BIOM Test Fixture

Final Proposal Report

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DISCLAIMER

TABLE OF CONTENTS

Contents

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 [3]. Recent advances in prosthetics and orthotics hold great promise for maximizing physical function for patients who have experienced severe extremity trauma [1]. 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 [1].

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. The goal is to eliminate the role of humans in testing phase and replace it with a test fixture to do all the testing.

Figure 1. Image of a prosthetic leg using a BiOM [6]

1.2 Project Description

The current project discusses the design for a BiOM. 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 [5]. 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.

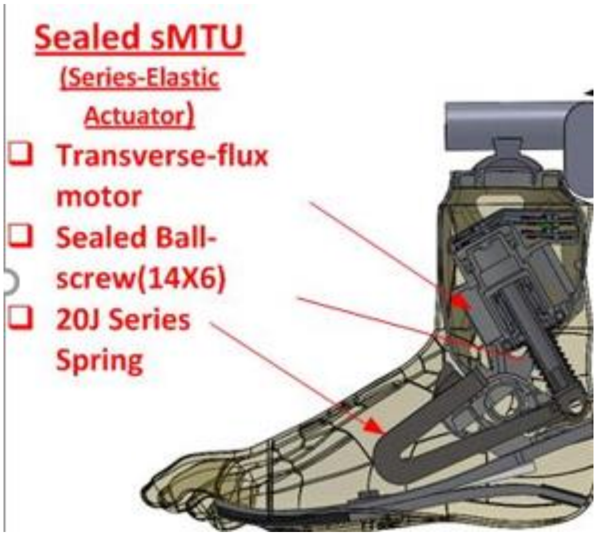


Figure 2. BiOM Ankle Architecture [14]

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 [15] 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.

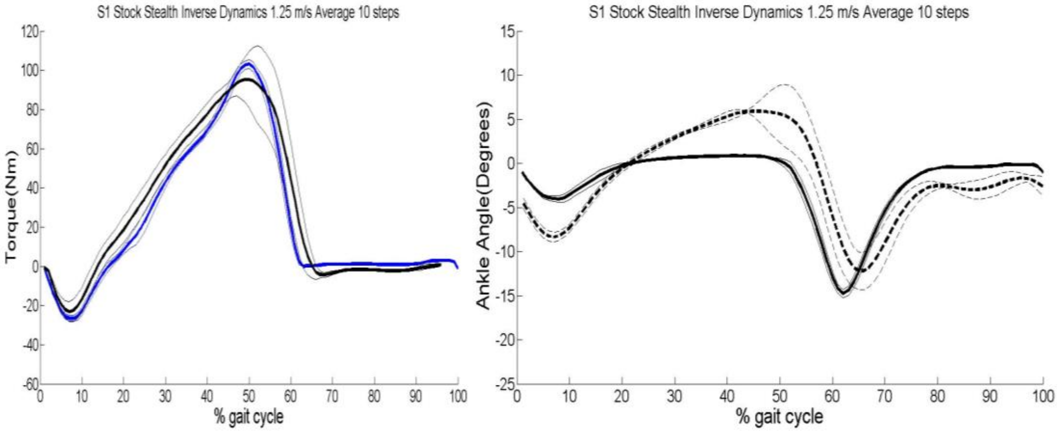


Figure 3. Torque and Ankle Angle: Stock Level Walking for 1.25 m/s [15]

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

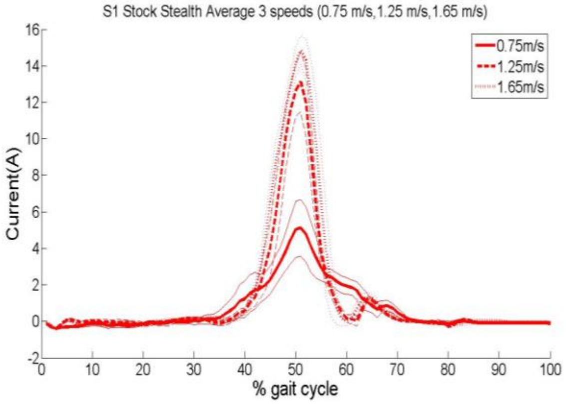


Figure 4. Current: Level Walking for 1.25 m/s [15]

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.

