Final Report

Senior Capstone Design Project

Open-Source 3D Printed Foot Prosthesis

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DISCLAIMER

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EXECUTIVE SUMMARY

With increasing number of people getting amputation, the prosthetic foot industry have gained attention, also since it is something really sensitive and important, the industry can be improved greatly. The team goal is to make a useful solution for people with below-knee amputees and by making it 3D printed that can lower the cost and can be solution for people that cannot afford big amount of money.

The team was given this project by W.L. Gore and Associates in making and designing an open source 3D printed foot prosthetic. The team was tasked with a project requirement that were given in the beginning of the project and the final design have to meet all of them.

- Mostly 3D printable
- Hold up to 215 lb
- weight must not succeed 8 lb
- Low cost
- Safe
- Limited filament materials

All these customer requirements then translated into engineering requirement. A thorough research has been done through the internet to study similar kind of the product to get the basic understanding about the product. The concepts for system and subsystem has been generated. All these concept of system and sub system have been evaluated based on the Pugh chart and decision matrix. The Pugh chart was used to narrow down the number of concepts and decision matric provides the best possible results.

Post finalization of design concept, a 3D CAD model was prepared. A lot of research has also been done to explore the possibilities of material for 3D printing filament. After the material finalization, the prototype of CAD model was 3D printed.

Parts of prosthetic leg (Socket, Pylon and foot) were assembled to get the finished product which was tested on residual limb of the amputees. Slight modification was also made to incorporate suggestion of the amputees. The final 3D CAD model will be shared to the open source from where the people will be able to download it anywhere and 3D print it for the use.

ACKNOWLEDGEMENTS

As a team, we would like to gratitude and thank to all those who helped us through this project.

- Special thanks for…
  - Dr. Sarah Oman.
  - Jenn Whealy.
  - Amy Swartz.

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1 BACKGROUND

1.1 *Introduction*

In recent times, the number of lower leg amputees has increased significantly [1]. So there was a need to provide a cost effective solution that can provide stability to the amputees while standing and walking. The aim of the project was to design a 3D printed foot prosthesis leg for below-knee amputees that should be inexpensive, reachable and also facilitate the hassle free installation and removal. The designs available across the world were either costly or not reliable. A large emphasis was paid during design to make the foot prosthesis leg affordable and reliable. The team's goal was to build an affordable 3D printed foot prosthetic. This enabled the amputees to get the design and 3D print the product anywhere in the world for their use. This whole project was sponsored by the Northern Arizona University. The other stakeholders were the people who have below knee amputees and the companies who are fabricating the below knee foot prosthetics. The team's client is Jenn. Jenn has a below knee amputee and she has volunteered to help us in our project by giving her valuable feedback. The team was expected to build a below knee foot prosthetic that should be reliable, simple to operate, hassle free installation and removal, inexpensive and easily accessible to the common people.

1.2 *Project Description*

The goal of this project is to create an affordable and available passive 3D printed mechanical prosthesis for below-knee amputees. This prosthesis should be able to reliably hold up to a weight of 215lb. The prosthesis should consist of 3D printed parts and may use other materials as long as all materials are readily available to the general public (no material should be custom, special ordered, or inaccessible outside university or companies). The new design will help in improving the general functionality of the health care industry, especially the sector dealing with neuromuscular disorders the weight of the limb must not exceed 7lbs (the average weight of an adult male lower-leg). Filament materials are limited to common material types such as ABS, PLA, PET, etc. The final deliverable should not be a prototype but the finished product [2].

1.3 *Original System*

There was no original system when the team started working on this project

2 REQUIREMENTS

The team goal was to fabricate a prosthesis leg for below-knee amputees that should be easy to install and remove, inexpensive, and reachable. The team had to collaborate with all the stakeholders to understand the basic requirements of the clients which need to be fulfilled. The basic client requirements were directly obtained from the end user since they would be using the product. The engineering requirements were directly obtained with the client requirements with some tolerances. Since the engineering requirements can easily be measured hence these will help us in evaluating the possible designs in future. A testing procedure should also needed to be evolved to ensure whether all the engineering requirements were met and fell into the permissible tolerances. House of quality (HOQ) diagram is a key component of Quality Function Deployment (QFD) which will guide the team members in translating the client requirement in to a real product. Since all the client requirement is not possible incorporate in single design, this will help us in prioritizing the basic needs of the users. The following subsections include the client requirement, engineering requirement, testing procedures and the HoQ diagram for prioritizing the client needs.

2.1 Customer Requirements (CRs)

The various stakeholders of these products are the lower limb amputees and the various companies that are fabricating similar type of foot prosthetic. Client requirements are the voice of the end-user. All the voices of clients and the people who are closely connected to them are collected and transformed into some meaningful requirements. The team has assigned a weight to all the client requirement for further analysis. **Table 1** represents the client requirements along with their associated weight. The weights are ranked from 1 to 9 according to the importance of the requirement, where "1" represents the least importance whether 9 highest importance.

Table 1: Client requirements

Client requirements	Weight
Portable	1
Weatherproof	1
Limited filament materials	5
Lightweight	9
Comfortable when wearing	6
Height adjustable	7
Robust	9
Safety	9
Mostly 3D printable	9
Low Cost	9
Easy manufacturability	7
Aesthetics	2
Physiological accuracy	4

The product, below-knee foot prosthesis, should be easy to handle and portable. Additionally, the finished product should be weatherproof that means their functionality should not be affected by changes in the climate, utilizes a limited filament materials and must be lightweight so that user will feel comfortable while wearing or carrying it. The user must feel comfortable using the product. The height of the prosthetic leg needs to be adjustable so that the foot prosthetic can be used by amputees of different heights. Safety is one of the major customer requirement in this product so that the user cannot get hurt while using the device. The purpose of this project is to help people that cannot afford a prosthetic legs available at the market because of higher cost. Hence a inexpensive solution can be provided using 3D printing which is not costly and easily accessible to common people. Last, the team are aiming in making the price as low as possible.

2.2 *Engineering Requirements (ERs)*

After listing all the customer requirement, the team formulated a list of engineering requirements that can easily be measurable. These engineering requirements are very crucial in evaluating the designs at the final demonstration. From the client requirements, the team has generated the engineering requirements which needs to be incorporated while designing the below knee foot prosthetic. All the engineering requirements are listed below in the **Table 2**.

Table 2: Engineering requirements

Engineering requirement	Target values	Customer requirement
Weight holding capacity of the prosthetic leg	215 lbs.	Robust
Weight	< 8 lbs.	Lightweight
Cost	550-1500 $	Low Cost
Filament material	ABS, PLA, PET, HIPS	Limited filament materials
Fits different height people	5’-0” to 6’-5”	Height adjustable
Reliability	99%	Safety
Durability	10 years	Waterproof
Hazards	0 Nos.	Safety & Aesthetics

2.3 *Testing Procedures (TPs)*

Testing procedures are the procedure by which the team can verify whether the customer requirements are fulfilled within the permissible limit. Since the engineering requirements are measurable quantity hence the testing procedures will be relatively simple. Weight holding capacity can be verified by putting the 215 lb weight over the socket and checked the maximum deformation. Weight can be recorded and verified. Total expenses has to be noted down to get the total expenditure. All 4 material (ABS, PLA, PET and HIPS) are commonly available at the open market. The height of the product can be measured with the help of scale. The length of both the extreme (Fully opened & fully compressed) can also be measured with the help of scale. Reliability and hazards can be verified by taking the feedback from the users. Durability can be verified by noting its service life.

2.4 *House of Quality (HoQ)*

The HoQ diagram is a component of the QFD diagram and a very important process in the product development. HoQ diagram resembles a house and used to relate the client requirements and product specifications. As shown in **Table 3,** the team have listed the client requirements on the left side of the wall, and engineering requirements at the roof. Weight is assigned to each requirement. The assigned weights are descriptive of the strength of the relationship being shown where a figure of ≤7 indicates a strong relationship, ≥ 3 indicates a weak one and 0 indicates a lack of a relationship. As a result of this analysis, the team will get the prioritized requirements of the clients.

