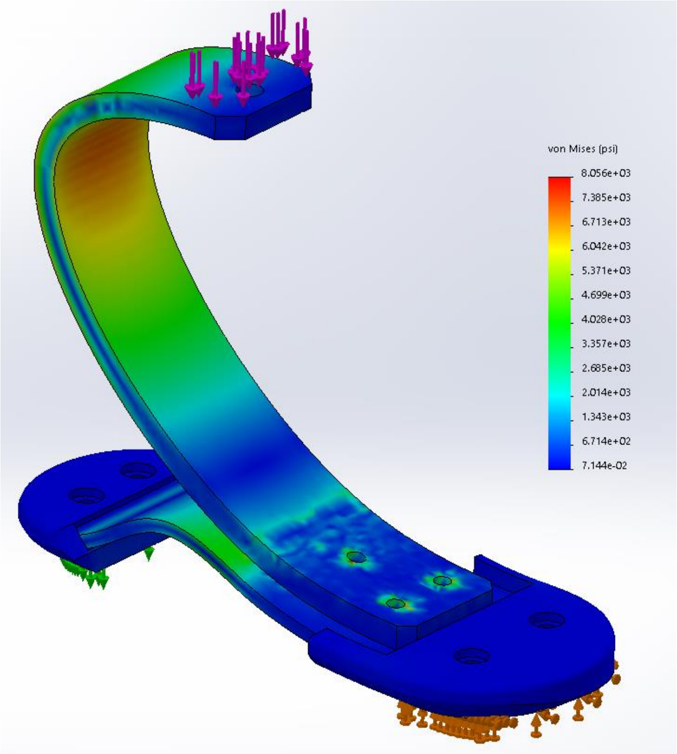


**Figure 15. FEA for stresses on Surf Foot with 100 lbs applied**

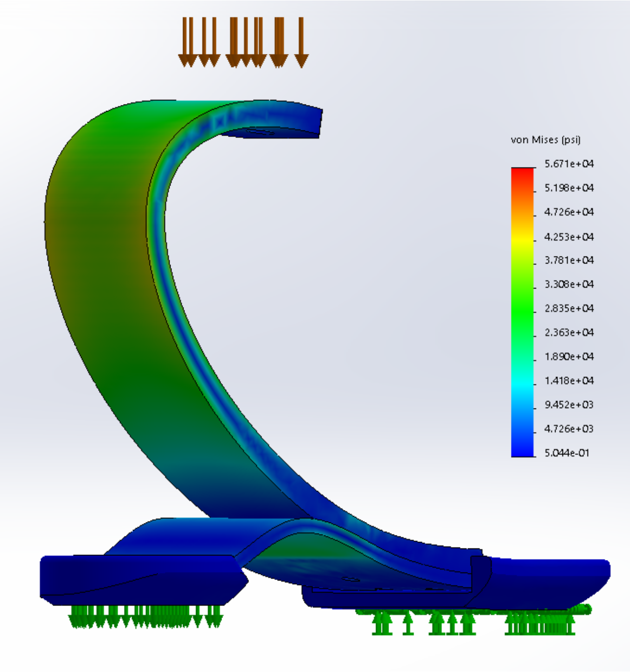


**Figure 16. FEA stresses on Surf Foot with 600 lbs applied**

FEA was performed on the prosthetic to find the maximum stresses and verify that the proposed design would be able to support Dana’s weight. The foot was constrained by being fixed at the toe-side and having a roller at the heel-side, and it was modeled as bonded. Maximum stresses are indicated by red and minimum stresses are indicated by blue. As you can see in Figures 15 and 16, maximum stresses occur at the furthest edge of the applied force, on the inside curve of the pylon, and where the binding barrels hold the foot and pylon together. Where these max stresses occur make sense due to a bending moment and the stresses at the holes.

Figure 15 shows the stresses found with 100 pounds applied where the pylon connects to the pyramid adapter. Since he weighs about 200 pounds, we halved that weight because he has two legs, and this trial simulates Dana standing as he normally would on his surfboard. The maximum stress is 8.06 ksi, which is well below the allowable stress of 500 ksi.

Figure 16 shows the stresses found with 600 pounds applied where the pylon connects to the pyramid adapter. This is three times Dana's weight and demonstrates that the prosthetic will not break from him walking or when applying a larger force to stand and catch a wave with a factor of safety of three. When standing up he will have more of his weight on the prosthetic, but we don’t anticipate this force getting anywhere near 600 pounds. In this model, the maximum stress is 56.7 ksi, once again well below the allowable stress.

As mentioned when discussing material selection, carbon fiber is resistant to fatigue, and the foot is never expected to be put under a load over an extended period of time such that creep may become an issue.  Therefore, we are confident the foot will be able to support Dana’s weight.

Figure 17 shows FEA performed on the surf foot to find the maximum deflection with 100 pounds applied. The same parameters that were applied to find maximum stresses were applied to find maximum deflection. There was a maximum deflection of 0.10 inches at the point of the applied load. This is good because Dana likes a bit of flexion in his foot while he is surfing.

Deflection with 600 pounds of applied force was also found. For this case there was a maximum deflection of 0.71 inches. We are unsure if the epoxy would hold after being strained that much, so it is absolutely vital to do testing before giving this prosthetic to Dana. For this image (figure 37) and further analysis, please refer to Appendix F.

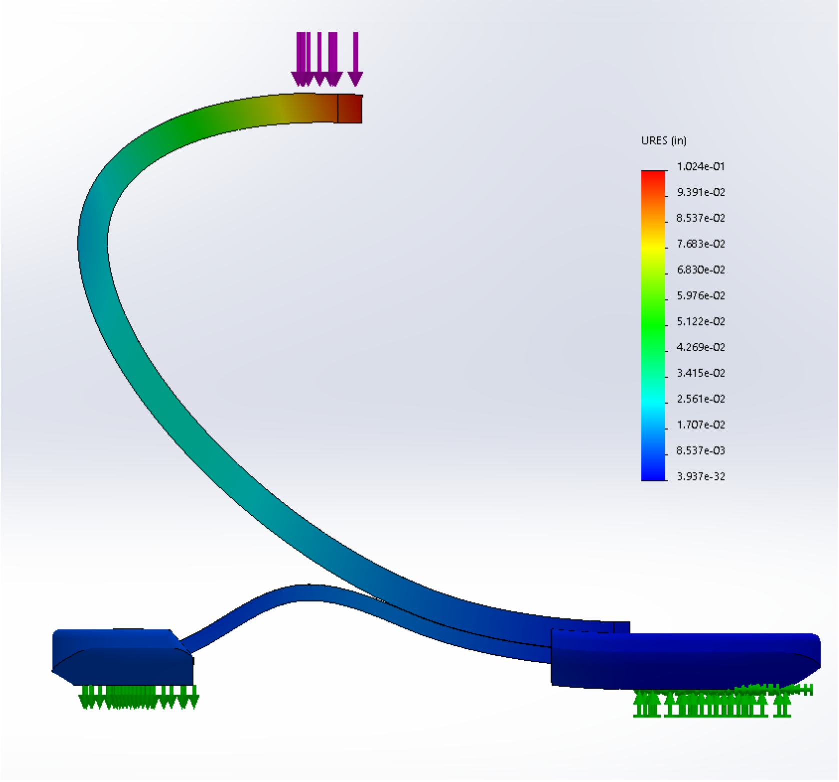


**Figure 17: FEA of deflection on Surf Foot with 100 lbs applied**

## Cost Breakdown:

Table III shows the cost breakdown for the project. Note the tax and shipping are estimates based on the total unit costs. The carbon fiber cloth will be donated to our team from Dr. Elghandour, and the 3D parts we need can be printed for free on campus through the QL+ Lab or Innovation Sandbox. Since campus has been shut down, our sponsor has connected us with Mark Oppenheimer who has been 3D printing the parts we needed throughout spring quarter. There may be a slight increase in total cost if Dana is not satisfied with one of the initial polyurethane samples we chose for the foot sleeve and requests that we order another shore hardness. However, by no means should we exceed our $1,000 dollar budget.

**Table III. Breakdown of Total Project Funds**

| **Breakdown of Total Project Funds** | | | |
|---|---|---|---|
| **Item Description** | **Source** | **Unit Cost** | **Total Cost** |
| Carbon Fiber Cloth | Dr. Elghandour | $0.00 | $0.00 |
| Carbon Fiber Epoxy/Hardener | Amazon | $74.95 | $74.95 |
| 3D Printed Molds | QL + Lab | $0.00 | $0.00 |
| VytaFlex 60A (2) | Smooth-On | $27.78 | $55.56 |
| VytaFlex 40A | Smooth-On | $27.78 | $27.78 |
| VytaFlex 20A | Smooth-On | $27.78 | $27.78 |
| Universal Mold Release | Smooth-On | $14.36 | $14.36 |
| Titanium Foot Pyramid Adapter | O&P Edge | $100.00 | $100.00 |
| Drill | Home Depot | $48.88 | $48.88 |
| Drill Bit (½”) | Home Depot | $3.97 | $3.97 |
| Mixing Stick | Home Depot | $0.98 | $0.98 |
| X-acto Knife | Home Depot | $3.97 | $3.97 |
| Spring Clamp (4) | Home Depot | $0.99 | $3.96 |
| Trigger Clamp (2) | Home Depot | $5.97 | $11.94 |
| Tax Estimate | | $30.00 | $30.00 |
| Total Shipping Estimate | | $100.00 | $100.00 |
| **TOTAL:** | | | **$504.13** |

## Safety Considerations:

As indicated by the name, this foot is designed specifically for surfing. Furthermore, it is designed specifically for Dana Cummings. It is not recommended for others to use this foot since it was designed specifically for Dana. It is also not suggested to walk with this foot except for going to and from the car while surfing, as walking on this foot for a long time can cause excess wear on the rubber pieces and could potentially damage them.

## Maintenance and Repair Consideration:

The main maintenance consideration is to wash the foot off with freshwater and then dry it after each use. Removing the salt, sand, and other metal oxides from the foot will minimize corrosion and extend the life of the foot.

## Product Realization

Due to the shut down of campus, our original manufacturing plan was unable to be completed. Our sponsor initially asked us to look into outsourcing the carbon fiber parts, but after hearing back from a few companies that they couldn’t take on our project or the completion date would be a few weeks past the end of the quarter, we were instructed to get the project as far along as possible before it was passed on to another team. Depending on how the COVID-19 situation develops, team member Sabrina Nelson can continue the project over the summer using on campus resources, or it can be pitched to the QL+ Student Association to be completed as a Quarterly Design Project in the Fall. To help ease the transition of this project to a new team, we have created a detailed manufacturing plan, which is shown in Appendix H.

Aside from adapters and fasteners, our team originally planned to manufacture each component of the prosthetic using resources on campus. The foot and pylon will both be made out of carbon fiber, which would have been available to us through the on campus Composites Lab. We were able to get all molds printed in the QL+ Lab before it closed, but the pylon mold was not high enough quality. Thanks to Mark Oppenheimer, we were able to get a higher resolution pylon mold printed that had more support and could withstand the forces put on it when the vacuum system is applied to it while the carbon fiber dries. A model of the mold for the foot is pictured in Figure 18 and detailed drawings for all molds are visible in Appendix C. Furthermore, images of each 3D printed mold are available in Appendix J. The next team to continue this project can use these foot and pylon molds to lay the carbon fiber using the epoxy and hardener shown in Appendix E, breather film and release film preventing adhesion to the molds and ensuring a thorough epoxy coating, and a vacuum system to create a constant pressure on the mold while the carbon fiber cures. This process will not require the carbon fiber to be cured in an oven because it will not be using pre-impregnated carbon fiber, based on advice given to us by Dr. Elghandour. The next team will have to use a tile saw with a large enough blade to cut the carbon pieces to shape, first cutting it into a rectangle to size. The manufacturing drawings (Appendix C) show the necessary chamfers to give the foot a rounder shape and the pylon chamfers. Standard sized drill bits will be used to drill the holes in the carbon fiber foot and pylon, taking special care to ensure the connecting holes align. After cutting, the carbon fiber has to be post-processed with a sealing coat of epoxy to ensure the fibers don’t delaminate.

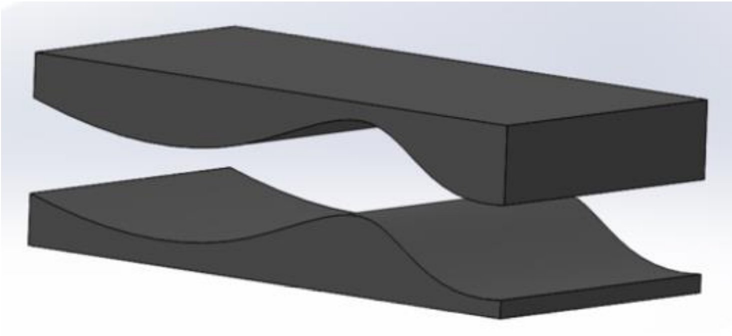


**Figure 18. Solid model of mold for foot component**

The rubber foot sleeve molds are designed to disassemble in order to easily remove the parts. The rubber components should not need to be drilled for through holes because the counterbored holes are incorporated into the molds. Any post-processing to the rubber components will also be necessary once they have cured.

Although campus facilities were shut down, after some discussion with QL+ the beginning of spring quarter we decided we would still try to manufacture the rubber components of the foot. Vanessa, the QL+ coordinator, was able to get us the supplies we had left on campus and we put together a new list of materials we'd need to manufacture.  The images below show part of the manufacturing process and our final results.

Refer to Appendix G for results and issues from previous pours and refer to Appendix J for images of the 3D printed components for the rubber molds.

**Figure 19. Set up of heel-side rubber mold before pouring liquid urethane**

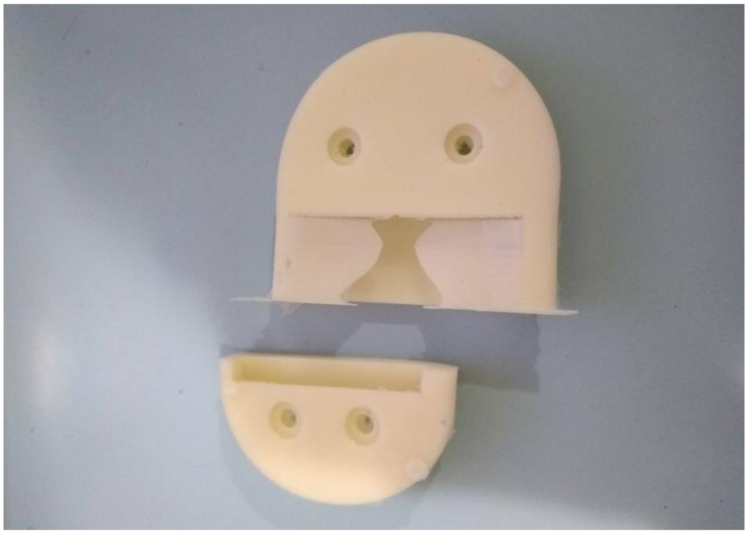


**Figure 20. Final rubber components prior to post-processing**

## Design Verification

Once the prosthetic is manufactured and assembled, it will need to go through a series of tests to make sure it satisfies our engineering specifications. The first of these tests will be a compression test in which it is loaded with 600 pounds to ensure that it can withstand three times the expected load. This test can be completed on campus using the compression testing machine in the Composites Lab. The prosthetic will also need to pass a submersion test to confirm that it does not accumulate any water during use because Dana will be submerging it multiple times per use. To do this, it will need to be weighed, dunked in a large tub of water, and weighed again. Lastly a drag test will need to be performed. In this test, a spring scale will be attached to the top of the prosthetic and used to measure the drag force created as it's pulled through the water. This is necessary because Dana's feet hang off the board into the water when he's on a shortboard. A number of measurement inspections will also need to be completed on the completed prosthetic, which are listed in Table IV, to ensure that it meets our engineering requirements. We have created a more detailed test plan, available in Appendix I, to guide the next team when they reach this point.

**Table IV. Tests and Inspections to be Completed on Assembled Prosthetic**

| Test Description | Specification | Process |
|---|---|---|
| Compression Test | 600 lbs (3x expected loading) | Test |
| Submersion Test | ≤ 0.1 lb | Test |
| Drag Test | $\leq 2\ \mathrm{lb}_f$ | Test |
| Height | 7.500 in | Inspection |
| Weight | 3.0 lbs | Inspection |
| Length of Foot | 9.00 in | Inspection |
| Surface Area of Foot | $31.50\ \mathrm{in}^2$ | Inspection |

## Conclusions and Recommendations

To summarize, the goal of this project was to design, manufacture, and test a non-slip surfing prosthetic for former Marine and transtibial left leg amputee Dana Cummings. Our project, named Surf Foot, was sponsored by the QL+ organization. Over the course of three quarters, our team carefully designed a prosthetic leg to meet the customer requirements and design specifications established from meetings with Dana in addition to the basic principles of engineering and biomechanics.

Our final design consisted of five key components: two pieces of carbon fiber, two rubber components, and an adapter. The rubber components were the key aspect of our design. Made from polyurethane, these components were implemented to improve the coefficient of friction and region of contact between Dana's prosthetic and surfboard in order to minimize slippage. The two carbon fiber pieces together served as the foot and pylon for the prosthetic, offering a nice balance between strength and elasticity that would allow Dana to hold a stable stance while surfing. The components would then be assembled using the specified binding barrels obtained from McMaster-Carr. Lastly, the adapter allows the prosthetic to attach to the socket on Dana's leg.

Unfortunately, we were unable to complete the manufacturing of the prosthetic due to the closure of on-campus facilities that resulted from the COVID-19 pandemic. However, we created a list of in-depth instructions concerning the manufacturing processes of the prosthetic so that a future QL+ team could complete the project once campus reopens. The manufacturing instructions include plans to build the carbon fiber components using materials and equipment that can be found in the Composites Lab on campus as well as SolidWorks models of the 3D printed molds that will be used to produce the polyurethane rubber components. In order to validate the safety and efficacy of our design, our team performed FEA using computer models. Further instructions regarding the physical testing of the final prototype is also provided for the future team to complete.