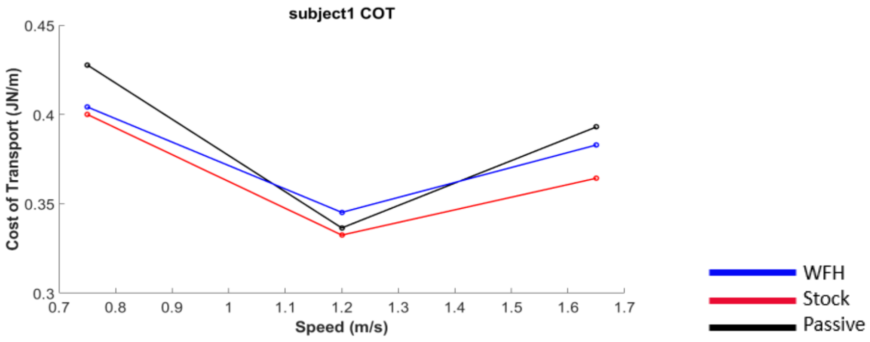


Figure 5. Cost of Transport [15]

Figure 6 and Figure 7 show the torque and angle for unstairs 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.

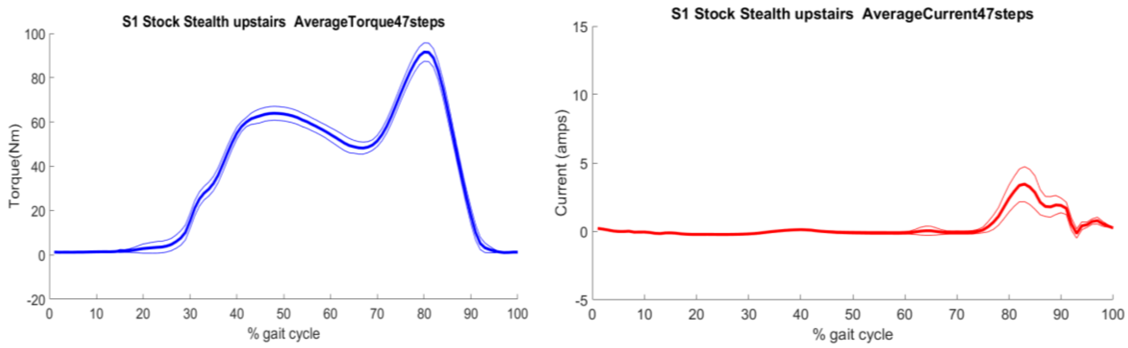


Figure 6. Upstairs: Torque and Current [15]

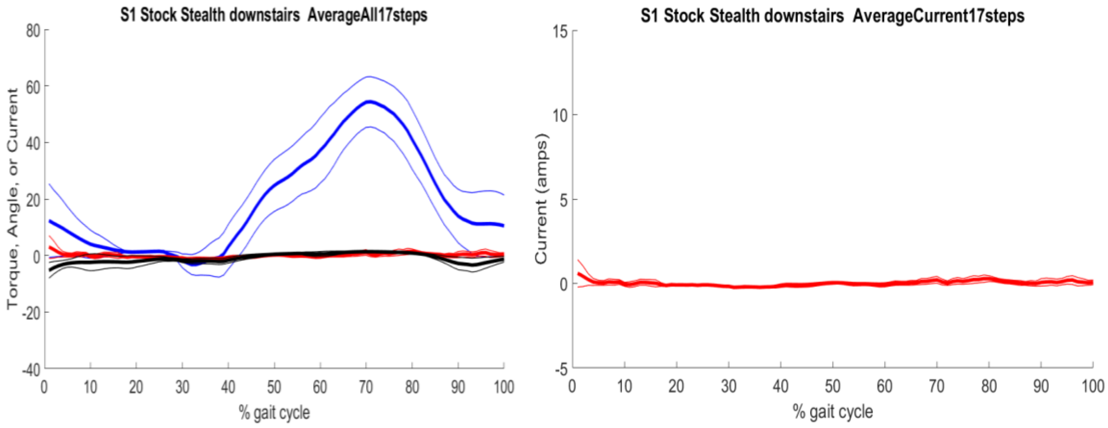


Figure 7. Downstairs: Torque, Ankle Angle and Current [15]

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.