Table 3: HoQ Diagram

Customer Requirement	Weight	1. Below Knee	2. Prosthetic leg must hold up 215 lbs	3. Can be printed in any 3D printer	4. Must weight 7 lbs	5. Limited filament materials (ABS, HIPS, Carbon Fiber)	6. Fits different height ranges from 5'-0"till 6'-5" persons height	7. Affordable	8. Easy to transport	9. Resistant to weather	10. Free ages use from 13 and higher	11. Does not damage the person leg	12. Comfortable to wear and use	Unit
1. Holds up to 215 adult male	9		9		9							3	3	lbs
2. Must be printed from 3D printer	9	3		9	3	9	9		6				3	N/A
3. Weight 8 at most	9		9	6	9	6	3		6			6	6	lbs
4. Limited filament materials	5		6	9	3	9		6		9			3	N/A
5. Fits different heights sizes	7	6	3	6	9	6	9		3		3		9	Inch
6. Easy to carry	1			3	9	6			9					N/A
7. Adjustable to all weathers	1			6	3	6				9		6		N/A
8. Comfortable	6	3	6		3	6	6	3	9				9	N/A
9. Safety	9				9	3				9	6	6	9	N/A
10. Free ages use	3						3	6	3		9	6	3	Year
11. low cost	9		3	6	3	9		9						$
Target ER Values		N/A	200	N/A	7	N/A	6"5	1500	N/A	N/A	N/A	N/A	N/A	
Absolute Technical Importance (ATI)		168	330	285	441	378	243	147	201	135	102	240	411	
Relative Technical Importance (RTI)		9	4	5	1	3	6	10	8	11	12	7	2	

Strong relationship = ≤7; Weak relationship = ≥3; No relationship = 0

As seen from the **Table 3**, Absolute Technical Importance for "Weight being ≤ 7 lb" is highest with the value 441. Hence it is most critical customer requirement that must be fulfilled. ATI for the "Free ages use from 13 and higher" is minimum that signifies that it is a least prioritized requirement. Relative technical importance is also listed at the last row of the **Table 3** which prioritizes all the customer requirements. Arranging the CRs in ascending order of RTI will give the descending order of priority.

3 EXISTING DESIGNS

A variety of products are available across the world for below knee amputees. The team conducted a thorough research on them through a number of sources like internet and by interviewing users who are using the similar kind of products. The major attention was paid on the similar designs that can fulfill all the clients' requirement. The pros and cons of the designs had been learnt by comparing it based on customer requirements through brainstorming sessions among all team members. During research, some existing designs that were important for our project are presented into following subsections.

3.1 Design Research

Over the years, a lot of research has been performed to replicate the exact characteristics of the human foot. There are a lot of designs that are available in the literature for below knee leg prosthetic. The team conducted a thorough research by utilizing the Google search engine. The team had also watched many videos available on the YouTube of similar product [3]. First, the team studied the characteristics of the human foot through literature [4, 5]. The team found many existing designs of the below knee foot prosthetics. Some designs were studied thoroughly to develop the basic understanding of its working and pros and cons of it. The team had also studied how the existing concepts can be implemented to make a simple, reliable, inexpensive and lightweight prosthetic leg. Some designs were investigated to make the height of prosthetic leg adjustable so that product will benefit the maximum number of populations. Our investigation aimed at combining all the best characteristics of the designs available across the globe to achieve a more functional prosthesis which satisfies the client's requirements. The designs considered in our investigations are discussed in the following sections.

3.2 System Level

The results of the investigations of some existing designs of below knee foot prosthesis are discussed in the following subsections. This section also includes that which characteristics of these existing designs can be incorporated to develop the best and inexpensive design.

3.2.1 Existing Design #1: Real Time Solution for Third World Amputees

A picture of lower limb foot prosthetic design is shown in **Figure 1**. Foot prosthetic was made using low temperature re-moldable thermoplastics. First, the limb of the amputees was covered with the plastic and fix to it properly so that it will not stick out from the limb. A socket of thermoplastic was wrapped around the residual limb and heated a little bit. Due to heat, thermoplastic socket took the shape of residual limb. Molded socket was removed and finishing was done. Further, finished socket then attached to the pylon. Since socket was accurately molded in shape of residual limb so there was no need of any attachment mechanism [6].

Thermoplastic was employed for fabricating these designs and these designs were very light, hard, easy to handle and also fulfilled our requirement of the light weight prosthetic. The best part of the design was that it utilized the re-moldable plastic while fabrication. Molding of the plastic can easily be done by heating it to the re crystallization temp [7]. Hence the shape of the socket can also be adjusted to fit the residual limb. This concept had motivated to the team to use a 3D printing material for building a prosthetic which can be reused and also it will not harm the environment. Socket was also detachable from the pylon which enabled the amputees to replace it, if required.

Figure 1: Prosthetic foot design for real time problem [6]

3.2.2 Existing Design #2: Adjustable Bicycle Limb

A picture of adjustable bicycle limb is shown in **Figure 2**. The bike seat was first removed from the frame and seat post was detached from the seat by loosening the bolts and washers. The seat post was the base upside down and forms the lower shin and foot. A 1" thick piece of wood was cut to a size of foot and lined with rubber on the undersurface to provide the friction so that the amputees would not fall. The seat support frame and rear wheel support are separated from the bike, and the rear wheel supports were bent to form the calf support for the socket. The feet was attached to the residual limb holder. The length was made adjustable at this junction. To provide the support to the residual limb a wooden disc was attached at the base of socket holder. The socket was attached to the socket holder by plastering around the arms of the socket holder and the prosthesis was held on with a suspension strap connecting the prosthesis to a belt worn around the waist [8].

The parts were made up of the steel so it was little heavy hence this material was not advisable to build our product. The best part of the design was the use of rubber at the foot base to provide the traction to prevent the amputees from falling [8]. The rubber is in-expensive and could be incorporated in team's design to enhance the comfort while walking. This Prosthetic leg was built from waste of a bike seat hence it will be cheaper and easily accessible into the market.

Figure 2: Adjustable bicycle Limb [8]

3.2.3 Existing Design #3: Elliptical/Circular Shaped Low-Cost Prosthetic

A picture of the prosthetic foot design is presented in **Figure 3**. A low-cost mono limb has been designed for less fortunate amputees using both circular and elliptical shaped shanks [9]. The flexibility of polypropylene caused the mono limb to deflect during walking which simulates ankle joint motion. The foot made of wood which resembled the actual foot was made and attached to the socket and pylon.

The specific thermoplastic material used for fabricating the foot prosthesis was polypropylene [9]. This material can also be used in our project due to its strength, flexibility and ductility. The best part of the design was that its socket and pylon are molded together. The major drawback of the design that its height cannot be adjusted after fabrication.

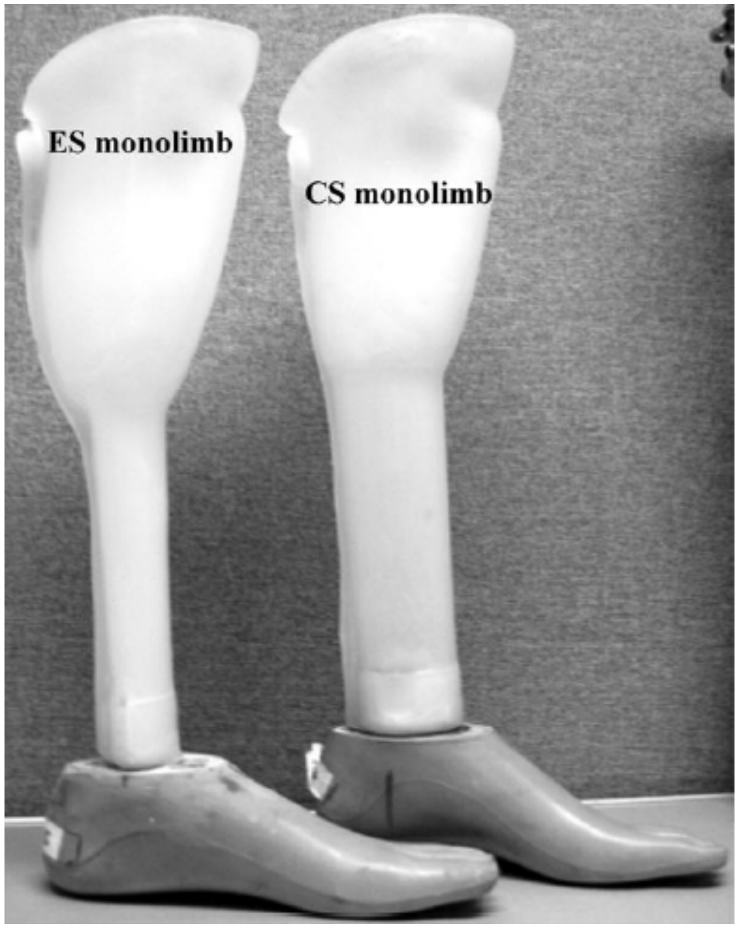


Figure 3: Elliptical/Circular Shaped Low Cost Prosthetic [9]

3.3 *Functional Decomposition*

In this project, the major aim was to create a 3D printed, inexpensive and reliable foot prosthetic so that it could provide the stability to the below knee amputees while standing and walking. As the name suggests, the major task was broken down to the much simpler task in the functional decomposition [10]. This had helped the team since it was easier to solve relatively simple task instead of trying to solve a bigger problem. This section includes the two subsections which explain the black box model and the hierarchical task analysis.

3.3.1 Black Box Model

A black box model is a model which represents the input and output of the specific systems without even knowing the internal working of the system [11]. The black box model was made for the below knee foot prosthetics and shown in **Figure 4**. The inputs to the black box model are the various forms of energy associated with it, materials and the signals which are being fed to model are shown in the left-hand side of the model. The output of the black box model will be the form of energy, the product and the function of product as the signal and presented in the model at the right side. A black box model for the 3D printed foot prosthetic is presented in **Figure 4** where all the input for material, energy and signal are shown at the left side of the black box with different types of arrow and all the output at the right side of it. The thick arrow represents the material, a lean arrow represents the form of energy and the dotted represents the signal. Final result will be the ability to stand and walk with the help of 3D printed foot prosthetics.

