Senior Capstone Design Project

Open-Source 3D Printed Foot Prosthesis

Team 18F04

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11-25-2018

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DISCLAIMER

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1 BACKGROUND

1.1 Introduction

In recent times, the number of lower leg amputees has increased significantly. So there is need to design a cost effective solution which can provide stability to the amputees while standing and walking. In this semester our aim of the project is to design a 3D printed foot prosthesis leg for below-knee amputees which is easy to install and remove, inexpensive, and reachable. The designs available across the world are not either costly or not reliable. A large emphasis is paid during design to make the foot prosthesis leg affordable and reliable. The team's goal is to build an affordable 3D printed foot prosthetic and its price should be very less than the market price throughout the world, which every person can afford it. This enables the amputees to get the design and 3D print the product anywhere in the world for their use. This whole project is sponsored by the Northern Arizona University. The product will be used by the below knee amputees so they will be our clients. The other stakeholders are the companies who are building the below knee foot prosthetics. The team's client is Dr. Sarah Oman. The team is expected to build a below knee foot prosthetics which is reliable, simple to operate, easy to install and uninstall inexpensive and easily available.

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 200lb adult male. 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 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.

1.3 Original System

The team's aim is to build a new and unique product which will fulfill all the end-user's requirement. Since it is not a re-engineered product there is no original product in existence which is considered for this report. The variety of products available online are studied to understand the pros and cons of the design and they will come up with a new product. This project involved the design of a completely new device. There was no original system when the project began.

2 REQUIREMENTS

Our team goal is to create a prosthesis leg for below-knee amputees that easy to install and remove, inexpensive, and reachable. The team has to collaborate with all the stakeholders to understand the basic requirements of the clients which need to be fulfilled. The basic client requirements are directly obtained from the end user since they will be using the product. The engineering requirements are 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. 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 and the HoQ diagram for prioritizing the client needs.

2.1 Client Requirements (CRs)

The various stakeholders of these products are the lower limb amputees and the various companies which are fabricating the similar 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 translated into some meaningful requirements. All the requirements have been assigned a weight for further analysis. **Table 1** represents the client requirements and their associated weight. The weights are ranked from 1 to 9 according to the importance of the requirement.

Table 1: Client requirements

Client requirements	Weight
Below Knee foot prosthesis	9
Robust	9
Use 3D print Material	9
Lightweight	9
Limited filament materials	5
Height adjustable	7
Portable	1
Weatherproof	1
Comfortable when wearing	6
Safety	9
Free ages use	3
Low Cost	9

The product should be a below-knee foot prosthesis that can be used by people of all ages. The prosthetic leg should be inexpensive, reliable and comfortable to wear so that the user will not feel uncomfortable and can afford it. It should be lightweight and portable to make it easier to not only move around with it, but also to handle. The height of the prosthetic leg should be adjustable so that it can fit to different height of amputees. Comfort is key when creating these prosthetic legs since and it alleviates any chances of the amputee feeling pain and therefore, it also needs to be safe so as not to damage the user's leg. Additionally, it should be weather proof meaning that their functionality should not be affected by changes in the climate. All in all, these client requirements should focus on creating a prosthetic leg that is will be more convenient and reliable for the end-user.

2.2 Engineering Requirements (ERs)

The engineering requirements are measurable quantities and are very important in evaluating the designs at the later stage. From the client requirements, the team has generated the engineering requirements which needs to be used in 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
Weight holding capacity of the prosthetic leg	200 lbs.
Weight	< 7 lbs.
Cost	550-1500 $
Filament material	ABS, PLA, PET, HIPS
Fits different height people	5'-0" to 6'-5"
Reliability	99%

2.3 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,** on the left side of the wall, we have the client requirements and at the roof engineering requirements. 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

House of Quality (HoQ)

Customer Requirement	Untis	Weight	1.Below Knee	2.Prosthetic leg must hold up 200 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
1. Below Knee	N/A	9	9	6		6		3				3	9	9
2.Holds up to 200 adult male	lbs	9		9		9							3	3
3.Must be printed from 3D printer	N/A	9	3		9	3	9	9		6				3
4.Weight 7 at most	lbs	9		9	6	9	6	3		6			6	6
5.Limited filament materials	N/A	5		6	9	3	9		6		9			3
6.Fits different heights sizes	Inch	7	6	3	6	9	6	9		3		3		9
7.Easy to carry	N/A	1			3	9	6			9				
8.Adjustable to all weathers	N/A	1			6	3	6				9		6	
9.Comfortable	N/A	6	3	6		3	6	6	3	9				9
10.Safety	N/A	9				9	3				9	6	6	9
11.Free ages use	Year	3						3	6	3		9	6	3
12.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

