THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF BIOMEDICAL ENGINEERING

JAIPUR FOOT PROJECT: COMPUTER SIMULATION FOR DETERMINATION OF STATIC AND CYCLIC STRESSES

SARAH SOMERS
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ABSTRACT

The purpose of my thesis is to explore the attachment mechanism that is currently in place to attach the Jaipur prosthetic foot to an artificial limb. The Jaipur foot is a handmade wood and rubber-based foot that is distributed to patients in need in India free of cost. The problem is that the foot to ankle attachment zone is often the first region to fail. This is due to the current design which creates stress concentrations at the attachment zone. The current design is a simple ledge for the limb to sit on and four screws around the ankle through the limb, which is usually a PVC pipe, into the rubber and wood of the foot. In addition to the stress concentration created at the holes, the holes allow water to seep into the wood interior and eventually cause it to rot.

I have analyzed the current design through computer modeling. My thesis is composed of two multiphysics models. One model measures the stress due to the stationary forces applied to the ankle and the second model tests the stress due to fatigue over a period of fluctuating stresses that imitate a stride. I predicted that the foot is failing due to the stress concentrations at the screws.

Arizona State University, Massachusetts Institute of Technology, and Penn State are all collaborating on research surrounding the Jaipur foot. The problem with the Jaipur foot is that it does not meet many international standards to get funding from sources like the United Nations or the Red Cross because each foot is handmade. Therefore, the universities are working together to improve the foot so that it can be mass produced quickly and cheaply. I hope that, overall, my project can help the collaborating universities improve the design of the Jaipur foot to include some aspects that allow for easy attachment to a prosthetic leg. I have compared the maximum stresses that will result from normal use of the Jaipur foot and leg assembly to acceptable standards and failure points of the materials that make up the assembly. I hope that the results of my study will allow the collaborating universities to move forward in their study of the Jaipur foot and redesign of the foot and leg assembly.

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ACKNOWLEDGEMENTS

I would like to thank Dr. Margaret Slattery for inviting me to join her work with the Jaipur foot project and for her insightful advice throughout every step of the thesis process. I would also like to thank her for her help in editing and reviewing my thesis. I would also like to thank Dr. Liz Kisenwether for her guidance along the way and her knowledge of the Jaipur foot project. Thank you as well to Dr. Peter Butler for his help in discussing the aims and direction of my project and for his help with reviewing drafts of the thesis.

Elyse Merkel who completed her undergraduate thesis on the Jaipur foot project as well was instrumental in training me and providing me with results from her project as a starting point for my project. For this I am very grateful. Thank you as well to Ryan Fleming and the members of his senior design team that generously provided me with data from their stride testing of the Jaipur feet.

Finally, I would like to thank all other members of the Jaipur foot team at Penn State, Arizona State, and the Massachusetts Institute of Technology. Without this team this project would not have been possible.

Chapter 1

Introduction

History of the Jaipur Foot

The Jaipur foot is a simple prosthetic foot distributed widely in India for amputees who cannot afford a commercial prosthetic limb. The Jaipur foot was designed by Dr. Pramod Karen Sethi, who began his career in orthopedic surgery in 1953 at the Swai Man Singh (SMS) Hospital in Jaipur India. At the time, the hospital had no resources for amputee victims who could not afford a long trip to Pune or New Delhi for artificial limbs. Dr. Sethi was instrumental in the process of setting up a rehabilitation center at the hospital and securing funding for the center so that he could provide his patients with prosthetic limbs in an attempt to get them off the streets and back to functional lifestyles. The major supporter of the project was Bhagwan Mahaveer Viklang Sahayata Samiti (BMVSS), a non-profit organization. At this center, a man named Ram Chander Sharma worked with patients as they went through rehabilitation. Sharma was skilled in a variety of handicrafts and art forms (Dr Pramod Karan Sethi) .

Originally, Dr. Sethi was providing his patients with low-cost imitations of traditional western prosthetics. However, when Dr. Sethi would see his patients later on after their release from the hospital, they would not be wearing the prosthetic that had been provided to them, and they would often be back on the streets begging. Many of the other doctors and staff at the hospital felt that the patients were just being lazy, but Dr. Sethi was determined to help them in any way he could so he interviewed his patients and asked them why they were not using the prosthetic provided to them. The problem with the stiff western-style prosthetic was that, due to the type of leg fitting it had to be attached to, it did not allow the patients to squat or kneel. These are two positions that are very important in Indian culture because Indians squat to use the restroom and many other activities are done squatting at the floor level especially in rural areas. Also, kneeling and bare footedness are important for prayer. The patients could not use the prosthetic feet provided barefoot, because the foot region necessitated a shoe. Shoes are not usually worn in rural areas due to the extra expense and the possibility of it getting caught in the mud (Dr Pramod Karan Sethi).

Dr. Sethi did not see anything that would fill the needs of his patients on the market, so he decided to begin work on his own version of a prosthetic foot and leg assembly. Sharma was also instrumental in the process of designing what would become the Jaipur foot due to his diverse background in materials and how best to handle them. The foot was designed to be flexible to allow for flexion for balance during tasks like squatting and kneeling as shown in figure 1.1. Originally, the foot was made of all rubber. Later, a wooden keel in the core of the foot was added for structural support, but the feet and legs continued to be made out of the simplest materials: rubber, wood, and aluminum. These materials allowed for barefoot walking and the rubber and aluminum performed well when exposed to moisture (Dr Pramod Karan Sethi).

Figure 1.1: Jaipur foot designed to allow for squatting

Unfortunately, the growing support and excitement for the Jaipur foot eventually led to its downfall. Dr. Sethi was awarded a Magsaysay Award for his work on the Jaipur foot, but Sharma was not acknowledged with Dr. Sethi and the original team was slowly dissolved and divided. This strain on the original creators of the foot halted the overall process, and research and development of the Jaipur foot project ceased. The production process was also never perfected and so the makers of the feet all have slight differences in their training and processes making the feet unregulated and non-standardized. Another problem is that the skin tone of the feet cannot be regulated properly and this is an important aesthetic consideration since most amputees do not wear a shoe with the foot and would like it to look as realistic as possible (Dr Pramod Karan Sethi).

Despite all of the problems, the Jaipur foot has still been used on hundreds of thousands of patients. However, little testing has been done to understand why it is so effective. Also, it is still not accepted by the international medical community because it does not meet quality and manufacturing standards. This is where our team comes in to test and characterize the feet.

Jaipur Foot Production:

Each Jaipur foot is individually created from a wooden ankle, a rubber core, and vulcanized rubber as seen below in Figure 1.2 (BMVSS ,Our History). The core of the foot is made from three main sets of blocks. This includes the ankle block which is made of laminated wood, the forefront block which is made of Micro Cellular Rubber (MCR) and the smaller heel and toe blocks also made of MCR. Often, these blocks are not a specified size, but are randomly chosen from a pile of roughly cut materials leading to inconsistency in the properties of the feet (“JaipurFoot_test_report_Dr. Mathur.pdf”).

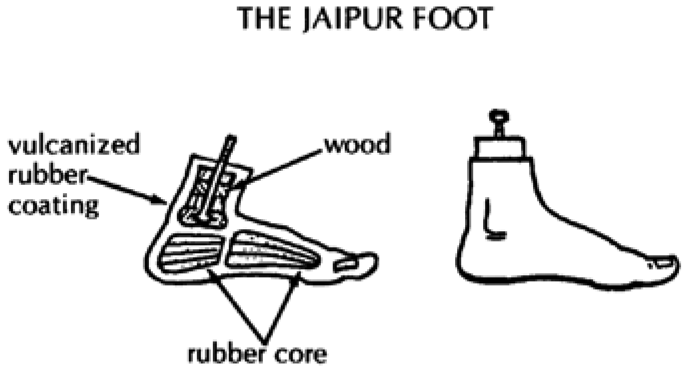


Figure 1.2: The Jaipur Foot ("The Mukti Limb")

The blocks are attached to each other using adhesive and then rubber cement is coated over the entire block assembly. This process is documented in figure 1.3a. Following this, the block assembly is coated in cushion rubber and then wrapped in tire cord to ensure that the assembly is held in place (figure 1.3b). Then, the assembly is re-coated in cushioned rubber (figure 1.3c) in preparation for the die molding. Finally, the foot is placed in the die to be shaped (figure 1.3d) (Merkle, E.).

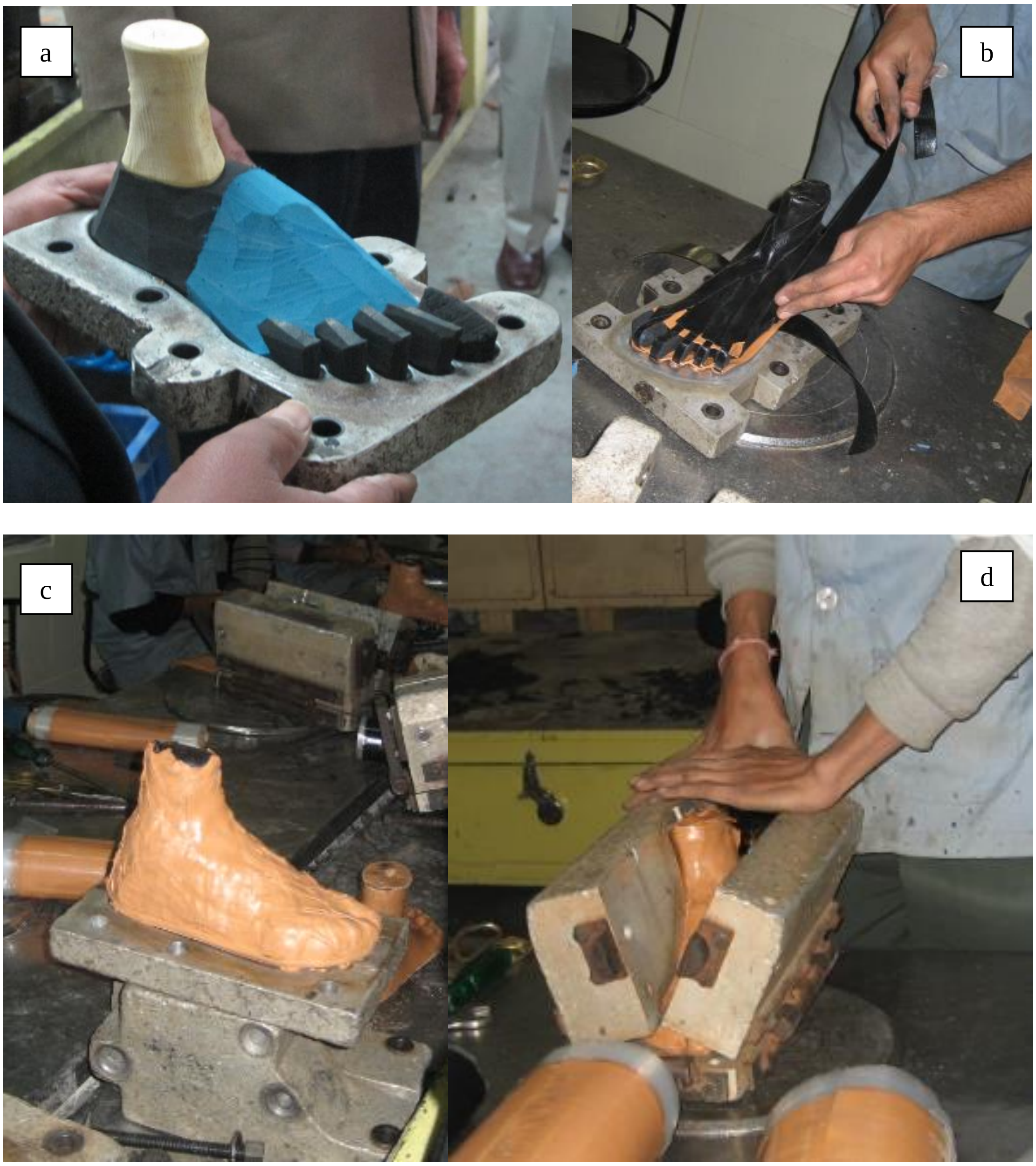


Figure 1.3: Jaipur foot manufacturing process in steps referred to as 3a-3d from top left to bottom right.

The foot is then attached to a polyurethane molded leg. The mold is created from plaster molding of the amputee’s leg as seen in figure 1.4 below.

Figure 1.4: Creating molds of the patients amputated limb

Problems with the Jaipur Foot

The problem with the current model of the Jaipur foot is that each foot is made separately by hand. This makes the process slower and more costly than necessary. Also, each foot is slightly different (BMVSS, Quality Control). Since there is no uniformity between the feet, there is no quality control. For this, and other reasons, BMVSS is not eligible for funding from organizations like the United Nations, the World Health Organization, and The Red Cross. The Indian Space Agency has created a new type of low cost prosthetic foot from polyurethane (PU). This foot can be made from a mold and, therefore, each foot is identical and the quality of the feet can be controlled. The PU foot is made from two types of polyurethane. The inside of the foot is made of a very dense PU to imitate the wood and rubber core of the Jaipur foot, and the outside is made of a less dense PU to imitate the vulcanized rubber of the Jaipur foot (Merkle, E.). The problem is, however, that from the compression testing we have done in the lab, the PU foot is significantly less sturdy than the Jaipur foot. Also, PU feet have been distributed in India and have had a much shorter lifetime than the Jaipur feet. Under the tutelage of Dr. Slattery and Dr. Kisenwether, our group is looking to characterize the Jaipur and prosthetic feet as well as determine key differences between the two feet in different applications such as flexion, supination, pronation, and ankle rotation. Also, the team is looking to characterize fatigue at pressure points during a stride with the Jaipur foot and PU foot.

Review of Jaipur foot project progress

In 2010 a group of students and professors from three universities, Massachusetts Institute of Technology (MIT), Arizona State University (ASU), and Pennsylvania State University (PSU), traveled to India to a location where Jaipur feet were being made and distributed to amputees. The group was able to see the feet being handmade. They were also able to see amputees who were returning for replacement feet. This is key because it allowed the group to see where the feet were failing, see figures 1.5-1.7. This failure and the unregulated and non-uniform way in which the feet were made were the driving factors behind the team's analysis of the current Jaipur feet and the current PU feet.

Figure 1.5: Ankle Failure

Figure 1.6: Ankle Failure

Figure 1.7: Ankle Failure

Here at PSU, several projects occurred before I was able to begin mine. The first project was completed by a senior design team in their Capstone course. The team was comprised of senior students who created a universal testing rig (UTR) to allow for various tests to be performed on the Jaipur foot. The group also looked at the foot's response in dorsal flexion and heel compression (Cao, et al.). Next, Elyse Merkle completed her undergraduate thesis by testing the foot in different ankle rotation positions. Also, another senior design group created a rig to attach the foot to that would simulate a walking motion. The foot was "walked" across a pressure plate to see if the foot can be used in a way that is similar to a natural stride.

My thesis work combines the results of these three previous projects. I have created computer models using SolidWorks and Comsol Multiphysics that mimic the cyclic and constant loads on the ankle attachment region of the foot in order to show the need for a new design. The models impose compressive stresses across the top of the ankle region similar to those expected from normal use of the current assembly. The first model is a constant compressive load to see how the weight of a normal human user causes stresses across the foot and ankle region. In the second model, a varying load is applied to the foot to mimic the compression the region would undergo during a stride cycle.

Chapter 2

Methods

Obtaining Elastic Modulus of Jaipur Foot From Rotation Testing

Four Jaipur feet were obtained from the group's trip to India. The four feet represented two different sizes and included two right feet and two left feet. The feet were labeled as ASU 1, ASU 2, PSU 1, and PSU 2 based on the original group that kept them from the schools involved in the project. Stress testing was performed on the feet in the following manner as a part of the thesis work of Elyse Merkel:

1. Force applied to inside of foot
    a. Front position
        i. 40 kgf over 60 secs
    b. Middle position
        i. 40 kgf over 60 secs
    c. Back position
        i. 40 kgf over 60 secs
2. Force applied to the outside of the foot
    a. Front position
        i. 25 kgf over 60 sec
    b. Middle position
        i. 40 kgf over 60 secs
    c. Back position
        i. 40 kgf over 60 secs

The force application scheme can be further visualized in Figure 2.1.

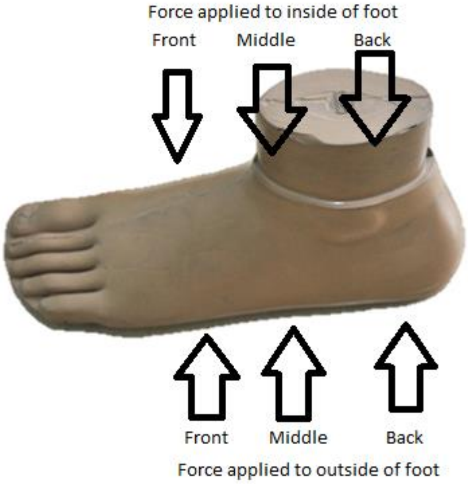


Figure 2.1: Force Application Scheme

A 40 kgf was applied over a 60 second interval for all regions except the outside back of the foot due to the high amount of deformation that occurred as the force was applied to this region. The feet were not meant to be tested until failure, so the force applied at this region was lessened.

The testing was completed following the protocol for a MTS compression tester. The foot was placed into the rig created by a group in the Capstone Senior Design course in the Spring 2012 semester. The setup is shown in figure 2.2 (Merkle, E.).

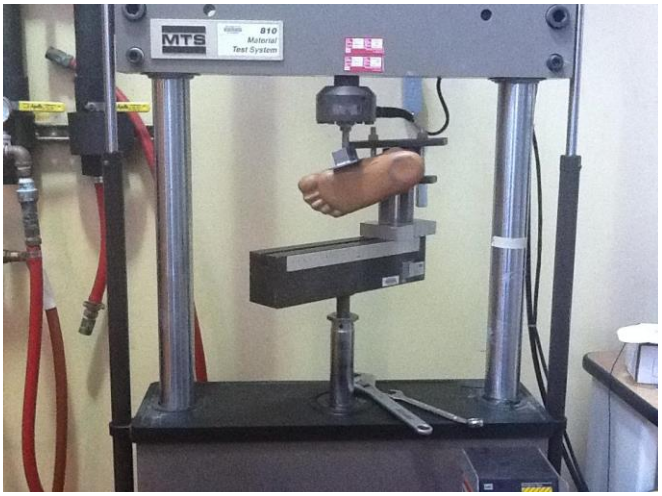


Figure 2.2: Compression Test Setup (shown in the interior front position)

Following the testing of the four Jaipur feet, graphs of the displacement of the foot due to the applied force were created also as a part of the thesis work of Elyse Merkel. I then created stress vs. strain curves for the region in which the feet were tested. I assumed that the compression plate came into contact with the foot over a circular cross section with a diameter of 1 in. This allows for a force application area of A=.7854 in. I then used equation 1 to convert the force at each displacement to stress.

$$\sigma = F/A \tag{1}$$

Then I converted the displacement data into strain using equation 2.

$$\varepsilon = \Delta l/l_0 \tag{2}$$

Since the plate of the compression test rested on the topmost section of the foot (either on the inside of the foot or the outside of the foot depending on the test being performed) I assumed that the original length l_0 of the infinitesimally thin element being strained was the diameter of the cross section of the foot at the region at which the force was applied. At the back region of the foot this diameter was 3.7 in. At the middle region of the foot this diameter was 3.4 in. At the front region of the foot the diameter was 3.2 in. These diameters were applied as the original lengths in equation 2.