Figure 4: Black Box model

3.3.2 Hierarchical Task Analysis

A hierarchical task analysis provides an understanding of the tasks users need to perform to achieve certain goals **[12]**.The team has break down the main task to the multiple sub-task and arranged in a systematic way to achieve the goal. With the help of hierarchical task analysis, the team was able to explore the multiple ways of performing the same sub-task. It also describes the interaction between the user and the product. This has also helped us in optimizing the sub-task to accomplish the goal. The hierarchical task analysis for the 3D printed foot prosthesis is as follows:

- · Finalize all the parameters for the design of prosthetic leg.
- · Finalization of material to be used for foot prosthetic.
- · Which machines to be employed
- · Where to find such kind of machine.
- · Inputs required for the machine.
- · Out-put of the machine.
- · Attachment arrangement of prosthetic leg to the residual foot.
- · 3D printing of pylon to attached the socket and foot.
- · Designing of base of prosthetic leg.
- · Fabrication of the base.
- · Attachment mechanism of the junction of socket to the pylon
- · Attachment mechanism of the junction of socket to the pylon
- · Finishing the product if required.
- · Ways of attaching the prosthetic to the residual limb.
- · Testing of the product by amputees.

A chart for the Hierarchical task analysis is explained with the help of **Figure 5** where all the task are shown in the two sub-level. It is divided into three main sub group based on the components of the Prosthetic leg.

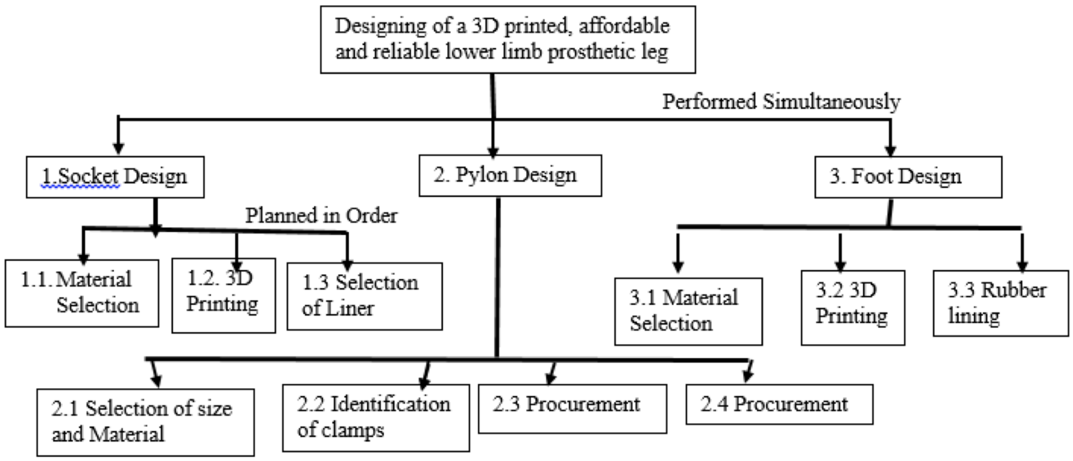


Figure 5: Hierarchal task analysis

3.4 Subsystem Level

The subsystem levels of the already existing designs addressing the requirements relevant to our project are as discussed below.

3.4.1 Subsystem #1: Foot Designs

Designing of foot is very crucial in this project as this will provide the base to the design. It will also affect the load transfer to the amputees. Some of the existing designs are discussed in the following subsections.

3.4.1.1 Existing Design #1: SACH Foot

Early designs for prosthetic feet were often a solid piece of wood. A similar design, the SACH (solid-ankle-cushioned-heel) is still in use because of its steady function, especially useful for individuals with lower activity levels. A SACH foot presented in **Figure 6**, typically has a rigid inner structure (wood or plastic) surrounded by a compressible foam cosmetic shell [13]. This foot is very light in comparison to the foot made of wood and also provides the flat face for the better stability. So, it can fulfills the customer's requirement of light weight and reliability. This design of foot is very hard so it will transfer the full jerk to the residual limb instead of absorbing it. Hence, this type of foot will not be comfortable while running.

Figure 6: SACH Foot [13]

3.4.1.2 Existing Design #2: Niagara Foot

A picture of the Niagara foot is presented in **Figure 7.** It is very simple yet inexpensive, practical, and sturdy. The foot is made from a single piece of plastic formed to replicate a normal human foot. The shape of the foot is to provide energy return [14]. This foot is made up of thermoplastic which can withstand the high weights and that would be very useful to our team since one of our customer requirements is to hold up to 215 lbs. This design of foot is little flexible which can absorb the jerks while running.

Figure 7: Niagara Foot [14]

3.4.1.3 Existing Design #3: Flex Foot

Flex foot is shown in **Figure 8**. A good prosthetic foot should also be strong, as it will be taking on huge force and torque as user walk and run. Feet must also be small enough to fit within a foot shell. A cosmetic covering is provided to get the better look. Being light, strong, and small, and yet functional and durable is the challenge [13]. This Flex foot is capable of withstanding huge force and torque, and that will also give an advantage to not just walk but also to run. This design will benefit the amputees which are involved in any kind of sports. Flex foot can easily absorb the jerk and increases the comfortability to the residual limb. Only major drawback of this design is that it is costly so may not be affordable to everyone.

Figure 8: Flex Foot [13]

3.4.2 Subsystem #2: Socket Design

The socket is the most important part of any prosthetic limb, if the socket doesn't match the residual limb's anatomy exactly, problems can occur [15]. It will govern the comfortability of the prosthetic foot. This will be the contact point of the prosthetic leg to the residual limb. So it should be selected in such a way that it will not pose any threat to the human body. Some designs of the socket of the prosthetic foot is presented in following sub-sections.

3.4.2.1 Existing Design #1: Supracondylar

One type of socket used in prosthetics limb is presented in **Figure 9**. As seen from figure there is not any separate attachment arrangement. The socket itself is sufficient to hold the weight of the prosthetic leg. The cushion is provided at the contact points of the residual limb. It is made of the thermoplastic enabling residual limb muscles to flex when walking, standing and sitting [15]. The socket of prosthetic legs is subjected to many socks/ jerks while its use during walking and running. This socket absorbs the socks due the flexibility of material. Comfort level can be achieved by using the extra cushion which can be provided by spending some money. Its flexibility and comfortability are its major qualities which can be utilized during the concept generation.

Figure 9: Supracondylar [15]

3.4.2.2 Existing Design #2: PTB with cuff

The design of the socket #2 is presented in **Figure 10**. It is clearly evident from the **Figure 10** that a separate shock is attached to hold the prosthetic limb. This can be useful to our project as a holding mechanism of prosthetic leg into the residual limb of the amputees. The weight of the full prosthetic foot will not directly come to the residual limb. Part of the weight of the prosthetic leg will be supported at the waist [16]. This design helps to relax the person thigh and the tension due to its own weight.

Figure 10: PTB with cuff [16]

3.4.2.3 Existing Design #3: Ininite Socket

The picture of one type of socket is presented in **Figure 11**. This socket helps the amputees for tightening and loosening according to their requirement. It is made of the flexible fiber plates and a belt is placed around the socket. By tightening and loosening the belt the socket will get tightened or loosened to the residual limb. The type of socket will fulfill the requirement of clients since it is easy to attach and detach and also it is in-expensive [17].This design creates tension on the person's thigh and knee in order to help the attachment of the sock and the foot. Major drawback of this design is its attachment to the residual. Limb which needs to be tightened can cause the irritation in the residual limb.

Figure 11: Ininite Socket [17]

3.4.3 Subsystem #3: Pylon design

Pylon design is also essential part of the foot prosthesis to transfer the reaction load to the residual limb. Its height is also important since height of both the foot should be equal to provide the stability during standing and walking otherwise it will not fulfill any purpose to the amputees. Some of the commonly used pylon designs are discussed in the following subsections.

3.4.3.1 Existing Design #1: Adjustable Pylon

Adjustable pylon is the simplex pylon which can be fabricated anywhere. It uses two different diameter pipes where one can easily go inside the other pipes. A clamp is attached between the pipes. To adjust the height clamp is released and inside pipe can be taken out or in according to the height of amputee [18]. After adjusting the height clamp is again tightened to fix the length of pylon. The components of the adjustable pylon are shown in **Figure 12**.

Figure 12: Component used in building adjustable pylon [18]

3.4.3.2 Existing Design #2: Pylon fixed to the foot

Pylon fixed to the foot base is shown in **Figure 13**. The top of the pylon will be fixed to the socket. It is one very cheap and also it is a very simple. The major pros of this product is that its height can be adjusted according to the need of the amputees. Its pylon and the foot has been fabricated as a unique part which can easily be assembled to the socket. Major drawback of this design is that even if the foot gets broken due to some reason then in that case amputees have to change the full part which makes it little costly to the amputees.

