# BIOM Test Fixture

# Midpoint Report


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# DISCLAIMER

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# EXECUTIVE SUMMARY

The current project discusses the design for a BiOM fixture. A BiOM is a fully computerized ankle-foot system, which imitates a human's lower limb, propelling the user forward with each step. The original project description provided by the sponsor is"To design an automated, programmable test fixture for the robotic prosthetic lower limb." The various customer requirements, engineering requirements and testing procedures have been outlined in the report detailing the specifics of design process, components used, cost, range of motion and durability among other aspects. Relevant research about existing BiOMs as well test fixtures has been thoroughly investigated from multiple sources. The motivation was to understand existing designs in order to learn the complexities that are integrated in the test fixture building process undertaken by our team. As part of this process, several designs (total 10) have been proposed and discussed with Dr. Tester. The pros and cons of every design have been evaluated as per the design matrix outlined in the report. Finally, an appropriate design was selection and proposed for testing. As described in the report, the various components of the design have been thoroughly evaluated and listed including the selection of hydraulic cylinder, actuator and the motor designed and selected as per the manufacturer's guidelines and recommended design guidelines. The test fixture size and material have been chosen as per the constraints placed by the design matrix. The strength of the materials and the soundness of design was validated using a finite element model that validated the design by comparing the maximum obtained stresses with the allowable stresses. The material and cross-section was chosen keeping in mind the economics of the design and the weight limits of the fixture without compromising on the strength and functional aspects of the design. The relevant details of the finite element model are provided in the appendix. The bill of materials shows details of the specific components used in the design proposed. Also, discussion and code related to programming the components as desired using Arduino has been provided.

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# 1 BACKGROUND

## *1.1 Introduction*

From medical literature, it is known that below knee amputations are among the most frequently performed major limb removals and one of the oldest surgically performed procedures [1]. Recent advances in prosthetics and orthotics hold great promise for maximizing physical function for patients who have experienced severe extremity trauma [2]. The origins of prosthesis derive from a geographic diversity of advanced civilizations such as India, Egypt, Greece and Rome. An ancient prosthetic leg in India enabled a queen to walk and return to the battlefield. Egypt developed prosthesis with the object of improving function and appearance. The Romans and Greeks advanced prosthetics for the intent of rehabilitation. In 1500's Ambroise Pare developed prosthesis resembling the modern prosthesis for lower limb. In the past decade transtibial prosthesis have been developed that function as a mechatronic robotic system [2].

BiOM® is a company that produces bionic propulsion technology for their prosthesis. This technology makes it possible for their prosthetic to have normal ankle stiffness and power during walking action. An image of the prosthetic leg using a BiOM is shown in Figure 1. The BiOM uses sensors, mechanical devices and a microprocessor chip using complex algorithm to produce power in a similar pattern as a human foot to fully replicate it and at the same time recovering 100% of the energy by propelling the prosthetic foot forward during the *stance* phase.


*Figure 1. Image of a prosthetic leg using a BiOM [3]*

The relevance of the above to the project is to eliminate the role of humans in testing phase and replace it with a test fixture to do all the testing. This requires a sound engineering design proposal that can be tested in a lab environment to achieve the desired outcome.

## 1.2 Project Description

The current project discusses the design for a BiOM fixture. A BiOM is a fully computerized ankle-foot system, which imitates a human's lower limb, propelling the user forward with each step, developed by Hugh Herr, a survivor of lower limb amputation at MIT Media Lab's Biotronic research group [4]. As part of these projects, several existing designs for prosthetic feet were evaluated based on conversation with the client and the literature survey on the Internet. Following is the original project description provided by the sponsor:

> "To design an automated, programmable test fixture for the robotic prosthetic lower limb."

A single actuator, pneumatic design was assigned for reference but the team was asked to design either for either a hydraulic or electric motor.

## 1.3 Original System

The sponsor and client for this project is Dr. Tester, who has been conducting research on the BiOM for several years testing and collecting data on its performance. Dr. Tester is also the chair of the Mechanical Engineering program at Northern Arizona University. The details of the original system are explained in the sections below.

### 1.3.1 Original System Structure

The original system structure is shown in Figure 2. It consists of a sealed sMTU (series-elastic actuator) with a transverse-flux motor, sealed ball screw and the 20J series spring.

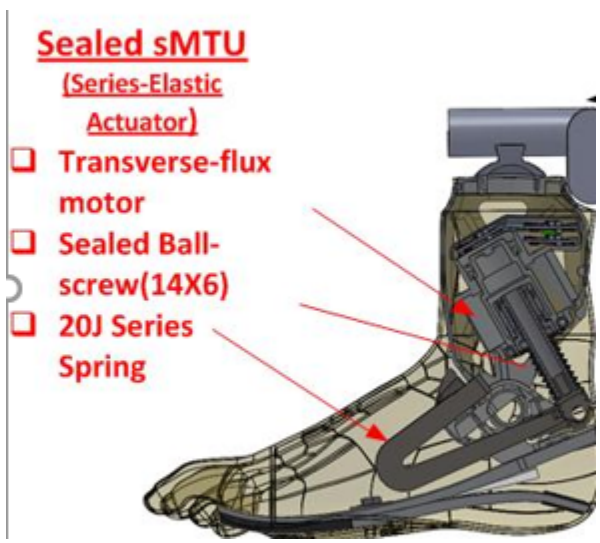


Figure 2. BiOM Ankle Architecture [5]

It also has a modular LiFePh battery, MTU Controller PCA, State Control/IMU PCA, Bluetooth and Smart Wifi.

### 1.3.2 Original System Operation

The original system of the BiOM Ankle architecture has many components including the Sealed sMTU, modular battery, MTU controller, state control, Bluetooth and wifi. It is packaged as a single, rigid flex PCA integral to sealed, direct drive ball screw actuator. The motor windings, motor position and the joint position are controlled using the MTU controller. The MTU controller is responsible for controlling the joint torque, reflex, impedance and position. It also has a neuromechanically muscle and a brushless motor driver. In addition, its shorted leads clutch model is used to save power. In terms of state control, it can control the following features – gait cycle state machine, modulation of MTU response, kinematic reconstruction, terrain discrimination, wireless communication and sMTU power management. Using the Bluetooth and wifi support, it can e used for clinical interface with a dashboard display with features of on-board data logging as well as remote logging.

### 1.3.3 Original System Performance

Measurements of the original BiOM system [6] are presented below. The measurements taken include torque, ankle angle and current plotted against the percent gait cycle. This is plotted for various terrains. In addition, to measure the performance, the cost of transport is also plotted as a function of speed.

Figure 3 shows that as the gait cycle changes the torque and angle change significantly. The highest torque and angle correspond to about 50% gait cycle. Then when the foot reaches the ground, the BiOM slows down at which point, the torque reaches zero and the angle is zero as well since its position is parallel to the ground.

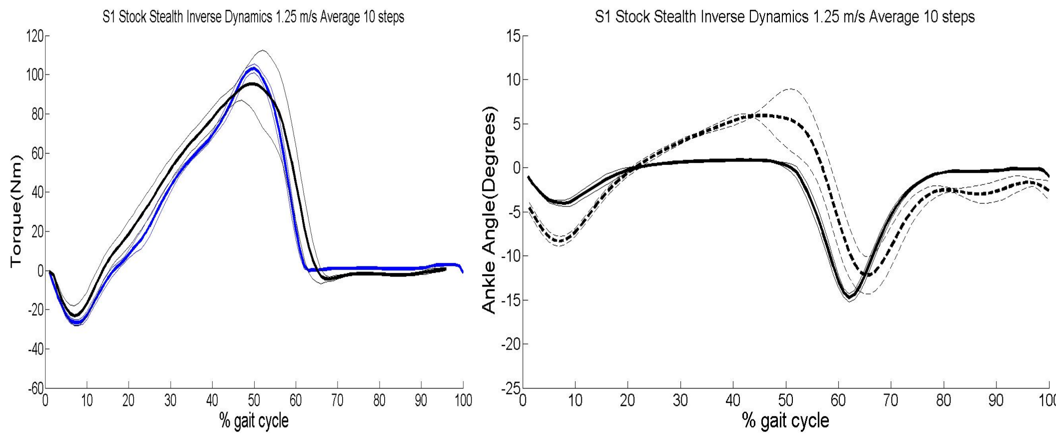


Figure 3. Torque and Ankle Angle: Stock Level Walking for 1.25 m/s [6]

Figure 4 shows that the highest current corresponds to the when the torque is the highest as well, which is expected.

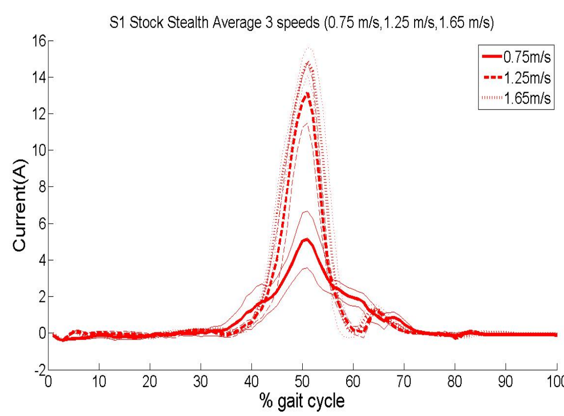


Figure 4. Current: Level Walking for 1.25 m/s [6]

Figure 5 shows good information about the transportation cost. The lowest cost occurs for a speed of 1.2 m/s and it would be best to optimize it at this speed if feasible.

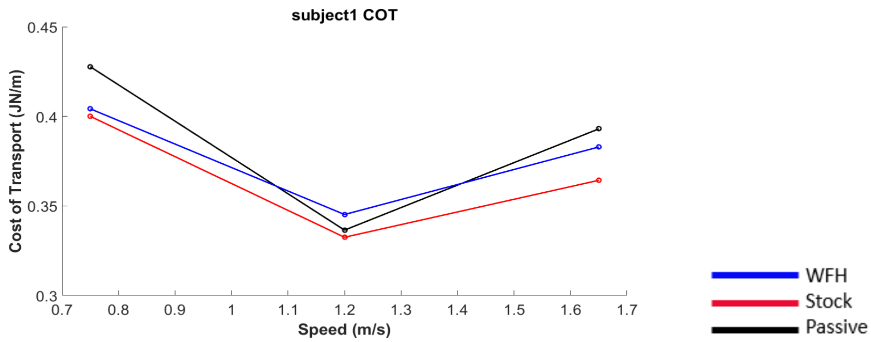


Figure 5. Cost of Transport [6]

Figure 6 and Figure 7 show the torque and angle for upstairs gait and going downstairs. As expected when climbing up since going against gravity takes additional effort, the torque is highest and the maximum is at 90% gait cycle when the prosthetic is raised at is highest position to climb up. On the other hand for the downstairs gait, the torque and angle are close to regular ground conditions.

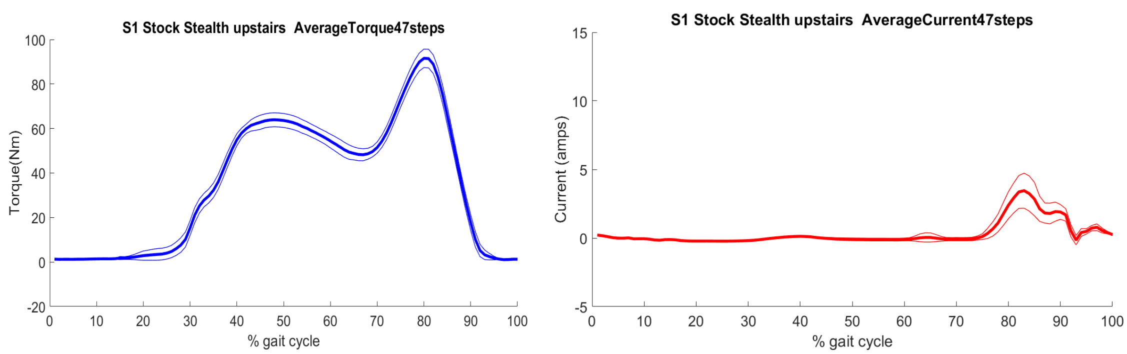


Figure 6. Upstairs: Torque and Current [6]

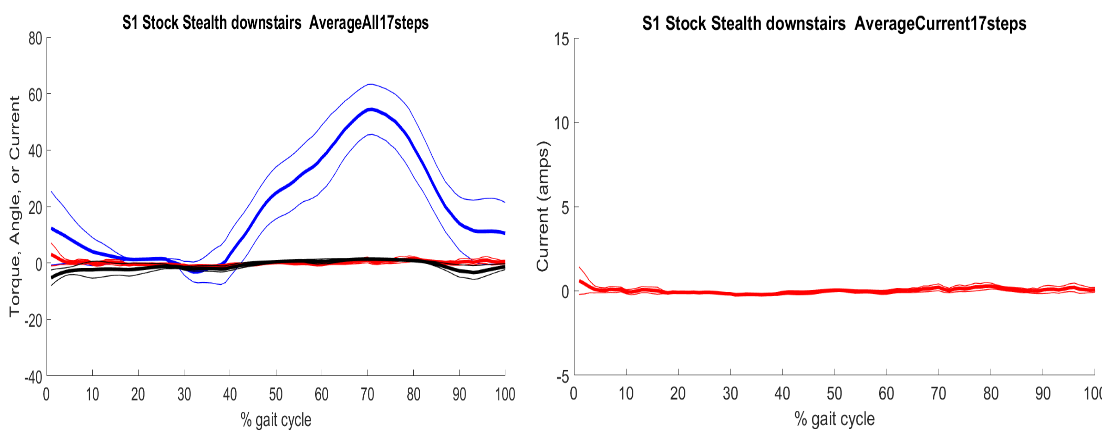


Figure 7. Downstairs: Torque, Ankle Angle and Current [6]

Figure 8 and Figure 9 show the torque and angle for grass and gravel conditions. The grass provides more cushioning and a sinking effect, so the force is more evenly spread out and the torque is lower for grass than that of gravel since gravel conditions do not absorb the impact as well as grass.

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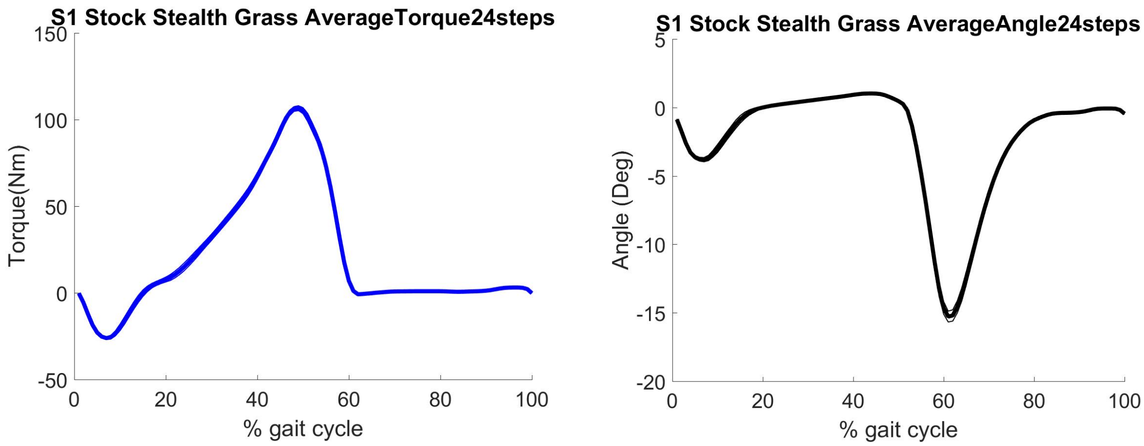



Figure 8. Grass: Torque and Ankle Angle versus % gait cycle [6]

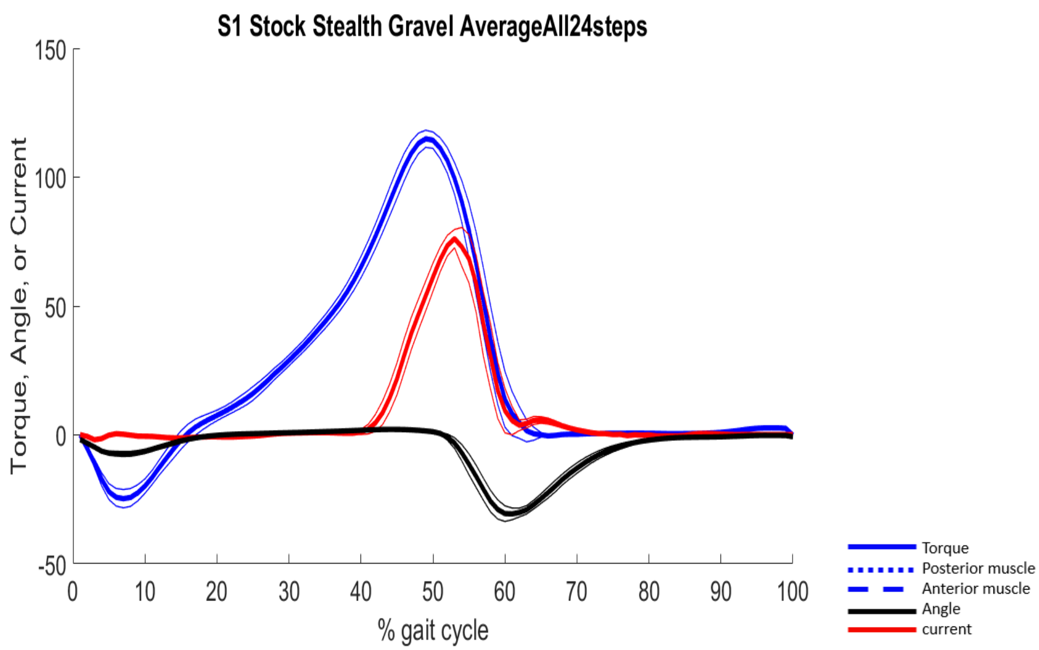



Figure 9. Gravel: Torque, Ankle Angle and Current versus % gait cycle [6]

The information from the original BiOM system, i.e, the torque, ankle angle and the current versus % gait cycle can be used to optimize the current text fixture.

### 1.3.4 Original System Deficiencies

The original system provides all the basic features necessary in the BiOM, but it only provides a planar movement. The designs produced in this lab report point to designs that are versatile in its utility and functionality, range of motion and overall design cost. Given that different clients have different customer requirements, the engineering can be different to suit the right need. The design options cover a broad spectrum varying from simple to complicated and their pros are cons are highlighted in their description.

# 2 REQUIREMENTS

In this section, data was collected from the client in order to better determine how to design for the test fixture. The customer requirements, engineering requirements, testing requirements and the house of quality details are outlined in this section.

## *2.1 Customer Requirements (CRs)*

Customer needs are goals set by the client of the project, to better clarify what they are looking for. The customer needs are then ranked based on importance on a scale from (1-5) as shown in Table 1 below.

A Test Fixture that can analyze the BiOM a prosthetic leg in a fixed and controlled environment is a primary customer requirement. In terms of the design, a good design that can work in an indoor laboratory environment (don't need to account for natural causes such as rain, wind and snow) is desired. For the functionality of the test fixture, it needs to replicate the same effects as if worn in real life. It also needs to be easy to transport and durable enough to withstand the forces acting on it over time. The hydraulic cylinder is sized as per the correct range of force desired following manufacturer's recommendations. Similarly, the pneumatic actuator is sized accordingly that couples with the hydraulic cylinder to pass the signal to it as per the Arduino controls code. The electric motor is also sized to operate the hydraulic cylinder as per manufacturer's recommendation.

*Table 1. Customer requirements set for BiOM test fixture are outlined*

| **Customer Requirement** | **Importance Rating (1 – 5)** |
|---|---|
| Test Fixture | 5 |
| Design | 5 |
| Functionality | 5 |
| Transportation | 1 |
| Durability | 4 |
| Hydraulic cylinder | 3 |
| Pneumatic Actuator | 2 |
| Electrical Motor | 1 |

## 2.2 Engineering Requirements (ERs)

Engineering requirements are set with the help of the customer needs by converting them into a scalable engineering requirement that can be tested for. The ERs and the specifications are listed in Table 2 below.

The size of the test fixture is an important requirement and needs to be as per the target specification to allow for optimal testing space. Calculations determine the sizing of the test fixture in all three dimensions. The time needed for testing is as per the testing procedure. The different types of planes for testing as discussed with Dr. Tester will be for flat ground level testing. The weight of the device and its material are factors that have been given much though and the recommendations for the material have been provided based on budget constraints keeping in mind that the total cost of the device needs to be less than $500. The hydraulic system is designed based on manufacturer's recommendations. The device responds like a foot for 2 degrees of freedom providing variation and flexibility.

*Table 2. Engineering Requirements set for BiOM test fixture are outlined*

| Engineering Requirement | Target Specification |
|---|---|
| Size | 80 cm x 40 cm x 35 cm |
| Time needed for testing | 15-25 minutes |
| Types of planes for testing | $0^{o}$ , level ground testing |
| Weight | <= 15Kg, 33lbs |
| Material | Carbon Fiber, Titanium and Aluminum<br>Withstand force of 200 Kg |
| Hydraulic system | 90 psi |
| A system able to respond exactly like a particular foot | Up to 2 degrees of freedom |

| | |
|---|---|
| Cost | <=500$ |

## 2.3 Testing Procedures (TPs)

Testing procedure explains how the engineering requirements set for the BiOM Test Fixture will be met. These TPs are details in Table 3 below.

*Table 3. Testing Procedures set for BiOM test fixture are outlined*

| Engineering Requirement | Specification | Testing Procedure |
|---|---|---|
| Size | 80 cm x 40 cm x 35 cm | Tape Measure |
| Time needed for testing | 15-25 minutes | Stop Watch |
| Types of planes for testing | $0^{\circ}$ , level ground testing | Protractor/Angle caliper |
| Weight | <= 15Kg, 33lbs | Newton Meter/Electronic scale |
| Material | Carbon Fiber, Titanium and Aluminum<br>Withstand force of 200 Kg | Hardness and Beam Deflection test in lab |
| Hydraulic system | 90 psi | Pressure Sensor |
| A system able to respond exactly like a particular foot | Up to 2 degrees of freedom | Visually |
| Cost | <=500$ | Receipts from purchases |
| | | |

## 2.4 Material and dimensions of BiOM test fixture using Bentley Autopipe

The dimensions of the selected design are detailed in Section 5. The frame for the test fixture will be fastened with screws that are designed to withstand the corresponding static and dynamic loads of the test fixture. The forces (static and dynamic) from the hydraulic piston representative of the weight of the person during testing determine requirement of the width (diameter) and material requirements. This is thoroughly analyzed using the stress analysis software (Bentley Autopipe) and the material and the diameter of the BiOM legs are selected accordingly in the test fixture. The diameter is optimized by varying the diameter as a parameter and analyzing if the fixture is able to sustain the stresses or not. The lowest diameter that succesfully meets the requirements is selected. Materials of stainless steel, aluminum and carbon fiber are proposed. Environment factors such as rusting and appearance are factors, but cost is also a big motivation to keep our design within budget. The details of selection are provided in Section 5.

## *2.5 Hydraulic Cylinder selection using Online Catalogues /Manufacturer Software*

It is important to selection the hydraulic cylinder for the test fixture based on engineering design. The hydraulic cylinder is the medium to replicate the weight of the person utilizing the BiOM. Both static and dynamic forces are accounted for which are discussed in Section 2.3.1.

The complete details of the procedure used for the section of the hydraulic cylinder are outlined in results section of Section 6. Following this procedure, the datasheet for a selection product (Part number: 577198) for hydraulic cylinder is shown in Appendix C, Section 8.3. As per the datasheet, the theoretical force of the selected hydraulic cylinder is between 2827 N and 3016 N at a working pressure of 6 bar. Further details are in the data sheet presented in the appendix.

## *2.6 Dimensions of the frame for BiOM text fixture*

The dimensions of the fixture are based on the length of the BiOM also taking into account the length of the hydraulic cylinder. In the computer model used to analyze the stresses, the hydraulic cylinder used to replicate the weight of the person is modeled as a concentrated force. However, in the fixture, the length of the hydraulic cylinder needs to be accounted for in determining the dimensions of the fixture. Assume X, Y and Z represent the horizontal, vertical and lateral dimensions of the fixture. The length of the BiOM in the model as described earlier is 27 inches.

A hydraulic cylinder of size 125 mm is sufficient for the current case to exert a force in the range of 1.1 kN to 100 kN based on [14], which is relevant for our case. Assume the length of the hydraulic cylinder to be 3 times its diameter. Hence the length of the hydraulic cylinder is 375 mm or 0.375 m (15 inches). Hence the total diagonal length of the fixture is 27+15=42 inches. The angle of the BiOM is 45 degrees. Hence, the dimension of X, Y and Z is $\frac{42}{\sqrt{2}}$=29.7 inches. Allowing some tolerance for miscellaneous connections, the dimension of X, Y and Z is expected to be between 30 and 35 inches.