3 EXISTING DESIGNS

A variety of products are available across the world for below knee amputees the team conducted a research on them. The team was supposed to conduct thorough research. The researched has been done 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 designs which will fulfill all the clients' requirement. The pros and cons of the designs are studied. During research, some existing designs which are important for our project are presented into following subsections.

3.1 Design Research

Over the years there has been a lot of research to replicate the exact characteristics of the human foot. There are a lot of designs of below knee leg prosthetic are available in the literature. The team has conducted a thorough research by utilizing the Google search engine. The team has also watched many videos available on the YouTube of similar kind of product. First the team has studied the characteristics of the human foot through literature. The team have found many existing designs of the below knee foot prosthetics. Some designs have been studied thoroughly to develop the basic understanding of its working and pros and cons of it. The team has also studied how the existing concepts can be used to make a simple, reliable, in-expensive and light weight prosthetic leg. Some designs have also been investigated to make the height of prosthetic leg adjustable to benefit the maximum number of populations. Our investigation aims at combining all the best characteristics of the design 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 sub-sections. This section also includes that which characteristics of these existing designs can be incorporated to develop the best and in-expensive design.

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

A picture of the lower limb foot prosthetic design is shown in **Figure 1**. Foot prosthetic is made using low temperature re-moldable thermoplastics. The socket of prosthetic foot is designed to fit on the amputee's residual limb in vary less time without the need for a trained prosthetist. Thermoplastic can also be used in our design to make the design light weight so that it can easily be carried to one place to another. Since the size of residual limb can also increase or decrease in volume so the concept of using re-moldable plastic turns out to be the best part of the design. Residual sockets can also be re-molded easily hence there will not be any support needed to hold the prosthetic leg.

First the limb of the amputees is covered with the plastic and fix to properly so that it will not stick out from the limb. A socket of thermoplastic is wrapped around the residual limb and heated a little bit. Due to heat the thermoplastic socket takes the shapes of residual limb. The molded socket is removed and finishing is done. The finished socket then attached to the pylon. Since the socket is accurately molded in the shape of residual limb so there is no need of any attaching mechanism [1].

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

3.2.2 Existing Design #2: Adjustable Bicycle Limb

A picture of adjustable bicycle limb is shown in **Figure 2**. The leg is built from waste of a bike seat hence it will be cheaper since the waste of a bike is used which is easily available. The parts are made up of the steel so it is little heavy. The best part of the design is use of rubber at the foot base to provide the traction to prevent the amputees from falling. The rubber is in-expensive and can be incorporated in team's design.

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

Figure 2: Adjustable bicycle Limb [2]

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. The specific thermoplastic material used for fabricating the foot prosthesis is polypropylene. This material can also be used in our project due to its strength, flexibility and ductility. The flexibility of polypropylene causes the mono limb to deflect during walking which simulates ankle joint motion. The best part of the design is that it socket and pylon are molded together. The major drawback of the design that it's cannot be adjusted after fabrication. The wooded foot which resembles the actual foot is made and attached to the socket and pylon.