One recommendation our team has is to incorporate treads into the 3D printed molds for the rubber components. This would help improve the grip of the prosthetic leg upon the surface of the surfboard. Furthermore, we recommend that a new testing protocol be made to evaluate how quickly the rubber components degrade with use so that Dana can effectively approximate when he must replace them.

## Acknowledgements

Thank you to Jon Monett and the rest of the QL+ organization for sponsoring and supporting this project.

Thank you Vanessa Salas for being our point of contact between QL+ and Dana and helping us coordinate presentations and get materials.

Thank you Dana Cummings for bringing us this challenge and sharing ideas on how to make a prosthetic leg specifically for surfing.  When it’s complete we hope it serves you well.

Thank you to our advisor, Dr. Jim Widmann for helping guide us through this project and keeping us on track throughout the year.

Thank you Dr. Elghandour for getting us access to the Composites Lab on campus and providing us with free carbon fiber.

Thank you Mark Oppenhiemer for printing our 3D molds when we were no longer to use campus facilities.

Thank you Tim Bump for answering all the questions we had about prosthetics and their parts.

## References

[1] “Association of Amputee Surfers.” *AmpSurf*, ampsurf.org/.

[2] Curran, Sarah A, and David K Lyle. “Adaptive Sports Ankle Prosthetics.” *Prosthetics and Orthotics International*, vol. 36, no. 3, 2012, pp. 370–375., doi:10.1177/0309364612453249.

[3] Schvirtz, Erica, et al. “Return to Surfing Using an Adapted Prosthesis: A Case Report.” *Prosthetics and Orthotics International*, vol. 42, no. 4, 2018, pp. 455–459., doi:10.1177/0309364618757785.

[4] Strbac, Matija, and Dejan B. Popovic. “Software Tool for the Prosthetic Foot Modeling and Stiffness Optimization.” *Computational and Mathematical Methods in Medicine*, 2012, doi:10.1155/2012/421796.

[5] Swanson, Caroline, et al. *Surf Leg*. *Surf Leg*.

[6] Ventura, Mark. “Surfwax Friction.” *News 2*, www.waveequation.com/surfwax_friction_data.html.

[7] “Rampro Activ and Swim Ankles.” Kingsley MFG Company: Orthotics &amp; Prosthetics Supplies, www.kingsleymfg.com/KMFGStore/Catalog_Product.asp?dept_id=3E1FE74E-250AFF-4B02-ACC7-521FECEAF42B&amp;product_id=RAM.

[8] *The H2O Collection*, PROTEOR USA, rushfoot.com/prosthetist-solutions/the-h2o-collection/.

# Appendices:

## Appendix A. Comparison of surf waxes

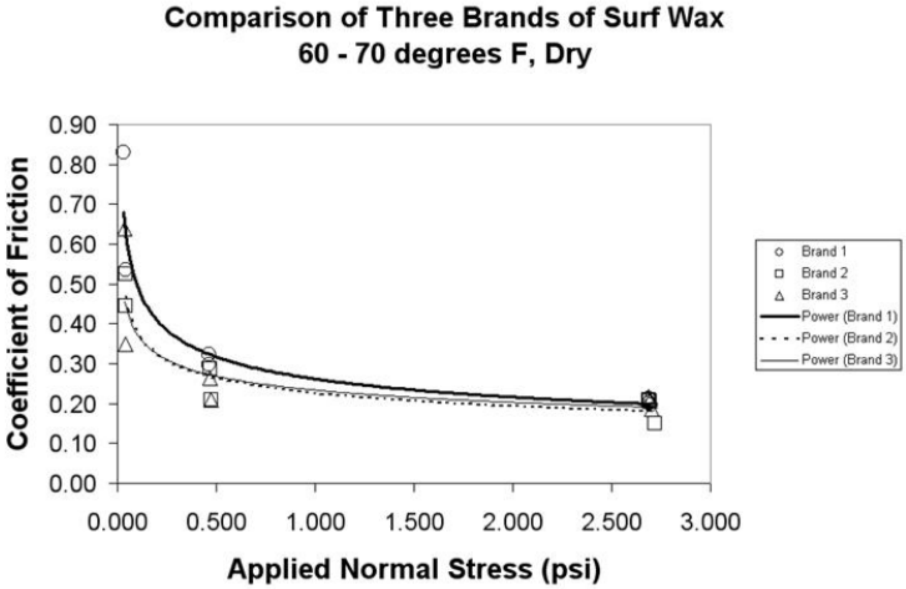
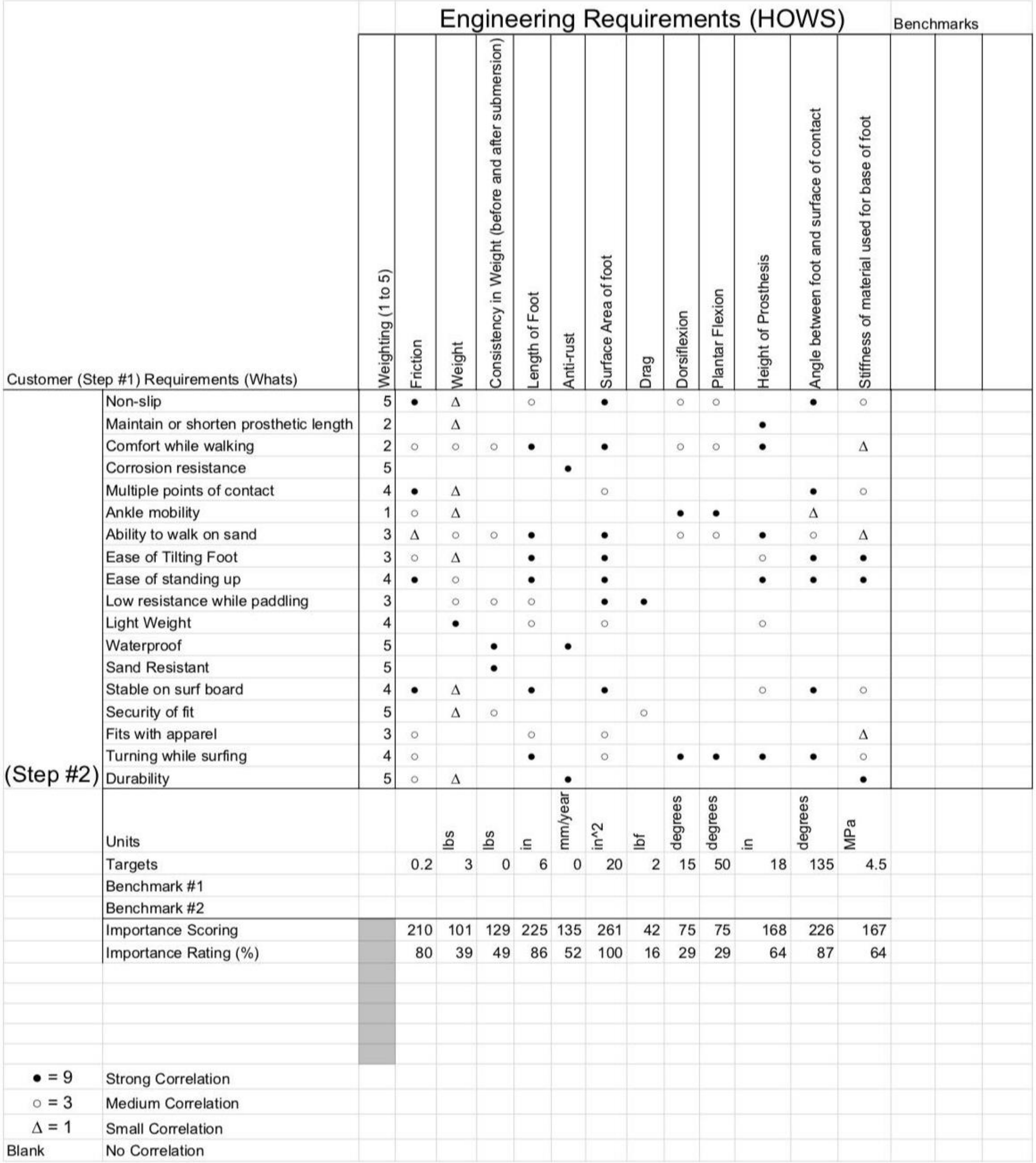


Figure 21. Comparison of three different surf waxes [6]

## Appendix B. QFD and Decision Matrices

### Table V: Quality Function Deployment (QFD)

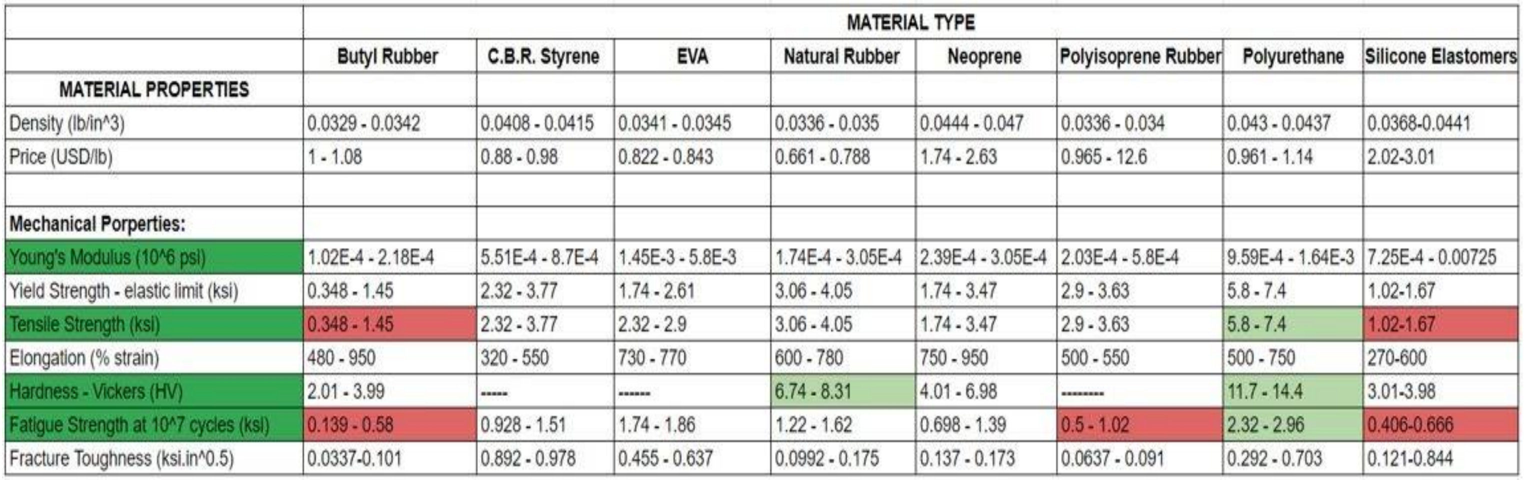


| | | | Engineering Requirements (HOWS) | | | | | | | | | | | | Benchmarks | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Customer (Step #1) Requirements (Whats) | | Weighting (1 to 5) | Friction | Weight | Consistency in Weight (before and after submersion) | Length of Foot | Anti-rust | Surface Area of foot | Drag | Dorsiflexion | Plantar Flexion | Height of Prosthesis | Angle between foot and surface of contact | Stiffness of material used for base of foot | | | |
| | Non-slip | 5 | ● | Δ | | ○ | | ● | | ○ | ○ | | ● | ○ | | | |
| | Maintain or shorten prosthetic length | 2 | | Δ | | | | | | | | ● | | | | | |
| | Comfort while walking | 2 | ○ | ○ | ○ | ● | | ● | | ○ | ○ | ● | | Δ | | | |
| | Corrosion resistance | 5 | | | | | ● | | | | | | | | | | |
| | Multiple points of contact | 4 | ● | Δ | | | | ○ | | | | | ● | ○ | | | |
| | Ankle mobility | 1 | ○ | Δ | | | | | | ● | ● | | Δ | | | | |
| | Ability to walk on sand | 3 | Δ | ○ | ○ | ● | | ● | | ○ | ○ | ● | ○ | Δ | | | |
| | Ease of Tilting Foot | 3 | ○ | Δ | | ● | | ● | | | | ○ | ● | ● | | | |
| | Ease of standing up | 4 | ● | ○ | | ● | | ● | | | | ● | ● | ● | | | |
| | Low resistance while paddling | 3 | | ○ | ○ | ○ | | ● | ● | | | | | | | | |
| | Light Weight | 4 | | ● | | ○ | | ○ | | | | ○ | | | | | |
| | Waterproof | 5 | | | ● | | ● | | | | | | | | | | |
| | Sand Resistant | 5 | | | ● | | | | | | | | | | | | |
| | Stable on surf board | 4 | ● | Δ | | ● | | ● | | | | ○ | ● | ○ | | | |
| | Security of fit | 5 | | Δ | ○ | | | | ○ | | | | | | | | |
| | Fits with apparel | 3 | ○ | | | ○ | | ○ | | | | | | Δ | | | |
| | Turning while surfing | 4 | ○ | | | ● | | ○ | | ● | ● | ● | ● | ○ | | | |
| (Step #2) | Durability | 5 | ○ | Δ | | | ● | | | | | | | ● | | | |
| | Units | | | lbs | lbs | in | mm/year | in^2 | lbf | degrees | degrees | in | degrees | MPa | | | |
| | Targets | | 0.2 | 3 | 0 | 6 | 0 | 20 | 2 | 15 | 50 | 18 | 135 | 4.5 | | | |
| | Benchmark #1 | | | | | | | | | | | | | | | | |
| | Benchmark #2 | | | | | | | | | | | | | | | | |
| | Importance Scoring | | 210 | 101 | 129 | 225 | 135 | 261 | 42 | 75 | 75 | 168 | 226 | 167 | | | |
| | Importance Rating (%) | | 80 | 39 | 49 | 86 | 52 | 100 | 16 | 29 | 29 | 64 | 87 | 64 | | | |
| ● = 9 | Strong Correlation | | | | | | | | | | | | | | | | |
| ○ = 3 | Medium Correlation | | | | | | | | | | | | | | | | |
| Δ = 1 | Small Correlation | | | | | | | | | | | | | | | | |
| Blank | No Correlation | | | | | | | | | | | | | | | | |

## Table VI: Pugh Matrix to compare concepts

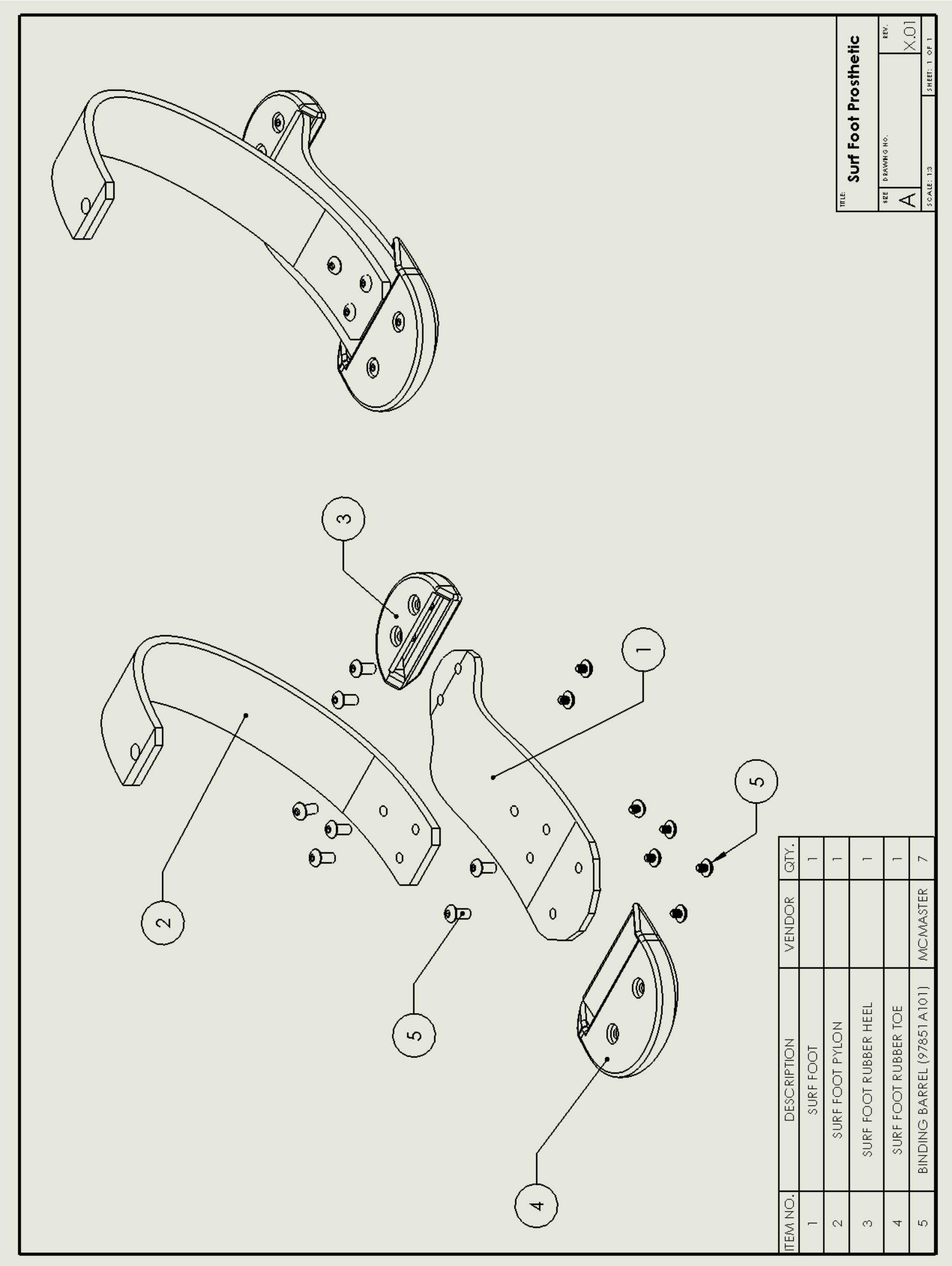
| |  |  |  |  |  |
|---|---|---|---|---|---|
| | Curved Edge | Rush Foot | Flat Edge | Springs | Ankle Adapter |
| Non-slip | S | S | | S | S |
| Comfort while walking | S | + | | + | - |
| Corrosion resistance | S | S | D | - | - |
| Multiple points of contact | + | + | | + | + |
| Ankle mobility | S | + | | + | + |
| Ability to walk on sand | S | S | A | S | - |
| Ease of Tilting Foot | + | S | | + | + |
| Ease of standing up | + | - | | + | + |
| Low resistance while paddling | S | S | T | S | S |
| Light Weight | S | - | | - | - |
| Waterproof | S | S | | - | - |
| Sand Resistant | S | S | U | - | - |
| Stable on surf board | S | + | | S | S |
| Security of fit | S | S | | S | S |
| Fits with apparel | S | S | M | S | S |
| Turning while surfing | + | + | | + | + |
| Durability | S | S | | - | - |
| | | | | | |
| Σ+ | 4 | 5 | | 6 | 5 |
| Σ- | 0 | 2 | | 5 | 7 |
| ΣS | 13 | 10 | | 6 | 5 |