Figure 13: Pylon fixed to the foot [19]

3.4.3.3 Existing Design #3: Pylon fixed to the socket

Picture of the pylon fixed to the socket is shown in **Figure 14**. The pylon is 3d printed along with the socket. It is the simplest design of the pylon. The advantage of this kind of pylon is that it can be easily attached and detached from the residual limb. It will be lighter since the whole pylon is printed with the lighter material. Only drawback of this kind of design is that its height cannot be adjusted.

Figure 14: Pylon attached to the socket [20]

4 DESIGNS CONSIDERED

The team's goal is to build an in-expensive, reliable, light weight and 3D printed lower limb foot prosthesis. The team has done an extensive research on the available designs across the globe and come up with the 10 best possible designs which will be evaluated further to get the best possible design that satisfies all the client needs. The design considered is explained in the following subsection along with its pros and cons. The explanation of some of the designs is placed at **appendix A.**

4.1 *Design #1: Spring*

Schematic diagram of the design is placed at **Figure 15**. A spring is attached from the socket to the foot. Advantage of using the spring is that it will absorb the reaction forces and impact while walking. The residual limb will be directly supported to the socket. There is not any mechanism so that the residual limb will be holding the weight of the prosthetic foot. The spring will get compressed when the foot will come in contact to the ground that may cause the discomfort to the amputees while walking. An assembly of socket, spring, pylon and Foot has been shown in the figure below. Spring is connected between the socket and the shoes which contracts and retracts during walking and running to reduce the sock and reaction to the residual limb. The drawback of this design is that it needs a different fixing mechanism for everyone since the anatomy of limbs may vary from amputee to amputee.

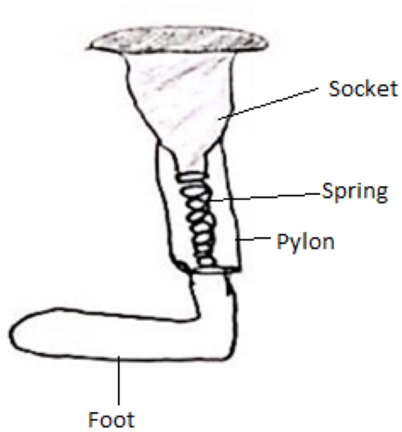


Figure 15: Spring loaded prosthetic leg.

4.2 *Design #2:* Split type prosthetic leg

A design of foot prosthetic is shown in **Figure 16**. The idea of this design is that instead of putting the load into one spot, by this design we can split the forces into several spots, which will lead in separating the loads through these pipes. This idea came because the team is trying to figure out some design that is lightweight (8 lbs. at most) and can hold up to 215 lb. unfortunately, this design has no adjustable heights and it is not comfortable for daily use, because it is wide in the below which leads to difficulties while wearing clothes.

Figure 16: Split Type Prosthetic Leg

4.3 ***Design #3:*** **Spider Web Prosthetic leg**

The design presented in **Figure 17** is inspired from a spider. A piece of wool is attached at the top of the spider legs. Residual limb sits at the top of the wool and the spider web grands the residual limb of the amputees. Design of the concept is very complex so this will be hard to build that may increase its cost. Also, it may not be able to sustain the 215 lbs weight. Its height cannot be adjusted. Major pros of the concept are that it is lightweight and comfortable.

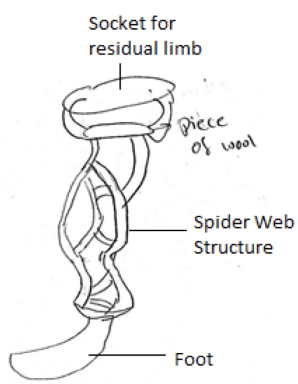


Figure 17: Spider web Prosthetic Leg

4.4 ***Design #4: Crutch***

Schematic diagram of the crutch is shown in **Figure 18.** At the top shocks is attached to hold the residual limb. A metal stick is place in between the pylon. Hole is made in the pylon as well as in the metallic stick to make its height adjustable. A pin is place in the pylon hold through the stick. To adjust the height, first remove the pin and push the stick inside the pylon and again put the pin to support. Due to the use of metallic parts, its weight will be little high so it will not be easy to carry it. It is a very simple design and easy to build.

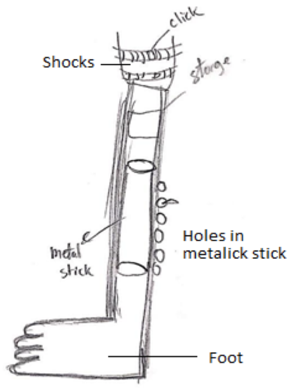


Figure 18: Crutch

4.5 *Design #5:* Air Suspension

The design presented in **Figure 19** makes use of the air suspensions. The foot is made of the metal strip and attached to the lower pylon. Socket is attached at the top of the pylon. At the junction of upper and bottom pylon air suspension is attached. As the air will be pumped into the suspension its height increases. Air suspensions are used to make the height adjustable. It will be costlier since it uses the air suspension and also it needs the regular maintenance. Its weight will not exceed 8 lbs. since the ABS and air suspensions are used. Major drawback of this design is that it is costly and requires regular maintenance.

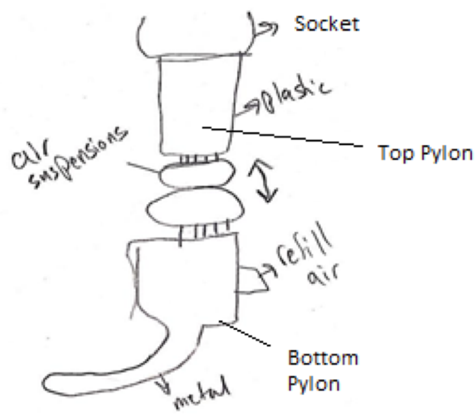


Figure 19: Foot prosthetic using air suspensions

4.6 *Design #6: Sea horse*

The bottom of the design presented in **Figure 20** is inspired from the sea-horse. The pylon is built from the curved plate. The two springs are attached to the pylon which absorbs the reaction force and impact. It is very hard to build. It specifically can be used by the athletics. The cost of the product will be high so it can't be used by the common people. Its height is also not adjustable. It will not be heavy since very less no. of parts are used for fabrication of the product. This design is very useful for the athletics since it will have the capacity to absorb the reaction forces due to jerks and provides the greater comfort to the amputees.

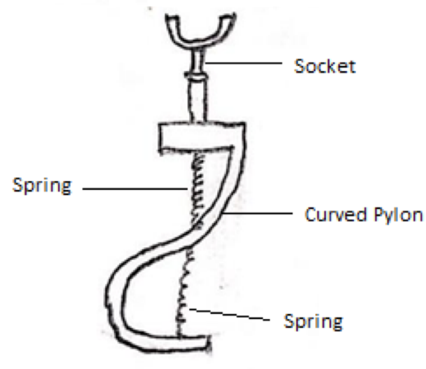


Figure 20: Sea-horse

5 DESIGN SELECTED – First Semester

A number of designs are considered for designing a below knee foot prosthetic. Total number of designs are considered for building a foot synthesis is ten designs. All the designs are evaluated in order to get the best design. The aim of the team is to build a 3D printed below knee foot prosthesis, which is inexpensive, light-weight, adjustable height and comfortable. All the designs are evaluated based on the client's need. The design which turns out to be the best is presented in **Figure 17.**

The following subsections include the way the team has reached to the best possible solution among the multiple possible solutions.

5.1 Rationale for Design Selection

The team has narrowed down to four possible designs, which perform well during the analysis out of the ten possible designs with the help of the Pugh Chart. First, in the Pugh chart analysis, a design is fixed as a datum with which all the designs are compared in the chart, which is the design of the sea horse **Figure 19**. In the Pugh chart the client needs are listed at the left and all the designs are evaluated with respect to the datum. The detailed Pugh chart is placed at the **Appendix B.** All the designs are evaluated and given one of the following, the '+' for positive, '-' for negative and 'S' considered same as the datum. The design which have got a greater number of '+' and less number of '-' is highlighted and considered for further analysis. Out of the 10 designs, the team end up getting multiple designs from the Pugh chart analysis that are highlighted in the **Table B.1** placed at **Appendix B** which are variants 4 (Crutch), 6 (Sea-horse), 8 (Gate Wall), and 10 (Versatile).

Designs shortlisted from the Pugh Chart analysis is further evaluated based on the client's needs with the help of the decision matrix. On the left side of the decision matrix place at the **Table B.2** in the **Appendix B**, all the client's requirements are displayed and weighted out of 1 is assigned to all the client's needs. The scores out of 100 is given to all the selected design variant. The scores are multiplied to the weight to get the weighted score. These weighted scores are summed up to get the final scores of the respective design variants. Variant 4 turns out to be the best with 88.4, so design variant 4 (Crutch design) is selected for building the below knee foot prosthetic. The selected design is satisfying the client's needs such as 3D printed, resettable, safe and unique.

The following paragraph will illustrates the specifications of the design selected and the subsystem's justification.