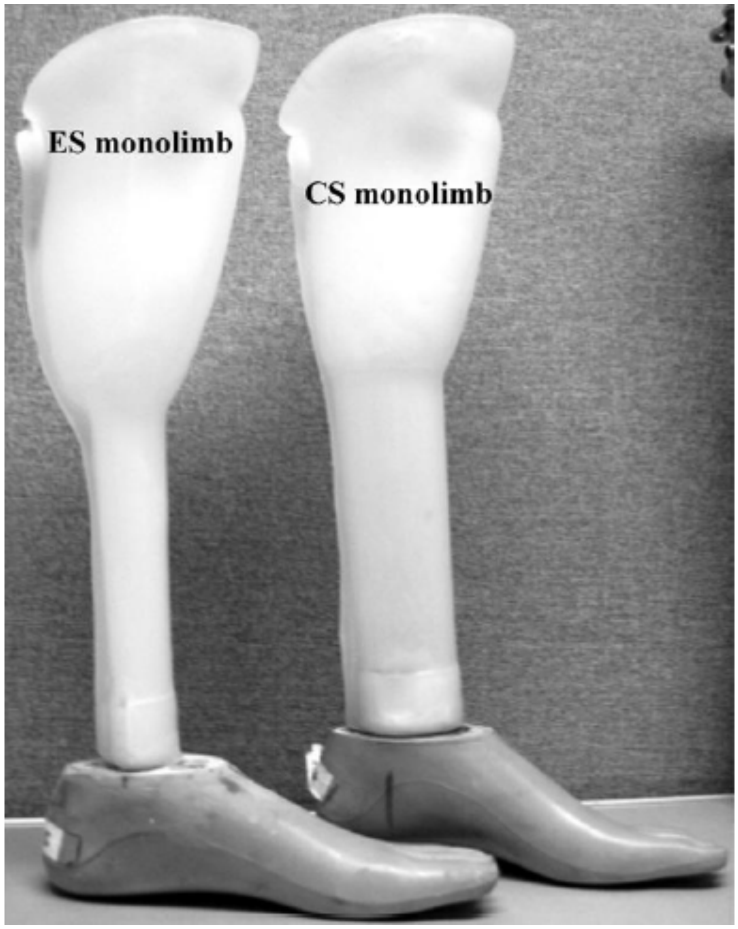

Figure 3: Elliptical/Circular Shaped Low Cost Prosthetic **[3]**

3.3 Functional Decomposition

In this project, the major aim is to create a 3D printed, inexpensive and reliable foot prosthetic so that it can provide the stability to the below knee amputees during standing and walking. As the name suggests, the major task is breaking down to the much simpler task. This will help the team since it is easier to solve relatively simple task instead of trying to solve a bigger problem. This section includes the two sub-sections 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. The black box model is 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, material and the signal which are beings fed to model and 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.

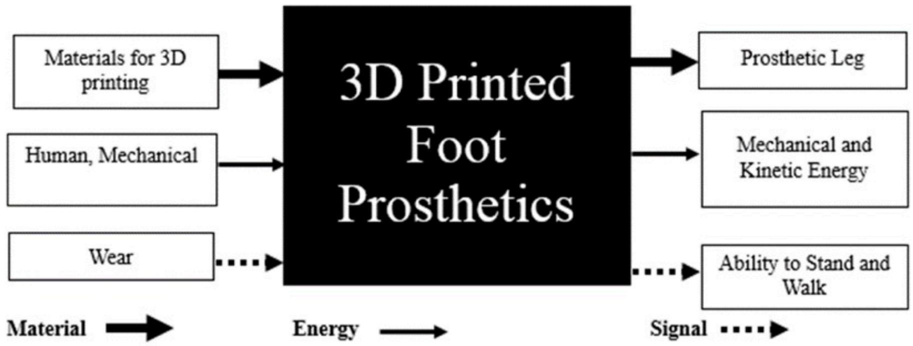

Figure 4: Black Box model

3.3.2 Hierarchical Task Analysis

A hierarchical task analysis provides an understanding of the tasks users need to perform to achieve certain goals **[4]**.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.

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 5**, typically has a rigid inner structure (wood or plastic) surrounded by a compressible foam cosmetic shell [5]. In our project we may use this SACH foot instead of the foot that we have already done in solid-works and the reason why is because it may give a steady for the users more than the design we have.

Figure 5: SACH Foot [5]

3.4.1.2 Existing Design #2: Niagara Foot

The Niagara foot presented in **Figure 6** is a 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 [6]. This design will help the team by thinking of using the same design of the foot to provide the energy. Also the material used in this design withstands high weights and that would be very useful to our team since one of our customer requirements is to hold up to 200 lbs. adult male.

Figure 6: Niagara Foot [6]

3.4.1.3 Existing Design #3: Flex Foot

Flex foot is shown in **Figure 7**. 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 [5]. This Flex foot will be useful for our design by handling huge force and torque, and that will also give an advantage to not just walk but also to run, and by that the users that play sports will also have benefits of this design.

Figure 7: Flex Foot [5]

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. 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

The socket of the prosthetics limb is presented in **Figure 8**. 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 [7]. This the team by understanding that there are types of sock which is important for the team to understand that there are types of comfort. Depending on the person who wants to buy the sheath that the team is using or spend more money and buy more comfortable one.

