BiOM Prosthesis Adapter – 18F01

Final Proposal Report

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EXECUTIVE SUMMARY

An adjustable adapter was needed to test the BiOM Ankle Prosthesis device, which was designed to attach the leg of the user to the BiOM Ankle Prosthesis to accurately represent how a person walks. This adapter was to fit different sized users, be lightweight, comfortable, durable, safe, cost effective, and have a quick attachment for the user. The adapter was designed to connect the BiOM Ankle Prosthesis device to the users bent knee held at a 90-degree angle per the customer's requirement.

There are three main subsystems to this project; the pylon – a rigid bar going from the Ankle Prosthesis to the knee, which was to accommodate height adjustability; the attachment – how the pylon will attach to the leg support; and the leg support – how the users leg will be held in place and supported. Including all the subsystems, the team came up with 20 different designs that would meet the customer needs which included a height adjustable pylon, two types of attachments which included a side attachment and under the knee attachment, and many different types of leg supports.

The final design chosen for the Prosthesis Adapter included a screw lever height adjustable pylon similar to something found on a bike seat, a below the knee attachment that attached the pylon and the leg support on both sides of the knee, and a leg support that included three different adjustable supporting devices, upper leg, lower leg, and below the knee, with springs attaching the pylon to the leg support. This design met all the customer requirements presented along with having many other benefits. These benefits included having adjustability in height and width of the user's leg, having the pylon rotate about the natural knee's axis of rotation which would allow for more natural walking form, and minimal material usage which would cut down on cost needed to manufacture the device.

Once the final design was chosen, a CAD model was created, and a prototype was constructed to scale to validate the design. The team learned valuable information from building the prototype which lead to a slight design change. A prototype of the final design will be constructed next semester to ensure the final design meets all the customer requirements prior to building the final product. After the prototype is built the team will work on constructing the final product and testing the final product. Testing the final design will include building parts of the design one at a time and testing them as they are built, then testing the final product together to ensure the product meets and exceeds the customer requirements.

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1 BACKGROUND
The BiOM Prosthesis Adapter project was proposed to the senior design capstone team as a solution to help test the BiOM ankle prosthesis during the testing phase for able bodied people. This section will discuss what the BiOM Prosthesis Adapter is and why it is important to the client, and what current technology is being used for this process.

1.1 Introduction
The BiOM Prosthesis Adapter project is to design an adapter that attaches a BiOM Ankle Prosthesis to a patient's bent knee. This adapter will allow the BiOM to be tested on an able-bodied person before integrating the prosthesis and adapter into society where the goal is to help below-the-knee amputees walk. The real intention of the project is to aid in research for the BiOM Ankle Prosthesis device to make improvements within the medical field. The design constraints for the prosthesis adapter include having a weight of less than 1 kg, reduced friction in the leg attachment for comfortability of the user, a height adjustable device up to 15 cm, having a quick 30 second attachment to the BiOM Ankle Prosthesis device as well as the leg, must be capable of supporting at least 200 pounds, an adjustable socket diameter of 7-20 cm, reduced cost of the adapter, and a high safety factor. The customer requirements were obtained from the clients; Thomas Huck, PhD student attending NAU; Dr. Zachary Lerner, Mechanical Engineering Research Professor; and Dr. Kiisa Nishikawa, Biology Research Professor. In addition to the clients, stakeholders for the project include the users to test the device, doctors and physical therapists, hospitals, and eventually below-the-knee amputees whom will benefit from the adapter upon the completion of the testing phase and completed research.

1.2 Project Description
The following is the original project description that was provided by Dr. Zachary Lerner and Dr. Kiisa Nishikawa.

> "*In order to test new control strategies, an adapter for the prosthesis is needed to allow attachment to an intact limb. This project will involve designing and building the adapter that attaches to the bent knee."* [1]

The BiOM Prosthesis Adapter is to connect the BiOM Ankle Prosthesis to the user at the knee. The user was specifically said to be an able-bodied person whom will test the adapter with the ankle prosthesis device to allow research to be conducted on the system before integrating the system into society. The team must come up with a design that will attach the BiOM Ankle Prosthesis to the bent knee of an able-bodied person for walking abilities.

1.3 Original System
This project involved the design of a completely new BiOM Prosthesis Adapter. There was no original system when the project began.

2 REQUIREMENTS
This chapter will provide the key requirements that must be met for the project. The requirements are categorized into customer requirements and engineering requirements. Under the customer requirements, the project's goals are enumerated. The engineering requirements will help justify the reliability and durability of the device. The customer requirements and engineering requirements were then combined in the House of Quality where they were compared to each other and determined which requirements were most important to the project.

2.1 Customer Requirements (CRs)

The main customer requirement for this project included creating a comfortable and simple design for the user. This main requirement was split up into having a quick attachment to the ankle prosthesis as well as attaching quickly to the bent leg of the user, having the adapter be adjustable in height for different users along with being adjustable around the knee for different sized people, keeping the design as light weight as possible, designing the device so that it could be taken apart easily, minimizing the cost of the device, making sure the device was comfortable to all users, and above all, designing the device to be as safe as possible while still meeting all the other customer requirements. The list of customer requirements and ultimate importance to the project can be found in **Error! Reference source not found.**. The importance w eight was determined by the customer. The more emphasis the customer had on a requirement, the higher the importance weight of that requirement was. The highest weighted customer requirements included the device needing to be light weight, adjustable, durable, safe, and reliable. This was because the client discussed the absolute importance of all these requirements.

Table 1: Customer Requirements

Customer Requirements	***Importance Weight***
Lightweight	5
Comfortable	4
Quick Attachment	3
Adjustable	5
Durable	5
Portable	4
Affordable	3
Safe	5
Reliable	5

2.2 Engineering Requirements (ERs)

The engineering requirements, found in **Error! Reference source not found.**, are verifiable, measurable, a nd objective requirements that were derived from the customer requirements. These requirements also contain a specific target value and justification, or rationale of the target selected with the tolerance. The first parameter that was considered was the weight of the design should be less than 1 kg. The friction generated from the device needs to be very minimal to enhance comfort for the user. The duration of attaching the device to the outside of the leg and the BiOM ankle prosthesis must be around 30 seconds. The height of the adapter must be adjustable up to 15 cm, while the diameter of the knee attachment adjustable to 7-20 cm. The device must not fail under the load of a grown adult which was set by the customer to be 200 lbs. The minimization of cost is achieved through consideration of all engineering design requirements and must be less than the allotted $2000 for the project. The factor of safety should be high, and this is achieved through proper engineering design and ultimately set by the client, which was assumed to be 2. The modulus of elasticity of the device represents the durability of the adapter and should be high because this requirement indicates the level of resistance it has against deformation whenever any stress is applied to it. The higher the modulus, the stiffer the device, but this should also not compromise on the safety and weight. This was assumed to be above 70 gigapascals (GPa).

Table 2: Target Values Associated with Engineering Requirements

Engineering Requirements	***Target Value***
Weight	< 1kg or 2.2 lb
Friction from Socket	≤ 0.3
Attach/Detach Time	< 30 seconds
Adjustment Height Range	<15 cm
Diameter of Socket	<20 cm and >7 cm
Applied Force	>890 N
Cost	Minimal ($) <$2000
Factor of Safety	2
Modulus of Elasticity	>70 GPa

2.3 Testing Procedures (TPs)

Testing Procedures will be used for every engineering requirement utilized in the device. For the engineering requirements stated above in

Table 2 and below in **Error! Reference source not found.**, testing procedures are as follows. The weight limit for the device, ER 1, will be tested by using a scale. The scale must read less than 2.2 pounds for the entire system. This is a straight forward test that can be accomplished using a scale in the Biomechatronics lab where the device will undergo other testing procedures. To test the friction in the socket, a force scale would be needed. This testing procedure will utilize the leg support and measure the static friction coefficient between the leg support and skin. By using a force scale, a material similar to skin would be placed on the leg support and pushed with the force scale until it slips. The coefficient of static friction could then be found by using a friction force equation given the force required to get the object to move on the leg support. To test the attach and detach time of the device, multiple people on the team would undergo timed tests to determine the average time it would take someone to attach and detach the system. If the average time to attach and detach the system is less than 30 seconds from someone who is unfamiliar with the adapter, then the adapter would satisfy that engineering requirement. The TP for the height adjustable pylon would include moving the pylon height to its maximum and minimum ranges and determine if the pylon height was 15 cm. A similar testing procedure would be used test the socket adjustment, which would be determined by team members. The leg support would be put into its minimum and maximum ranges to determine if it would meet the engineering requirements. To determine if the system could support the applied force, the weak parts of the system prone to failure would be tested one at a time with the applied force. This would be done with an apparatus to keep the device upright, and weights that would add up to about 200 pounds. The system would be tested for the leg support, the attachment, and the pylon, then the entire system would be tested together. A weight of 200 pounds would be stacked on the device using a leg support to keep the device upright to determine if the device could support the applied weight. Cost will be determined using a bill of materials to determine if the system is less than the $2000 allotment. A factor of safety would be determined by applying two times the amount of stress to the system by putting two times the applied load to the system. If the system is stable after applying two times the applied load, it will have passed the factor of safety testing procedure. The reliability of the system will be determined with a material analysis and multiple fatigue tests for the metal pylon. The device would be worn by different members of the team after determining the fatigue test results and the team members would be put the device through different kinds of stress including hopping, jogging, stepping, dropping, and falling to determine if the device would hold up under significant kinds of stress it was not designed to withstand.

2.4 House of Quality (HoQ)

The House of Quality, shown in Table 3, defines the relationship between the customer requirements and the engineering requirements. Weighted scores were given to every customer requirement which were determined by the customer. Given the weighted score of the customer requirements, the team determined key requirements for the system which included weight, adjustability, durability, safety, and reliability. The engineering target values were provided in

Table 2. For example, it is required that the net weight of the device should be less than 1 kg and the system must cost less than $2000, while the modulus of elasticity is defined as the resistance of deformation, as indicated by modulus of elasticity, must be less than 70 GPa. The engineering requirements were also ranked in importance with the most important requirements being cost and safety factor while friction from socket and speed of attachment were least important. There were two different types of importance ranks within the house of quality. These included the absolute importance and the relative importance. This importance is categorized into those that are absolute and relative. The absolute importance was calculated by multiplying the weighted score by the rank of the requirement, where as the absolute importance was calculated by dividing the absolute importance by the total importance. Tolerance of each target value was also provided for the use of tolerances needed for specific engineering requirements.

Table 3: House of Quality

Customer Requirements \ Engineering Requirements	Weight	Weight	Friction from Socket	Attach/Detach Time	Adjustment Height Range	Diameter of Socket	Applied Force	Cost	Factor of Safety
Lightweight	5	9					3	3	3
Comfortable	4		9					1	3
Quick Attachment	3			9					
Adjustable	5			3	9	9		3	3
Durable	5	3					9	3	9
Portable	4	3			3	3			
Affordable	3	1	3		1	1		9	
Safe	5						1		9
Reliable	5	3					1	3	9
Units		kg	≤ 0.3	sec	cm	cm	N	$	unitless
Target Value		<1 kg	N/A	<30sec	<15	7<>20	>800	N/A	3
Absolute Technical Importance		75	45	42	60	60	60	76	87
Relative Technical Importance		15%	9%	8%	12%	12%	12%	15%	17%
Rank Order of Importance		2	5	6	3	3	4	1	1

3 EXISTING DESIGNS

This chapter begins with the research of existing designs related to the prosthesis adapter that the team will be designing. The research aided in furthering the knowledge of the team in the prosthetic field. Following the research of existing designs, the team developed a functional decomposition which includes a black box model and functional model. Once the function of the system was understood, research on the subsystem level began. This allowed the team to evaluate the system in several components to assist with brainstorming potential designs which can be found in chapter 4 of this report.