5.2 Design Description

After intensive thought to choose the final design of this project, all the members of the team agreed to choose the design that is shown in (Figure 21) to be the final design for the project. This design consists of 5 parts, the supporting channel, connecting rod, pins, height adjustable part and the spring. The supporting channel, connecting rod and pins are all one part because they have the same function that is to help the person to attach the below knee leg with the prosthetic leg and help the person to walk. Also the supporting channel should be worn with a shelter to stop any purses to allergies in the leg which is represented # 2, 1, 4 in (Figure 21).

The second part is adjustable height part which solves the purpose of adjusting the height of the below knee foot prosthetic according to the height of amputees, which is represented #3 in (Figure 21).

The last part is foot, it is created in such a way that it gives a bouncy feeling while walking or running to replicate exact characteristic of a human foot, which is represented #5 in (Figure 21).

Properties of filament used in 3D printing is listed along with their properties in Table 4. The material selected for fabrication of prosthetic leg is HIPS. The reason for choosing the HIPS that it has the maximum tensile strength limit, inexpensive, rigid and it lowers down the moisture content for absorption.

All the properties for possible option of 3D printing material is listed in Table 4. After using Figure 21 and Figure 22 to calculate the moment, then using these equations again for the filaments HIPS, carbon fiber, CF and CF-ABS. The **Table 4** shows the solution for the other filament materials.

Table 4: Properties of different material data Based on British Plastics Federation and Buckley data

	ABS	HIPS	CF	CF-ABS
Tensile Strength (psi)	4100	3190	87022	5221
Flexural Strength (psi)	304000	3083350	142136	870226
Maximum water absorption (%)	0.3	0.2	0.15	0.18
Coefficient of Linear Thermal Expansion (in/in Fx10^-5)	5.6	4.5	4.2	4.32
Cost ($/kg)	19.61	12	28	22

The computational method is performed to estimate the center of mass, flexion angle, and moment of ankle by considering horizontal line at knee and hip as shown in **Figure. 21**. The equations are estimated considering the equilibrium equations in the motions of both X and Y:

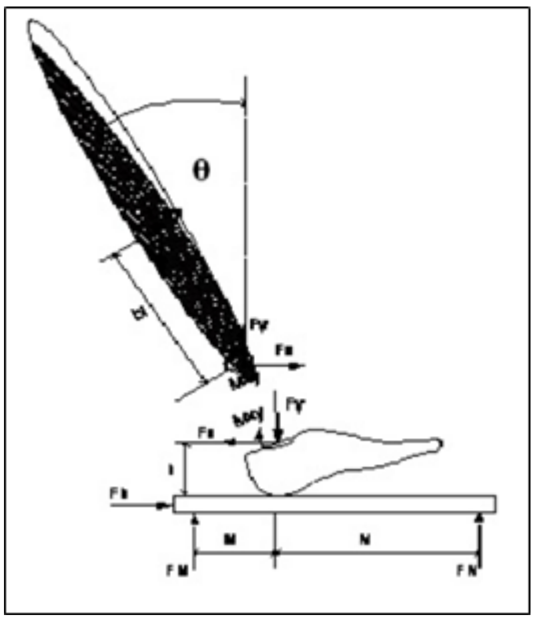


Figure 21: Free body diagram of Foot. Retrieved From (Mohammed 121)

Forces in X-direction

$$F_x = M_t \times x_c \tag{1}$$

$$F_y = M_t(g + y_c) \tag{2}$$

The angle between tilted surfaces with vertical plane is given by:

$$\theta = \frac{2tan\left(-K_1 \pm \sqrt{K_1^2 + \sqrt[2]{\left(K_2^2 - K_3^2\right)}}\right)}{K_3 - K_2} \tag{3}$$

The point of force is given by:

$$x_c = b_i \sin \sin \theta \ , y_c = b_i \cos \cos \theta \tag{4}$$

The point moment ankle is given by:

$$M_{xy} = F_N N - F_M M + F_h h - mga \tag{5}$$

$$K_1 = (M_t + m)l - \left(Mt^2 b_i^2\right) - I(F_N - F_M) \tag{6}$$

$$K_2 = F_h l \tag{7}$$

$$K_1 = \left(M_t b_i (F_N N - F_M M + F_h h)\right) \tag{8}$$

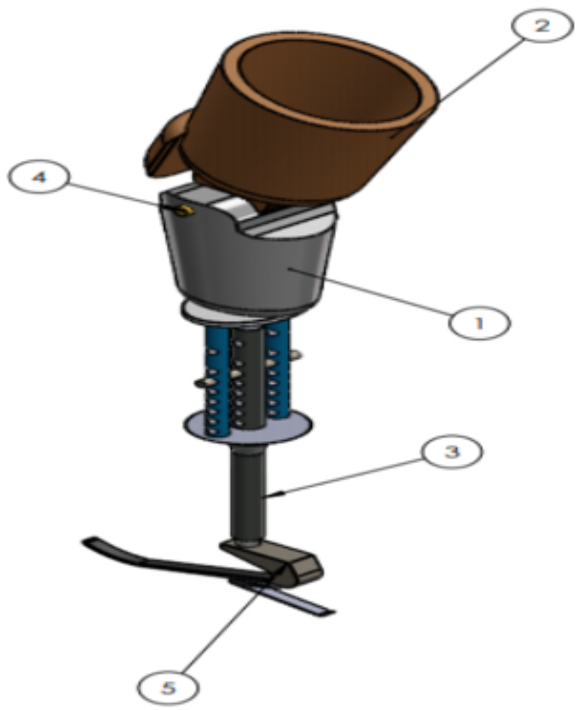


Figure 23: Cad model of Final design

6 PROPOSED DESIGN – First Semester

In this part the team has discussed all the parts needed for the 3D printed foot prosthesis to operate. The parts of the first semester proposed design are the lower joint, supporting channel, metal stick, pin, foot and sheath. All the parts except the sheath was printed in a 3D printer, and after attaching them together the team created the design. The sheath has been bought from a website called amputee store, which was the final part needed to complete the design. The first semester prototype made it possible to 3D print the whole design, but in terms of meeting the customer requirements there were some problems that faced the team such as not holding the required weight which was 200 lbs. and the middle parts was not accurate in adjusting the heights of the device. Design changes will be addressed later in the report in section 7.

6.1 Bill of Materials

As shown in table 5, it contains all the parts needed and how much it cost either to buy them or print them in a 3D printer. The cost of the materials that have been printed is an estimate from the company STAX after the team has called them. Finally the sheath was ordered from the website.

Table 5: Bill of Materials

Bill of Materials							
Team							
Part #	**Part Name**	**Qty**	**Functions**	**Material**	**Cost**	**Link to Cost estimate**	
1	Lower Joint	1	Attaches the sheath to the leg	PLA	450	N/A	$50
2	Supporting channel	1	Support	PLA	300	N/A	$95
3	Metal stick	2	Stand	PLA	150	N/A	$40
4	Pin	2	Supporting	PLA	50	N/A	$5
5	Foot	1	Spring	PLA	300	N/A	$30
6	Sheath	1	Attaches the sheath to the leg	Wool	45	[13]	$100
Total Cost Estimate:							$320

6.2 CAD Model and Exploded View

This part shows the 3D printed foot prosthesis in Solidworks with the first semester proposed design and each part by itself. To show each dimension of the each part.

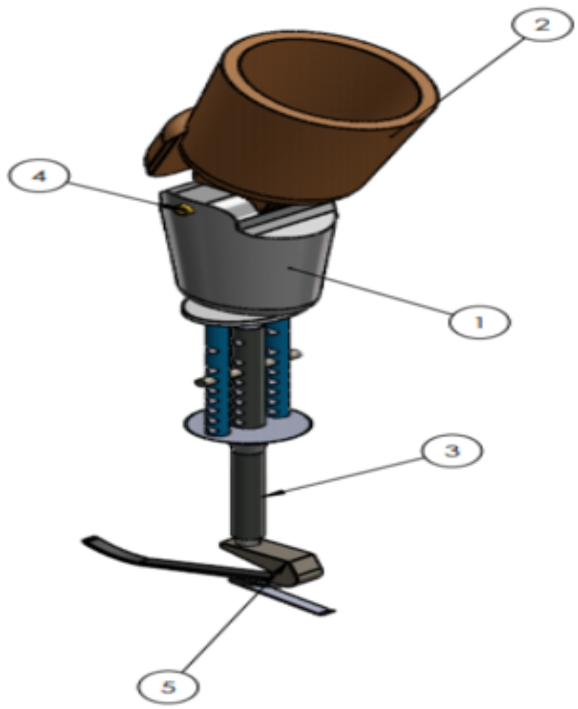


Figure 24: First semester proposed design with labeled parts

Figure 25: First semester proposed design

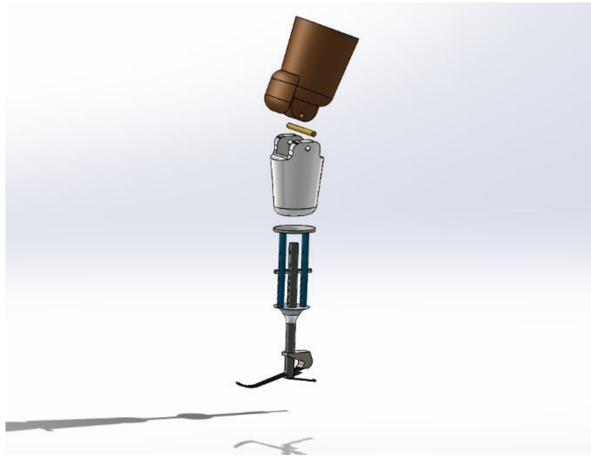


Figure 26: Exploded View of the First semester proposed Design

6.3 Resource List

Table 6: Resource List

Category	Resources	Location	Expertise
Team 4	Abdulwahab	NAU	Student
	Ali	NAU	Student
	Omar	NAU	Student
	Salman	NAU	Student
Technical Advisor and Instructor	Dr. Sarah Oman	NAU	Instructor
	Amy Swartz	NAU	T.A.
Client	Jenn Whealy	Flagstaff	Client
Facilities	Cline Library	NAU	3D Printing

