BiOM Prosthesis Adapter – 18F01

Final Proposal Report

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EXECUTIVE SUMMARY

The BiOM Ankle Prosthesis Device is an advanced robotic ankle which allows people with below-the-knee amputees the ability to walk unassisted. An adjustable adapter was needed to test the BiOM Ankle Prosthesis device for research purposes. The adapter was to span from the BiOM Ankle Prosthesis device to the bent knee of an able-bodied person to allow research to be conducted on the ankle prosthesis without the need of an impaired subject. This adapter was to fit different sized users, be lightweight, comfortable, durable, safe, cost effective, and have a quick attachment for the user.

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 was constructed to ensure the final design met all customer requirements prior to building the final product. After the prototype was built the team worked on constructing the final product and testing the final product. Testing the final design included 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 met and exceeded 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 discusses 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 goal of the project was to design an adapter that attaches a BiOM Ankle Prosthesis to a patient's bent knee. This adapter allowed the BiOM to be tested on an able-bodied people before integrating the prosthesis 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, research labs looking for solutions to test ankle prostheses, and the professors at NAU who currently work with the BiOM Ankle Prosthesis.

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 connects the BiOM Ankle Prosthesis to the users 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 was to 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. Currently in the Human Performance Lab at NAU, the BiOM Ankle Prosthesis test includes attaching the BiOM to a stick and putting a downward force on the stick to actuate the BiOM. This was not a very effective design and professors and researchers asked for a more reasonable and realistic designed device.

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 helped determine the design 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. Testing procedures discuss how each part of the device will be tested to meet the engineering requirements.

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 Table 1. The importance weight 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 Table 2, are verifiable, measurable, and 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 team later discussed with the client the difficulty with creating such a large design with a small weight constraint and the client upped the weight requirement to less than 4 kg. The friction generated from the device needed 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 had to be less than 60 seconds. The height of the adapter was to be adjustable up to 12 cm, while the circumference of the knee attachment adjustable from 30-65 cm. The device must not fail under the load of a grown adult which was set by the customer to be 200 lbs with a factor of safety of 3.

The factor of safety should be high to ensure reliability, and this was achieved through proper engineering design and ultimately set by the client, which was assumed to be 3. 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 team would like to stay under a $1000 budget when building the final product, only including materials used in the design. The client would like the adapter to last around 10 years to test the BiOM, setting the last engineering requirement to a lifetime of the whole system to 10 years.

Table 2: Target Values Associated with Engineering Requirements

Engineering Requirements	***Target Value***
Weight	< 4 kg
Coefficient of Friction from Socket to skin	≤ 0.3
Attach/Detach Time	< 60 seconds
Adjustment Height Range	<12 cm
Adjustment of Socket Circumference	30 – 65 cm
Applied Force	>890 N
Cost	<$1000 for system
Factor of Safety	3
Lifetime	10 years

2.3 Testing Procedures (TPs)

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

Table 2, 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 4 kilograms for the entire system. This is a straight forward test that can be accomplished using a scale in the Biomechatronics lab.

To test the friction in the leg support, a comfort test will be conducted using 10 unbiased volunteers. The volunteers tried the leg support on and put their leg at a 90-degree angle on a rigid surface and rated the comfort from 0 to 10 with 10 being very comfortable and 0 being painful.

To test the attach and detach time of the device, a sample of 10 different people 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 60 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 range was 12 cm. A similar testing procedure would be used test the leg support circumferences. 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 600 pounds due to the factor of safety of 3. 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 600 pounds would be stacked on each part of the device separately. The pylon would be held in the upright position with a plate across the top where a load of 600 pounds would be applied. A support system would be 1 inch below the weighted plate in case of failure. If the test does fail, the forced plate will hit the support system. The leg support would be tested in a similar fashion by keeping the device upright and applying a force of 600 pounds to the system.

Cost was determined using a bill of materials to determine if the system is less than the $1000 allotment. A factor of safety would be determined by putting the pylon, leg support, and attachment through a stress test to determine the ultimate failure stress respective to the actual applied stress.

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 the three team members after determining the fatigue test results and the team members would 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.

A summary of the TP's is shown below in Table 3.

Table 3: Testing Procedures

Requirements	***Testing Procedure***
Weight	Scale
Coefficient of Friction of the Leg Support	Force Scale
Attach/Detach time	Timed Tests of 10 different people
Height Adjustable	Measuring height range of the pylon
Leg Support Adjustable	Measuring range of socket diameter
Applied force to the system	Apply 600 lbs to the system to determine failure
Cost	Bill of Materials
Factor of Safety	Determine the ultimate stress of the pylon, leg support, and attachment through failure testing
Reliability	Apply stress to the system that it was undersigned for

2.4 House of Quality (HoQ)

The House of Quality, shown in Table 4, 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 4. For example, it is required that the net weight of the device should be less than 4 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, whereas 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 4: 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 by benchmarking 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.

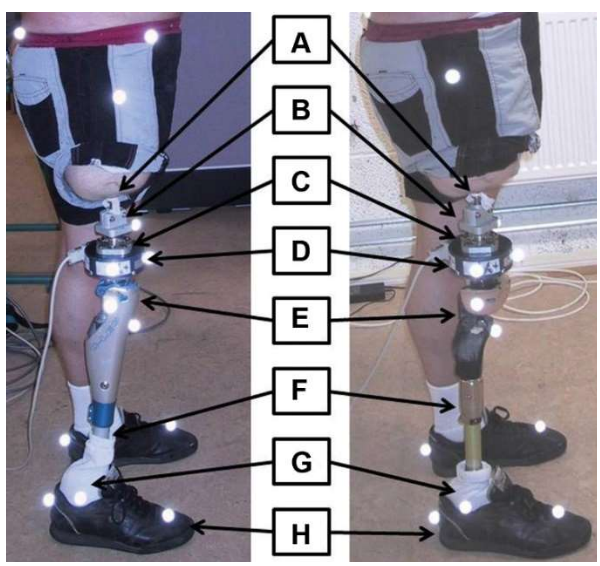


Figure 2: U.S. Department of Veteran Affairs Prosthesis [3]

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 was to be designed for an able-bodied person, so the device could be tested during the testing phase. The BiOM Prosthesis Adapter was to have three main subsystems – pylon, attachment, and leg support – and would 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.

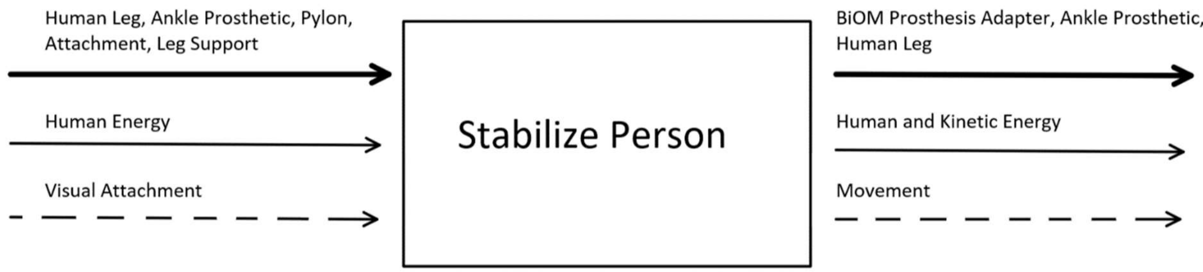


Figure 4: Black Box Model

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 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.

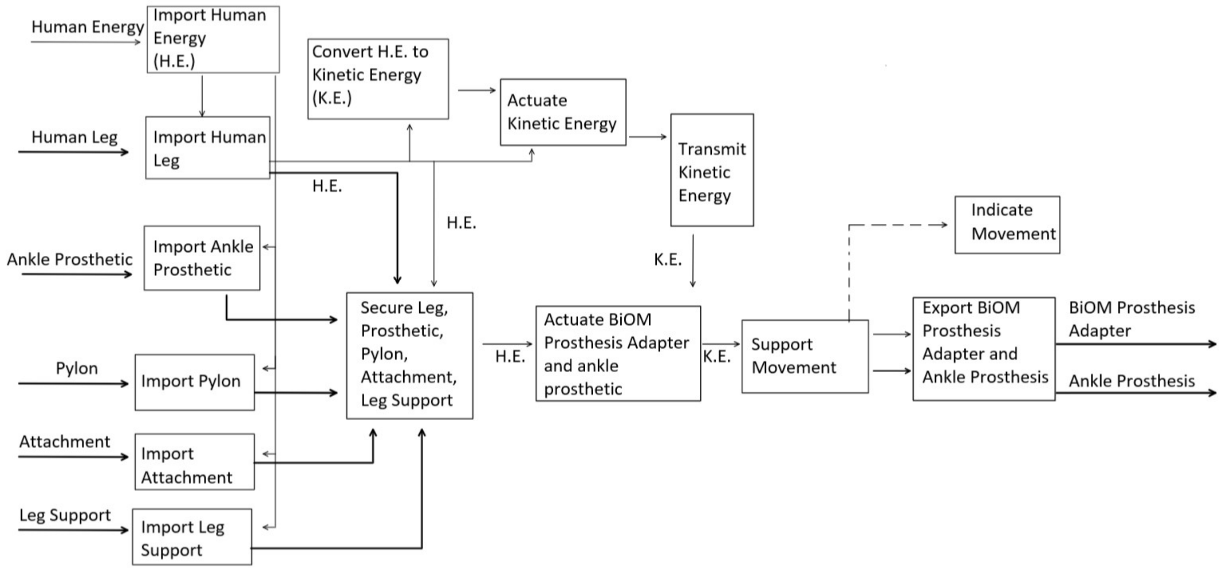


Figure 5: Functional Model

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.

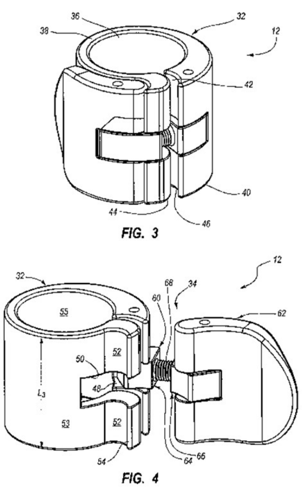


Figure 7: Trekking Pole Clamp [7]

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.

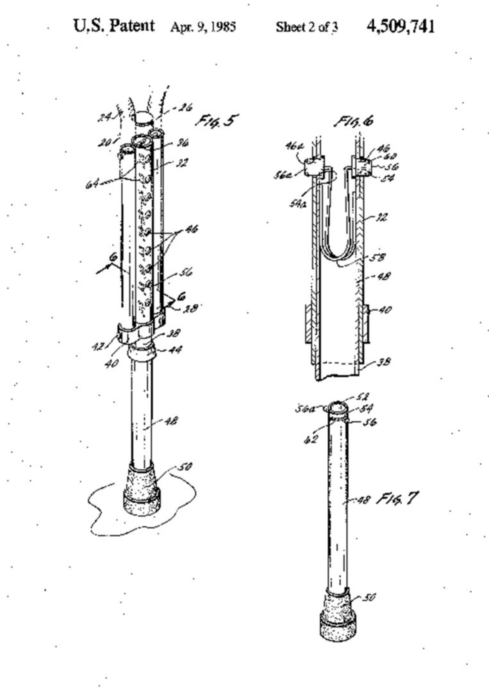


Figure 8: Height Adjustable Crutch [8]

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 essential to connect the pylon to the leg support. Without this subsystem, it would be impossible to create a device with rotation of the pylon about the knee.

3.4.2.1 Existing Design #1: Crutch Attachment – Two Symmetrical Bars

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 by having two beams range from each side of the leg support to meet up directly under the knee to the pylon.

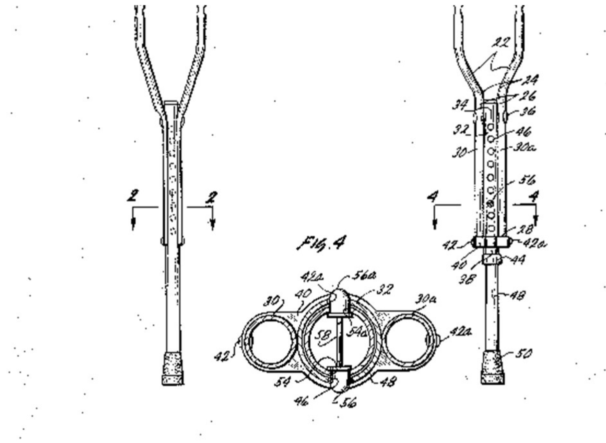


Figure 9: Crutch Attachment to Underarm Rest [8]

3.4.2.2 Existing Design #2: Powered Prosthesis Adapter

The powered prosthesis adapter shown in Figure 10 has a below the knee attachment. This type of attachment would allow the pylon to rotate about the knee joint to allow more natural walking. This system seems to have a lot of electrical components just above the ankle, which is not part of the scope of the project, however, this does show that the adapter is powered and moves respective to the leg as a normal lower leg would move. This design could benefit the team by showing that it is possible to attach an adapter directly below the knee. However, this design has a stiff leg support and shows that the pylon is directly attached to the leg support not allowing rotation about the knee joint, but about a couple centimeters below the natural axis of rotation.