3.1 Design Research

Research for the project was conducted using the benchmarking method to determine current technologies that relate to the project. Using Google Scholar, below knee amputee prosthesis' and leg supports were researched to compare the design requirements of the project to existing designs. The focus when executing this research was finding quantifiable specifications, designs that create a fundamental understanding of the prosthesis the team will be designing, and/or designs that have different elements that could be implemented in the team's original design. The research of these existing designs also aided in creating the functional decomposition found in section 3.3, as well as team brainstorming which is discussed in section 4. Although benchmarking does not give the team extensive knowledge of the prosthetic field, it allows the team to see what designs have worked in the past and have been implemented successfully. Extensive research and technical analysis will be required in the future to gain a better understanding of what designs would be successful, but this benchmarking helped inspire creativity in the brainstorming and design process.

3.2 System Level

This section of the report includes existing designs related to the prosthesis adapter that the team will be designing. The benchmarking method used in this section helped the team further their knowledge on past and current prosthesis designs for below-the-knee amputees. The research of existing designs will be compared to the customer and engineering requirements to allow for a better understanding of prosthetics when brainstorming for the design process begins.

3.2.1 Existing Design #1: Basic Below Knee Prosthesis

The below knee prosthetic leg shown in Figure 1 is a basic design that includes a liner, socket, pylon, and the prosthetic foot. Orthomedics refer customers to prosthetists who determine socket designs, suspension systems, and the type of prosthetic foot depending on body type, personal preference, and activity [2]. This resource is relevant in terms of understanding the basic design of a below knee prosthesis. The liner and socket type are what assist with comfort for the user, and the pylon, depending on the material used, allows for a rigid support that is durable. This design is a simple design that was used to help determine the basic design of the adapter. To determine concepts for possible adapter designs, the team thought the idea of the socket liner and the metal pylon tube would benefit the system.

Figure 1: Orthopedics below Knee Prosthetic [2]

3.2.2 Existing Design #2: Bone-Anchored Transfemoral Prosthesis

The two prostheses shown in Figure 2 were designed by the U.S. Department of Veteran Affairs. The designs are complex, anchored into an amputee's stump [3]. These designs are useful because the documentation includes analysis for measuring the load applied to the knee, foot, and more. This analysis shows that the designs are not only durable and reliable but provides an idea of the analysis that will be conducted in the prototyping stage of the project. Attachment is surgical, therefore not a quick attachment, and the weight of each prosthesis exceeds the weight limit for the design requirements, but the designs show how different aspects of a prosthesis design can affect maximum loading that can be applied to the prosthesis [3]. Unfortunately, due to the scope of this project this attachment design cannot be used. A useful part of this design the team will implement into the design will be where the design will bend and the design of the pylon. The attachment must accurately replicate how a person's leg bends at the knee joint, and this design utilizes a bending knee joint that would be very beneficial for the team's design.

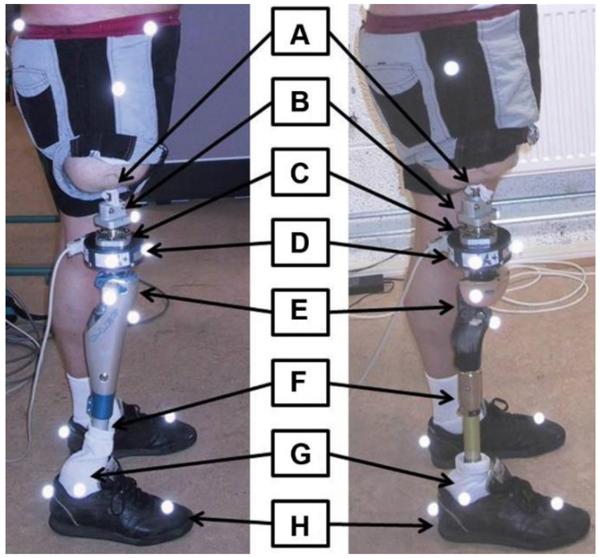

Figure 2: U.S. Department of Veteran Affairs Prosthesis [3]

3.2.3 Existing Design #3: iWALK 2.0 Hands Free Knee Crutch

The design shown in Figure 3 is not a prosthetic, but it relates to several design requirements discussed in chapter 2. The iWALK allows a user with a leg injury to walk without the pain and inconvenience of crutches or scooters [4]. The main difference between this design and a prosthesis adapter is that this knee crutch design is for injured people, not amputees, but that difference is negligible. This knee crutch design is height adjustable, portable, durable, easy to put on and take off, somewhat comfortable, and is affordable. This design is very beneficial for the team considering it takes in account almost all the customer needs and the scope of the project. The team needs to design an adapter that allows an able-bodied person to walk and test the BiOM Ankle device. The team will utilize and change the leg support design of the iWALK to fit the customer needs. This will include keeping the 90-degree angle in the knee, attaching the leg to the leg supports using straps, and attaching the pylon below the knee.

Figure 3: iWALK 2.0 Hands Free Knee Crutch [4]

3.3 Functional Decomposition

The BiOM Prosthesis Adapter's main function is to attach a person's bent leg to the BiOM Ankle Prosthesis and help stabilize them, so they can stand and walk on their own. This device is to be designed for an able-bodied person, so the device can be tested during the testing phase. The BiOM Prosthesis Adapter is to have three main subsystems – pylon, attachment, and leg support – and will be attached to the ankle prosthesis device when completed. When the device is in use, it will require the able-bodied person who is testing the ankle prosthesis device to attach their leg to the adapter to support themselves.

3.3.1 Black Box Model

Before brainstorming concepts for a possible BiOM Prosthesis Adapter, the team needed to have a rough idea of what the device needed to accomplish. This included knowing what would go into the system, what the system will ultimately be able to accomplish, and what is expelled from the system while the device is working. The team had decided to show this in a black box model shown in Figure 4. The black box model was used to simplify the adapter into material subsystems, energy, and signals. The material subsystems that go into the adapter design include the pylon, leg support, and attachment for the leg support and pylon, a human leg to power the system, and an ankle prosthesis to stabilize the system. The energy required to make the system work was human energy since this device is to be simple and include no other energies. The signal to show that the system was ready to work was a visual signal of the all the subsystem materials attached to one another and the person's leg attached to the subsystems. All these inputs were combined to ultimately stabilize the person. The outputs of the device had to include the BiOM Prosthesis Adapter and Ankle Prosthetic attached together while using human and kinetic energy to help transport the person into forward moving motion, with a visual signal of movement. The Black Box Model helped the team simplify the design, so concepts would be able to be discussed. The simpler the inputs and outputs of the design, the more creative concepts could be created. These ideas were just a baseline for the team to start brainstorming.

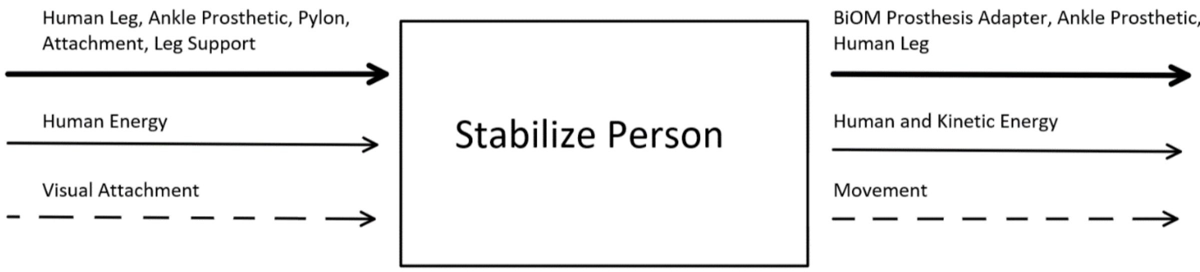

Figure 4: Black Box Model

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

After the Black Box Model was made and the device was stripped down into the simplest of tasks, a Functional Model, shown in Figure 5Figure 5, was drafted to split up the different subsection materials, energy, and signals to see how the parts intact with one another before, during, and after operation. As shown previously in the Black Box Model, the Functional Model has the same inputs such as human energy, and all the subsystem materials such as the pylon, leg support, the attachment for the leg support and pylon, the ankle prosthetic, and a human leg. These subsystem materials were combined using human energy to secure the adapter together, which included the pylon, leg support, and attachment, secure the ankle prosthesis onto the adapter, and secure the leg onto the leg support located on the adapter. Once the materials were secure, human energy was used to actuate the BiOM Prosthesis Adapter and the ankle prosthetic, which then supported movement with human and kinetic energy. This created a visual signal that indicated movement and had an output of the BiOM Prosthesis Adapter and ankle prosthesis.

The Functional Model helped the team understand the system more in depth, and how different subsystems reacted with the different energies to produce a functioning prosthesis device. This was integral to the team's concept design due to understanding the system in depth before deciding what concepts would be ideal for this specific device. Concepts had to be brainstormed with the functional model to help guide concepts. If the concepts brainstormed matched with what was to be put into the system and what was to come out of the system along with simply being able to secure all the subsystem material, transfer energy, and actuate the device so it could support movement, then that concept would ideally work for the device.

After the functional model was built and discussed, the team came up with concepts for the BiOM Prosthesis Adapter which is discussed in the next section.

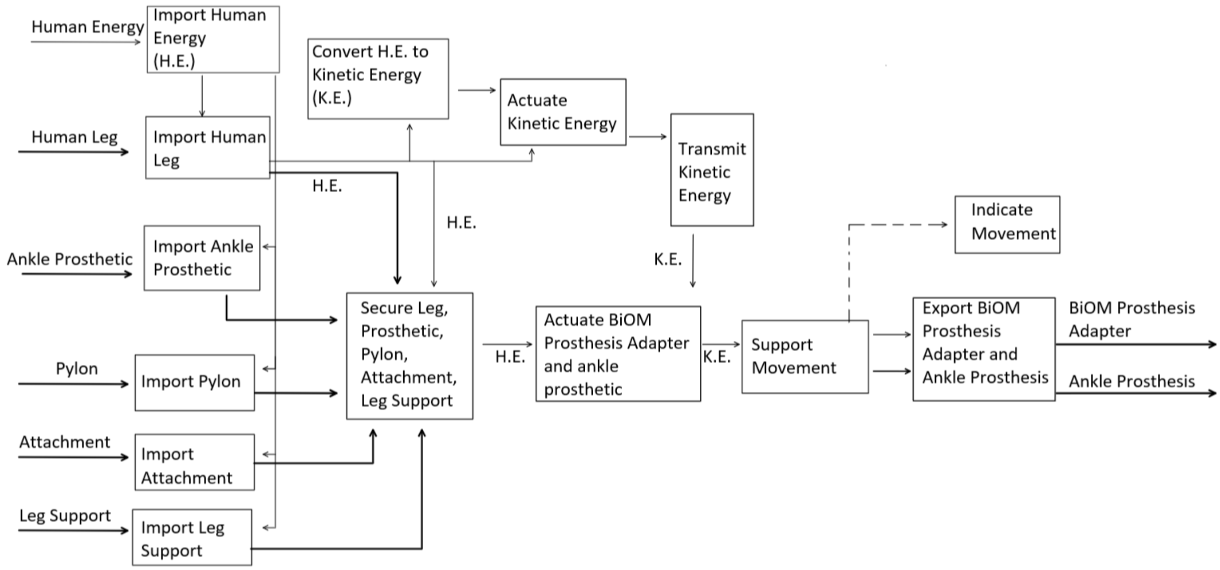

Figure 5: Functional Model

3.4 *Subsystem Level*

This section includes the research of existing designs that relate to the subsystem level. This research allowed the team to better understand the subsystems influence on the overall system and learn about existing designs related to each subsystem.

3.4.1 Subsystem #1: Adjustable Pylon

The pylon will be most relevant for the stability of the system. Although the material of the pylon is important, research on material options will be performed during the technical analysis portion of the project. The research completed for the pylon subsystem in this section will focus on different methods that can be used for adjusting the pylon while maintaining the integrity of the subsystem.

3.4.1.1 Existing Design #1: Bike Seat Adjustment

To create a height adjustable pylon, the team came across the screw lever adjustment that is commonly found on bicycles. The bike seat adjustment, shown in Figure 6, is used to adjust bike seats in the vertical direction [6]. The lever would be disengaged and screwed until the collar was snug around the pole, then the lever was engaged to ensure the two pipes would not slip. This bike seat adjustment would be very beneficial in the pylon design to ensure it would be height adjustable. This design ensures that the pylon could be adjusted to the exact height the user needed without any tolerances. Another very beneficial use for the bike adjustment pylon is the time it takes to adjust the height. The process to adjust the height using the bike lever is made to be quick and easy so that people could adjust their bike seats as needed without tools and in a short amount of time.