	Engineering Building	NAU	Team's Meetings
Suppliers	Home Depot	Flagstaff	Hardware/Part Manufacturing
	AutoZone	Flagstaff	Hardware
	Amazon	Website	Hardware
	NAPA Auto Parts	Flagstaff	Hardware

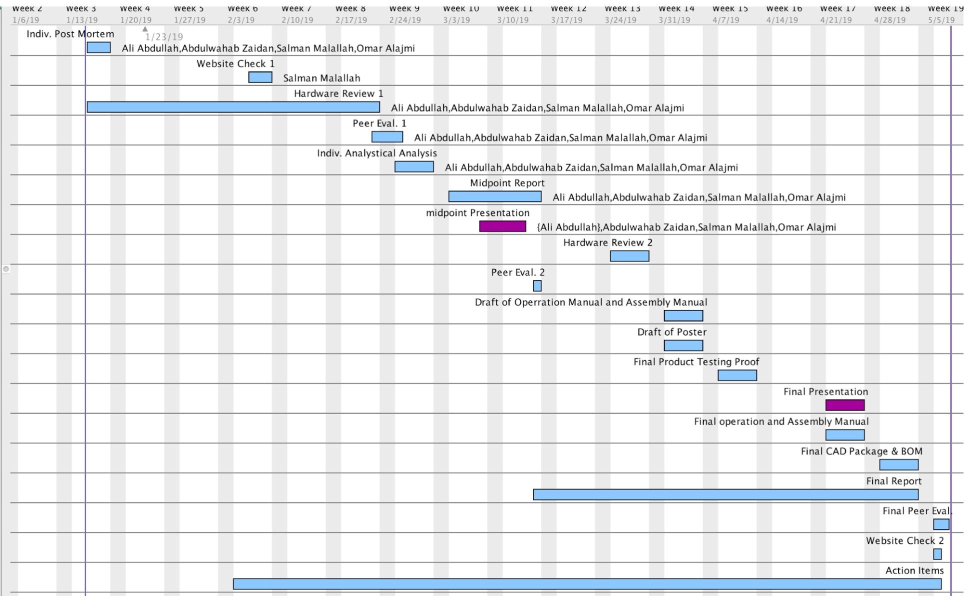
6.4 Implementation Plan

The steps of manufacturing the design that will be built in Spring semester will be addressed in the this paragraph. Most of the implementation plan was going through solidworks for designing two of the biggest parts in the design which are the supporting channel and the foot. And that is because the pricing of 3D printing is very low in terms of the cost, and one of the customer requirements requires at least one part to be 3D printed. The other reason is that solidworks gives the team the space to change the dimensions based on the client's sizes in her below knee and her height. The middle parts such as the PVC pipes are purchased from Home Depot, and the aluminum pipes are purchased from McMaster-Carr.

As a team we have split the work for next semester as shown in Table 7. All the assignments and reports are divided equally on the team members except the website check 1 and 2 will be completed by Salman, and the Solidworks will be created and drawn by Ali and Salman. Other individual assignments that the team members will work individually such as the analytical analysis and the post mortem.

Table 7: Gantt chart for second semester

Name	Begin date	End date
Indiv. Post Mortem	1/16/19	1/18/19
Website Check 1	2/6/19	2/8/19
Hardware Review 1	1/16/19	2/22/19
Peer Eval. 1	2/22/19	2/25/19
Indiv. Analystical An...	2/25/19	3/1/19
Midpoint Report	3/4/19	3/15/19
midpoint Presentation	3/8/19	3/13/19
Hardware Review 2	3/25/19	3/29/19
Peer Eval. 2	3/15/19	3/15/19
Draft of Operration ...	4/1/19	4/5/19
Draft of Poster	4/1/19	4/5/19
Final Product Testin...	4/8/19	4/12/19
Final Presentation	4/22/19	4/26/19
Final operation and...	4/22/19	4/26/19
Final CAD Package ...	4/29/19	5/3/19
Final Report	3/15/19	5/3/19
Final Peer Eval.	5/6/19	5/7/19
Website Check 2	5/6/19	5/6/19
Action Items	2/4/19	5/6/19



7 IMPLEMENTATION – Second Semester

This section explains what has happened in the second semester of the capstone. The explanations will be about the changes that has been done in the design and these changes had happened, the processes manufacturing needed in order to build the design and the resources needed in order to build the design.

The process that it took the team in order to build the design step by step.

7.1 Manufacturing

7.1.1 supporting channel Manufacturing

The way in order to build the supporting channel you need to open Excel program which is linked to Solidworks program and put your dimension is Excel program because it will automatically the dimensions solidworks will change, for example the outer diameter of the of the supporting. Figure 27 shows the supporting channel after it is printed.
The resources needed are:

- The files which are the excel linked in solidworks
- A laptop which has solidworks
- A place where you could print 3D to send the files of the dimensions added

Figure 27: Supporting Channel

7.1.2. Pipes

7.1.2.1PVC Pipes

For the PVC pipe you should go to home depot and buy four things which are two pvc pipes one has an outer diameter of 1-¼ and the second one has an outer diameter of 1, ¼ diameter zinc wing nut and ¼ zinc screw. Then taking the PVC to a machine shop to cut the height of the PVC pipes in 6 inches for both diameters and also making holes with the size ¼ and the height difference between each hole is 0.5 inch. then you have two PVC pipe that can slide into and out of each other, then finding the best height that fits you insert the screw into the two PVC pipes and apply the wing nut from the other side to stop the PVC from moving.

The resources needed are:

- Going to Homedpot and buying two PVC pipes with the outer diameter of one being 1 and the second one is 1-1/4 , with one wing nut size diameter ¼ and a long screw diameter ¼.
- Going to any machine shop that can cut and drill holes for PVC pipes. Cut both PVC pipes with the length of 6 inches and check if they are exactly the same.
- Then after that drill holes on both PVC pipes horizontal and the distance between them is 0.5 inches
- Then put one pipe inside the other and add the screw from one side and will go throw both pipes and then add the wing nut on the other side in order to make it stable.

Figure 28 PVC Pipes attached on

7.1.2.2 Aluminium Pipes

For the aluminum you need to order the aluminum pipes in McMASTER-CARR website , you will order two general purpose aluminum tubing, three foot long . One has the outer diameter of 1-¼ , 0.065 wall thickness and the other one has an outer diameter of 1 with 0.049 thickness wall. Then going to auto parts and buying bk house clamps with diameter of 1.5 and NCB insul sealing wrap. Then you take the aluminum pipes and take them to a machine shop to cut the two aluminum pipes from three feet to six inch, then you have two pipes which can slide inside each other you can adjust the height which works best for you and after that you will wrap it with the sealing wrap and attach the clamp with the small aluminum pipe.

The resources needed are:

- Ordering two aluminum pipes from McMASTER- CARR, one have the outer diameter of 1 and the other one is 1-¼.
- Next going to Auto parts shop and buying one clamp with a diameter of 1.5 and buying one NCB insul sealing wrap.
- Then taking the aluminum pipes and going to machine shop to cutting both aluminum pipes in the length of 6 inches for both of them.
- Then wrapping the insul sealing wrap with the aluminum pipe of the diameter of one.
- After that putting the pipes one inside the other and apply the clamp on the aluminum part that has a diameter of one.

7.1.3 Foot

The foot only needs to printed from the The laptop

The resources needed are:

- Need the file that is only solidworks and has the foot
- Then you need a laptop that has solidworks

- Need to send your work to a place where it has a 3D printer in order to print the foot

Last step is that either using the aluminum pipes or the PVC these two both will fit in the holes of the supporting channel and the foot with a little twist. The total cost can found in the bill of material **Table B.3** in the **Appendix B**,.

7.2 Design Changes

Many parts has been changed since last semester which are the supporting channel, middle parts, and the foot. Next subsections will illustrate every change in every part of the design.

7.2.1 Supporting Channel

First, the supporting channel had major changes since the team has met the new client Jenn. Our client has no bones in her below knee so that has limited and reduces the team's options and solutions of the supporting channel. Any other design of the supporting channel made the client feel pain, so that is why the team has changed the design **Figure 28**. The new design of the supporting channel works as follows, the client should wear the liner first, put her below knee in the supporting channel.