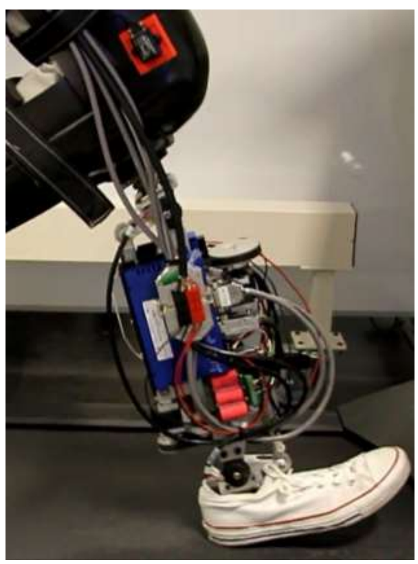


Figure 10: Powered Prosthesis Adapter [9]

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 11, shows how the leg could be supported but still allow the knee to bend [10]. 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 11: T Scope Premier Post-Op Knee Brace [10]

3.4.3.2 Existing Design #2: One Piece, Rigid Knee Support

Shown in Figure 12 is a rigid leg support connect to a powered prosthesis [9]. This leg support is one piece ranging from the upper thigh to the lower shin. This does not allow any movement of the users leg and keeps the leg at a constant 90-degree angle. This leg support could benefit the teams design by keeping the leg at a 90-degree angle per the customer requirement, but it would not allow any attachments to the knee at the axis of rotation. Since this leg support is one ridged piece, it would take a lot of material which could impede the teams design due to the weight restriction.

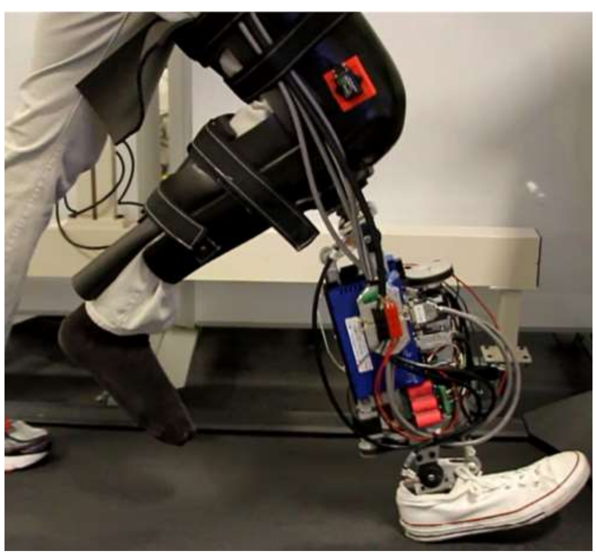


Figure 12: Rigid Knee Support [9]

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.

4.1 Design #1: Three Cuffs Single Crutch

Figure 13 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. This design was chosen from the results of the Pugh Carts located in Appendix A. The leg support is shown in Table 9, design 3; the attach is shown in Table 11, design 23; and the pylon is shown in Table 10 design 13. 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.

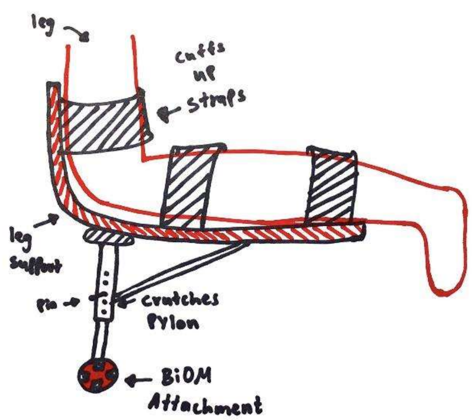


Figure 13: Final Sketch 1

4.2 Design #2: Two Straps Hiking Pylon

The second design shown in Figure 14 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, shown in Appendix A, Table 9, design 3. 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 as seen in Table 10, design 16. The attachment can be seen in Table 11, design 24 as a ball joint. The ball joint would allow rotation of the pylon with respect to the leg support. 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 was not considered comfortable because the leg was forced into a rigid leg support, which was not adjustable.

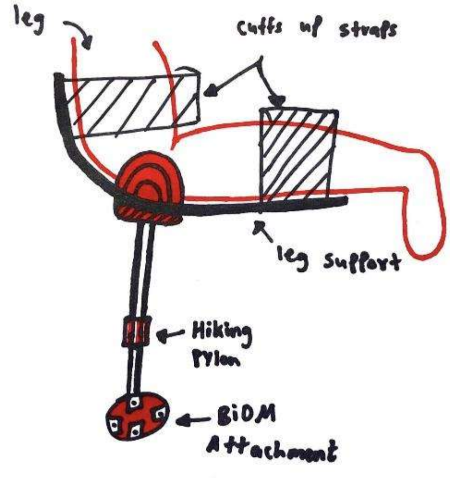


Figure 14: Final Sketch 2

4.3 Design #3: Premium Two Straps Bike Pylon

Figure 15 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 can be seen in Table 9, with a combination of designs 2, 3, and 5; the attachment can be seen in Table 11, design 23; and the pylon can be seen in Table 10, design 17. This combination of designs would be a strong choice because the leg support has an extended bar to distribute the force applied and improve stability, while controlling 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.

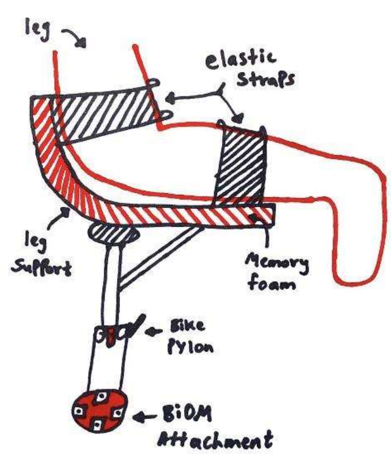


Figure 15: Final Sketch 3

4.4 *Design #4: Premium Two Straps Hiking Pylon*

Figure 16 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 where the subsystems can be found in the Pugh Charts of Appendix A. 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.

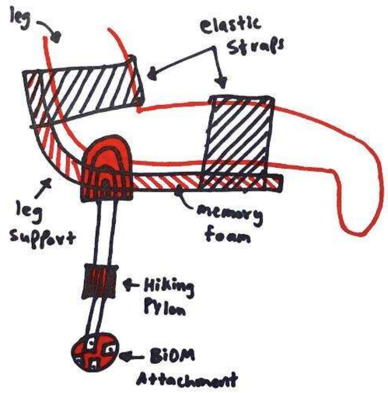


Figure 16: Final Sketch 4

4.5 *Design #5: Basic Two Cuff Hiking Pylon*

Figure 17 showed the fifth design which was lightweight and had quick attachments, although the leg support was not as comfortable as other designs. The subsystems of this design were chosen from Pugh Charts located in Appendix A. The leg support is shown in Table 9, design 3; the attachment is shown in Table 11, design 23; and the pylon is shown in Table 10, design 16. 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.

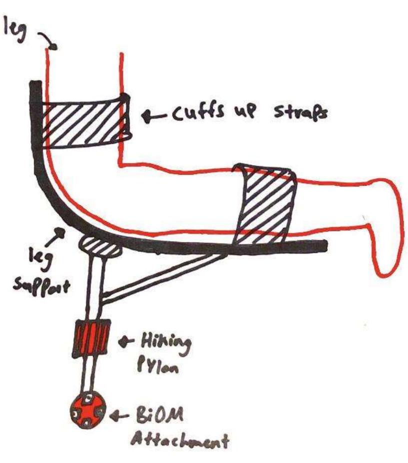


Figure 17: Final Sketch 5

4.6 Design #6: Bio Inspired-1 Thread Pylon

Figure 18 shown below is designed to be light weight and comfortable. The cloud leg support, shown in Table 9, design 5, is to act as a comfortable socket that the users leg would be in contact with. The ball joint, shown in Table 11, design 24, makes it easy and movable easily and it enhances the mobility of this design. The thread pylon, shown in Table 10, design 15 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. There would be a large stress concentration directly below the knee joint causing less reliability to the system.

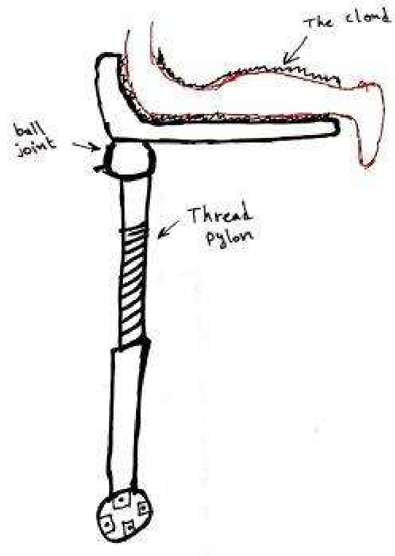


Figure 18: Final Sketch 6

4.7 Design #7: Two Velcro Straps Slots Pylon

Figure 19 was designed to improve the comfortability of the leg and is easily adjustable. The slot pylon, shown in Table 10, design 14, allows the system to be height adjustable, and the adjusting sets near the knee allow the angle of the leg to be adjusted. The leg support, shown in Table 9, design 7 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.

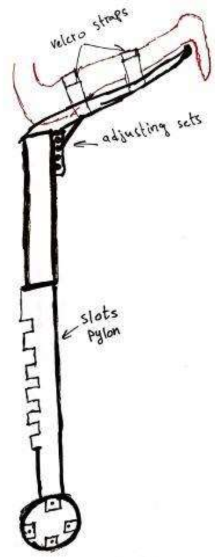


Figure 19: Final Sketch 7

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

Figure 20 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, shown in Table 9, design 6, allows the leg to be attached to the leg support and adjust to different leg sizes while also being comfortable. The dual side attachment, shown as design 19 in Table 11, is an attachment that spans the knee and allows for more support of the device along with rotation of the pylon about the axis of the knee.

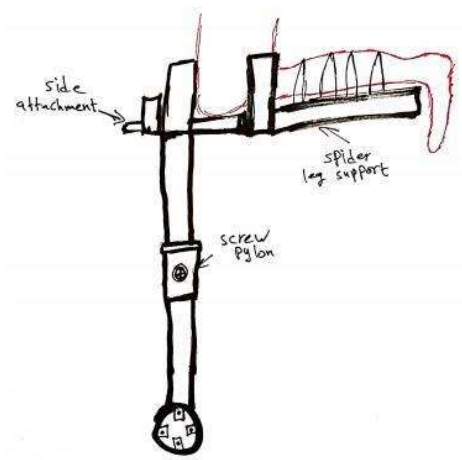


Figure 20: Final Sketch 8

4.9 Design #9: Bio Inspired-3 Telescoping Pylon

Figure 21 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 shown as design 10 in Table 10 is very comfortable, and it also allows up and down adjustment. The ball joint attachment shown as design

24 in Table 11 allows the pylon to adjust angle during a walking stride. The sand leg support shown as design 9 in Table 9 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.

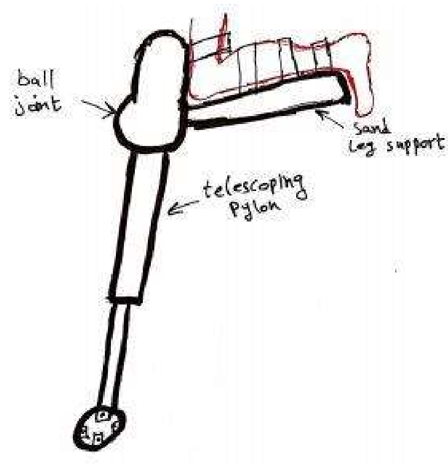


Figure 21: Final Sketch 9

4.10 Design #10: Three Velcro Straps Double Crutches Pylon

Figure 22 shows the three Velcro straps double crutches pylon design. This is among the most suitable designs; however, it is a very heavy design. This design utilizes the crutches pylon shown as design 12 in Table 10 to make the system height adjustable with the pins. It also utilizes the crutches attachment shown as design 22 in Table 11, 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 shown as design 7 in Table 9. This design would ensure all customer requirements are met except weight. It is durable, stable, and rotates about the knee joint axis allowing for a more natural walking position.