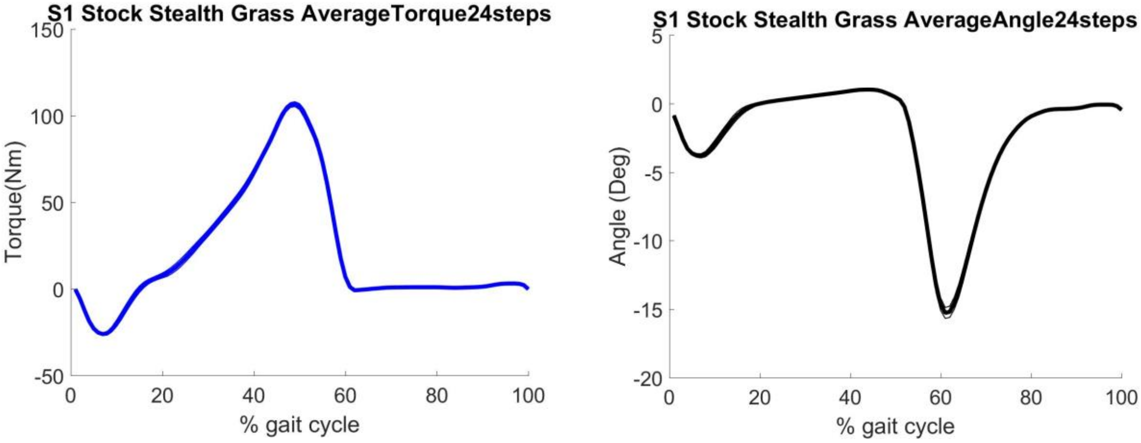


Figure 8. Grass: Torque and Ankle Angle versus % gait cycle [15]

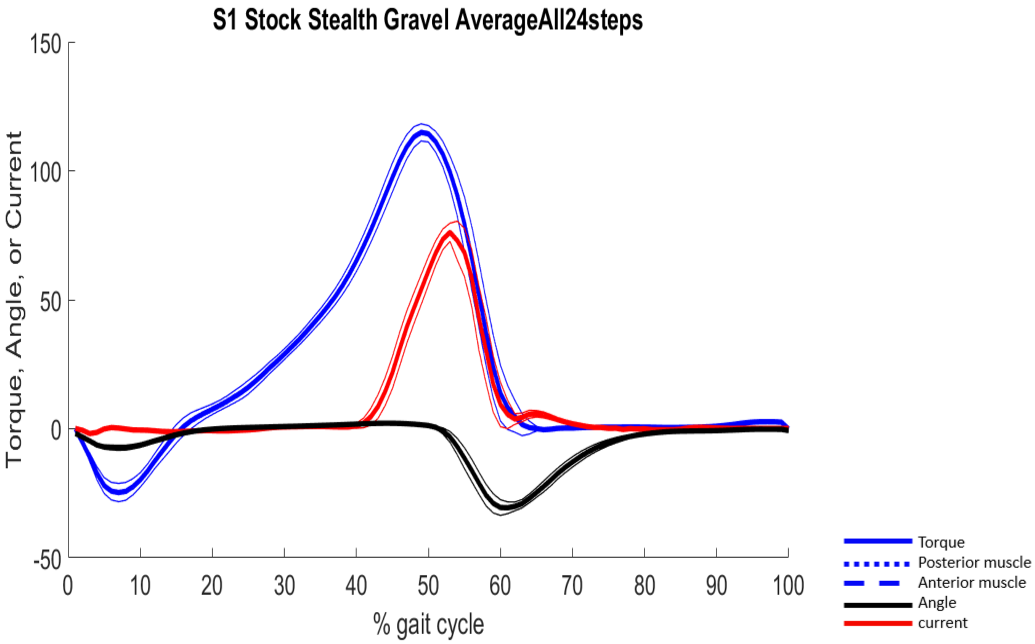


Figure 9. Gravel: Torque, Ankle Angle and Current versus % gait cycle [15]

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. After meeting with the clients, a Black Box Model, Functional Model and House of Quality is conducted to help as a guide.