Figure 6: Hope Quick Release Seat Clamp [6]

3.4.1.2 Existing Design #2: Hiking Pole Clamp

Figure 7 below shows the hiking pole clamp which is designed to adjust the height of hiking poles for different sized people. The team decided this would be a beneficial design to implement into the pylon height adjustment design because it is designed to be a quick and easy adjustment. The trekking pole clamp would attach the two parts of the pylon and clamp them together, so they would be able to slide up and down when the clamp is disengaged making the pylon adjustable in height [7]. This design would benefit the team to make the pylon height adjustable since its fast and easy to use by everyone. It does not require any tools for adjustability, but a hiking pole is only used to support part of a human's weight to stabilize them while hiking, so if the team were to utilize this design, it would have to be modified to be able to support a fully-grown adult.

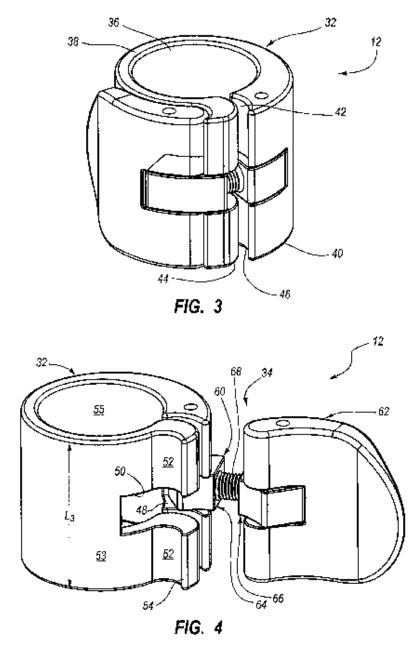

Figure 7: Trekking Pole Clamp [7]

3.4.1.3 Existing Design #3: Height Adjustable Crutch

Another design the team looked at for an adjustable pylon was a crutch design which is shown in Figure

8. When people break their legs, they are given crutches to assist in walking. This design is robust enough to support a fully grown adult and the pins in the design allow the pylon to be height adjustable [8]. The team thought this design would benefit the adapter system due to the ease of adjustability. The design does not require any tools to adjust the height and it can be adjusted in less than a minute. Because of the pins in this design, the height can only be adjusted in increments and it would not be a very precise adjustment for the needed height of the user.

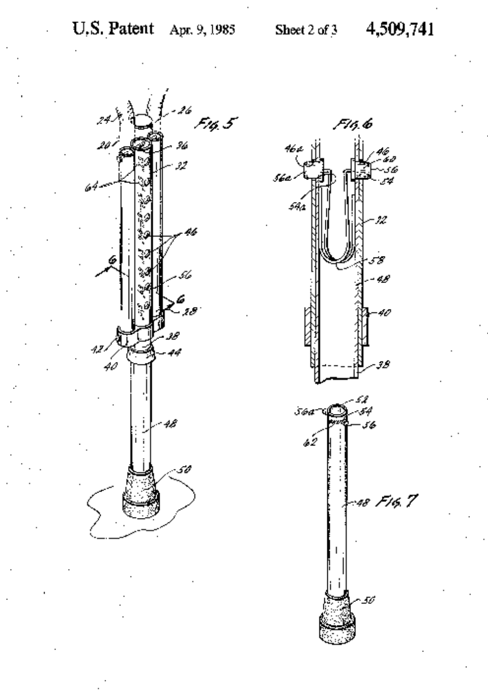

Figure 8: Height Adjustable Crutch [8]

3.4.2 Subsystem #2: Attachment

The primary role of the attachment is to connect the pylon to the leg support. The attachment will need to be rigid, have equal distribution throughout the knee, and not compromise comfortability. The attachment is essentially the connector for the other two subsystems that the team is analyzing.

3.4.2.1 Existing Design #1: Crutch Attachment

To attach the pylon to the leg support, the team researched the crutch attachment shown in Figure 9. The pylon was attached vertically, then two bars split at the top of the pylon to adjust to the arm rests [8]. The team thought this design would be beneficial for the design of the adapter so that the pylon would be able to attach to the leg directly under the knee opposed from the side. This would allow the user to walk in a more natural manor.

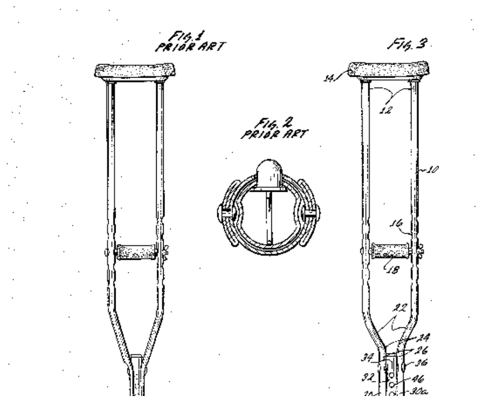

Figure 9: Crutch Attachment to Underarm Rest [8]

3.4.3 Subsystem #3: Leg Support

The leg support subsystem is responsible for supporting the leg of the person who is testing the BiOM ankle prosthesis. The support must be able to help to leg maintain fixed once the device is put on, and at the same time, be comfortable.

3.4.3.1 Existing Design #1: Post-Operation Knee Brace

The post-operation knee brace, seen in Figure 10, shows how the leg could be supported but still allow the knee to bend [9]. The team thought this design would benefit the system due to the rotation about the knee joint and the adjustable straps about the upper and lower legs. The black straps on the upper and lower legs are adjustable by Velcro which would allow the system to adapt to different sized people when testing the device. There is a joint that allows the knee to bend at its axis of rotation. This would allow the pylon to attach at the axis of rotation at the knee to provide a more natural movement for the user.

Figure 10: T Scope Premier Post-Op Knee Brace [9]

4 DESIGNS CONSIDERED

To determine possible concepts to fit the scope of the project, the team used a modified 4-3-5 method to generate ideas based on the updated customer and engineering requirements. Each group member had to come up with three subsystems sketched individually. Everyone could then pass it to the next person to come up with their own three new subsystems or edit the sketches they had received. From beginning to end of the concept generation, the team had managed to come up with a total of twenty-four sketches, three of which are bio-inspired.

After completing the cycle, the team created a Pugh chart and decision matrix utilizing the customer requirements as the criterion to grade the sketches. The team kept in mind the customer requirements to make sure the designs were customer oriented and would satisfy the client. However, not all the customer requirements were applied to all the subsystems. Using the decision matrix, the team evaluated the design that would yield the maximum utilization to the customer, which meant to choose designs that had positive marks. As an example, one of the customer requirements was to construct a design for the customer to use comfortably. This criterion was applied on the subsystem that has contact with the body of the user.

4.1 Design #1: Three Cuffs Single Crutch

Figure 11 shown was the first design considered. It consisted of having a cast-like leg support with the leg being tied down the three straps to secure the leg to the leg support. The leg support was attached to the pylon directly below the knee with another rigid bar going from the pylon to the shin for extra support. The pylon had pins to make the system height adjustable. The system had high durability because the pylon was designed like crutches, so it could support the human body. Moreover, it was considered stable because the attachment was constructed to distribute the applied force. However, it required time to adjust the attachment, the angle of the leg support, and finally tie the three straps to secure the leg. Because the design had precise adjustment, it added to the weight and it made the design heavier than the other possible designs.

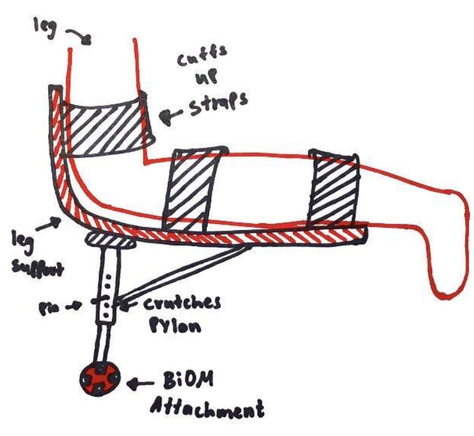

Figure 11: Final Sketch 1

4.2 Design #2: Two Straps Hiking Pylon

The second design shown in Figure 12 was more focused on a lightweight design. This design had a minimal leg support with only two straps attaching the leg to the leg support. The leg support itself was one rigid piece that supported the entire leg. The leg support was then attached to the pylon directly below the knee with an adjustment lever similar to one found on hiking poles. This design was considered a more lightweight design because it has less adjustable parts while also being durable and precise. On the other hand, it would take more time to adjust since it must be adjusted manually. Moreover, the design is not comfortable enough because the leg support had only one state, which was not adjustable.

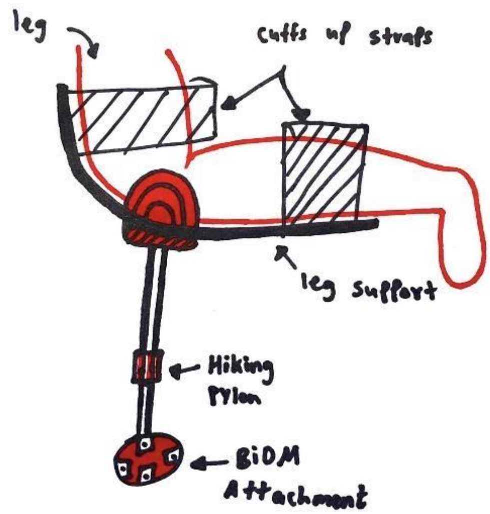

Figure 12: Final Sketch 2

4.3 Design #3: Premium Two Straps Bike Pylon

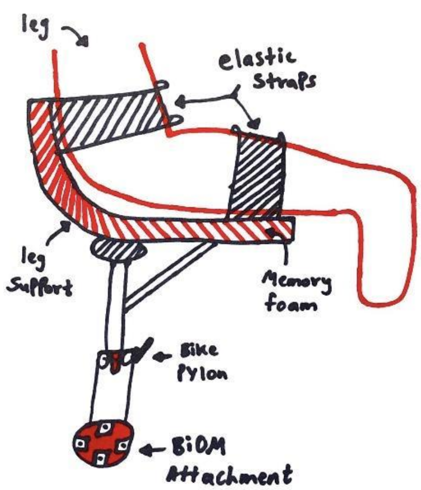

Figure 13 showed design 3, which had an adjustable lever similar to bike seats. This decreased the time to adjust the pylon into the right height and could hold a person as it has been in previous bicycle designs. The only difference between design 3 and design 2 was the manner in which the height could be adjusted, and the comfortability of the leg support. The leg support has an extended bar to distribute the force applied and improve stability at the same time, this part controlled the angle. The leg support was designed to have memory foam that provided comfort for the user. The only disadvantage of this design was the added weight from the rigid bar and memory foam.

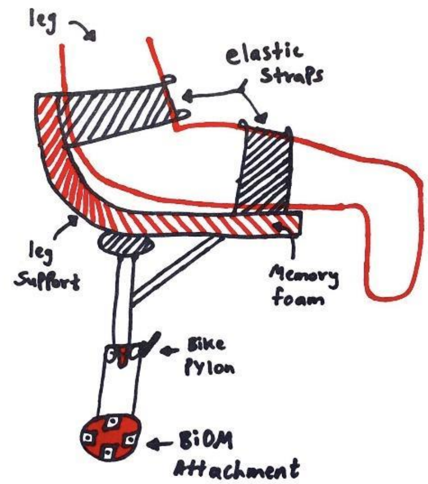

Figure 13: Final Sketch 3

4.4 Design #4: Premium Two Straps Hiking Pylon

Figure 14 showed the fourth design considered which was constructed to be light weight and didn't contain many functions. Design 4 was a combination of design 3 and design 2. The pylon was designed to be precise but would take time to adjust. The memory foam in the leg support helped improve the comfort in the design yet, the leg support is fixed in one setup, so the user would not be able to control the angle. Finally, the two straps were designed to have quick attachment.