**Table VII: Foot Sleeve Decision Matrix**



| | MATERIAL TYPE | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Butyl Rubber | C.B.R. Styrene | EVA | Natural Rubber | Neoprene | Polyisoprene Rubber | Polyurethane | Silicone Elastomers |
| MATERIAL PROPERTIES | | | | | | | | |
| Density (lb/in^3) | 0.0329 - 0.0342 | 0.0408 - 0.0415 | 0.0341 - 0.0345 | 0.0336 - 0.035 | 0.0444 - 0.047 | 0.0336 - 0.034 | 0.043 - 0.0437 | 0.0368-0.0441 |
| Price (USD/lb) | 1 - 1.08 | 0.88 - 0.98 | 0.822 - 0.843 | 0.661 - 0.788 | 1.74 - 2.63 | 0.965 - 12.6 | 0.961 - 1.14 | 2.02-3.01 |
| | | | | | | | | |
| **Mechanical Porperties:** | | | | | | | | |
| Young's Modulus (10^6 psi) | 1.02E-4 - 2.18E-4 | 5.51E-4 - 8.7E-4 | 1.45E-3 - 5.8E-3 | 1.74E-4 - 3.05E-4 | 2.39E-4 - 3.05E-4 | 2.03E-4 - 5.8E-4 | 9.59E-4 - 1.64E-3 | 7.25E-4 - 0.00725 |
| Yield Strength - elastic limit (ksi) | 0.348 - 1.45 | 2.32 - 3.77 | 1.74 - 2.61 | 3.06 - 4.05 | 1.74 - 3.47 | 2.9 - 3.63 | 5.8 - 7.4 | 1.02-1.67 |
| Tensile Strength (ksi) | 0.348 - 1.45 | 2.32 - 3.77 | 2.32 - 2.9 | 3.06 - 4.05 | 1.74 - 3.47 | 2.9 - 3.63 | 5.8 - 7.4 | 1.02-1.67 |
| Elongation (% strain) | 480 - 950 | 320 - 550 | 730 - 770 | 600 - 780 | 750 - 950 | 500 - 550 | 500 - 750 | 270-600 |
| Hardness - Vickers (HV) | 2.01 - 3.99 | ----- | ------ | 6.74 - 8.31 | 4.01 - 6.98 | -------- | 11.7 - 14.4 | 3.01-3.98 |
| Fatigue Strength at 10^7 cycles (ksi) | 0.139 - 0.58 | 0.928 - 1.51 | 1.74 - 1.86 | 1.22 - 1.62 | 0.698 - 1.39 | 0.5 - 1.02 | 2.32 - 2.96 | 0.406-0.666 |
| Fracture Toughness (ksi.in^0.5) | 0.0337-0.101 | 0.892 - 0.978 | 0.455 - 0.637 | 0.0992 - 0.175 | 0.137 - 0.173 | 0.0637 - 0.091 | 0.292 - 0.703 | 0.121-0.844 |

## Appendix C: Detailed Drawings



| ITEM NO. | DESCRIPTION | VENDOR | QTY. |
|---|---|---|---|
| 1 | SURF FOOT | | 1 |
| 2 | SURF FOOT PYLON | | 1 |
| 3 | SURF FOOT RUBBER HEEL | | 1 |
| 4 | SURF FOOT RUBBER TOE | | 1 |
| 5 | BINDING BARREL (97851A101) | MCMASTER | 7 |