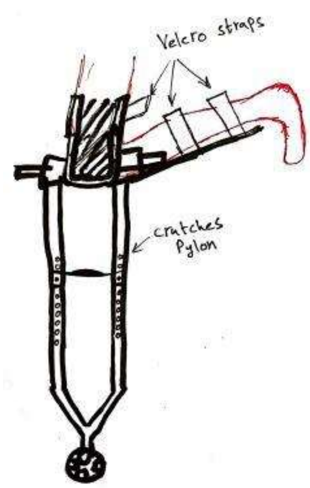


Figure 22: Final Sketch 10

5 DESIGN SELECTED – First Semester

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.

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 using the Decision Matrices located in Appendix B, Table 15. 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 rated from 0 to 100 on the above criteria. Design three, shown in Figure 15 had the best combinations of these requirements scoring an overall 74.95 out of 100. This was the highest score for any sketch in the decision matrix which was closely followed by design 5 with a score of 73.9. After considering the top five designs, shown in Table 15: Final Designs 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. This specific design is also light weight when considering material and could be cost effective and aesthetically pleasing. The team therefore considered the design that will be most suitable for the user and the client.

5.1.2 Final Selected Design

After discussing the chosen initial design with the client, new ideas came to light as well as a more in-depth understanding of what the system was supposed to accomplish. The client stated that the leg was to be held at a set 90-degree angle. The attachment was to act as the lower part of the leg to where it would be able to bend independently of the upper leg. This led 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 meant the attachment to the leg support had 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 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 allowed the user to walk in a more natural manor because when they put weight on the pylon, it stayed in place and once weight is released off the pylon at the end of the stride, the spring returned to its original state which would be slightly extended to start the next walking stride.

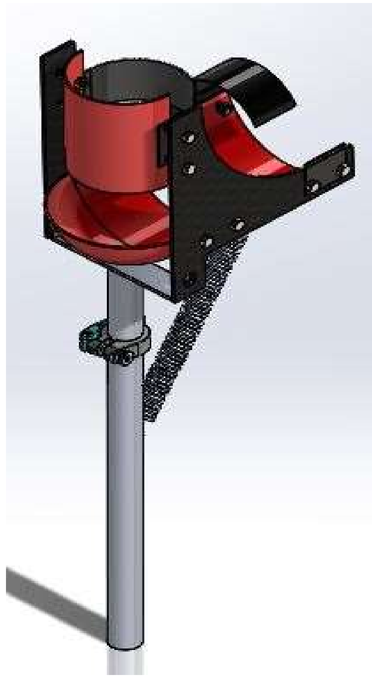


Figure 23: Final Design

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 and 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. The result of building the prototype was the device acted as a peg leg system instead of a rotating knee joint. The client specified to having a system that replicated a human knee, so a new attachment system was modified to rotate the pylon about the knee axis.

Figure 24: Prototype Front View

Figure 25: Prototype Side View

5.2.2 Materials

The team decided to use thermoplastic – a plastic that is formed through heat treatment – for the cuffs 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 was custom made by the team and in the shape of a triangle or inverted quarter circle to avoid any high stress spots at sharp corners, shown in Figure 26. This filleted radius should help avoid failure of this component in shear stress.

Figure 26: L-shaped carbon fiber leg support

The stress in the 'L' shaped beam was calculated by using equation 1 below 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.

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

Equation 1 takes into account the bending stress and shear stress applied to the element, and 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. 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 the 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.

$$Reserve\ Factor = \frac{Applying\ stress}{Allowable\ stress} \tag{4}$$

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.

$$F_y = F = \frac{10}{\sqrt{3}} \quad (8)$$

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

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

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 was made and tested before fabricating the final product. The second prototype was intended to 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 was 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 included loose bolts at the location of the knee joint to accurately represent the rotation about the knee instead of a bearing. A spring then attached 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 was 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 first prototype was constructed, flaws within the system were found so the team came up with a plan for the second prototype. The finalized materials are shown in Table 16 located in Appendix E. 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 were needed, what the part was 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 part numbers correspond to the different subsystems. Part 1.1 and 1.2 include the pylon subsystem, parts 2.1-2.2 were the carbon fiber leg supporting system, parts 3.1-3.4 include anything in contact with the leg to secure it to the leg support, parts 4-4.1.4 include the spring system, parts 5.1-5.4.2 are the fasteners in the system, and parts 6,7, and 8 are the bearing, bike clamp, and BiOM Attachment, respectively.

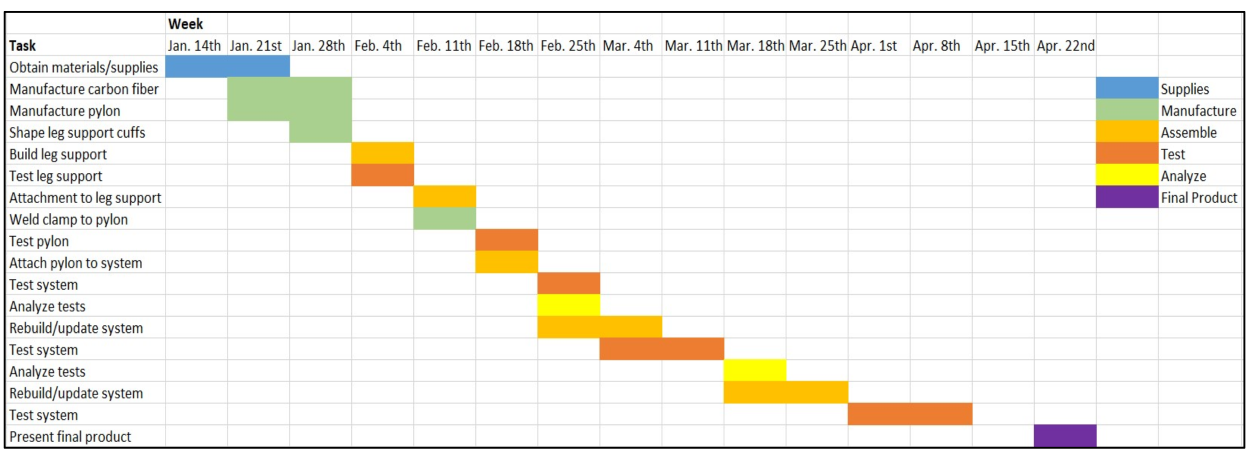
The initial design had the pylon made of 2024 T3 Aluminum tubing obtained from McMaster-Carr. This material was chosen for its strength and lightweight characteristics. The only modifications that needed to be done to the aluminum rod upon arrival would be to cut a slit in the top of both rods where the quick release clamp would be located. Carbon fiber was used for the attachment supports due to its strength and ability to be formed into specific molds. The carbon fiber was be obtained through Rock West Composites as pre-preg carbon fiber, meaning it already has the epoxy mix in the carbon fiber fabric [12]. The bolts and nuts were obtained from a hardware store. The fasteners were chosen for their ability resist shearing when the system is in use. The leg support cuffs were made of thermoplastic for the ability to shape and mold while being flexible and supportive. The thermoplastic was obtained from Interstate Plastics in sheets where the team would cut and shape the plastic. This allowed the cuffs to be shaped to a person's leg for a more secure attachment. Velcro was used to secure the leg to the thermoplastic leg cuffs. This insured the user's leg would not slip out of the leg supports. The Velcro straps were obtained from Amazon. The quick release clamp was obtained from Amazon already assembled.

6.3 Implementation of Chosen Design

For the team to implement the chosen design, there was a need for specialized equipment. As stated in chapter 6.2, specific materials with specific processes was needed to build the design. The material that required the most facilities and tools was 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 were cut out to proper dimensions with scissors, then placed on top of each other in the correct formation. The pre-preg carbon fiber was then vacuum bagged with proper supplies such as heat resistant plastic, gummy tape, and breather material. It was then put in a composite's oven provided by the composite's 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 [12]. Once the heating process was complete, the carbon fiber was stiff and had rough edges, that needed to be trimmed off. This was 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 were used outside while using the proper protective gear which included face masks, respirators, hearing protection, clothing protection, closed toed shoes, and gloves. Holes were then drilled into the carbon fiber where the bolts are located. 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 was needed for all carbon fiber processes. The use of carbon fiber in the system helped when creating the triangle and U-shaped supports. For the aluminum pylon, only a small slit need to be made where the tubes will be in contact with each other. This was 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 were cut and heated using a heat gun provided by the Biomechatronics lab. This allowed the thermoplastic to take the shape of the desired cuff. To connect the quick release clamp onto the aluminum pylon, the clamp was placed over the aluminum pylon. 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 ranged from January to April and mapped out all the major tasks that needed to be completed for building the final product. This included 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 final design was drafted using Solidworks to determine correct dimensions and accurately model the system. A drawing of the CAD Prosthesis Adapter model can be found in Figure 27 and Figure 28. Parts are labeled and numbered in Figure 30 below. 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 27: CAD Model, Isometric View of Prosthesis Adapter

Figure 28: CAD Model, Side View of Prosthesis Adapter

Shown below in Figure 29 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 30 shows the drawing of the prosthesis adapter with all the different parts labeled that correspond with the bill of materials.

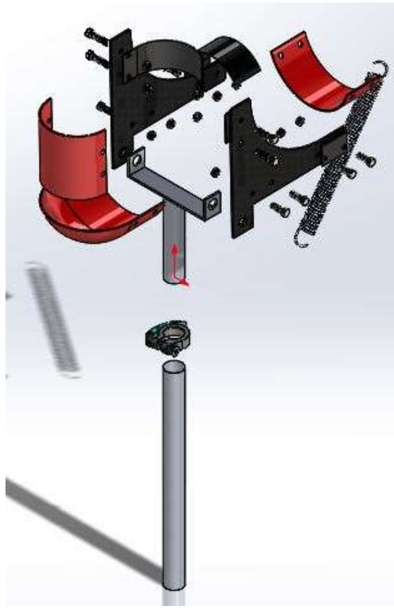


Figure 29: CAD Model, Isometric Exploded View of Prosthesis Adapter

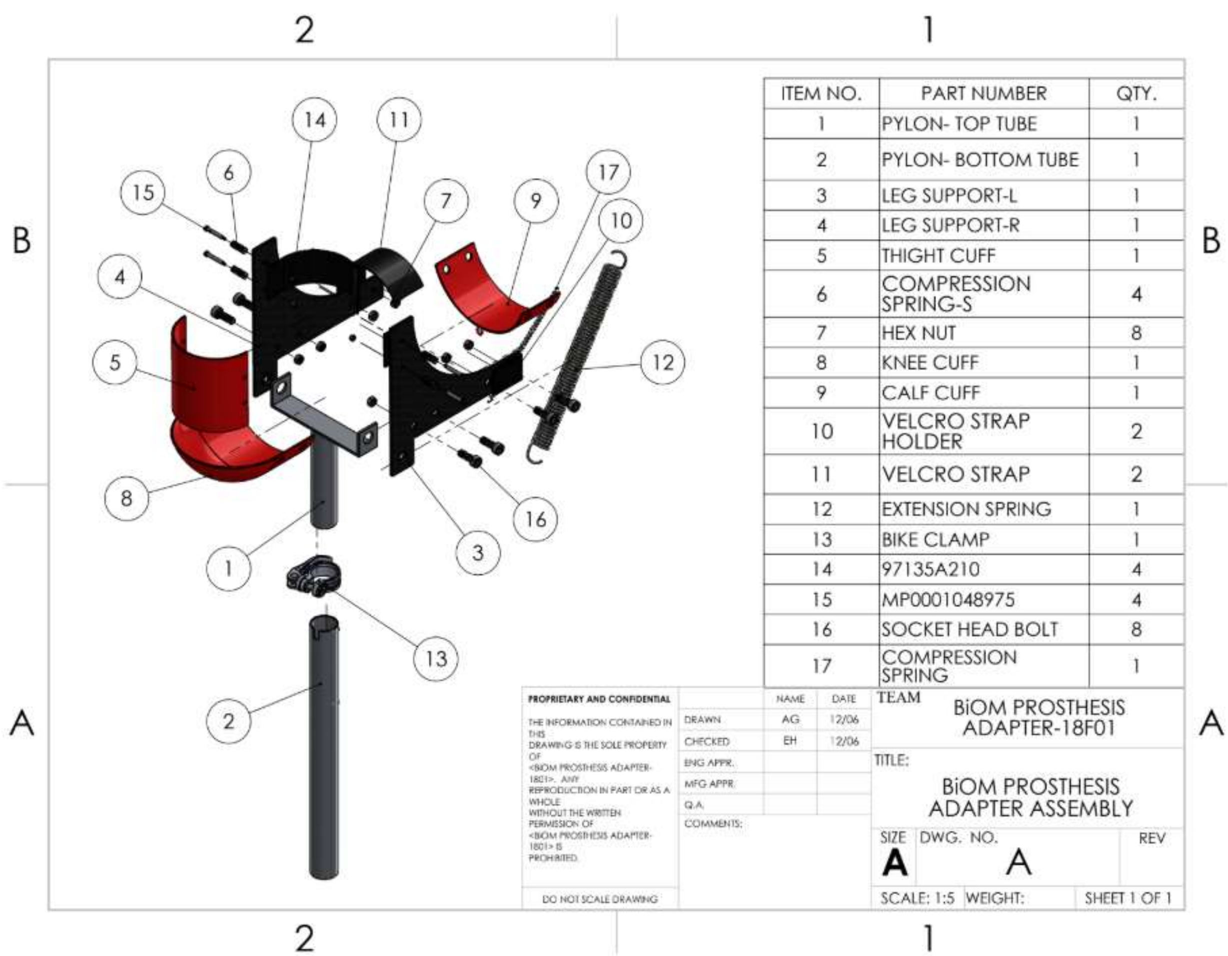


Figure 30: CAD Prosthesis Adapter Drawing

7 IMPLEMENTATION

Chapter 7 discusses the steps the team took to implement the final design. This includes manufacturing of all parts necessary for the final design, issues the team encountered when manufacturing the device, and how the issues were fixed. It also discusses the different design changes the project underwent due to difficulties in the manufacturing process.