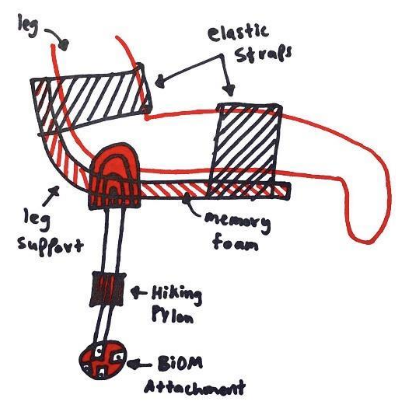

Figure 14: Final Sketch 4

4.5 Design #5: Basic Tow Cuffs Hiking Pylon

Figure 15 showed the fifth design which was lightweight and had quick attachment, although the leg support was not as comfortable as other designs. Design 5 was the same as design 1 with the one difference being the number of straps to attach the leg to the leg support. The leg support was adjustable in angle, and the attachment bar could improve the stability. The hiking pylon allowed the design to be height adjustable while the rigid bar allowed more support at the leg.

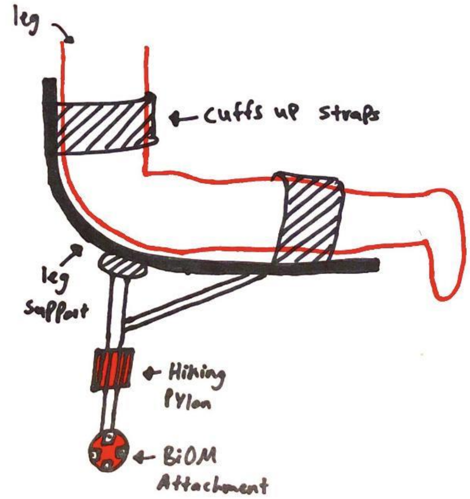

Figure 15: Final Sketch 5

4.6 Design #6: Bio Inspired-1 Thread Pylon

Figure 16 shown below is designed to be light weight and comfortable. The cloud is to act as a comfortable socket that the users leg would be in contact with. The ball joint makes it easy and movable easily and it enhances the mobility of this design. The thread pylon is relatively long to improve stability along with being height adjustable.This design would not be very stable due to the ball joint and thread pylon since there is only one point of contact.

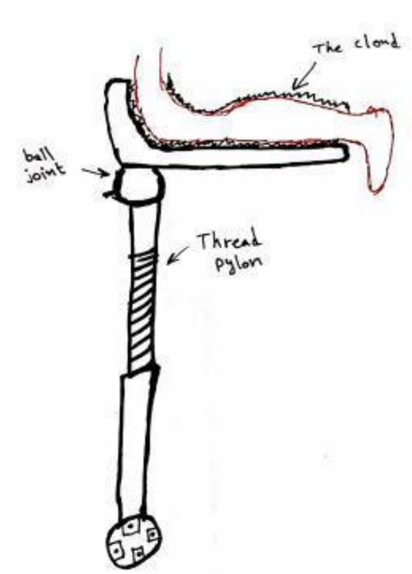

Figure 16: Final Sketch 6

4.7 Design #7: Two Velcro Straps Slots Pylon

Figure 17 was designed to improve the comfortability of the leg and is easily adjustable. The slot pylon allows the design to be height adjustable, and the adjusting sets near the knee allow the angle of the leg to be adjusted. The leg does not have much mobility and thus helps keep it at a fixed angle that is user defined. However, this design is relatively heavier compared with other designs.

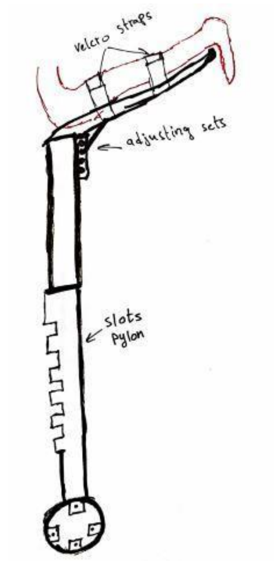

Figure 17: Final Sketch 7

4.8 Design #8: Bio Inspired-2 Side Screw Pylon

Figure 37 shows design 8, which was heavy but very comfortable among other designs. The screw pylon helps in adjusting the design up and down thus making it very movable. It also allows sideways adjustment and the client can put in whatever angle he or she desires. The spider leg support allows the leg to be attached to the leg support and adjust to different leg sizes while also being comfortable. The dual side attachment around the knee allows for more support of the device along with rotation of the pylon about the axis of the knee.

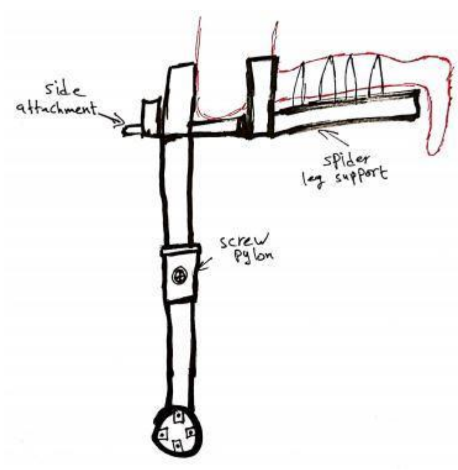

Figure 18: Final Sketch 8

4.9 Design #9: Bio Inspired-3 Telescoping Pylon

Figure 19 was designed to be light, comfortable, and highly movable. It allows the position of the leg and the ankle the leg is held at to change positions. The telescoping pylon is very comfortable, and it also allows up and down adjustment. The ball joint attachment allows the pylon to adjust angle during a walking stride. The sand leg support was designed to help comfort in the leg support with the straps attaching the leg to the leg support. The sand support is meant to form to the persons leg as it is to be made of sand.

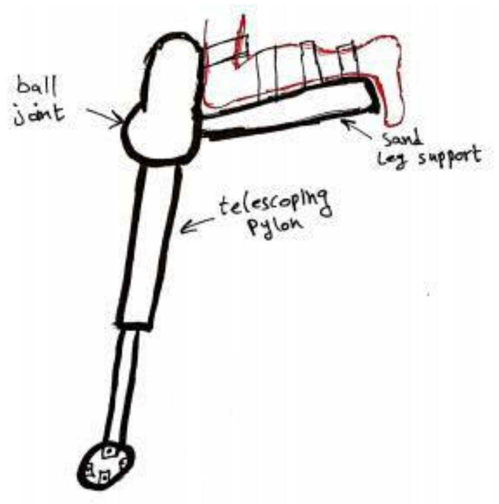

Figure 19: Final Sketch 9

4.10 Design #10: Three Velcro Straps Double Crutches Pylon

Figure 20 This design is among the most suitable designs; however, it is a very heavy design. This design utilizes the crutches pylon to make the system height adjustable with the pins. It also utilizes the crutches attachment, so the pylon would be able to attach below the knee. The attachment is connected at the knee joint to ensure proper rotation of the pylon about the knee joint axis. The leg support is then attached to the leg via Velcro straps.

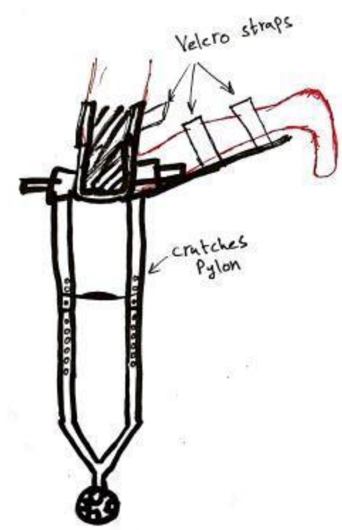

Figure 20: Final Sketch 10

5 DESIGN SELECTED – First Semester

This chapter will provide detailed information on the chosen design the team will construct. After concept generation and discussing the strengths and weaknesses of each design, with Pugh Charts and Decision Matrices shown in Appendices A through C, a design was chosen that met all the customer and engineering requirements discussed in Chapter 2. The final design is shown and described blow.

5.1 Rationale for Design Selection

5.1.1 Initial Selected Design

The engineering and customer requirements were critically analyzed for each of the ten designs. This included analyzing the safety, cost, comfort, modulus of elasticity, durability, quick attachment, lightweight, stability, and reliability amongst others for each individual design. The top 10 designs were presented in a decision matrix located in Appendix B where each design was rated 0 to 100 depending on the given criteria. Design three had the best combinations of these requirements, seen in Figure 21 below. After considering each of these five designs carefully with the results from the decision matrix, the team came to a decision to choose design three as the final design. The design is adjustable, and this increases the level of comfortability to the user. The team therefore considered the design that will be most suitable for the user and the client.

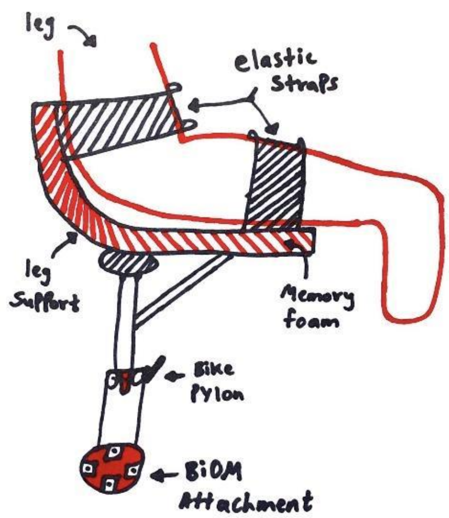

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Figure 21: Final Sketch 3

5.1.2 Final Selected Design

After discussing the chosen design with the client, new ideas came to light as well as a more in-depth understanding of what the system is supposed to accomplish. The client stated that the leg is to be held at a 90-degree angle. The attachment is to act as the lower part of the leg to where it will be able to bend independently of the upper leg. This lead the team to discuss new concepts based off the older concept seen as the prototype discussed in the next section. Since the pylon was to move independently of the upper leg, there would need to be a point where the pylon connected to the leg support would be able to rotate. In order for this to accurately represent how a person walks, the axis of rotation of the pylon must be the same axis of rotation of the user's knee. This would mean the attachment to the leg support would have to be a side attachment to ensure the rotation would be about the knee axis. Since the team thought it would be more beneficial for the user to have a pylon directly below the knee, the side adapter was modified to connect to both sides of the knee and taper down into one rigid bar below the knee. This can be seen in Figure 22 and Figure 23 where the leg supports shown in red are attached to rigid bars. The rigid bars are then attached to the knee support where the knee would bend to ensure the rotation about the knee axis using a bearing. That attachment is then directed below the knee to be attached to the adjustable pylon. There is a spring stretching from the pylon to the lower leg support to help accurately model the swing of a person's lower leg. This spring would allow the user to walk in a more natural manor because when they put weight on the pylon, it will stay in place and once weight is released off the pylon at the end of the stride, the spring would return to its original state which would be slightly extended to start the next walking stride. A previous design of the adapter seen in Figure 24 and Figure 25 was modified to get the final design seen in Figure 22.

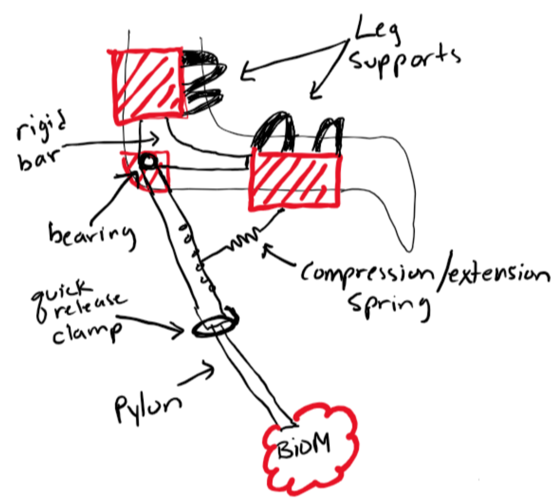


Figure 22: Final Design Side View

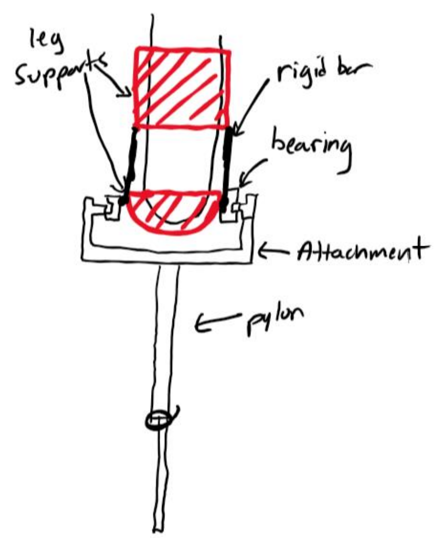


Figure 23: Final Design Front View

5.2 Design Description

This chapter will go in depth on the chosen design. It will discuss the prototype and how the process of building a testing the prototype changed the final design, and the different types of materials that will be used for the final product.