Figure 22. Detailed Drawing of Assembly with Bill of Materials

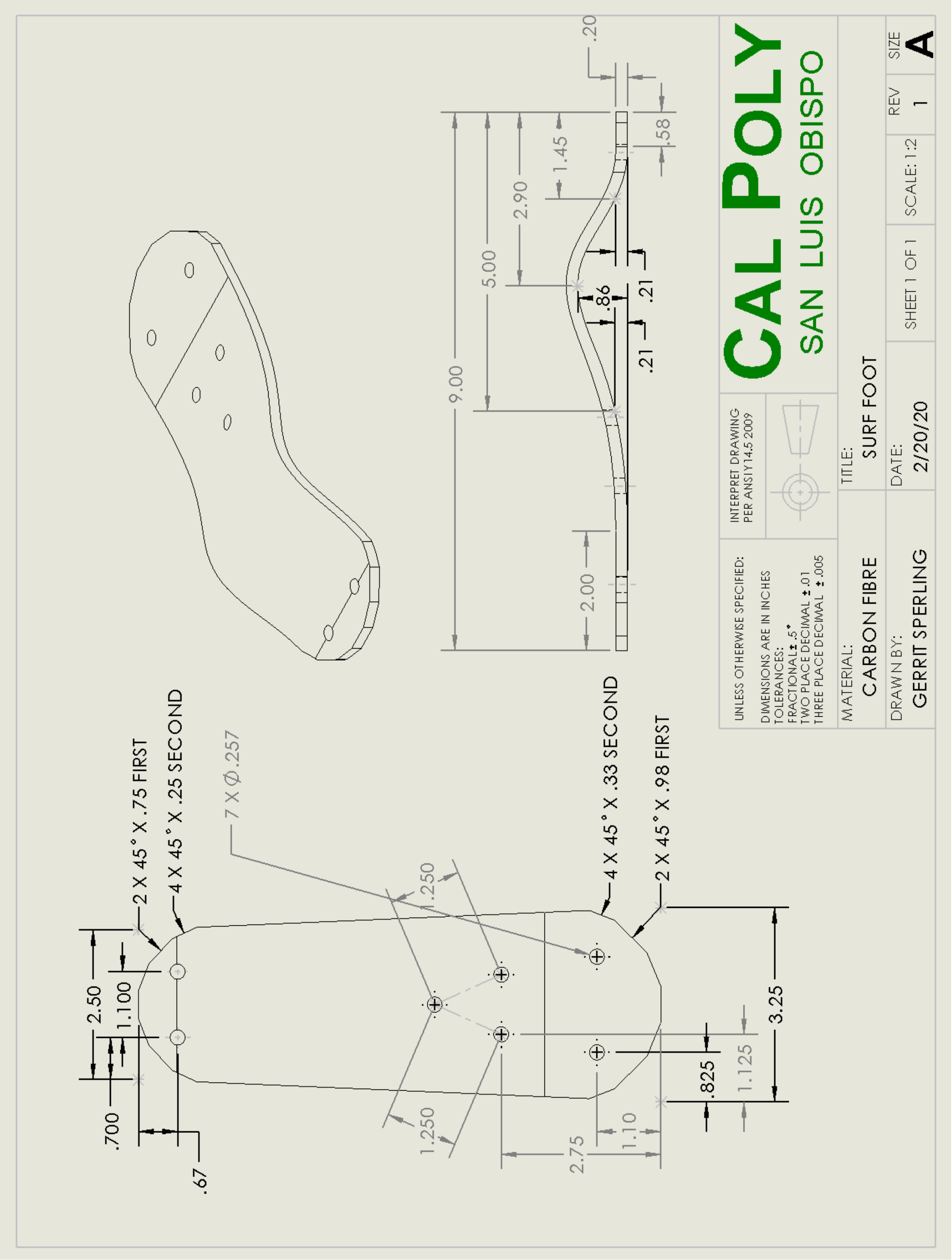


Figure 23. Detailed Drawing of Foot Part

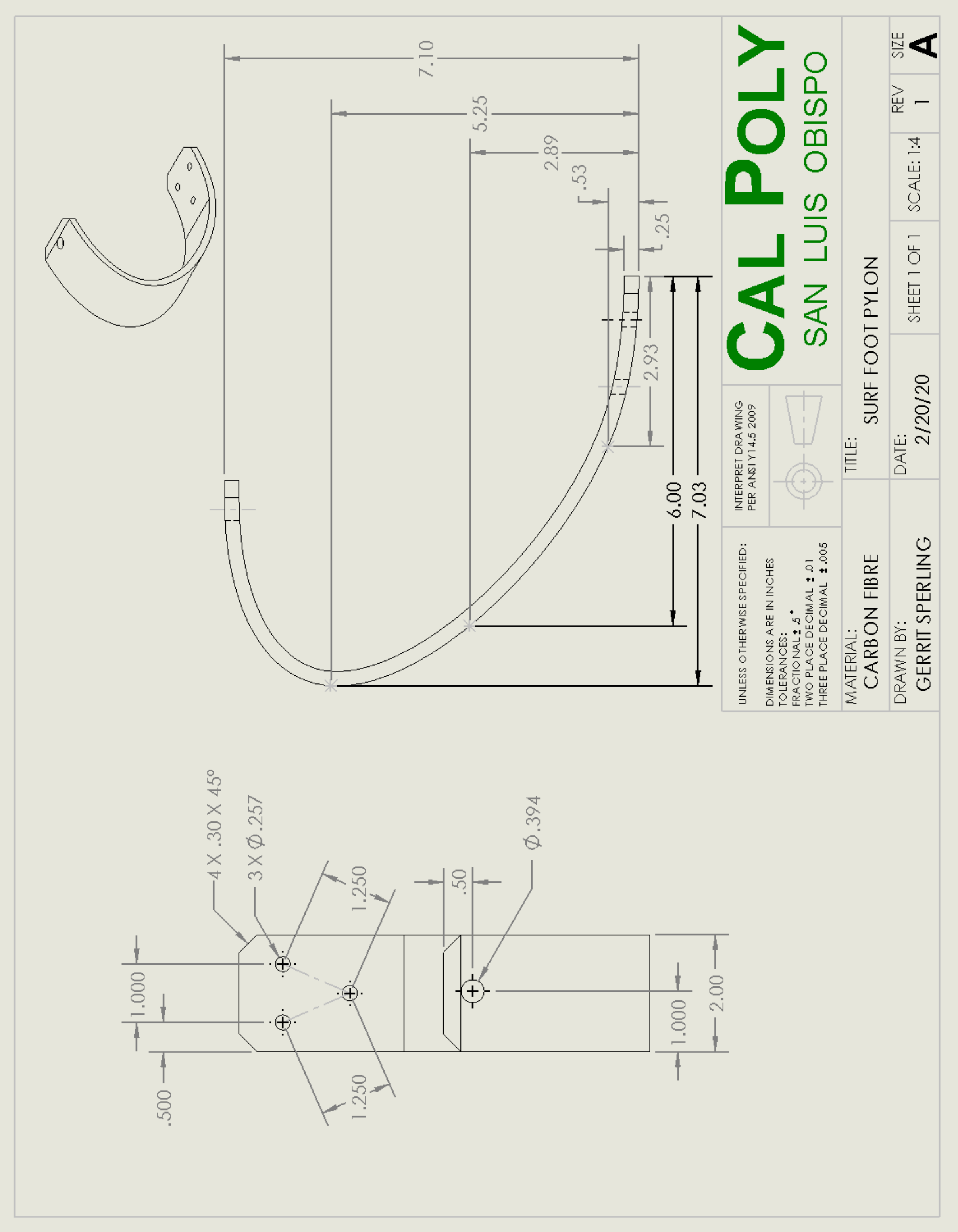


**Figure 24. Detailed Drawing of Pylon Part**

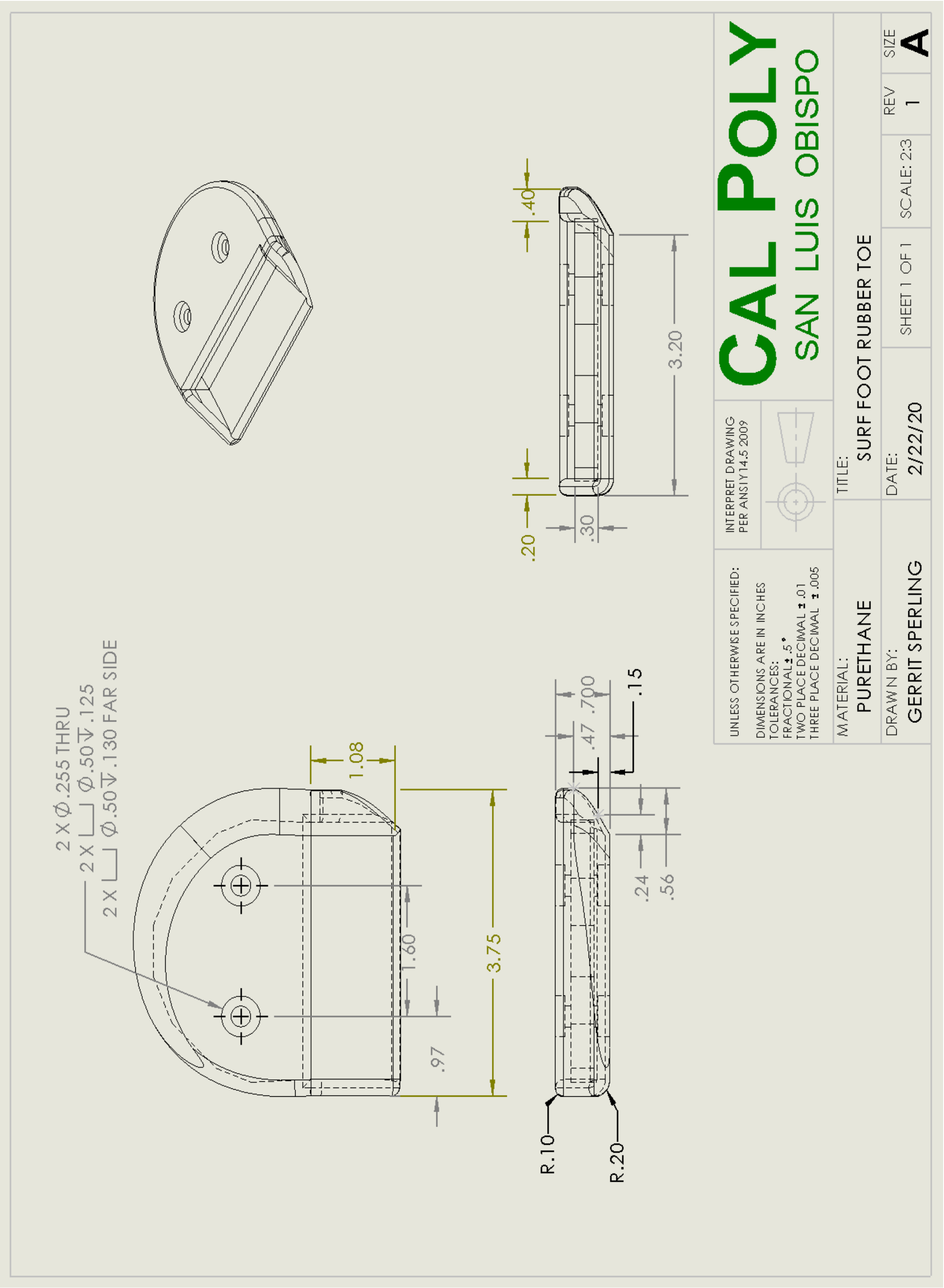


**Figure 25. Detailed Drawing of Rubber Toe Part**

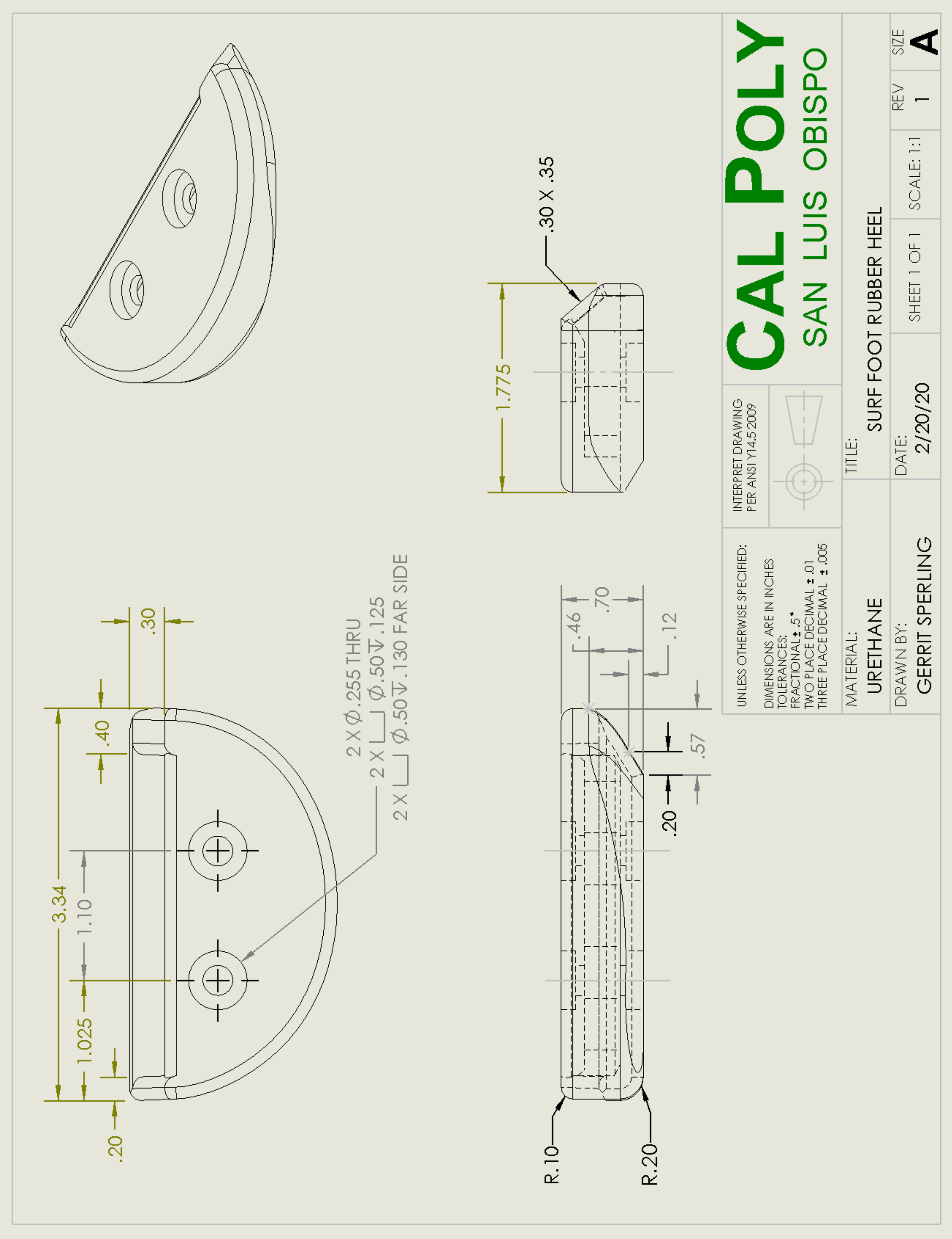


Figure 26. Detailed Drawing of Rubber Heel Part

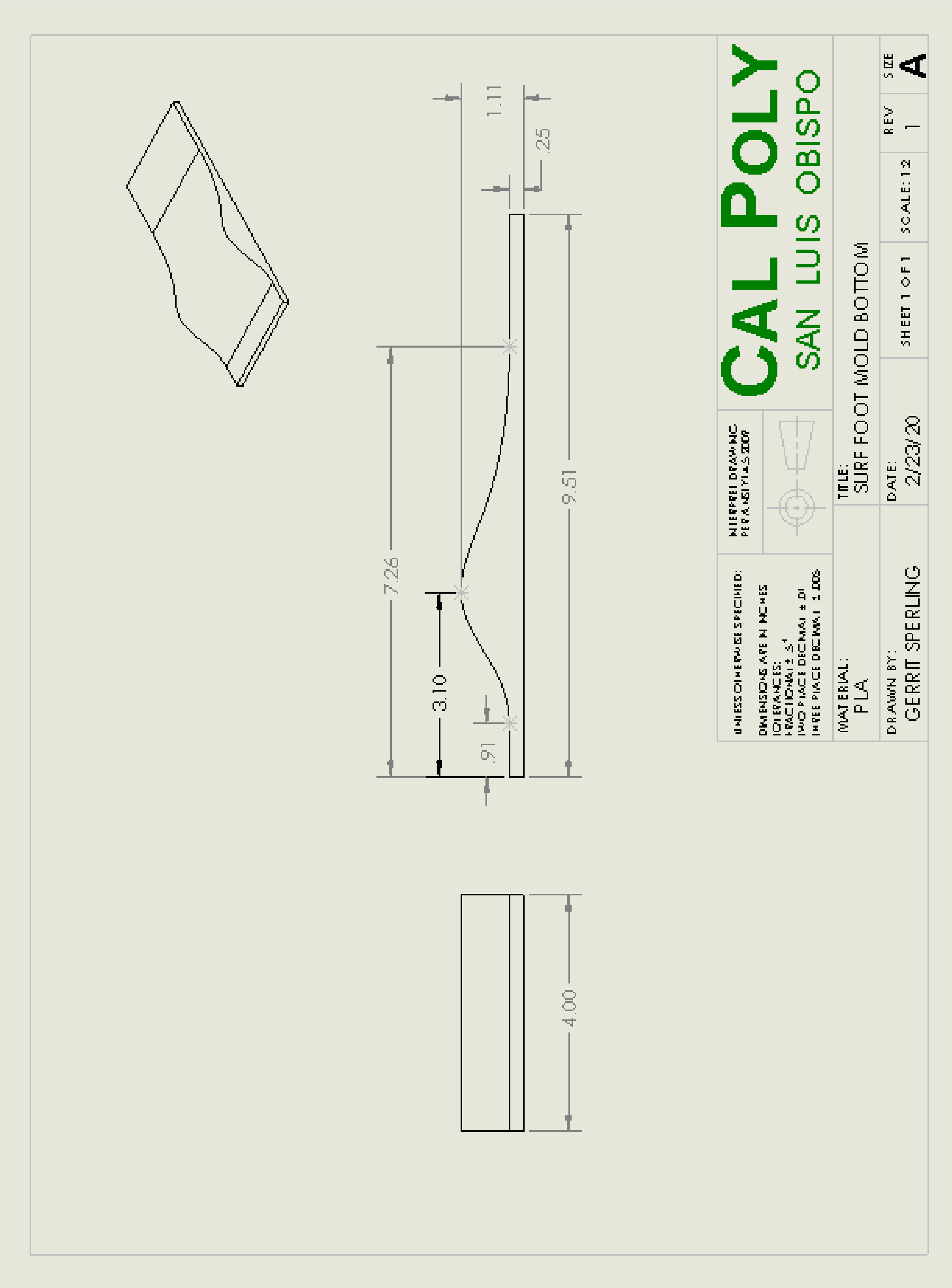


**Figure 27. Detailed Drawing of Bottom Mold for Foot**

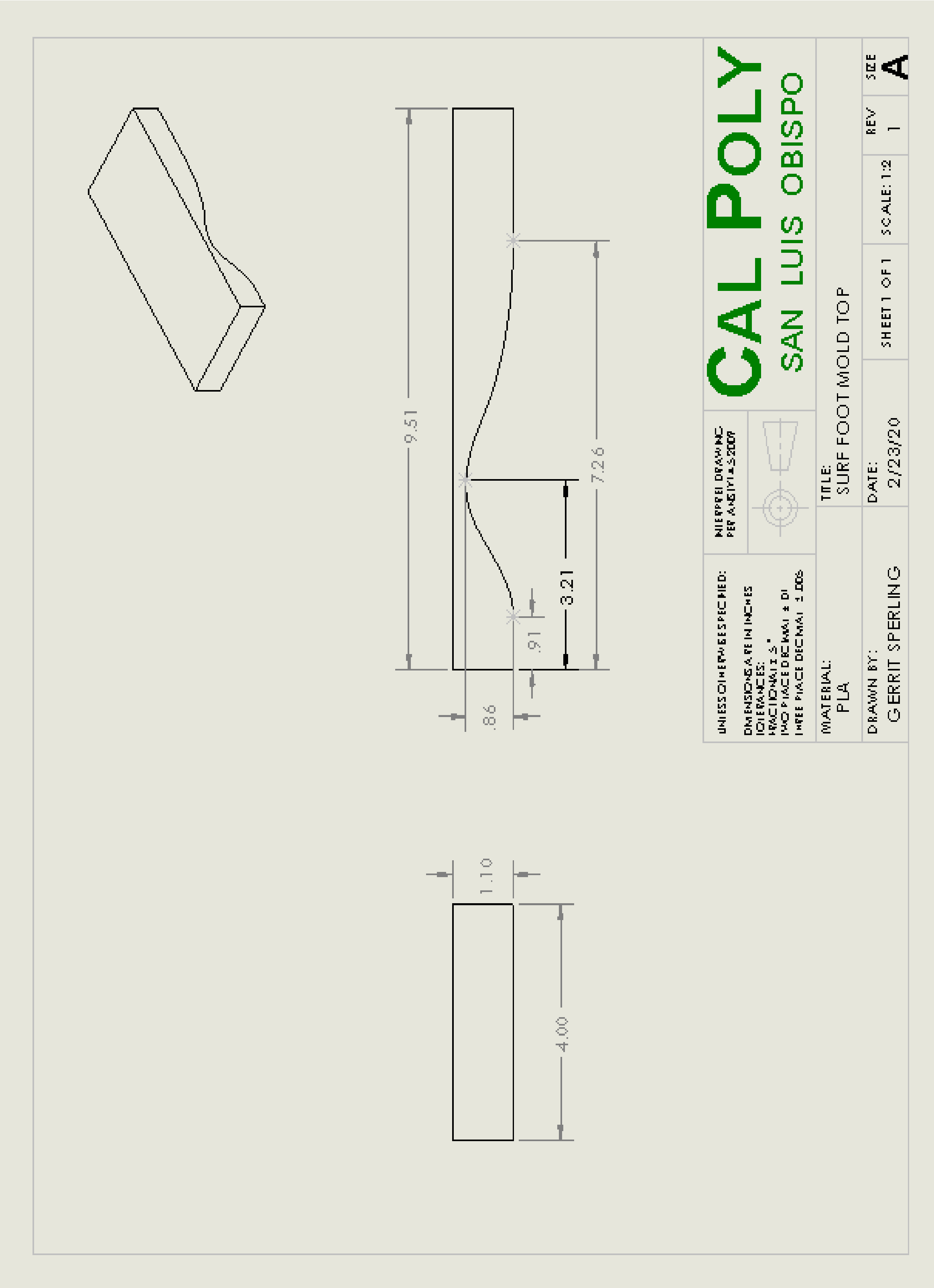


Figure 28. Detailed Drawing of Top Mold for Foot