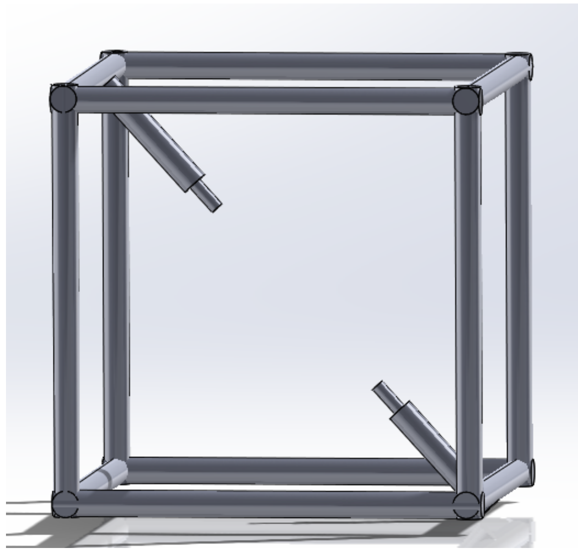


*Figure 10. CAD Model of the body frame to which the BiOM test fixture is attached*

## 2.7 House of Quality (HoQ)

House of Quality is a diagram that shows the relationship between customer needs and the engineering requirements as detailed in Table 4 below.

*Table 4. House of Quality is outlined below*

| Customer Requirement | **Weight** | **Engineering Requirement** | size ( 80x40x35 cm) | time needed for testing(15-25 minutes) | types of planes for testing | Weight (<= 15Kg, 33lbs) | Material ( Carbon Fiber and Titanium offer lower weight, Aluminum ) | Hydraulc system ( 90 psi ) | A system able to respond exactly like a particular foot | Cost ( <500$) | Rotation | Torque |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.A Test Fixture that can analyze the BiOM a prosthetic leg in a fixed and controlled environment | 5 | | 3 | 3 | 3 | 3 | 9 | 9 | 9 | 3 | 9 | 9 |
| 2. A good design that can work in an indoor laboratory environment | 4 | | 9 | 1 | 3 | | 3 | | | 1 | | |
| 3.can replicate the same effects as if worn in real life | 4 | | | 9 | 3 | 9 | 3 | 3 | 9 | | 9 | 9 |
| 4. Easy to transport | 2 | | 3 | | | | | 1 | | | | |
| 5. durability, needs to with stand forces over time | 3 | | 1 | 9 | | 9 | 9 | | 3 | 1 | 1 | 1 |
| 6. elctric motor or hydraulic system | 1 | | | 1 | | 3 | | 9 | 3 | 9 | 9 | 9 |
| 7. Frame that doesn't obstruct the battery for the BiOM | 3 | | 9 | 1 | | 3 | 1 | | | | | |
| **Absolute Technical Importance (ATI)** | | | 87 | 86 | 39 | 117 | 99 | 68 | 93 | 31 | 93 | 93 |
| **Relative Technical Importance (RTI)** | | | 4 | 5 | 7 | 1 | 2 | 6 | 3 | 8 | 3 | 3 |

The customer needs and engineering requirements are outlined in this table and a weightage is associated as shown in the table to each item. As shown, emphasis for customer requirement in terms of weight is for a test fixture that can analyze the BiOm in a fixed and control environment. Similarly, for different engineering requirements, the weightage is as shown in the table. Based on the different weightages, the absolute and relative technical importance of the requirement is found. Thus, the house of quality is an important tool is assessing the relative importance of various components of the design.

# 3 EXISTING DESIGNS

In this section, several existing designs found and studied in the literature are presented that are similar to the re-engineered design adopted by our team. The basic research surrounding the BiOM is briefly discussed before delving into the specific existing designs. The characteristics of the prosthesis itself are directly influenced by the gait of the patient. Previous gait analysis has shown that when walking, a sound ankle produces substantially more work than any other joint of the lower limbs and hence the replacement of the power generation at the ankle is one of the biggest challenges in replicating no pathological gait by means of prosthesis [6]. These challenges can be addressed through advances made in the field of robotics and mechatronics. Before delving into specific designs, a broad overview of the classification of today's prosthetic feet is presented in Figure 11.

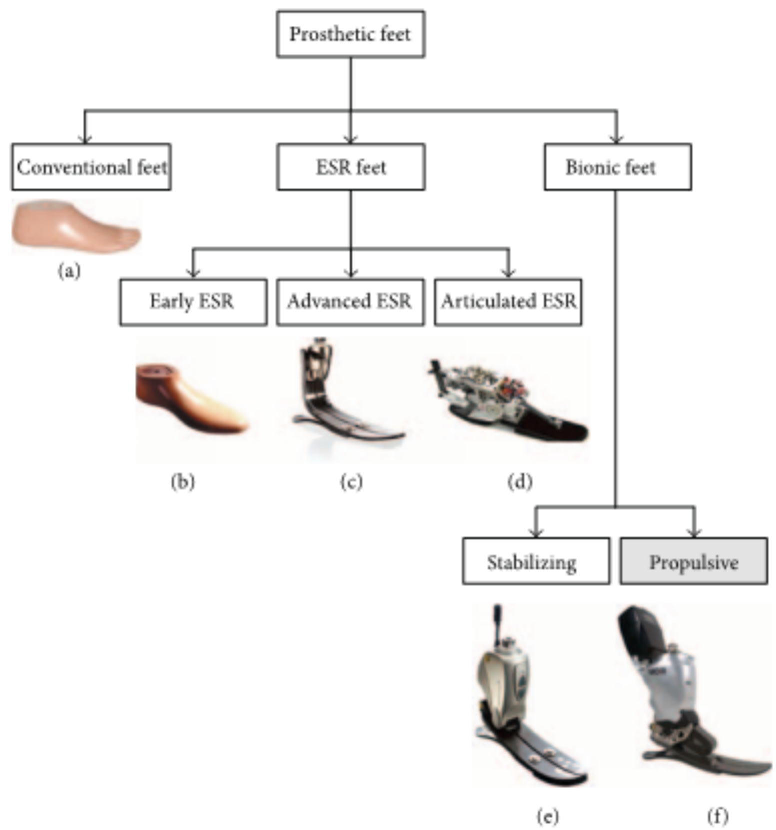



*Figure 11. Categorization of today's prosthetics showing (a) SACH foot, (b) SAFE foot, (c) CESR foot, (d) Ossur's Flex-Foot, (e) Ossur's Proprio Foot, and (f) Walk's Powerfoot BiOM*

As shown in Figure 11, the prosthetic leg can be broadly categorized either as conventional feet, ESR feet and Bionic feet. The ESR feet can be sub divided into early EST, advanced SRY and articulated ESR. Then the Bionic feet can be subdivided as Stabilizing and Propulsive feet.

Our interest in this report falls under the category of Bionic feet. Specifically, the bionic feet is defined as a mechanical device with one or more active components used either for stabilization of the foot or to provide active push-off properties that is worn by an individual

Most of today's commercialized powered transtibial prosthesis use actuation to provide stabilization of the ankle-foot complex. Examples are Motion and Raize Foot (Fillauer), the Elan foot (Endolite), and the Proprio Foot (Ossur) [1]. This kind of prosthesis uses either hydraulic or electric actuation to provide natural ankle kinematics.

## 3.1 Design Research

The specific area related to our design is related to the propulsive bionic feet. The propulsive ankle-foot prosthesis can be categorized based on their actuation method as follows:

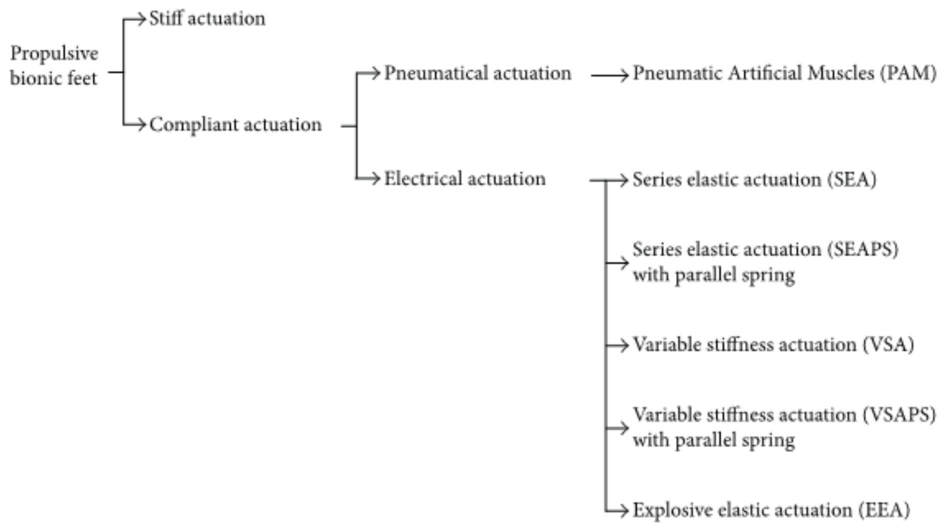



*Figure 12. Categorization of propulsive bionic feet based on actuation method [1]*

As shown in Figure 12, based on the actuation principle, a primary distinction can be made between ankle foot prosthesis powered with stiff or compliant actuation. The compliant actuators can be divided as either pneumatic or electrical. Depending on the stiffness, the electrical actuation can be further subdivided into four categories – series elastic (SEA), series elastic with parallel spring (SEAPS), variable stiffness (VSAPS) and explosive type (EEA).

It is interesting to note why researchers have opted for one of the other, i.e., a pneumatic actuator or an electric actuator. Pneumatic actuators originally were chosen because of their design and setup corresponds best to the musculoskeletal structure and properties of human beings. This explains why these actuators are generally called pneumatic artificial muscles. On the other hand, the electrically driven actuators have the advantage of reducing the power requirements of the driver resulting in smaller, less heavy and cheaper actuation setup.

The classification of bionic feet as discussed above provided an important starting point for our design on fixtures since the principles behind the activation of various components and the relation between different components of design were discussed in such great detail unfolding the layer of complexity that is essential to understand to design the fixture for this project.

## 3.2 System Level

Some of the existing designs that were found in the literature are listed in this section and described in addition to benchmarking them based on custom criteria.

### 3.2.1 Existing Design #1: Simple Test Fixture at Northern Arizona University (NAU)

The first research for this project was around the research done at NAU to design a simple test fixture for a powered foot ankle prosthesis.

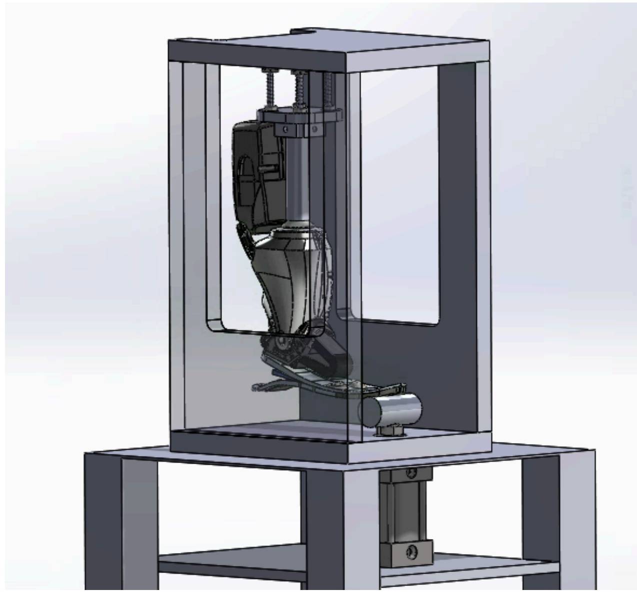


*Figure 13. Design of a simple test fixture by Northern Arizona University [8]*

A single displacement step function is used as input to the system. The maximum force required to stimulate powered plantar flexion was obtained from past experiments with subjects. A pneumatic piston actuator was used that was double action, controlled by single solenoid valve that can simulate toe off reaction. Compliant pylon connections used absorbed transverse and normal forces. The expected results were to record repeatable output for all five stages of walking for various parameters such as weight of the subject, foot size and the length of the limb.

### 3.2.2 Existing Design #2: SPARKy project of Arizona State University

As discussed in the research by Caputo et al [9] on human locomotion, the SPARKy project started at the Arizona State University that uses a robotic tendon actuator (including a 150 W brushed DC motor) to provide 100% of the push off power required for walking while maintaining intact gait kinematics. The first prototype (SPARKy-1) as shown in Figure 14, was shown to store and release approximately 16 J of energy per step, while an intact ankle of 80 kg subject at 0.8 Hz walking rate needs approximately 36 J. The second prototype SPARKY-2 was built with a lighter and more powerful roller screw transmission and brushless DC motor. Both designs on SEA attached between heel and leg. This robotic tendon is controlled to provide the ankle torque and power necessary for propulsion during gait. The third prototype SPARKy-3 was designed to actively control inversion and eversion as well as plantar flexion and dorsiflexion while providing high power for running and jumping. This research led to the development of the powered prosthesis ODYSSEY and JackSpring, both available commercially.

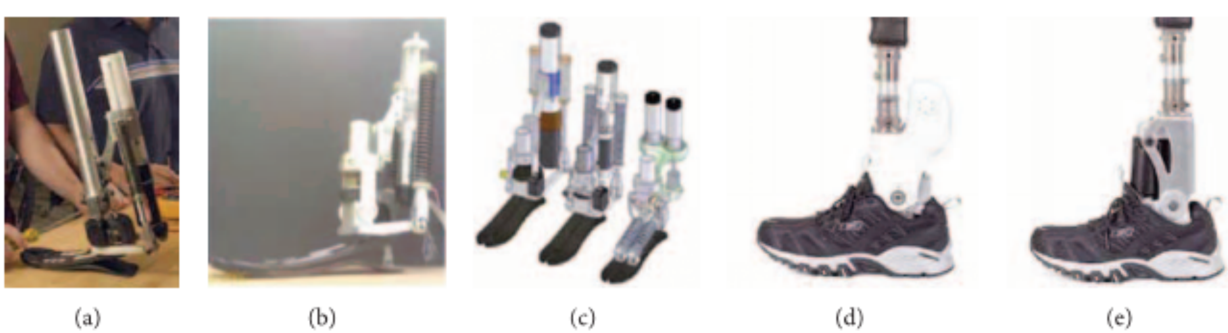



*Figure 14. Ankle foot prototypes of SPARKy project developed by Arizona State Univeristy, USA.*

*a) SPARKy-1, (b) SPARKy-2, (c) SPARKy 1, 2 and 3 (d) ODYSSEY and (e) JackSPring [9]*

### 3.2.3 Existing Design #3: Tethered Fixture by UCL-Belgium

Researchers at UCL-Belgium (Universite Catholique de Louvain) were inspired by the SPARKy project at ASU, and built a 2-degree of freedom (DOF) TT prosthesis. The research by Cherelle et al [1] discusssd the actuation principles of bionic devices and how they can be applied to test fixtures in great details. On their research on SPARKy, their design consists of a series of springs in the foot with a motor assembly and a 2-DOF ankle joint as shown in Figure 15. The BiOM required a power of 60 W. A 120 W Maxon EC powermax 22 with a 4.8:1 reduction and ball screw assembly was chosen to fulfil the requirements of the ankle-foot prototype. The intent was to develop a new control strategy based on adaptive oscillators.

*Figure 15. Tethered prosthesis developed by Carnegie Mellon University, USA [1]*

## *3.3 Functional Decomposition*

The functional decomposition of the design is described in this section with the details in the following subsections.

### 3.3.1 Black Box Model

In order to get a quantitative estimate in understanding prosthetic feet, we can look into the research by winter [10]. As an example, if we consider a subject walking at normal cadence produces a peak torque at the ankle join of approximately 1.6 Nm/kg in a very small amount of time (+/- 0.2 s for a walking rate of 1 step/s), consuming herby on average 0.35 J/kg of mechanical energy per step, then, the generated power at push off reaches 3.5 to 4.5 W/kg. Assuming 75 kg as the weight of the subject, the maximum torque output of approximately 120 Nm is required with a power output between 250 and 350 W. This can be an approximate criterion for the development of propulsive devices. These parameters to validate the selection and validate of our proposed selections for the hydraulic cylinder and the BiOM engineering analysis model results proposed for our test fixture. This is discussed in greater detail in Section 6.3.

The figure below shows the generic inputs and outputs that need to be roughly accommodated for.


*Figure 16. BiOM test fixture Black Box Model*

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

The functional decomposition of the BiOM design under consideration are discussed under the following categories:

a. Engineering Requirements
b. Robotics
c. Mechatronics

The engineering requirements define the criteria and the requirements for the design that provide the basis and inspiration for the design. The robotics and the mechatronics are the other two important components of design of BiOM that are closely integrated. The brain of the BiOM is the mechatronics that uses complex algorithms to achieve the necessary movements, but the actual movements are not possible without the robotics or the mechanical devices that are controlled by the algorithm. The feedback loop of the control system that connects the sensors that provide input to the microprocessor and the mechanical devices such as the actuator is a complex one.

## *3.4 Subsystem Level*

The requirements relevant to the current project are discussed in this section in reference to the existing designs.

### 3.4.1 Approach:

The design approach used in the existing designs can greatly help the project to understand and implement lessons already learnt from existing research. The approach to the design is the first step in getting a holistic understanding of the project and it is important to rule out any fatal flaws in the beginning of the project if possible than to find out at the end. The existing projects will help in this respect.

#### *3.4.1.1 Existing Design #1: Tethered Prosthesis by CMU*

The approach used by the existing design by CMU incorporates testing the BiOM by a human wearing it and walking on the treadmill. In the current design proposed and selected (Design-1), there is option of using the frame with a hydraulic cylinder or connecting a sleeve to the screw to be worn by the human. So, the testing platform and approach is similar to our design.

#### 3.4.1.2 Existing Design #2: SPARKy Project at ASU

The first prototype built by ASU SPARKy-1 was shown to store and release approximately 16 J of energy per step, while an intact ankle of a 80 kg subject at 0.8 Hz walking rate needs approximately 36 J [1]. The main approach used was to put forward simplicity over functionality to build a workable prototype. This paid off because they were able to eventually increase functionality in their follow up designs.

#### 3.4.1.3 Existing Design #3: Tethered Prosthesis by UCL-Belgium

The approach used by the tethered prosthesis by UCL-Belgium is actually the missing link between the SPARKy-2 and SPARKy-3 projects similar to the approach taken in the current design.

*Figure 17. Ankle Prosthesis prototype developed by UCL-Belgium [1]*

### 3.4.2 Subsystem #2: Control

The overall functionality of the design is the most crucial part of the design. Existing research provides a great deal of information of the controls used in the literature. Although the application of the controls may be different for the current project, it is always possible to use the existing controls and even improve them for our purpose to improve their functionality.

#### 3.4.2.1 Existing Design #1: Tethered Prosthesis by CMU

The tethered prosthesis by CMU incorporates ankle joint and a carbon fiber strut as shown in the figure below. There is also a series spring that connects to the cable drive. In the current design a hydraulic cylinder takes its place. Overall, the controls used by CMU are similar to the currently proposed design.

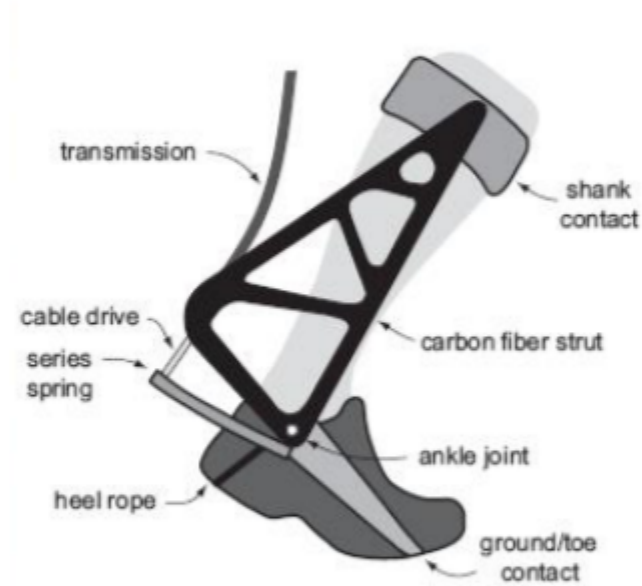



*Figure 18. Schematic of exoskeleton used by CMU [10]*

#### 3.4.2.2 Existing Design #2: SPARKy Project at ASU

The SPARKy project at ASU uses a robotic tendon actuator to provide 100% push off power while walking to maintain intact gait kinematics. The current design incorporates a hydraulic cylinder in its place and achieves the same purpose.

#### 3.4.2.3 Existing Design #3: Tethered Prosthesis by UCL-Belgium

The tethered prosthesis by UCL-Belgium borrows ideas from the SPARKy project and it incorporates an arrangement of springs in the foot in series. The current design uses a hydraulic cylinder in its place. But during the development stage, depending on the measurements taken for gait, if an improved design is needed, out team has some basis to fall back on.

### 3.4.3 Strategies:

The strategies are ideas that make the project original. If the right strategy is used, even a seemingly simple design can prove to be quite effective. The literature survey provides strategies that have worked but they also show what strategies have not worked. Possibly by changing the way they were implemented earlier, we can use some of the effective strategies to work for us to design a new system since part of the brainstorming is to take a fresh look at current ideas and improve them.

#### 3.4.3.1 Existing Design #1: Tethered Prosthesis by CMU

The strategy used by CMU is to emulate a universal ankle-foot exoskeleton [11]. Since the design is a simple one, implementation is easy. Our strategy is also similar where the design selected among the proposed designs is the one that is easy to build that has a fine balance between functionality and constructability.

#### 3.4.3.2 Existing Design #2: SPARKy Project at ASU

The strategy used by the SPARKy Project at ASU is to keep the design simple to and compromise versatility to be able to build a simpler prototype faster. Using a series of simple designs they were able to eventually launch the commercial products ODYSSEY and JackSpring, now available in the market.

#### 3.4.3.3 Existing Design #3: Tethered Prosthesis by UCL-Belgium

The strategy used by UCL-Belgium is to study existing designs and fill in the gaps. Thus, the design they have used is the missing link between SPARKy-2 and SPARKy-3 developed by ASU. Thus, it is important to study the current designs to improve upon them. This is the same strategy the current design is adopting as well.

# 4 DESIGNS CONSIDERED

After investigating the designs available in the literature and brainstorming the pros and cons of the existing designs that are rated using custom benchmarking, our team has come up with the following designs. The sketches of the designs are provided in this section and explained.

## *4.1 Design #1: Featuring Versatility and Innovation*

Design-1 focused in this section are targeted towards providing emphasis such that it is versatile and innovative.

The design as shown in Figure 19 consists of a text fixture body frame attached with a hydraulic cylinder connected to the BiOM that acts as human weight. This replicates the forces exerted by the human on the prosthetic leg. The prosthetic itself consists of another hydraulic cylinder connected to the BiOM microprocessor and attached to the carbon fiber leg. A battery attached to the prosthetic supplies the power to the device. It contains a cloth sleeve to attach to the human leg and a screw that connects to the BiOM.

Pros of the Design: 1) the carbon fiber leg is lightweight and has great strength and thus can support a larger weight. 2) It is also flexible so as to distribute the forces evenly to the ground when the foot touches the ground when the BiOM is required to slow down. 3) During the stance phase, the electric battery that supplies power to the hydraulic cylinder is able to lift the lightweight carbon fiber leg with ease.  4) The design also has a cloth sleeve that has durable cushioned material that attaches to the human leg and provides a snug and comfort fit by distributing the forces at the contact point. 5) The dual hydraulic cylinder design provides 2 degrees of freedom.

Cons of the Design: 1) although two hydraulic cylinder provides two degrees of freedom improving the functionality of the prosthetic, the ball and socket motion of the ankle cannot be replicated here. 2) The battery limits the power, but that is true for any power prosthetic leg. It is important to optimize the power requirement during the testing phase.

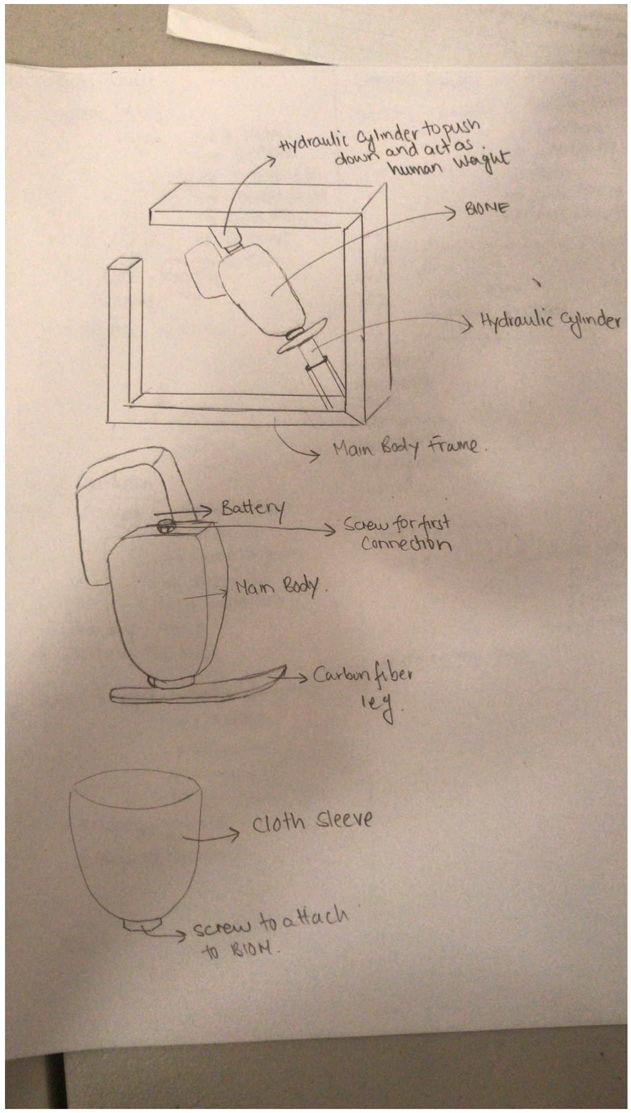



*Figure 19. Design-1 considered by the team*

### *4.2 Design #2: Featuring calibrated mechanical device force bag*

The next design-2 shown in *Figure 20* consists of the text fixture where the BiOM is connected to a robot instead of a human for testing. A forces bag is attached to the prosthetic to enable motions in calibrated directions. The bottom of the leg is connected to a metallic leg that provides pivoting motion in a single plane.