Figure 8: Supracondylar [7]

3.4.2.2 Existing Design #2: PTB with cuff

The design of the socket #2 is presented in **Figure 9**. It is clearly evident from the **Figure 9** 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 [8]. This design helps to relax the persons thigh and the tension will be on the knee.

Figure 9: PTB with cuff [8]

3.4.2.3 Existing Design #3: Ininite Socket

The picture of one type of socket is presented in **Figure 10**. 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 [9].This design creates tension on the persons thigh and knee in order to help the attachment of the sock and the foot.

Figure 10: Ininite Socket [9]

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 [10]. After adjusting the height clamp is again tightened to fix the length of pylon. The components of the adjustable pylon are shown in **Figure 11**.

Figure 11: Component used in building adjustable pylon [10]

3.4.3.2 Existing Design #2: Pylon fixed to the foot

Pylon fixed to the foot base is shown in **Figure 12**. The top of the pylon will be fixed to the socket by socket. The height of the pylon cannot be adjusted.

Figure 12: Pylon fixed to the foot [11]

3.4.3.3 Existing Design #3: Pylon fixed to the socket

Picture of the pylon fixed to the socket is shown in **Figure 13**. 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 13: Pylon attached to the socket [12]

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 14**. 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.

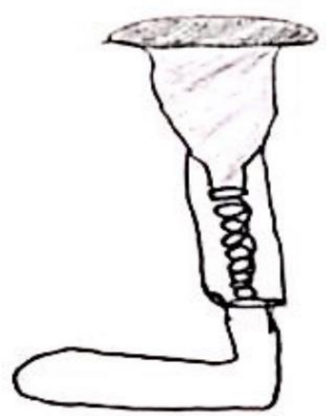

Figure 14: Spring

4.2 Design #2: Split

A design of foot prosthetic is shown in Figure 15. 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 (7 lbs. at most) and can hold up to 200 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 15: Split

4.3 Design #3: Spider Web

The design presented in **Figure 16** 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 200 lbs weight. Its height cannot be adjusted. Major pros of the concept are that it is light weight and comfortable.

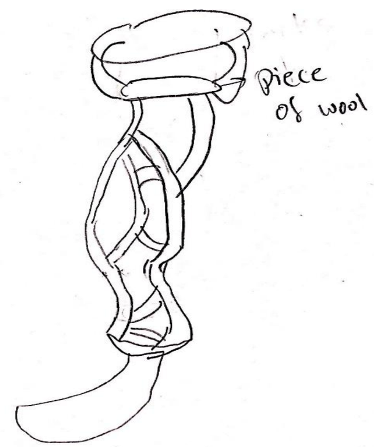

Figure 16: Spider web

4.4 Design #4: Crutch

Schematic diagram of the crutch is shown is **Figure 17.** 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.

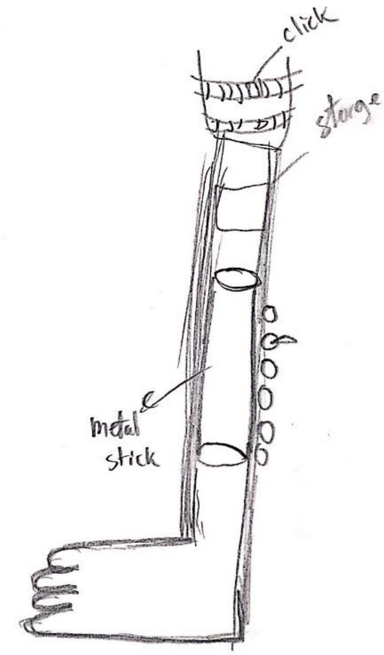

Figure 17: Crutch

4.5 Design #5: Air

The design presented in **Figure 18** 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 7 lbs. since the ABS and air suspensions are used.

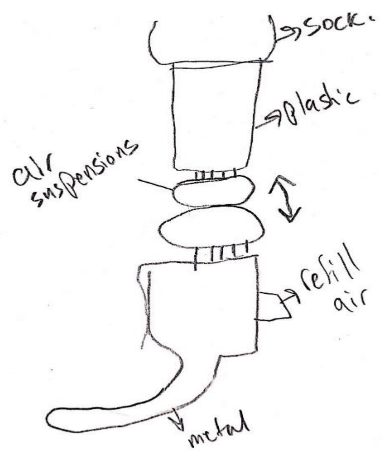

Figure 18: Foot prosthetic using air suspensions

4.6 Design #6: Sea horse

The bottom of the design presented in **Figure 19** 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.