Following the modification of the stress strain graphs, I determined an elastic modulus for each region of the foot based on the graphs I had created. The elastic modulus was taken to be the slope of a linear regression line fit to the linear region of each graph. The elastic moduli of a particular region (say back outside) were averaged over the four feet to determine an average elastic modulus for each region of the foot. The variation in the elastic moduli can be attributed to the fact that each Jaipur foot is handmade and may contain varying shapes and sizes of wooden blocks inside the vulcanized rubber.

Modeling of Jaipur Foot Using SolidWorks

The next step in my process was to model the Jaipur foot and ankle attachment through an assembly in Solidworks. The foot and ankle attachment was creates using five different parts combined in an assembly. The parts were created individually and then mated together in SolidWorks. The parts are as follows ("JaipurFoot test report Dr. Mathur".):

The block in the interior rear of the foot: The block was made of MCR and is a simple extrusion of a rectangular sketch.

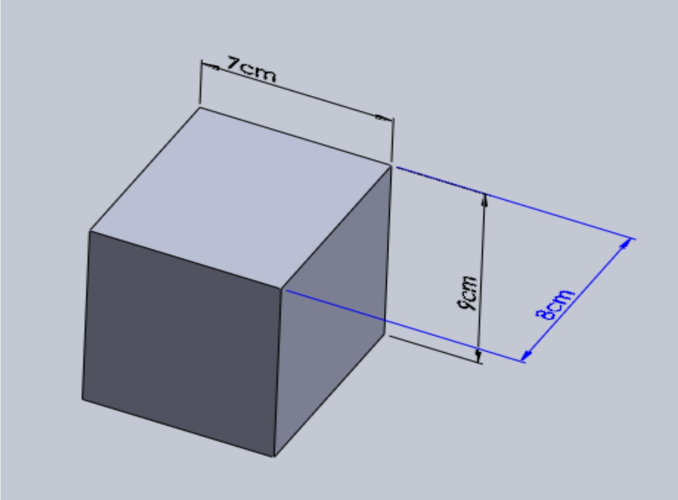


Figure 2.3: Interior Block 1

The block in the middle region of the foot: The block for the middle portion of the foot was created using the lofting tool. The loft was created using a sketch of two rectangles drawn on parallel planes. This block is also made of MCR.

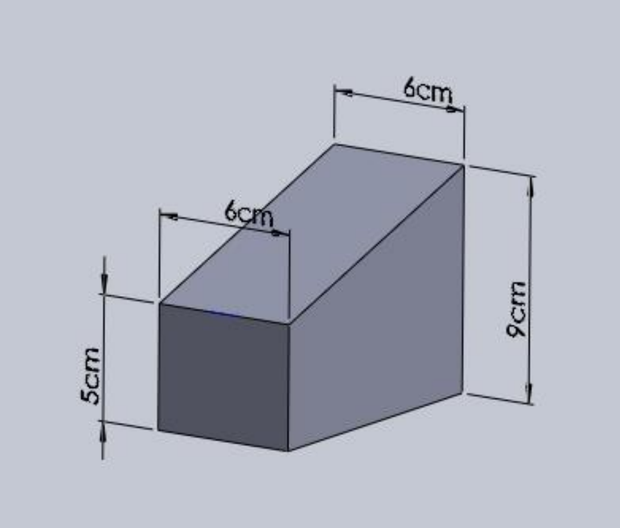


Figure 2.4: Interior block 2

The toe block: The block for the toe region was made using a simple extrude. This block is made of MCR.

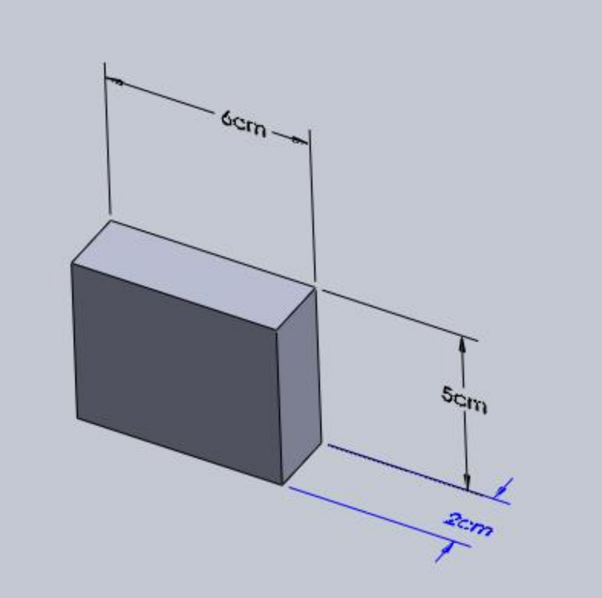


Figure 2.5: Toe Block

The block in the upper region of the foot: The final block inside the foot region of the assembly is also made of MCR and was made by extrusion.

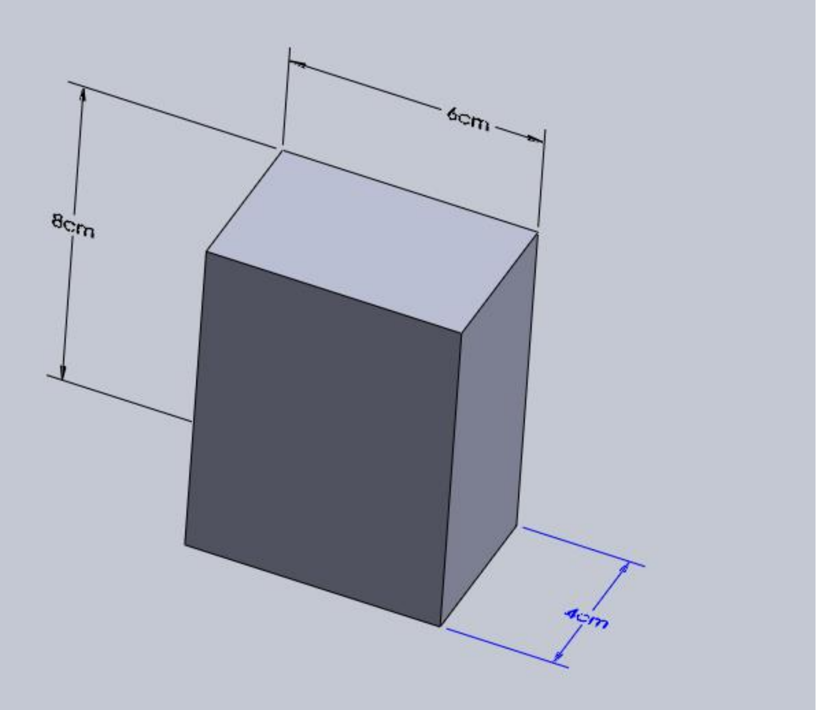


Figure 2.6: Upper foot block

The instep of the foot and outside of the foot: The instep and outside of the foot were created by sketching the profile of the cross section of the foot in the middle of the foot across a plane dividing the foot laterally. Then the profile was extruded and cut to fit the proper edge characteristics using the swept cut. Finally, the regions of the foot where the block is inside the rubber were removed using an extruded cut. See the profile of the cross section in figure 2.7 and the instep and outside in figures 2.8 and 2.9 respectively. These regions are made of vulcanized rubber.

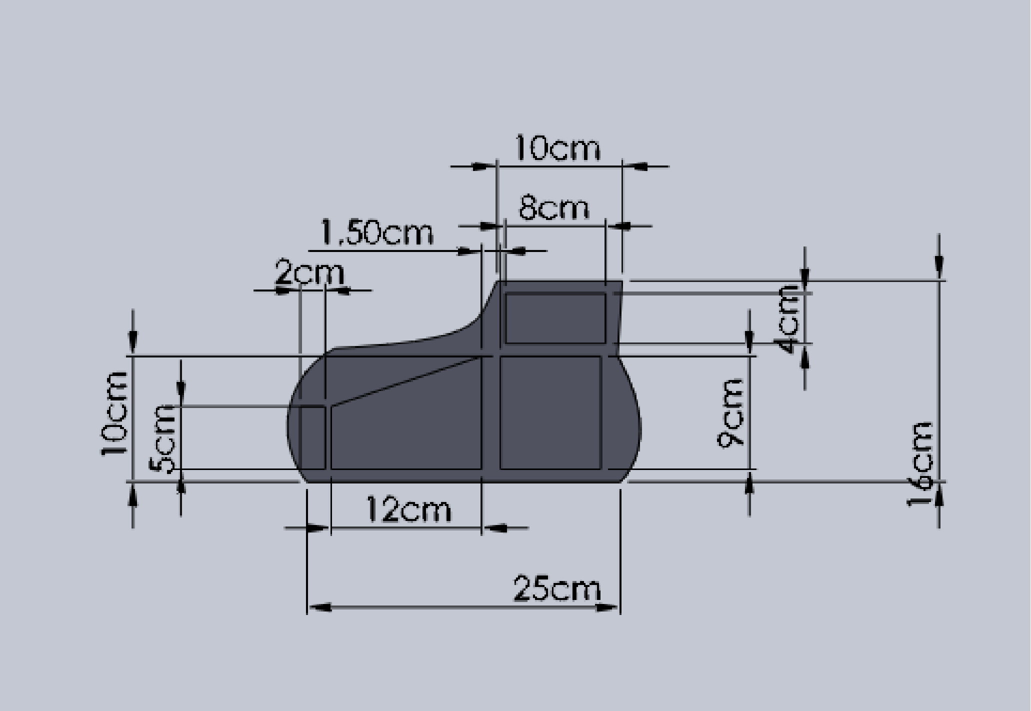


Figure 2.7: Cross section of interior and exterior side of foot for extrusion

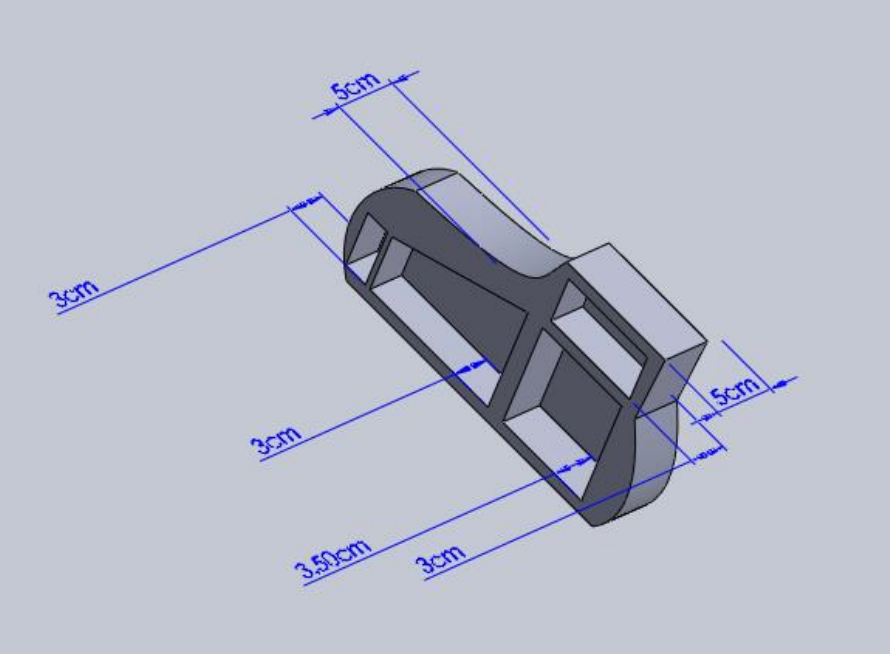


Figure 2.8: Instep

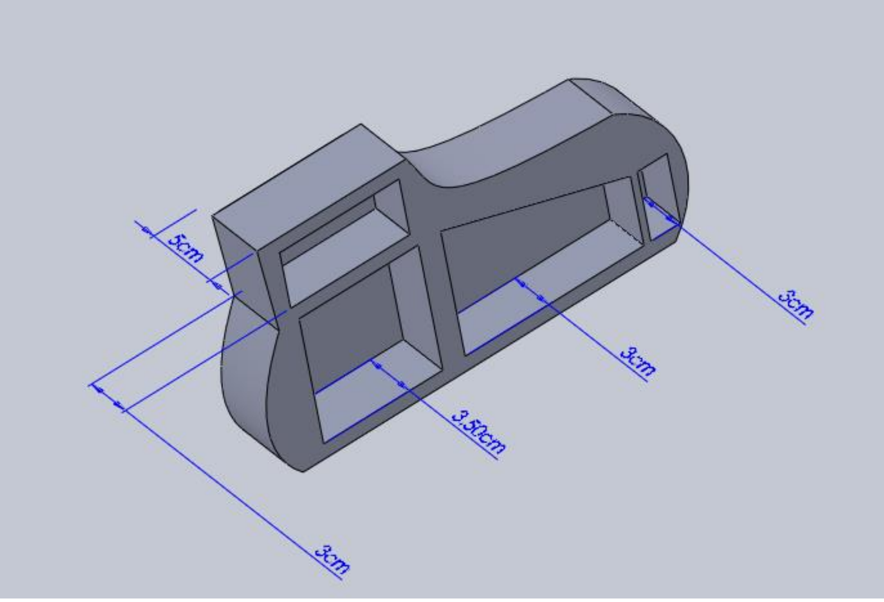


Figure 2.9: Outside of foot

The PVC ankle attachment region: The region where the PVC leg attaches to the foot can be modeled by a simple cylinder that rests on top of the ankle ridge on the foot. Figures 2.10 and 2.11 show the exterior PVC pipe region of the ankle. Figure 2.12 shows the rubber exterior region of the ankle. Figure 2.13 shows the cylindrical wooden block at the center of the ankle region and figure 2.14 shows the screw that holds the assembly together. The screw was simplified by removing geometric intricacies like the threading because these features caused problems with the mesh in later steps.