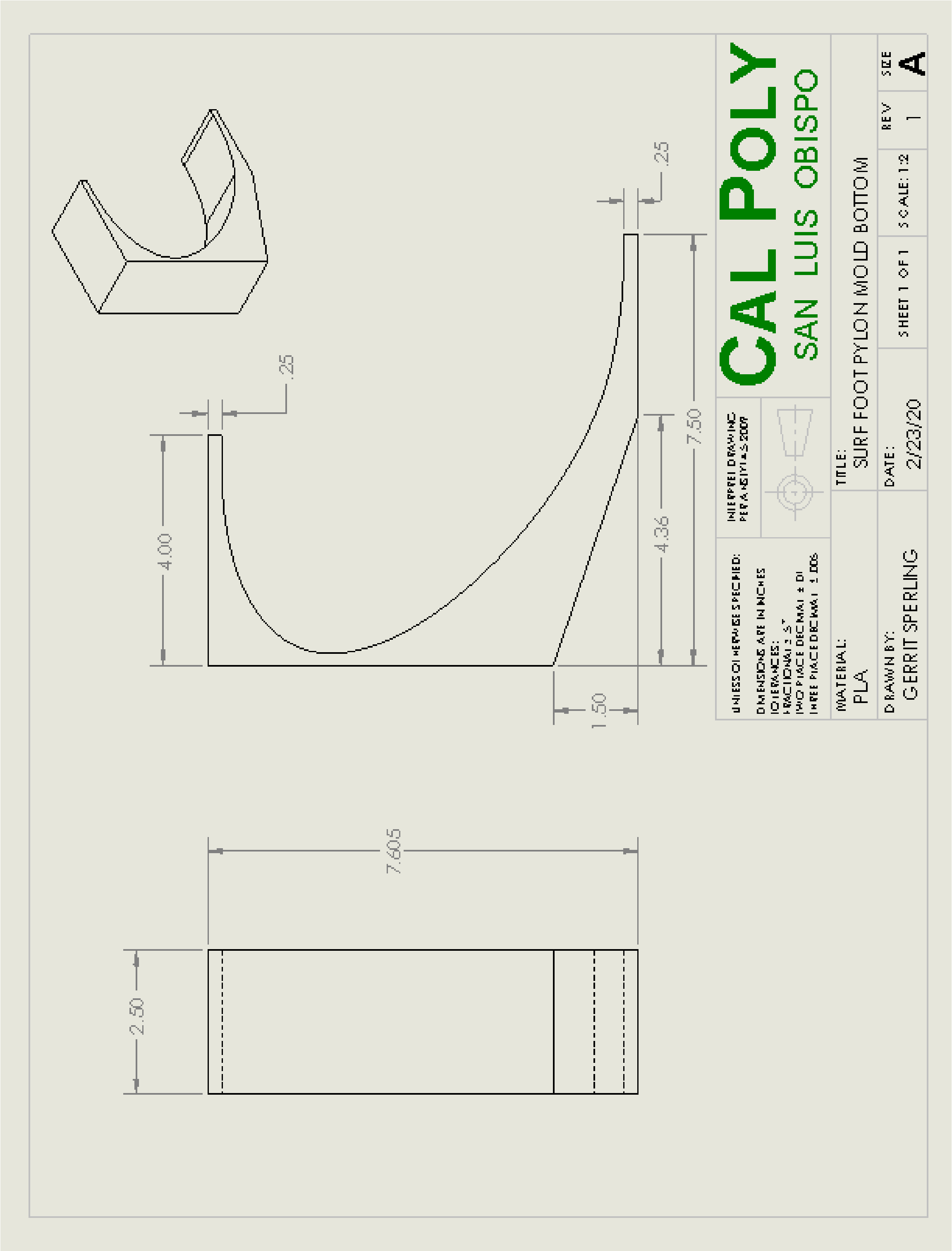


**Figure 29. Detailed Drawing of Outer Mold for Pylon**

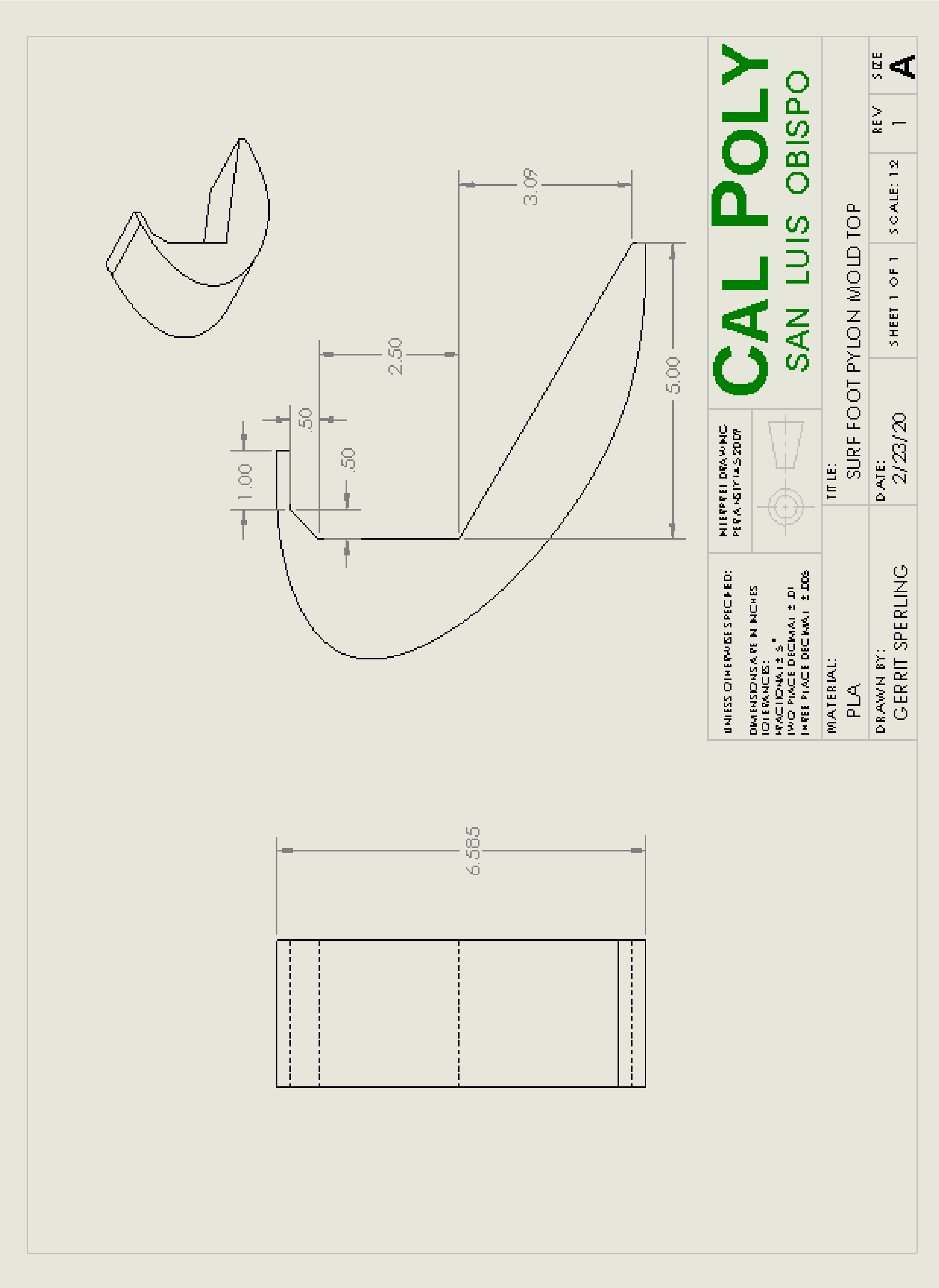


Figure 30. Detailed Drawing of Inner Mold for Pylon

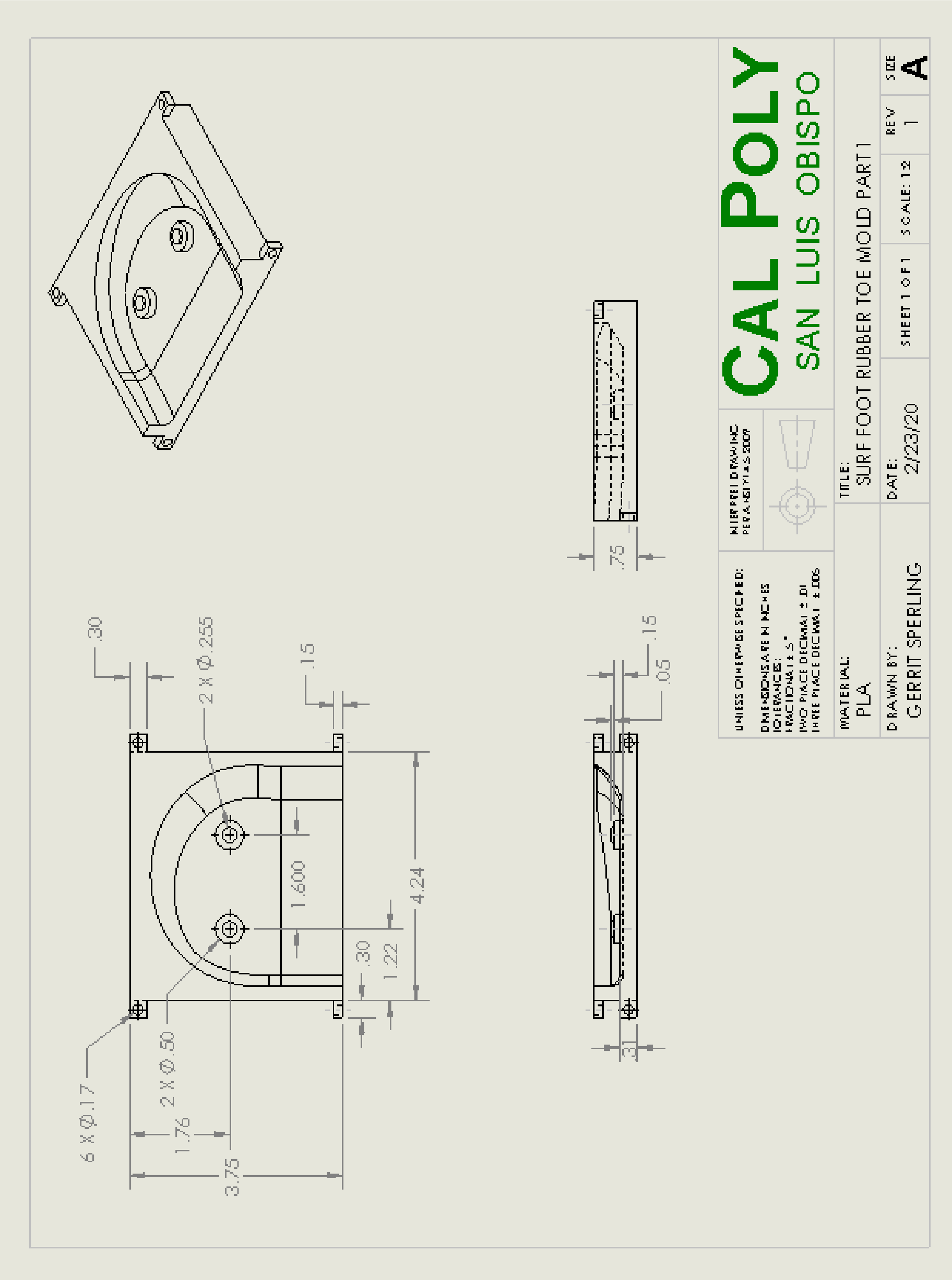


**Figure 31. Detailed Drawing of Bottom Outer Mold for Rubber Toe**

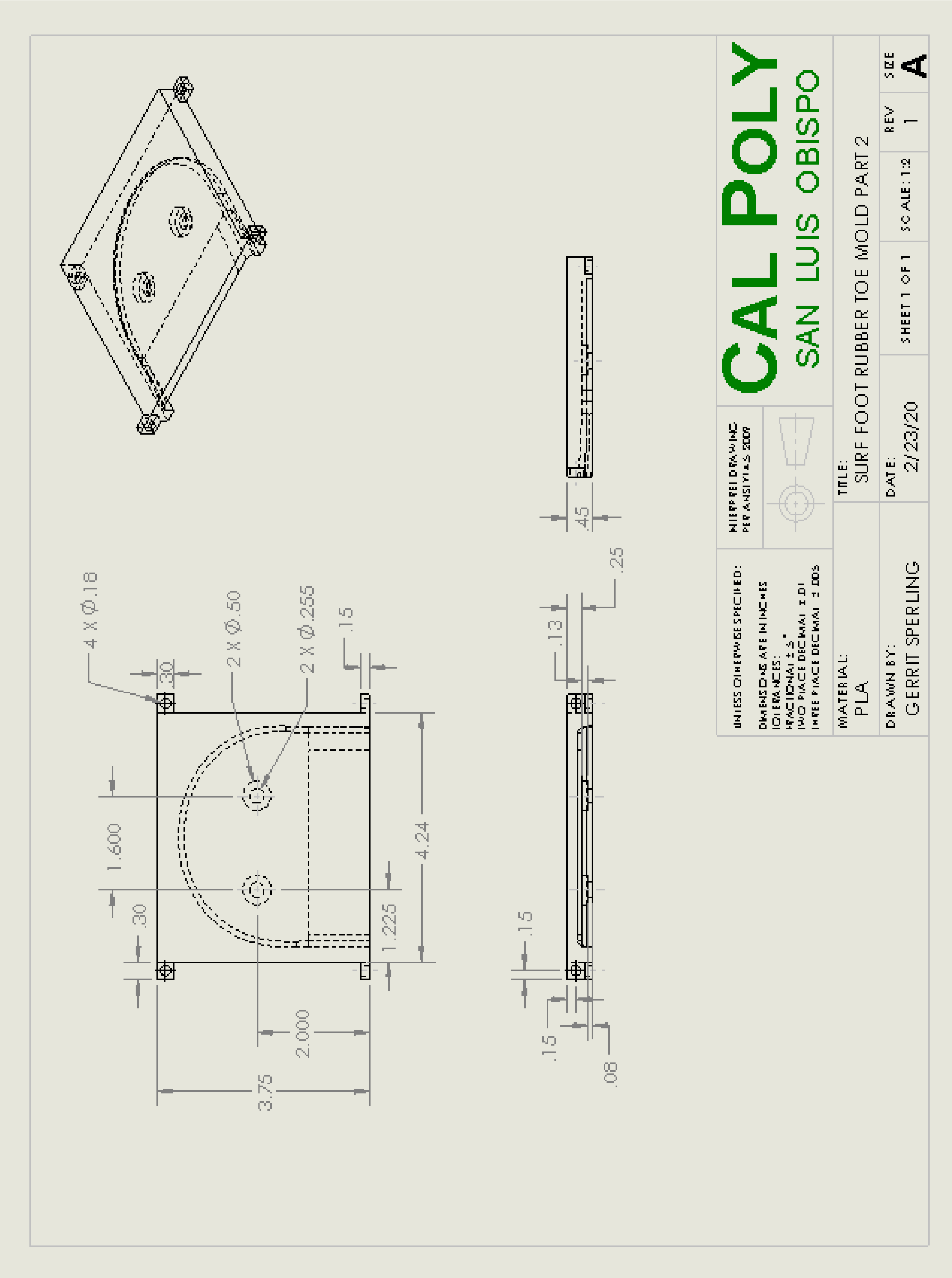


Figure 32. Detailed Drawing of Top Outer Mold for Rubber Toe

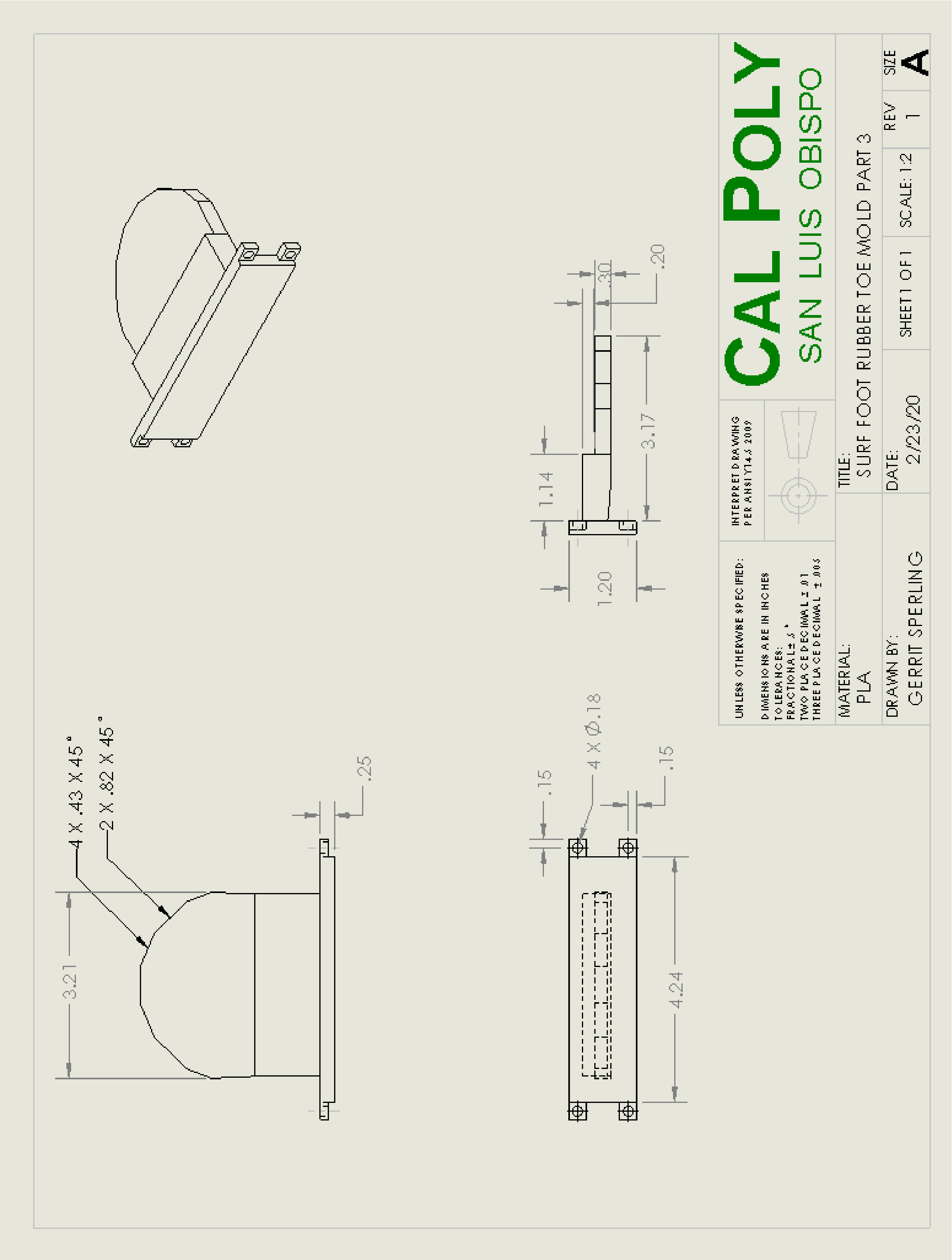


Figure 33. Detailed Drawing of Inner Mold for Rubber Toe

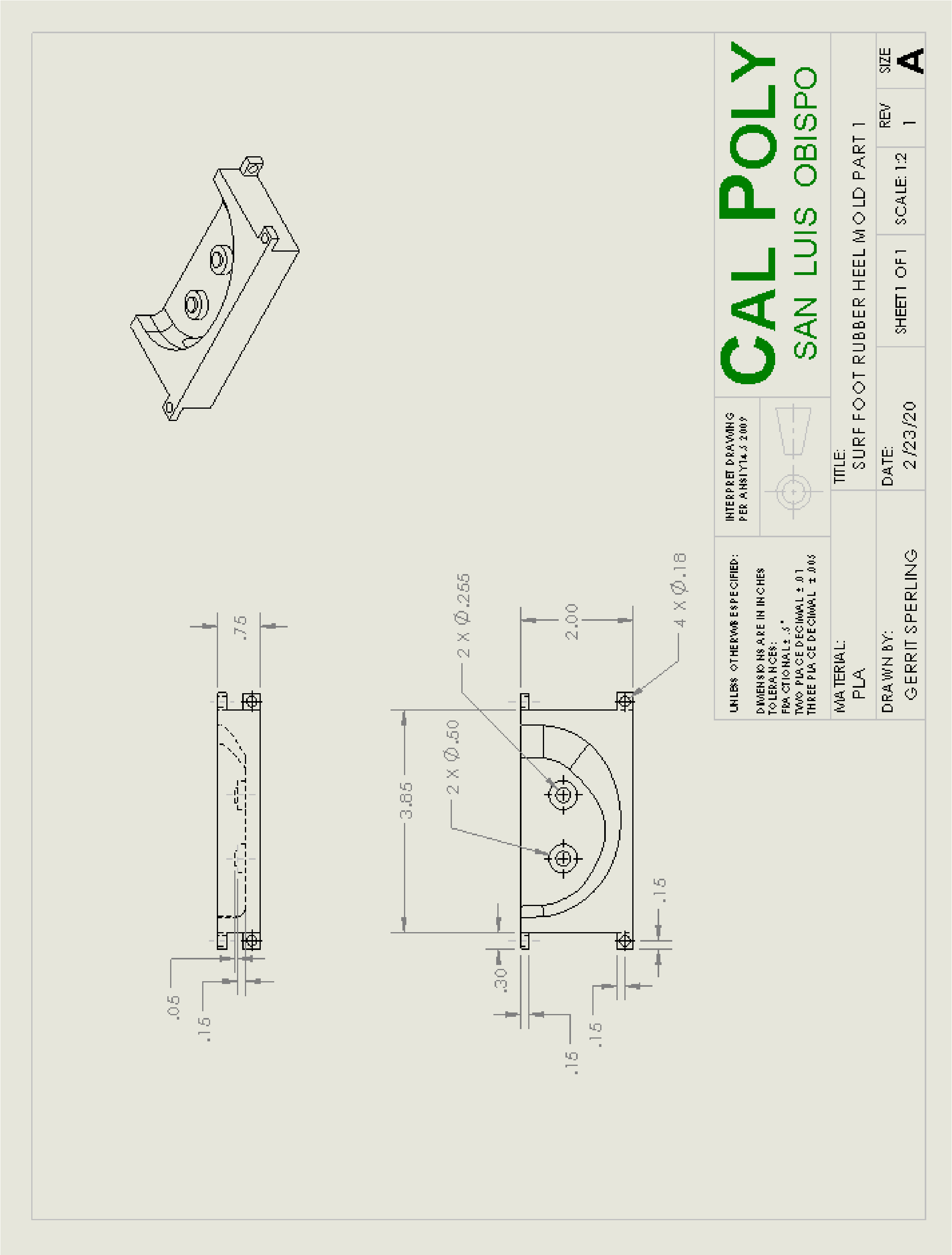
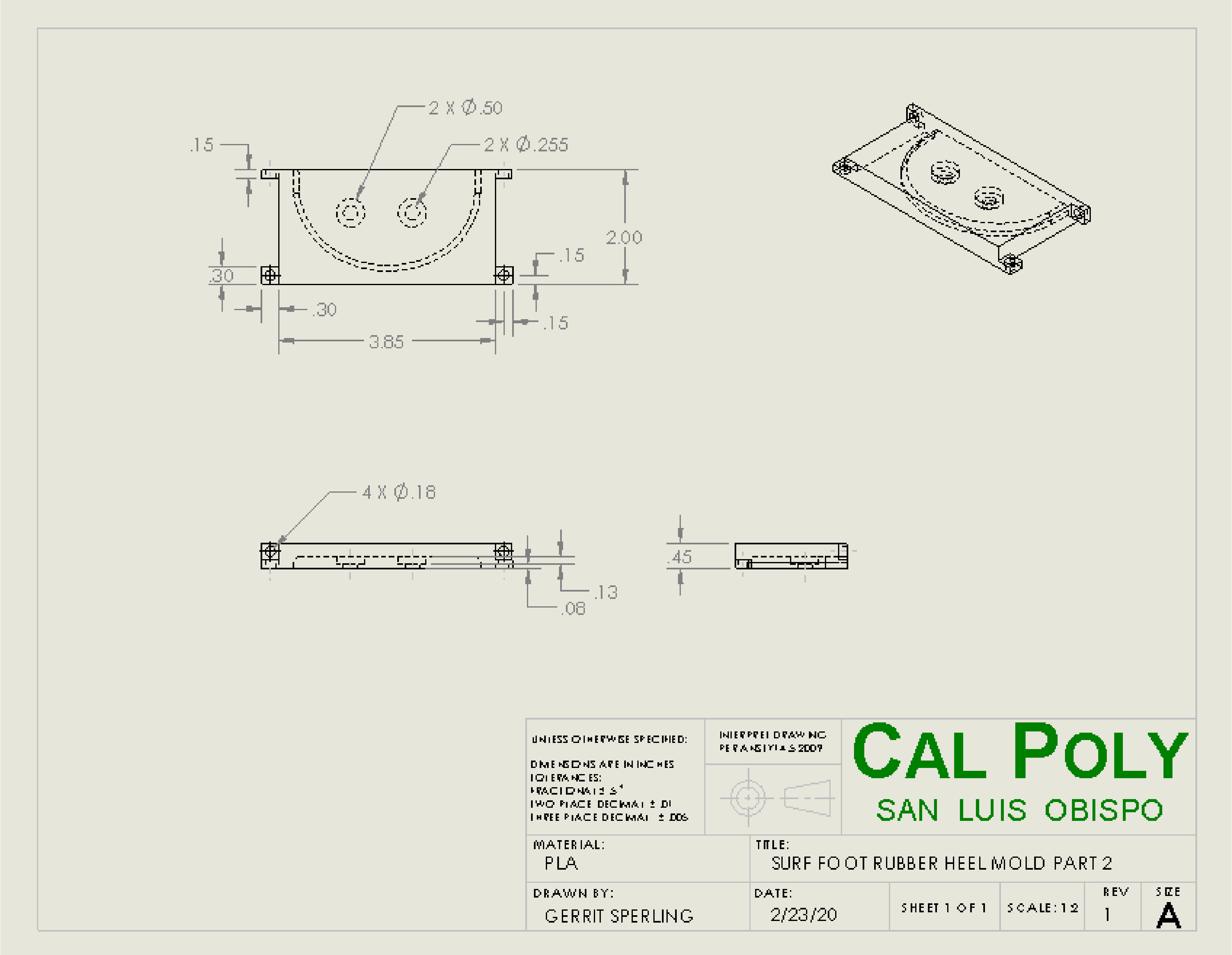