5.2.1 Prototype

Below shown in Figure 24 and Figure 25 is the first constructed prototype of the final proposed design. The prototype was based off a previous more simplistic design and was built to scale using PVC piping, nuts, bolts, aluminum bars, and thermoplastic cuffs with Velcro to attach to the user. The team tested the prototype on themselves to determine flaws the design might have and how it could be improved. Currently, the design acts more like a peg leg which was not the initial intent of the design. To fix this, the L-shaped aluminum bar will be entirely one piece and be converted to carbon fiber and reshaped into a triangle, and the U-shaped bar attachment will need to be extended to be connected at the knee joint. A bearing would need to be installed at the knee joint between the L-shaped aluminum bar and the U-shaped bar to ensure 1 degree of freedom (DOF) movement of the pylon. It was also noted that the prototype was an older version of the design without a knee support, which caused the upper leg support to rise on the leg of the user and the user's knee to hit the attachment U-support causing it to be uncomfortable. This would be fixed by implementing a below the knee support as seen in the initial drawing to properly support the lower leg. Since building the prototype and discovering flaws to the design, the team implemented new designs to help insure the system will meet the customer needs which was seen in the previous section.

Figure 24: Prototype Front View

Figure 25: Prototype Side View

5.2.2 Materials

The team decided to use thermoplastic for the cuffs of the device because it is easily formed with heat and the plastic has enough flexibility to form around the user's legs. The rigid bars are planned to be made of carbon fiber due to the significant amount of stress within the 'L' shaped frame. The carbon fiber will be custom made by the team and in the shape of a triangle or inverted quarter circle to avoid any high stress spots. This was because stress in the 'L' shaped beam calculated by

$$\sigma = \frac{F}{A} + \frac{My}{I} \tag{1}$$

Where σ represents the stress in the material, F represents the axial force applied to the system, A represents the cross-sectional area at the location of the axial force, M represents the moment about the axis due to the axial force, y represents the location in the cross-sectional area where the stress will be largest, and I represents the area moment of inertia of the cross section. Equation 1 proves that the stress at the elbow of the 'L' shaped rigid bar would be at a maximum, therefor to minimize that stress, either a radius needs to be designed into the rigid bar to make the cross sectional area larger, or the rigid bar needs to be designed as a triangle to avoid any failures at the high stress spot. The validation as to why this would work is because with both the designs, the cross-sectional area would be larger, so the stress would be minimized. This also allows the stress along the plate to be distributed across a larger area.

The best material for the pylon was thought to be 2024 T3 Aluminum hollow piping due to a technical analysis done by the team. It proved that 2024 T3 Aluminum was the most beneficial material for the pylon opposed to PVC piping and steel. This was because it was very durable and lightweight to help the team meet customer requirements. This was determined by using equation 2 where σ is the stress at the point of interest, *F* is the applied force in the axial direction, *A* is the cross sectional area of the pylon in terms of Diameter, *D*, ρ is the density of the material in terms of *D*, *L* is the length of the pylon, *g* is the universal gravitational constant, *M* is the moment about the axis due to the applied force in terms of *D*, *y* is location in the cross section where stress is largest (on the outer diameter of the pylon) from the axis in terms of *D*, and *I* is the area moment of inertia in terms of *D*.

$$\sigma = \frac{F}{A} + \rho L g + \frac{My}{I} \tag{2}$$

The maximum stress in the system, σ was calculated using equation 3 below where FS is the factor of safety which was assumed to be 2, and σ_{yield} was to be the yield stress of the material.

$$\sigma = \sigma_{yield} \times FS \tag{3}$$

From equation 2 and 3, the diameter was calculated to be 1.5" with a thickens of 0.035" when using a hollow 2024 T3 Aluminum pipe. The MATLAB code used to solve for the diameter is located in Appendix D. A quick release clamp would be used to allow the system to be height adjustable and Velcro straps would be used with the leg supports to allow the leg supports to be width adjustable depending on the user's preference.

Another analysis was used to calculate the stress at the point where the pylon would be adjustable. The stress at this point is critical because of the possibility of fracture if the force exceeds allowable stress. Assumptions considered included; the full body weight is split equally between the real leg and prosthetic leg, the pylon can move in every direction with no hindrance, weight on the bicycle pylon is considered to be equally split weight since the arch point is minimal, and the human body will apply a force of 8880 N. By considering these assumptions, the reserve factor was calculated from equation 4.

$$\text{R}eserve\ Factor = \frac{Applying\ stress}{Allowable\ stress} \tag{4}$$

The reserve factor shows that Aluminum would be the most beneficial material to sustain the force when subjected to pressure and does not compromise the device. The applied stress was found to be $\sigma = 0.090798\ MPa$. On the other hand, the allowable stress of Aluminum is 55 MPa. Thus, the Reserve Factor is:

$$Reserve\ Factor = \left(\frac{0.090798}{55}\right) = 0.0017 \tag{5}$$

Aluminum is the best material to use because of its robust nature and is non toxic. The pressure analysis given in terms of reserve factor will help the team to wisely choose the correct material during manufacturing (implementation phase). In this way, the engineering and customer requirement will be full filled and thus the project goal realized.

The focus of the attachment analysis is to determine the stress applied over the support by the leg. It was assumed that the knee load acts as a point load, two directional forces are considered due to the angle present at the lower side of foam, and the total point force on the support is approximately10 pounds. From the line diagram constructed from the free body of prosthesis adapter, the forces and moment were evaluated. The calculation indicates that no forces are acting on the point load in the x direction and all the weight will put complete force in the downward direction. By considering this situation, the stress is determined from equation 6.

$$\sigma = \frac{F}{A} \tag{6}$$

Since the load is acting on point, the Area in such case is

$$A = 1\ in^2 = 0.00694\ ft^2 \tag{7}$$

The magnitude of force acting on the y-direction is given by equation 8.

$$F_y = F = \frac{10}{\sqrt{3}} \tag{8}$$

The force in x-direction is zero. The stress is thus;

$$Stress = \sigma = \frac{\frac{10}{\sqrt{3}}}{0.00694} = 831.92\frac{lb_f}{ft^2} \tag{9}$$

This is the stress that will be applied over the prosthetic leg. This value will help the team to in selection of materials to use and hence the building of robust leg support. The analysis will also aid in the cost evaluation of the whole project and the overall implementation of the project.

6 PROPOSED DESIGN – FIRST SEMESTER

This chapter will discuss how the team will plan on implementing the final design for the Adapter system. This will include the process for prototyping, a breakdown of all the resources needed for the design which includes information, people, materials, and facilities. A bill of materials for the final design will be presented along with an assembly of the finalized system.

6.1 Final Prototype

Once the prototype was fabricated in the previous chapter, the team learned of many flaws with the old design. This included the pylon acting like a peg leg instead of having a 1 DOF axis rotation about the knee joint. The users knee also slid into the rigid bar support that attached the pylon to the leg supports. To fix this, a new prototype is to be made and tested before fabricating the final product. The second prototype will be an updated version of the first prototype. The difference between the two is that the second prototype will include a knee support, and the U shaped rigid bar will be extended to attach at the knee joint with a bearing. The rigid bar attachment support will be split up into two different rigid systems, one to connect the leg supports together in the form of a triangle, and one will be the U shaped rigid bar located under the knee. The prototype will include loose bolts at the location of the knee joint to accurately represent the rotation about the knee instead of a bearing. A spring would then attach the pylon to the upper leg, so the team would be able to test if the spring system will work as expected. The materials for the prototype will be the same as the first prototype; PVC piping for the pylon, aluminum bars for the rigid attachment system, nuts and bolts as connectors and a make-shift bearing, and thermoplastic and Velcro for the leg supports.

6.2 Bill of Materials

After the team constructed the first prototype and found flaws within the system, the team came up with a plan for the second prototype, which also included discussing the materials needed for the final design to ensure the design would be robust enough to support a fully-grown person. The finalized materials are shown in Table 4. The Bill of Materials includes the different part numbers which correspond to the CAD drawing shown in the next section, the part name, how many parts are needed, what the part is supposed to accomplish within the design, the material and dimension used for the part, the cost of the part, and where the part was obtained. The pylon is planned to be made of 2024 T3 Aluminum tubing obtained from McMaster-Carr. This material was chosen for its strength and lightweight characteristics. The only modifications that need to be done to the aluminum rod upon arrival would be to cut a slit in the top of both rods where the quick release clamp would be located. Carbon fiber will be used for the attachment supports due to its strength and ability to be formed into specific molds. The carbon fiber will be obtained through Rockwest Composites as pre-preg carbon fiber, meaning it already has the epoxy mix in the carbon fiber fabric [11]. The bolts and nuts will be obtained from a hardware store such as Home Depot and must be strong and able to resist shearing when the system is in use. The leg support cuffs were chosen to be made of thermoplastic because of the materials ability to be shaped when heated and hold its form when it cools along with having very flexible yet supportive characteristics. The thermoplastic will be obtained from Interstate Plastics in sheets where the team would cut and shape the plastic. This will allow the cuffs to be shaped to a person's leg for a more secure attachment. Velcro will be used with the thermoplastic cuffs to attach the leg to the system. This will insure the user's leg will not slip out of the leg supports. The Velcro straps will be obtained from Amazon or any widely used store such as Walmart. The quick release clamp will be obtained from Amazon already assembled.

Table 4: Bill of Materials

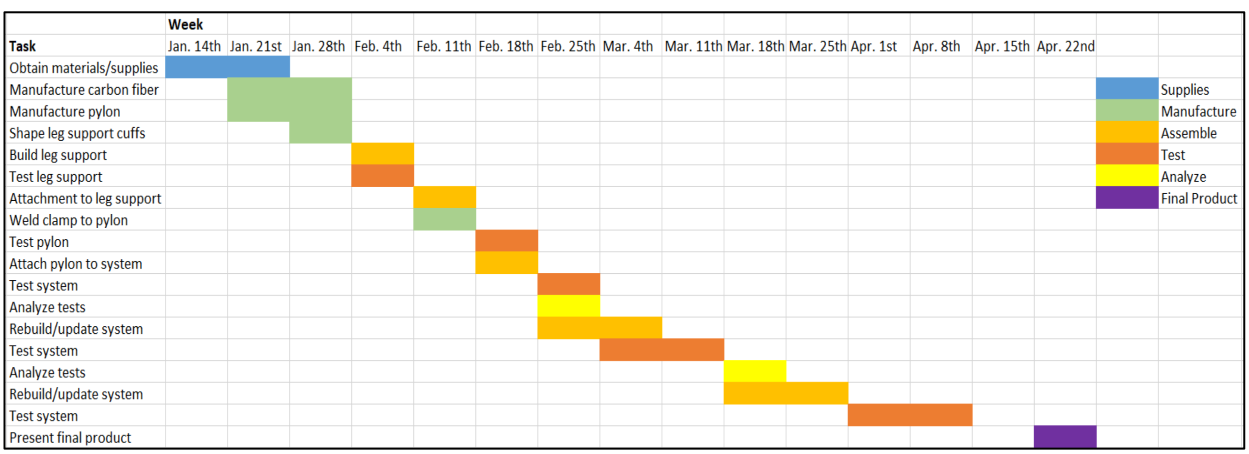
Part #	Part Name	Qty	Description	Functions	Material	Dimensions	Cost	Company
1	Pylon	2	Silver Tubing	Support weight	High Strength 2024 Aluminum	1.5" OD & 1 ft. Lg.	$20	McMaster-Carr [10]
2.1	L-Shaped Attachment Frame	2	L-Shaped / Black	Frame support	Carbon Fiber	8" x 8" x 1 3/8"	$80	Rockwest Composites [11]
2.2	U-Shaped Attachment Frame	1	U-Shaped / Black	Frame support	Carbon Fiber	5" x 3" x 1 3/8"	$50	Rockwest Composites [11]
2.3	Bolts	12	Silver	Hold system together	Stainless Steel	1/4" x 1/2" - 20	$0.34	Home Depot [12]
2.4	Nuts	12	Silver	Hold system together	Stainless Steel	1/4" - 20	$0.30	Home Depot [12]
3.1	Leg Support Thigh Cuff	1	Black	Leg Support	Thermoplastic	8" x 3"	$15	Interstate Plastics [13]
3.2	Leg Support Calf Cuff	1	Black	Leg Support	Thermoplastic	6" x 3"	$10	Interstate Plastics [13]
3.3	Leg Support Strap	2	Black	Leg Support	Nylon w/ Velcro	1 1/2" x 12"	$5.00	Interstate Plastics [13]
4	Quick Release Clamp	1	Round Clamp	Pylon adjustment	Stainless Steel	34.9 mm	$33.65	Amazon [14]
				Total Cost Estimate:			$326.33	