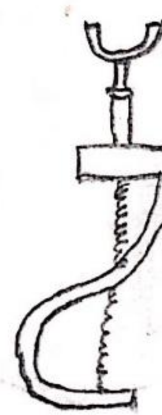

Figure 19: Sea-horse

5 DESIGN SELECTED – First Semester

A number of designs are considered for designing a below knee foot prosthetic. Total no. of design considered for the building a foot synthesis is 10. All the designs are evaluated to get the best design. The aim of the team is to build a 3D printed below knee foot prosthesis which is in-expensive, light weight, adjustable and comfortable. All the designs are evaluated based on the client need. The design which turns out to be the best is presented in **Figure 20.**

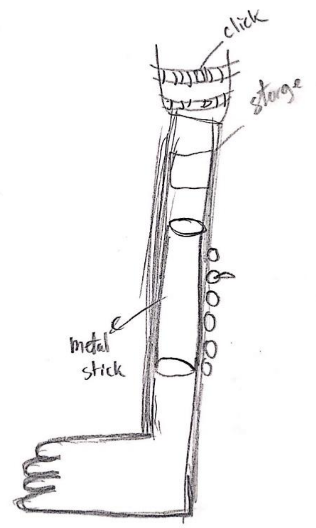

Figure 20: Crutch

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

5.1 Rationale for Design Selection

Pugh chart is a basic tool to evaluate all the possible designs. The team has narrowed down to four possible designs, which perform well during the analysis out of the 10 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 Pugh chart the client needs are listed at the left and all the designs are evaluated with respect to a datum. The datum design is the base concept of all of the team's designs, which is chosen by the team. 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 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 requirements are displayed and weight out of 1 is assigned to all the client 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 is selected for building the below knee foot prosthetic.

To evaluate these possible designs, decision matrix is employed. In the decision matrix the client needs are listed at the left and all the possible designs are evaluated to find out the best possible design. The detailed decision matrix is placed at the **Appendix E.** In the matrix a weight is given to each client needs and based on those the score is given to each design.

The selected design is satisfying the client needs such as 3D printed, resettable, safe and unique.

5.2 Design Description

After intensive thought to choose the final design of this project, members agreed to choose the design that shown in (Figure 21) to be the final design for the project. This design consists of 5 parts. First, the supporting channel which represent #1 in (figure 21) is connecting with lower joint (#2 in figure 21) via a pin (#4 in figure 21), to help the users to move their below-knee forward and back in order to facilitate walking. In addition, the leg is designed with holes as shown in (#3 figure 21) to choose the appropriate size for the user, and all the user need to put the pin in the hole appropriate to the person who needs it to install the appropriate length of leg. Last part of the design is a foot shown in (#5 figure 21), which is a spring to make balance for the person who is wearing it. The spring is connected to the leg and it has a heel on the back of the foot to absorb the weight pressure when walking. The materials that the 3D printed foot will be either ABS, PET, HIPS, PLA or Nylon. The last time that the team called STAX Company who will print the foot advised us to print it with the material nylon and that's why the team is using for the estimate.

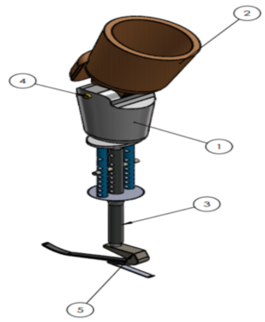

Figure 21: Final design

6 PROPOSED DESIGN – First Semester

In this part the team is discussing all the parts needed for the 3D printed foot to work. The parts are lower joint, supporting channel, metal stick, pin, foot and sheath. All the parts except the sheath will be printed in a 3D printer and attaching them will create the design. The sheath will be bought by itself from a website called amputee store, which will be the final part needed.

6.1 Bill of Materials

As shown in table 4, 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 will be printed is an estimate from the company STAX after the team called them and the sheath must be ordered from the website.