7.1 Manufacturing Process

7.1.1 Pylon

To manufacture the pylon subsystem of the final design, this included attaching the BiOM attachment to the lower pylon and cutting slits in the upper pylon where the upper and lower pylons meet to attach the bike clamp. To attach the BiOM attachment, the attachment was unscrewed to its largest diameter, and slipped over the bottom pylon. The screws on the attachment were tightened to secure it to the pylon. This process only required an Allen key. To attach the bike clamp to the pylon, little slits were made along the long axis of the pylon. This allowed the tubing to contract when the clamp was tightened, not allowing any slippage between the upper and lower pylons. This process required access to a tilesaw. After the slit was made in the upper pylon using a tile saw, the bike clamp was slipped over the upper pylon, and the lower pylon slipped inside the upper pylon and clamped. Eight holes in the upper pylon were drilled using a drill press to allow the attachment subsystem to attach to the pylon.

7.1.2 Attachment

To manufacture the attachment, the prepreg carbon fiber was laid up and hardened. This required access to vacuum bagging materials such as an airtight vacuum bag, a vacuum with a nozzle and hose heat resistant to 275 degrees Fahrenheit, and an oven. The prepreg carbon fiber was cut to shape and laid over an aluminum mold. This included using a bandsaw to cut the mold to size, then clamping in a vice while hitting it with a rubber mallet to form the rigid U shape. The sides of the U shape needed to be at a distinct 90-degree angle to work for the system. The prepreg carbon fiber was then laid over the aluminum mold, using 12 layers. The 12-layer distinction was determined through a composite's analysis. The analysis utilized equation 10 and the promal program to determine the number of layers of carbon fiber needed to ensure the attachment would not break under the applied load. Additional calculations for the carbon fiber analysis are shown in Appendix D.

$$\sigma_{allow} = \frac{F \times L \times \left(l \times \frac{t_{1-ply}}{2}\right)}{w \times \left(\frac{\left(l \times t_{1-ply}\right)^3}{12}\right)} \tag{10}$$

σ_{allow} represents the maximum stress seen by the attachment with a factor of safety. F represents the force applied to each side of the attachment, L represents the distance from the center axis of the attachment to the forces applied to the attachment, l represents the number of layers of carbon fiber needed in the lay-up, w is the width of the attachment, and t_{1-ply} is the thickness of one layer of carbon fiber. From equation 10, it was determined that the number of layers needed for the carbon fiber attachment to not break under loading was 9, but due to not having access to an autoclave and possible delaminations and voids within the product, 3 additional layers were used to total 12 layers of carbon fiber for the U-bar lay-up.

This entire component was then placed in a vacuum bag, vacuum sealed, and placed in an oven at 275 degrees Fahrenheit for 2 hours. This allowed the prepreg carbon fiber to harden into the U shape. After the hardening process was complete, the sides of the component were sharp, so the entire component was filed using an electric Dremel. After the sides were Dremeled, holes were drilled through each side to allow the shoulder bolts to pass through for rotation about the leg support. This required access to a drill press and a carbide tipped drill bit slightly larger than the ½" shoulder bolt. Four additional holes were drilled in the bottom of the bar to allow the pylon to attach to the system.

7.1.3 Leg support

To manufacture the leg support, the carbon fiber sides were laid up and hardened similar to the process of the attachment. The only difference between the carbon fiber leg supports and the attachment was the leg supports were flat and will not require a customized mold. The prepreg carbon fiber was cut to shape and laid up on top of an aluminum plate. It was then vacuum sealed and placed in the oven to harden. This was repeated for two identical carbon fiber leg supports. After the hardening process is complete, both supports were sanded down using a Dremel, similar to the attachment. Multiple holes were drilled through the carbon fiber to allow the cuffs to be attached. One hole for the upper thigh support was drilled in the upper corner of the L support, and one hole was drilled in the lower corner for the calf cuff attachment to the L-support. A larger hole was drilled in the 90-degree corner for the bearing. This required a drill press and carbide tipped drill bits. The bearing was so large that no drill bit would cut the carbon fiber in a large enough hole, so the team used use a ½" drill bit to drill a pilot hole, and Dremel out the center of the hole to allow the bearing to fit properly.

The calf cuff, thigh cuff, and knee cuffs were then manufactured out of thermoplastic. This required a heat gun and a mold to mold the thermoplastic around. The thermoplastic was measured and cut to the proper dimensions using a bandsaw, then the thermoplastic was heated up using a heat gun and molded using a team members leg. The cuffs were then drilled to allow the bolts to attach the cuffs to the L shaped supports. This was done using a drill press. After the holes were drilled, the cuffs were attached to the leg support using bolts and springs. The leg cuffs were placed on the leg support with a shoulder bolt going through both components with a small compression spring between the materials to allow flexibility to the user's leg. The Velcro straps were secured to the cuff using Chicago bolts. One hole was drilled in the radius of the calf cuff to allow attachment of the spring system.

7.1.4 System

After the three main subsystem components were built, the system was put together. This included adhering the bearing into the L support and attaching the U bar component to the leg support using shoulder bolts. This allowed the U bar to rotate relative to the leg support about the knee axis. The pylon was then attached to the U bar. This required drilling four holes in the carbon fiber attachment and eight holes in the upper pylon. The compression and extension springs were then attached to the system using the holes drilled into the calf cuff. Foam was placed on all the cuffs to provide extra cushion and comfort for the user. The system could then be adjusted to the user's height and leg width using the Velcro straps, bike clamp, and springs, which was then attached to the BiOM ankle prosthesis for use in research.

7.2 Design Changes

7.2.1 Pylon

During the fabrication process of the pylon, problems were encountered when trying to attach the BiOM attachment to the lower pylon. This included the outer diameter of the lower pylon being 1 mm too large to fit into the BiOM attachment. To fix this problem, the lower pylon was taken to the NAU machine shop, building 98C, put on a lathe to shave down the outer circumference to fit inside the attachment. The finished product can be seen in Figure 31.

Figure 31: Lower Pylon with BiOM Attachment

The team decided that it would be more beneficial for the project if the pylon was made entirely from carbon fiber because of its lightweight and strength characteristics. The team ordered two new pylons made of carbon fiber that were already cured. The BiOM attachment fit perfectly over the end of the smaller pylon, and the smaller pylon fit inside the larger pylon. The only issue was with the bike clamp attachment being too large. A smaller bike clamp attachment was purchased and used. The manufacturing process stated above was used to manufacture the rest of the pylon. The carbon fiber tubing and attachment can be seen in Figure 32.

Figure 32: Carbon fiber tubing with attachment using 8 screws

Due to the change of material in the pylon, a new spring attachment was needed for the spring system. This was designed to be a carbon fiber bracket epoxied onto the pylon as a pin support shown in Figure 33.

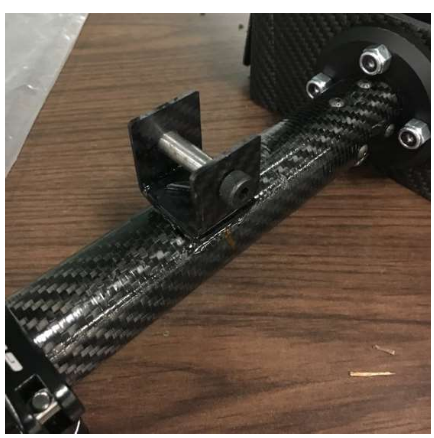


Figure 33: Pylon Pin for Spring System

7.2.2 Attachment

While fabricating the carbon fiber attachment, a problem manufacturing the aluminum mold was encountered. Originally, the thickness of the aluminum mold was to be 50 mm, but while trying to bend the mold into the 90-degree angles, the sides would snap off due to a small cross-sectional area and too much stress in that area. This was fixed by upsizing the cross section by 5 mm for each mold. The aluminum mold was found to hold at 90-degrees when the width of the aluminum component was 75mm. The prepreg carbon fiber could then be laid up and hardened using the process stated above. The finalized U-bar is shown in Figure 34.

Figure 34: U-Bar Attachment

7.2.3 Leg support

To manufacture the leg support, a few problems occurred during the prepreg layup process. This included a delamination during the hardening process. While the two L shaped components were hardening, there was not enough pressure for the carbon fiber to adhere to itself. There was a one-layer delamination in one support, and a 4-layer complete delamination in the second support. This was fixed by applying epoxy to one complete side of the L shape and clamping the two delaminated sides together and hardening for 24 hours for both components. This fixed both delamination's in the components and the post processing for carbon fiber could be completed as stated above in chapter 7.1. The completed carbon fiber manufacturing is shown below in Figure 35. The thermoplastic cuffs were completed as stated above.

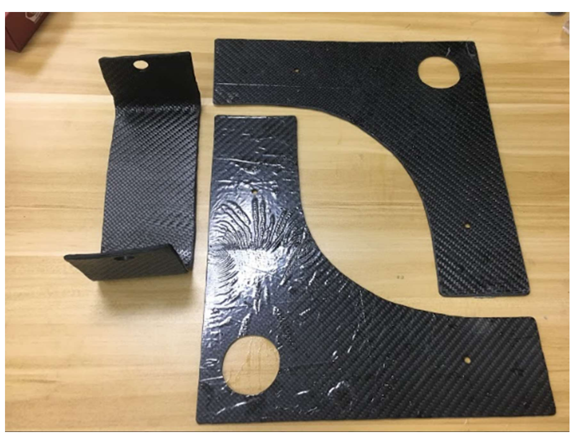
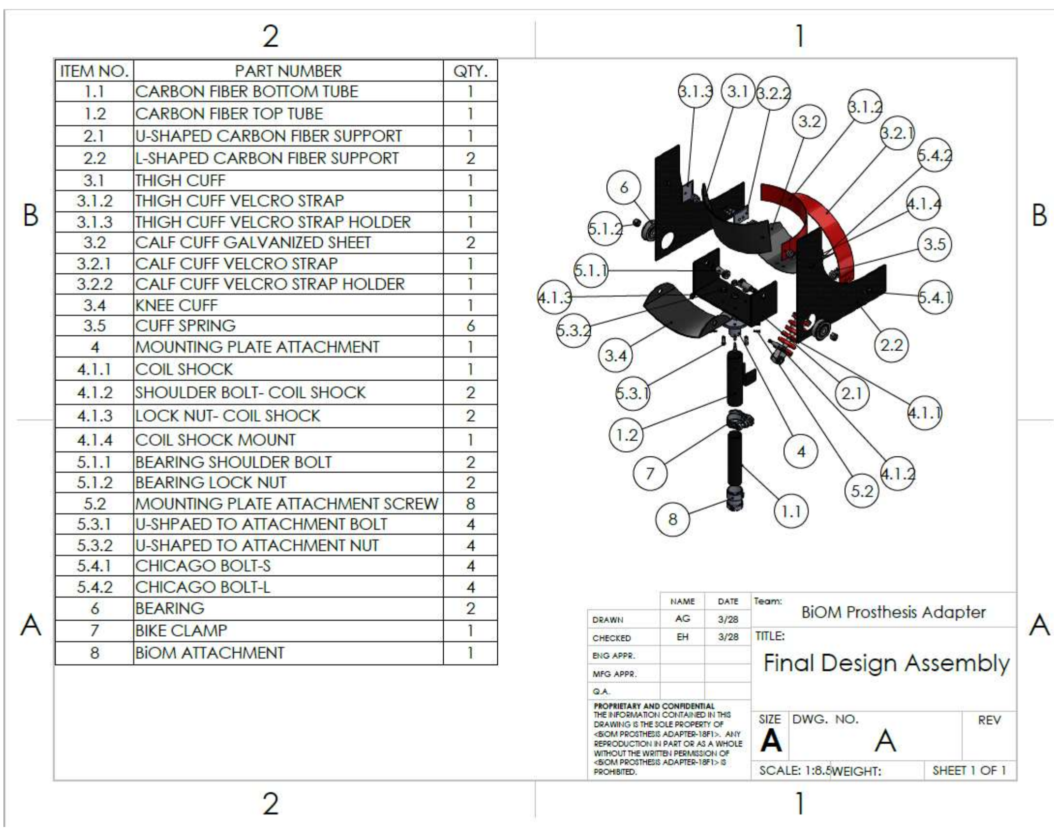


Figure 35: Manufactured Carbon Fiber Components

7.2.4 System

When assembling the system, issues within the spring mechanism were found. This included needed a stiffer more rigid surface to attach the upper spring to. This was fixed by creating a steel bracket with a pin and attaching it to a galvanized sheet of steel using four bolts. That sheet of galvanized steel was then bent to form the shape of the thermoplastic calf cuff and placed on the outside of the cuff. This allowed less deformation in the thermoplastic when the spring was compressed. The completed system is shown in Figure 36 with the exploded view of the CAD model with labeled parts in Figure 37.