PROS: 1) In the testing environment, instead of connecting the prosthetic to a frame as in the earlier design, in this design the robot is independent to provide the forces replicating the forces exerted by the human leg. 2) The forces bag consists of mechanical devices that provide motion as calibrated by integrating with the BiOM. This flexibility provides motion in multiple directions. 3) The motion of the leg itself is pivoted at the bottom, so it helps with providing flexibility of the leg motion.

CONS: 1) Depending on the number of calibrations performed to the mechanical devices in the force bag, the force bag can get bulky with improved functionality. 2) The base of the foot is restricted to a planar motion although it does allow motion and provides flexibility.

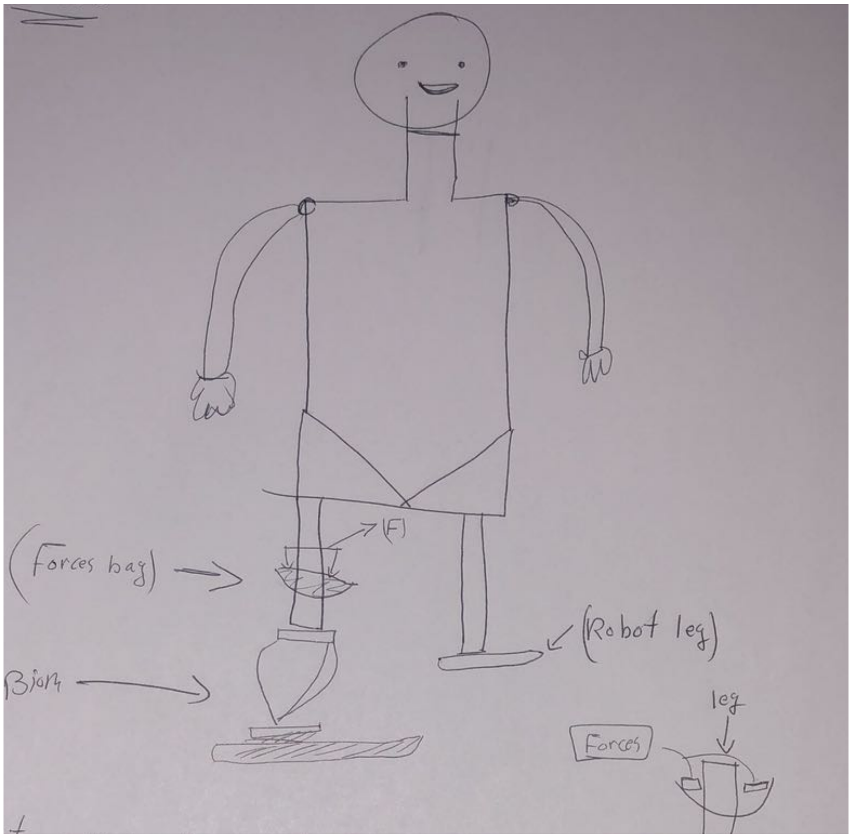



*Figure 20. Design-2 considered by the team*

## *4.3 Design #3: Featuring Multitasking and functionality*

The next design shown in Figure 21 selected is similar to the previous design, but is very unique. This is a multi-test device that is connected to two BiOM that work in unison when needed but can also work independently. The inspiration for this design comes from the octopus leg that can multitask at the same time.

PROS: 1) The success of this design depends on the algorithms that are used to integrate the two BiOMs providing the best functionality to the prosthetic. So, it can be very versatile 2). The multiple legs provide stability that is much needed in uneven terrain 3). Also, the contact with the ground can be adjusted to distribute the forces in such a way that the balance is maintained while the force is distributed. 4) The legs are also capable of rotation a neck of the connection that allows changing the position of the legs if needed. 5) The length of the legs and the connector can be adjusted during testing to provide optimal performance.

CONS: 1) The integration of two BiOMs can make programming the microprocessor very complicated and the testing can be a challenge 2) Since the primary motion of the legs is vertical and rotational, although the carbon fiber leg provides flexibility, it is still restricted in motion, but very well capable of providing the balance needed.

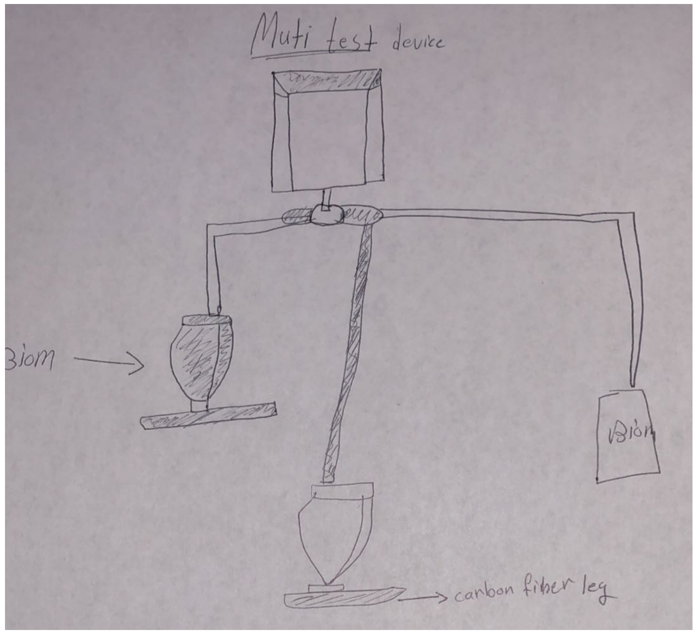



*Figure 21. Design-3 considered by the team*

## 4.4 Design #4: Featuring smart device

The next design shown in *Figure 22* is a smart device that is located in the BiOM leg. This design is similar to a regular BiOM but the smart device is programmed to provide additional functionality to the microprocessor design to measure the torque, speed and design. An octopi and how we can test more than one BiOM at the same time inspired the design.

PROS: 1) It is equipped with sensors to interact with the surroundings so that information can be processed by the smart device and integrated with the BiOM to optimize the motion of the loop. 2) This device needs training since the smart device can be trained to perform well using Artificial Intelligence (AI) with every use. This unique feature of this design will also allow integration with the smart devices (e.g. Phone) that the patient is carrying. 3) The device can be customized to the patient's needs. If a different patient uses the same prosthetic, a different mode in the smart device can be selected to suit the patient. Thus, the versatility of the design is in not only in improved functionality through use of AI but also provides multiple modes for different patients.

CONS: 1) Since this design integrates the BiOM microprocessor with the AI, initial learning and integration can be very challenging 2) The design itself is a simple design but the range of motion may be lacking that can be compromised by the functionality

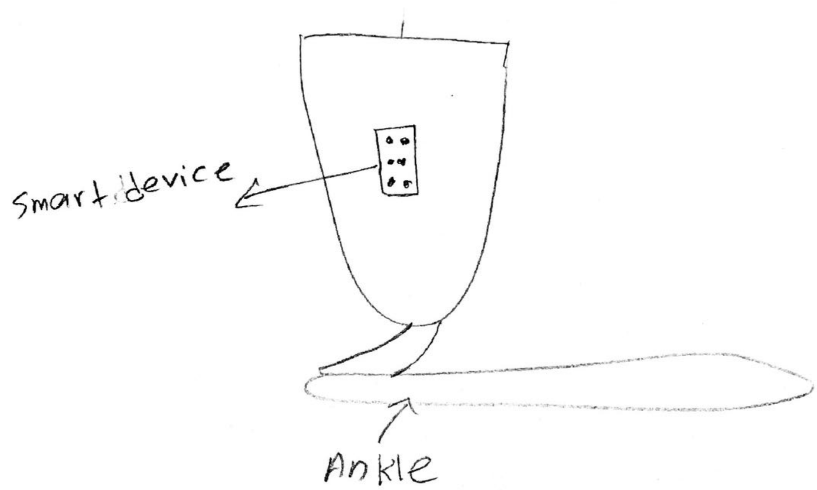



*Figure 22. Design-4 considered by the team*

### 4.5 Design #5: Featuring robustness

The next design shown in *Figure 23* considered by the team consists of an assembly of springs connected to the prosthetic that is integrated with the design. The intent of this design is robustness where the patient can use the leg to run, jump, swim and lead a normal life. In contrast to the previous designs, since this design is focused on extreme motions such as jumping, it incorporates springs that act as shock absorbers that can distribute the impact forces due to an impulse.

PROS: 1) Robust design suited for rugged terrains, increased load and impact forces 2) The springs not only add comfort but also help with balance in uneven terrains 3) Allows physical activity to the patient

CONS 1) since the design is focused on robustness, the range of motion and functionality of the leg itself may be slightly compromised

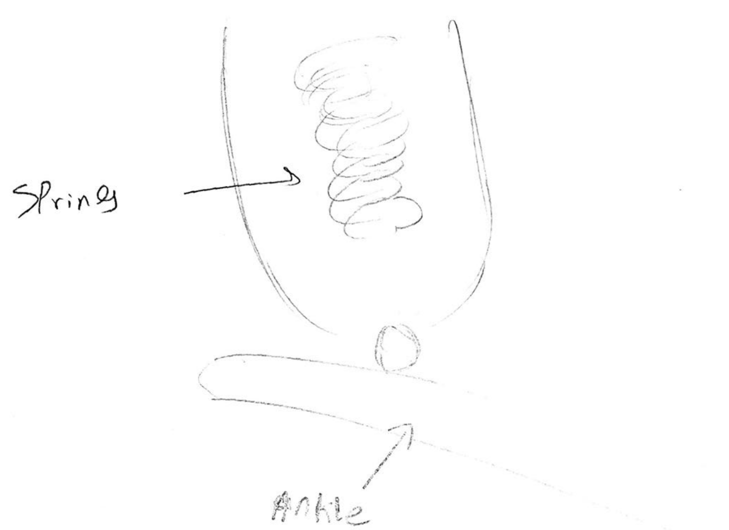



*Figure 23. Design-5 considered by the team*

## 4.6 Design #6: Featuring Range of Motion

The designs focused in this section target a range of motion as well as an integrating automation with manual control.

In this design shown in Figure 24, the focus is on the range of motion for the prosthetic. This design consists of a motors connected to the body of the prosthetic integrated to the BiOM. The bottom of the prosthetic consists of a ball and socket joint replicating the human ankle. The design leans towards providing a more natural gait and a range of motions for maximum flexibility in finer motions.

PROS: 1) The ball and socket joint replicates the human ankle and provides smooth three-dimensional motion (3 DOF). 2) The strength of the design is its simplicity where the number of parameters that need to be optimized when integrating with the BiOM is reduced because of the fewer components.

CONS: 1) The device may be restricted in terms of strength and impact forces it can withstand, but that can be found only during testing 2) Controlling the pivot motions perfectly requires graduated motions in multiple directions that challenges the mechanical integrity of the ball and socket joint

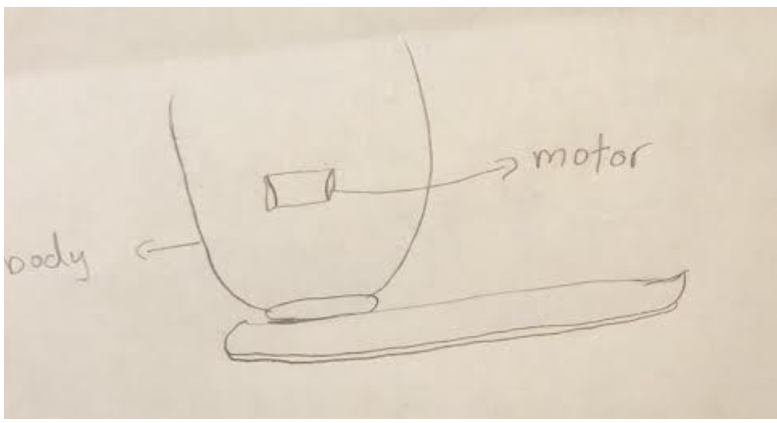



*Figure 24. Design-6 considered by the team*

## 4.7 Design #7: Featuring integration of manual control with optimal automation

The next design shown in Figure 25 consists of a lever that is attached to the prosthetic leg that is connected to the BiOM. This unique design takes the load off of the BiOM microprocessor to some degree. The function of the lever is to quickly adjust the position of the leg by manually controlling it while the prosthetic leg is not in motion. When the leg is in motion, the controls of the BiOM microprocessor take into effect by easing the motion and recovering the energy exerted by the foot.

PROS: 1) The combination of the BiOM and the mechanical lever provides greater control and adaptation to the patient's taste. 2) This design can help reduce the cost of the device at the same time giving some level of control to the user as opposed to being completely automated

CONS 1) The lever may require maintenance and if the functionality of the mechanical lever is compromised then the full-fledged functions of the BiOM cannot be used, 2) The aesthetics of the prosthetic can be compromised

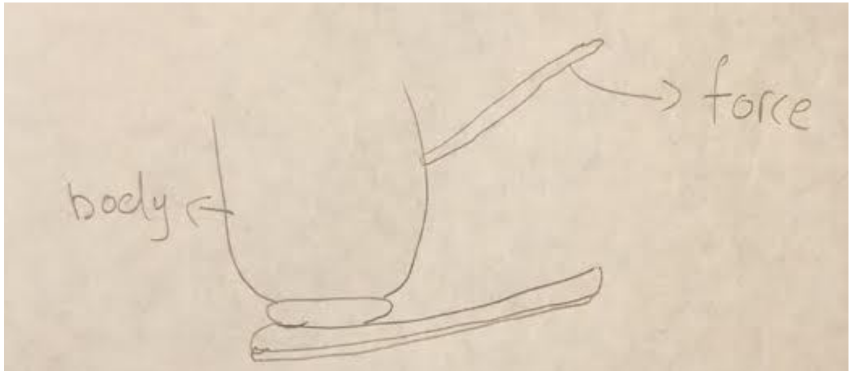



*Figure 25. Design-7 considered by the team*

## 4.8 Design #8: Featuring Economics

The designs focused in this section have an objective of keeping the cost down.

The following design shown in Figure 26 consists of two hydraulic cylinders connected in series with a curved iron rod. This configuration is connected to the BIOM. In this design the unique shape of the leg and the positioning of the hydraulic devices assist in torque and rotational motion.

PROS: 1) Design is robust and simple, however provides a range of motion at the same time 2) The design uses an iron plated with a rustproof material primarily to reduce cost but it can be substituted for more affordable materials. 3) Although the iron rods are rigid the shape of the rods along with hydraulic devices allows the range of motion

CONS: 1) The device can be bit heavy, which translates to a bigger batter and motor power. So, although the objective is to keep the overall cost low, it can be slightly offset by the bigger motor size needed.

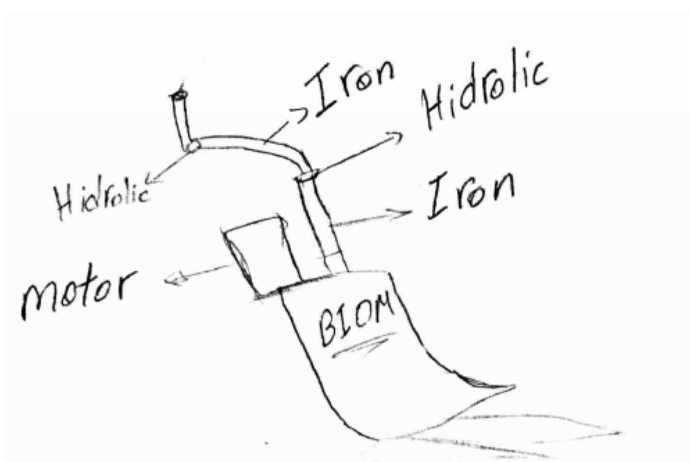



*Figure 26. Design-8 considered by the team*

The following design shown in Figure 27 in similar to the one just discussed, but it uses an assembly of springs instead of hydraulic/pneumatic actuators. The spring assembly is connected to the iron rod that is also connected to the biOM and the motor. The uniqueness of this design is that the spring/damper assembly not only serves to absorb the shocks during the motion providing comfort, but also designed to handle heavy weights. Furthermore, since they are flexible they are also used to provide the range of motion lacking in designs without spring assemblies.

PROS: 1) The spring assembly provides limited three-dimensional motion while providing comfort and supporting heavy weight, 2) The simple design consisting of iron rod makes the device very economical to use 3) The biggest advantage of this device is that the prosthetic can also be used when it runs out of battery in some situations if special attachments can be provided to it. The springs ensure comfort while walking.

CONS: 1) If the device is not optimized, the design can get heavy required a bigger motor and thus cannot be used in the manual mode when the prosthetic runs out of power

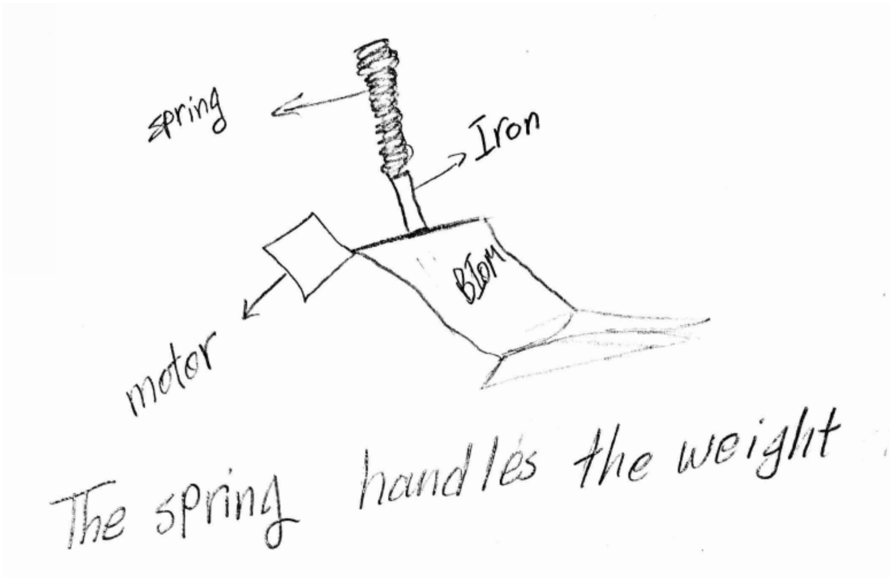



*Figure 27. Design-9 considered by the team*

# 5 DESIGN SELECTED – First Semester

Based on the various designed proposed in the previous section, every device has its own pros and cons and hence it is very difficult to select a final design for implementation. However, given that design a BiOM required a thorough understanding of the algorithms in order to program the microprocessor to integrate with the mechanical devices, it certainly requires a learning curve. In addition, cost is a big factor in designing these systems. So, it may be wise to start with the design which is economical and simple and slowly work towards more efficient and complicated designs that provide versatility as the team gets more proficient in programming the algorithms and using AI for this application.

The design selected is the first design (Design-1) presented in the report.

## *5.1 Rationale for Design Selection*

The rationale behind selecting this design is primarily practicality. Although some of the other designs may be better in terms of functionality and utility, given the time, budget and learning curve constraints, the team decided to go with a design that is simple and practical and at the same time efficient. Design-1 as selected has many pros as mentioned in the previous section. It incorporates a hydraulic cylinder and integrates it motion with the BiOM. It has a carbon fiber leg that is lightweight and provides great strength at the same time. The cloth sleeve provides grip and comfort to the patient and can be customized to improve in these aspects. The frame can be built with relative ease and the prototype can be built if needed since the design is simple yet effective.

Also, the key customer and engineering requirements detailed in Section-2 have been met for this design.

The details are shown in the decision matrix below where the critical criteria and concepts rated for various designs are – fixed and controlled environment, able to be tested in an indoor environment, be able to replicate the effects of design in real life, transportation ease, durability, choice of hydraulic cylinder, pneumatic actuator and the electrical motor.

| Criteria/Concept | design 1 | design 2 | design 3 | design 4 | design 5 | design 6 | design 7 | design 8 | design 9 | design 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A Test Fixture that can analyze the BiOM a prosthetic leg in a fixed and controlled environment. | + | + | + | + | + | - | - | - | - | + |
| A good design that can work in an indoor laboratory environment (don't need to account for natural causes such as rain, wind and snow) | + | - | + | | + | - | - | + | + | + |
| Can replicate the same effects as if worn in real life. | + | + | S | S | S | - | - | - | - | + |
| Easy to transport. | S | - | S | S | S | + | + | + | + | S |
| Durability, needs to with stand forces over time. | + | - | - | S | S | + | S | S | S | - |
| Hydraulic cylinder | + | + | + | - | - | - | - | + | + | - |
| Pneumatic Acutator | - | - | - | - | - | - | + | - | - | - |
| Electrical Motor | - | + | - | - | - | + | - | - | - | + |
| Σ+ | 5 | 4 | 3 | 2 | 2 | 3 | 2 | 3 | 3 | 4 |
| Σ- | 2 | 4 | 3 | 3 | 3 | 5 | 5 | 4 | 4 | 3 |
| ΣS | 1 | 0 | 2 | 3 | 2 | 0 | 1 | 1 | 1 | 1 |

## *5.2 Design Description*

The selected shown in Figure 28 consists of a text fixture body frame attached with a hydraulic cylinder connected to the BiOM that acts as human weight. This replicates the forces exerted by the human on the prosthetic leg. The prosthetic itself consists of another hydraulic cylinder connected to the BiOM microprocessor and attached to the carbon fiber leg. A battery attached to the prosthetic supplies the power to the device. It contains a cloth sleeve to attach to the human leg and a screw that connects to the BiOM.

Because the design uses carbon fiber leg is lightweight and has great strength and thus can support a larger weight. It is also flexible so as to distribute the forces evenly to the ground when the foot touches the ground when the BiOM is required to slow down. Also, during the stance phase, the electric battery that supplies power to the hydraulic cylinder is able to lift the lightweight carbon fiber leg with ease. The design also has a cloth sleeve that has durable cushioned material that attaches to the human leg and provides a snug and comfortable fit by distributing the forces at the contact point. The dual hydraulic cylinder design provides 2 degrees of freedom.

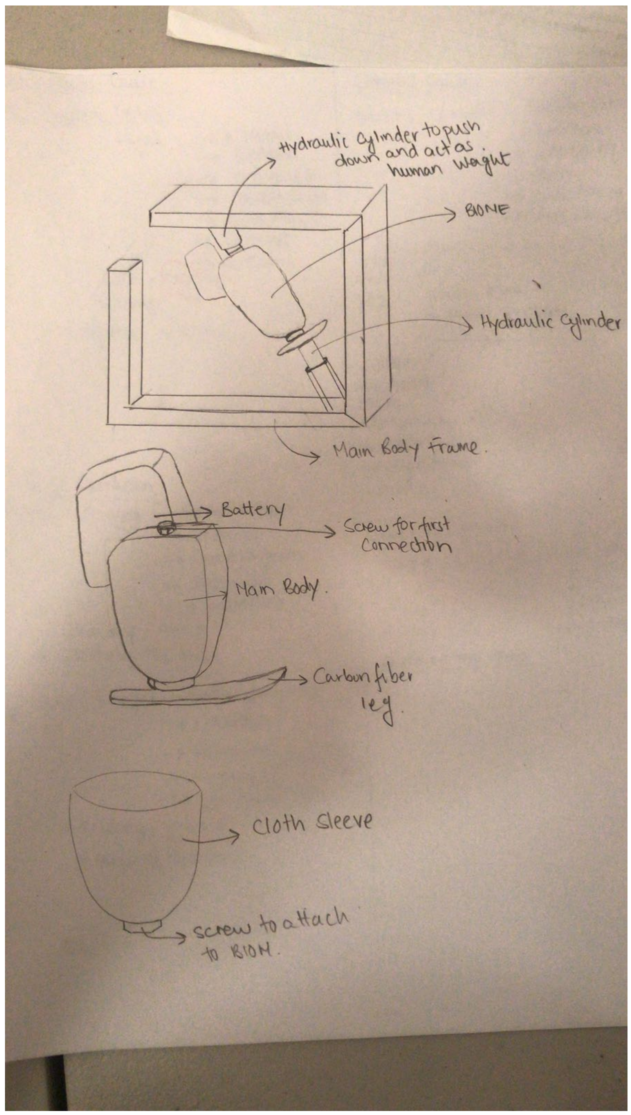



Figure 28. Design selected (Design-1) by the team

# 6 PROPOSED DESIGN

## 6.1 Introduction

The selected design for the BiOM test fixture was shown in the previous Section 5.2 in Figure 28. In this section, the CAD models of the sketch are presented. In addition, proper engineering analysis is performed to ascertain their selection for the test fixture to be built. The BiOM test fixture assembly consists of firstly, the the BiOM leg that needs to widthstand the forces exerted by the subject, secondly, the hydraulic cylinder that is representative of the subject exerting the forces on the BiOM and thirdly, the frame that holds the hydraulic cylinder and the BiOM in position. The frame dimensions need to accommodate the extend cylinder dimensions as the piston retracts.