6.3 *Implementation of Chosen Design*

For the team to implement the chosen design, there will be a lot of materials and specialized equipment needed. As stated in chapter 6.2, specific materials with specific processes will be needed to build the design. The material that will require the most facilities and tools is the carbon fiber. Carbon fiber is hard to work because it requires a lot of protective gear and special equipment. To use carbon fiber for the system, the pre-preg sheets of carbon fiber will need to be cut out to proper dimensions with scissors, then placed on top of each other in the correct formation. The pre-preg carbon fiber will then need to be vacuum bagged with proper supplies such as heat resistant plastic, gummy tape, and breather material. It would then need to be put in a composites oven provided by the composites lab at 275 degrees Celsius for 90 minutes while in a continuous vacuum. This is to ensure there will be no voids within the carbon fiber and it will cure properly [11]. Once the heating process is complete, the carbon fiber will be stiff and have rough edges, that will need to be trimmed off. This will be done by using a wet saw or Dremel tools provided by the Biomechatronics lab. Since carbon fiber is very dangerous to work with in confined spaces, the tools will have to be used outside while using the proper protective gear which would include face mask, respirator, hearing protection, clothing protection, closed toed shoes, and gloves. Holes will then need to be drilled into the carbon fiber where the bolts will be. This can also be done using a drill press and diamond tipped carbide drill bits provided by the Biomechatronics lab or the Machine Shop on campus. Again, all the protective gear will need to be worn for all carbon fiber processes. The use of carbon fiber in the system will help when creating the triangle and U-shaped supports. For the aluminum pylon, only a small slit needs to be made where the tubes will be in contact with each other. This can be done using a bandsaw provided by the Biomechatronics lab. Face protection is needed when operating the bandsaw. To make the leg supports from the thermoplastic, the obtained thermoplastic sheets would be cut and heated using a heat gun provided by the Biomechatronics lab. This would allow the thermoplastic to take the shape of the desired cuff. To connect the quick release clamp onto the aluminum pylon, the clamp will need to be welded onto the aluminum pylon. This can be done using the campus machine shop. Other tools and materials needed for the implementation of the design would include plyers and a hand drill or screw driver.

Shown in Table 5 is the planned implementation schedule. The schedule ranges from January to April and maps out all the major tasks that need to be completed for building the final product. This includes gathering the supplies, manufacturing all the different parts, assembling the system, testing the system, analyzing the tests and rebuilding the system as needed until the final product is complete.

Table 5: Implementation Schedule January-April



6.4 *CAD Model*

The first prototype design was drafted using Solidworks to determine correct dimensions and accurately model the system. The CAD model can be seen below in **Error! Reference source not found.**. A d rawing of the CAD Prosthesis Adapter model can be found in Figure 26 Figure 29and Figure 27. The leg supports are shown in red and Velcro straps are shown as black straps attached to the leg supports. The gray parts of the CAD model are the rigid attachment supports which is connected to the Aluminum pylon with the quick release clamp. There is a spring attaching the pylon to the bottom leg support to help the rotation of the pylon.

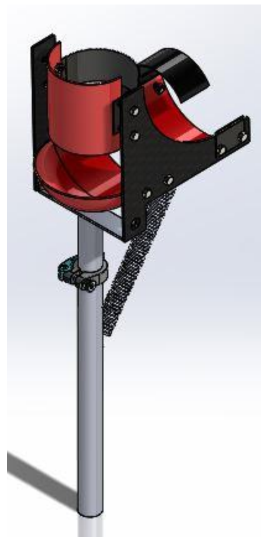


Figure 26: CAD Model, Isometric View of Prosthesis Adapter

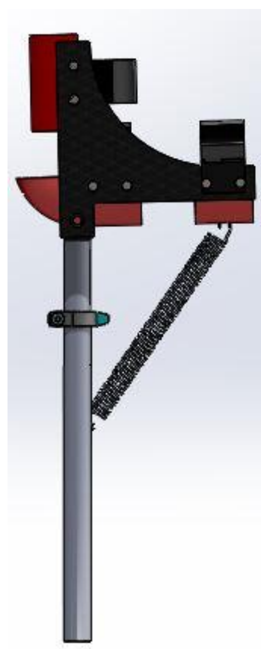


Figure 27: CAD Model, Side View of Prosthesis Adapter

Shown below in Figure 28 is the exploded view of the entire prosthesis adapter system. This includes the three-red leg supports, the black Velcro straps, the black triangular rigid bars to attach the leg supports to the pylon, the pylon rod with the screw lever, the spring to attach the pylon and the lower leg support, and all the bolts needed to assemble the entire system. The team plans on implementing this final concept design in a prototype next semester to ensure the design will work and meet all customer requirements. Figure 29 shows the drawing of the prosthesis adapter with all the different parts labeled that correspond with the bill of materials.

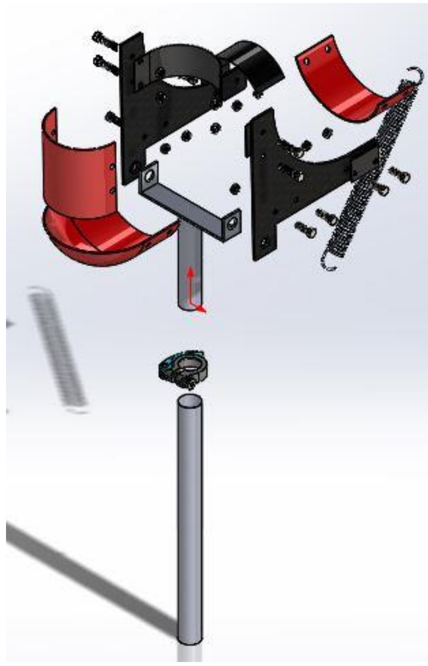


Figure 28: CAD Model, Isometric Exploded View of Prosthesis Adapter

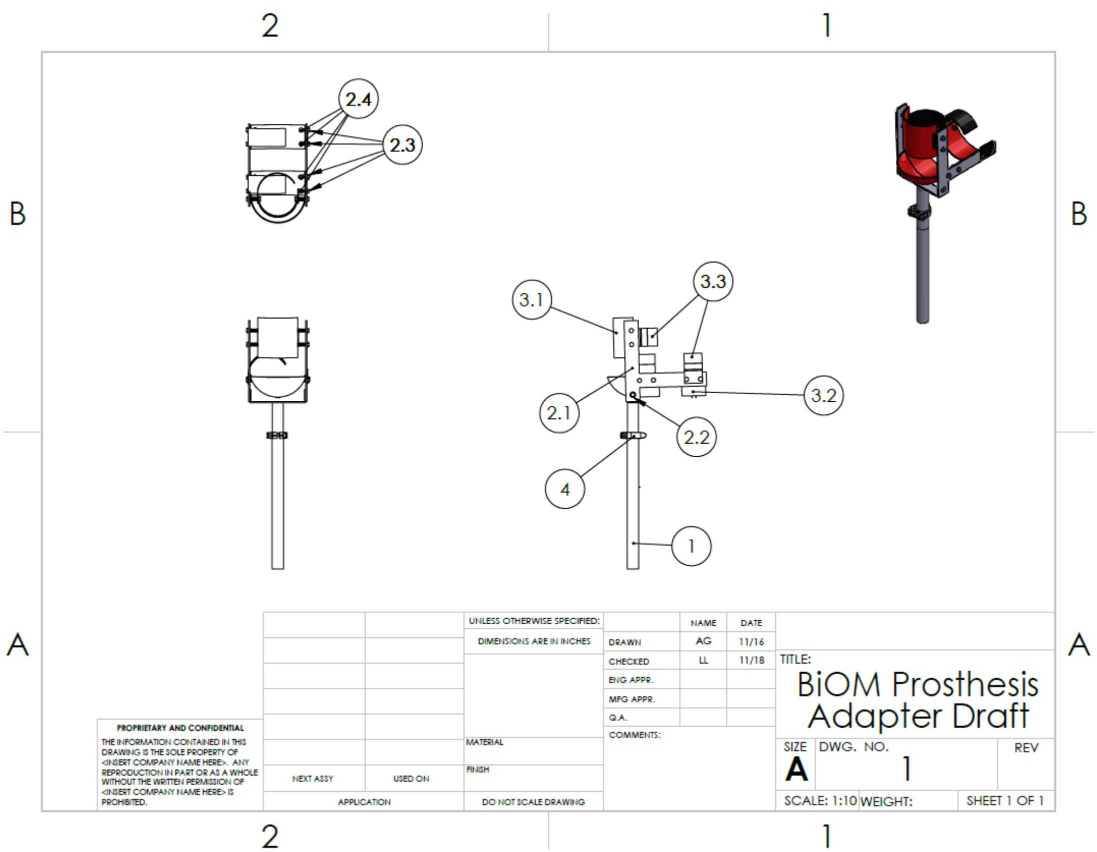


Figure 29: CAD Prosthesis Adapter Drawing

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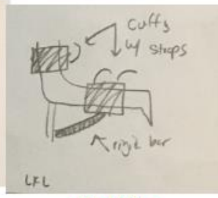
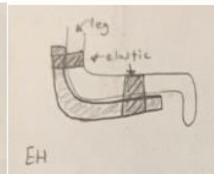
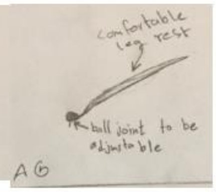
8 APPENDICES

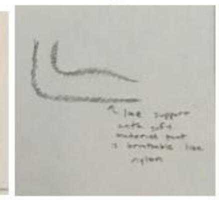
8.1 *Appendix A: Subsystem Pugh Charts*

Table 6: Leg Support Pugh Chart

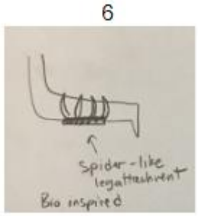


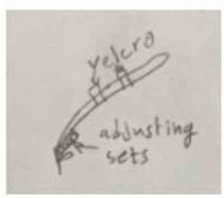


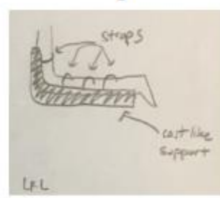




Criteria	DATUM (1) DATUM	2 Rigid Bar	3 El Hefe	4 Ball/Joint	5 The Cloud
Safety	0	0	0	-1	-1
Durable	0	1	1	-1	-1
Light Weight	0	0	-1	1	1
Adjustable	0	0	0	0	0
Quick Attachment	0	1	1	0	0
Comfortable	0	0	1	1	1
Number better: S+	+0	+2	+3	+2	+2
Number worse: S-	0	0	-1	-2	-2
Number same: S0	6	4	2	2	2