Figure 36: Leg Support



ITEM NO.	PART NUMBER	QTY.
1.1	CARBON FIBER BOTTOM TUBE	1
1.2	CARBON FIBER TOP TUBE	1
2.1	U-SHAPED CARBON FIBER SUPPORT	1
2.2	L-SHAPED CARBON FIBER SUPPORT	2
3.1	THIGH CUFF	1
3.1.2	THIGH CUFF VELCRO STRAP	1
3.1.3	THIGH CUFF VELCRO STRAP HOLDER	1
3.2	CALF CUFF GALVANIZED SHEET	2
3.2.1	CALF CUFF VELCRO STRAP	1
3.2.2	CALF CUFF VELCRO STRAP HOLDER	1
3.4	KNEE CUFF	1
3.5	CUFF SPRING	6
4	MOUNTING PLATE ATTACHMENT	1
4.1.1	COIL SHOCK	1
4.1.2	SHOULDER BOLT- COIL SHOCK	2
4.1.3	LOCK NUT- COIL SHOCK	2
4.1.4	COIL SHOCK MOUNT	1
5.1.1	BEARING SHOULDER BOLT	2
5.1.2	BEARING LOCK NUT	2
5.2	MOUNTING PLATE ATTACHMENT SCREW	8
5.3.1	U-SHPAED TO ATTACHMENT BOLT	4
5.3.2	U-SHAPED TO ATTACHMENT NUT	4
5.4.1	CHICAGO BOLT-S	4
5.4.2	CHICAGO BOLT-L	4
6	BEARING	2
7	BIKE CLAMP	1
8	BiOM ATTACHMENT	1

Figure 37: Final Design CAD Model

8 TESTING

During testing, the team tested each subsystem separately to ensure they met their respective requirements. The system was then tested to determine if the device would meet the customer requirements. The different customer requirements tested are summarized in Table 6 showing the requirement with the value it had to meet.

Table 6: Customer Requirements and Target Values

Requirements	***Target Values***
Light Weight (kg)	4
Comfortable	8/10 rating
Quick Attachment (sec)	60
Pylon Extension Range (cm)	12
Small/Large Calf Cuff Circumference (cm)	30-45
Small/Large Thigh Cuff Circumference (cm)	35-65
Durable	2 hours of continuous use
Affordable	$1000
Safe	FS of 3

8.1 Pylon

The pylon tests included determining if the pylon had an extension range of 12 cm and was able to hold a fully-grown person. To determine if the pylon met the extension range requirement, the pylon was set to its minimum length, measured with a tape measure, and set to its maximum length and measured again. The difference in the dimensions determinized if the range requirement was met. The photos of testing the pylon range can be seen in Figure 38 and Figure 39 where the minimum dimension was 23 cm and maximum dimension as 36 cm to have a total extension range of 13 cm.

Figure 38: Minimal Pylon Range

Figure 39: Maximum Pylon Range

The second pylon test included determining the force required to make the pylon slip or buckle axially. This was done by standing the pylon upright with the attachment to the U-bar on top, seen in Figure 40, in the extended position on top of a force plate in the Biomechatronics lab. Two tables were placed side by side next to the pylon and the pylon was extended about two inches above the height of the tables.

Figure 40: Pylon with Attachment

A force was applied downward over the top of the plate until the clamp slipped. The force data was obtained and shown in Figure 41 for Newtons and Pounds. From the data, the pylon slipped at about 775 N (175 lbs).

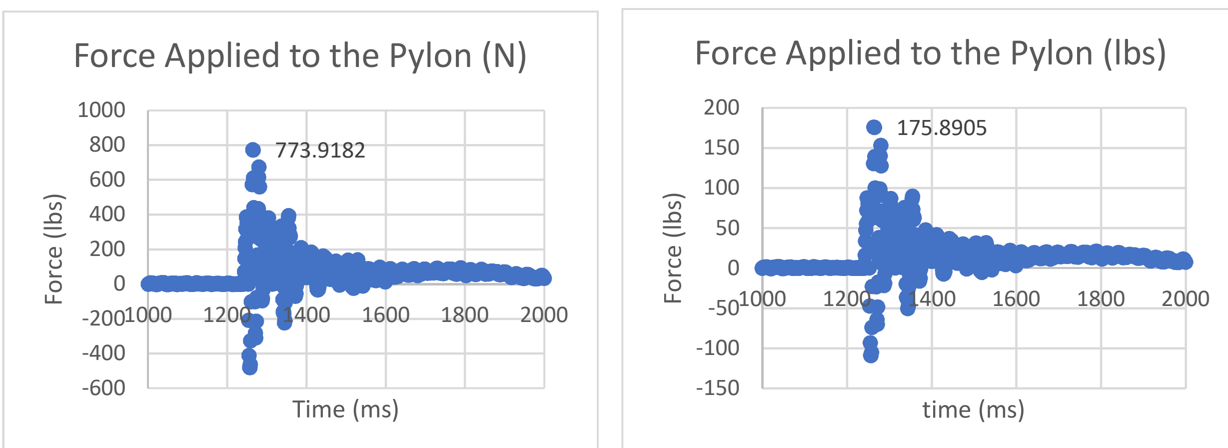


Figure 41: Force Data for Pylon Test in Newtons and Pounds

8.2 Attachment

The attachment system had one main test to ensure it would not break under the applied load. This consisted of using a similar testing procedure for the pylon, except the U-bar was attached to the pylon attachment as seen in Figure 42. A flat plate was put over the top of the U-bar and force was applied and measured over a force sensor in the Biomechatronics lab. The U-bar did not break under any testing and therefore satisfies the customer requirement as it exceeded the factor of safety.

Figure 42: U-bar Test Setup

8.3 Leg Support

The leg support system had three main tests, the comfort test, timing test, and dimension test. The comfort test included finding 10 unbiased volunteers to try on the leg support. They would be given instruction on how to put it on their leg and were then timed while securing the system to their leg without any help. The volunteers then placed their leg in the leg support on a table and rated the system for comfort on a scale of 0 to 10 with 0 being painful and 10 being very comfortable. The leg support comfort test can be seen in Figure 43. The volunteers gave an average comfort rating of 8.3/10 and had an average time to securing the system to their leg in 19.11 seconds.

Figure 43: Leg Support Comfort Testing Setup

To determine if the circumference of the leg cuffs was sufficient, both the thigh and calf cuff circumferences were measured using a tape measure. The Velcro straps were placed in the smallest position and the circumference was measured. The Velcro straps were then placed in the largest position and the circumference was measured again. This was repeated for the other cuff and the differences were taken between the largest and smallest position. An example of how this was done can be seen in Figure 44. With both cuffs, the circumferences ranges did not meet the smaller requirements. This was fixed by manufacturing smaller thermoplastic cuffs that could be switched out based on the size of the user.

Figure 44: Calf Cuff Circumference Measurements

8.4 System

To ensure the entire system was valid for the intended use, the weight, cost, and durability were determined. The entire system was weighed to be 1.7 kg, which was below the maximum weight requirement of the system. A small bill of materials was used to determine if the stand-alone-system was less than $1000. The small bill of materials for the stand-alone-system can be seen in Table 7. The system cost about $315. To determine the durability of the system, the device was used with the BiOM Ankle Prosthesis device for two hours. This determined if the device would withstand the stress of constant use. The device suffered catastrophic failure at the location of the spring to the pylon after a force over the limit was applied. The device was temporarily fixed but a new design should be considered for the connecting point in the future.

Table 7: Stand-Alone-System Bill of Materials

Parts	***Quantity***	***Cost***
Bike Clamp	1	$7.99
Compression Spring	1	$3.53
Carbon Fiber Sticker	1 roll	$8.52
Shoulder Bolts	2	$5.04
Lock Nuts	2	$2.03
Small Compression Springs	6	$6.70
Chicago Bolts	6	$11.20
Comfortability Foam	3 Pcs	$6.80
Velcro Straps	2	$5.91
Thermoplastic Cuffs	3 sheets	$9.70
Bearings	2	$66.84
Pylon Attachment	1	$14.99
Carbon Fiber Upper Pylon	1	$12.50
Carbon Fiber Lower Pylon	1	$13.75
Galvanize Sheet	-	$2.39
Prepreg Carbon Fiber	4 square foot units	$135.16
	Total	**313.05**

8.5 *Summary of Testing Procedures*

Based off the above testing procedures, the device exceeded all but three testing procedures, two of which were not critical system failures. The requirements are stated, and the results are compared to the target values in Table 8. The calf cuff circumference test initially failed due to not having the smaller required circumference range. This was corrected by fabricating new smaller cuffs from thermoplastic which the user would be able to switch out as needed. Since the pylon slipped at an applied force of 175 pounds, the system did not have an overall factor of safety of 3. This slippage was not a critical failure as the system was still useable during and after the pylon slipped, and the user would be unharmed. This led the team to determine the critical factor of safety of the system, which occurred at the point where the carbon fiber hinge was epoxied to the carbon fiber upper pylon to hold the spring system. The critical factor of safety for the system was 3.2. The device underwent failure during the durability test but was temporarily fixed until a new solution is determined.

Table 8: Testing Procedure Results

Requirements	***Target Values***	***Results***	***PASS/FAIL/ CORRECTED***
Light Weight (kg)	4	1.7	PASS
Comfortable	8/10 rating	8.3/10 rating	PASS
Quick Attachment (sec)	60	19.11	PASS
Pylon Extension Range (cm)	12	13	PASS
Small/Large Calf Cuff Circumference (cm)	30-45	27 – 41.5/41 – 48	CORRECTED
Small/Large Thigh Cuff Circumference (cm)	35-65	30 – 42.5/42 – 68	CORRECTED
Durable	2 hours of continuous use	---	FAIL* & CORRECTED
Affordable	$1000	$313.05	PASS
Safe	FS of 3	Critical FS of 3.2	FAIL**

Fail: Was tested for durability, device broke after applying a load above the limit of the project.*
*Fail**: Part of the initial test failed, but it was not a critical failure for the system*

9 CONCLUSIONS

Wrapping up the project, a post mortem analysis was conducted to determine how successful the team was in completing the project and what could be improved. This included how well the team worked together, the project performance, problems encountered by the team, and lessons learned throughout this project.

9.1 Contributions to project success

Overall the main purpose and goals of the project were met. The client asked to design and build a device that spanned from the BiOM Ankle Prosthesis device to an able-bodied person in order for them to test the ankle prosthesis without the need of an impaired subject. The team had met the initial purpose of the project by delivering a device to the client that had met their expectations. Expanding on that, all the goals of the project were met as well. This included all the customer requirements stated in chapter 2. All the goals outlined by the client were kept in mind throughout the project and every goal was tested to ensure the device would not fail in that region. This allowed the team to deliver a working a reliable device to the client for use in the Human Performance Lab at NAU for BiOM Ankle Prosthesis testing.