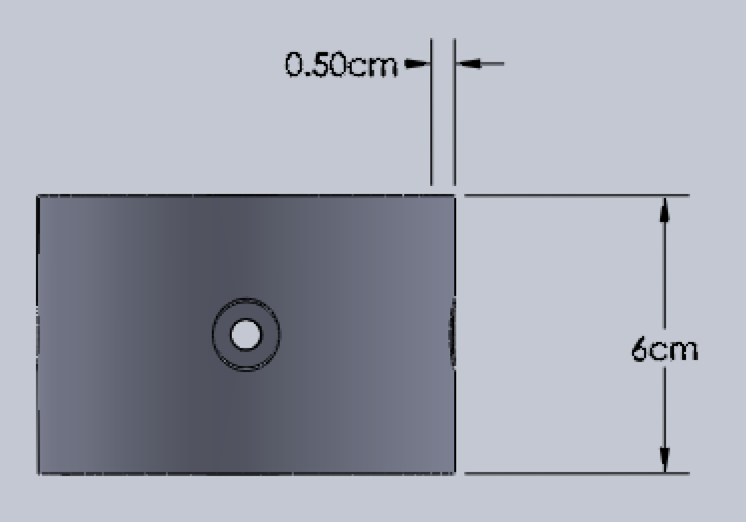


Figure 2.10: Side view of PVC ankle

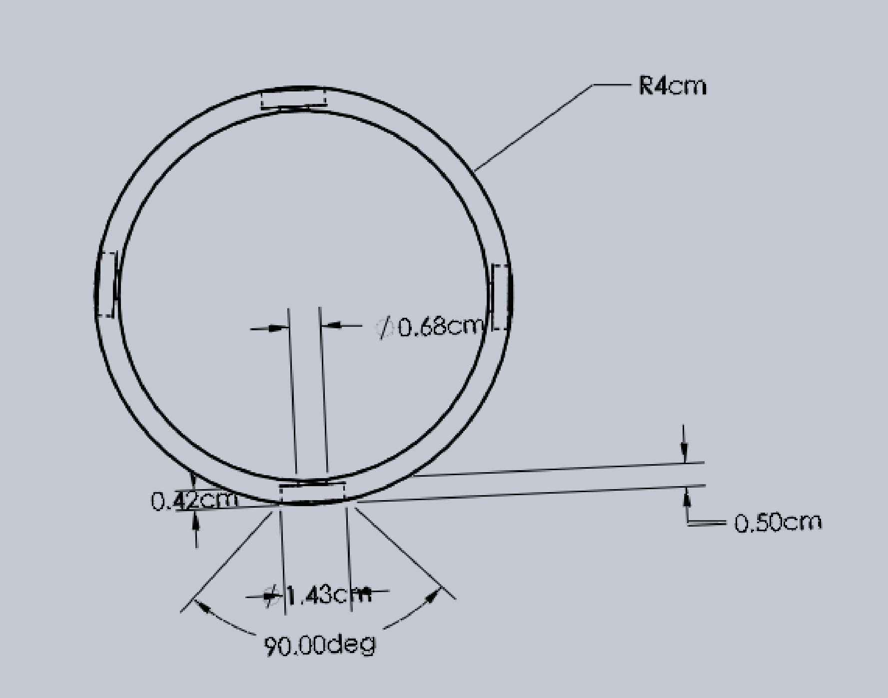


Figure 2.11: Top view of PVC ankle

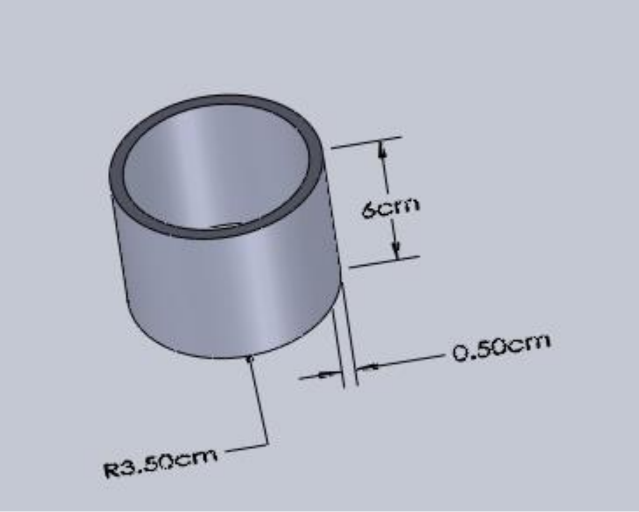


Figure 2.12: Rubber coating of ankle block

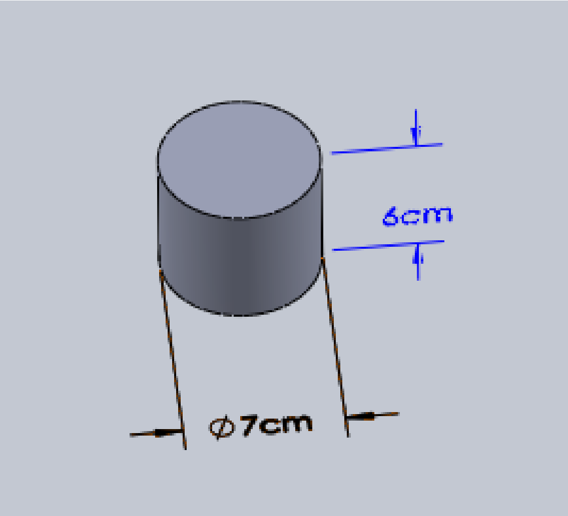


Figure 2.13: Cylindrical wooden center of ankle region

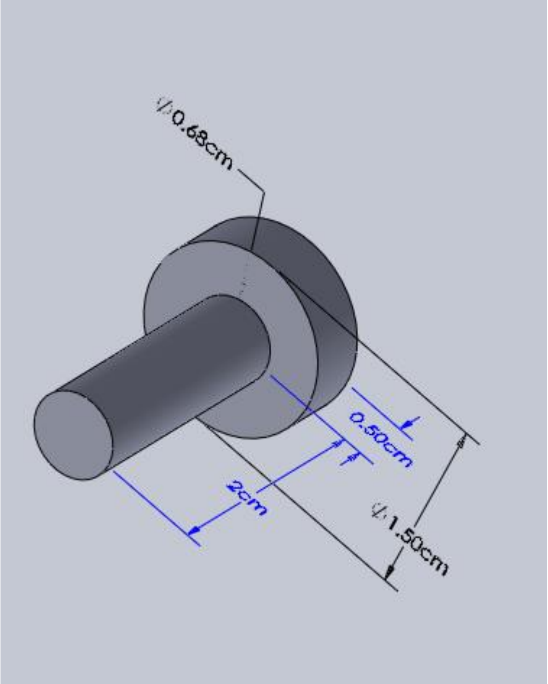


Figure 2.14: Screw for ankle attachment

Modeling of Static Stress on Ankle Attachment Using Comsol Multiphysics

Following the completion of the SolidWorks model of the Jaipur foot and PVC attachment, I exported the assembly into COMSOL Multiphysics. The goal of the first model was to determine the regions of maximum stress concentrations under a single load distributed around the edge of the PVC pipe leg. I used a distributed load of 60 kg to represent an average sized adult. This mass was distributed as a pressure. The force due to the mass was calculated using the equation 3.

$$F = m * g \qquad (3)$$

Therefore, the 60 kg mass will exert a 588 N force. The pressure was then calculated using equation 4.

$$P = F/A \qquad (4)$$

Since the PVC pipe is typically ⅛ in thick and has an exterior diameter of 5 cm, the area over which the force is applied is 8.64 cm^2 as calculated using equation 5.

$$A = \Pi(d_{ext}/2)^2 - \Pi(d_{int}/2)^2 \qquad (5)$$

The pressure was thus calculated as 680 kPa and applied over the PVC cross section.

Next, an equal and opposite force occurs across the base of the foot each time a step is taken. This can be represented in COMSOL as a distributed load across the base of the foot. Using the measure command in SolidWorks I determined the area of the base of the foot. It was 124.16 cm^2. I then used equation 4 again to determine the pressure. I calculated this to be 47358 Pa. I also fixed the base of the foot so it was not free to rotate because when a patient actually uses the prosthetic, their foot will be restricted by the surface on which they are stepping.

Following the creation of the SolidWorks parts of the cylindrical wood block, the rectangular wood block, the wedge shaped front block, the outside rubber of the foot, the inside rubber of the foot, and the top region of rubber at the ankle surrounded by the PVC pipe, I mated the parts together in SolidWorks. I also mated these screws into my design. The results of the mating assembly can be seen below in figures 2.15-2.17. Figure 2.15 is an isometric view of the exterior of the foot assembly. Figure 2.16 is an interior view of the foot from the side showing the screws and the blocks inside the foot. Figure 2.17is another interior shot of the foot highlighting the screws and front wedge block.

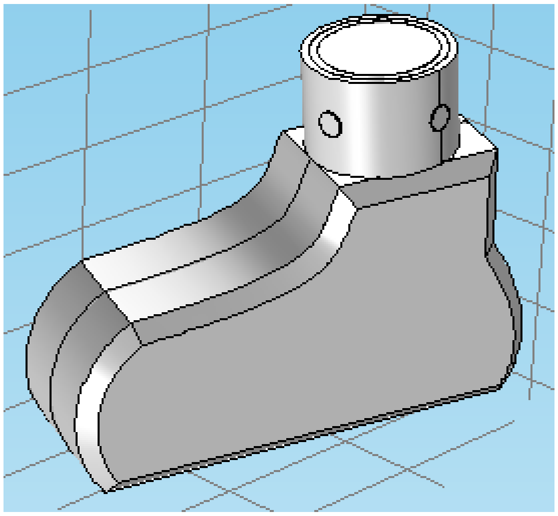


Figure 2.15: Isometric view of exterior of foot model

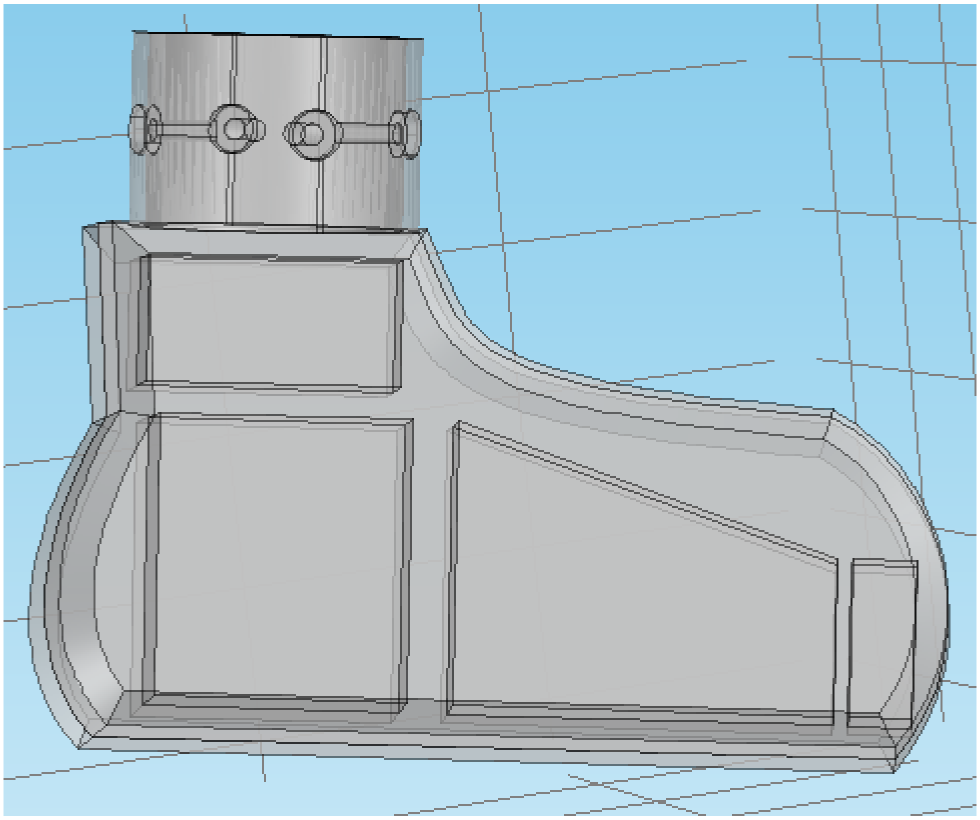


Figure 2.16: Interior view of the model from the side showing interior blocks and screws

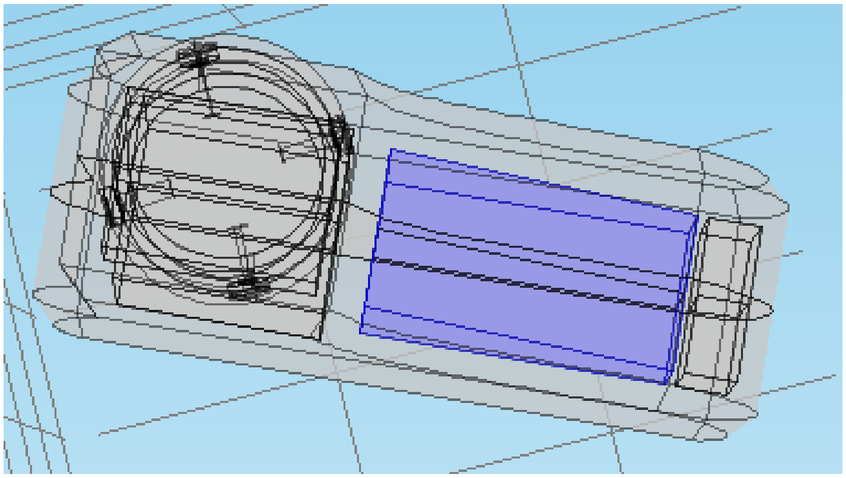
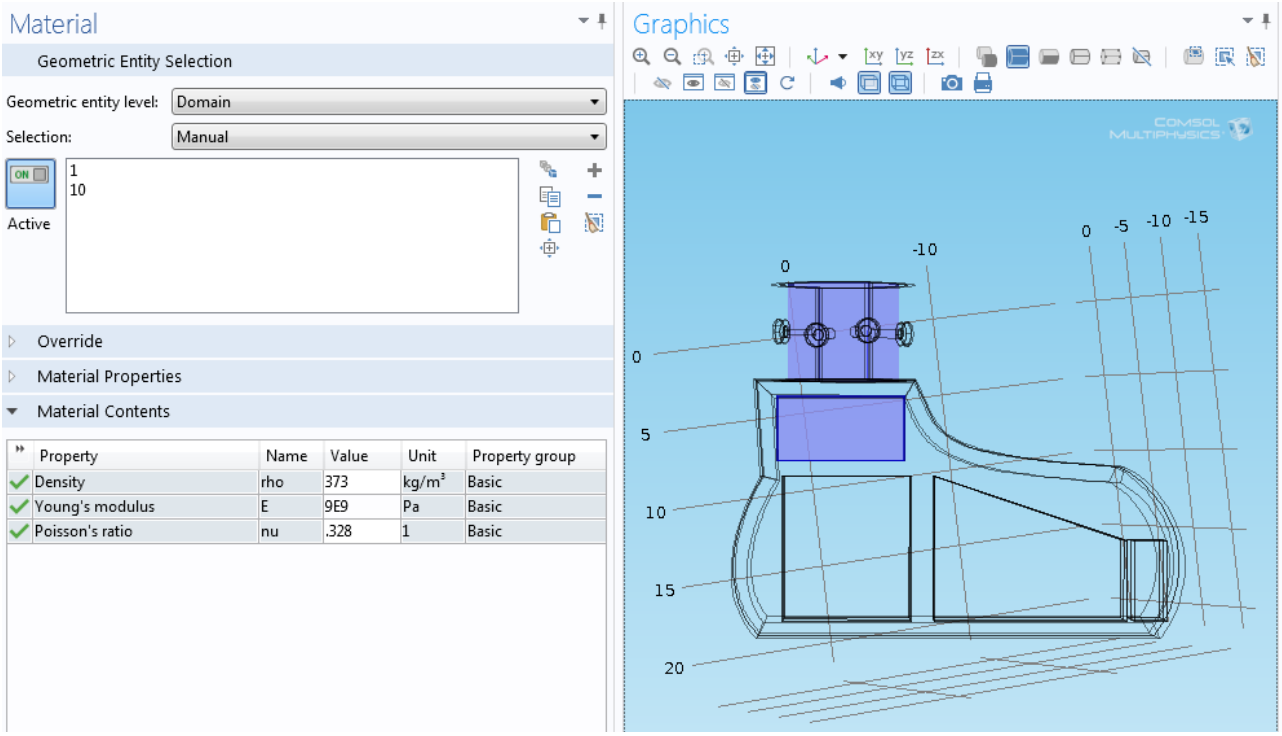


Figure 2.17: Interior view of foot highlighting interior screws and accentuating the front wedge block

Following the creation of the SolidWorks assembly, I imported the model to COMSOL Multiphysics. In COMSOL, I selected a structural mechanics study. I then selected solid mechanics. First, I defined the material of each section of the assembly as seen in figures 2.18-2.22 below. For the vulcanized rubber seen in figure 2.21 ("Tensile Stress-Strain Properties of Vulcanized or Thermoplastic Rubber (ISO 37).") and MCR in figure 2.22 (“Jaipur Foot test report Dr. Mathur”), I had to do an external search and define my own material based on the constants I obtained from my search because there was no given COMSOL material that was similar to the vulcanized rubber used to create the Jaipur feet ("Densities of Miscellaneous Solids."). Please note that in each figure, the purple selected region is the region defined by the material properties given to the left of the drawing.



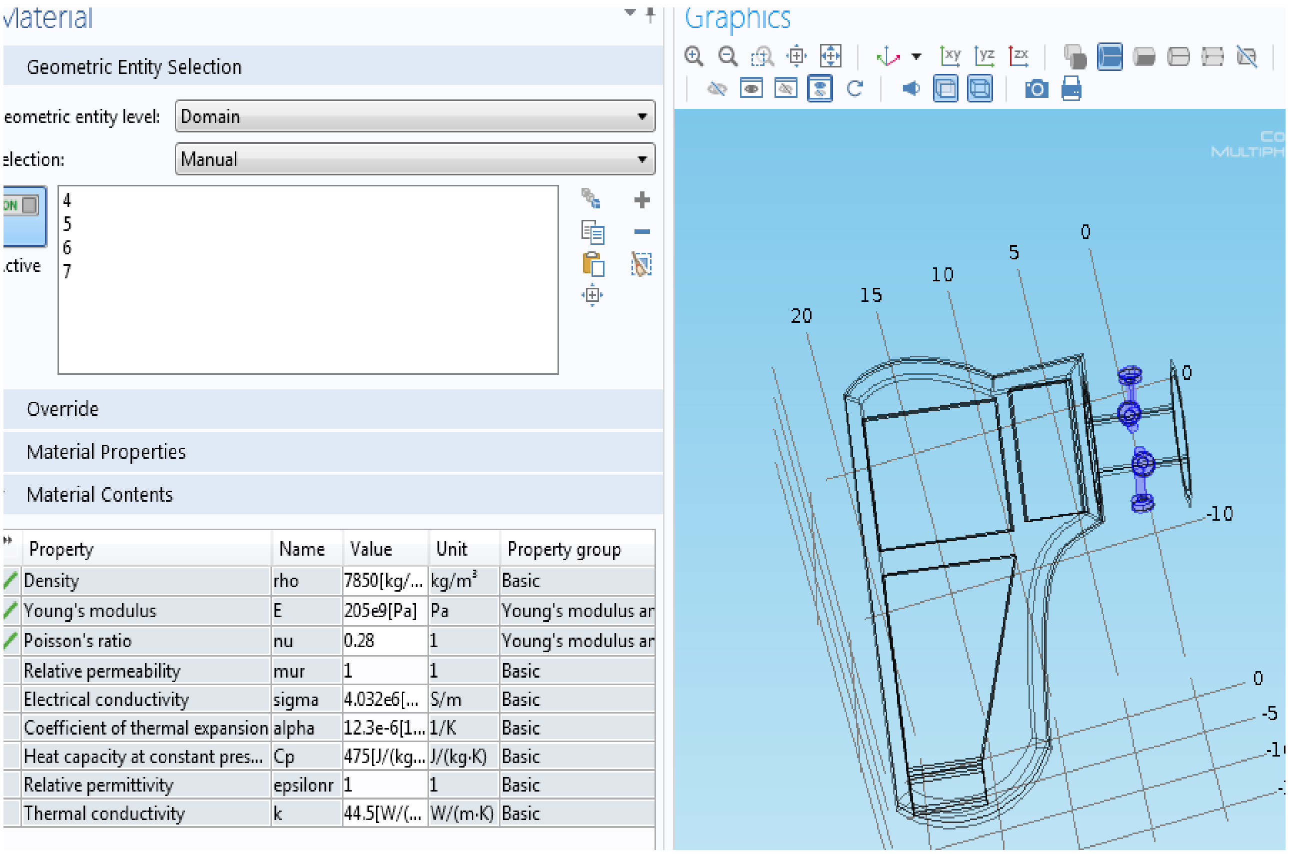
Geometric entity level: Domain

Selection: Manual

1
10

Property	Name	Value	Unit	Property group
✓ Density	rho	373	kg/m³	Basic
✓ Young's modulus	E	9E9	Pa	Basic
✓ Poisson's ratio	nu	.328	1	Basic