Figure 34. Detailed Drawing of Bottom Outer Mold for Rubber Heel



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING
PER ANSI Y14.5 2009

CAL POLY
SAN LUIS OBISPO

MATERIAL:
PLA

TITLE:
SURF FOOT RUBBER HEEL MOLD PART 2

DRAWN BY:
GERRIT SPERLING

DATE:
2/23/20

SHEET 1 OF 1

SCALE: 1:2

REV
1

SIZE
A

Figure 35. Detailed Drawing of Top Outer Mold for Rubber Heel

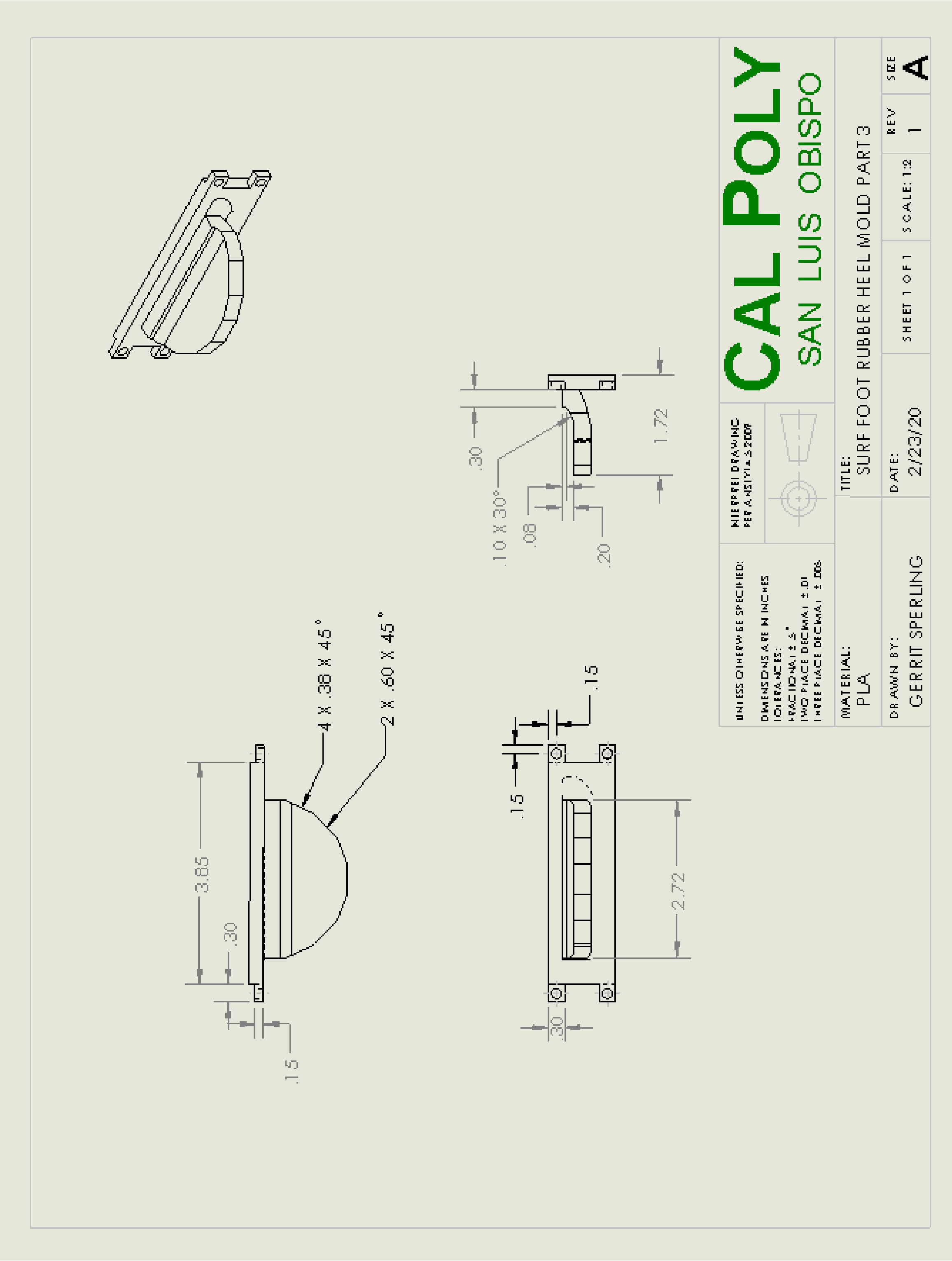


Figure 36. Detailed Drawing of Inner Mold for Rubber Heel

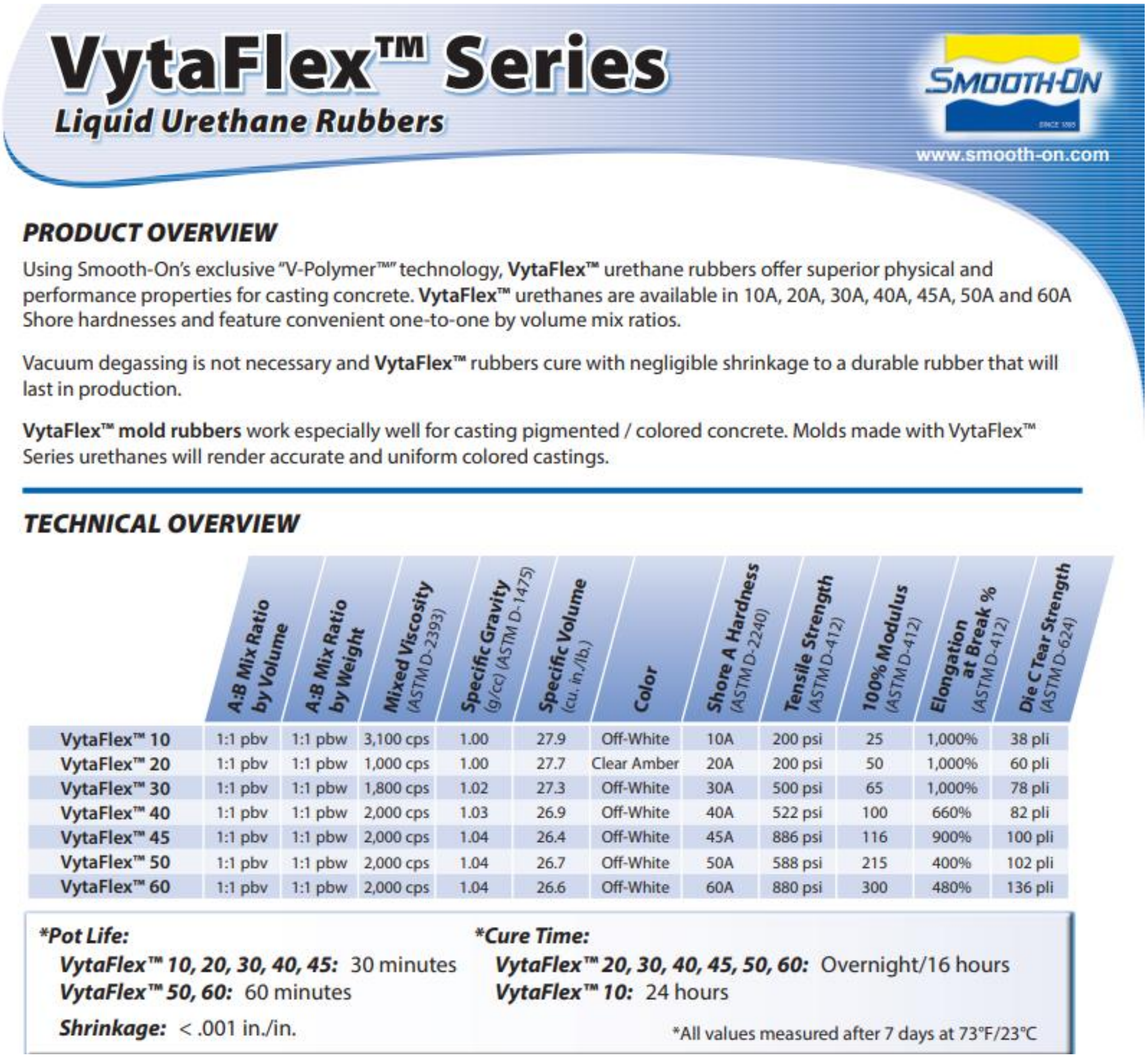
## Appendix D. List of vendors, contact information, and pricing

### Table VIII. Vendor Information

| Item | Source | Contact Information | Price |
|---|---|---|---|
| Carbon Fiber Epoxy/Hardener Kit | Amazon | https://www.amazon.com/ | $74.95 |
| VytaFlex 60 | Smooth-On | https://shop.smooth-on.com/ | $27.78 |
| VytaFlex 40 | Smooth-On | https://shop.smooth-on.com/ | $27.78 |
| VytaFlex 20 | Smooth-On | https://shop.smooth-on.com/ | $27.78 |
| Titanium Foot Pyramid Adapter | SPS | https://www.spsco.com/ | $100.00 |

## Appendix E. Vendor supplied component specifications and data sheets

Specification Sheet for VytaFlex Series Polyurethane Rubbers:



# VytaFlex™ Series

## Liquid Urethane Rubbers

SMOOTH-ON
www.smooth-on.com

### PRODUCT OVERVIEW

Using Smooth-On's exclusive "V-Polymer™" technology, **VytaFlex™** urethane rubbers offer superior physical and performance properties for casting concrete. **VytaFlex™** urethanes are available in 10A, 20A, 30A, 40A, 45A, 50A and 60A Shore hardnesses and feature convenient one-to-one by volume mix ratios.

Vacuum degassing is not necessary and **VytaFlex™** rubbers cure with negligible shrinkage to a durable rubber that will last in production.

**VytaFlex™ mold rubbers** work especially well for casting pigmented / colored concrete. Molds made with VytaFlex™ Series urethanes will render accurate and uniform colored castings.

### TECHNICAL OVERVIEW

| | A:B Mix Ratio by Volume | A:B Mix Ratio by Weight | Mixed Viscosity (ASTM D-2393) | Specific Gravity (g/cc) (ASTM D-1475) | Specific Volume (cu. in./lb.) | Color | Shore A Hardness (ASTM D-2240) | Tensile Strength (ASTM D-412) | 100% Modulus (ASTM D-412) | Elongation at Break % (ASTM D-412) | Die C Tear Strength (ASTM D-624) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **VytaFlex™ 10** | 1:1 pbv | 1:1 pbw | 3,100 cps | 1.00 | 27.9 | Off-White | 10A | 200 psi | 25 | 1,000% | 38 pli |
| **VytaFlex™ 20** | 1:1 pbv | 1:1 pbw | 1,000 cps | 1.00 | 27.7 | Clear Amber | 20A | 200 psi | 50 | 1,000% | 60 pli |
| **VytaFlex™ 30** | 1:1 pbv | 1:1 pbw | 1,800 cps | 1.02 | 27.3 | Off-White | 30A | 500 psi | 65 | 1,000% | 78 pli |
| **VytaFlex™ 40** | 1:1 pbv | 1:1 pbw | 2,000 cps | 1.03 | 26.9 | Off-White | 40A | 522 psi | 100 | 660% | 82 pli |
| **VytaFlex™ 45** | 1:1 pbv | 1:1 pbw | 2,000 cps | 1.04 | 26.4 | Off-White | 45A | 886 psi | 116 | 900% | 100 pli |
| **VytaFlex™ 50** | 1:1 pbv | 1:1 pbw | 2,000 cps | 1.04 | 26.7 | Off-White | 50A | 588 psi | 215 | 400% | 102 pli |
| **VytaFlex™ 60** | 1:1 pbv | 1:1 pbw | 2,000 cps | 1.04 | 26.6 | Off-White | 60A | 880 psi | 300 | 480% | 136 pli |

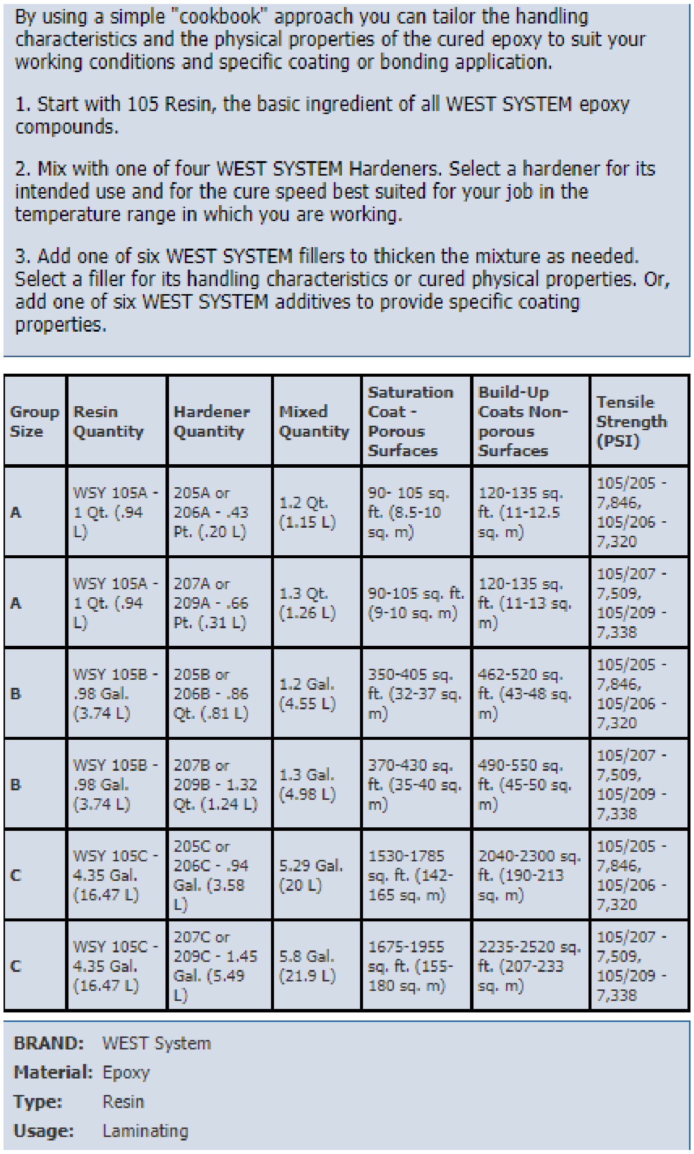
***Pot Life:***
***VytaFlex™ 10, 20, 30, 40, 45:*** 30 minutes
***VytaFlex™ 50, 60:*** 60 minutes

***Cure Time:***
***VytaFlex™ 20, 30, 40, 45, 50, 60:*** Overnight/16 hours
***VytaFlex™ 10:*** 24 hours

***Shrinkage:*** < .001 in./in.

*All values measured after 7 days at 73°F/23°C

Specification Sheet for Carbon Fiber Resin/Hardener:



By using a simple "cookbook" approach you can tailor the handling characteristics and the physical properties of the cured epoxy to suit your working conditions and specific coating or bonding application.

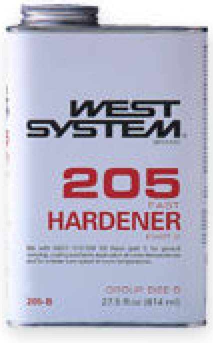
1. Start with 105 Resin, the basic ingredient of all WEST SYSTEM epoxy compounds.

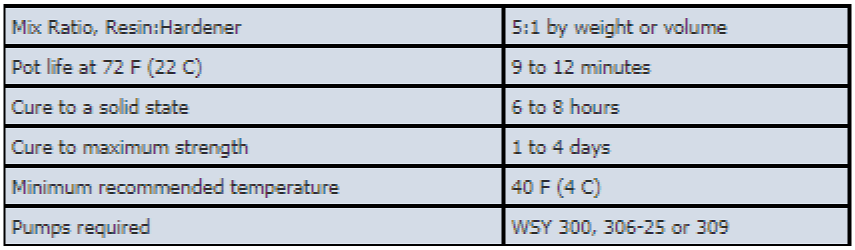
2. Mix with one of four WEST SYSTEM Hardeners. Select a hardener for its intended use and for the cure speed best suited for your job in the temperature range in which you are working.