Overall, the team functioned well during the second semester of the project. This was due to following the team charter written by the team in the first week of the project to discuss coping strategies and ground rules. The team had efficiently used each meeting to make progress on the project discussing future plans as well as ensuring everyone was on track with their current parts. Each team member delivered quality results on time. This was improved by using weekly action items. Each member made a list of items they were required to complete by the end of the week and the indicate which items were complete and which were in progress. This helped the team stay on track with the project as well as splitting up the work equally between all members. The most beneficial thing the team implemented for the success of the project was distributing up roles and specific assignments to each member. Dividing up entire tasks ensured that there were no communication errors between members of who was to complete what and when. This way, one member completed an action item and it could be checked by other members of the team. This also proved beneficial to the team dynamic because the task could be completed on their own time as long as it was completed by the due date set by the team.

In terms of project performance, product quality was the most positive aspect. This was due to the customer being very happy with the final product for it not only working and passing their requirements, but the team ensured the device was aesthetically pleasing while meeting those customer needs. This was solely due to the carbon fiber components and the spring mechanism. The carbon fiber contributed to the robust design and light weight aspect of the final product while the spring mechanism contributed to the robust design and ensured the device would work as it was supposed to by placing the pylon back into its starting position for the new gait cycle.

Throughout the project, the team learned many lessons – both technical and teamwork related. Technical lessons learned by the team included ensuring that all analyses and calculations for the project were checked thoroughly by team members. This included all back of the envelope calculations, technical analyses on bearings, bolts, shafts, and carbon fiber. Due to some calculations that went unchecked by the entire team, some parts were bought and returned due to dimension errors. After this, the team was checking other members work more in-depth. Other technical lessons learned by the team included how to properly work with carbon fiber components and machine different materials using the machine shop. A major technical lesson the team learned was the importance of prototyping the device. The team had a design in mind and was under the impression it would work the first time without prototyping or creating a proof of concept. This taught the team that no matter how small the design change was, it needed to be prototyped to ensure it would work as expected. With every new design change, there will be effects elsewhere in the system in which nobody will expected.

Some teamwork related lessons the team learned was group work, being responsible, and decision making. Early on in the project, there were some complications with one group member making it difficult to carry out decisions and progress in the project. This taught everyone the value of communication and how everyone must work together to get even the slightest thing done or the entire project could be behind. Due to this complication, the member left the group later in the project and the other members of the team continued to practice good communication and getting the parts of the project done that they took responsibility for. This improved the morale and the effectiveness of the entire project making group decisions easier and meetings more on task. From this, the team learned valuable lessons of how to work professionally and efficiently in group settings by being responsible and using communication to make group decisions.

9.2 Opportunities for Improvements

Throughout the project, many aspects could have been improved. Although the final product worked and was up to the expectations of the client, it was not an easy process to get a working system by the deadline. This was particularly due to the spring system. In the first semester of the project, one group member took charge of designing the spring system. This was to be completed before the final proposal deadline in December but was not. The deadline was extended to January but was still not met. It was again extended to February and again was still not met. The other three team members had then decided to take on the spring system themselves as the timeline for the final product was fast approaching. The spring system was designed and manufactured only once two weeks before the final product was due but there were issues with getting the system to work properly due to not reviewing the degrees-of-freedom of the system. This meant that the spring system was designed as a fixed-fixed support but needed to rotate about both points to allow movement of the pylon. This was overlooked due to the tight schedule the team was now operating on. A quick proof of concept was constructed, and new ideas came to light. From this the team decided to use a bike spring hydraulic for the spring system which improved the final design drastically. Although at the end of the project the spring system worked as the team had planned, it was a very stressful and time sensitive process that none of the team members would like to repeat. In the future to avoid this, the team will ensure that all aspects of the project were met on time with no more of a two-week extension to any part of the project. This would help ensure the project stays on the original timeline. Any issues with members not delivering would be resolved immediately instead of waiting until the deliverable was complete – if it would be completed.

Another issue with the final product was the weight. Originally the client wanted the system to weigh less than one kilogram, but due to the size of the device, the weight limit would have been extremely hard to meet. The client was very understanding of this and made the weight limit flexible up to 4 kg. In the future, the team would develop new ideas to ensure all initial customer requirements were met, although this customer requirement was flexible, future ones may not be.

The final product worked as the customer had intended, but due to a scope change of the project earlier in the first semester, the spring system was added and not refined for better options. A way to improve this would be to get the concept that the client was expecting and brainstorm better ideas of how to achieve the same results. This would include not taking the spring system idea as the only way to meet their requirements, but also looking at different ideas such as a knee actuation using motors, a torque spring, or hydraulics. The entire project was not fully defined until December, and the final product could have been improved by talking about the concepts of design in more detail while also prototyping the design ideas to determine which ones would be most beneficial for the project.

9.3 Future Work

Although the final product is completed, there are some improvements the team would like to highlight for future work on the design. As stated above, the team would have liked to brainstorm more ideas for rotation about the knee joint but ran out of time. This could be improved in the future by implementing a torque sensor to the knee joint between the pylon and leg support to measure the amount of toque at the knee to allow a motor to be placed at the location to actuate the knee joint. Another possible solution of the spring system spanning from the pylon to the leg support would be adding a toque sensor at the knee joint. This would be more aesthetically pleasing as well as limit the spots in the design that could potentially fail. Due to the leg support not securing a smaller leg without switching the calf and thigh cuffs out for a smaller person, a new leg support could be constructed to improve the switching time of the support. This would include switching the entire leg support out at the attachment point of the pylon, so only 4 bolts would have to be taken out and replaced making for a quick leg support switch for different users.

After durability testing was completed on May 3rd, a few other flaws to the design were found. Currently the lower pylon slips inside the upper pylon due to the outer diameter of the smaller tubing being too small for the larger tubing to clamp around. This could ideally be fixed by special ordering a slightly larger tube from Rock West Composites that would just fit inside the upper pylon. The upper pylon was proven to be about 5 cm too long and would need to be trimmed down to work with people under 5'10". This was not determined until this late in the project due to not having access to the Ankle Prosthesis device. During testing, the Velcro straps ripped off, this could be improved by using eyelets around the holes of the Velcro to create a more robust hole in which the applied stress from the leg would not break the Velcro at the eyelet. The leg support device proved to feel differently with the BiOM Ankle Prosthesis than without it, and due to this extra weight and new addition to the system, the leg support became uncomfortable to the user around the knee region. A fast and easy fix would be to put padded foam on top of the U-bar support to ensure when the knee support deflected, it would not run straight into the carbon fiber support. A more ideal fix would be to use a stiffer material for the knee cuff. Additionally, at the knee region of the device, the rotation location was not perfectly at the center of the knee. This would require moving the bearing location slightly forward in the leg support, so it would be slightly forward of the upper leg. This would allow the pylon shank to be in line with the upper leg.

During testing with the powered BiOM Ankle Prosthesis, the device suffered catastrophic failure at the spring location. This was partially due to testing the device out of the range of weights for the specific support, but mainly due to not having a strong enough adhesive to hold the spring support to the pylon. The current epoxy used to hold the bracket to the pylon was 205/206 hardener resin specifically used for carbon fiber lay-up. This specific epoxy does not have a large shear modulus and therefore couldn't withstand the shearing force applied to the system at that time. A fast fix for this failure, which was completed the day after failure, was using the same epoxy mixture and to note that it would be a temporary fix until a better design could be fabricated. A possible fix for this would be to create a collar along the upper pylon in which the spring mechanism could slide along the axis of the pylon. The issue with creating a design in this region includes not having any extruded items on the inside of the upper pylon as it would interfere with the height adjustment of the lower pylon. Other than a collar mechanism for the upper pylon, a faster fix for this would include bolting the hinge to a flat plate which would then be bolted to the very top of the upper pylon. This would allow it to be secured to the pylon without any bolts interfering with the height adjustment.

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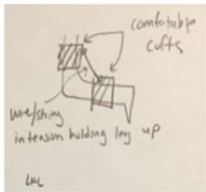
11 APPENDICES

11.1 Appendix A: Subsystem Pugh Charts

Table 9: Leg Support Pugh Chart

DATUM (1)



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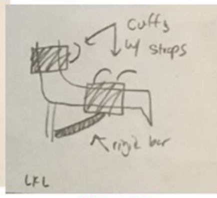

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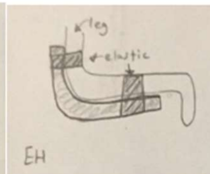

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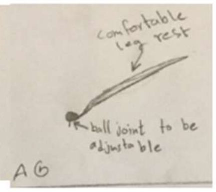
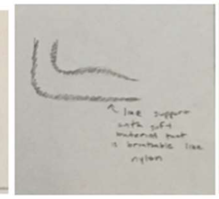
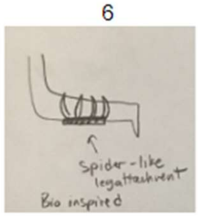


5



Criteria	DATUM	Rigid Bar	El Hefe	Ball/Joint	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

6



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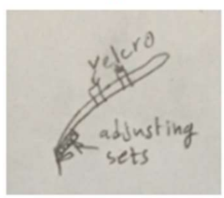
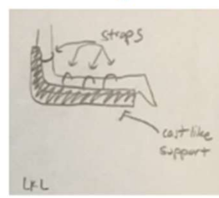


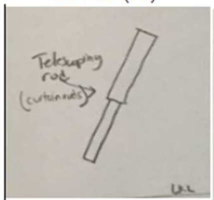
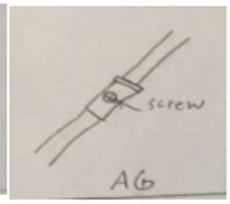
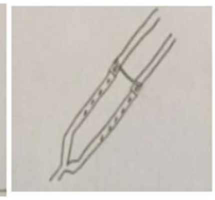
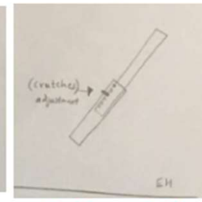
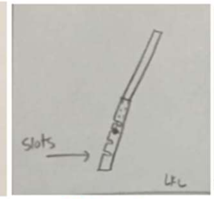
8



9

Criteria	The Spider	Straps	The Cast	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 10: Pylon Pugh Chart

	DATUM(10)	11	12	13	14
					
Criteria	Telescoping rod pylon	Screw pylon	Crutches pylon	Crutches pylon2	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

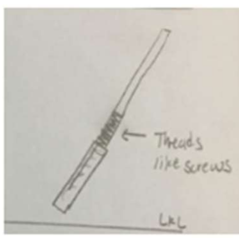
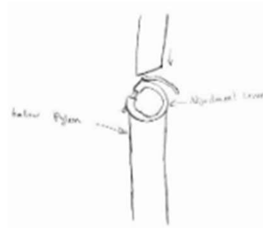
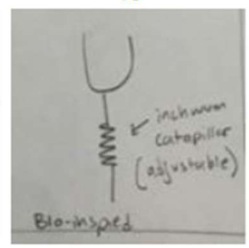
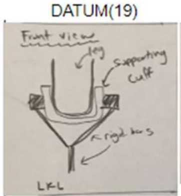
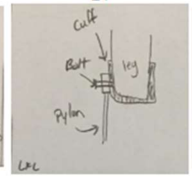
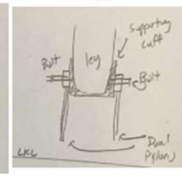
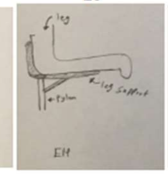
	15	16	17	18
				
Criteria	Thread pylon	Hiking pylon	Bike pylon	Catapiller pylon
Safety	-1	1	1	-1
Durable	0	0	1	0
Light Weight	0	1	1	0
Adjustable	1	1	1	0
Quick Attachment	0	0	0	1
Stable	-1	1	1	-1
Quick Adjustment	1	1	1	0
Number better: S+	+2	+5	+6	+1
Number worse: S-	-2	0	0	-2
Number same: S0	3	2	1	4

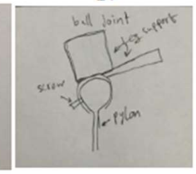
Table 11: Attachment Pugh Chart











	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

11.2 Appendix B: Subsystem Decision Matrices

Table 12: 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 13: 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 14: 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**