Figure 2.18: Defining material properties of wood blocks in COMSOL



Material

Geometric Entity Selection

eometric entity level: Domain

election: Manual

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4
5
6
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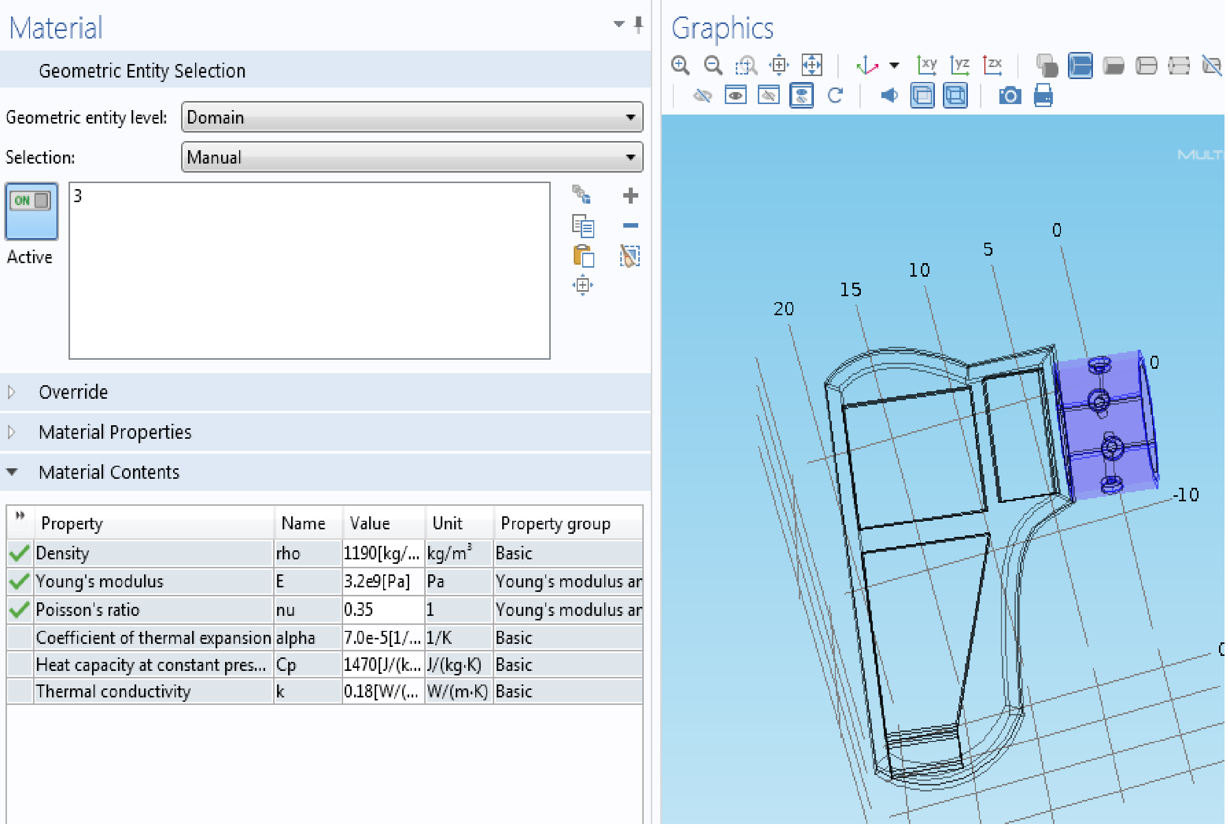
Override

Material Properties

Material Contents

Property	Name	Value	Unit	Property group
Density	rho	7850[kg/...	kg/m³	Basic
Young's modulus	E	205e9[Pa]	Pa	Young's modulus ar
Poisson's ratio	nu	0.28	1	Young's modulus ar
Relative permeability	mur	1	1	Basic
Electrical conductivity	sigma	4.032e6[...	S/m	Basic
Coefficient of thermal expansion	alpha	12.3e-6[1...	1/K	Basic
Heat capacity at constant pres...	Cp	475[J/(kg...	J/(kg·K)	Basic
Relative permittivity	epsilonr	1	1	Basic
Thermal conductivity	k	44.5[W/(...	W/(m·K)	Basic

Figure 2.19: Defining material properties of steel screws in COMSOL



Geometric Entity Selection

Geometric entity level: Domain

Selection: Manual

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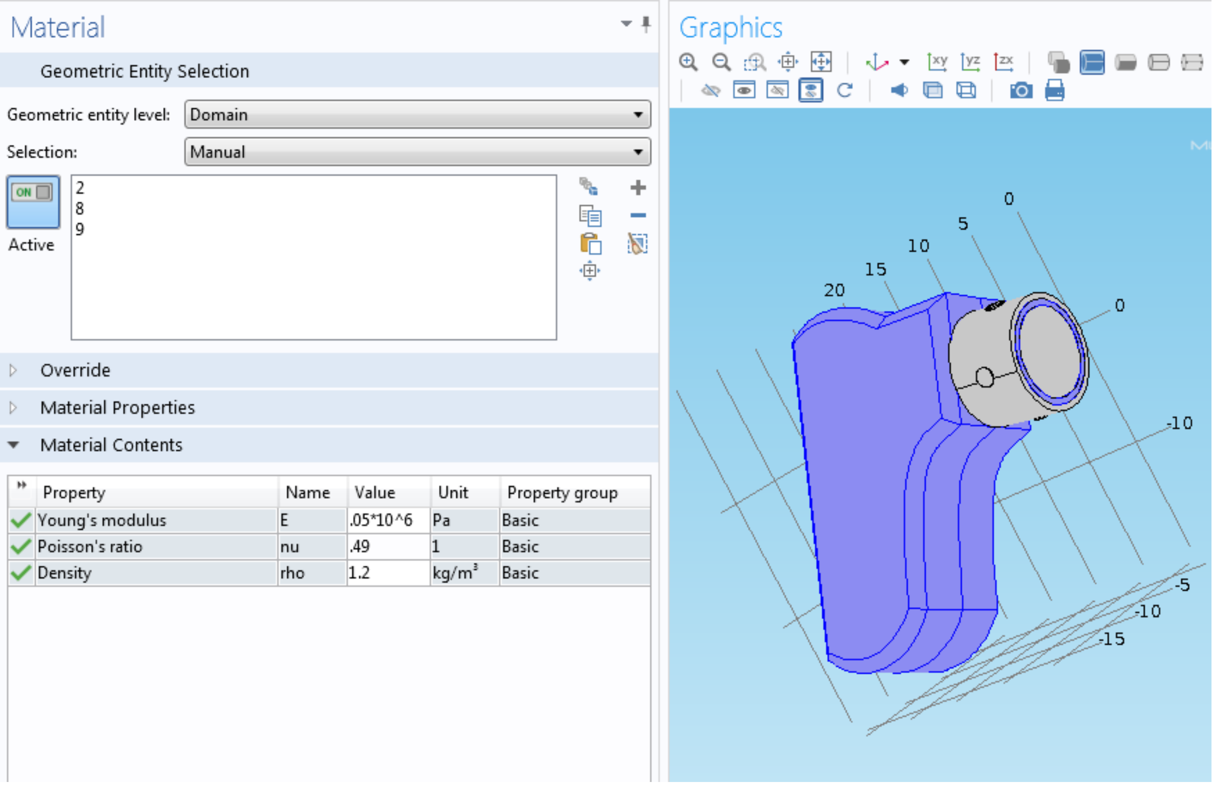
3

	Property	Name	Value	Unit	Property group
✓	Density	rho	1190[kg/...	kg/m^3	Basic
✓	Young's modulus	E	3.2e9[Pa]	Pa	Young's modulus ar
✓	Poisson's ratio	nu	0.35	1	Young's modulus ar
	Coefficient of thermal expansion	alpha	7.0e-5[1/...	1/K	Basic
	Heat capacity at constant pres...	Cp	1470[J/(k...	J/(kg·K)	Basic
	Thermal conductivity	k	0.18[W/(...	W/(m·K)	Basic

Figure 2.20: Defining the material properties of PVC leg section in COMSOL



Geometric Entity Selection

Geometric entity level: Domain

Selection: Manual

2
8
9

Active

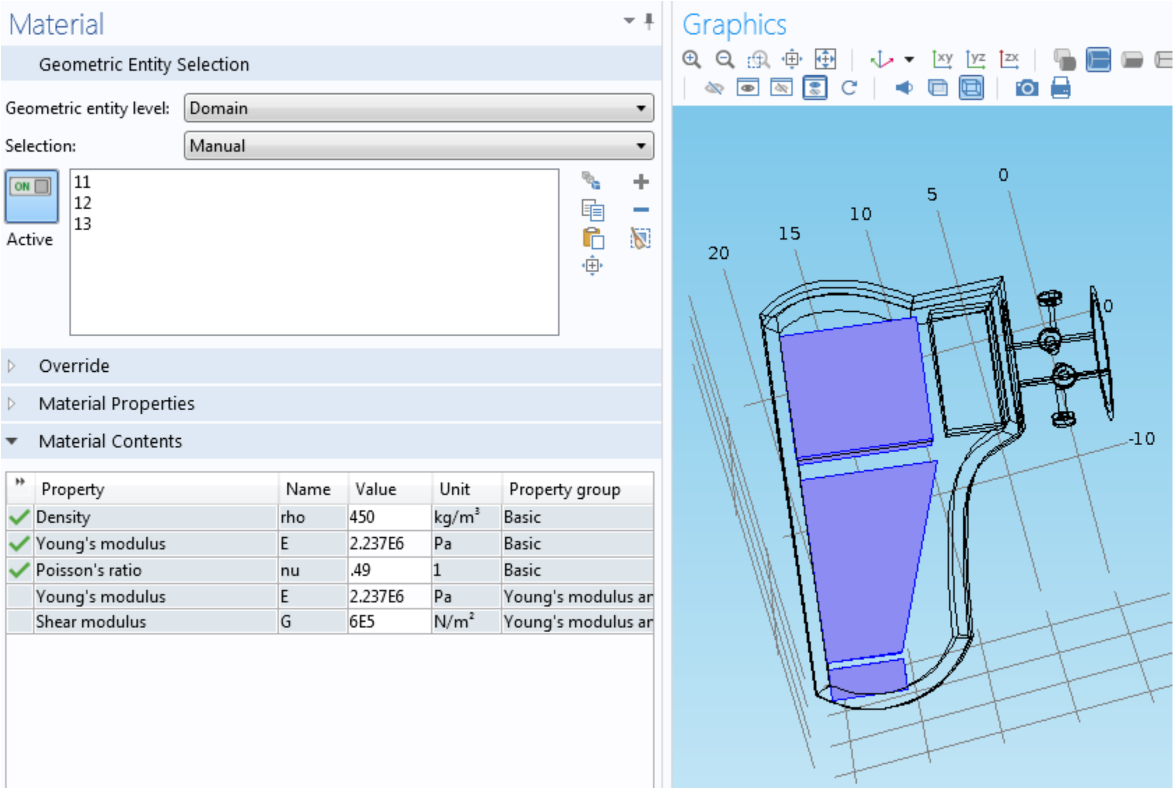
Override

Material Properties

Material Contents

	Property	Name	Value	Unit	Property group
✓	Young's modulus	E	.05*10^6	Pa	Basic
✓	Poisson's ratio	nu	.49	1	Basic
✓	Density	rho	1.2	kg/m^3	Basic

Figure 2.21: Defining material properties of vulcanized rubber exterior in COMSOL



Material

Geometric Entity Selection

Geometric entity level: Domain

Selection: Manual

11
12
13

Active

Override

Material Properties

Material Contents

	Property	Name	Value	Unit	Property group
✓	Density	rho	450	kg/m³	Basic
✓	Young's modulus	E	2.237E6	Pa	Basic
✓	Poisson's ratio	nu	.49	1	Basic
	Young's modulus	E	2.237E6	Pa	Young's modulus ar
	Shear modulus	G	6E5	N/m²	Young's modulus ar

Figure 2.22: Defining Material properties of MCR interior blocks

Following the definition of the materials, I defined the applied forces, the initial conditions, and the fixed boundaries. First, I defined the initial displacement and velocity at all points to be zero. Next, I fixed the bottom of the foot in space. This simulates the inability of the bottom of the foot to move once the person has stepped and is standing on the foot due to the restriction of the ground on which they are standing. Finally, I defined a downward force of 440 kPa around the top of the PVC leg. This is due to the fact that the entire person’s weight (approximated as an average of 588 N) will be distributed across the top of the PVC leg. This region of force application can be seen in figure 2.23.

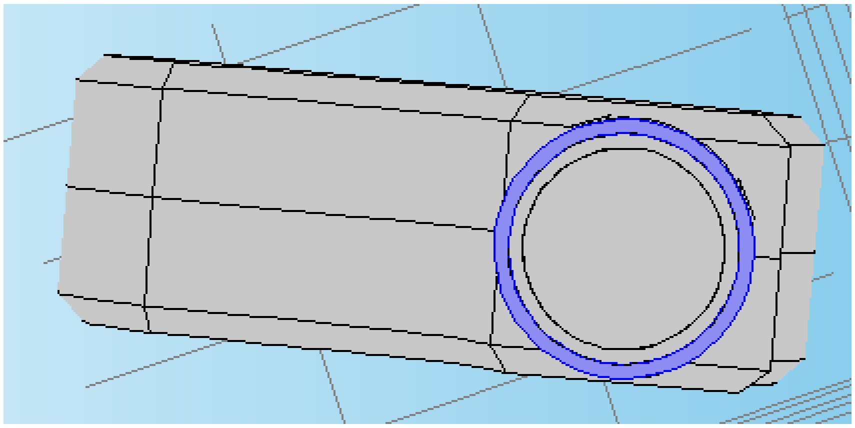


Figure 2.23: Region of downward force application

To balance this force, there must be an equal and opposite force from the ground on which the amputee is standing up to the bottom of the foot. I therefore defined a force of 588 N distributed across the bottom of the foot. Since the area of the bottom of the foot is .02 m^2, I applied a distributed load upward of 29400 Pa (figure 2.24).

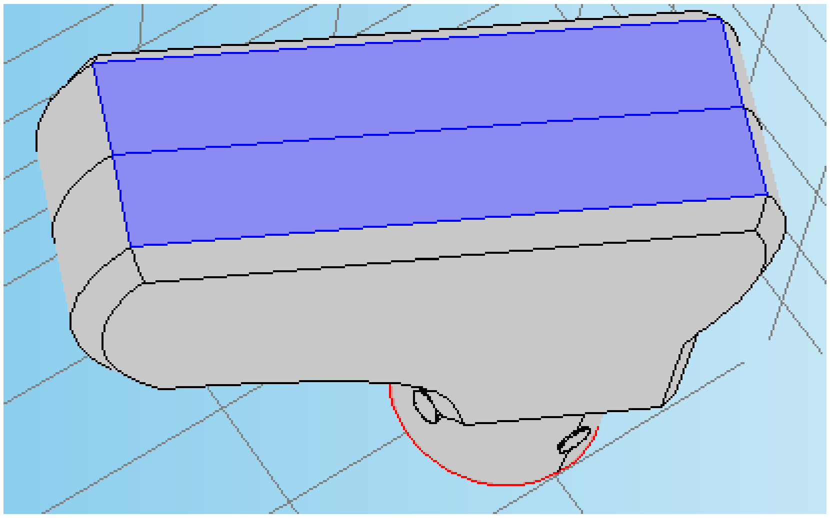


Figure 2.24: Region of upward force application

Following the application of the loads and boundary conditions, I created a mesh for finite element analysis. I used a fine, physics controlled mesh (figure 2.25).

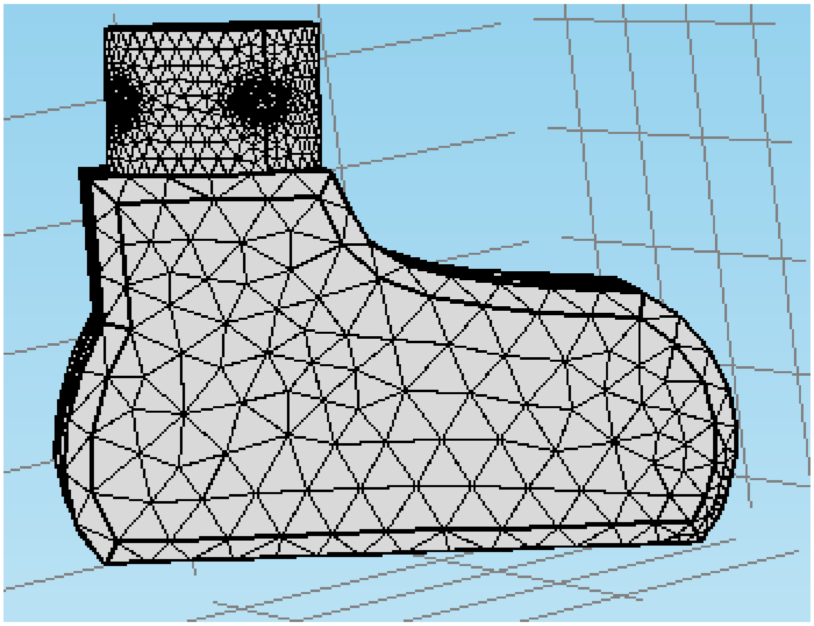


Figure 2.25: Fine, physics controlled mesh for finite element analysis

Following the original stationary study I also completed the same study with a parametric sweep of the mass. This means that the study will compute the stress across the ankle region based on different values of the mass of the person standing on the prosthetic. This will help to determine the relationship between the mass and the maximum von mises stress. The goal is that once this relationship is determined, the mass necessary to cause the materials of the ankle to yield can be determined.

To complete the parametric sweep, I defined a parameter for the mass with units of kilograms. Then, under the study I added a parametric sweep with the values ranging from 40 kg to 120 kg with a value every 10 kg. I did this so that there would be enough values and a large enough range to allow for the determination of the maximum stress as a function of the mass applied to the prosthetic. Finally, I change the force applied to the top and bottom of the foot to a function of the mass instead of the previous calculated values. The pressure applied to the top of the foot was written as mass*9.8/.001335 since the area of the application is .001335 m^2. The pressure applied upward to the bottom of the foot was written as mass*9.8/.02 because the area of the application is .02 m^2. At this point I computed the model again.

Obtaining Pressure Distribution of a stride from Pressure Plate Results

A group of bioengineering capstone design students led by Ryan Fleming looked to compare the pressure distribution of a stride using the Jaipur foot to that of a regular foot and a mass produced polyurethane foot. The group created a rig to simulate the motion of the leg swing associated with a stride. They then attached the Jaipur feet and the other polyurethane mass produced feet to the rig under a load of 45 kg. Figure 2.26 shows the results of a representative Jaipur foot with the peaks representing the maximum pressure that was experienced at each point of the foot during a single stride. There is a notable increase in pressure at the rear and front of the foot for the portions of the stride that correspond to the heel striking the ground and the toes pushing off the ground to begin the next stride (Fleming, et al.).

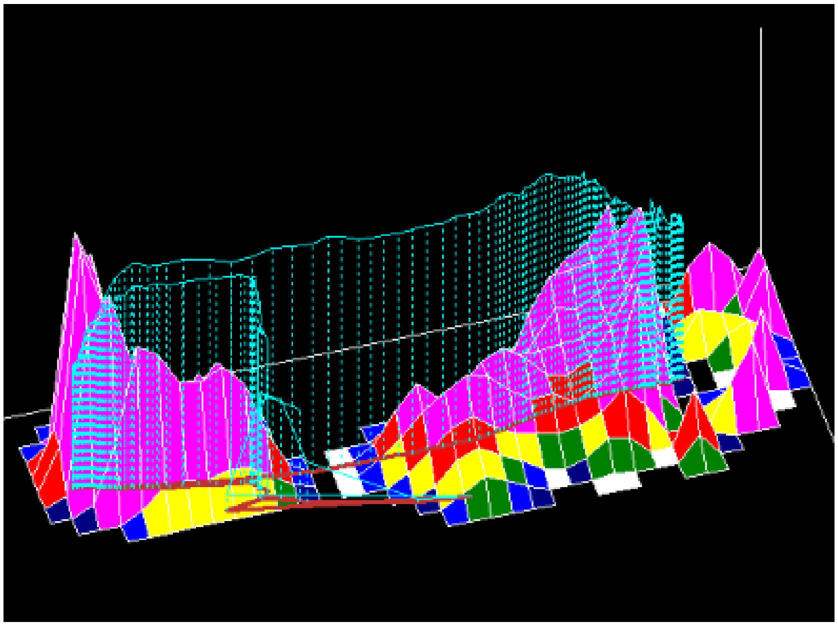


Figure 2.26: Jaipur foot pressure data

The same pressure plate that gave the peak pressures shown above also provided the total pressure across the foot at each instant of the stride. Figure 2.27 shows the resulting pressure graph of the stride of a representative Jaipur foot (Flemming, et al.).