Table 4: 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	Nyon	450	N/A	
2	Supporting channel	1	Support	Nylon	300	N/A	
3	Metal stick	2	Stand	Nylon	150	N/A	
4	Pin	2	Supporting	Nylon	50	N/A	
5	Foot	1	Spring	Nylon	300	N/A	
6	Sheath	1	Attaches the sheath to the leg	Nylon	45	[13]	
Total Cost Estimate:							1295

6.2 CAD Model and Exploded View

This part shows the 3D printed foot in Solid-works with the final and each part by itself. To show each dimension of the each part.

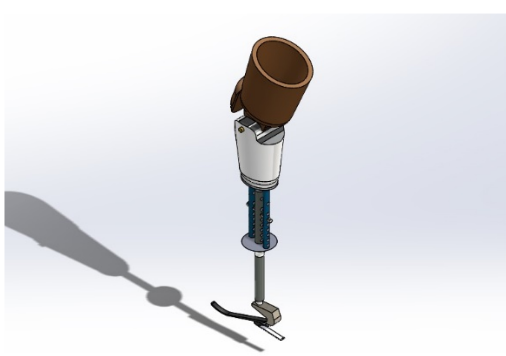

Figure 22: Final design

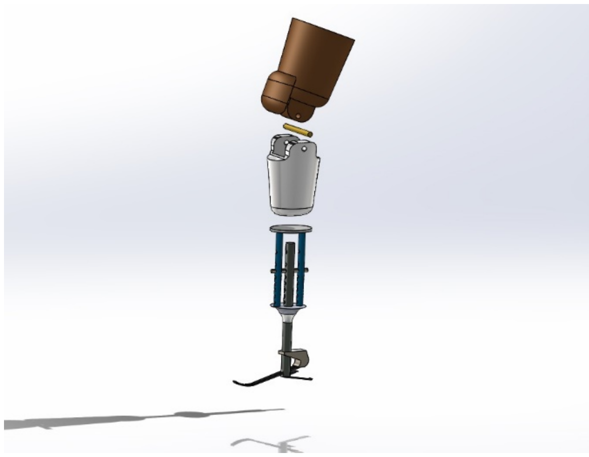

Figure 23: Exploded View of Final Design

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7 APPENDICES

7.1 Appendix A: The heel

7.1.1 Design # 7

The **Figure A.1** shows a simple lower lib 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 200 lb. Major drawback of this prosthetic foot design is that its height can't be adjusted.

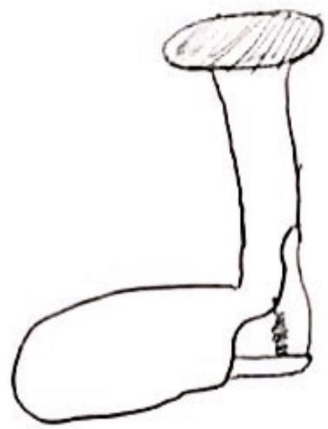


Figure A.1: The heel

7.1.2 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.

Figure A.2: Gate Wall

7.1.3 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. It's weight will also be greater so the user will not be able to carry it easily.

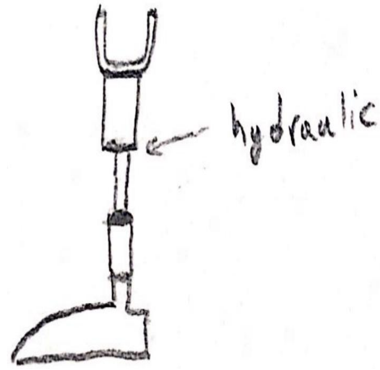


Figure: A.3: Hydraulic System

7.1.4 Design # 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.

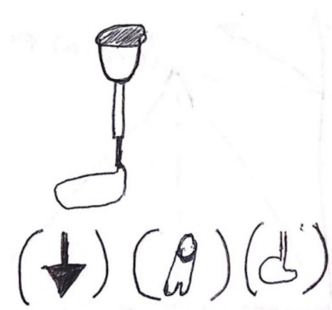


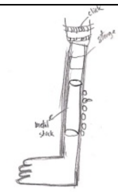
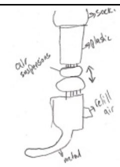
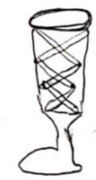
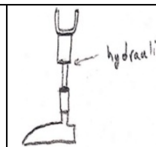
Figure: A.4: Versatile

7.2 *Appendix B:*

7.2.1 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

7.2.2 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	Weight Score	Score	Weight Score	Score	Weight 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