3. Add one of six WEST SYSTEM fillers to thicken the mixture as needed. Select a filler for its handling characteristics or cured physical properties. Or, add one of six WEST SYSTEM additives to provide specific coating properties.

| **Group Size** | **Resin Quantity** | **Hardener Quantity** | **Mixed Quantity** | **Saturation Coat - Porous Surfaces** | **Build-Up Coats Non-porous Surfaces** | **Tensile Strength (PSI)** |
|---|---|---|---|---|---|---|
| **A** | WSY 105A - 1 Qt. (.94 L) | 205A or 206A - .43 Pt. (.20 L) | 1.2 Qt. (1.15 L) | 90- 105 sq. ft. (8.5-10 sq. m) | 120-135 sq. ft. (11-12.5 sq. m) | 105/205 - 7,846, 105/206 - 7,320 |
| **A** | WSY 105A - 1 Qt. (.94 L) | 207A or 209A - .66 Pt. (.31 L) | 1.3 Qt. (1.26 L) | 90-105 sq. ft. (9-10 sq. m) | 120-135 sq. ft. (11-13 sq. m) | 105/207 - 7,509, 105/209 - 7,338 |
| **B** | WSY 105B - .98 Gal. (3.74 L) | 205B or 206B - .86 Qt. (.81 L) | 1.2 Gal. (4.55 L) | 350-405 sq. ft. (32-37 sq. m) | 462-520 sq. ft. (43-48 sq. m) | 105/205 - 7,846, 105/206 - 7,320 |
| **B** | WSY 105B - .98 Gal. (3.74 L) | 207B or 209B - 1.32 Qt. (1.24 L) | 1.3 Gal. (4.98 L) | 370-430 sq. ft. (35-40 sq. m) | 490-550 sq. ft. (45-50 sq. m) | 105/207 - 7,509, 105/209 - 7,338 |
| **C** | WSY 105C - 4.35 Gal. (16.47 L) | 205C or 206C - .94 Gal. (3.58 L) | 5.29 Gal. (20 L) | 1530-1785 sq. ft. (142-165 sq. m) | 2040-2300 sq. ft. (190-213 sq. m) | 105/205 - 7,846, 105/206 - 7,320 |
| **C** | WSY 105C - 4.35 Gal. (16.47 L) | 207C or 209C - 1.45 Gal. (5.49 L) | 5.8 Gal. (21.9 L) | 1675-1955 sq. ft. (155-180 sq. m) | 2235-2520 sq. ft. (207-233 sq. m) | 105/207 - 7,509, 105/209 - 7,338 |

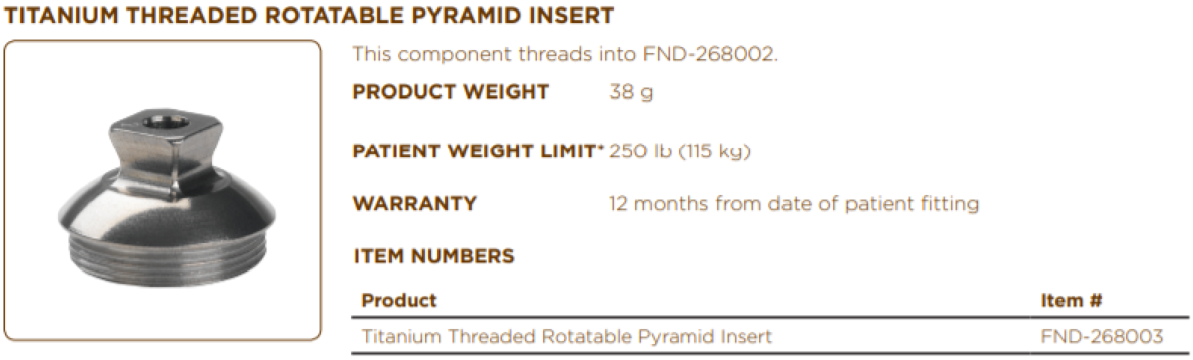
| | |
|---|---|
| **BRAND:** | WEST System |
| **Material:** | Epoxy |
| **Type:** | Resin |
| **Usage:** | Laminating |





| | |
|---|---|
| Mix Ratio, Resin:Hardener | 5:1 by weight or volume |
| Pot life at 72 F (22 C) | 9 to 12 minutes |
| Cure to a solid state | 6 to 8 hours |
| Cure to maximum strength | 1 to 4 days |
| Minimum recommended temperature | 40 F (4 C) |
| Pumps required | WSY 300, 306-25 or 309 |

Specification Sheet for Adapters:



**TITANIUM THREADED ROTATABLE PYRAMID INSERT**

This component threads into FND-268002.

**PRODUCT WEIGHT** 38 g

**PATIENT WEIGHT LIMIT*** 250 lb (115 kg)

**WARRANTY** 12 months from date of patient fitting

**ITEM NUMBERS**

| Product | Item # |
|---|---|
| Titanium Threaded Rotatable Pyramid Insert | FND-268003 |

Note: No specification sheet is available online for our specific titanium foot pyramid, but this vendor also sells a similar pyramid that does have a specification sheet available.

## Appendix F. Further FEA Analysis

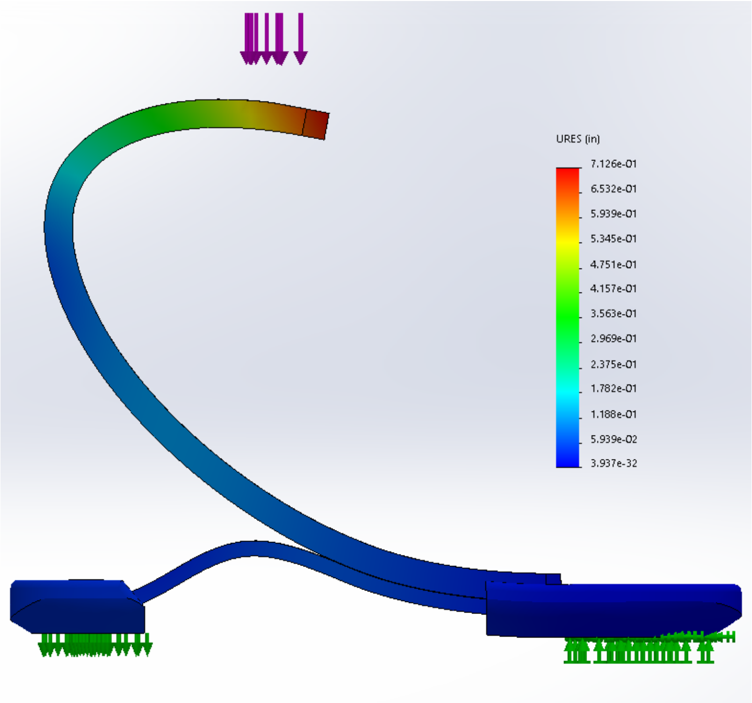


**Figure 37: FEA of deflection on Surf Foot with 600 lbs applied**

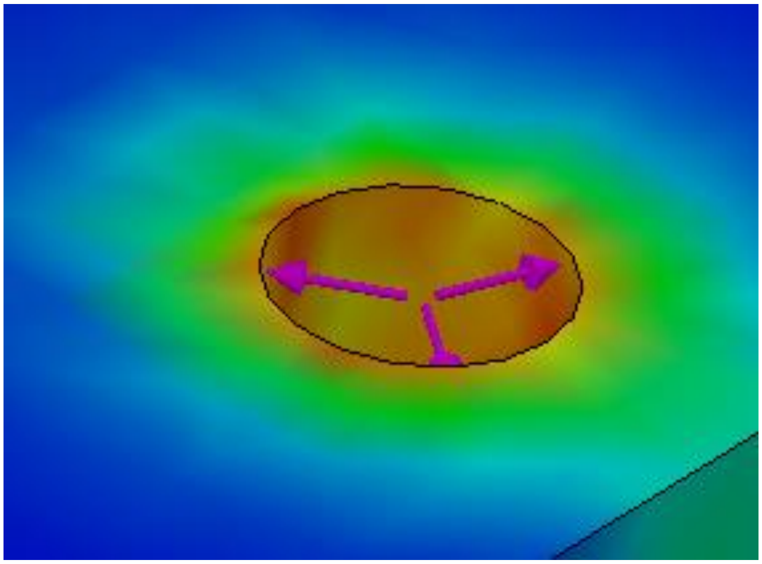


**Figure 38: FEA of stresses at the adapter of Surf Foot with 300 lbs applied**

Figure 38 shows the stresses at the adapter, which is where the force is applied from. With 300 pounds, the maximum stresses well 14.4 ksi, well below the allowable 500 ksi.

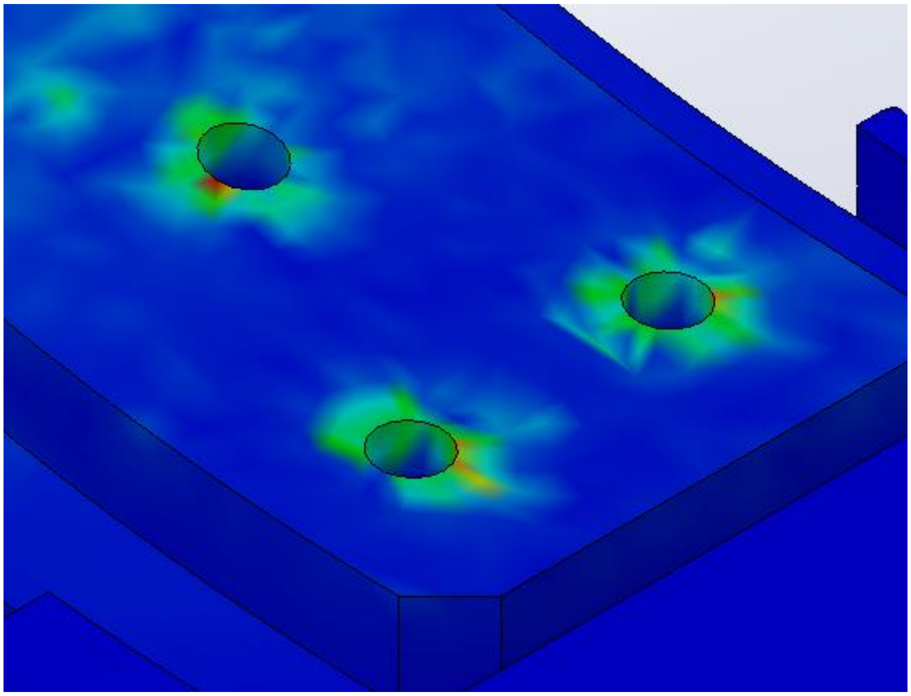


**Figure 39: FEA of bolt stresses on Surf Foot**

Figure 39 shows that some of the highest stresses occur where the binding barrels will be used to hold the pylon and foot together. With 600 pounds applied, these stresses could reach up to about 57 ksi. The ultimate tensile strength of 316 stainless steel is about 84 ksi, giving us a factor of safety of about 1.5 should there ever be that much weight applied. If the bolts broke, however, they would not snap like carbon fiber would, and those could easily be replaced.

## Appendix G: Initial Rubber Pour

Our team poured one set of rubber components using the molds printed in the QL+ Lab. The results of this initial pour can be seen in Figures 40 and 41 below. These rubber sleeves turned out very porous and would not come off of the molds in one piece. We believe this is because we waited too long to use the liquid urethane. It has a very short shelf life and should have been used sooner. Also, the release agent used did not work. As a result, we had to get new molds made by Mark, new liquid urethane, and proper release agent.

**Figure 40. Toe-side result of initial pour**

**Figure 41. Heel-side of initial pour**

Once proper mold release and liquid urethane were used, we did not experience these problems.

## Appendix H. Detailed Manufacturing Plan

### Rubber Component Manufacturing

1. Create stl files from SolidWorks parts to 3D print each part for the front and back rubber molds. ABS or PLA should be used as material.

    a. To optimize the quality of the print, molds should be printed so no support material is necessary on the interior of the mold.

2. Apply mold release to molding surfaces and assemble the molds. Do this by using ½ inch long, ¼ - 20 screws to align the molds properly, then use clamps to secure each component of the mold in place on all sides. See figure 19 for a proper set up.

3. Mix two part liquid urethane and pour into each mold; follow instructions for rubber to know when it has finished curing.

**NOTE:** Smooth-on liquid urethane and mold release was used for best results.

4. Remove rubber components from molds and cut off any flashing that may have occurred.

### Carbon fiber Manufacturing

1. Manufacturing of Carbon fiber molds
    a. Begin with 3D printing of STL files of the foot and pylon molds
        i. To optimize the quality of the print, molds should be printed on their side, so curves of molds are in the XY plane.
    b. Post processing of molds is necessary to ensure proper surface finish of carbon fiber
        i. Brush on a layer of epoxy to necessary surfaces of molds and let cure.
        ii. When cured, sand epoxied surfaces starting with a heavy grit sandpaper (80 or 100 grit), working up to 600 grit. On higher grits, utilize wet sanding to ensure the grits of the sandpaper stay clean.
        iii. The epoxied sides of the molds should feel extremely smooth to the touch, with no bubbles or visible scratches. If bubbles or scratches are present, repeat steps (1bi-1bii). If molds pass inspection, they are now ready to use in manufacturing.
2. Manufacturing of Foot and Pylon
    a. Ensure proper molds have been selected
    b. fiber layers calculation
        i. Measuring the thickness of each fiber layer will be necessary to determine how many layers to achieve target thickness.
    c. Calculating epoxy (50% resin, 50% epoxy)

    i. After cutting the layers of carbon fiber to slightly oversized from the dimensions of the molds, where there are fibers overhang outside of the molds, the mass of the fibers must be weighed.
    ii. The ratio of fiber to epoxy by mass should be approximately 50% of each. Calculate the amount of epoxy and hardener according to the manufacturer specifications per epoxy.
  d. Wet layup
    i. Ensure release films are placed on each side of the mold, and breather film is prepared for the top of the mold to allow excess epoxy to escape.
    ii. Mix epoxy thoroughly, and orient fibers in the repeated pattern of 0/45/90/-45/0 to maximize strength in all directions. Each layer should be thoroughly coated in epoxy with excess epoxy squee-geed out.
  e. Clamping
    i. Put the top part of the foot mold onto the wet layup with the proper breather and release films and clamp the two halves of the mold together tightly. Let cure.
    ii. The pylon mold needs to be clamped both vertically and horizontally to ensure rigidity of thin mold walls. The same breather films and release films are required at the top layer. Ensure the molds are solid and securely clamped and let cure.
  f. Post processing
    i. Cut foot to shape with a tile saw.
      1. Start with cutting width, mark width difference at heel and toe, use tile saw.
      2. Chamfer according to detailed drawings.
    ii. Cut pylon to shape with dremel and water.
      1. Carefully mark out the shape in carbon fiber blank and cut using a dremel, ensuring water is used to keep dust down.
    iii. Locate and drill holes perpendicular to their surface.
    iv. Apply a hot coat of epoxy by brushing epoxy on with a chip brush. Ensure an even coat and thoroughly coat all freshly cut surfaces.

## Appendix I. Detailed Test Plans

**Test Name**: Compression Test

**Purpose:** To ensure the prosthetic can safely withstand the load placed on it by the user with a factor of safety of 3

**Scope:** Safety

**Equipment:** Compression Testing Machine – Servo-hydraulic tester, tape measure

(Note: fixtures may need to be made to secure prosthetic in place during testing)

**Hazards:** In the event that the prosthetic fractures during testing, fragments could become projectiles

**PPE Requirements**: Safety goggles

**Facility:** Cal Poly Composites Lab

**Procedure:** (List number steps of how to run the test, can include sketches and/or pictures):

1) Take initial measurement of height of prosthetic (see measurement test protocol for specific details on how to measure height)
2) Place prosthetic vertically in fixtures: the foot portion of prosthetic should be in contact with the bottom fixture, and the pyramid adapter should be in contact with the upper fixture
3) Ensure prosthetic is secured and will not shift during testing before continuing
4) Set compression load to 600 lbs (2668.93 N)
5) Run test
6) Repeat test three times
7) Remove prosthetic from fixtures
8) Measure the height of prosthetic again and compare to initial height to determine if there is plastic deformation

**Results:**

Pass Criteria: Prosthetic is loaded with 600 lbs and experiences a maximum of 0.25 inches of deformation

Fail Criteria: Prosthetic cannot withstand 600 lbs of compressive force or prosthetic experiences a plastic deformation of more than 0.25 inches.

**Test Date(s):**

**Test Results:**

| Parameter | Target Requirement | Tolerance | Actual Value |
|---|---|---|---|
| Compression Load | 600 lbs | Min | |
| Change in Height | 0.0 in | -0.25 | |

**Performed By:**

---

**Test Name**: Submersion Test

**Purpose:** To ensure the prosthetic does not hold water in it after submersion

**Scope:** Waterproof functionality

**Equipment:** Scale, large tub of water

**Hazards:** N/A

**PPE Requirements**: N/A

**Facility:** Cal Poly campus or home

**Procedure:** (List number steps of how to run the test, can include sketches and/or pictures):

1) Zero balance/scale
2) Weigh (dry) prosthetic using balance/scale and record value
3) Dunk entire prosthetic in large tub of water
4) Rotate prosthetic under water to expose any air pockets that might be trapped upon submersion
5) Remove prosthetic from water and weigh again without drying off first
6) Record this value and subtract the initial weight from it

**Results:**

Pass Criteria: Prosthetic gains less than 0.1 lbs after being submerged in water

Fail Criteria: Prosthetic holds more than 0.1 lbs of water after being submerged

**Test Date(s):**

**Test Results:**

| Parameter | Target Requirement | Tolerance | Actual Value |
|---|---|---|---|
| Initial Weight | 3 lbs | ± 0.5 | |
| Final Weight | 3 lbs | ±0.5 | |
| Change in Weight | 0.0 lbs | +0.1 | |

**Performed By:**

---

**Test Name**: Drag Test

**Purpose:** To ensure the prosthetic does not produce an unreasonable amount of drag force when the user is paddling out on a short board

**Scope:** Usability

**Equipment:** Large body of water, spring scale, string/fishing line

**Hazards:** Drowning, loss of prosthetic

**PPE Requirements**: Life jacket (if test is performed by someone who cannot swim)

**Facility:** Body of water such as Cal Poly pool or in the ocean

**Procedure:** (List number steps of how to run the test, can include sketches and/or pictures):

1) Attach end of spring scale to pyramid adapter on top of prosthetic using string/fishing line

2) Depending on what is easily accessible, hold prosthetic and spring scale in a swimming pool or the ocean
3) The average surfer paddles out at 2.3 mph [SURFER Magazine] so the spring scale should be pulled through the water at about 2.3 mph and the resulting force on the spring scale should be recorded

**Results:**

Pass Criteria: Drag force created by prosthetic is 2 lbs (8.896 N) or less when pulled through water

Fail Criteria: Drag force created by prosthetic is greater than 2 lbs (8.896 N) when pulled through water

**Test Date(s):**

**Test Results:**

| Parameter | Target Requirement | Tolerance | Actual Value |
|---|---|---|---|
| Drag Force | 2 $lb_f$ (8.896 N) | Max | |

**Performed By:**

---

**Test Name**: Measurement Inspection

**Purpose:** To ensure the prosthetic meets engineering specifications associated with size

**Scope:** Size

**Equipment:** Tape measure, scale

**Hazards:** N/A

**PPE Requirements**: N/A

**Facility:** Cal Poly campus or home

**Procedure:** (List number steps of how to run the test, can include sketches and/or pictures):

Weight Measurement:

1) Zero balance/scale
2) Place prosthetic on balance/scale
3) Record measurement

Height and Length Measurements:

1) Using tape measure, measure from base of the rubber piece to top of pyramid adapter
2) Record measurement
3) Measure from edge of front rubber piece to edge of rear rubber piece
4) Record measurement

Rubber Surface Area Measurement:

1) Looking at bottom of front rubber piece, measure length and width of rectangular section that contacts the ground to find the area
2) Measure radius of half-circle portion that contacts the ground to find the area
3) Find area of binding barrel holes by measuring the diameter of each and subtracting the areas from the half-circle area
4) Add areas of rectangle and half-circle (after subtracting binding barrel holes) and record this measurement
5) Looking at the bottom of the rear rubber piece, measure the radius of the half-circle portion that contacts the ground. This portion is not a perfect half-circle, so multiple radii measurements will have to be made and the average of these numbers can be used to find the area.
6) Find areas of binding barrel holes by measuring diameter and subtracting these areas from the half-circle area. Record this measurement.
7) Add the total area from the front rubber piece and the total area from the rear rubber piece to find the overall surface area of the rubber components

Estimate of Area of Base of Prosthetic:

1) Measure length from front edge of front rubber piece
2) Measure width of carbon fiber foot piece
3) Multiply measurements to find estimate of the total surface area of the bottom of the prosthetic

**Results:**

Pass Criteria: Measurements of prosthetic are within acceptable tolerances of each target requirement

Fail Criteria: Measurements of prosthetic are not within acceptable tolerances of each target requirement

**Test Date(s):**

**Test Results:**

| Parameter | Target Requirement | Tolerance | Actual Value |
|---|---|---|---|
| Weight | 3 lbs | ± 0.5 | |
| Height | 7.5 in | ± 0.05 | |
| Length | 9.635 in | ± 0.15 | |
| Width | 2.895 in | ± 0.1 | |
| Front Rubber Bottom Half-Circle Area | 4.375 $in^2$ | ± 0.25 | |
| Front Rubber Bottom Rectangular Area | 3.25 $in^2$ | ± 0.25 | |
| Front Rubber Bottom Total Surface Area | 7.625 $in^2$ | ± 0.5 | |
| Back Rubber Bottom Surface Area | 2.709 $in^2$ | ± 0.25 | |
| Total Rubber Bottom Surface Area | 10.334 $in^2$ | ± 0.75 | |
| Area of Base of Prosthetic | 27.893 $in^2$ | ± 1.382 | |

**Performed By:**

## Appendix J: Images of 3D printed molds

Figure 42. 3D printed foot mold

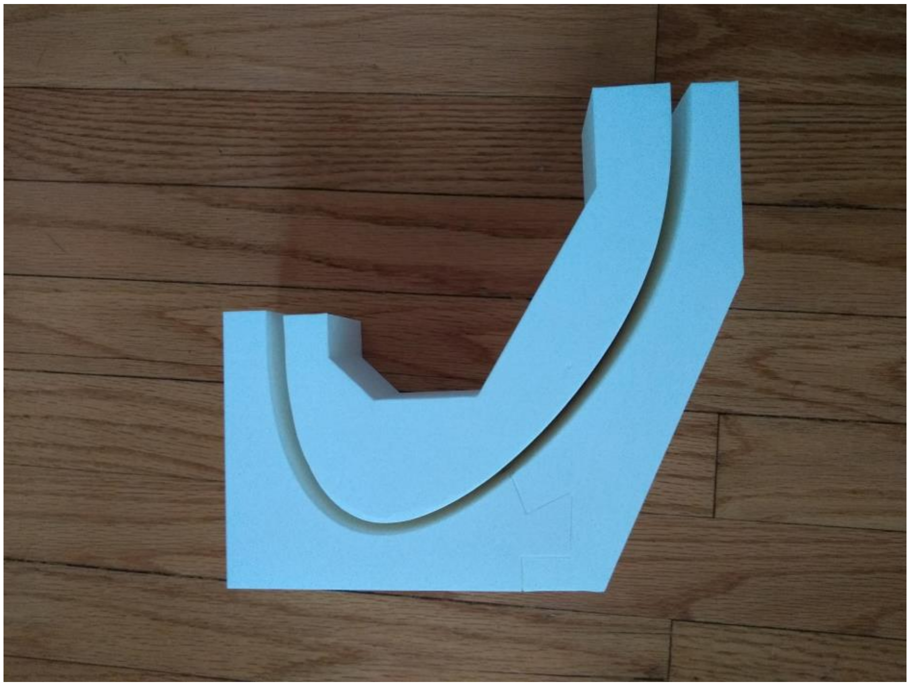


Figure 43. 3D printed pylon mold

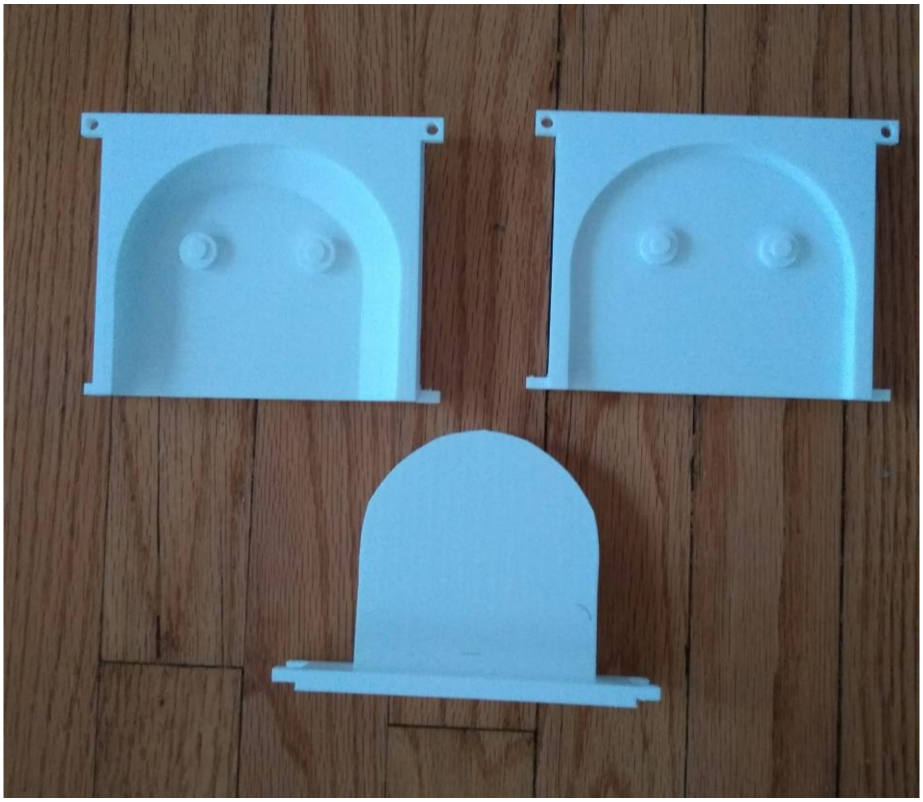
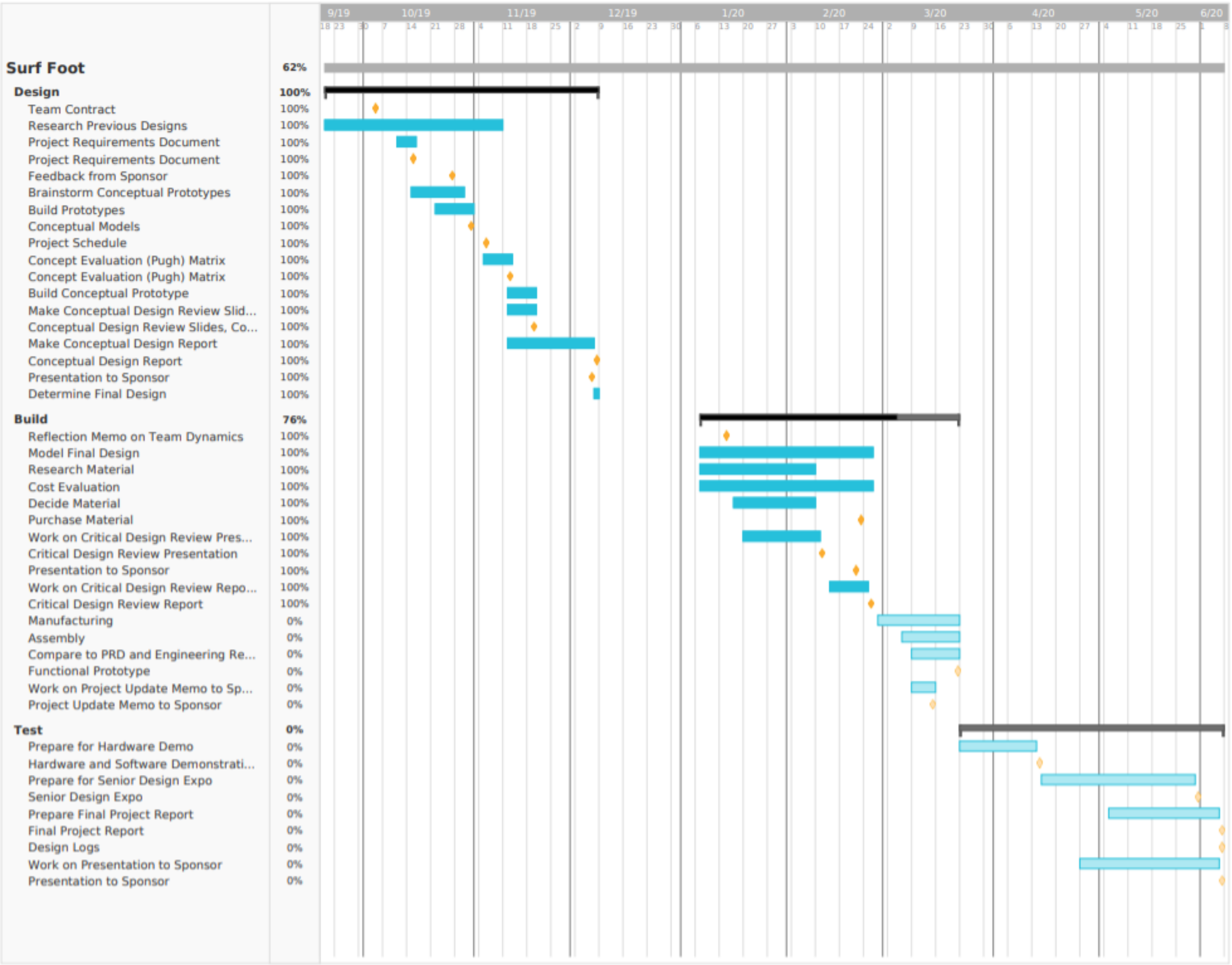


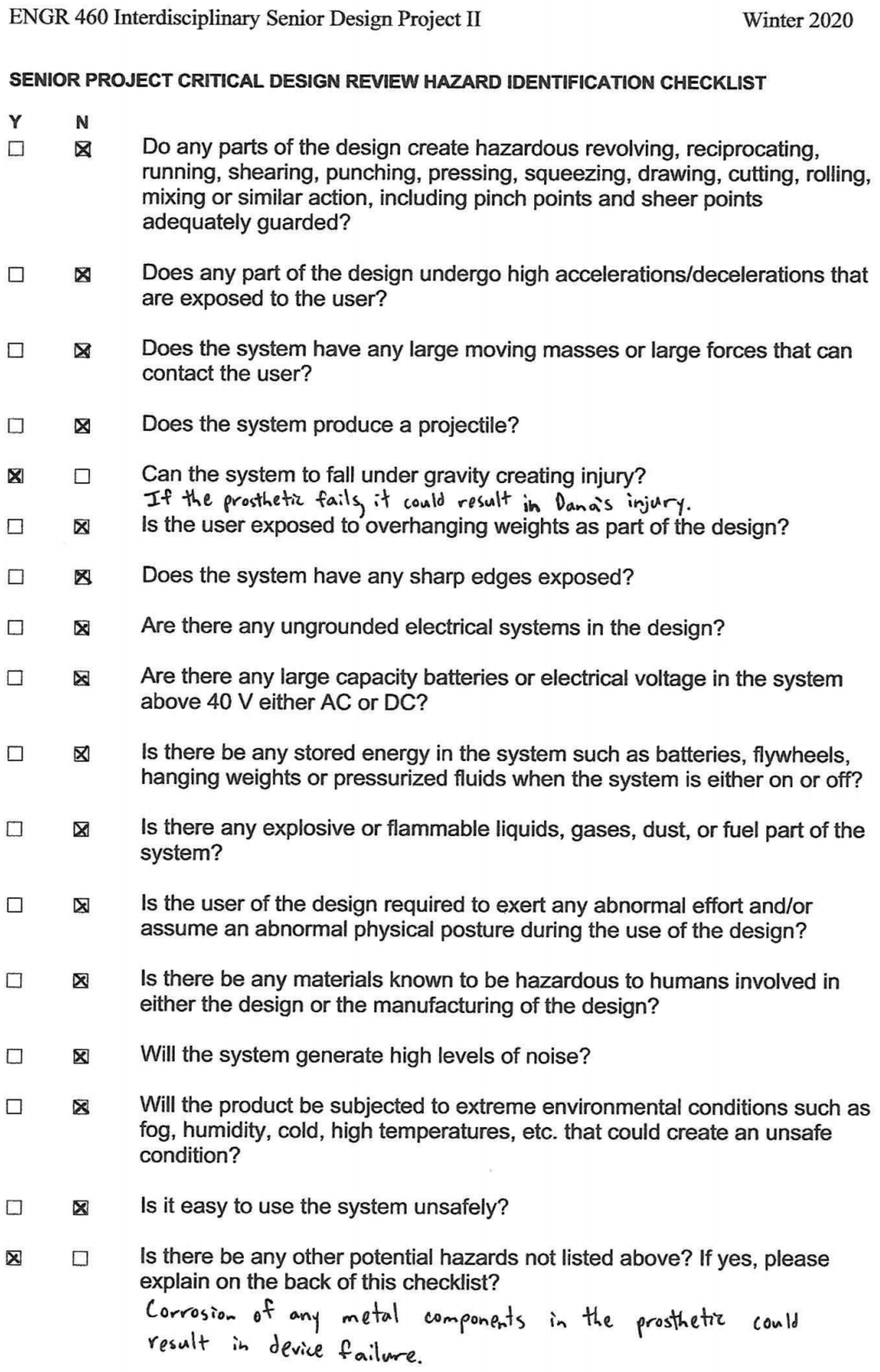
**Figure 44: 3D printed toe-side rubber mold**

## Appendix K. Gantt Chart



| | |
|---|---|
| **Surf Foot** | **62%** |
| **Design** | **100%** |
| Team Contract | 100% |
| Research Previous Designs | 100% |
| Project Requirements Document | 100% |
| Project Requirements Document | 100% |
| Feedback from Sponsor | 100% |
| Brainstorm Conceptual Prototypes | 100% |
| Build Prototypes | 100% |
| Conceptual Models | 100% |
| Project Schedule | 100% |
| Concept Evaluation (Pugh) Matrix | 100% |
| Concept Evaluation (Pugh) Matrix | 100% |
| Build Conceptual Prototype | 100% |
| Make Conceptual Design Review Slid... | 100% |
| Conceptual Design Review Slides, Co... | 100% |
| Make Conceptual Design Report | 100% |
| Conceptual Design Report | 100% |
| Presentation to Sponsor | 100% |
| Determine Final Design | 100% |
| **Build** | **76%** |
| Reflection Memo on Team Dynamics | 100% |
| Model Final Design | 100% |
| Research Material | 100% |
| Cost Evaluation | 100% |
| Decide Material | 100% |
| Purchase Material | 100% |
| Work on Critical Design Review Pres... | 100% |
| Critical Design Review Presentation | 100% |
| Presentation to Sponsor | 100% |
| Work on Critical Design Review Repo... | 100% |
| Critical Design Review Report | 100% |
| Manufacturing | 0% |
| Assembly | 0% |
| Compare to PRD and Engineering Re... | 0% |
| Functional Prototype | 0% |
| Work on Project Update Memo to Sp... | 0% |
| Project Update Memo to Sponsor | 0% |
| **Test** | **0%** |
| Prepare for Hardware Demo | 0% |
| Hardware and Software Demonstrati... | 0% |
| Prepare for Senior Design Expo | 0% |
| Senior Design Expo | 0% |
| Prepare Final Project Report | 0% |
| Final Project Report | 0% |
| Design Logs | 0% |
| Work on Presentation to Sponsor | 0% |
| Presentation to Sponsor | 0% |

## Appendix L. Safety Checklist



ENGR 460 Interdisciplinary Senior Design Project II Winter 2020

**SENIOR PROJECT CRITICAL DESIGN REVIEW HAZARD IDENTIFICATION CHECKLIST**

| Y | N | |
|---|---|---|
| ☐ | ☒ | Do any parts 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 adequately guarded? |
| ☐ | ☒ | Does any part of the design undergo high accelerations/decelerations that are exposed to the user? |
| ☐ | ☒ | Does the system have any large moving masses or large forces that can contact the user? |
| ☐ | ☒ | Does the system produce a projectile? |
| ☒ | ☐ | Can the system to fall under gravity creating injury?<br>If the prosthetic fails, it could result in Dana's injury. |
| ☐ | ☒ | Is the user exposed to overhanging weights as part of the design? |
| ☐ | ☒ | Does the system have any sharp edges exposed? |
| ☐ | ☒ | Are there any ungrounded electrical systems in the design? |
| ☐ | ☒ | Are there any large capacity batteries or electrical voltage in the system above 40 V either AC or DC? |
| ☐ | ☒ | Is there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids when the system is either on or off? |
| ☐ | ☒ | Is there any explosive or flammable liquids, gases, dust, or fuel part of the system? |
| ☐ | ☒ | Is the user of the design required to exert any abnormal effort and/or assume an abnormal physical posture during the use of the design? |
| ☐ | ☒ | Is there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design? |
| ☐ | ☒ | Will the system generate high levels of noise? |
| ☐ | ☒ | Will the product be subjected to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc. that could create an unsafe condition? |
| ☐ | ☒ | Is it easy to use the system unsafely? |
| ☒ | ☐ | Is there be any other potential hazards not listed above? If yes, please explain on the back of this checklist?<br>Corrosion of any metal components in the prosthetic could result in device failure. |