11.2.1 Appendix B: Final Design Sketches Decision Matrix

Table 15: 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

11.3 Appendix C: Final Design Sketches

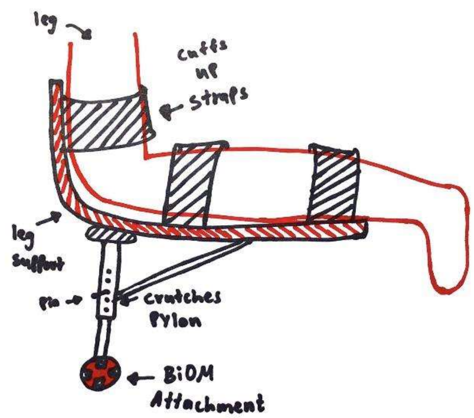


Figure 45: Final Sketch 1

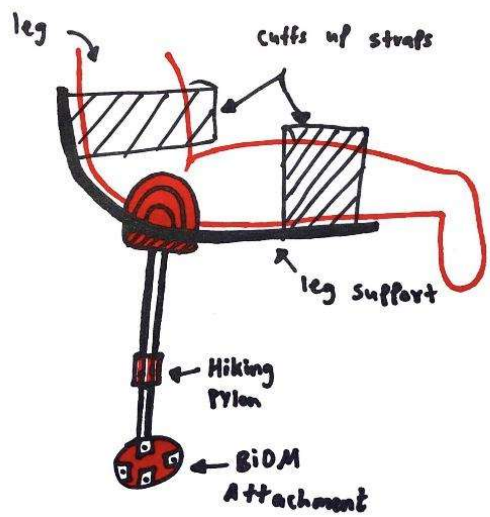


Figure 46: Final Sketch 2

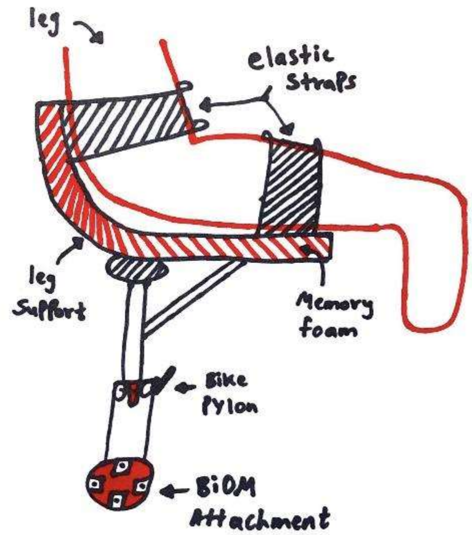


Figure 47: Final Sketch 3

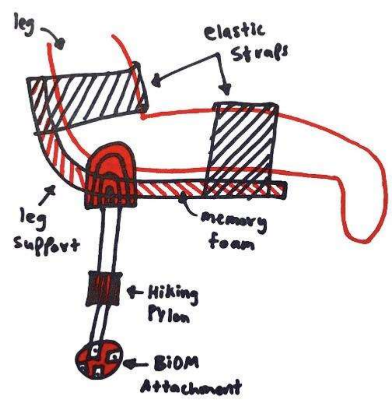


Figure 48: Final Sketch 4

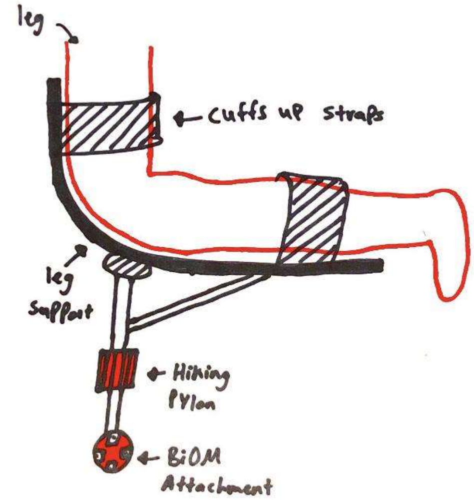


Figure 49: Final Sketch 5

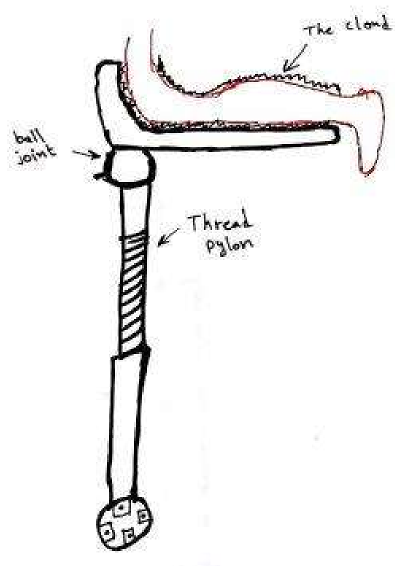


Figure 50: Final Sketch 6

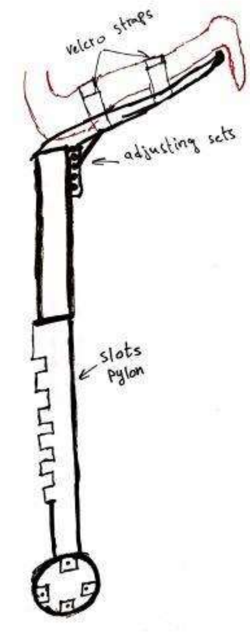


Figure 51: Final Sketch 7

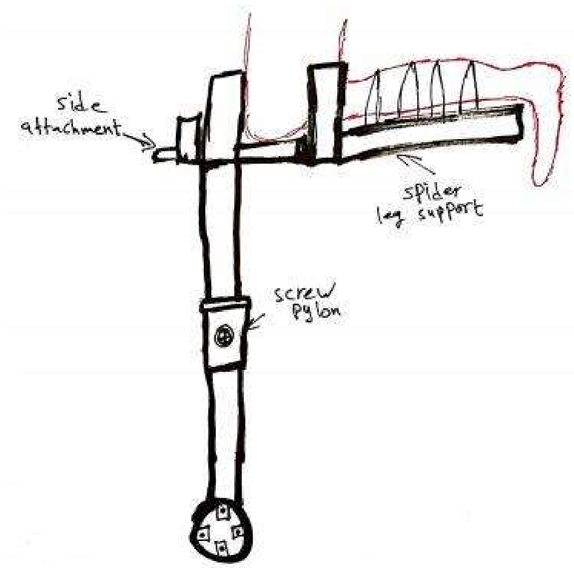


Figure 52: Final Sketch 8

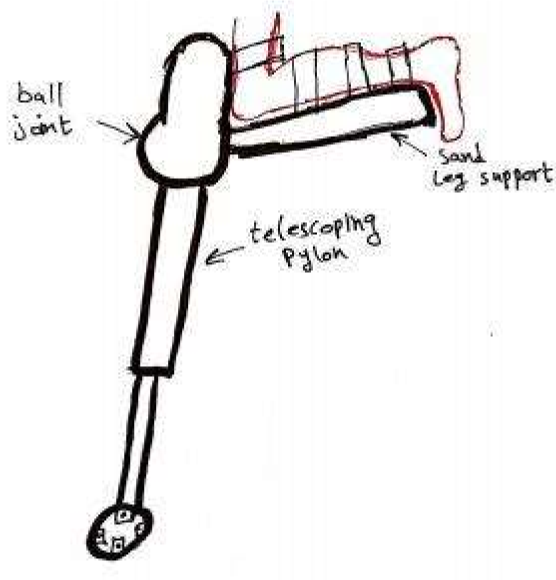


Figure 53: Final Sketch 9

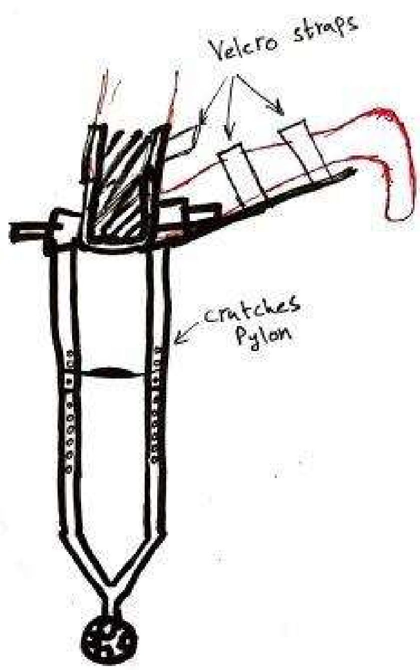


Figure 54: Final Sketch 10

11.4 Appendix D: Technical Analysis

11.4.1 Structural Analysis of the Pylon to Determine Diameter

```
%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)
```

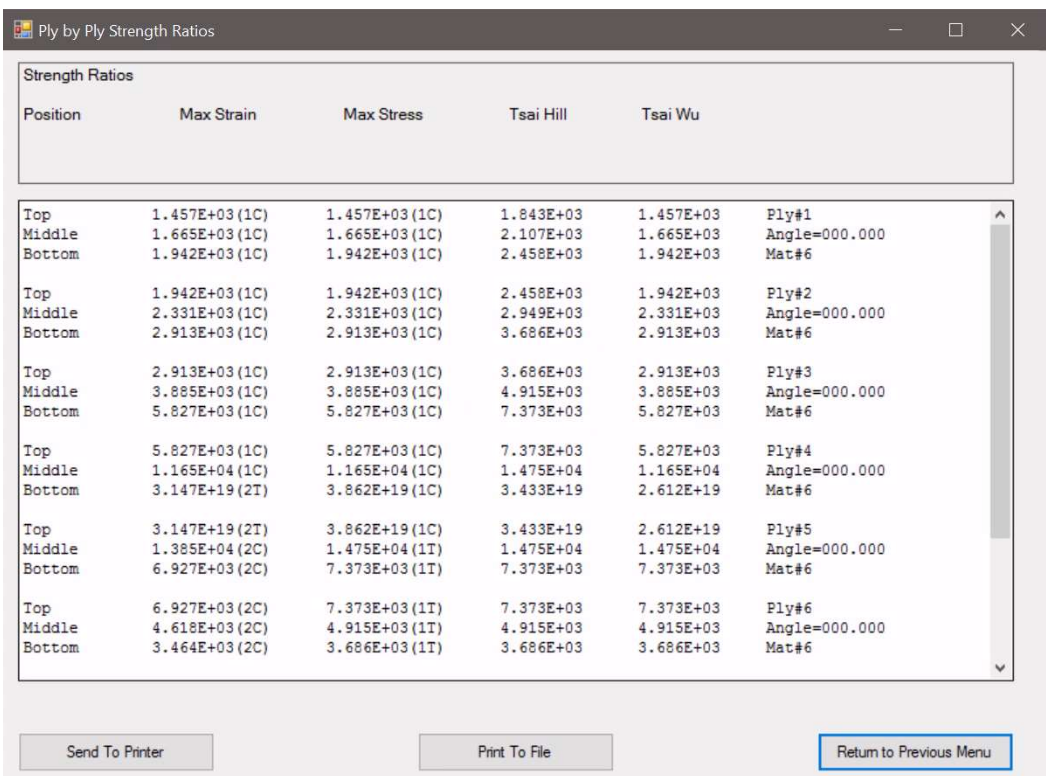
```
fprintf('The weight for a diameter of 0.875" and thickness of 0.12" is %f lbs\n',W3)
fprintf('The weight for a diameter of 1.0" and thickness of 0.25" is %f lbs\n',W4)
disp('end program')
```

11.4.2 Composites Analysis of U-Bar

List of Symbols

F = Applied force to one side of U-bar (N)
FS = Factor of Safety
I_{xx} *= Moment of Inertia About Long Axis* (mm^4)
L = Length from U-bar Central Axis to Outer Side (mm)
l = Number of Carbon Fiber Layers
M = Applied Moment to the System (N-mm)
M_x *= Applied Moment to the System Normalized by Width Along the Long Axis (N)*
$(M_x)_{fail}$ *= Bending Moment at First Ply Failure using Tsai Wu Criteria (N)*
t = Thickness of U-bar Cross Section
$t_{1\text{-}ply}$ *= Thickness of 1 Ply of Carbon Fiber (mm)*
w = width of cross section (mm)
z = Distance from Neutral Axis to the ply in failure (mm)
σ_x *= Bending Stress Along the Long Axis (MPa)*
$(\sigma_x)_{ult}$ *= Ultimate Bending Stress of U-bar (MPa)*
$(\sigma_x)_{allow}$ *= Allowable Bending Stress Considering Factor of Safety (MPa)*