In the following three sections detailed information is provided in regards to how the final selections are made adhering to the ERs and CRs. In summary,

1) The BiOM leg dimensions are selected to be 2” hollow cylinder. The material was selected to be Schedule 40 Stainless Steel. This is based on the estimate from the engineering analysis performed using the software called Bentley Autopipe. See section 6.2 for details.
2) The hydraulic cylinder model and part number selection is based on the manufacter’s catalogue of the custom software as well as calculations performed as the references outlined. See Section 6.3 for details.
3) Finally, the dimensions of the test frame and its assembly are discussed in Section 6.4

## 6.2 Procedure for Selection of BiOM test fixture material and size

The BiOM test fixture consists of BiOM with the legs that form the main load bearing component that needs to withstand both the weight of the subject (static and dynamic forces) as well as light enough to keep the weight of the text fixture low. We also need to satisfy the engineering requirements along with keeping the cost low. In this regards, our team has decided to adopt a hollow pipe that has both the strength as well as low weight factor that suits our requirement. However, detailed engineering analysis is necessary to select and adopt the correct dimensions used the test fixture. The estimation of the diameter of the pipe and selection of material can be modeled and analyzed using a stress analysis software.

Figure 29 below shows the CAD model of the hollow cylinder which represents the leg of the BiOM test fixture. The assembly of the test fixture consists of the BiOM leg shown in figure below and the hydraulic cylinder connected to the BiOM frame. The frame of the test fixture and the hydraulic cylinder are shown and discussed the following two sections (Section 6.3 and Sectin 6.4) along with their selection procedure.

*Figure 29. CAD Model of the BiOM leg used in test fixture. The diameter and material selection procedure are detailed in this section.*

The proposed design is tested using the software Bentley Autopipe 11.01.00.23. Autopipe provides a comprehensive and advanced software tool specialized in as a point force at point A00. A guide support is used at point A01. The hydraulic cylinder and the frame are modeled as a damper and an anchor in the pipe stress analysis. As shown in results below, the hydraulic cylinder used to act as human weight is represented software At point A03. The dimensions of the model are indicated in inches. The total length of the design in the model is 27 inches (2.25 feet). The reference axis is also shown in the model.

### 6.2.1 SELECTION OF MATERIAL FOR TEST FIXTURE

Two materials – Stainless steel and carbon fiber are considered in this report. The analysis is however performed only using Stainless steel Sch80 pipe. The material properties of stainless steel are obtained from the software database and are shown below in Figure 30.

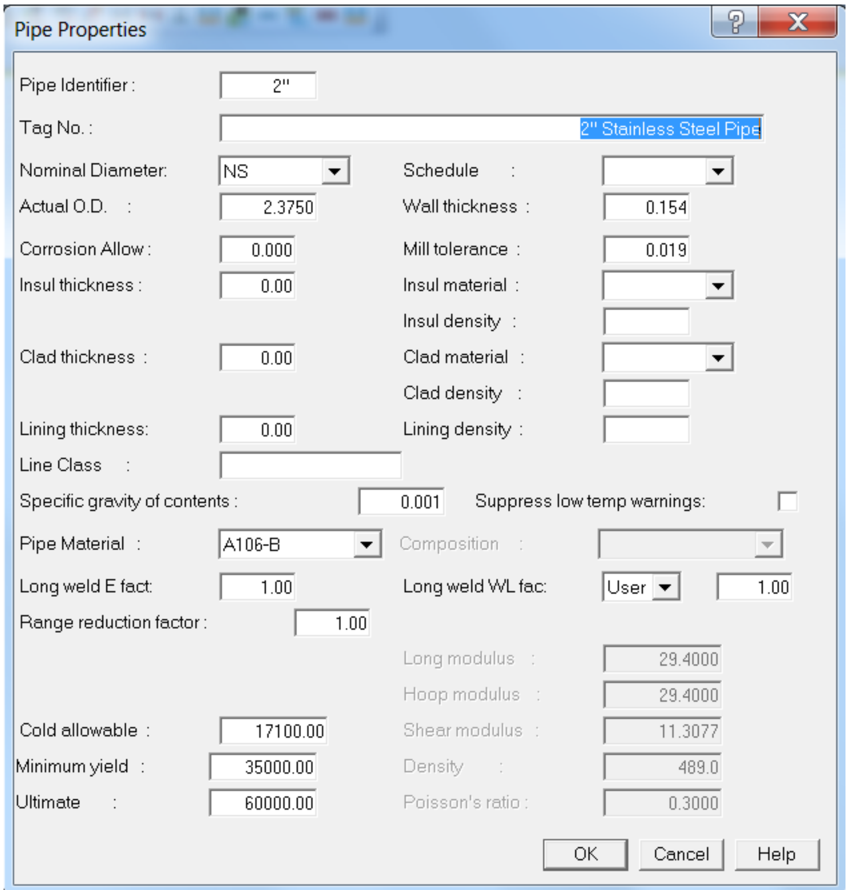



*Figure 30. Table showing the material properties as per Bentley Autopipe database for 2" Schedule 40 stainless steel.*

Pipe Sizes: For the sake of optimization, two pipe sizes of stainless steel pipe are considered – 1 inch diameter pipe and 2" diameter pipe. The stresses in the pipe are analyzed for both the pipe sizes. As shown from the analysis, the stresses in the pipe for the 1" pipe exceed the allowable stresses for the 1" pipe. Hence a 1" pipe is not suitable for the design. The 2" pipe satisfies the requirements and is able to sustain the stresses due to the load considered. The angle used for the analysis is 45 degrees. The point load used for the analysis is the maximum weight of the person – 287 lb (130 kg).

A representation of the BiOM test fixture model as designed in AutoPipe for the selection of diameter and material of the BiOM test fixture is shown in the following three figures. The figures shown how the crucial forces are represented and modeled in the software.

The line diagram of the Autopipe model used for stress analysis is shown in Figure 31 below.

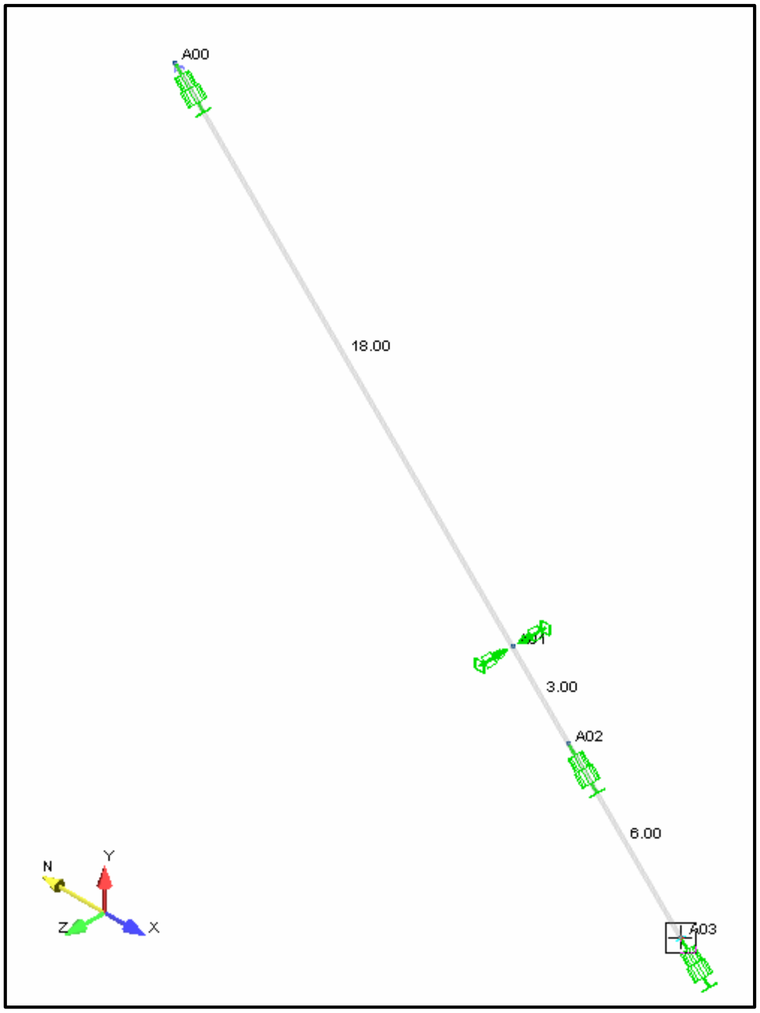



*Figure 31. Snapshot of the BiOM modeled using Bentley Autopipe software for stress analysis.*

A zoomed version of the different components of the model is shown in Figure 32, Figure 33 and Figure 34. As shown in Figure 32, the concentrated load of 287 lb is shown at point A00. Figure 33 and Figure 34 show the guide support and the anchor at the bottom end of the model to represent the fixed frame.

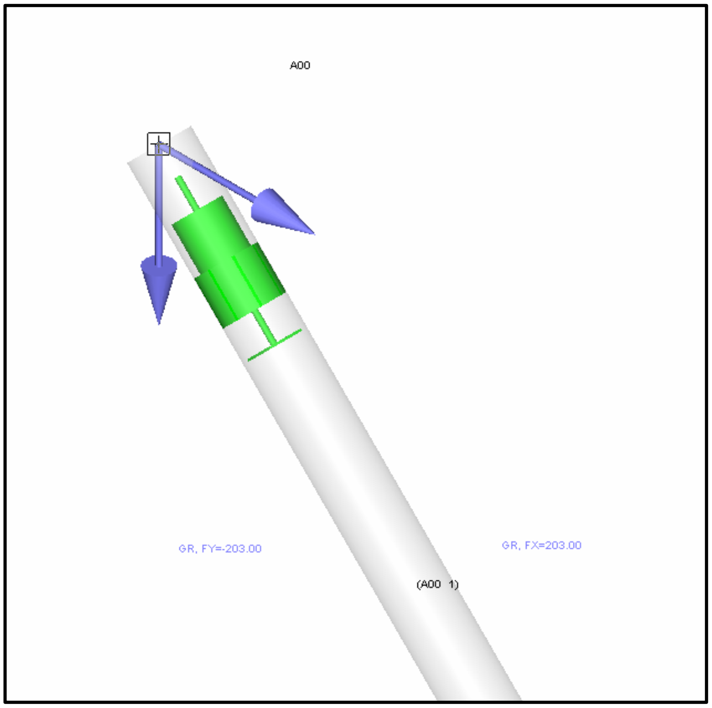


*Figure 32. Zoomed portion of the top segment of the stress analysis model using Bentley Autopipe*

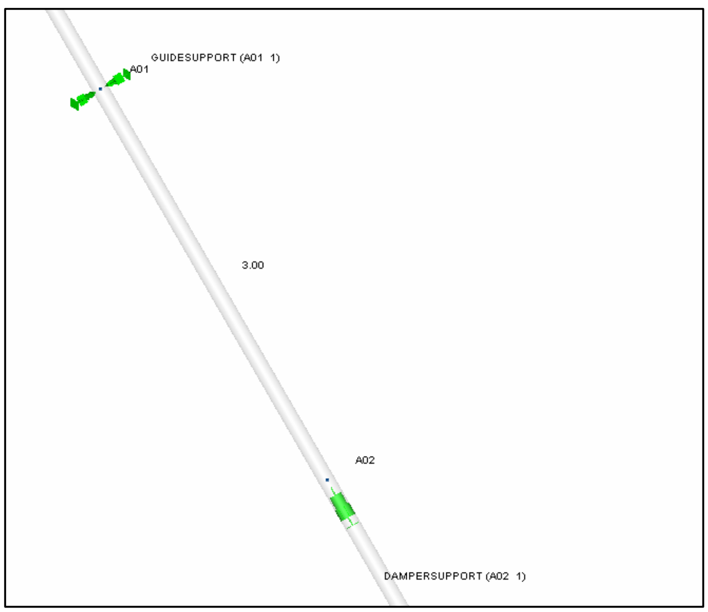


*Figure 33. Zoomed portion of the middle segment of the stress analysis model using Bentley Autopipe*

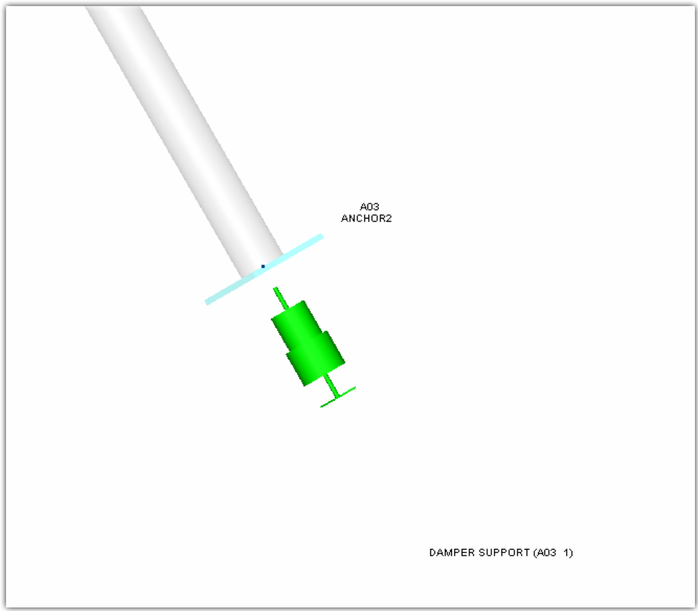



*Figure 34. Zoomed portion of the bottom segment of the stress analysis model using Bentley Autopipe*

The next section describes the results of the analysis using Autopipe and how both the diameter of the BiOM and material selection for the test fixture are finalized.

### 6.2.2 SELECTION OF DIAMETER OF TEST FIXTURE USING ENGINEERING ANALYSIS

As mentioned earlier, without a thorough engineering analysis that estimates the components used in the test fixture to be built, the testing of the test fixture is not likely to be successful if not optimal. In this regards, this section is devoted to explaining the results of how the section of 2” schedule 40 stainless steel pipe is arrived at as the selected material for the BiOM.

As described in the results below, the 1” pipe was found to be insufficient. Note that since the pipe is hollow, the weight of the BiOM is reduced, however to adhere to the budget limitations, the optional material of carbon fiber was not used as detailed in the next section.

**RESULTS OF ANALYSIS:**

The results of the stress analysis using Bentley Autopipe [12] are shown below for both the 2” schedule 40 pipe and 1” schedule 40 pipe. A results table showing the various stress and the allowable stresses are also listed. The forces and moments in the model are also listed in the table below. In summary, the 1” pipe fails the stress analysis test. However, the 2” pipe passes the stress analysis test.

INTERPRETATION OF LEGEND : In the color coded results showing the stresses in the pipe, blue represents smaller stresses and red represents higher stresses. A stress ratio less than 1.0 is acceptable but a stress ratio greater than 1.0 is not acceptable. As shown from the results below, the stress ratio is greater than 1.0 for 1” pipe and the stress ratio is less than 1.0 for the 2” stainless steel pipe. Hence, a 2” stainless steel pipe is recommended. A comparison with carbon fiber is discussed next.

The results include a safety factor of 2.0 for allowable longitudinal and shear stresses. The results also include a safety factor of 2.5 for allowable hoop stress. In addition to the stresses provided due to the loads, stresses are also calculated due to thermal fluctuation. However, the stresses in this case due to thermal load are not significant. Hence the stresses due to thermal load are not presented in the report.

**Results for 2” diameter Schedule 40 Stainless Steel (Successful Case):**

The stress ratio using a color-coded depiction, a table showing the stresses and a table showing the forces/moment are shown below for the 2” diameter schedule 40 stainless steel pipe used for the BiOM. The stress ratios are shown in Figure 35. The values of maximum stresses and force/moment are shown in Figure 36 and Figure 37 respectively.

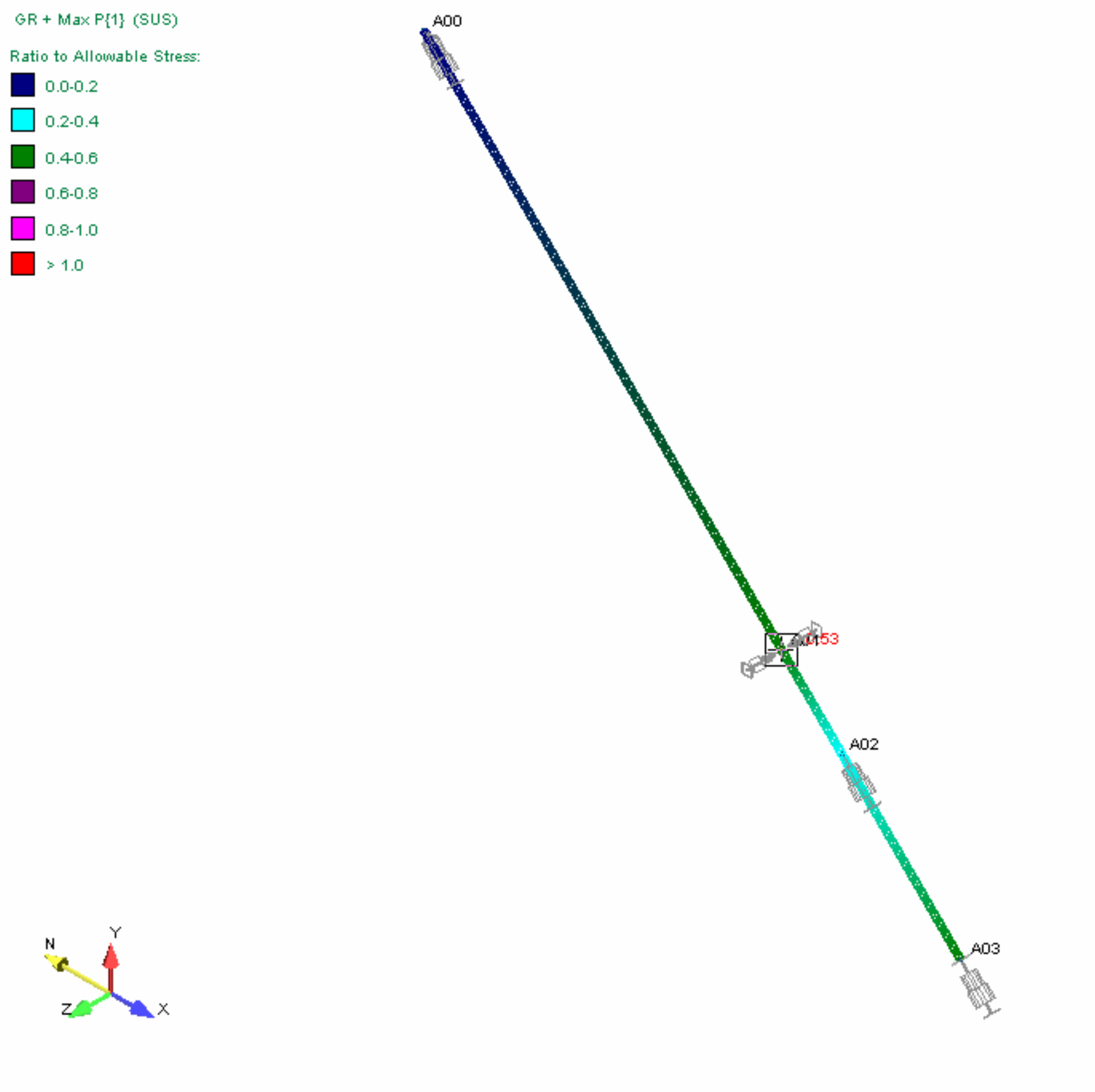



*Figure 35. The stresses for 2-inch pipe are shown using the stress ratio that is color-coded using the colors denoted in the legend*

Result Review

Displacement | Force/Moment | Anchor | Support | **Code Stresses** | Frequency | Mode Shape | General Stress

| | Seg | Point | Combination | Category | Stress | Allowable | Ratio | Pressure | Bending | Ma (Sus) | Mb (Occ) | Mc (Exp) | SIF | Equation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | psi | psi | | psi | psi | ft-lb | ft-lb | ft-lb | | |
| ▶ | A | A00 | Max P{1} | Hoop | 123 | 17100 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0.00 | 3 |
| | A | | GR + Max P{1} | Sustain | 57 | 17100 | 0.00 | 57 | 0 | 0 | 0 | 0 | 1.00 | 15 |
| | A | A00 | TR:Amb to T1{1 | Expansion | 0 | 25650 | 0.00 | 0 | 0 | 0 | 0 | 0 | 1.00 | 17 |
| | A | | Amb to T1{1} | Expansion | 0 | 25650 | 0.00 | 0 | 0 | 0 | 0 | 0 | 1.00 | 17 |
| | A | | Max P{1} | Hoop | 123 | 17100 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0.00 | 3 |
| | A | A01 | GR + Max P{1} | Sustain | 9078 | 17100 | 0.53 | 57 | 9021 | 421 | 0 | 0 | 1.00 | 15 |
| | A | | TR:Amb to T1{1 | Expansion | 0 | 25650 | 0.00 | 0 | 0 | 0 | 0 | 0 | 1.00 | 17 |
| | A | | Amb to T1{1} | Expansion | 0 | 25650 | 0.00 | 0 | 0 | 0 | 0 | 0 | 1.00 | 17 |
| | A | | Max P{1} | Hoop | 123 | 17100 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0.00 | 3 |
| | A | A02 | GR + Max P{1} | Sustain | 4255 | 17100 | 0.25 | 57 | 4198 | 196 | 0 | 0 | 1.00 | 15 |
| | A | | TR:Amb to T1{1 | Expansion | 4235 | 25650 | 0.17 | 0 | 4235 | 0 | 0 | 198 | 1.00 | 17 |
| | A | | Amb to T1{1} | Expansion | 4235 | 25650 | 0.17 | 0 | 4235 | 0 | 0 | 198 | 1.00 | 17 |
| | A | | Max P{1} | Hoop | 123 | 17100 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0.00 | 3 |
| | A | A03 | GR + Max P{1} | Sustain | 3993 | 17100 | 0.23 | 57 | 3936 | 184 | 0 | 0 | 1.00 | 15 |
| | A | | TR:Amb to T1{1 | Expansion | 12704 | 25650 | 0.50 | 0 | 12704 | 0 | 0 | 594 | 1.00 | 17 |
| | A | | Amb to T1{1} | Expansion | 12704 | 25650 | 0.50 | 0 | 12704 | 0 | 0 | 594 | 1.00 | 17 |

Record 1

*Figure 36. The table shows the stresses for the 2" schedule 40 stainless steel pipe used for the BiOM*

Displacement | **Force/Moment** | Anchor | Support | Code Stresses | Frequency | Mode Shape | General Stress

| | Seg | Point | Combination | FX | FY | FZ | FR | MX | MY | MZ | MR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | lbf | lbf | lbf | lbf | ft-lb | ft-lb | ft-lb | ft-lb |
| ▶ | A | A00 | Gravity{1} | 203 | -203 | 0 | 287 | 0 | 0 | 0 | 0 |
| | A | A00 | Thermal 1{1} | 0 | -0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | A | | GRT1{1} | 203 | -203 | 0 | 287 | 0 | 0 | 0 | 0 |
| | A | | Gravity{1} | 203 | -269 | 0 | 337 | 0 | 0 | 421 | 421 |
| | A | A01 - | Thermal 1{1} | 0 | -0 | 0 | 0 | 0 | 0 | -0 | 0 |
| | A | | GRT1{1} | 203 | -269 | 0 | 337 | 0 | 0 | 421 | 421 |
| | A | | Gravity{1} | 292 | -180 | 0 | 343 | 0 | 0 | 421 | 421 |
| | A | A01 + | Thermal 1{1} | -47 | -47 | 0 | 66 | 0 | 0 | -0 | 0 |
| | A | | GRT1{1} | 245 | -227 | 0 | 334 | 0 | 0 | 421 | 421 |
| | A | | Gravity{1} | 292 | -191 | 0 | 349 | 0 | 0 | 196 | 196 |
| | A | A02 - | Thermal 1{1} | -47 | -47 | 0 | 66 | 0 | 0 | 198 | 198 |
| | A | | GRT1{1} | 245 | -238 | 0 | 342 | 0 | 0 | 394 | 394 |
| | A | | Gravity{1} | 292 | -191 | 0 | 349 | 0 | 0 | 196 | 196 |
| | A | A02 + | Thermal 1{1} | -47 | -47 | 0 | 66 | 0 | 0 | 198 | 198 |
| | A | | GRT1{1} | 245 | -238 | 0 | 342 | 0 | 0 | 394 | 394 |
| | A | | Gravity{1} | 292 | -213 | 0 | 362 | 0 | 0 | -184 | 184 |
| | A | A03 | Thermal 1{1} | -47 | -47 | 0 | 66 | 0 | 0 | 594 | 594 |
| | A | | GRT1{1} | 245 | -260 | 0 | 357 | 0 | 0 | 410 | 410 |

Record 1

*Figure 37. The table shows the forces/moments for the 2" schedule 40 stainless steel pipe used for the BiOM*

The output for the successful stress analysis test using the 2" stainless steel pipe is presented in Appendix-8.2.