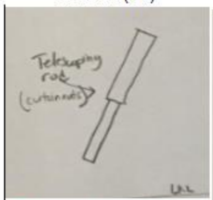


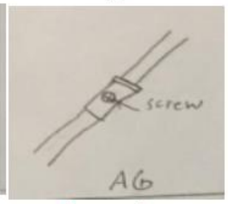


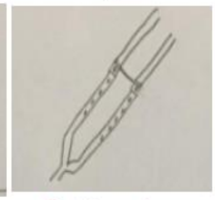


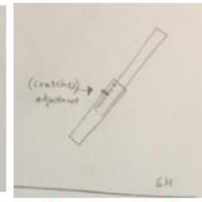
Criteria	6 The Spider	7 Straps	8 The Cast	9 Bowl of Sand
Safety	-1	0	1	-1
Durable	0	0	1	0
Light Weight	-1	1	-1	-1
Adjustable	1	1	0	-1
Quick Attachment	0	0	0	-1
Comfortable	0	0	0	1
Number better: S+	+1	+2	+2	+1
Number worse: S-	-2	0	-1	-4
Number same: S0	3	4	3	1

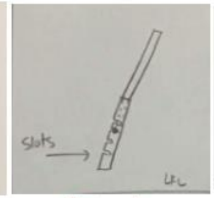
Table 7: Pylon Pugh Chart



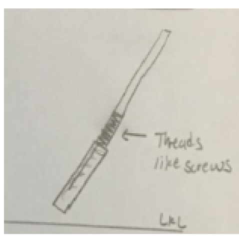


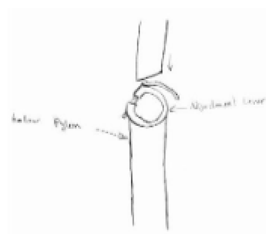


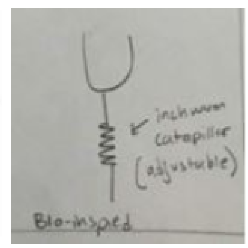




Criteria	DATUM(10) Telescoping rod pylon	11 Screw pylon	12 Crutches pylon	13 Crutches pylon2	14 Slots pylon
Safety	0	1	1	1	0
Durable	0	1	1	0	1
Light Weight	0	0	-1	0	0
Adjustable	0	0	-1	-1	-1
Quick Attachment	0	-1	-1	-1	0
Stable	0	1	1	0	0
Quick Adjustment	0	0	0	0	1
Number better: S+	+0	+3	+3	+1	+2
Number worse: S-	0	-1	-3	-2	-1
Number same: S0	7	3	1	4	4

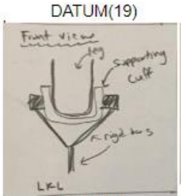
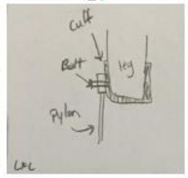
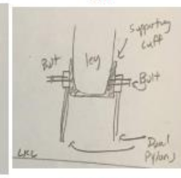
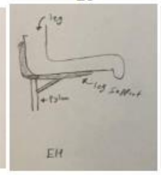
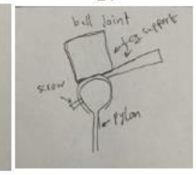






Criteria	15 Thread pylon	16 Hiking pylon	17 Bike pylon	18 Catapiller pylon
Safety	-1	1	1	-1
Durable	0	0	1	0
Light Weight	0	1	1	0
Adjustable	1	1	1	0
Quick Attachment	0	0	0	1
Stable	-1	1	1	-1
Quick Adjustment	1	1	1	0
Number better: S+	+2	+5	+6	+1
Number worse: S-	-2	0	0	-2
Number same: S0	3	2	1	4

Table 8: Attachment Pugh Chart

	DATUM(19)	20	21	22	23	24
						
Criteria	DATUM	Under Knee	Parallel	Double up	Truss	Ball Joint
Safety	0	-1	0	1	1	0
Durable	0	0	0	1	1	0
Light Weight	0	1	1	-1	0	0
Quick attachment	0	-1	1	0	1	-1
Stable	0	-1	0	1	1	0
Number better: S+	+0	+1	+2	+3	+4	+0
Number worse: S-	0	-3	0	-1	0	-1
Number same: S0	5	1	3	1	1	4

8.2 *Appendix B: Subsystem Decision Matrices*

Table 9: Attachment Decision Matrix

SET 1		Sketch 19		Sketch 20		Sketch 21	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Safety	25%	40	10	60	15	30	7.5
Durable	17%	40	6.8	60	10.2	40	6.8
Quick Attachment	15%	20	3	50	7.5	60	9
Lightweight	18%	40	7.2	60	10.8	50	9
Stability	25%	50	12.5	20	5	60	15
Total	**100%**		**39.5**		**48.5**		**47.3**

SET 1		Sketch 22		Sketch 23		Sketch 24	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Safety	25%	80	20	90	22.5	60	15
Durable	17%	50	8.5	60	10.2	70	11.9
Quick Attachment	15%	60	9	70	10.5	30	4.5
Lightweight	18%	60	10.8	50	9	60	10.8
Stability	25%	70	17.5	80	20	40	10
Total	**100%**		**65.8**		**72.2**		**52.2**

Table 10: Pylon Decision Matrix

SET 2		Sketch 10		Sketch 11		Sketch 12		Sketch 13		Sketch 14	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Safety	23%	50	11.5	60	13.8	100	23	75	17.25	20	4.6
Durable	25%	20	5	50	12.5	90	22.5	60	15	30	7.5
Lightweight	20%	90	18	80	16	70	14	80	16	70	14
Adjustable	22%	80	17.6	20	4.4	70	15.4	95	20.9	85	18.7
Quick attachment	10%	80	8	50	5	60	6	70	7	55	5.5
Total	**100%**		**60.1**		**51.7**		**80.9**		**76.15**		**50.3**

SET 2		Sketch 15		Sketch 16		Sketch 17		Sketch 18	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Safety	23%	40	9.2	90	20.7	100	23	20	4.6
Durable	25%	30	7.5	60	15	70	17.5	35	8.75
Lightweight	20%	90	18	90	18	90	18	70	14
Adjustable	22%	75	16.5	80	17.6	90	19.8	20	4.4
Quick attachment	10%	85	8.5	80	8	80	8	75	7.5
Total	**100%**		**59.7**		**79.3**		**86.3**		**39.25**

Table 11: Leg Support Decision Matrix

SET 3		Sketch 1		Sketch 2		Sketch 3		Sketch 4		Sketch 5	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Safety	15%	60	9	90	13.5	100	15	30	4.5	40	6
Durable	15%	50	7.5	80	12	90	13.5	50	7.5	30	4.5
Lightweight	10%	80	8	70	7	40	4	100	10	80	8
Adjustable	19%	60	11.4	40	7.6	50	9.5	80	15.2	0	0
Quick Attachment	19%	40	7.6	80	15.2	90	17.1	70	13.3	30	5.7
Comfortable	22%	80	17.6	80	17.6	90	19.8	90	19.8	100	22
Total	**100%**		**61.1**		**72.9**		**78.9**		**70.3**		**46.2**

SET 3		Sketch 6		Sketch 7		Sketch 8		Sketch 9	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Safety	15%	40	6	80	12	80	12	20	3
Durable	15%	60	9	75	11.25	80	12	30	4.5
Lightweight	10%	90	9	25	2.5	30	3	10	1
Adjustable	19%	40	7.6	90	17.1	75	14.25	85	16.15
Quick Attachment	19%	80	15.2	85	16.15	85	16.15	50	9.5
Comfortable	22%	70	15.4	70	15.4	90	19.8	80	17.6
Total	**100%**		**62.2**		**74.4**		**77.2**		**51.75**

8.3 Appendix B: Final Design Sketches Decision Matrix

Table 12: Final Designs Decision Matrix

SET 1		Final Sketch 1		Final Sketch 2		Final Sketch 3		Final Sketch 4		Final Sketch 5	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Safety	17%	80	13.6	70	11.9	80	13.6	60	10.2	80	13.6
Durable	15%	85	12.75	75	11.25	90	13.5	70	10.5	75	11.25
Quick Attachment	10%	60	6	70	7	70	7	70	7	70	7
Lightweight	16%	30	4.8	50	8	40	6.4	70	11.2	70	11.2
Stable	13%	70	9.1	50	6.5	75	9.75	50	6.5	70	9.1
Adjustable	14%	90	12.6	75	10.5	80	11.2	80	11.2	75	10.5
Comfortable	15%	80	12	60	9	90	13.5	90	13.5	75	11.25
Total	100%		70.85		64.15		74.95		70.1		73.9

SET 1		Final Sketch 6		Final Sketch 7		Final Sketch 8		Final Sketch 9		Final Sketch 10	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Safety	17%	40	6.8	25	4.25	60	10.2	60	10.2	70	11.9
Durable	15%	45	6.75	30	4.5	70	10.5	55	8.25	75	11.25
Quick Attachment	10%	10	1	55	5.5	40	4	40	4	50	5
Lightweight	16%	80	12.8	50	8	70	11.2	10	1.6	25	4
Stable	13%	30	3.9	20	2.6	50	6.5	60	7.8	90	11.7
Adjustable	14%	55	7.7	40	5.6	50	7	70	9.8	45	6.3
Comfortable	15%	60	9	45	6.75	60	9	80	12	70	10.5
Total	100%		47.95		37.2		58.4		53.65		60.65