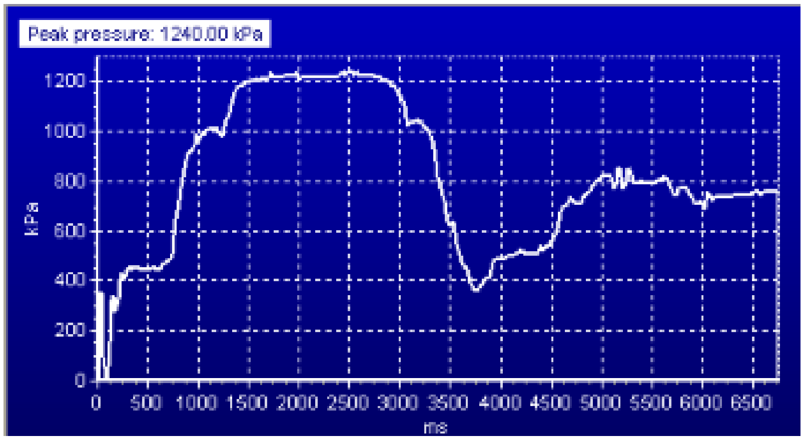
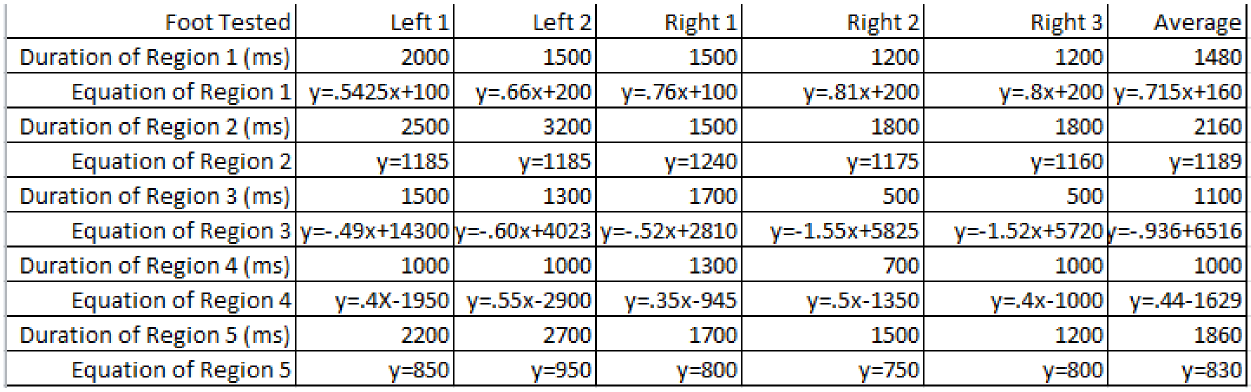


Figure 2.27: Pressure as a function of time throughout the stride of Jaipur foot

Data from the graph in figure 2.27 and the corresponding data of the other 3 Jaipur feet were combined and analyzed using matlab to form an averaged piecewise function to represent the pressure applied to the bottom of the Jaipur foot as a function of the time within the stride. The other data used to compute the average pressure throughout the stride can be seen in Apppendix A. This analysis led to an averaged piece-wise function. The averaging method can be seen in table 2.1, and the resulting graph of the average function is shown in figure 2.28.



Foot Tested	Left 1	Left 2	Right 1	Right 2	Right 3	Average
Duration of Region 1 (ms)	2000	1500	1500	1200	1200	1480
Equation of Region 1	y=.5425x+100	y=.66x+200	y=.76x+100	y=.81x+200	y=.8x+200	y=.715x+160
Duration of Region 2 (ms)	2500	3200	1500	1800	1800	2160
Equation of Region 2	y=1185	y=1185	y=1240	y=1175	y=1160	y=1189
Duration of Region 3 (ms)	1500	1300	1700	500	500	1100
Equation of Region 3	y=-.49x+14300	y=-.60x+4023	y=-.52x+2810	y=-1.55x+5825	y=-1.52x+5720	y=-.936+6516
Duration of Region 4 (ms)	1000	1000	1300	700	1000	1000
Equation of Region 4	y=.4X-1950	y=.55x-2900	y=.35x-945	y=.5x-1350	y=.4x-1000	y=.44-1629
Duration of Region 5 (ms)	2200	2700	1700	1500	1200	1860
Equation of Region 5	y=850	y=950	y=800	y=750	y=800	y=830

Table 2.1: Piecewise function determination for modeling of a single stride

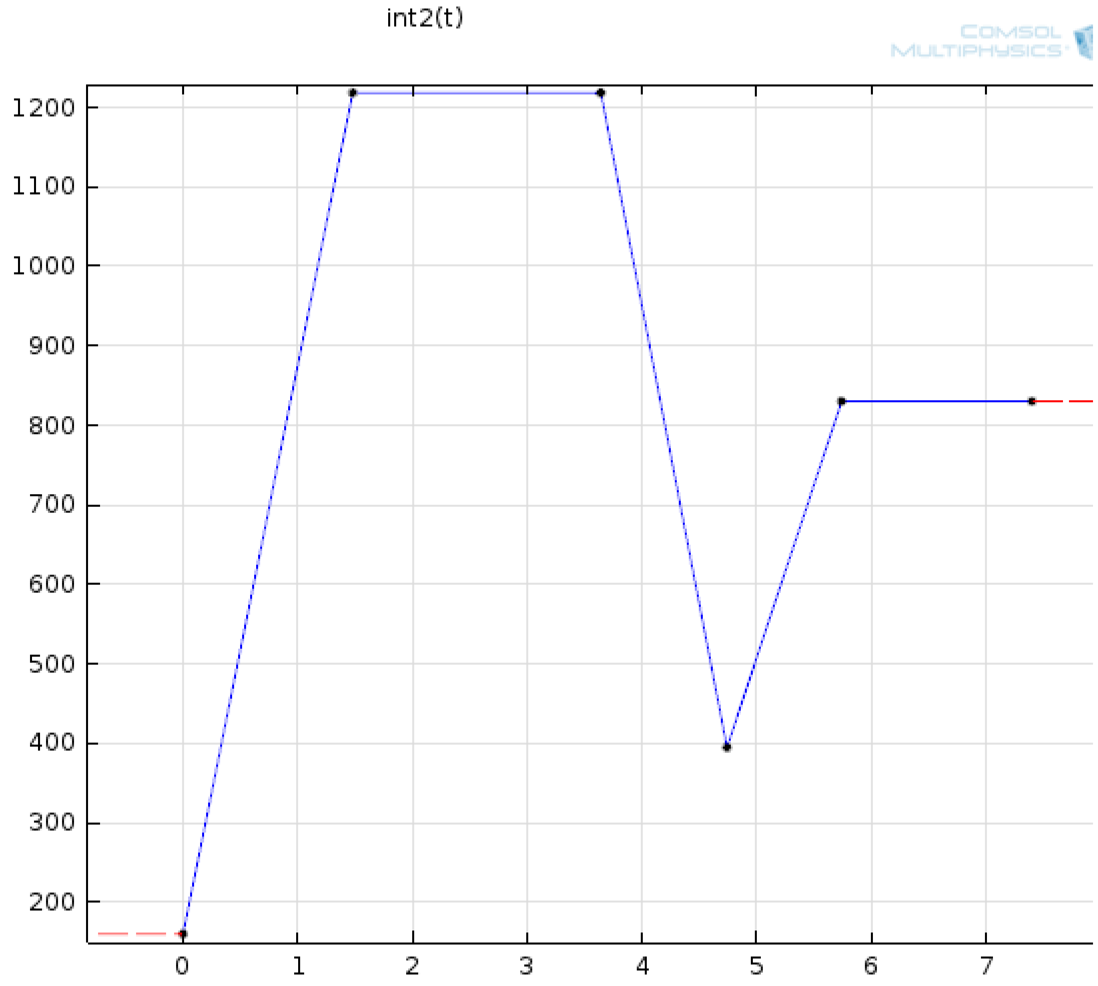


Figure 2.28: Input into cyclic model (pressure (kPa) vs time (s))

Modeling response to cyclic stride pressure using comsol multiphysics

The purpose of this COMSOL model was to determine how the current ankle attachment reacts to fatigue stress. Thus, I created a time dependent model that followed the same physical model as the first comsol model with the same material properties, but different inputs as the pressure. The foot is pressurized during the part of the step when it is striking the ground. During this time, I assumed that the distributed force across the top of the ankle would be the same as in the first model or 440 kPa. I used the piecewise equation obtained in the previous section as the time dependent response of the pressure across the bottom of the foot.

The first major peak in pressure is the heel strike of the prosthetic as it initiates the stride. The second smaller peak is the toe-off as the prosthetic leaves contact with the pressure plate completely. For my model, I created a function of the pressure over one stride (figure 2.28)

Once I had determined the piecewise function based on the average of the previous pressure plate data, I created a new COMSOL model. This time, the model was time dependent. I input the same SolidWorks model, but this time the pressure across the bottom of the foot was a function of time following the function I had determined from previous data. Thus in the boundary load I input the interpolation (int(t)) and multiplied this value by 1000 because the function is in kPa and the input must be in pascals.

Chapter 3

Results

Stationary study to detemnine maximum stress concentration due to constant loading

Figures 3.1 and 3.2 show the von mises stress in the ankle region after application of a force corresponding to a person weighing 60kg standing on the prosthetic. Von mises stress is a way of determining how several different normal and shear stresses combine to see if they will cause the material to yield (Norton).

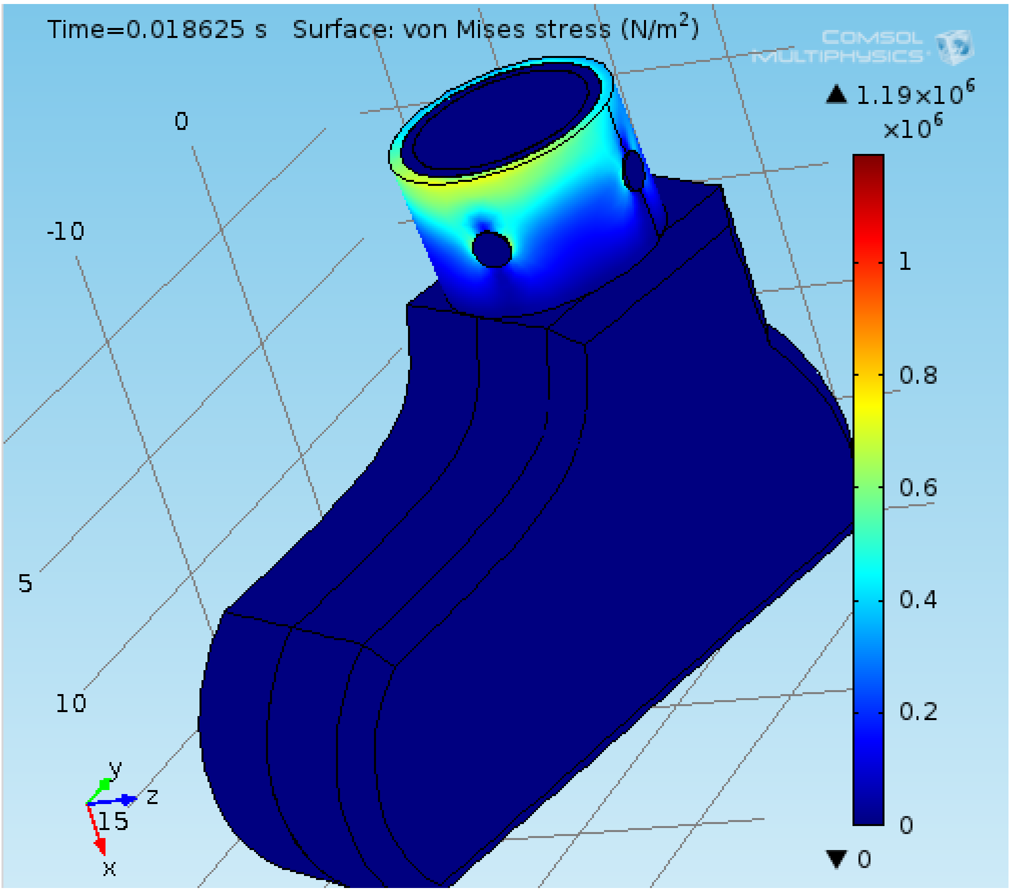
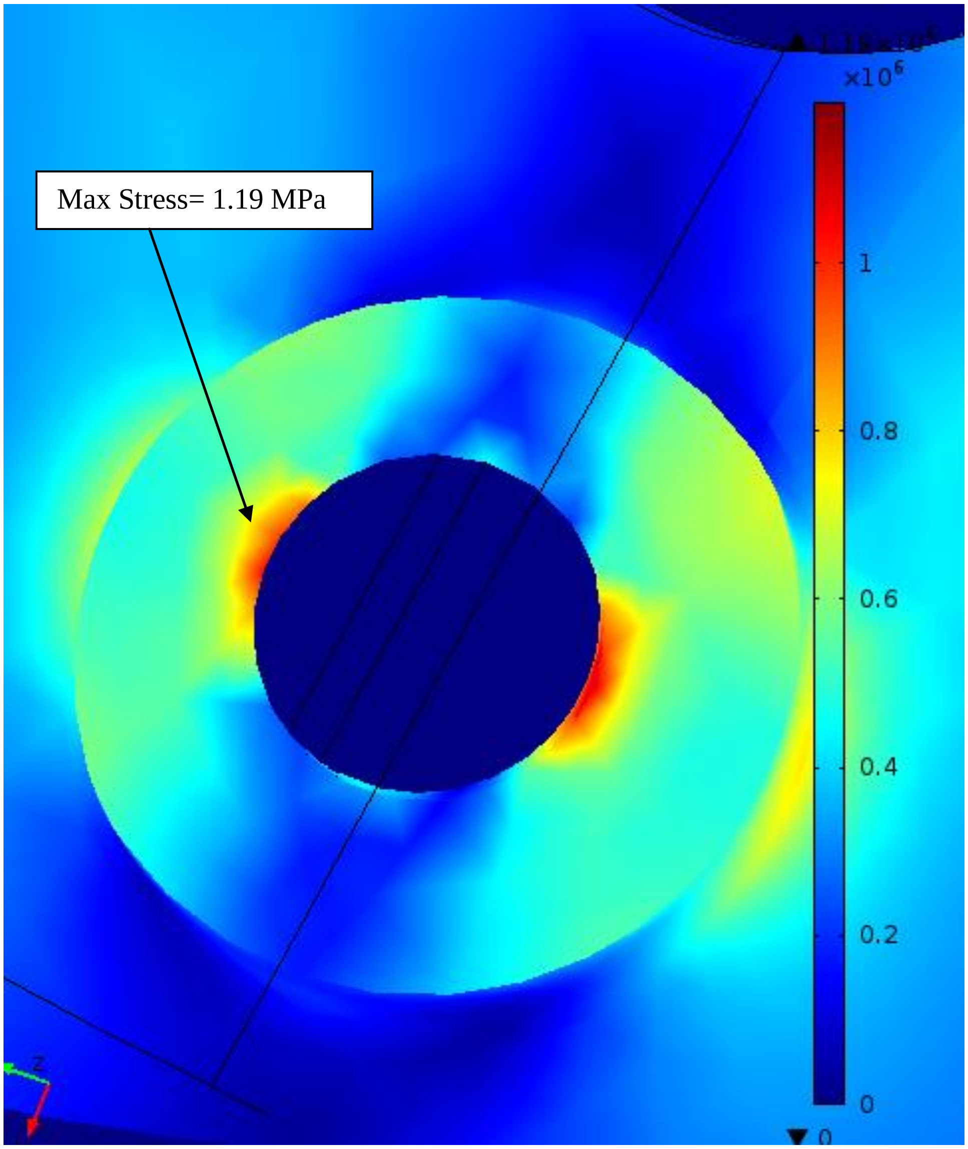


Figure 3.1: Results of stationary study (60kg person)



Max Stress= 1.19 MPa

Figure 3.2: Stress concentration at screw-ankle interface (60kg person)

Following the initial computation of von mises stress for a 60 kg person, I performed a parametric sweep of the mass. I varried the mass of the person using the prosthetic from 40 kg up to 120 kg to determine how the ankle stresses would be affected by users of different mass. The results of the parametric sweep can be seen in figures 3.3 to 3.11. The maximum von mises stress in each case is shown in the upper right at the top of the scale bar.