## Results for 1” diameter Schedule 40 Stainless Steel (Failed Case):

The stress ratio using a color-coded depiction, a table showing the stresses and a table showing the forces/moment are shown below for the 1” diameter schedule 40 stainless steel pipe used for the BiOM.

Schedule 80 steel properties are used. 1-inch diameter is not sufficient to bear the load since the stresses exceed the allowable stress and hence the stress ratio exceeds 1. Figure 38 below shows the stress ratios along the length of the model. As seen, red indicates stress ratios greater than 1.0. Hence, the 1” pipe is not suitable for our design. The corresponding maximum stress values and the force/moments are shown in Figure 39 and Figure 40 respectively.

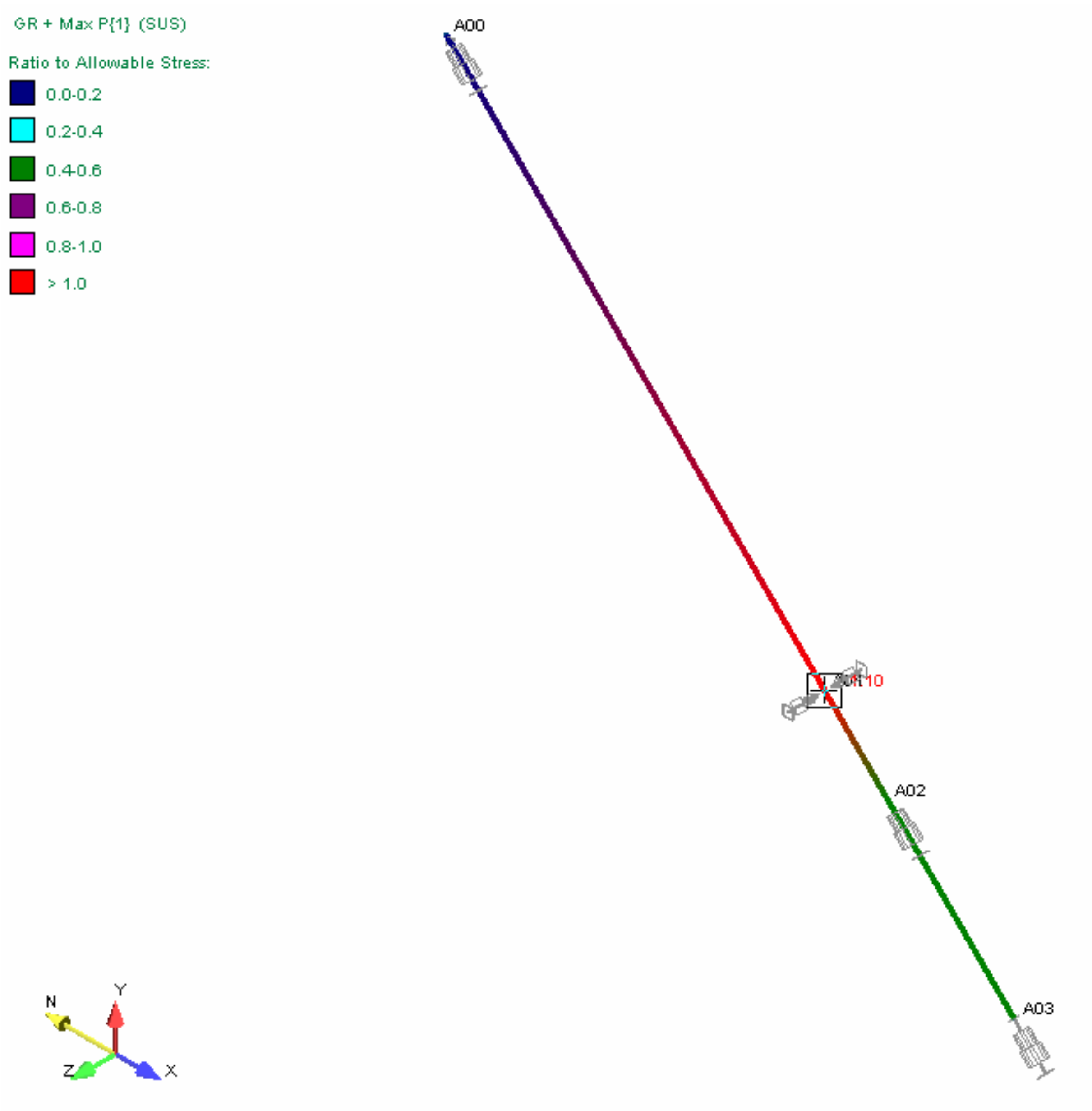
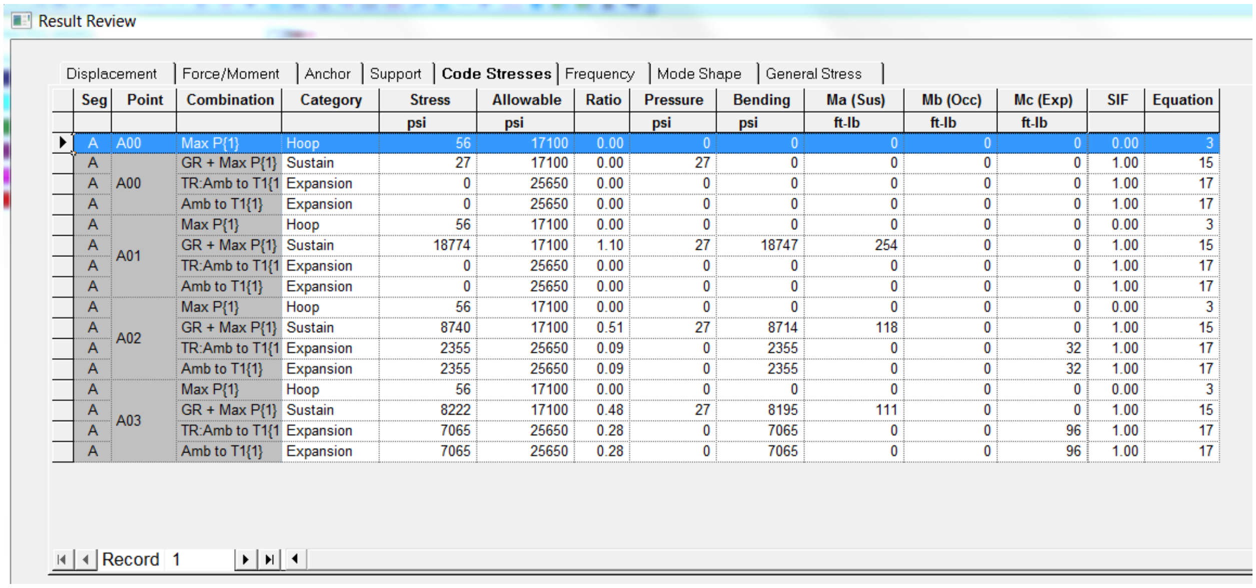



*Figure 38. The stresses for 1-inch pipe are shown using the stress ratio that is color-coded using the colors denoted in the legend*



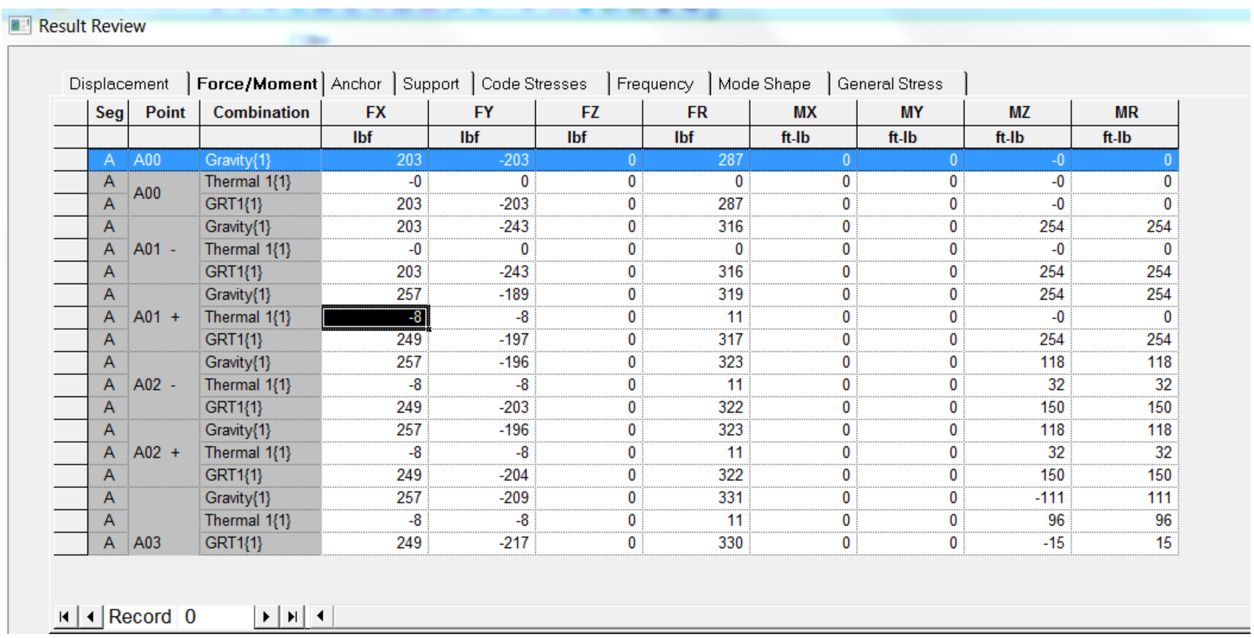
Result Review

Displacement | Force/Moment | Anchor | Support | **Code Stresses** | Frequency | Mode Shape | General Stress

| Seg | Point | Combination | Category | Stress | Allowable | Ratio | Pressure | Bending | Ma (Sus) | Mb (Occ) | Mc (Exp) | SIF | Equation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | psi | psi | | psi | psi | ft-lb | ft-lb | ft-lb | | |
| A | A00 | Max P{1} | Hoop | 56 | 17100 | 0.00 | 0 | 0 | 0 | 0 | 0 | 0.00 | 3 |
| A | | GR + Max P{1} | Sustain | 27 | 17100 | 0.00 | 27 | 0 | 0 | 0 | 0 | 1.00 | 15 |
| A | A00 | TR:Amb to T1{1 | Expansion | 0 | 25650 | 0.00 | 0 | 0 | 0 | 0 | 0 | 1.00 | 17 |
| A | | Amb to T1{1} | Expansion | 0 | 25650 | 0.00 | 0 | 0 | 0 | 0 | 0 | 1.00 | 17 |
| A | | Max P{1} | Hoop | 56 | 17100 | 0.00 | 0 | 0 | 0 | 0 | 0 | 0.00 | 3 |
| A | | GR + Max P{1} | Sustain | 18774 | 17100 | 1.10 | 27 | 18747 | 254 | 0 | 0 | 1.00 | 15 |
| A | A01 | TR:Amb to T1{1 | Expansion | 0 | 25650 | 0.00 | 0 | 0 | 0 | 0 | 0 | 1.00 | 17 |
| A | | Amb to T1{1} | Expansion | 0 | 25650 | 0.00 | 0 | 0 | 0 | 0 | 0 | 1.00 | 17 |
| A | | Max P{1} | Hoop | 56 | 17100 | 0.00 | 0 | 0 | 0 | 0 | 0 | 0.00 | 3 |
| A | | GR + Max P{1} | Sustain | 8740 | 17100 | 0.51 | 27 | 8714 | 118 | 0 | 0 | 1.00 | 15 |
| A | A02 | TR:Amb to T1{1 | Expansion | 2355 | 25650 | 0.09 | 0 | 2355 | 0 | 0 | 32 | 1.00 | 17 |
| A | | Amb to T1{1} | Expansion | 2355 | 25650 | 0.09 | 0 | 2355 | 0 | 0 | 32 | 1.00 | 17 |
| A | | Max P{1} | Hoop | 56 | 17100 | 0.00 | 0 | 0 | 0 | 0 | 0 | 0.00 | 3 |
| A | | GR + Max P{1} | Sustain | 8222 | 17100 | 0.48 | 27 | 8195 | 111 | 0 | 0 | 1.00 | 15 |
| A | A03 | TR:Amb to T1{1 | Expansion | 7065 | 25650 | 0.28 | 0 | 7065 | 0 | 0 | 96 | 1.00 | 17 |
| A | | Amb to T1{1} | Expansion | 7065 | 25650 | 0.28 | 0 | 7065 | 0 | 0 | 96 | 1.00 | 17 |

Record 1

*Figure 39. The table shows the stresses for the 1" schedule 40 stainless steel pipe used for the BiOM*



Result Review

Displacement | **Force/Moment** | Anchor | Support | Code Stresses | Frequency | Mode Shape | General Stress

| Seg | Point | Combination | FX | FY | FZ | FR | MX | MY | MZ | MR |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | lbf | lbf | lbf | lbf | ft-lb | ft-lb | ft-lb | ft-lb |
| A | A00 | Gravity{1} | 203 | -203 | 0 | 287 | 0 | 0 | -0 | 0 |
| A | A00 | Thermal 1{1} | -0 | 0 | 0 | 0 | 0 | 0 | -0 | 0 |
| A | | GRT1{1} | 203 | -203 | 0 | 287 | 0 | 0 | -0 | 0 |
| A | | Gravity{1} | 203 | -243 | 0 | 316 | 0 | 0 | 254 | 254 |
| A | A01 - | Thermal 1{1} | -0 | 0 | 0 | 0 | 0 | 0 | -0 | 0 |
| A | | GRT1{1} | 203 | -243 | 0 | 316 | 0 | 0 | 254 | 254 |
| A | | Gravity{1} | 257 | -189 | 0 | 319 | 0 | 0 | 254 | 254 |
| A | A01 + | Thermal 1{1} | -8 | -8 | 0 | 11 | 0 | 0 | -0 | 0 |
| A | | GRT1{1} | 249 | -197 | 0 | 317 | 0 | 0 | 254 | 254 |
| A | | Gravity{1} | 257 | -196 | 0 | 323 | 0 | 0 | 118 | 118 |
| A | A02 - | Thermal 1{1} | -8 | -8 | 0 | 11 | 0 | 0 | 32 | 32 |
| A | | GRT1{1} | 249 | -203 | 0 | 322 | 0 | 0 | 150 | 150 |
| A | | Gravity{1} | 257 | -196 | 0 | 323 | 0 | 0 | 118 | 118 |
| A | A02 + | Thermal 1{1} | -8 | -8 | 0 | 11 | 0 | 0 | 32 | 32 |
| A | | GRT1{1} | 249 | -204 | 0 | 322 | 0 | 0 | 150 | 150 |
| A | | Gravity{1} | 257 | -209 | 0 | 331 | 0 | 0 | -111 | 111 |
| A | | Thermal 1{1} | -8 | -8 | 0 | 11 | 0 | 0 | 96 | 96 |
| A | A03 | GRT1{1} | 249 | -217 | 0 | 330 | 0 | 0 | -15 | 15 |

Record 0

*Figure 40. The table shows the stresses for the 1" schedule 40 stainless steel pipe used for the BiOM*

### 6.2.3 OTHER OPTIONS FOR SELECTION OF MATERIAL FOR BIOM

**COMPARISON USING CARBON FIBER:**

The second material considered for the design is carbon fiber [13]. There are pros and cons to using carbon fiber. The pro is the increased strength. As a comparison, steel has a tensile modulus of about 29 million psi (200 million kPa). Thus, the strongest carbon fibers are ten times stronger than steel and eight times that of aluminum, not to mention much lighter than both materials, 5 and 1.5 times respectively. The con is the expense. Using carbon fiber is also advantageous in terms of its weight. If cost is a constraint, then the recommended option is to use 2” schedule 40 stainless steel for the design. Using Aluminum is also a good option. However, if cost is not a constraint and weight is a preference, carbon fiber is the preferred material for the design.

## 6.3 Procedure for selection of Hydraulic Cylinder

It is very important to select the hydraulic cylinder as per the engineering requirements and designed correctly that delivers the required estimated force. In this regards, the detailed steps are outlined below that describe how the final force and design working pressure are selected based on Festo catalogue selector [15]. The CAD model of the hydraulic cylinder is shown below in Figure 41. The exact image of the selected hydraulic cylinder model CDC-80, and the drawings showing the manufacturer dimension of the exact selection - Part number 543311 are available on the manufacturer's website [15].

The hydraulic cylinder is connected to the BiOM test fixture, which are both connected to the frame discussed in Section 6.3.

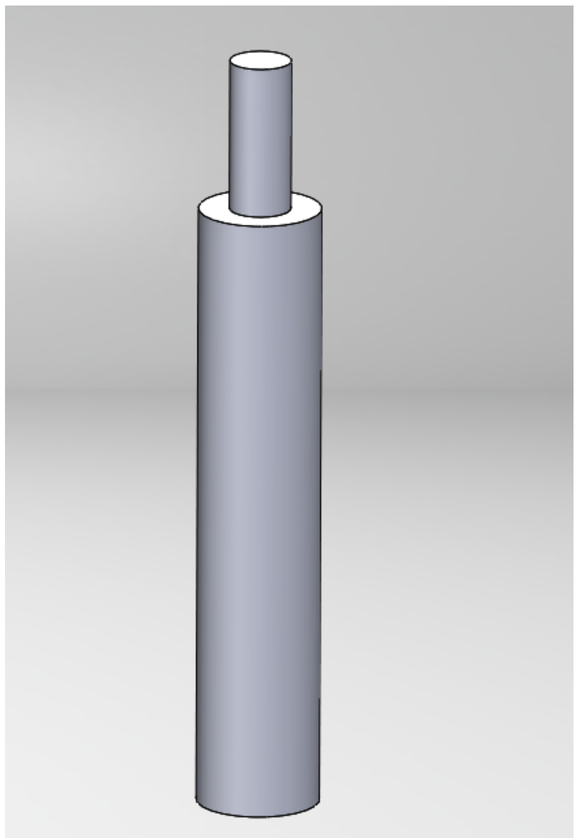


*Figure 41. CAD model of the hydraulic cylinder*

**SELECTION OF HYDRAULIC CYLINDER**

The following steps are followed in the selection of Hydraulic Cylinder:

Steps followed are below:

1. Since, the weight of the person is 130 kg, select a cylinder with at least 1300 N force.

2. Based on reference 12 (see link https://www.engineeringtoolbox.com/hydraulic-force-calculator-d_1369.html). From the acting force versus cylinder pressure graph, a cylinder with diameter 125 mm or less is appropriate in order to obtain a 1.3 kN force or higher. Several design selections are possible based on where our design point is on the graph. See Figure 42 below for the design options for the hydraulic cylinder.

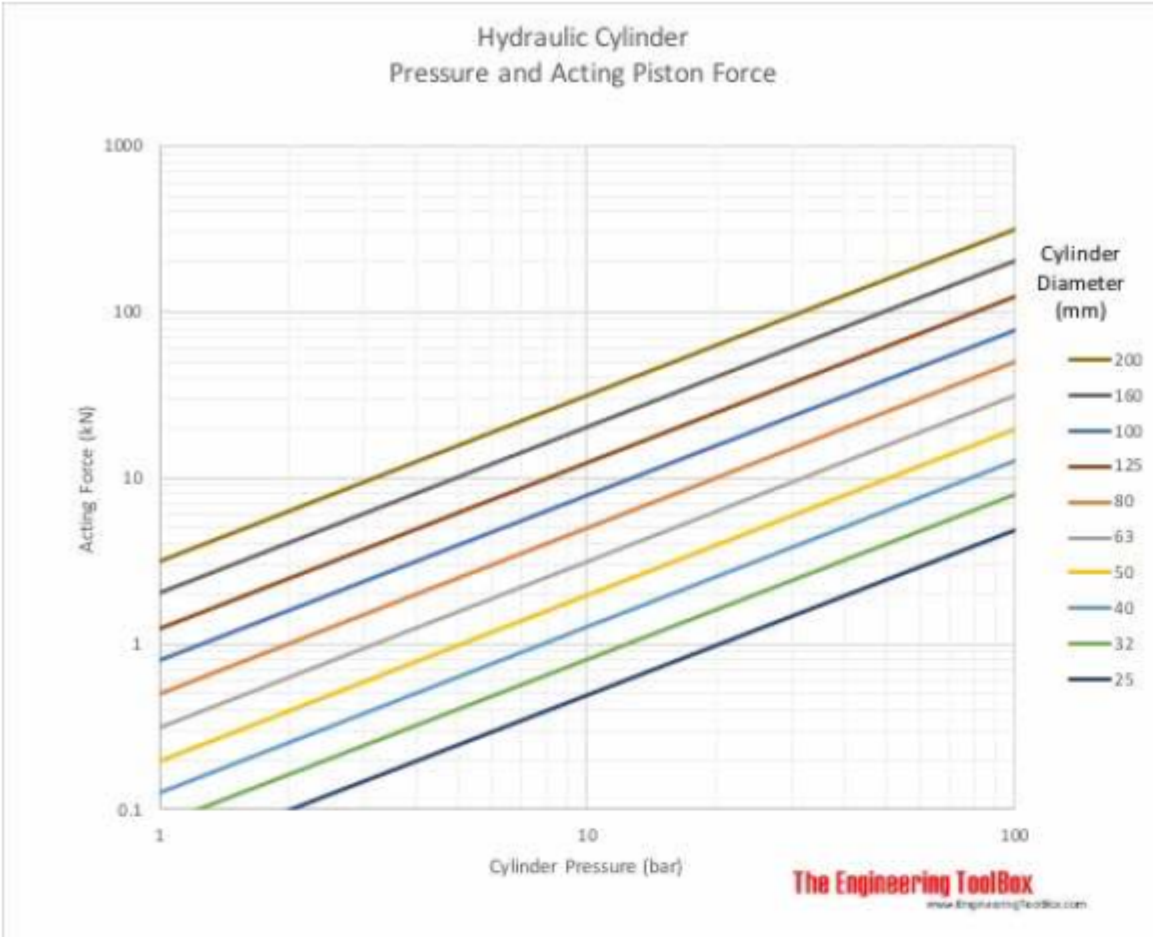



*Figure 42. Plot of Acting force of the hydraulic cylinder versus the cylinder pressure*

3. To simplify the process and select a hydraulic cylinder in the range of 1300 N and 3250 N (with a 2.5 safety factor), use the Festo catalogue selector in [15]

4. The datasheet for a selection product (Part number: 577198) for hydraulic cylinder is shown in Appendix C in Section 8.3. As per the datasheet, the theoretical force of the selected hydraulic cylinder is between 2827 N and 3016 N at a working pressure of 6 bar. Further details are in the data sheet presented in the appendix.

The selected Hydraulic Cylinder has the following features:

Design: With the CDC (Clean Design Compact) cylinder series, the ADN modular system has been expanded to include an easy to clean compact cylinder variant It is based on ISO 21287 for compact cylinders and, like the compact cylinder ADN, features short strokes and a compact design The compact cylinder CDC is designed as a double-acting pneumatic cylinder with piston, piston rod and profile barrel.

Easy to clean: Clean Design means smooth surfaces without slots and edges, which means fewer places where dirt can collect For hygiene reasons, the threads on the cylinder caps should be sealed with suitable blanking screws Resistant to conventional cleaning agents Increased corrosion protection

Easy to Assemble: Comprehensive range of mounting accessories for just about every type of installation Contactless position sensing via proximity sensors

Versatile: The variants can be configured according to individual needs thanks to the modular product system Greater flexibility thanks to the wide range of variants

Mounting: With through screws - Direct mounting

Size: Space savings of up to 50% compared with cylinders to standard ISO 15552

The operating pressure can be varied between 0.8 to 10 bar. Position sensing is possible using contactless position sensor. Technical support from Festo for customization of the hydraulic cylinder is available via the phone or through email at support.nl@festo.com.

## *6.4 Design of the BiOM test fixture Frame Size for testing*

**DIMENSIONS OF THE FIXTURE**

The BiOM test fixture is attached to the frame shown in Figure 43 below. There are many options as to how the frame can be built. Our team has decided to use screws to hold the frame together. The design of the screws is based on the forces used in the engineering analysis presented in Section 6.2. The frame dimensions allow for the extension of the hydraulic cylinder that is representative of the test subject exerting forces on the BiOM. The CAD model of the frame is shown below.