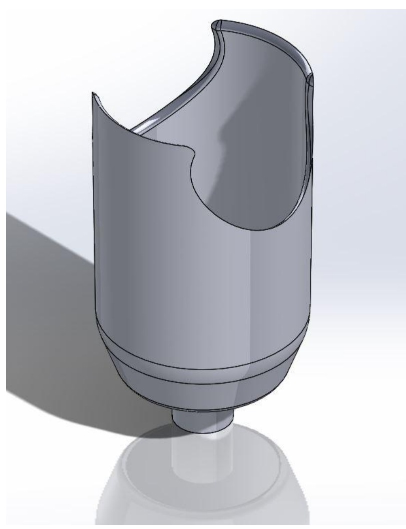


Figure 28: New design of the supporting channel

7.2.2 Adjustable length Parts

For the middle parts the old design was very heavy, and not very accurate in adjusting the height for the below knee amputees, so the team has figured out another solution that is lighter, less expensive, and very accurate in adjusting the height using either aluminum or PVC pipes **Figure 29 & 30**. In addition the previous middle parts design was meant to be customized which is against one of our customer requirements (worldwide).

Figure 29: Aluminum pipes with clamps

Figure 30: PVC pipes with holes

7.2.3 Foot

The old design of the foot was weak when 3D printed and can't stand the weight that is required to hold up to which is 215 lb because it broke when the force is applied in the testing. There was no engineering analysis that was done on the foot. Also it does not the right hole to connect with the middle parts which are the aluminum or PVC pipes. So the team has made a new design of the foot that can withstand the require weight (215 lb.) and has the right hole to connect with the middle parts **Figure 31**.

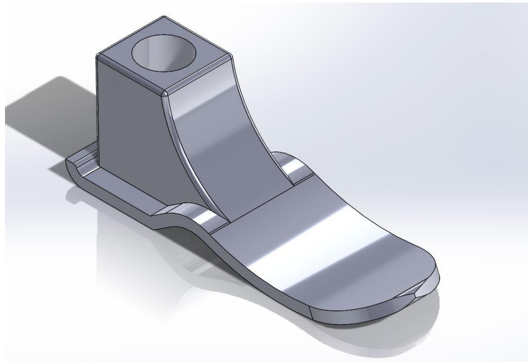


Figure 31: New design of the foot

7.3 Final Design

The figure 32 shows the selected final design of our project after testing the design and made sure that it meets all of the requirement. The final design contain 6 parts. As shown in table 7.

Table 7: Final design parts

Part #	Name #
1	Foot
2	Small PVC
3	Big PVC
4	Supporting channel
5	Head screw
6	Steel cup nut

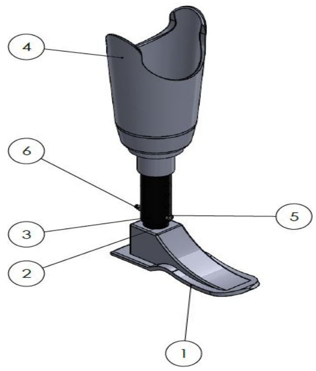


Figure 32: Final design parts

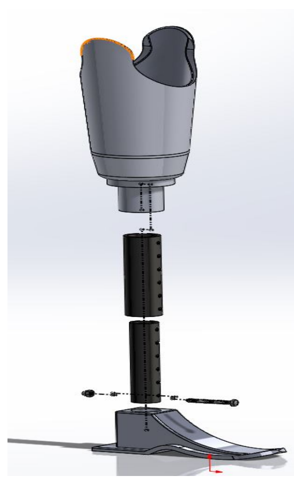


Figure 33: Exploded view of Final Design

8 Testing

This section explains the tests that are done in order to meet the customer requirements. This section also explains the results of the design if it can be used by person or not.

8.1 Testing:

The testing was taken in the machine shop at building (98C) using the machine called hand press. A hand press machine can be used for pressing and removing bearings and mostly used to know the amount of force needed before the material breaks. Figure 34. There were three tests done in the machine shop. The first test was taken on the full design being positioned at an angle. The second test was on the full design standing up straight to see how much force it can withstand. The last test was on the PVC pipes by itself because the team wanted to see If anything would happen with the PVC pipes since they are fixed with a zinc metal screw.

Figure 34: Hand Press Machine

8.2 Results

8.2.1 Test 1: Test on the Hand Press

The result of the first test was not done because as soon as we fixed it to the hand press it broke. Figure 35 shows how the design was added to the hand press before it broke with an old foot and Figure 36 shows the foot that was actually broken.

Figure 35: Position of the foot that was used

Figure 36: Broken foot

8.2.2 Test 2: Test on the hand press

The results of the second test was that the design was put up straight and three push of the hand press was added on a metal piece that weighs 7 pounds. The reason why the metal block was added in order to fix the hand press metal. There was not an exact amount of force calculated because the hand press didn't have a dial gauge. The gauge that is found on the hand press machine is used to measure the Psi, so the equation was used to come with the result:

$$A = \pi r^2$$

$$A = \pi \times 2.5^2 = 19.634$$

$$F = P \times A$$

$$F = 19.634 \times 50 + 7 = 988.74$$

The workers that operated on the machine shop said that one click is about 50 Psi and the video shows that there were three clicks which means that the design held more pressure than the amount that was required (219).

Figure 37: Design assembly

8.2.3 Test 3: Test on the hand Press

The third test was testing the PVC pipes alone with the same amount of pressure that we used to test the whole assembled design. The result was positive with no changes what's so ever.

Figure 38: PVC pipes

Figure 39: The holes that were made on the PVC pipes

8.2.4 Test 4: Test on the weight of the design

Using the body scale to measure the weight of the total design which is 7 lb.

8.3 Meeting the requirements:

Table 8: CR & MR.

CR	Meeting the Requirements
Below Knee	Fits the descriptions
Holds up to 215 lb adult male	Test 2 shows that is could withstand 300 lb
Must be printed from 3D printer	The supporting channel and the foot are 3D printed
Weights 8 lb at most	Test 4 show it weighs 7 lb
Limited filament materials	PLA is the material that team printed it in and it can also be printed in other material types fr example ABS and carbon fiber.
Fits different height sizes	The adjustable height (PVC pipes) are height adjustable.
Comfortable	Since each individual has a different cut of the leg so there is no perfect size leg at the bottom, that's why the team recommends the person to wear a liner for more comfort.
Safety	After testing the design it is safe to say that is perfect for three months

9. Conclusion

9.1 Contrib. to Project Success

The team was designing a prosthetic leg that had to meet certain specifications. The total weight of the mechanical device had to be less than 8 lbs. comfort for the person wearing it, durability, and safety were the main specifications required. Other requirements needed in the design were robustness, low costs and adjustability of the prosthetic foot. The team was able to perform all these specifications without facing a lot of difficulties. To complete this project in time, we needed to form some ground rules in order to cope with excess work load. First, the team divided different tasks among the members of the group. Each task had to be completed within a specified amount of time.

One person did a comprehensive research on the existing designs of the prosthetic leg. Another team member performed the black box model of the design so that the team could fully understand the task at hand. Two members organized the hierarchy of tasks so that we could systematically understand what the whole project entailed. This involved organizing the main tasks and their related sub-tasks. Finally we all designed the prosthetic foot by putting together the supporting channel, PVC pipes, spring and all the other components. The rule stated that each member had to perform the task in the best way possible and complete it in time. Most of the things went as planned, however the existing designs were too many when compiling. As a team t each partner had to assist the other to help finish the task on time.

The most positive aspects of project performance were time management and the cost. We were able to keep time and lower the design costs in the most efficient way. However, there were negative aspects experienced when designing the prosthetic leg. The quality of the product did not meet the expected standards because we had to use cheaper materials when designing the prosthetic leg. To improve the quality of our design, we used fabrication methods to make our construction materials better. This tactic significantly increased the quality of our product. We also utilized the three dimensional solid work designs to help us view the prosthetic foot in real life. The 3D method helped us modify the design hence increased the quality of our product.

9.2 Opport. For Improvement

The team have faced some problems when designing the prosthetic foot. First, some of the specifications originally stated began to bring a lot of challenges. This device had to be robust to enhance its durability therefore the team needed strong materials like steel and aluminum when designing some of the components. However, some of these materials were too heavy conflicting the specification that stated that the prosthetic leg had to be light. The team have opted to use carbon fiber which is light and very strong. However this material was too expensive and would compromise the cost which was also a specification needed in the design. When implementing the design, the team had to change the original dimensions used because of the changes of the size of the clients below knee amputees. This process was very tiresome and time consuming because the team had to keep altering the dimensions of the prosthetic leg.

The team took some organizational actions to improve the performance of our design. First the team communicated frequently so that the team could understand what was needed in the project. Communication helped us to brainstorm ideas when designing the complex components of the prosthetic leg. The chairman had to evaluate all the tasks performed by the team members. This ensured that all the members did their tasks in the correct manner. To improve the group performance the team identified potential roadblocks like laziness, low morale and negative arguments. All these aspects were eliminated from our team by encouraging and motivating each other hence increasing our productivity. This group design made us learn a lot of technical lessons. The team were able to learn project management as an integral part of mechanical engineering. The team were able to learn how one applies scientific and mathematical skills to solve day to day project. This group design has made us know how to effectively manage and utilize resources without wasting money. The team also have learnt how to work in teams and utilize the time given when working in any project.