Promal Program Results


Ply by Ply Strength Ratios

Strength Ratios

Position	Max Strain	Max Stress	Tsai Hill	Tsai Wu	
Top	1.457E+03(1C)	1.457E+03(1C)	1.843E+03	1.457E+03	Ply#1
Middle	1.665E+03(1C)	1.665E+03(1C)	2.107E+03	1.665E+03	Angle=000.000
Bottom	1.942E+03(1C)	1.942E+03(1C)	2.458E+03	1.942E+03	Mat#6
Top	1.942E+03(1C)	1.942E+03(1C)	2.458E+03	1.942E+03	Ply#2
Middle	2.331E+03(1C)	2.331E+03(1C)	2.949E+03	2.331E+03	Angle=000.000
Bottom	2.913E+03(1C)	2.913E+03(1C)	3.686E+03	2.913E+03	Mat#6
Top	2.913E+03(1C)	2.913E+03(1C)	3.686E+03	2.913E+03	Ply#3
Middle	3.885E+03(1C)	3.885E+03(1C)	4.915E+03	3.885E+03	Angle=000.000
Bottom	5.827E+03(1C)	5.827E+03(1C)	7.373E+03	5.827E+03	Mat#6
Top	5.827E+03(1C)	5.827E+03(1C)	7.373E+03	5.827E+03	Ply#4
Middle	1.165E+04(1C)	1.165E+04(1C)	1.475E+04	1.165E+04	Angle=000.000
Bottom	3.147E+19(2T)	3.862E+19(1C)	3.433E+19	2.612E+19	Mat#6
Top	3.147E+19(2T)	3.862E+19(1C)	3.433E+19	2.612E+19	Ply#5
Middle	1.385E+04(2C)	1.475E+04(1T)	1.475E+04	1.475E+04	Angle=000.000
Bottom	6.927E+03(2C)	7.373E+03(1T)	7.373E+03	7.373E+03	Mat#6
Top	6.927E+03(2C)	7.373E+03(1T)	7.373E+03	7.373E+03	Ply#6
Middle	4.618E+03(2C)	4.915E+03(1T)	4.915E+03	4.915E+03	Angle=000.000
Bottom	3.464E+03(2C)	3.686E+03(1T)	3.686E+03	3.686E+03	Mat#6

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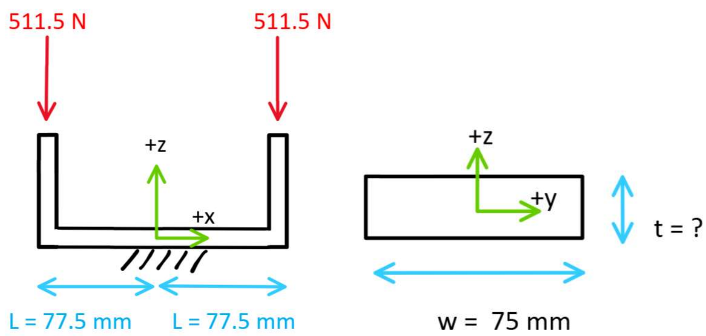
Simplified Model



Equations used to solve for number of layers

$$\sigma_x = \frac{M \times z}{I_{xx}} \tag{D1}$$

$$\sigma_x = \frac{M \times z}{I_{xx}} \tag{D2}$$

$$I_{xx} = \frac{w \times t^3}{12} \tag{D3}$$

$$z = \frac{t}{2} \tag{D4}$$

$$\sigma_x = \frac{12 \times M_x}{t^2} \tag{D5}$$

$$(\sigma_x)_{ult} = \frac{6 \times (M_x)_{fail}}{t^2} \tag{D6}$$

$$\sigma_{allow} = \frac{(\sigma_x)_{ult}}{FS} \tag{D7}$$

$$\sigma_{allow} = \frac{F \times L \times \left(l \times \frac{t_{1-ply}}{2}\right)}{w \times \left(\frac{\left(l \times t_{1-ply}\right)^3}{12}\right)} \tag{D8}$$

11.5 Appendix E: Bill of Materials

Table 16: Bill of Materials

Part #	*Part Name*	*Vendor*	*Description/Dimensions*	*Function*	*qty*	*cost/qty*	*Overall Cost*
1.1	Carbon Fiber Bottom Pylon	Rock West Composites	TUBE - ROUND - INFINITUBETW - STANDARD MODULUS - TWILL - SIZE 3 - 27.965 X 30.099 X 609.6 mm	Support weight	1	$49.99	$49.99
1.2	Carbon Fiber Top Pylon	Rock West Composites	TUBE - ROUND - INFINITUBETW - STANDARD MODULUS - TWILL - SIZE 4 - 31.75 X 33.884 X 609.6 mm	Support weight	1	$54.99	$54.99
2.1	L-Shaped/ U-Shaped Carbon Fiber Support	Rock West Composites	Prepreg carbon fiber Toray T300 3K twill weave 250F resin 1003.3 mm wide x 0.279 mm thick	Frame support	5 sqft. units	$33.79	$168.95
3.1	Cuffs	Plastics 2000	Kydex V Sheet 304.8 mm x 304.8 mm 2.997 mm thick	Leg Support	2	$3.60	$7.20
3.2	Velcro Straps	Amazon	609.6 mm x 50.8 mm Cinch Straps - 5 Pack	Leg Support	1	$14.78	$14.78
3.3	Cuffs	Plastics 2000	Kydex V Sheet 304.8 mm x 304.8 mm 2.362 mm thick	Leg Support	2	$3.30	$6.60
3.4	Cuffs	Plastics 2000	Kydex V Sheet 304.8 mm x 304.8 mm 2.032 mm thick	Leg Support	2	$3.10	$6.20
3.5	Cuff Springs	McMaster-Carr	smaller compression spring: Length of 14.986 mm, OD of 17.043 mm and ID of 13.386 mm	Secure Calf	1 pkg	$6.70	$6.70

3.6	Foam	Amazon	Neoprene Sponge Foam Rubber Roll with Adhesive 381 mm x 1524 mm x 3.175 mm	Comfortibility	1	$13.80	$13.80
3.6.1	Foam	Amazon	Neoprene Sponge Foam Rubber Roll with Adhesive 381 mm x 1524 mm x 6.35 mm	Comfortibility	1	$14.80	$14.80
4	Mounting Plate Attachment	Rock West Composites	CARBONNECT - MOUNTING PLATE KIT - ALUMINUM - FOR 25.4 mm ID ROUND TUBING	Hold system together	1	$14.99	$14.99
4.1.1	Coil Shock	Single Track Bicycle Shop	Mountain Bike Rear Coil Shock	Allows the pylon to move forward	1	$0.00	$0.00
4.1.2	Shoulder Bolt - Coil Shock	Copper State Bolts & Nuts	5/16 X 1 1/2" (1/4-20) Socket Head Shoulder Bolt Plain	Hold coil shock together	2	$0.00	$0.00
4.1.3	Lock Nut - Coil Shock	Copper State Bolts & Nuts	1/4-20 Grade C All Metal Hex Lock Nut Zinc	Hold system together	2	$0.00	$0.00
4.1.4	Coil Shock Mount	Rock West Composites	ANGLE - TWILL - 90 DEGREE SHARP - 1.50" LEGS X 0.08" THICK	Holds coil shock to the pylon	2	$3.99	$7.98
4.2	Coil Shock Compression Spring	Amazon	Forney 72667 Wire Spring Compression (10-874), 1-3/8-Inch-by-6-Inch-by-.120-Inch	Allows the pylon to move forward	1	$13.48	$13.48
5.1.1	Bearing Shoulder Bolt	McMaster-Carr	shoulder bolts : Alloy Steel Shoulder Screws 12.7 mm OD and 25.4 mm long. Thread size of 9.525 mm -16	Hold system together	4	$2.52	$10.08
5.1.2	Bearing Lock Nut	McMaster-Carr	Locknuts : 6061 aluminum threadsize of 9.525 mm -16	Hold system together	1 pkg	$4.06	$4.06
5.2	Mounting Plate Attachment Screws	McMaster-Carr	Alloy Steel Low-Profile Socket Head Screw Black-Oxide, 6-32 Thread Size, 12.7 mm Long	Hold system together	1 pkg	$9.63	$9.63

5.3.1	U-Shaped to Attachment Bolt	Copper State Bolts & Nuts	Black-Oxide Alloy Steel Socket Head Screw 12-24 Thread Size, 5/8" Long	Hold system together	4	$0.00	$0.00
5.3.2	U-Shaped to Attachment Nut	Copper State Bolts & Nuts	Low-Strength Steel Serrated Flange Locknut Zinc-Plated, 12-24 Thread Size	Hold system together	4	$0.00	$0.00
5.4.1	Chicago Bolts	McMaster-Carr	Steel Low-Profile Binding Barrels and Screws 8-32 Thread Size, for 4.763 mm - 6.35 mm Material Thickness	Hold system together	1 pkg	$11.48	$11.48
5.4.2	Chicago Bolts	McMaster-Carr	Steel Low-Profile Binding Barrels and Screws 8-32 Thread Size, for 19.05 mm - 25.4 mm Material Thickness	Hold system together	1 pkg	$11.20	$11.20
6	Bearings	McMaster-Carr	bearings: High-Load Sealed Ball Bearing with shaft diameter of 12.7 mm and OD of 44.45 mm	Allows Smooth Rotation	2	$33.42	$66.84
6.1	Chicago Bolts	McMaster-Carr	Steel Low-Profile Binding Barrels and Screws 8-32 Thread Size, for 3.175 mm - 4.763 mm Material Thickness	Hold system together	1 pkg	$10.68	$10.68
7	Bike Clamp	Amazon	Gub Bike Seat Post Clamp Tube Clip Quick Release Aluminium Alloy , 34.9mm	Pylon adjustment	1	$7.99	$7.99
8	BiOM Attachment	Hanger Clinic	Stainless Steel Attachment with 4 screws that clamps on the BiOM	Attaches the pylon to the BiOM	2	$0.00	$0.00
	Aluminum Top Pylon	McMaster-Carr	General Purpose Aluminum Tubing 31.75 mm OD, 1.651 mm Wall Thickness	Support weight	1	$26.38	$26.38
	Aluminum Bottom Pylon	McMaster-Carr	General Purpose Aluminum Tubing 34.925 mm OD, 1.473 mm Wall Thickness	Support weight	1	$34.81	$34.81
	Cuffs	Plastics 2000	Kydex V Sheet 304.8 mm x 304.8 mm 1.524 mm thick	Leg Support	2	$2.80	$5.60

Telescoping Clamp	Rock West Composites	TELESCOPING CLAMP - INFINITUBETW - SIZE 4	Pylon adjustment	1	$27.99	$27.99
Bike Clamp	Amazon	ODIER Bike Bicycle Quick Release SeatPost Clamp 34.9mm 31.8mm MTB Bike Road Bike Casual Bike Seatpost Clamp	Pylon adjustment	1	$8.29	$8.29
Chicago Bolts	McMaster-Carr	Steel Low-Profile Binding Barrels and Screws 8-32 Thread Size, for 6.35 mm - 9.525 mm Material Thickness	Hold system together	1 pkg	$11.61	$11.61
Compression Spring	McMaster-Carr	Spring-Tempered Steel Compression Spring 254 mm Long, 73.812 mm OD, 59.538 mm ID	Allows the pylon to move forward	1	$19.09	$19.09
Vacuum Bag Sealent Tape	Rock West Composites	Vacuum bag sealant tape 12.7mm x 9.144 m roll	Close the oven bags	1	$9.99	$9.99
Oven Bags	Amazon	Reynolds Oven Bags, Large, 5 ct	Carbon Fiber Lay-up	1	$8.44	$8.44
Disposable Suit	Amazon	Disposable Suit	Protection	1	$7.45	$7.45
Vinyl Gloves	Amazon	Vinyl Gloves	Protection	1	$6.45	$6.45
Zinc-Galvanized Sheet	McMaster-Carr	Zinc-Galvanized Low-Carbon Steel Sheet 609.6 x 1219.2 x 0.483 mm	To Form the Carbon Fiber	1	$19.17	$19.17

Carbon Fiber Sticker Film	Amazon	304.8 x 1524 mm 4D Carbon Fiber Black Vinyl Vehicle Wrapping Sticker Film	Provides nice appearance	1	$8.52	$8.52
Compression Spring	McMaster-Carr	302 Stainless Steel Corrosion-Resistant Compression Springs 5" Long, 1.219" OD, 0.939" ID	Allows the pylon to move forward	1	$3.53	$3.53
Compression Spring	McMaster-Carr	302 Stainless Steel Corrosion-Resistant Compression Springs 5" Long, 0.875" OD, 0.635" ID	Allows the pylon to move forward	1	$3.25	$3.25
Compression Spring	McMaster-Carr	Compression Spring 6" Long, 0.875" OD, 0.635" ID	Allows the pylon to move forward	1	$12.99	$12.99
Compression Spring	McMaster-Carr	302 Stainless Steel Corrosion-Resistant Compression Springs 5" Long, 0.75" OD, 0.54" ID	Allows the pylon to move forward	1	$11.63	$11.63
Elastic Band	Amazon	Resistance Loop Exercise Bands		1	$10.95	$10.95
Torque sensor	Transducer Techniques	TRT-500 / 500 in-lb	Future work	1	$675.00	$675.00
Aluminum Sheet	McMaster-Carr	6061 Aluminum Sheet 2.032 mm Thick, 304.8 x 304.8 mm	To Form the Carbon Fiber	1	$18.36	$18.36
					Total	**$1,441.92**
					Tax & Shipping	**$492.92**
					Sub Total	**$1,934.84**