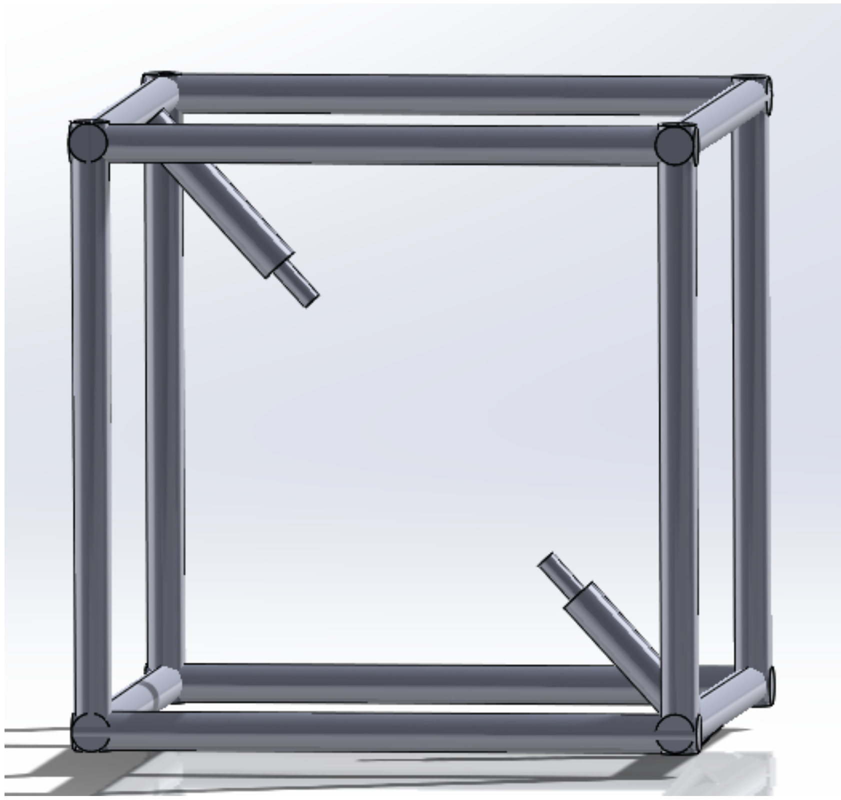


*Figure 43. CAD model of BioM Frame test fixture*

The dimensions of the fixture are based on the length of the BiOM also taking into account the length of the hydraulic cylinder. In the computer model used to analyze the stresses, the hydraulic cylinder used to replicate the weight of the person is modeled as a concentrated force. However, in the fixture, the length of the hydraulic cylinder needs to be accounted for in determining the dimensions of the fixture. Assume X, Y and Z represent the horizontal, vertical and lateral dimensions of the fixture. The length of the BiOM in the model as described earlier is 27 inches. A hydraulic cylinder of size 125 mm is sufficient for the current case to exert a force in the range of 1.1 kN to 100 kN based on [14], which is relevant for our case. Assume the length of the hydraulic cylinder to be 3 times its diameter. Hence the length of the hydraulic cylinder is 375 mm or 0.375 m (15 inches). Hence the total diagonal length of the fixture is 27+15=42 inches. The angle of the BiOM is 45 degrees. Hence, the dimension of X, Y and Z is $\frac{42}{\sqrt{2}}$=29.7 inches. Allowing some tolerance for miscellaneous connections (fasteners, attachments, supports and clearances), the dimension of X, Y and Z is expected to be between 30 and 35 inches.

The exploded view of the CAD model is shown in figure below.

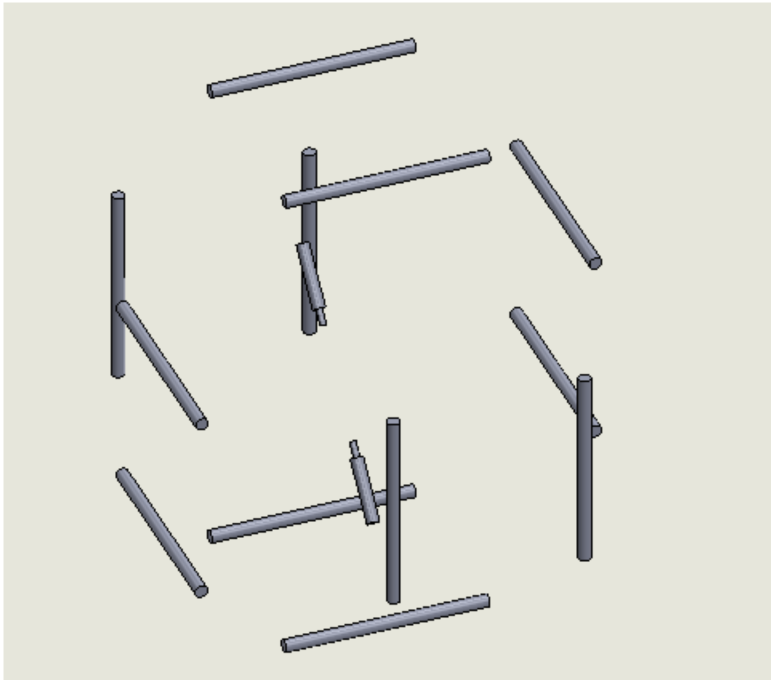


Figure 44. CAD model of the exploded view of the frame

It is proposed that the components of the frame will not be welded. Instead, they will be fastened using screws to provide us with the flexibility to accommodate the testing procedures during the testing of the test fixture. Fasteners, braces and other structural pipe fittings may also be used to add additional support to the frame.

The bill of materials is included in Appendix D.

## 7. IMPLEMENTATION

When implementing the BiOM prototype there are some few changes that were considered before the testing process. The original prototype of the design used a Bentley Auto-pipe as the main structural support for the BiOM leg. This Auto-type utilized the hydraulic cylinder when maintaining the dynamic and static forces of the prototype. These forces have been accounted for in section 2.3.1. The changes made utilized a hollow pipe as the structural frame because it is lighter than the Bentley Auto-pipe. The low weight factor meets our engineering requirement in table 2 (target specification <= 15 kilograms or 33 pounds). This specification was advantageous because facilitated mobility and greatly reduced the power consumption.

In the original design, aluminum had been recommended as the secondary construction component because it was cheap. However, we opted for carbon fiber as the secondary material [13]. Carbon fiber was considered, because it had the higher tensile strength than aluminum. Steel been one of the strongest materials has a tensile modulus of about 200 million psi. Carbon fiber is ten times stronger than steel and eight times stronger than aluminum meeting the durability standards required by the customer. Carbon fiber has an advantage because it has a low weight than aluminum. This material does not corrode like most metals hence further meeting the durability standards of the customers.

### 7.1 MANUFACTURING

The manufacturing process involve the use of computation procedures to predict the aspects of humans walking [16]. However, the computational models cannot fully predict the responses that predict mechanical changes occurring in the leg. To increase the efficiency in the manufacturing process, the prosthetic leg has to be physically tested with a live person to enhance functionality. The functionality of the prosthetic leg is manufactured with laboratory techniques that provide tools and explanations in locomotion research [16]. Torque and force determined simulations require virtual systems with springs designed mimic the force-fields. To perform the manufacturing processes, we emphasized on the mechanical importance by using motor tethered units and light-weight prosthesis.

#### 7.1.1 Mechanical manufacturing

This involves the manufacturing of mechanical and an electrical system that has a control system, flexible tether, instrumental prothesis and an off-board motor. Mechanical manufacturing includes the combination of the hydraulic cylinder and the pneumatic actuator which are responsible for generating torque.

The motor voltage was also regulated with an Industrial motor-drive embedded with a state controller the voltage analogue signals [17]. The transmission in the system was connected with a two gears ratio, springs, screw shaft and step response. An outer conduit was then connected to a motor frame in one end while the prothesis frame was connected by joining the pneumatic actuator and hydraulic cylinder. The force generated in the motor is directed to the prothesis without depending on the workspace position. To fully complete the tether, the sensor cables are connected together. The conversion of the transmitted forces was designed by conducting an instrumentation on the prosthesis end. In the prosthetic joint in the ankle, plantarflexion ankle forces allowed the rotation in relation to frame work of the prosthesis [17]. A series of leaf-springs were connected to the protruding toe segment. This segment bulges towards the back in relation to the angular joint in the ankle [17]. Series aligned springs were added to the decoupled toe segment to improve irregular ground-contact and non-uniform torque. A calibrated torque-based model used the spring with low tension to facilitate upward toe movement in the spring.

Theoretically, the minimum mass required to meet the weight requirements of the design were derived by relating the properties of the material together with a geometric constant. An optical mass in the springs and leaf were performed in the calculation by utilizing classical mechanics models in the equation:

$$\sigma = \frac{F}{A} = E.\epsilon, \qquad \Delta x = \iota.\epsilon, \qquad m = \rho A l$$

$\sigma$ = uniform material stress,
F= spring force,
A= spring cross-sectional area
E= elastic modulus material
$\epsilon$= strain of material
$\Delta x$=spring displacement
$l$= spring length
m= mass of spring
$\rho$ =density of material
The geometric parameters $A$ (area) and $l$ (length) are set by applying the maximum force $Fm$. A maximum displacement $\Delta xm$ is selected with an allowed maximum stress $\sigma_a$ while $m$ is the minimum mass of the spring. This can be expressed mathematically by:

$$A = \frac{F_m}{\epsilon_m}, \qquad l = \frac{\Delta\, x_m}{\epsilon_m} = \frac{\Delta\, x_m . E}{\sigma_a} \ and \ m = \frac{\rho . E}{\sigma_a^2} \ . F_m . \Delta\, x_m$$

The deflection and peak load combined the autonomous geometric parameters by considering the minimum mass. This relationship can be expressed by:

$$m = 2. C_g . \frac{p.E}{\sigma_a^2} . U$$

Cg= constant considered from the geometry of the spring
U=$\frac{1}{2} F_m . \Delta x_m$= stored maximum amount of energy in the spring
Cg=1
The bending forces in the leaf-spring are normally cantilevered in a rectangular beam: []

$$\sigma_m = \frac{M.y}{I}, \Delta x = \frac{F.l^3}{3.E.I}, \ I = \frac{1}{12}.b.h^3, m = \rho.b.h.l$$

$\sigma_m$= maximum stress
M-F. I is moments support of the spring (100KN/ 2= 50)
y= ½ .h maximum distance from the center   0.012 meters
I= cross sectional area of the inertia movement [2' hydraulic spring]   $\pi.0.00508^2 = 0.0052 \ squared\ meters$
b= width of spring= 0.0001 meters
h- height of spring= 0.12 meters [17]
maximum stress in the pneumatic actuator =$\frac{50\times0.012}{0.0052} = 115.4 \ newtons$
spring displacement in actuator= $\frac{50\times0.12^3}{3\times7850kg/m3\times0.052m} = 0.0000071 \ meters$
note the elasticity of carbon steel used in the actuator is 7850 kg/m3

**7.1.2. Manufacture of control sensors.**

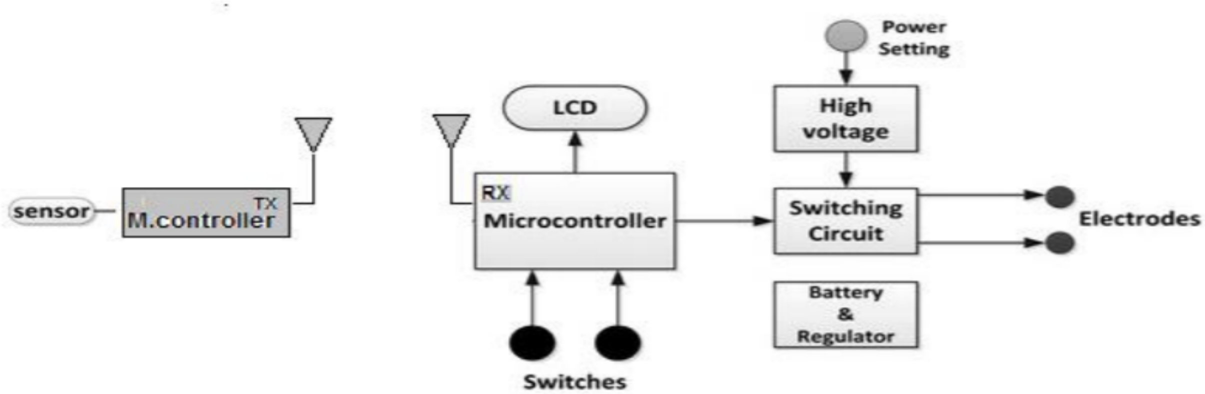
The ankle position and spring displacement measurements of the were computed by utilizing a calibration model. To calibrate the maximum torque, the current in the motor had to be lowered to meet the operating parameters. The measurements of the model were then measured by modelling the torque ankle as a function of the angle ankle while the pulley angle of the prothesis was fitted by regressing coefficients of least squares. The torque control responsiveness of the prothesis leg in different loads was gotten by:

$$w_m = K_p(T_d - T)$$

Wm= velocity command in the motor driver
Kp= proportional gain

Td and T= anticipated and angular measurements of the torque [17]
Programming the BIOM foot prototype.
To meet the engineering requirement that allows the system to be flexible and responsive like a real foot. To perform this function effectively WIFI support, Bluetooth and an MTU controller was needed to act as the power management unit for the BIOM prototype. A biomedical engineering innovation called FES (Functional Electronic Stimulation) was used to produce muscle movements which allow movement by supplying the nervous system with electrical impulses. The FES device will be attached to the MTU controller to trigger wireless communication through a Bluetooth device.
The Functional Electronic Stimulation consists of the following components: sensors, user control unit, power battery, stimulating unit, operating electrodes and clinical stimulation features as shown in the figure 45 below.

*Figure 45 [19]*

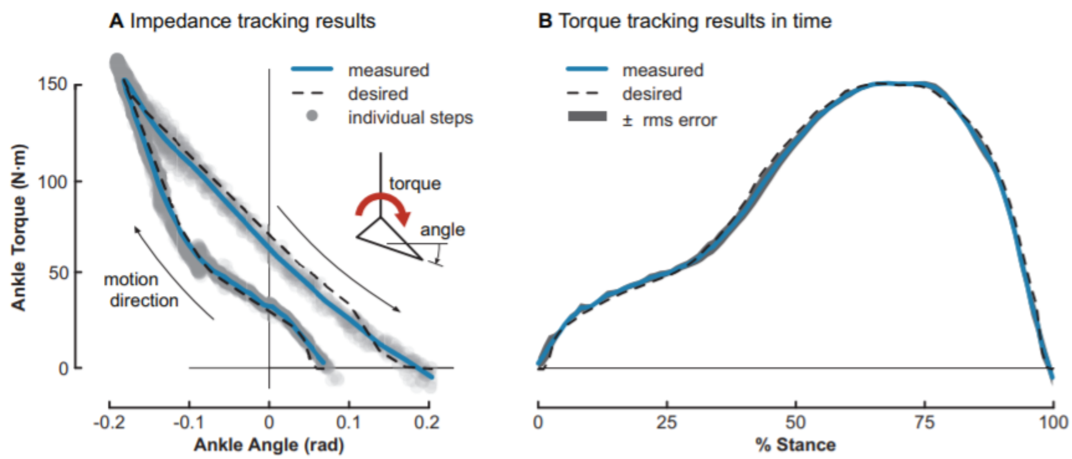



Some force sensitive sensors are connected with the MTU controller via input pins to show the simulated forces occurring in the lower limb. Goniometers sensors are also installed in the ankle joint to measure the angular displacements. Electromyograph sensors are connected to the electrode to provide measurements muscle activity. The measurement of the motion in the x, y and z direction is done using an accelerometer by utilizing analogue voltage. These sensors facilitated Bluetooth enabled wireless communication meeting the recommended specifications like cheapness, energy efficiency, low weight and minimum external support.
The MTU controller is fitted in an Arduino board with USB input, 13 output pins, setting button and a power jack-pin. An operating voltage of about 12 volts is supplied by the modular battery. This means the 5 volts needed in the Arduino board may cause overheating if 12 volts are allowed in the circuit. To prevent this a 20 to 50 Kilo- Ohms resistors are put to allow a current of about 40 milli amperes to pass through [19]. 5 LED lights (A0 A1 A2 A3 A4 and A5) are connected with the digital pins [19]. A reference voltage of 5 volts is connected with 6 analogue input of the Arduino providing a 10-bit resolution [19]

**7.2 Design changes**

The implementation of the manufacturing process was done assessing the prosthesis of the ankle foot. This assessment required an incorporation of design concepts on the electrical and electric systems of the prosthetic foot. The mechanical system was tested by observing the systematic changes by varying the control parameters like weight, leg angle, and current. A superior performance of the leg prototype was mainly achieved by changing the torque band width and loaded mass.

Functionality assessments were also done by conducting robotic walking trials in real-life conditions. At low torques, time tracked errors were measured at in varying angle space in *figure 47* below. [17]




The implementation also required the energy contribution that could affect human performance and the specifications considered such as battery, motor and the size of the spring. Systems that could control the torque were related with the velocity and the power changes from the battery.

Some of the problems encountered in the implementation process were the frequent alterations that were caused by the power changes. These changes could have resulted in errors when determining the torque, velocity displacement recorded in the prototype foot. When generating the configuration of the prosthetic leg, the motor dynamics and delay in communication could have brought irregular angle values limiting our ability to determine the angular torque.

The maximum torque was calibrated when running the current in the motor continuously. Measured models of the ankle torque in relation to ankle angle was fitted using regression squares. This calibration started from 0 kilograms to determine the deviation coefficient in the pully angle under different loads. The feedback of the proportion was determined by:

$$w_m = K_p(T_d - T)$$

Wm= velocity command in the motor driver

Kp= proportional gain

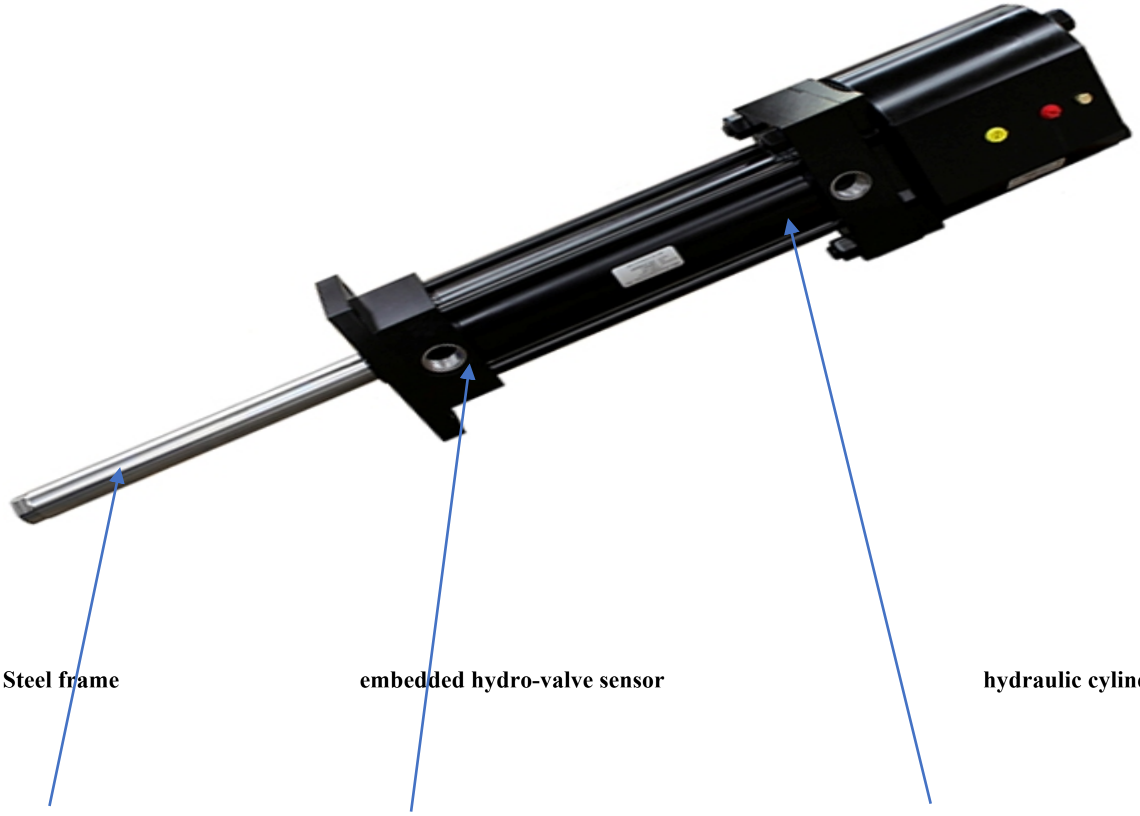
Td and T= anticipated and angular measurements of the torque [17]

**Solid works of the prosthetic foot.**

The hydraulic cylinder in the prosthetic leg has to support a maximum weight of 130 kilograms. The hydraulic power gets its energy from an electric pump driven by a modular battery. The customer specifications on the device have view the need for stability, reliability and durability as important parameters in our project. The control system needed in this device is controlled with a mechanical circuit which comprises of a hydraulic cylinder connected to a steel frame. The hydraulic cylinder (lower-limb) is connected to a hydro feedback sensor attached to a steel frame (upper limb).

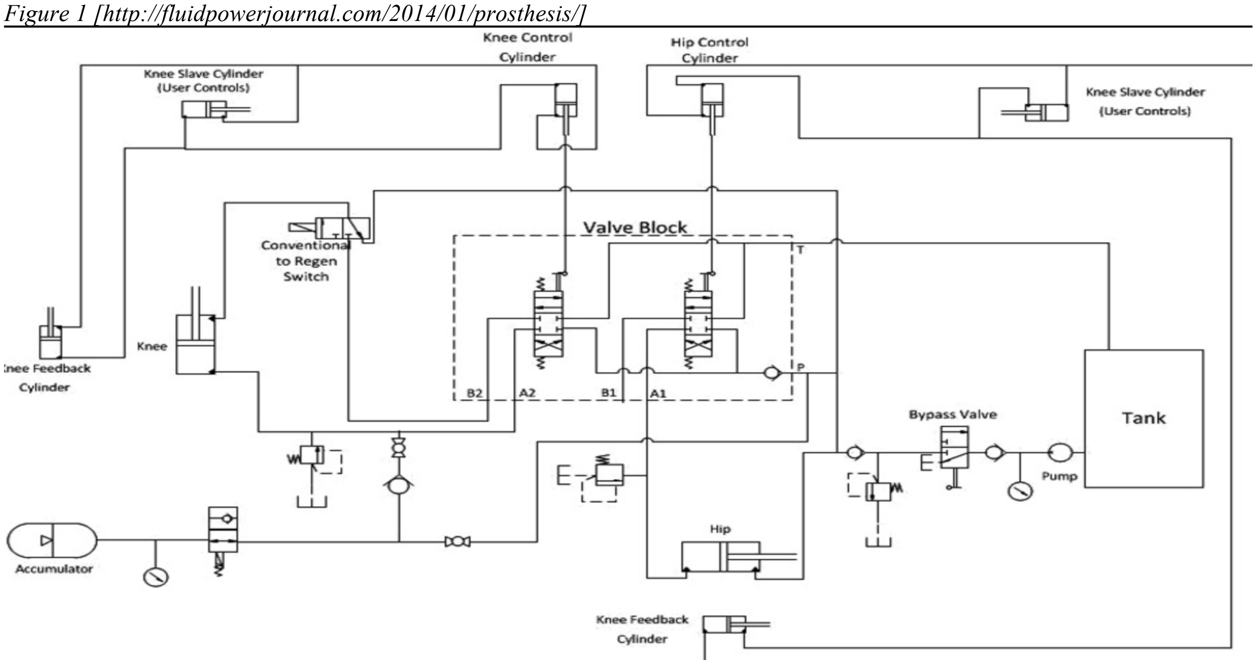
The steel frame and input cylinders are joined together with a hydro-force valve sensor connected in a series network. To maintain the needed pressure and force generated by the device, the hydro-force valve sensor is connected to an MTU microcontroller to allow maximum optimization of the system. System optimization produces the right pressure even when performing at maximum loads.