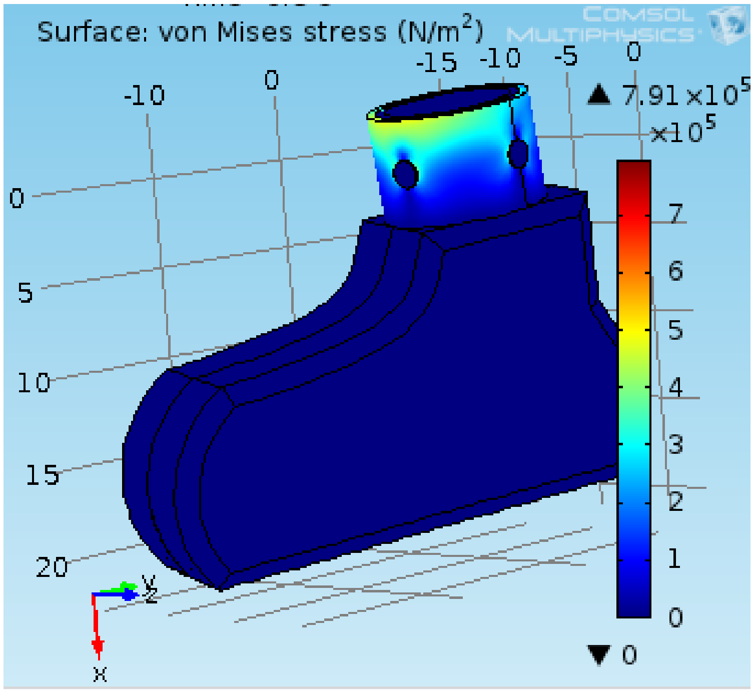


Figure 3.3: Results of stationary study (40 kg person)

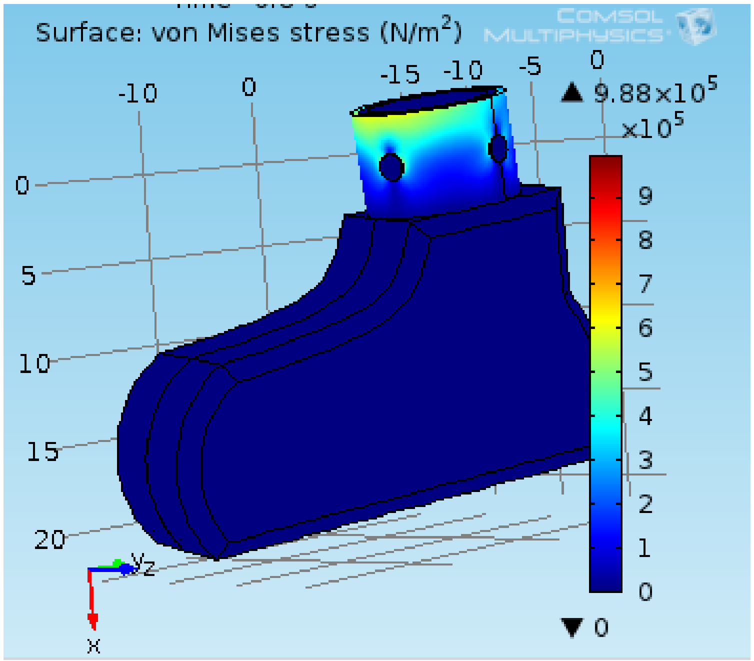


Figure 3.4: Results of stationary study (50 kg person)

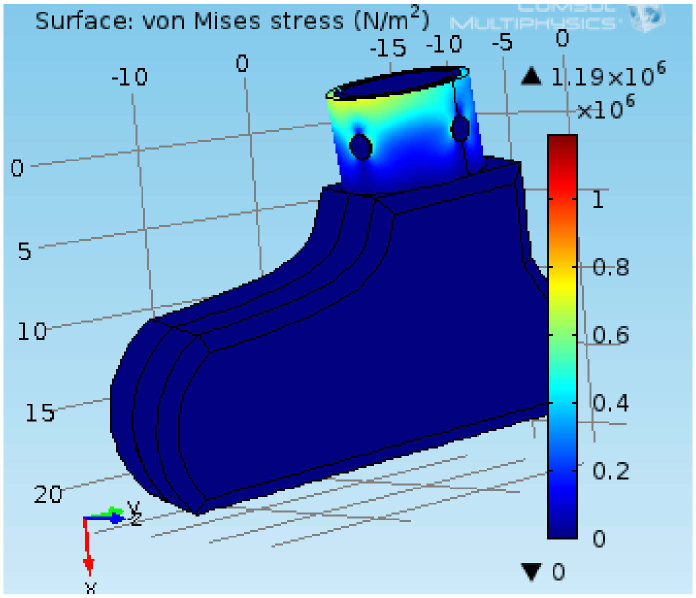


Figure 3.5: Results of stationary study (60 kg person)

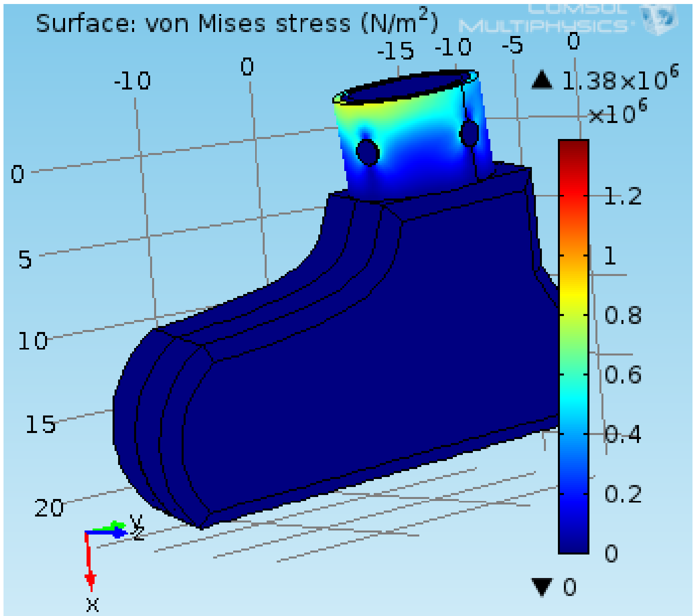


Figure 3.6: Results of stationary study (70 kg person)

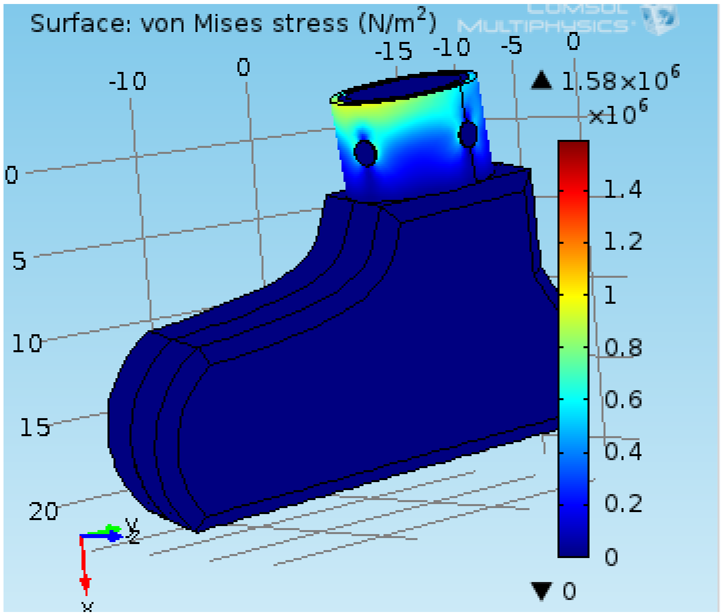


Figure 3.7: Results of stationary study (80 kg person)

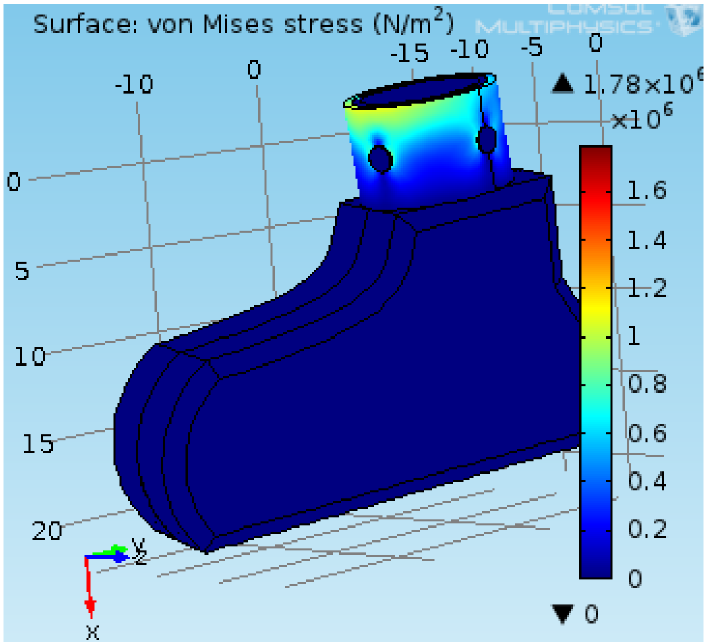


Figure 3.8: Results of stationary study (90 kg person)

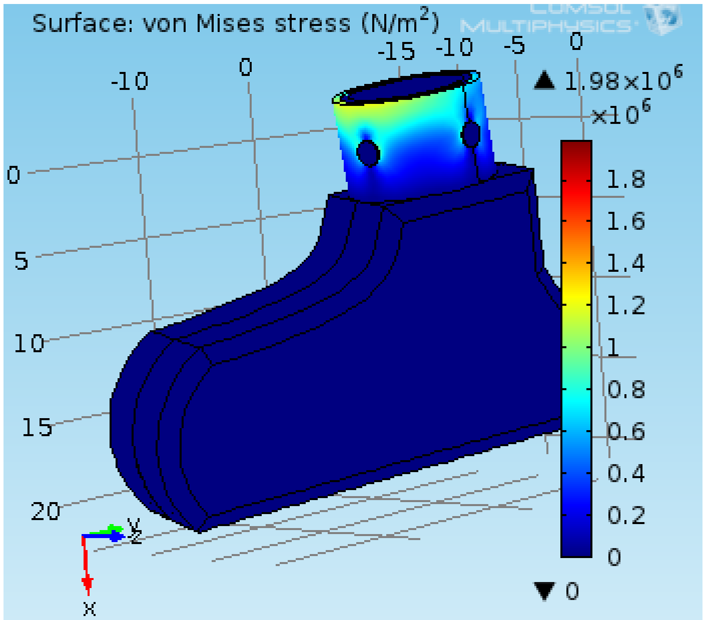


Figure 3.9: Results of stationary study (100 kg person)

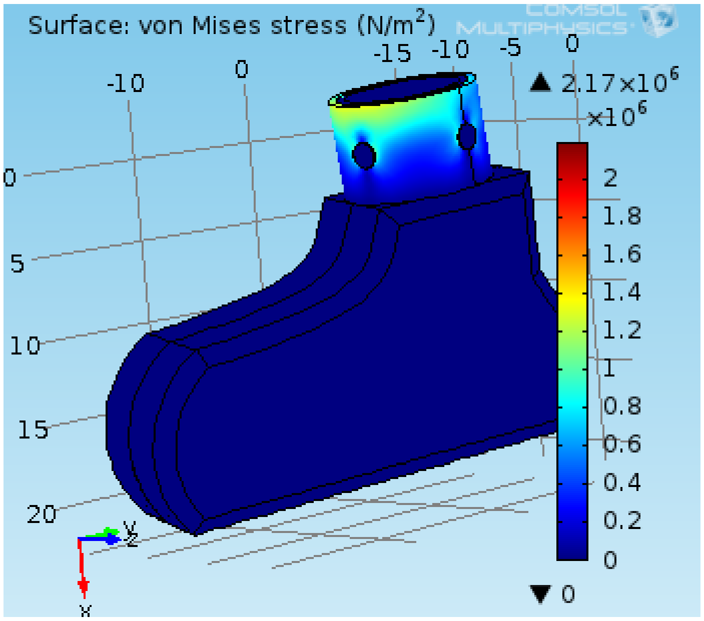


Figure 3.10: Results of stationary study (110 kg person)

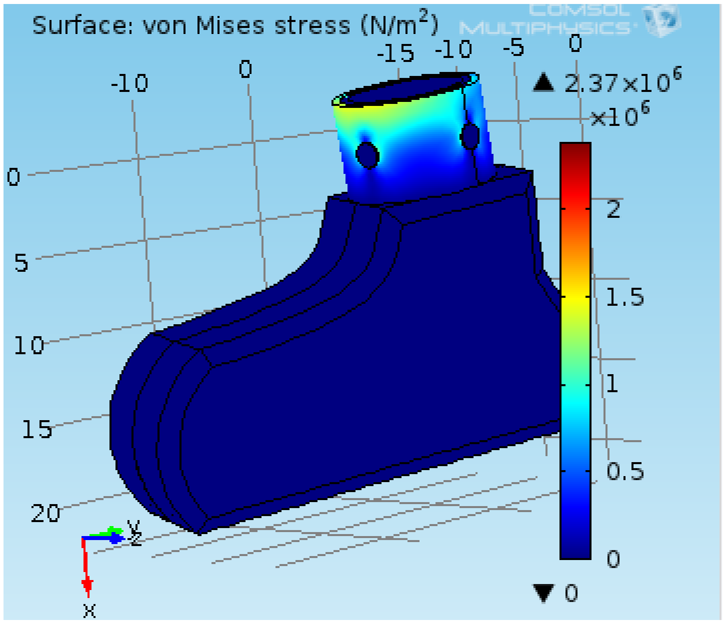


Figure 3.11: Results of stationary study (120 kg person)

Following the parametric sweep, I compiled a graph of the maximum von mises stress for the varying masses of users (figure 3.12).

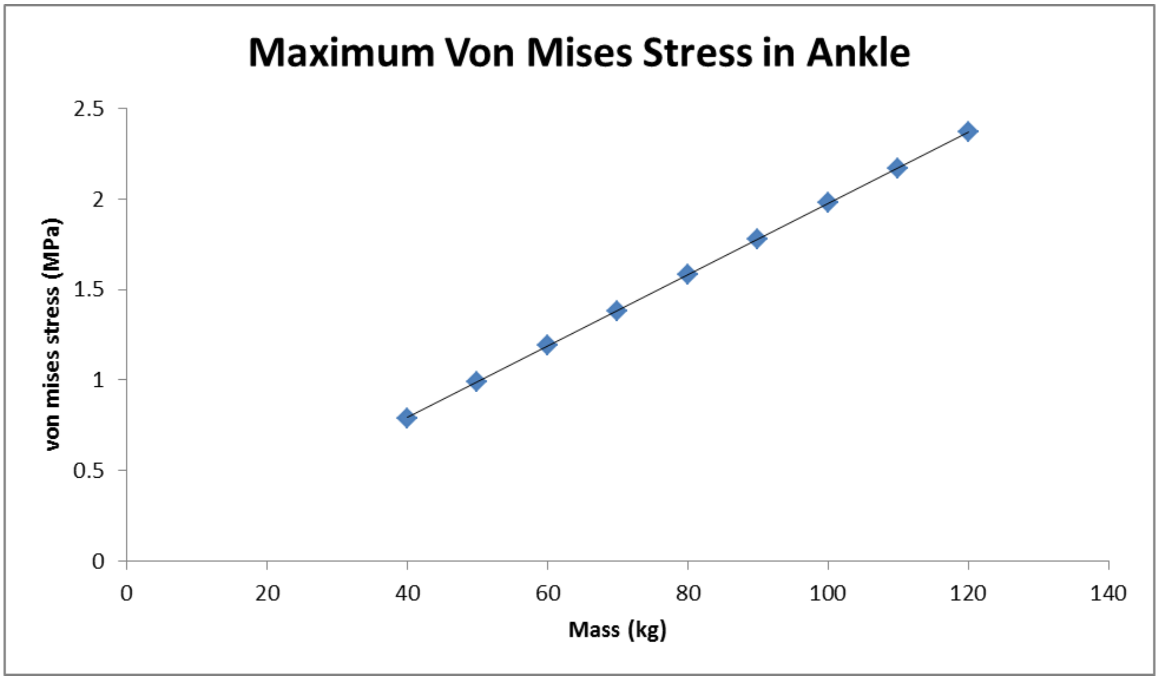


Figure 3.12: Max stresses from stationary study parametric sweep

Time dependent study to determine response to cyclic loading

The next thing I explored was the effect that the cyclic loading of a stride would have on the foot and ankle assembly. To do this, I looked to the work of Ryan Fleming and his senior design team. As explained in the methods section, his team explored the pressure fluctuation throughout a stride. They did this by simulating a stride with 5 different Jaipur feet. Figures A.1 to A.5 in Appendix A are the results of this study (Fleming, et al.). The input function of pressure across the bottom of the foot can be seen in figure 2.28.

The results of the study can be seen in figures 3.13 to 3.16. A video of the response can be seen in the separate video file as noted in Appendix C. Figure 3.13 shows the stress across the ankle region at the onset of the pressure function and figure 3.14 is a view of the screw interface at the same time. Figure 3.15 shows the stress across the ankle region at the end of the stride and figure 3.16 shows the stress at the screw interface at the end of the stride. Further figures showing the stress at different time steps can be seen in Appendix B.