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6 APPENDICES

6.1 Appendix A:

6.1.1 Design # 7 *The heel*

The **Figure A.1** shows a simple lower limb foot prosthetic. The socket, pylon and the foot is printed simultaneously. A spring is attached to the base of the foot to absorb the impact loads. Its will be lighter in weight since only the fiber/ plastics cab be used to build it. Spring increases its comfortability. It can easily withstand the required load of 215 lb. Major drawback of this prosthetic foot design is that its height can't be adjusted and the socket dimensions also cannot be changed after 3D printing.

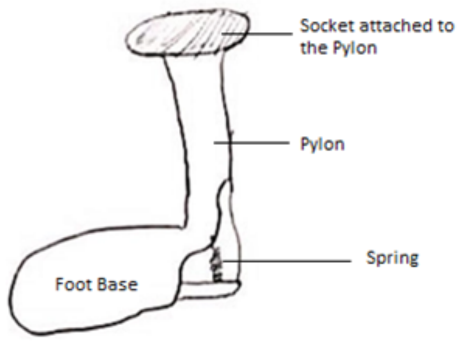


Figure A.1: The heel

6.1.2 Design #8 Gate Wall

A schematic design of the gate wall is place at **Figure A.2**. A gate wall structure is used in the place of pylon. At the top socket is attached. The base of the gate wall is attached to the synthetic foot. Due to the gate wall structure, its height can be adjusted easily. It is easy to handle, in-expensive, easy to build and comfortable to the amputees. Major drawback is its complexity and weight. It should be cleaned regularly to avoid any corrosions.

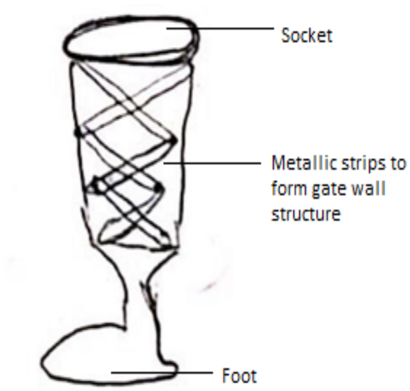


Figure A.2: Gate Wall

6.1.3 Design # 9 Hydraulic System

In the design presented in **Figure A.3**, hydraulic system is used in between the pylon to make the height adjustable. At the top of the pylon a socket is attached and at the base a synthetic foot is attached. Due to use of the hydraulics, its complexity will increase which will results in the high cost. Its maintenance cost is also high. It can easily support the 200lb weight. Its weight will also be greater so the user will not be able to carry it easily.

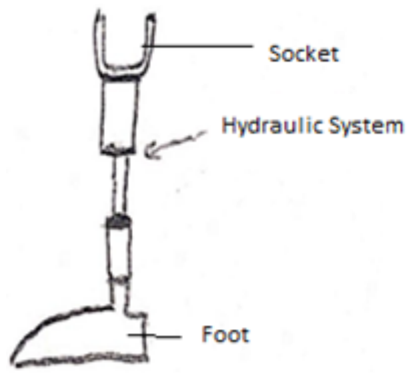


Figure: A.3: Hydraulic System

6.1.4 Design # 10 Versatile

Design shown is **Figure A.4** is versatile. Its foot can be changed according to the need of user. Foot design is made for all climbing, swimming, and walking. The foot can easily be installed by tightening and loosening the nut and bolt. A socket is attached at the top of the pylon which is comfortable for the amputees. Major advantage of this design is that amputees has freedom to adjust its foot according to their need and also its height can be adjusted with the help of nut and bolt assembly.

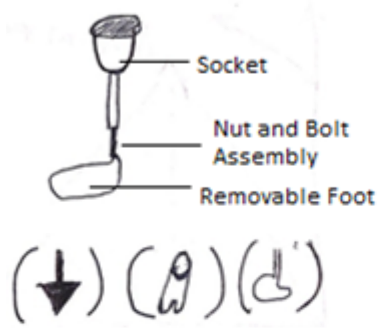


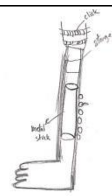
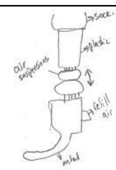
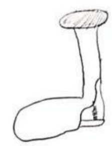
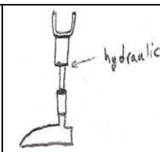
Figure: A.4: Versatile

6.2 *Appendix B:*

6.2.1 Pugh Chart

Design variant 6 has been taken as a datum and all other designs have given scores of '+' '_' 's' for good, bad and satisfactory performance respectively with respect to the datum. Final score is evaluated by deducting the no. of minus from the no. of plus. The design which gets the highest score is selected. The design variant 4, 6, 8 and 10 turns out to be the best among 10 variants. These 4 design are further evaluated based on the client needs.

Table B.1: Pugh Chart

Concept									
Criteria	1	2	3	4	5	6	7	8	9
Fits different height sizes	-	-	-	+	S	D	-	+	S
Comfortable	-	-	+	+	S		+	S	-
Limited filament material	S	-	S	S	-	A	S	S	-
Weight 7lb at most	S	S	+	+	-		S	-	-
Holds up to 200lb person	S	S	-	+	S	T	S	+	+
Factor of safety	-	S	-	S	S		-	+	S
$\Sigma +$	0	0	2	4	0	U	1	3	1
$\Sigma -$	3	3	3	0	2		2	1	3
ΣS	3	3	1	2	4	M	3	2	2

6.2.2 Decision Matrix

Decision matrix is shown in the below table B.2. The total score are calculated after summing up the weighted score. The variant 4 of design got the highest score hence selected for the implementation.

Table B.2: Decision Matrix

	Weight	Variant 4		Variant 6		Variant 8		Variant 10	
Criterion		Score	Weight Score	Score	Weigh t Score	Score	Weigh t Score	Score	Weigh t Score
1. Fits different height sizes	0.18	100	18	80	14.4	100	18	60	10.8
2. Comfortable	0.1	70	7	70	7	50	5	50	5
3. Limited filament material	0.2	90	18	40	8	60	12	80	16
4. Weight 7lb at most	0.14	70	9.8	100	14	30	4.2	100	14
5. Holds up to 200lb person	0.24	90	21.6	70	16.8	100	24	90	21.6
6. Factor of safety	0.14	100	14	80	11.2	70	9.8	100	14
Totals	1		88.4		71.4		73		81.4
Relative Rank			1		4		3		2

Table B.3: Bill of Materials

Part #	Name #	Qty#	Description#	Material#	Dimension#	Cost#	Link to the cost estimate#
1	**Foot**	**6**	**3D printed foot based on infill**	**PLA**	**8.29*3.00*3.00 in**	**$30 $30 $30 $30 $30 $30**	https://nau.edu/library/makerlab/
2	**Small PVC**	**1**	**PVC pipe attached to the foot**	**PVC**	**6*1-1/4 in**	**$1.17**	https://www.homedepot.com/s/pvc%2520pipe?NCNI-5
3	**Big PVC**	**1**	**PVC pipe attached to the socket**	**PVC**	**6*1 in**	**1.62**	https://www.homedepot.com/s/pvc%2520pipe?NCNI-5
4	**Supporting channel**	**1**	**Supporting channel based on infill**	**PLA**	**7.00*4.5*10.00 in**	**$80 $95 $38 $37 $50 $50**	https://nau.edu/library/makerlab/
5	**Head screw**	**1**	**Holds the PVC pipes**	**Steel**	**¼"- 20**	**$0.42**	https://www.mcmaster.com/92620a551
6	**Steel cup nut**	**1**	protects threads	**Steel**	**¼"- 28**	**$0.76**	https://www.mcmaster.com/91855a470
	Liner	**1**	**Helping the socket to hold the below knee**	**Cotton and Nylon**	**Depends on the person**	**Donation $0.00**	https://amputeestore.com/
	Big hose clamp	**1**	**Aluminum pipe attached to the foot**	**Aluminum**	**6*1-1/4 in**	**$8.18**	https://www.napaonline.com/
	Small hose clamp	**1**	**Aluminum pipe attached to the socket**	**Aluminum**	**6*1 in**	**$11.47**	https://www.napaonline.com/
	Insul sealing wrap	**1**	**Remove any intruder air while putting the liner inside the socket**	Fabric Harness Tape	3.6 x 3.6 x 0.6 inches	**$18.88**	https://www.napaonline.com/
	Big Aluminum pipe	**1**	**Aluminum pipe attached to the foot**	**aluminum**	**6*1-1/4 in**	**$26.38**	https://www.napaonline.com/
	Small Aluminum pipe	**1**	**Aluminum pipe attached to**	**aluminum**	**6*1 in**	**$18.8**	https://www.napaonline.com/

			the socket				
					Total cost	**$617.68**	