*Hydraulic cylinder with steel frame CAD diagram*




A schematic diagram of the hydro-force circuit is shown in the figure below:

*Figure 1 [http://fluidpowerjournal.com/2014/01/prosthesis/]*

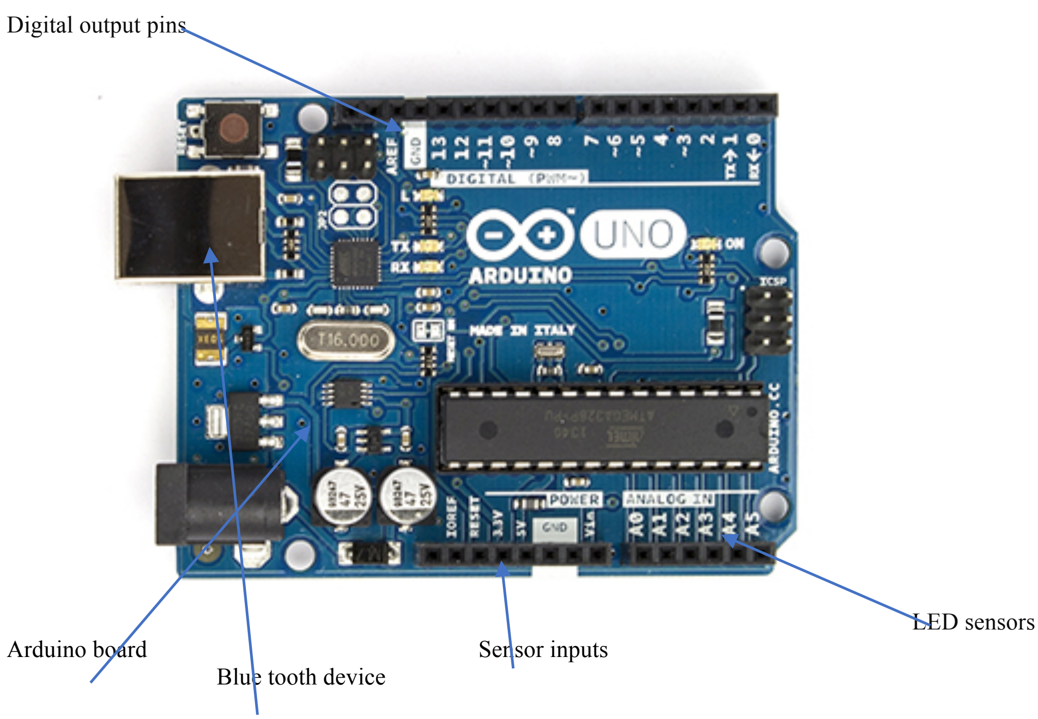


**The microcontroller and Arduino board**

The hydraulic actuator is installed in the prosthetic leg to act as the reference point of the control unit. A microcontroller controller acts as the control unit of the system with the hydro- force valves acting as the information transmitters. This device comprises of a Force sensitive sensor are connected with the microcontroller via input pins to show the simulated forces occurring in the lower limb. [ source: January 6, 2014, from http://home.roboticlab.eu/en/examples /sensor/force] Goniometers sensors are also installed in the ankle joint to measure the angular displacements. Electromyograph sensors are connected to the electrode to provide measurements muscle activity. The measurement of the motion in the x, y and z direction is done using an accelerometer by utilizing analogue voltage. Generally, these sensors detect and monitor force, change in slope, speed and different surface walk. A Bluetooth device utilizes wireless transfer of information to the sensors in the microcontroller. All these systems help us meet certain specifications in the project like; a 15 to 25-minute testing time, a 90-psi hydraulic pressure sensitivity, and enabling the prosthetic leg to function like a real foot.

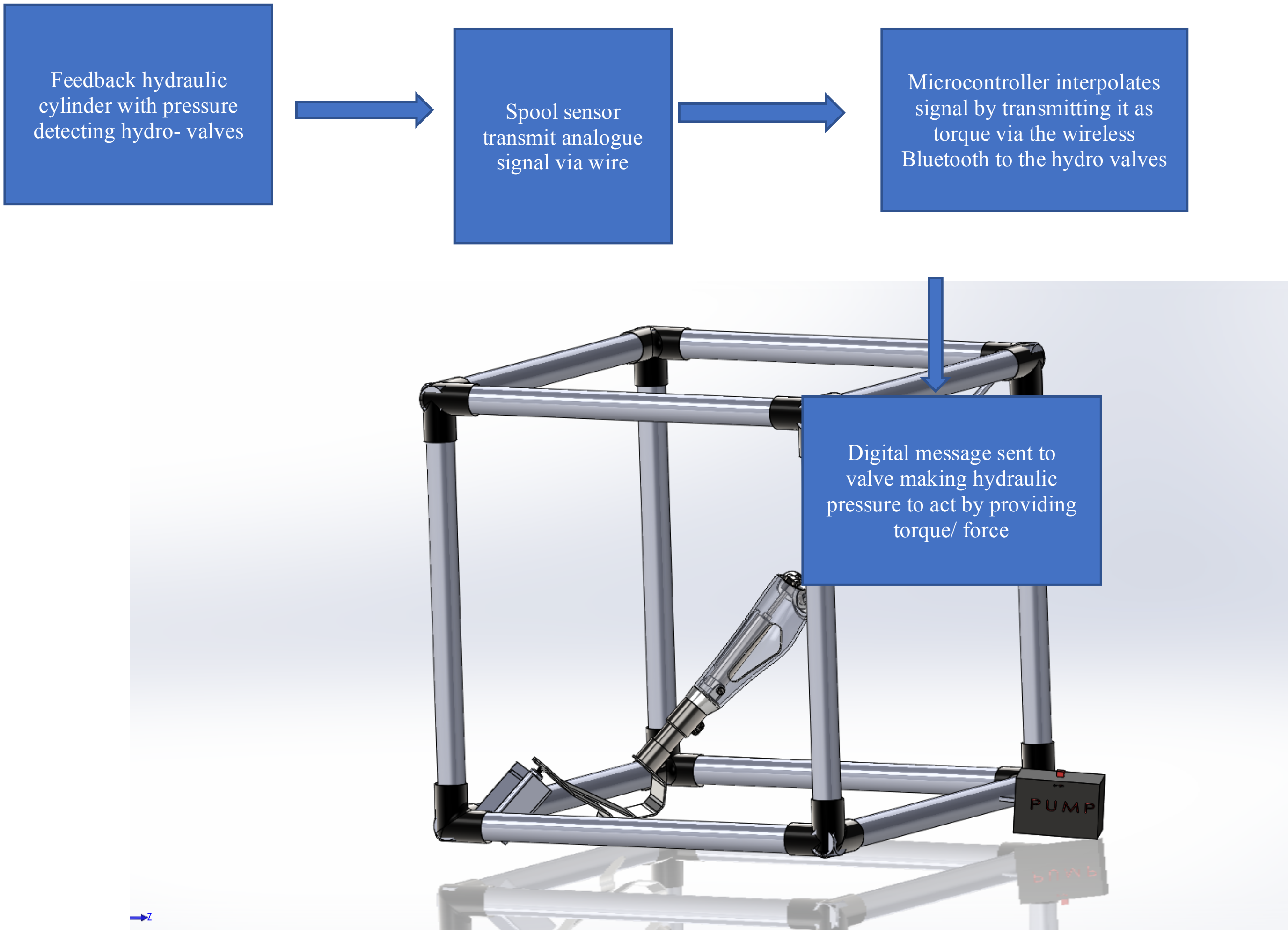
The MTU controller is fitted in an Arduino board with USB input, 13 output pins, setting button and a power jack-pin. An operating voltage of about 12 volts is supplied by the modular battery. This means the 5 volts needed in the Arduino board may cause overheating if 12 volts are allowed in the circuit. To prevent this a 20 to 50 Kilo- Ohms resistors are put to allow a current of about 40 milli amperes to pass through. 5 LED lights (A0 A1 A2 A3 A4 and A5) are connected with the digital pins. A reference voltage of 5 volts is connected with 6 analogue input of the Arduino providing a 10-bit resolution.

*A foot prosthetic CAD microcontroller*

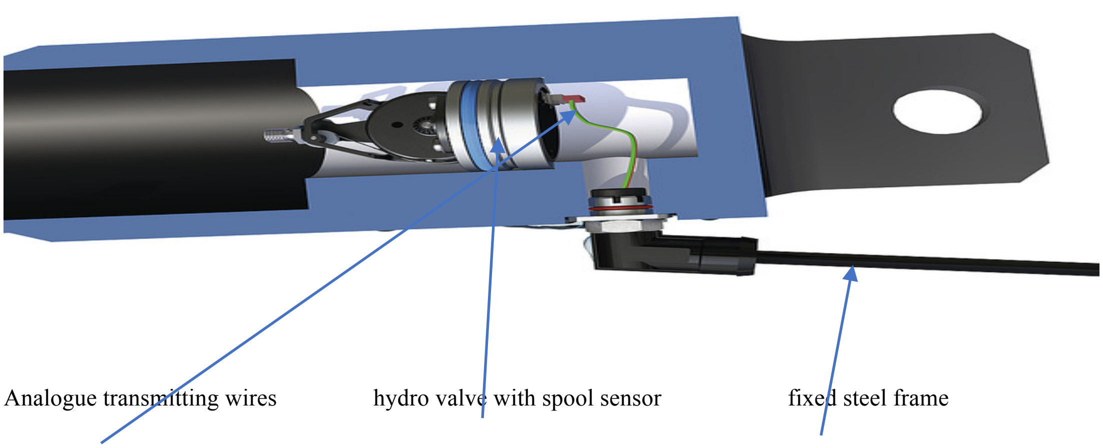



**Connection of the feedback hydraulic cylinder to micro controller.**

This connection occurs through the use of high- performance hydro-valves like the PVG 32 and the steering valves like the EHPS. A spool positioned sensor gets the signals from the valves from an input pot and directs them to the microcontroller that controls the functioning processes of the hydraulic cylinder. The analogue input moves to the microcontroller inform of pressure through a wire while the force output is transmitted by the Bluetooth to the control sensors in the valves as the recommended force or torque. A sample block diagram is shown below:




CAD diagram showing wire transporting pressure signals to the microcontroller

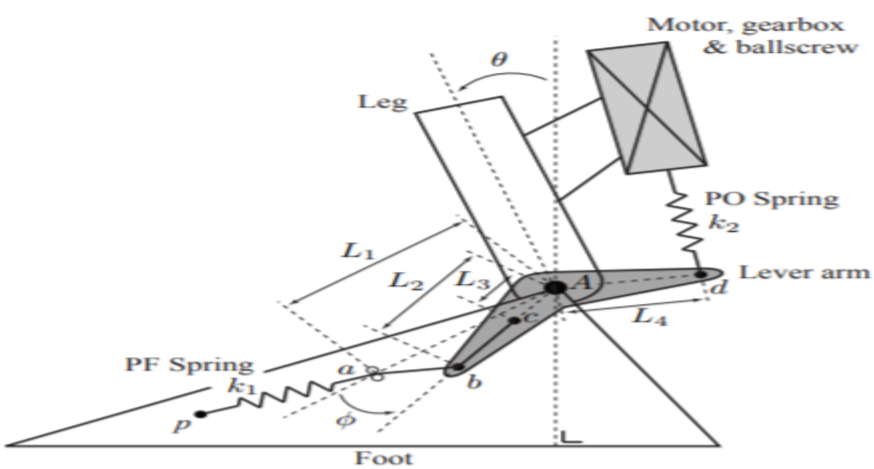



The corners bolts and screw for the steel pipes form the external components of the BIOM prototype. The steel pipes and bolts must be strong to maintain the stress while the hydraulic cylinder must support the exerted force by transmitting it to the movable parts of the foot. An effective distribution of forces and stress maintains the structural integrity of the prototype maintaining flexibility in motion. An external structure of the steel pipes and hydraulic cylinders are shown below.

To understand the external mechanical design of the prothetic foot, we have to incoporate the actuators in the hydraulics because they store energy in springs that help in tranmitting motion. Bulcky actuators are used  when producing high torque for a short period. The prothetic leg has three mainparts the lever, leg and foot. The table below shows the esential parts of the prosthetic foot.

| | |
|---|---|
| $\theta$ | Angle between lower foot and upper limb ( leg) |
| ∅ | Angle between foot and lever |
| PF | Spring stiffness *k1* |
| a, b and c | Rotational axis of L1, L2 nad L3 |
| PO | Spring stiffness *k2* |
| Fixed position d | Rotational axis of L4 |

*A Schematic Diagram of The Dimensions of The Prosthetic Foot Is Shown Below:*

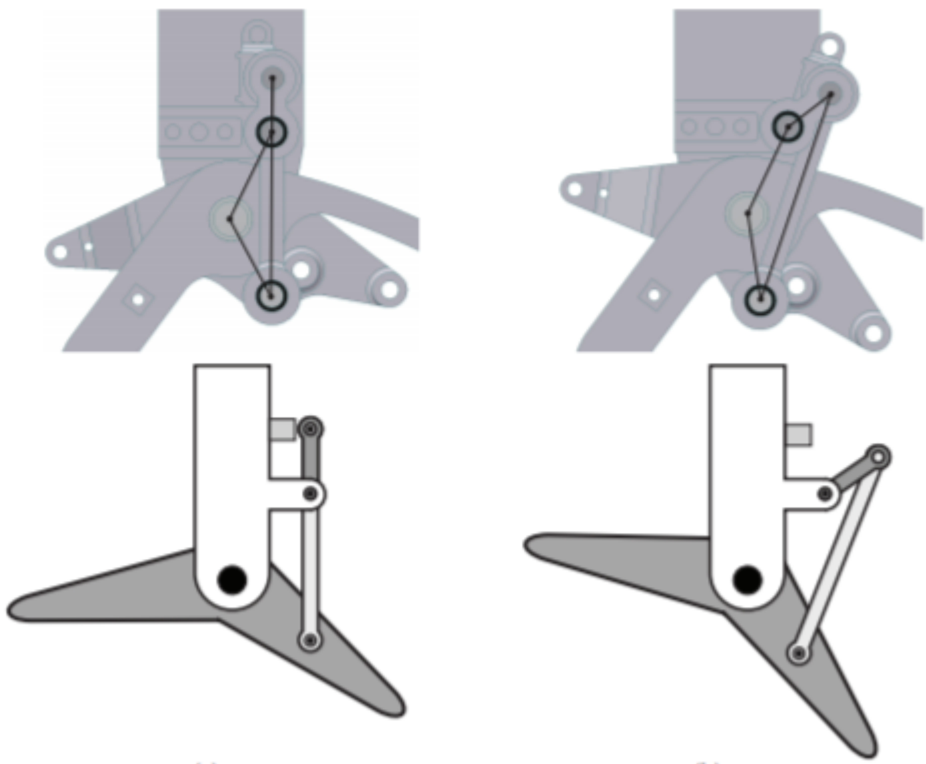



The dimensions of the lever and the stiffness of the spring have been shown in the table below.

| Lever length | Spring stiffness |
|---|---|
| L1 | K1= 300N/mm |
| L2 | V0,1= 5mm |
| L3 | K2- 120N/mm |
| L4 | V0,2= 0mm |

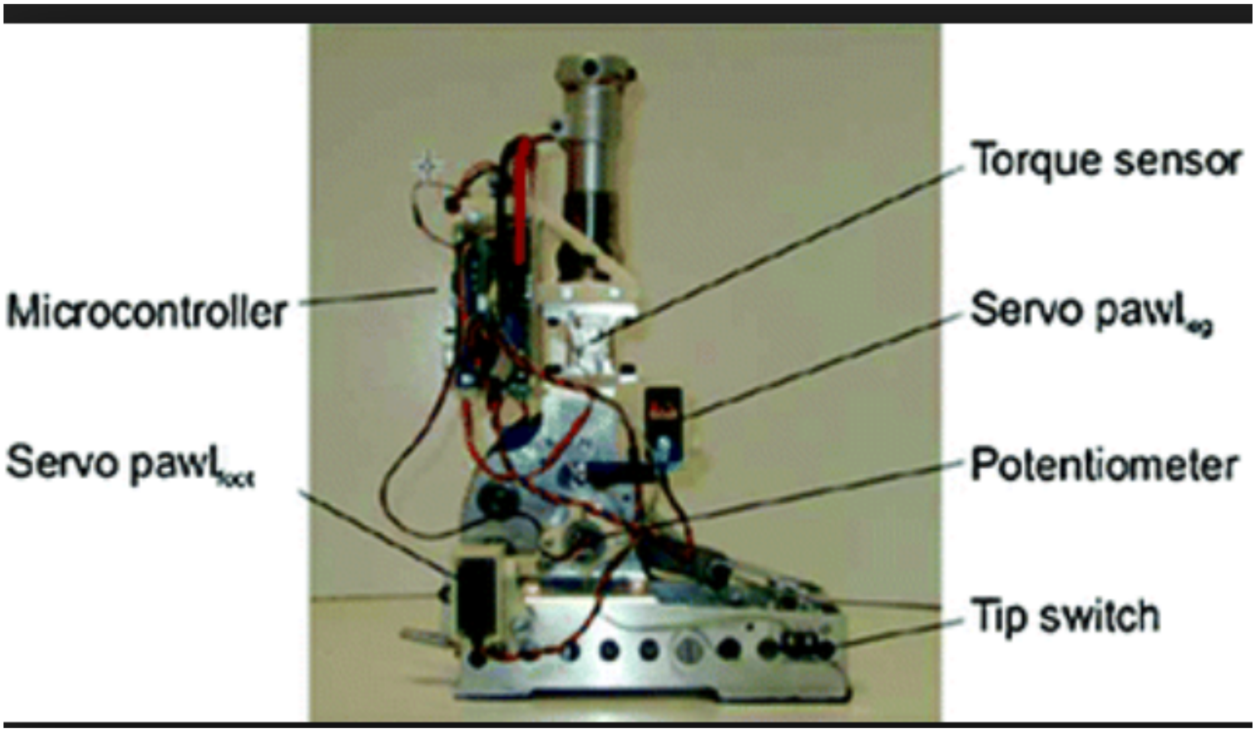
Source[https://www.google.com/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&ved=2ahUKEwiFz7X1_4rcAhUIwBQKHa1sA8sQ5TV6BAgBEAs&url=http%3A%2F%2Fmech.vub.ac.be%2Fmultibody%2Ftopics%2FProstheticDevices%2FAMP-Foot2.0%2FBioRob12.pdf&psig=AOvVaw1kYmoI4VXZ3p2ValkkfynO&ust=1530984500621030]

For example, a person with a weight of 75 kilograms will produce a 120 Nm torque. The articulation of the angle has moving range of about + 10 degrees at maximum dorsiflexion to – 20 degrees ae maximum plantarflexion. The maximum loading capacity at the PF and PO spring can be more or less than 40 Nm from either a locked and unlocked position as shown in the diagram below.



A CAD representation of the prosthetic foot has been shown below.

The connection between the microcontroller and the hydraulic cylinder is shown in the figure below:




**8 Testing**

Testing is very important when designing a prosthetic leg because the clinical and medical conditions involved in such a procedure. The biomechanics involved in body tissues mainly revolve around the pressure on the socket, friction around movable parts, response to mechanical loads plus tissue response to other physical conditions. A proper understanding in biomechanics will improve the fitting procedures needed to make us comprehend the residual stress that need to be catered for in a BIOM foot prototype. Recent surveys have showed that prosthetic foot amputees experience irritation in the skin, pain, dermatitis and other discomforts [20]. The testing procedures of the BIOM foot prototype needs an effective designed interface that will provide stability, comfort, effective load transmission, mobility and proper prosthetic plug-fit.

Computation tests methods.

To increase the bio-mechanic efficiency in the socket/BIOM foot prototype computational testing methods are used to conduct a stress/ strain stress on the tissues. The computational models are done with CAD technologies because they can provide quantitative information on how the load is transferred between the socket and foot prototype. This type of tests can be predicted by modelling a parametric analysis of motion, strain and stress to determine the best design [20].

A linear static analysis model considers the infinitesimal and linear deformation occurring in the BIOM prototype. Assumptions made in this test ignore the linear properties of the materials used and the frictional forces on the interface. This procedure meets our specifications of a small testing time that is about 10 to 30 minutes. A nonlinear analysis considers the nonlinear properties considers the frictional force by utilizing iterative procedures [20].

This was done by performing trials by fixing the prosthetic foot upside down and hanging known weights from the lower part of the BIOM foot. A variety of weights and angle variations were done to determine the operating conditions of our prototype on each operating condition. The maximum torque was calibrated when running the current in the motor continuously. The mathematical representation of the forces acting on the hydraulic cylinder can be represented by:

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

σ = uniform material stress,
F= spring force,
A= spring cross-sectional area [17]

**Problems encountered in calibration tests methods.**

The nonlinear methods require more time because of the complex iterative procedures and large deformation tests required in the analysis. Analytical simulations of the soft tissues neat the connecting socket exhibit complex mechanical properties that have large deformations that are difficult to simulate. Frictional simulations of the prosthetic foot and the lower limb may experience large displacements limiting the qualitative feedback of the tests.

**Mechanical and frictional tests**

These tests are mainly done on the skeletal and prosthetic socket to determine the pressure and force distribution on the prototype. Frictional phenomena between different bodies in contact involve testing the coefficient of friction on the skin surface, testing shear forces and measuring the relative motion between the bodies in contact. The frictional tests are done by determining coefficients of materials like Pelite, cotton sock, Silicone, nylon and aluminum were tested and had a 0.46 coefficient average [19]. This test was done to determine the functionalities of the skin under different conditions.

Biaxial shear forces tests are done by simulating skeletal movements of the device. Radiographic techniques measure the load conditions by using ultra sound techniques. Movements allowed to transmit ultrasound by conducting multiple tests. The prosthesis can be determined by utilizing the mathematical formulae below:

$$\sigma_m = \frac{M.y}{I}, \Delta x = \frac{F.l^3}{3.E.I},$$

$\sigma_m$= maximum stress
F. = exerted force
$\Delta x$ =maximum displacement
E= elastic modular of material
*l*= length of the steel pipe [17]

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# 8 APPENDICES

## *8.1 Appendix A: Additional Design Sketch*

The following design shown in the below figure shows a sketch of the design that is similar to Design-2 show in the body of the report. However, in this case instead of a robot, a robotic arm is used to exert the downward force that replicates the human leg exerting force on the prosthetic. The design consists of two arms connected to each other by a pivot joint and the bottom portion of the prosthetic is constructed of a metal leg that can withstand the force exerted by the robotic arm. Since there are two pivots, there are three-dimensional motion can achieved in this design. The advantage of this design is that it is a simple design. The disadvantage of the design is to figure out how the stance can absorb the impact forces without a hydraulic cylinder, damper or spring assembly. However, depending on the terrain, this arrangement may be favorable to certain clients.

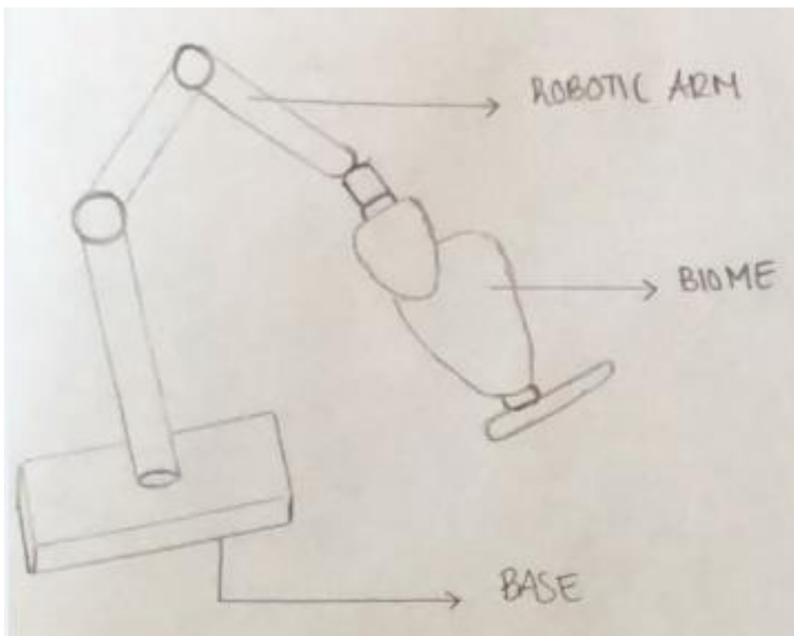


Figure 45. Design-10 proposed by the team

### *8.2 Appendix B: Output from Bentley Autopipe Stress Analysis Software for 2" Schedule 40 stainless steel pipe used*

------------------------------------------------------------------------------------------------------------
-
Biom1-2inSteel
04/25/2018 AUTOPIPE STRESSES                                        BENTLEY
                                                                    AutoPIPE Standard
11:23 PM                                                            11.01.00.23
------------------------------------------------------------------------------------------------------------ -

```
                              ******    ****** *****
     *                        *      ** *       **
    ***          **           **   ** ** **   ** **
     **
     **        ******         **   ** ** **   ** **
   **  ****  ** **  *****  *******  ** *******  *****
 *********
        *  **  ** ** **  ** **      ** **       **
  **      ** **  ** ** **  ** **      ** **       **
                                                *****
 **       *******  ** *****  **      ** **       **
```

Pipe Stress Analysis and Design Program

Version: 11.01.00.23

Edition: Standard

Developed and Maintained by

BENTLEY SYSTEMS, INCORPORATED
1600 Riviera Ave., Suite 300
Walnut Creek, CA 94596

```
***********************************************************
**          AUTOPIPE SYSTEM            **
**          INFORMATION                **
**                                     **
***********************************************************
```

SYSTEM NAME : Biom1-2inSteel

PROJECT ID : AUTOPIPE STRESSES

PREPARED BY : ______________________________
GROUP 7 – BIOM TEST FIXTURE

CHECKED BY : ______________________________

1ST APPROVER : ______________________________

2ND APPROVER : ______________________________

| | |
|---|---|
| PIPING CODE | : ASME B31.1 |
| YEAR | : 2016 |
| VERTICAL AXIS | : Y |
| AMBIENT TEMPERATURE | : 70.0 deg F |
| COMPONENT LIBRARY | : AUTOPIPE |
| MATERIAL LIBRARY | : B311-16 |
| MODEL REVISION NUMBER | : 0 |

*** Model changed and analysis results are outdated. Please re-analyze ***

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T A B L E O F C O N T E N T S