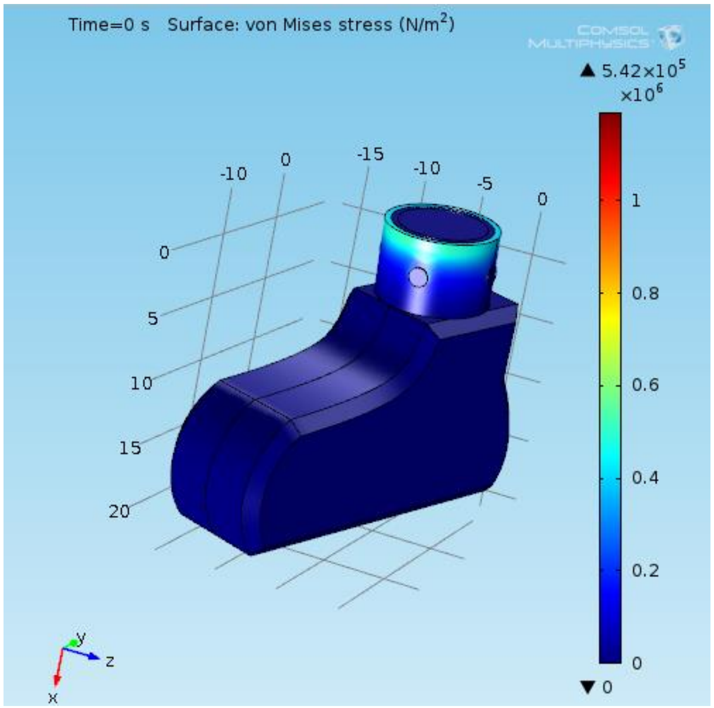


Figure 3.13: Cyclic loading stress at time = 0 sec

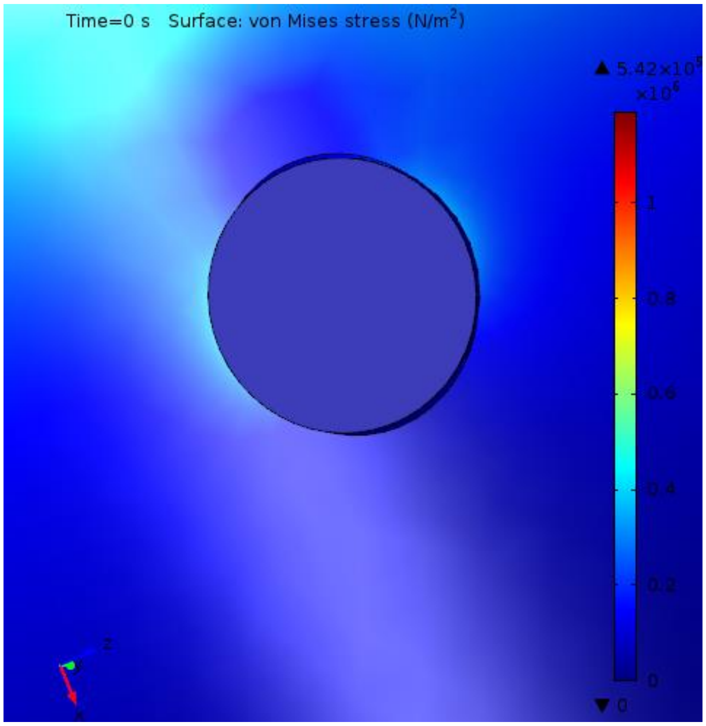


Figure 3.14: Cyclic loading stress at time = 0 sec at screw interface

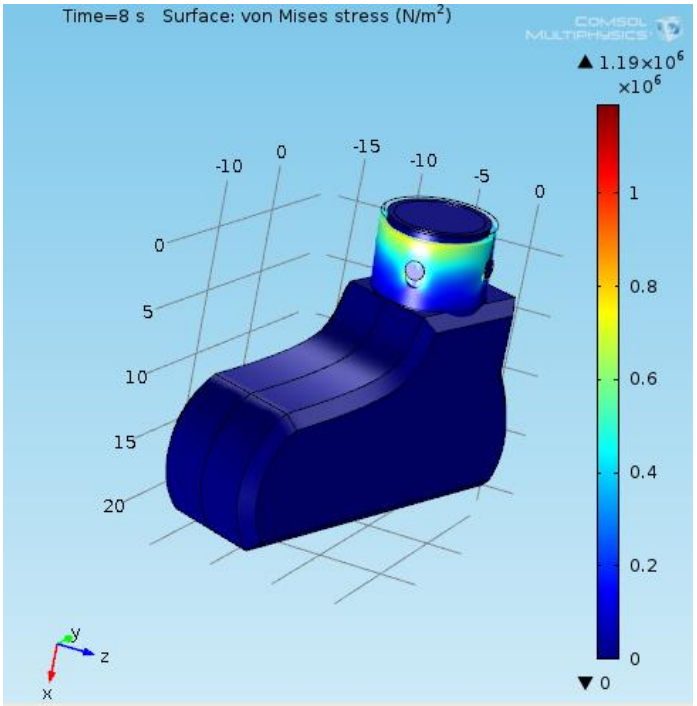


Figure 3.15: Cyclic loading stress at time = 8 sec

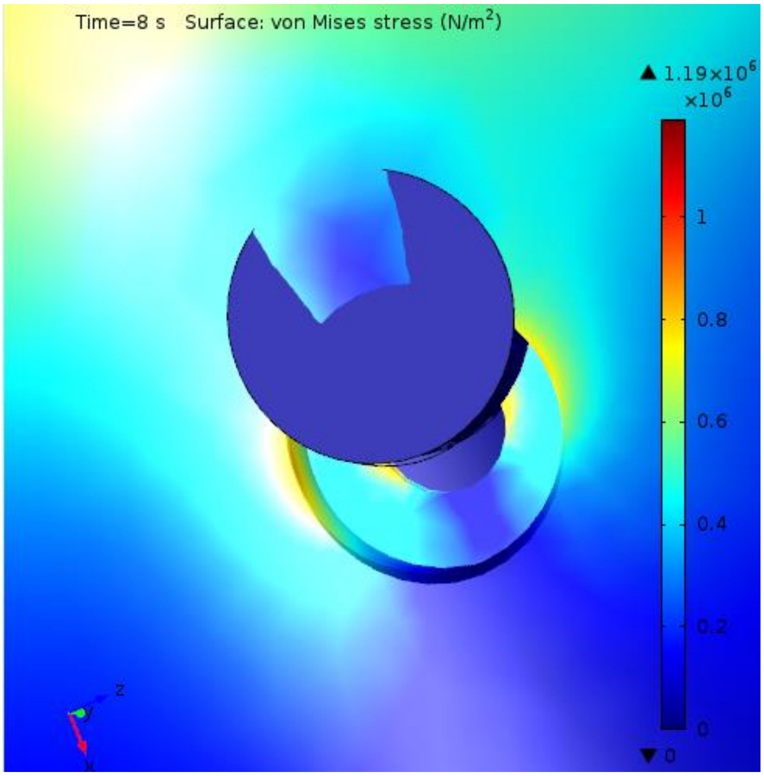


Figure 3.16: Cyclic loading stress at time = 8 sec at screw interface

Chapter 4

Discussion

Stationary study to determine maximum stress concentration due to constant loading

From the results of the stationary study and parametric sweep a few important notes can be made. First, as seen in figure 3.2, it can be noted that, as predicted, the highest stress occurs at the hole-screw interface in the ankle region. This makes sense because the geometric irregularity of the hole creates a stress concentration which can be modeled as the nominal stress multiplied by a concentration factor. This stress concentration factor (K_t) can be estimated using equation 6.

$$K_t \approx 1.58990 - .63550 \log(d/D) \tag{6}$$

Where d is the diameter of the hole and D is the diameter of the cylindrical piece of PVC (Norton). Thus, the stress concentration factor in the case of the ankle region of the Jaipur foot can be estimated as 2.27.

From the parametric sweep of the mass parameter, a function can be created that predicts the maximum von mises stress as a function of the mass of the person using the prosthetic. This result can be seen in figure 3.12. The maximum stress can be written as:

$$\text{Max stress} = .0197(\text{mass}) + .0021 \tag{7}$$

This function can then be used to extrapolate what force would have to be applied to the ankle region for it to reach the point of yielding. Since the maximum stress occurs at the screw-PVC interface, yielding will occur when the stress at this point reaches the yield strength of the weaker of the two materials. The yield strength of PVC is 51.71 MPa (Considine, 2006). Assuming that the carbon steel used for the screws is of the lowest grade and quality, the yield strength is still

179 MPa (Norton). Thus, the yield strength of the PVC is the limiting factor and once the von mises stress reaches 51.71 MPa, the ankle region will begin to deform.

To determine when the mass at which this occurs, I solved equation 7 by plugging in 51.71 MPa in as the max stress. This allowed me to determine that the ankle would begin to deform when the mass of the person using the prosthetic reaches 2624.7 kg. This is an extremely high mass. However, it must be noted that this does not account for spikes in the pressure being applied to the ankle perhaps from jumping on the prosthetic. It is still unlikely that this can account for a large enough change in the force applied across the top of the ankle to cause the ankle to deform.

This means that the ankle fails due to other factors such as fatigue stress and changing material properties such as the rotting of the wood that occurs when water seeps into the ankle block. Analysis of the results from the cyclic model can be helpful in determining when the ankle will fail due to fatigue stress. Fatigue analysis can be used to determine how many cycles of loading and unloading a material can go through before failure. The amplitude of the stress cycle (σ_a) in the case of the Jaipur foot is .595 MPa because the maximum von mises stress is 1.19 MPa and the load cycles between this and 0 MPa when the prosthetic user's other foot is bearing all of the weight and the prosthetic is moved forward in the air for the next step. The ultimate tensile strength (S_{ut}) is typically 52MPa for PVC and the fatigue strength (S_f') of low quality PVC is about 15MPa (Nass). The following equations (Norton) can be used to create a plot of the fatigue behavior (figure 4.1):

$$S_m = .75 * S_{ut} \text{ for axial loading} \qquad (8)$$

$$S_f = C_{load} C_{size} C_{surf} C_{temp} C_{reliab} S_f' \qquad (9)$$

All of the C values are correction factors based on properties of the specific application. In the Case of the Jaipur foot, C_{load}=.7 because the load is axial. C_{size} =.777 in based on equation 10 and the fact that the diameter of the PVC is 80mm.

$$C_{size}=1.189d^{-.097} \tag{10}$$

I assumed C_{surf} and C_{temp} are both 1 based on the idea that the ankle has no major surface defects and the temperature during use of the foot remains below 450℃. I chose C_{reliab} to be .62 because this ensures that as many as 99.9999% of the samples will not fail before the determined number of cycles (Norton). Using these values I calculated S_m= 39 MPa and S_f =5.06 MPa. Following these calculations I created a graph of the fatigue behavior and extrapolated the line between Sf and Sm to determine where it would cross the alternating stress amplitude and therefore fail (figure 4.1).

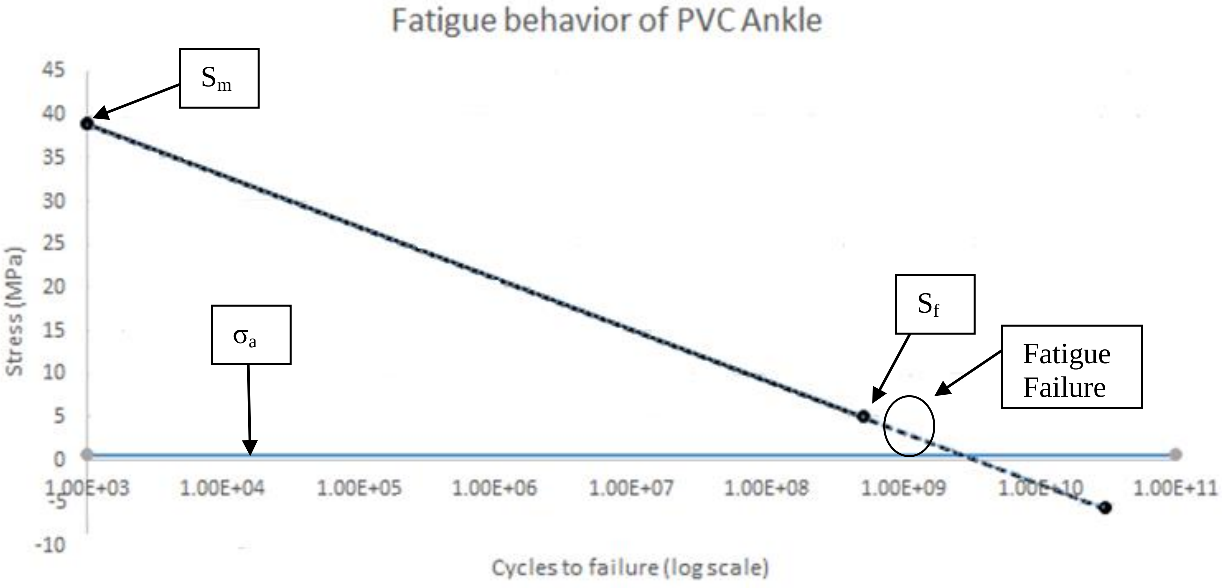


Figure 4.1: Fatigue failure graph for PVC ankle

From this graph, it can be estimated that the ankle will fail after $2.82*10^9$ cycles. This is a fairly high estimate. This number could be inaccurate because it does not account for the fatigue of any parts but the outer PVC ankle. For example it does not account for any loss in structural support due to water entering the wooden block inside the ankle and causing it to rot.

Chapter 5

Conclusion

Stationary Study

From this study, several conclusions can be drawn. First, from the stationary study, I was able to determine a function for the maximum von mises stress as a function of the mass of the person using the prosthetic. This function is equation 7. From this function I was able to determine that a stationary load is unlikely to cause the ankle region to yield.

Cyclic Study

Following the stationary study, I created a cyclic study that applied varying pressure across the bottom of the prosthetic foot throughout a stride (the results of the capstone project). From this study, I was able to see the change in the stress distribution across the ankle and was also able to determine the amplitude of the stress fluctuation (σ_a). From this data, and material constants determined from a literature search, I was able to create a fatigue graph of the PVC ankle region. From this graph I determined that the ankle region would fail after $2.82*10^9$ cycles.

Future Directions

There are several future directions that this project could take. First, a new geometry of the ankle region could be created and tested using the same models to determine if the new geometry would reduce the stress concentrations at the screw-ankle interface. Also, the model could have another time-dependent parameter that more accurately modeled the change in the properties of the wood ankle block that so often account for the failure of the prosthetic. Also, the stress caused by squatting could be contributing to the failure of the ankle region. A model to determine the bending stress due to the squatting position could be useful. Finally, the geometry of the foot could be more accurately depicted. The reason for simplification was so that the model would solve, but with more time perhaps a more accurate, yet still solvable, geometry could be created.