8.4 *Appendix C: Final Design Sketches*

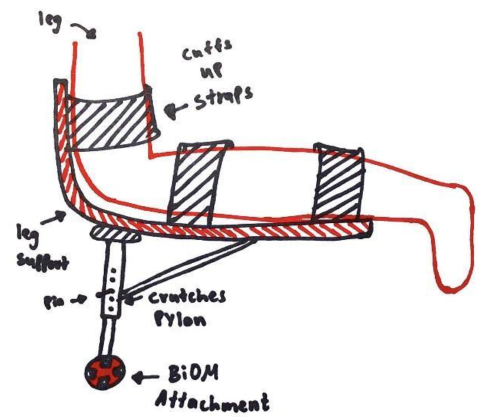


Figure 30: Final Sketch 1

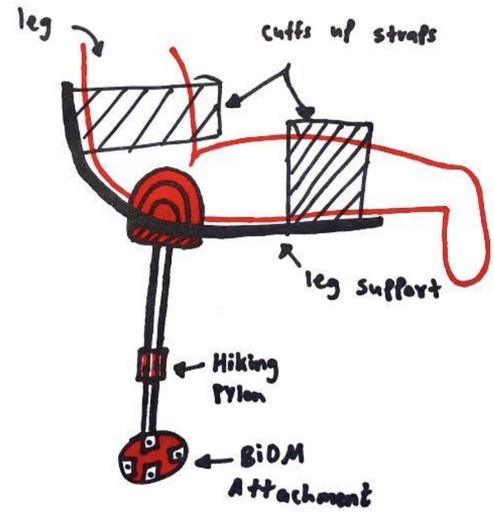


Figure 31: Final Sketch 2

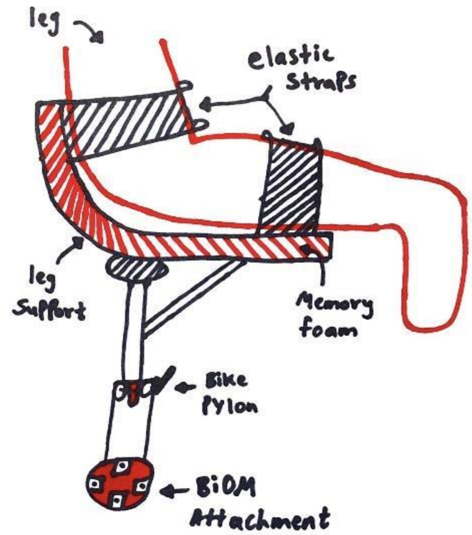


Figure 32: Final Sketch 3

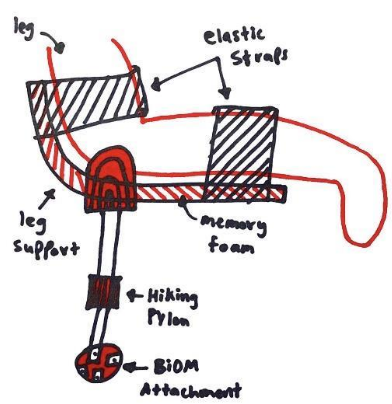


Figure 33: Final Sketch 4

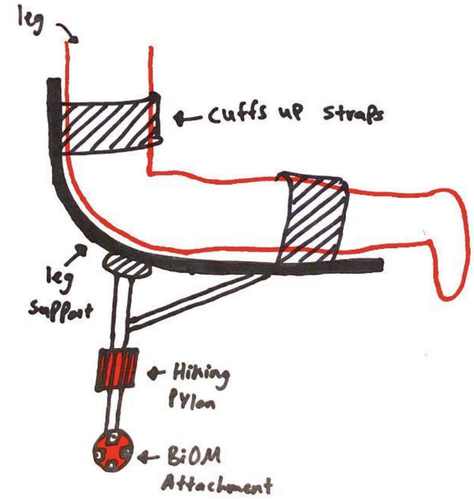


Figure 34: Final Sketch 5

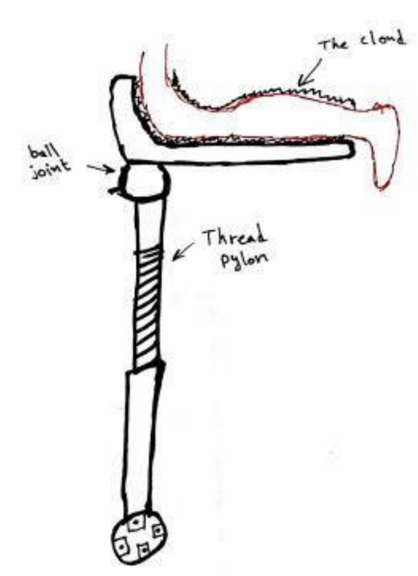


Figure 35: Final Sketch 6

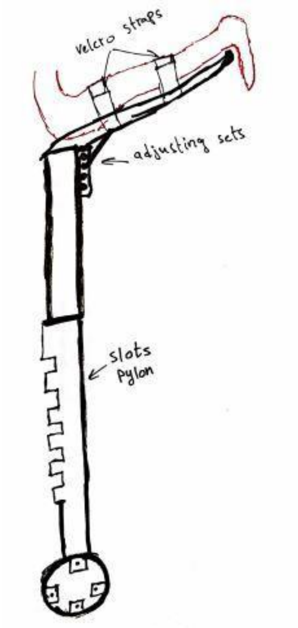


Figure 36: Final Sketch 7

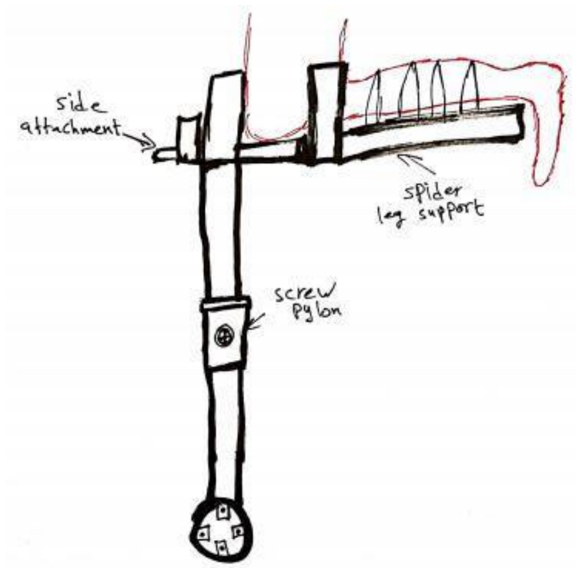


Figure 37: Final Sketch 8

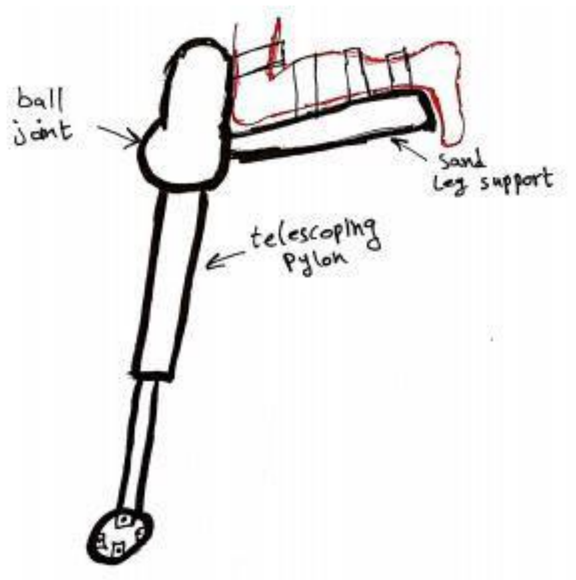


Figure 38: Final Sketch 9

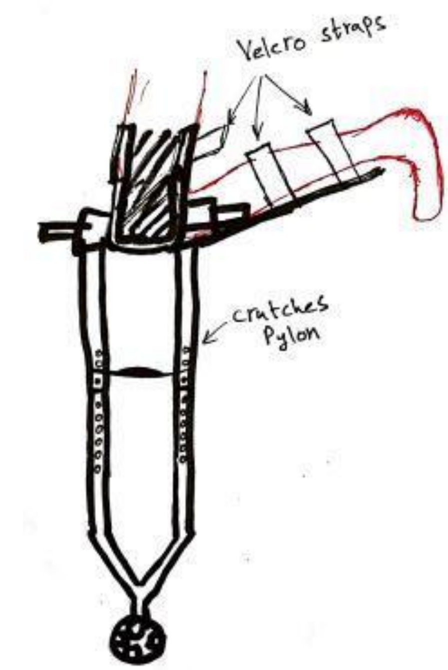


Figure 39: Final Sketch 10

8.5 *Appendix D: Technical Analysis*

```
%Leah Liebelt
%CAPSTONE Technical Analysis
clear; clc; close all;
%%
% OBJECTIVES
% DETERMINE STRESSES IN PYLON FROM SIDE ATTACHMENT
% DETERMINE BEST MATERIAL AND MINIMUM DIAMETER OF PYLON FOR SIDE
ATTACHMENT
%%
% ASSUMPTIONS
% FACTOR OF SAFETY OF 2
% RIGID ATTACHMENT
% HOLLOW PYLON
% WEIGHT OF PERSON = 200 LBS
%%
% VARIABLES
% m= mass of pylon
% t_cast= thickness of casting material
% w= width of leg
% R= Reaction Force
% M= Moment at support
% t_pipe= thickness of piping for pylon
% D= Outer diameter of piping
% L= length of pylon
% V=volume of pylon
%%
%VARIABLES
FS = 2;
F = 200*4.44822; %N
g = 9.81; %m/s^2
w = 18/100; %m
L = 0.5; %m
t_cast = 1/100; %m
t_in = input('What is the desired thickness of the pipe in inches?\n'); %in
t = t_in*0.0254;
%%
%ALUMINUM 2024 T3
yield_Al = 289.5*10^6; %N/m^2
stress_Al = yield_Al/FS; %N/m^2
p_Al = 2712; %kg/m^3
syms D_Al
y_Al = D_Al/2; %m
I_Al = pi/64*(D_Al^4 - (D_Al - 2*t)^4); %m^4
A_Al = pi/4*(D_Al^2 - (D_Al-2*t)^2); %m^2
M_Al = F*(w/2+t_cast+D_Al/2);
eqn = stress_Al == F/A_Al + p_Al*L*g +M_Al*y_Al/I_Al;
solution_Al = vpasolve(eqn, D_Al);
sol_Al = solution_Al(solution_Al>0)*1000;
sol_Alin = sol_Al/25.4;
fprintf('The minumum diameter for 2024 T3 Aluminum is %f mm\n',sol_Al)
fprintf('The minumum diameter for 2024 T3 Aluminum is %f in\n',sol_Alin)
W_Al = pi/4*((sol_Al(1)/1000)^2-((sol_Al(1)/1000)-2*t)^2)*L*p_Al*g;
W_Alin = pi/4*((sol_Al(1)/1000)^2-((sol_Al(1)/1000)-2*t)^2)*L*p_Al*g/4.44822;
fprintf('The weight of the Aluminum pylon is %f N\n',W_Al)
fprintf('The weight of the Aluminum pylon is %f lbs\n\n',W_Alin)
%%
```

```
%PVC
yield_PVC = 55.2*10^6; %N/m^2
stress_PVC = yield_PVC/FS; %N/m^2
p_PVC = 1400; %kg/m^3
syms D_PVC
y_PVC = D_PVC/2; %m
I_PVC = pi/64*(D_PVC^4 - (D_PVC - 2*t)^4); %m^4
A_PVC = pi/4*(D_PVC^2 - (D_PVC-2*t)^2); %m^2
M_PVC = F*(w/2+t_cast+D_PVC/2);
eqn = stress_PVC == F/A_PVC + p_PVC*L*g +M_PVC*y_PVC/I_PVC;
solution_PVC = vpasolve(eqn, D_PVC);
sol_PVC = solution_PVC(solution_PVC>0)*1000;
sol_PVCin = sol_PVC/25.4;
fprintf('The minumum diameter for PVC is %f mm\n',sol_PVC)
fprintf('The minumum diameter for PVC is %f in\n',sol_PVCin)
W_PVC = pi/4*((sol_PVC(1)/1000)^2-((sol_PVC(1)/1000)-2*t)^2)*L*p_PVC*g;
W_PVCin = pi/4*((sol_PVC(1)/1000)^2-((sol_PVC(1)/1000)-2*t)^2)*L*p_PVC*g/4.44822;
fprintf('The weight of the PVC pylon is %f N\n',W_PVC)
fprintf('The weight of the PVC pylon is %f lbs\n\n',W_PVCin)
%%
%STEEL ASTM A36
yield_St = 250*10^6; %N/m^2
stress_St = yield_St/FS; %N/m^2
p_St = 7850; %kg/m^3
syms D_St
y_St = D_St/2; %m
I_St = pi/64*(D_St^4 - (D_St - 2*t)^4); %m^4
A_St= pi/4*(D_St^2 - (D_St-2*t)^2); %m^2
M_St = F*(w/2+t_cast+D_St/2);
eqn = stress_St == F/A_St + p_St*L*g +M_St*y_St/I_St;
solution_St = vpasolve(eqn, D_St);
sol_St = solution_St(solution_St>0)*1000;
sol_Stin = sol_St/25.4;
fprintf('The minumum diameter for A36 Steel is %f mm\n',sol_St)
fprintf('The minumum diameter for A36 Steel is %f in\n',sol_Stin)
W_St = pi/4*((sol_St(1)/1000)^2-((sol_St(1)/1000)-2*t)^2)*L*p_St*g;
W_Stin = pi/4*((sol_St(1)/1000)^2-((sol_St(1)/1000)-2*t)^2)*L*p_St*g/4.44822;
fprintf('The weight of the steel pylon is %f N\n',W_St)
fprintf('The weight of the steel pylon is %f lbs\n\n',W_Stin)
disp('end program')
```

MATLAB Code to Determine Weight of the Aluminum Pylon using Diameters from McMaster-Carr

```
%Leah Liebelt
%Technical Analysis
clear; clc; close all;
%McMaster-Carr Weight Analysis
L=19.685; %in
pf=169.3046; %lb/ft^3
p=pf/(12^3); %lb/in^3
D1=1.5; %in
D2=1.5; %in
D3=0.875; %in
D4=1; %in
t1=0.035; %in
t2=0.065; %in
t3=0.12; %in
t4=0.25; %in
W1=pi/4*(D1^2-(D1-2*t1)^2)*L*p; %lb
```

```
W2=pi/4*(D2^2-(D2-2*t2)^2)*L*p;
W3=pi/4*(D3^2-(D3-2*t3)^2)*L*p;
W4=pi/4*(D4^2-(D4-2*t4)^2)*L*p;
fprintf('The weight for a diameter of 1.5" and thickness of 0.035" is %f lbs\n',W1)
fprintf('The weight for a diameter of 1.5" and thickness of 0.065" is %f lbs\n',W2)
fprintf('The weight for a diameter of 0.875" and thickness of 0.12" is %f lbs\n',W3)
fprintf('The weight for a diameter of 1.0" and thickness of 0.25" is %f lbs\n',W4)
disp('end program')
```