D I S P L A C E M E N T S

| Point name | Load combination | TRANSLATIONS (in ) X | Y | Z | ROTATIONS (deg ) X | Y | Z |
|---|---|---|---|---|---|---|---|
| *** Segment A begin *** | | | | | | | |
| A00 | Gravity{1} | -3.159 | -3.163 | 0.000 | 0.000 | 0.000 | 1.454 |
| | Thermal 1{1} | -2.930 | -3.070 | 0.000 | 0.000 | 0.000 | 1.125 |
| | GRT1 {1} | -6.088 | -6.233 | 0.000 | 0.000 | 0.000 | 2.579 |
| A01 | Gravity{1} | 0.001 | -0.001 | 0.000 | 0.000 | 0.000 | 0.384 |
| | Thermal 1{1} | 0.023 | -0.023 | 0.000 | 0.000 | 0.000 | 1.125 |
| | GRT1 {1} | 0.024 | -0.024 | 0.000 | 0.000 | 0.000 | 1.509 |
| A02 | Gravity{1} | 0.074 | 0.073 | 0.000 | 0.000 | 0.000 | -0.004 |
| | Thermal 1{1} | 0.497 | 0.466 | 0.000 | 0.000 | 0.000 | 1.000 |
| | GRT1 {1} | 0.571 | 0.539 | 0.000 | 0.000 | 0.000 | 0.996 |
| A03 | Gravity{1} | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Thermal 1{1} | 1.000 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | GRT1 {1} | 1.000 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| *** Segment A end *** | | | | | | | |

S U P P O R
( Force - lbf , Moment - ft- T F O R C E S
lb , Tran. - in , Rot. - deg )

Conne G L O B
Point/ ct/ Load L O C A L A L
Supp. Dir Defor Dir Defor
ID Type Combination n Force m n Force m
-------- -------- --------------------- ---- -------- -------- ---- -------- --------
Tag No.:
<None> for -
A00 Gravity{1} w 0.003 X 3.159
Dampe -
A00 l r Y 3.163
:RIGI
Stiff D Z 0.000
for -
Thermal 1{1} w 0.099 X 2.930
Comp. -
Wt : 0.250 Y 3.070
Z 0.000
for -
GRT1{1} w 0.103 X 6.088
-
Y 6.233
Z 0.000
Tag No.: GUIDESUPPORT dow
A01 Gravity{1} n 126 0.000 X -89 0.001
Guid -
A01 l e left 0.000 Y -89 0.001
:RIGI for
Stiff D w 0.001 Z 0.000
Thermal 1{1} up 66 0.000 X 47 0.023
Comp. -
Wt : 0.250 left 0.000 Y 47 0.023
for
w 0.033 Z 0.000
dow
GRT1{1} n 60 0.000 X -42 0.024
-
left 0.000 Y -42 0.024
for
w 0.034 Z 0.000

| | | | | | | |
|---|---|---|---|---|---|---|
| Tag No.: DAMPERSUPPORT | | | for | | | |
| A02 | Damp | Gravity{1} | w | 0.001 | X | 0.074 |
| A02 l | +Wnd | | | | Y | 0.073 |
| | :RIGI | | | | | |
| Stiff | D | | | | Z | 0.000 |
| | | | for | | | |
| Comp. | | Thermal 1{1} | w | 0.022 | X | 0.497 |
| Wt : | 0.250 | | | | Y | 0.466 |
| | | | | | Z | 0.000 |
| | | | for | | | |
| | | GRT1{1} | w | 0.023 | X | 0.571 |
| | | | | | Y | 0.539 |
| | | | | | Z | 0.000 |
| Tag No.: DAMPER SUPPORT | | | bac | | | |
| A03 | Dampe | Gravity{1} | k | 0.000 | X | 0.000 |
| A03 l | r | | | | Y | 0.000 |
| | :RIGI | | | | | |
| Stiff | D | | | | Z | 0.000 |
| | | | bac | | | |
| Comp. | | Thermal 1{1} | k | 0.000 | X | 1.000 |
| Wt : | 0.250 | | | | Y | 1.000 |
| | | | | | Z | 0.000 |
| | | | bac | | | |
| | | GRT1{1} | k | 0.000 | X | 1.000 |
| | | | | | Y | 1.000 |
| | | | | | Z | 0.000 |

R E S T R A I N T R E A C T I O N S

| Point name | Load combination | FORCES (lbf ) X | Y | Z | Result | MOMENTS (ft-lb ) X | Y | Z | Result |
|---|---|---|---|---|---|---|---|---|---|
| ------ | ---------------------- | ------ | ------ | ------ | ------ | ------- | ------- | ------- | ------- |
| A00 | Damper Tag No.: <None> [ID: A00 1] | | | | | | | | |
| | Gravity{1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Thermal 1{1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | GRT1 {1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| A01 | Guide Tag No.: GUIDESUPPORT [ID: A01 1] | | | | | | | | |
| | Gravity{1} | -89 | -89 | 0 | 126 | 0 | 0 | 0 | 0 |
| | Thermal 1{1} | 47 | 47 | 0 | 66 | 0 | 0 | 0 | 0 |
| | GRT1 {1} | -42 | -42 | 0 | 60 | 0 | 0 | 0 | 0 |
| A02 | Damp +Wnd Tag No.: DAMPERSUPPORT [ID: A02 1] | | | | | | | | |
| | Gravity{1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Thermal 1{1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | GRT1 {1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| A03 | Anchor Tag No.: ANCHOR2 | | | | | | | | |
| | Gravity{1} | 292 | -214 | 0 | 362 | 0 | 0 | -184 | 184 |
| | Thermal 1{1} | -47 | -47 | 0 | 66 | 0 | 0 | 594 | 594 |
| | GRT1 {1} | 245 | -260 | 0 | 358 | 0 | 0 | 410 | 410 |
| A03 | Damper Tag No.: DAMPER SUPPORT [ID: A03 1] | | | | | | | | |
| | Gravity{1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Thermal 1{1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | GRT1 {1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

55

G L O B A L F O R C E S & M O M E N T S

| Point name | Load combination | FORCES (lbf) X | Y | Z | Result | MOMENTS (ft-lb) X | Y | Z | Result |
|---|---|---|---|---|---|---|---|---|---|
| *** Segment A begin *** | | | | | | | | | |
| A00 | Gravity{1} | 203 | -203 | 0 | 287 | 0 | 0 | 0 | 0 |
| | Thermal 1{1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | GRT1 {1} | 203 | -203 | 0 | 287 | 0 | 0 | 0 | 0 |
| A01 - | Gravity{1} | 203 | -269 | 0 | 337 | 0 | 0 | 421 | 421 |
| | Thermal 1{1} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | GRT1 {1} | 203 | -269 | 0 | 337 | 0 | 0 | 421 | 421 |
| A01+ | Gravity{1} | 292 | -180 | 0 | 343 | 0 | 0 | 421 | 421 |
| | Thermal 1{1} | -47 | -47 | 0 | 66 | 0 | 0 | 0 | 0 |
| | GRT1 {1} | 245 | -227 | 0 | 334 | 0 | 0 | 421 | 421 |
| A02 - | Gravity{1} | 292 | -191 | 0 | 349 | 0 | 0 | 196 | 196 |
| | Thermal 1{1} | -47 | -47 | 0 | 66 | 0 | 0 | 198 | 198 |
| | GRT1 {1} | 245 | -238 | 0 | 342 | 0 | 0 | 394 | 394 |
| A02+ | Gravity{1} | 292 | -191 | 0 | 349 | 0 | 0 | 196 | 196 |
| | Thermal 1{1} | -47 | -47 | 0 | 66 | 0 | 0 | 198 | 198 |
| | GRT1 {1} | 245 | -238 | 0 | 342 | 0 | 0 | 394 | 394 |
| A03 | Gravity{1} | 292 | -213 | 0 | 362 | 0 | 0 | -184 | 184 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Thermal 1{1} | -47 | -47 | 0 | 66 | 0 | 0 | 594 | 594 |
| GRT1 {1} | 245 | -260 | 0 | 357 | 0 | 0 | 410 | 410 |

*** Segment A end ***

CODE COMPLIANCE

ASME B31.1 (2016)
(Moments in ft-lb ) (Stress in psi )

| Point name | Load combination | Ma (Sus.) | Mb (Occ.) | Mc (Exp.) | S.I.F | Eq. no. | Load type | Code Stress | Code Allow. |
|---|---|---|---|---|---|---|---|---|---|
| *** Segment A begin *** | | | | | | | | | |
| A00 | Max P{1} | | | | | ( 3) | HOOP | 123 | 17100 |
| | GR + Max P{1} | 0 | | | 1.00 | (15) | SUST | 57 | 17100 |
| | TR:Amb to T1{1} | | | 0 | 1.00 | (17) | DISP | 0 | 25650 |
| | Amb to T1{1} | | | 0 | 1.00 | (17) | DISP | 0 | 25650 |
| A01 | Max P{1} | | | | | ( 3) | HOOP | 123 | 17100 |
| | GR + Max P{1} | 421 | | | 1.00 | (15) | SUST | 9078 | 17100 |
| | TR:Amb to T1{1} | | | 0 | 1.00 | (17) | DISP | 0 | 25650 |
| | Amb to T1{1} | | | 0 | 1.00 | (17) | DISP | 0 | 25650 |
| A02 | Max P{1} | | | | | ( 3) | HOOP | 123 | 17100 |
| | GR + Max P{1} | 196 | | | 1.00 | (15) | SUST | 4255 | 17100 |
| | TR:Amb to T1{1} | | | 198 | 1.00 | (17) | DISP | 4235 | 25650 |
| | Amb to T1{1} | | | 198 | 1.00 | (17) | DISP | 4235 | 25650 |
| A03 | Max P{1} | | | | | ( 3) | HOOP | 123 | 17100 |
| | GR + Max P{1} | 184 | | | 1.00 | (15) | SUST | 3993 | 17100 |
| | TR:Amb to T1{1} | | | 594 | 1.00 | (17) | DISP | 12704 | 25650 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Amb | T1{1 | | | | DIS | | 2565 |
| to | } | 594 | 1.00 | (17) | P | 12704 | 0 |

***

Segment A end ***

R E S U L T S U M M A R Y
---------------------------

Maximum displacements (in)
---------------------------

| | | | |
|---|---|---|---|
| Maximum X : | -6.088 | Point : A00 | Load Comb.: GRT1{1} |
| Maximum Y : | -6.233 | Point : A00 | Load Comb.: GRT1{1} |
| Max. total: | 8.713 | Point : A00 | Load Comb.: GRT1{1} |

Maximum rotations (deg)
-----------------------

| | | | |
|---|---|---|---|
| Maximum Z : | 2.579 | Point : A00 | Load Comb.: GRT1{1} |
| Max. total: | 2.579 | Point : A00 | Load Comb.: GRT1{1} |

Maximum restraint forces (lb)
-----------------------------

| | | | |
|---|---|---|---|
| Maximum X : | 292 | Point : A03 | Load Comb.: Gravity{1} |
| Maximum Y : | -260 | Point : A03 | Load Comb.: GRT1{1} |
| Max. total: | 362 | Point : A03 | Load Comb.: Gravity{1} |

Maximum restraint moments (ft-lb)
---------------------------------

| | | | |
|---|---|---|---|
| Maximum Z : | 594 | Point : A03 | Load Comb.: Thermal 1{1} |
| Max. total: | 594 | Point : A03 | Load Comb.: Thermal 1{1} |

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R E S U L T S U M M A R Y
----------------------------

Maximum pipe forces (lb)
-------------------------

| | | | |
|---|---|---|---|
| Maximum X : | 292 | Point : A01 | Load Comb.: Gravity{1} |
| Maximum Y : | -269 | Point : A01 | Load Comb.: Gravity{1} |
| Max. total: | 362 | Point : A03 | Load Comb.: Gravity{1} |

Maximum pipe moments (ft-lb)
-----------------------------

| | | | |
|---|---|---|---|
| Maximum Z : | 594 | Point : A03 | Load Comb.: Thermal 1{1} |
| Max. total: | 594 | Point : A03 | Load Comb.: Thermal 1{1} |

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R E S U L T S U M M A R Y
----------------------------

Maximum sustained stress
Point ps : A01
Stress i : 9078
Allowable psi : 17100
Ratio : 0.53
Load combination : GR + Max P{1}

Maximum displacement stress
Point ps : A03
Stress i : 12704
Allowable psi : 25650
Ratio : 0.50
Load combination : Max Range

Maximum hoop stress
Point ps : A00
Stress i : 123
Allowable psi : 17100
Ratio : 0.01
Load combination : Max P{1}

R E S U L T S U M M A R Y
---------------------------

Maximum sustained stress ratio
Point ps : A01
Stress i : 9078
Allowable psi : 17100
Ratio : 0.53
Load combination : GR + Max P{1}

Maximum displacement stress ratio
Point ps : A03
Stress i : 12704
Allowable psi : 25650
Ratio : 0.50
Load combination : Max Range

Maximum hoop stress ratio
Point ps : A00
Stress i : 123
Allowable psi : 17100
Ratio : 0.01
Load combination : Max P{1}

* * * The system satisfies ASME B31.1 (2016) code requirements * * *
* * * for the selected options * * *

### *8.3 Appendix C: Datasheet for the selection of hydraulic cylinder*

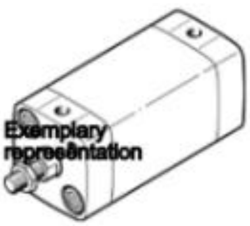
Also see https://www.festo.com/cat/en-gb_gb/data/doc_ENGB/PDF/EN/CDC_EN.PDF

## Compact cylinder
## CDC-80- -

Part number: 543311

FESTO

Based on ISO 21287, Clean Design




## Data sheet

Overall data sheet – Individual values depend upon your configuration.

| Feature | Value |
| --- | --- |
| Stroke | 1 ... 500 mm |
| Piston diameter | 80 mm |
| Based on the standard | ISO 21287 |
| Cushioning | P: Flexible cushioning rings/plates at both ends |
| Assembly position | Any |
| Design structure | Piston<br>Piston rod |
| Position detection | For proximity sensor |
| Variants | Extended male piston rod thread<br>Piston rod with special thread<br>Extended piston rod<br>Through piston rod<br>Heat resistant seals, max. 120°C<br>Single-ended piston rod |
| Working pressure | 0.6 ... 10 bar |
| Mode of operation | double-acting |
| Operating medium | Compressed air in accordance with ISO8573-1:2010 [7:4:4] |
| Note on operating and pilot medium | Lubricated operation possible (subsequently required for further operation) |
| Corrosion resistance classification CRC | 3 - High corrosion stress |
| Food-safe | See Supplementary material information |
| Ambient temperature | -20 ... 120 °C |
| Theoretical force at 6 bar, return stroke | 2,827 N |
| Theoretical force at 6 bar, advance stroke | 2,827 ... 3,016 N |
| Mounting type | Optional<br>with through hole<br>with internal (female) thread |
| Pneumatic connection | G1/8 |
| Material cover | Wrought Aluminum alloy<br>Anodized |
| Material piston rod | High alloy steel, non-corrosive |
| Material cylinder barrel | Wrought Aluminum alloy<br>Anodized |

### 8.4 *Appendix D: Bill of Materials*

Table 5 below shows the list of items needed for the project and the estimated retail cost of the items.

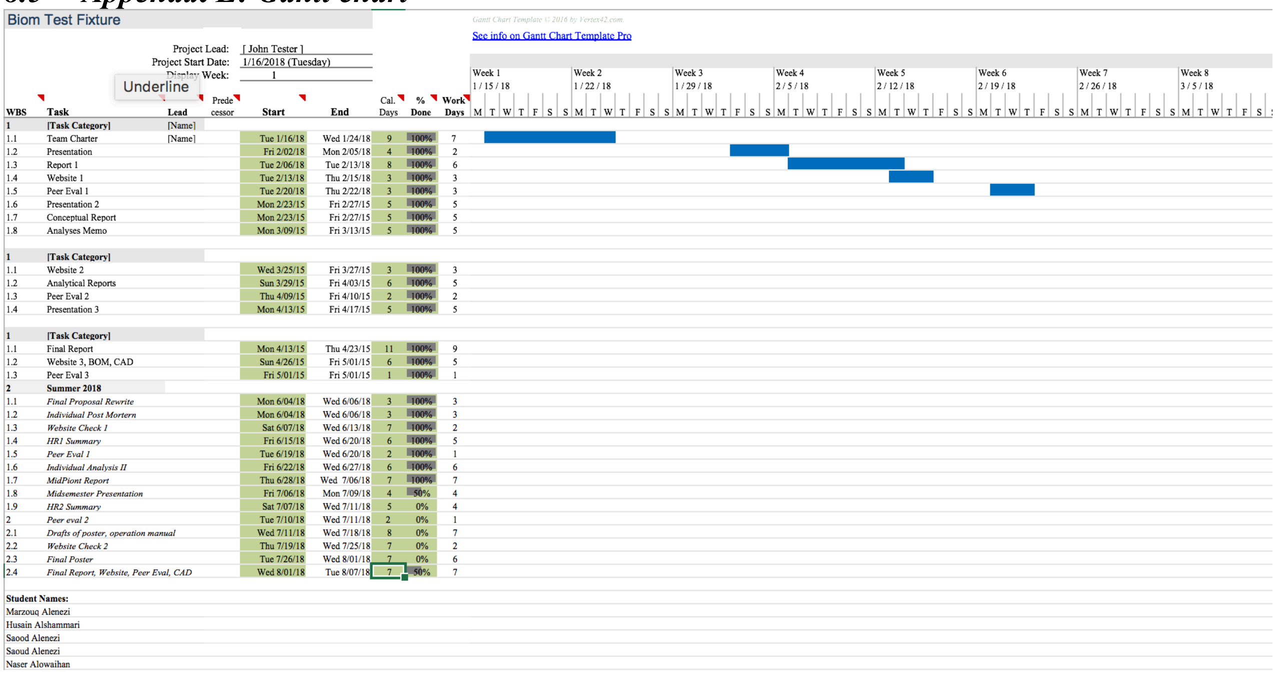
*Table 5. Bill of Materials*

| **Item** | **Manufacturer** | **Retail Cost** | **Quantity** | **Total Retail Cost** |
|---|---|---|---|---|
| 2" Stainless Steel Sch 40 pipes | Metals4UOnline.com[1] | $38.40 | 1 | $38.40 |
| Screws | Amazon | $10 | 1 | $10 |
| Fasteners | Amazon | $10 | 1 | $10 |
| Bolts | Amazon | $10 | 1 | $10 |
| Fittings[2] | www.zoro.com | $10 | 8 | $80 |
| Hydraulic Cylinder | Festo<br>Call 1-866-GO-FESTO | | 1 | |
| Battery | www.revzilla.com | $89.85 | | $89.85 |
| Shipping Charges | All above | $75 | 1 | $50 |
| Grand Total | | | | $288.25 |

**Sources:**


1. https://www.metals4uonline.com/stainless-steel-pipe-sch-40-304-2in?gclid=Cj0KCQjwu_jYBRD8ARIsAC3EGCLpVmyKc3t23cJGxu6MCx6essMxF3Ld-- eSGMhF9sftNQ2fLZwbnVMaAqdMEALw_wcB
2. https://www.zoro.com/zoro-select-structural-fitting-side-outlet-elbow-4uj32/i/G1562093/feature-product?gclid=Cj0KCQjwu_jYBRD8ARIsAC3EGCJp16lp7VhXhOLtXvgUsp-YJVDwvoX1S4lI7TyuiafqRiY6BG2Wt4kaAhuBEALw_wcB

## 8.5 *Appendix E: Gantt chart*




| WBS | Task | Lead | Predecessor | Start | End | Cal. Days | % Done | Work Days |
|---|---|---|---|---|---|---|---|---|
| **1** | **[Task Category]** | [Name] | | | | | | |
| 1.1 | Team Charter | [Name] | | Tue 1/16/18 | Wed 1/24/18 | 9 | 100% | 7 |
| 1.2 | Presentation | | | Fri 2/02/18 | Mon 2/05/18 | 4 | 100% | 2 |
| 1.3 | Report 1 | | | Tue 2/06/18 | Tue 2/13/18 | 8 | 100% | 6 |
| 1.4 | Website 1 | | | Tue 2/13/18 | Thu 2/15/18 | 3 | 100% | 3 |
| 1.5 | Peer Eval 1 | | | Tue 2/20/18 | Thu 2/22/18 | 3 | 100% | 3 |
| 1.6 | Presentation 2 | | | Mon 2/23/15 | Fri 2/27/15 | 5 | 100% | 5 |
| 1.7 | Conceptual Report | | | Mon 2/23/15 | Fri 2/27/15 | 5 | 100% | 5 |
| 1.8 | Analyses Memo | | | Mon 3/09/15 | Fri 3/13/15 | 5 | 100% | 5 |
| **1** | **[Task Category]** | | | | | | | |
| 1.1 | Website 2 | | | Wed 3/25/15 | Fri 3/27/15 | 3 | 100% | 3 |
| 1.2 | Analytical Reports | | | Sun 3/29/15 | Fri 4/03/15 | 6 | 100% | 5 |
| 1.3 | Peer Eval 2 | | | Thu 4/09/15 | Fri 4/10/15 | 2 | 100% | 2 |
| 1.4 | Presentation 3 | | | Mon 4/13/15 | Fri 4/17/15 | 5 | 100% | 5 |
| **1** | **[Task Category]** | | | | | | | |
| 1.1 | Final Report | | | Mon 4/13/15 | Thu 4/23/15 | 11 | 100% | 9 |
| 1.2 | Website 3, BOM, CAD | | | Sun 4/26/15 | Fri 5/01/15 | 6 | 100% | 5 |
| 1.3 | Peer Eval 3 | | | Fri 5/01/15 | Fri 5/01/15 | 1 | 100% | 1 |
| **2** | **Summer 2018** | | | | | | | |
| 1.1 | *Final Proposal Rewrite* | | | Mon 6/04/18 | Wed 6/06/18 | 3 | 100% | 3 |
| 1.2 | *Individual Post Mortern* | | | Mon 6/04/18 | Wed 6/06/18 | 3 | 100% | 3 |
| 1.3 | *Website Check 1* | | | Sat 6/07/18 | Wed 6/13/18 | 7 | 100% | 2 |
| 1.4 | *HR1 Summary* | | | Fri 6/15/18 | Wed 6/20/18 | 6 | 100% | 5 |
| 1.5 | *Peer Eval 1* | | | Tue 6/19/18 | Wed 6/20/18 | 2 | 100% | 1 |
| 1.6 | *Individual Analysis II* | | | Fri 6/22/18 | Wed 6/27/18 | 6 | 100% | 6 |
| 1.7 | *MidPiont Report* | | | Thu 6/28/18 | Wed 7/06/18 | 7 | 100% | 7 |
| 1.8 | *Midsemester Presentation* | | | Fri 7/06/18 | Mon 7/09/18 | 4 | 50% | 4 |
| 1.9 | *HR2 Summary* | | | Sat 7/07/18 | Wed 7/11/18 | 5 | 0% | 4 |
| 2 | *Peer eval 2* | | | Tue 7/10/18 | Wed 7/11/18 | 2 | 0% | 1 |
| 2.1 | *Drafts of poster, operation manual* | | | Wed 7/11/18 | Wed 7/18/18 | 8 | 0% | 7 |
| 2.2 | *Website Check 2* | | | Thu 7/19/18 | Wed 7/25/18 | 7 | 0% | 2 |
| 2.3 | *Final Poster* | | | Tue 7/26/18 | Wed 8/01/18 | 7 | 0% | 6 |
| 2.4 | *Final Report, Website, Peer Eval, CAD* | | | Wed 8/01/18 | Tue 8/07/18 | 7 | 50% | 7 |

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Source code for main program

The source code main program of the MTU controller is:
Declare variables for main program,
Configuration of outside ports,
Initialize LCD Display to display start up,

```
int force=20; // define the pressure difference of hydraulic cylinder;
 int mus1A=0; // choose starting value of the muscles in limb1
 int mus1B=0; // choose starting value of the muscles in limb 2
 int inc1A=0; // define the speed of pressure difference for mus1A int inc1B=stp;

void setup () {
 pin Mode (3, OUTPUT); // assign port 3 as output
 pinMode(5, OUTPUT); // assign port 5 as output
pinMode(6, OUTPUT); // assign port 6 as output
```

```
}
void loop() {
 analogWrite(3, mus1A); // assign port 3 to mus1A
analogWrite(5, mus1B); // assign port 5 to mus1B
void set up() {
pinMode(3, OUTPUT); // assign port 3 as output
pinMode(5, OUTPUT); // assign port 5 as output
pinMode(6, OUTPUT); // assign port 6 as output
 pinMode(9, OUTPUT); // assign port 9 as output
 pinMode(10, OUTPUT); // assign port 10 as output
 pinMode(11, OUTPUT); // assign port 11 as output }
 void loop() {
 analogWrite( for , muscle in lower and upper limb;
mus3A); // assign port 3 to muscle 2 analogWrite(4, mus1); // assign port 5 to mus1 analogWrite(6, mus3C); // assign port 6 to mus1C analogWrite(9, mus1); // assign port 9 to mus2A analogWrite(10, mus2B); // assign port 10 to mus 1 analogWrite(11, mus1); // assign port 11 to mus1
end loop
}
```



...