Appendix A

Results of Capstone project to determine cyclic model

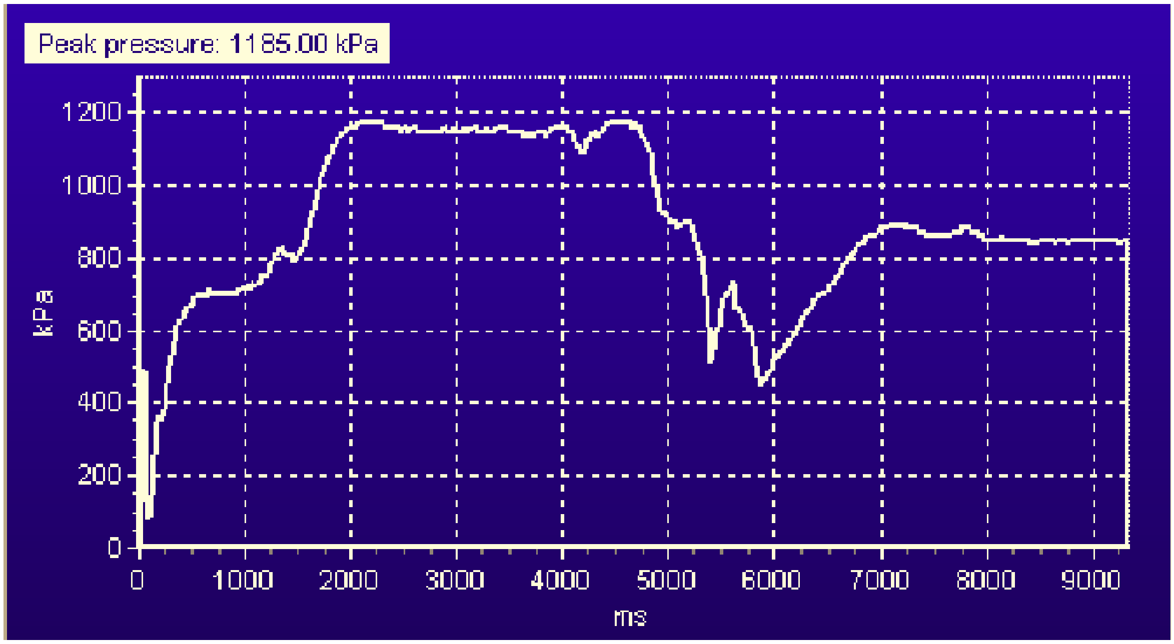


Figure A.1: Pressure of a stride Jaipur left foot 1

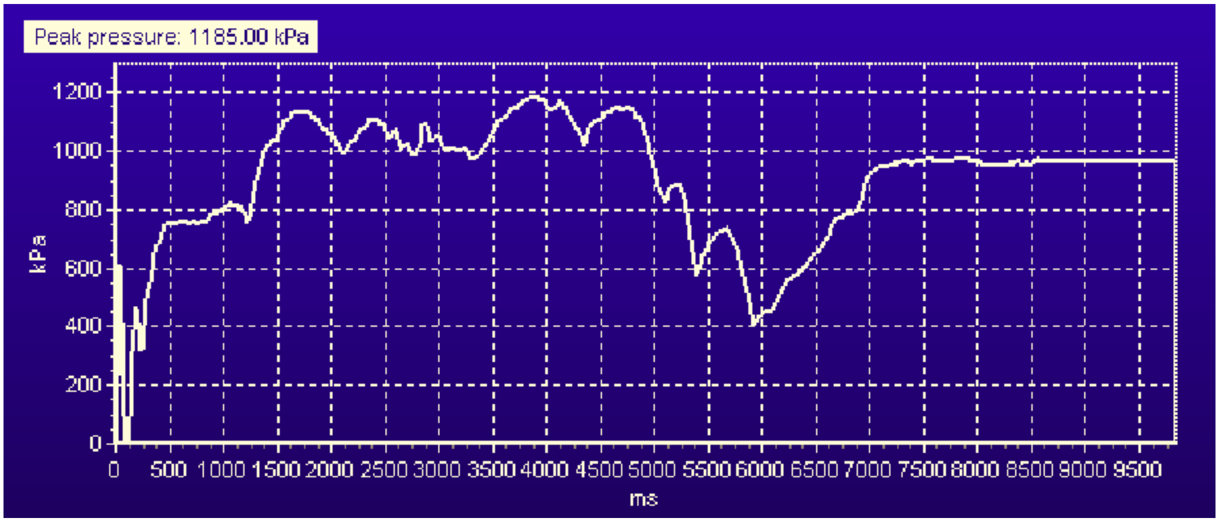


Figure A.2: Pressure of a stride Jaipur left foot 2

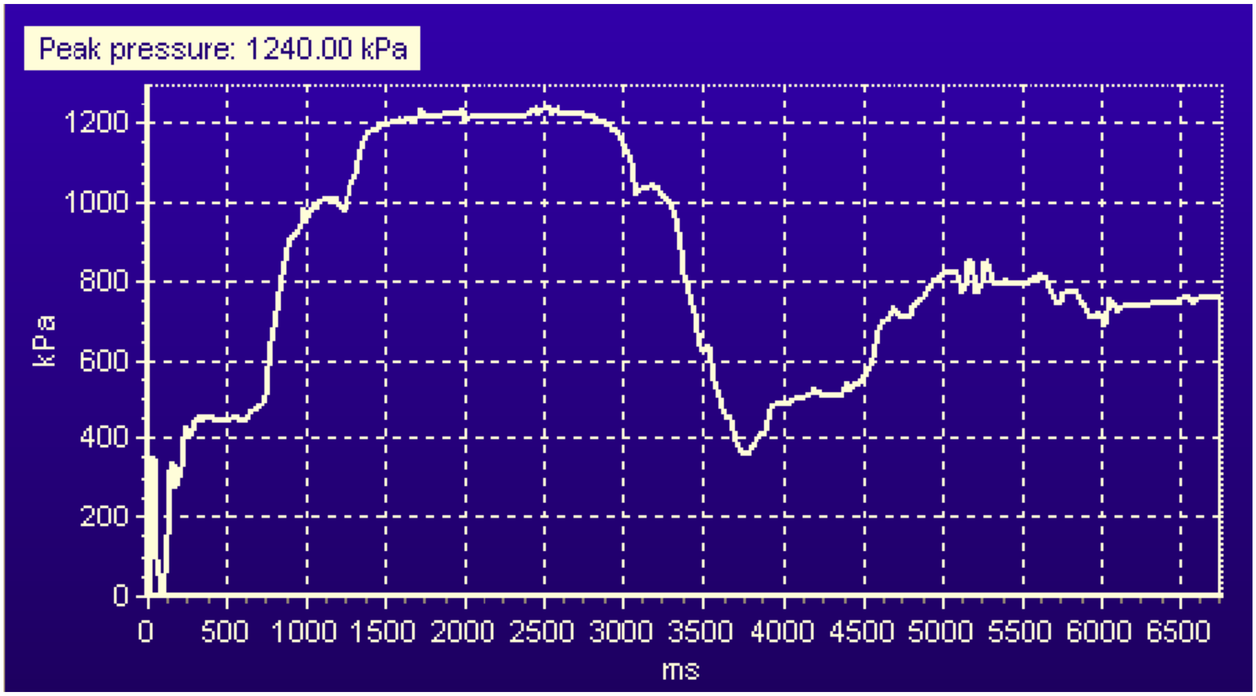


Figure A.3: Pressure of a stride Jaipur right foot 1

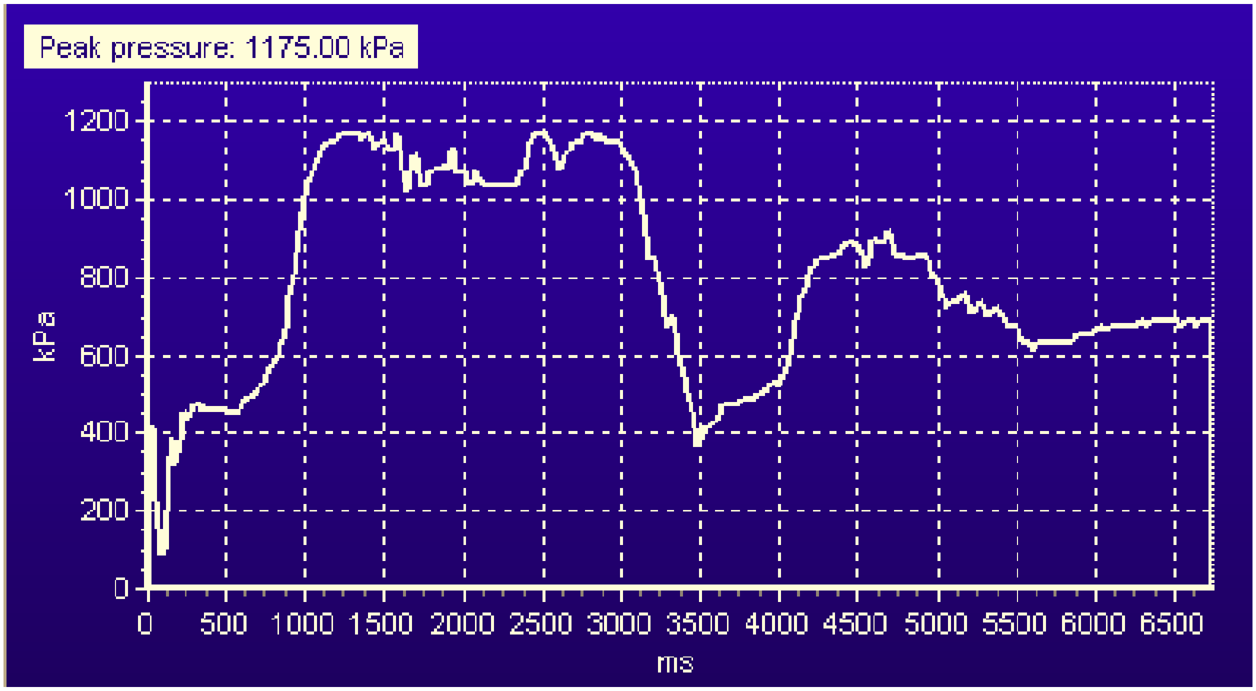


Figure A.4: Pressure of a stride Jaipur right foot 2

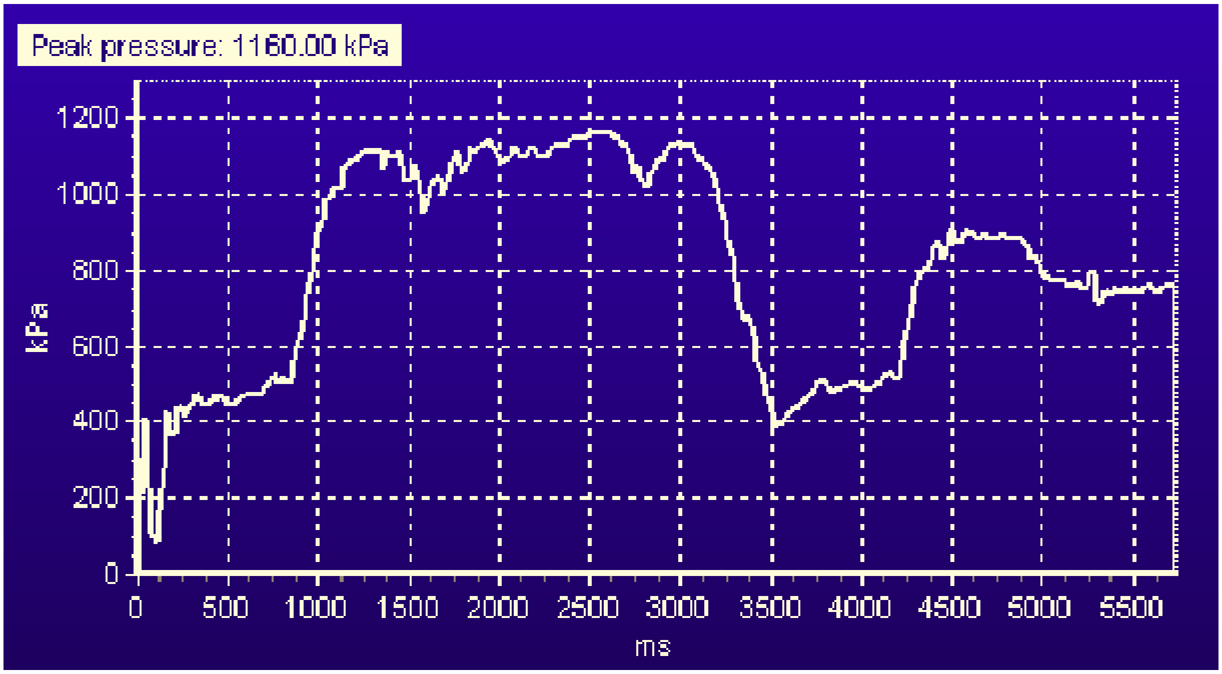


Figure A.5: Pressure of a stride Jaipur right foot 3

Appendix B

Detailed results of cyclic study

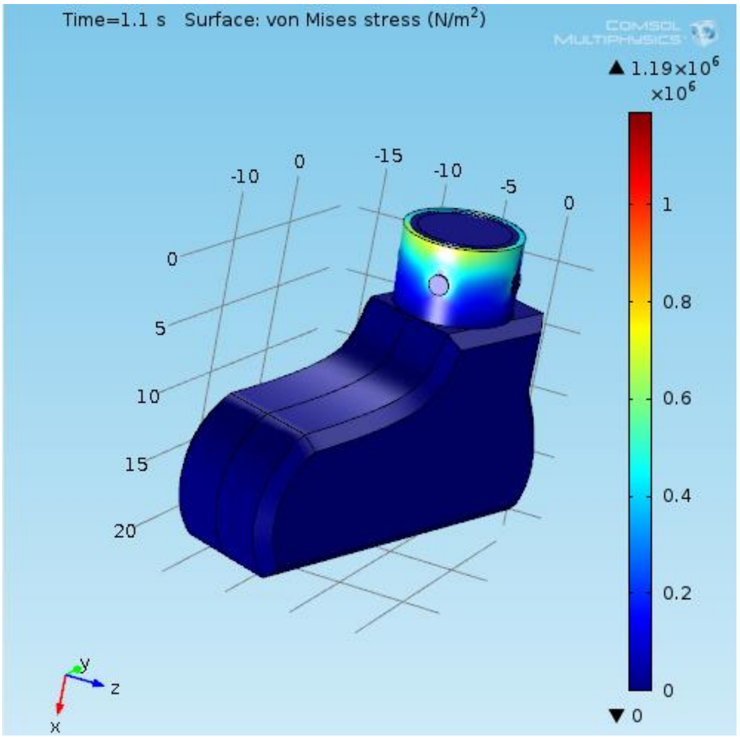


Figure B.1: Cyclic loading stress at time = 1.1 sec

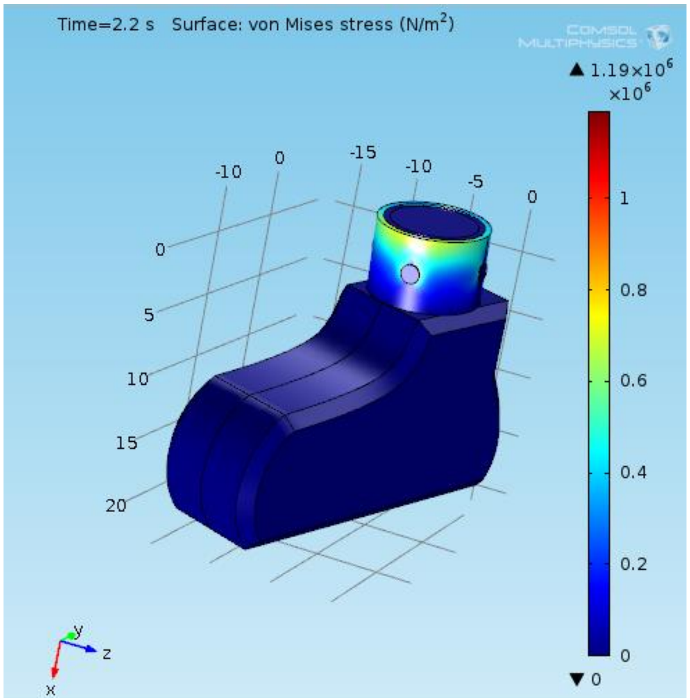


Figure B.2: Cyclic loading stress at time = 2.2 sec

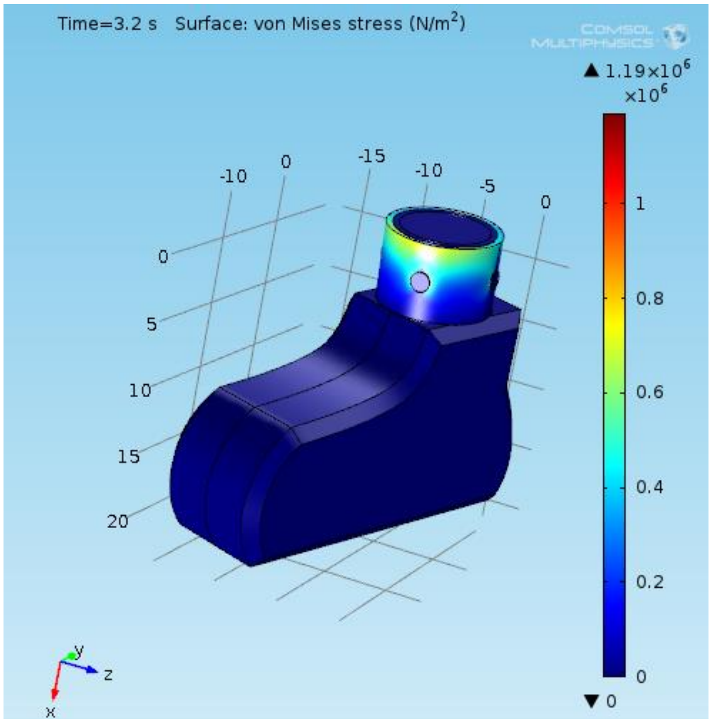


Figure B.3: Cyclic loading stress at time = 3.2 sec

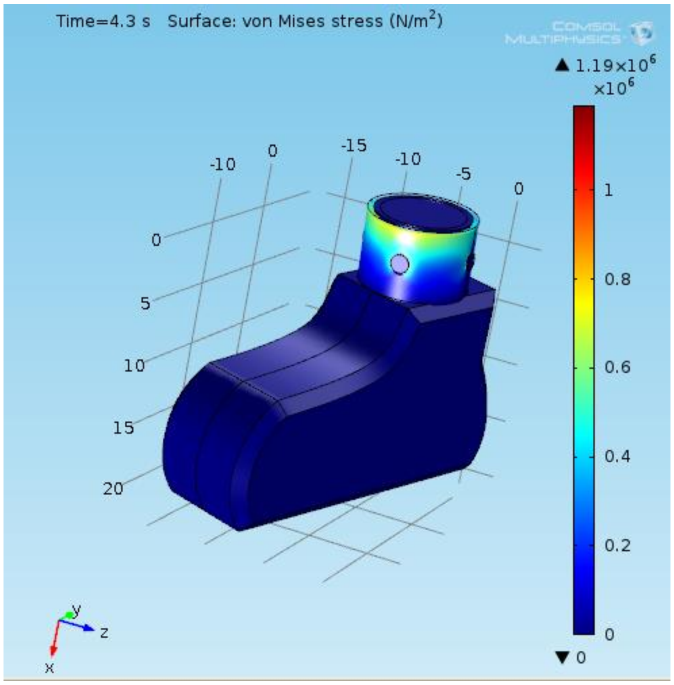


Figure B.4: Cyclic loading stress at time = 4.3 sec

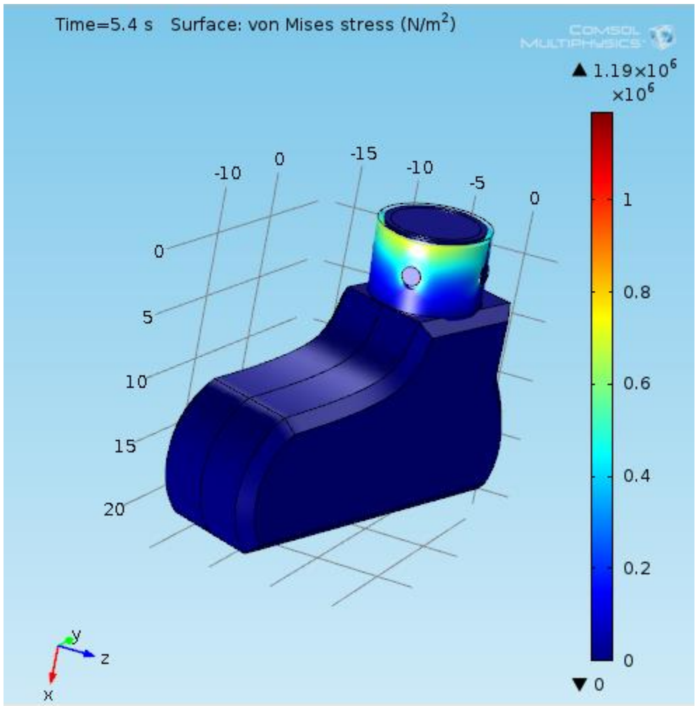


Figure B.5: Cyclic loading stress at time = 5.4 sec

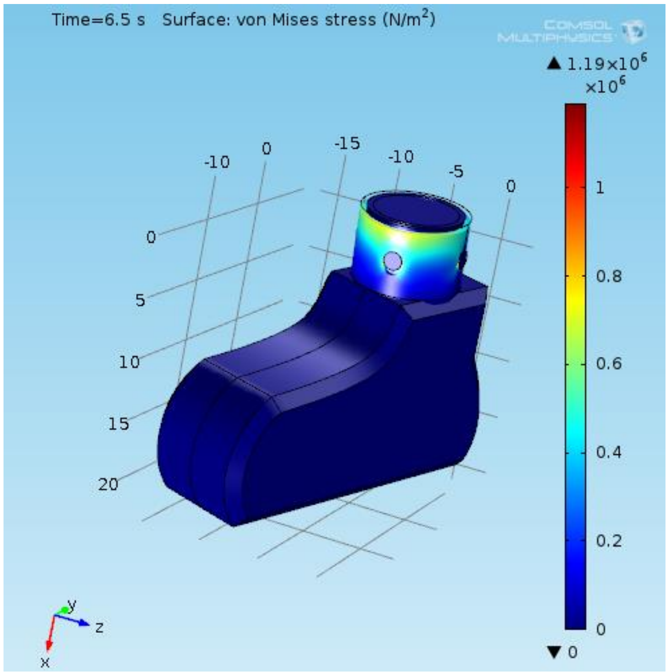


Figure B.6: Cyclic loading stress at time = 6.5 sec

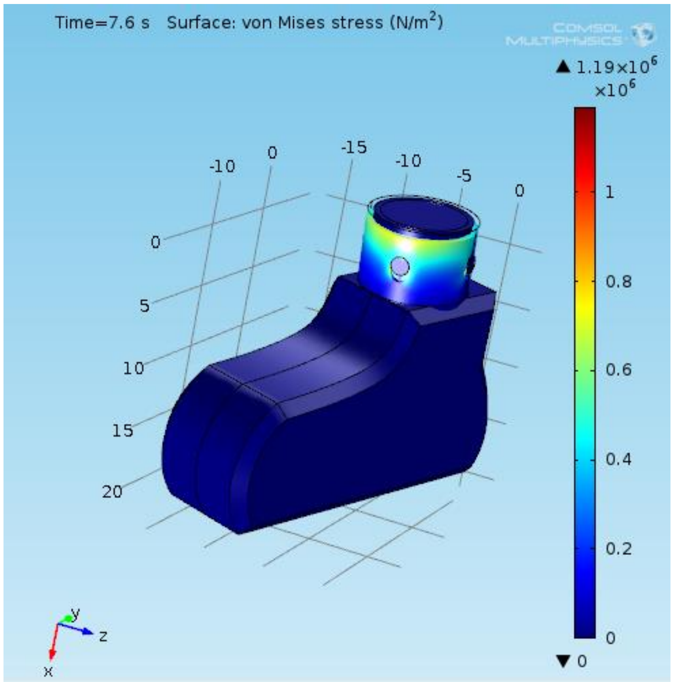


Figure B.7: Cyclic loading stress at time = 7.6 sec

Appendix C

Video of Cyclic Stress Response

See video submitted as a separate file.

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ACADEMIC VITA

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Education:

Pennsylvania State University, University Park, PA *May 2014*
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Bachelors of Science in Bioengineering
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Relevant Coursework:

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Material Science 259: Properties and Processing of Engineering Materials
Bioengineering 401: Introduction to Bioengineering Research and Design

Experience:

Undergraduate Researcher: *May 2013-August 2013*
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Responsibilities include: Aiding doctoral candidates with their research to develop a vaccine for HIV and presenting on my contribution to the research.

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Lifeguard: *2007-Present*
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