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).

BiOM Customer Needs

Customer needs	***Importance Rating (1 – 5)***
A Test Fixture that can analyze the BiOM a prosthetic leg in a fixed and controlled environment.	5
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)	5
Can replicate the same effects as if worn in real life.	5
Easy to transport.	1
Durability, needs to with stand forces over time.	4
Hydraulic cylinder	3
Pneumatic Actuator	2
Electrical Motor	1

2.2 Engineering Requirements (ERs)

Engineering requirements is set with the help of the Customer Needs by converting it into a scalable engineering requirement that can be tested for.

Engineering Requirements

Engineering Requirements	***Specifications***
Size	(80x40x35 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 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.

Testing Procedures

Engineering Requirements	***Specifications***	***Testing Procedure***
Size	(80x40x35 cm)	Tape Measure
Time needed for testing	15-25 minutes	Stop Watch
Types of planes for testing	0^{o}, level ground testing	Protractor/Angle caliper
weight	<= 15Kg, 33lbs	Newton Meter/Electronic scale
Material	Carbon Fiber, Titanium and Aluminum 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 House of Quality (HoQ)

House of Quality is a diagram showing the relationship between the Customer Needs and the Engineering requirements

House of Quality (HoQ)												
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

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 [3]. 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 10.

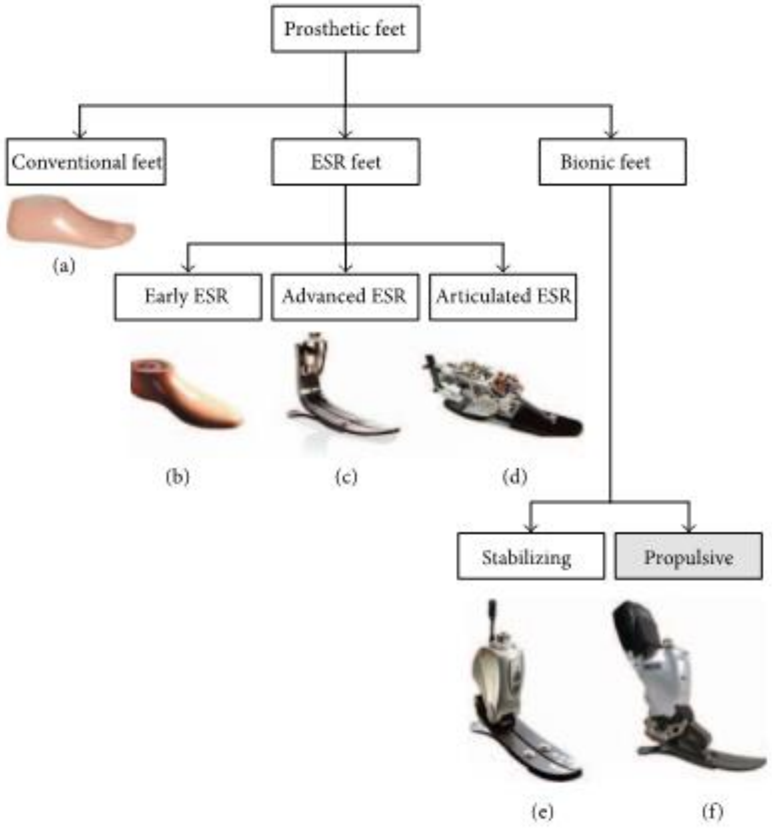


Figure 10. Categorization of today's prosthetics showing (a) SACH foot, (b) SAFE foot, (c) CESR foot, (d) Ossur's Flex-Foot, (e) Ossur's Proprio Foot, and (f) Walk's Powerfoot BiOM

As shown in Figure 10, 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) [3]. 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:

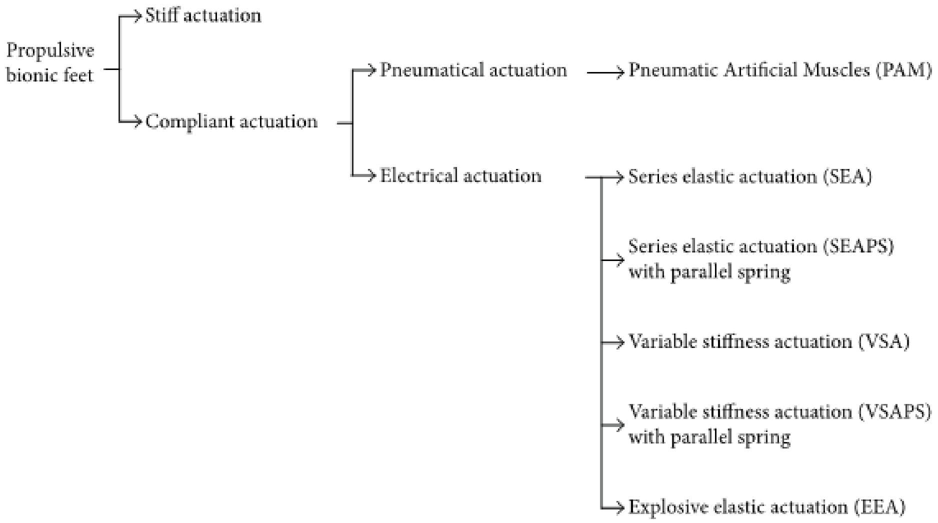


Figure 11. Categorization of propulsive bionic feet based on actuation method [3]

As shown in Figure 11, 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.

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: Tethered Prosthesis by Carnegie Mellon University

Caputo and Collins [7] at Carnegie Mellon University developed an experimental, tethered prosthesis to provide powered push off work to subjects walking on a treadmill to understand the relationship between the control parameters and performance as shown in Figure 12. This device has a single degree of freedom and is actuated via a flexible cable transmission by a motor using a series-elastic torque control scheme. It produces up to 232 Nm push off torque and controlled by a 1.61 kW motor. It has a range of motion of 14 degrees,

Figure 12. Tethered prosthesis developed by Carnegie Mellon Univeristy, USA [7]

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

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 13, 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.

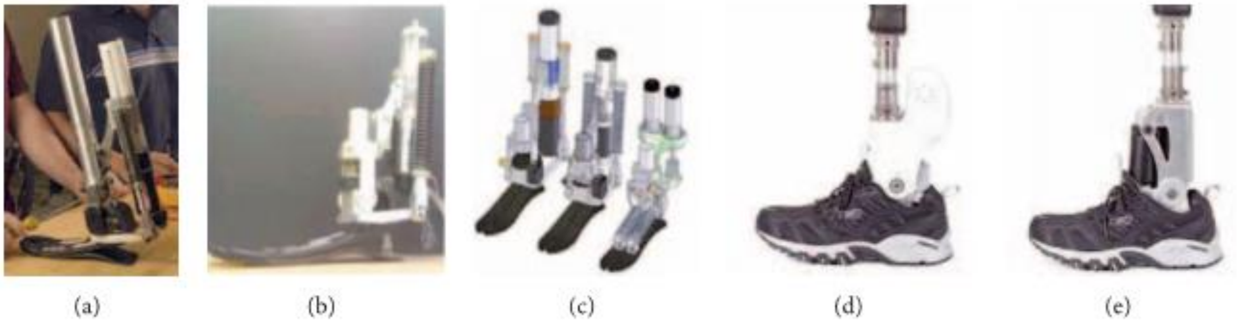


Figure 13. Ankle foot prototypes of SPARKy project developed by Arizona State Univeristy, USA. a) SPARKy-1, (b) SPARKy-2, (c) SPARKy 1, 2 and 3 (d) ODYSSEY and (e) JackSPring [8]

3.2.3 Existing Design #3: Tethered Prosthesis 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. It consists of a series of springs in the foot with a motor assembly and a 2-DOF ankle joint as shown in Figure 14. The prosthesis 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 14. Tethered prosthesis developed by Carnegie Mellon University, USA [3]

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 [4]. 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.

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 [3]. 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 15. Ankle Prosthesis prototype developed by UCL-Belgium [3]

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.

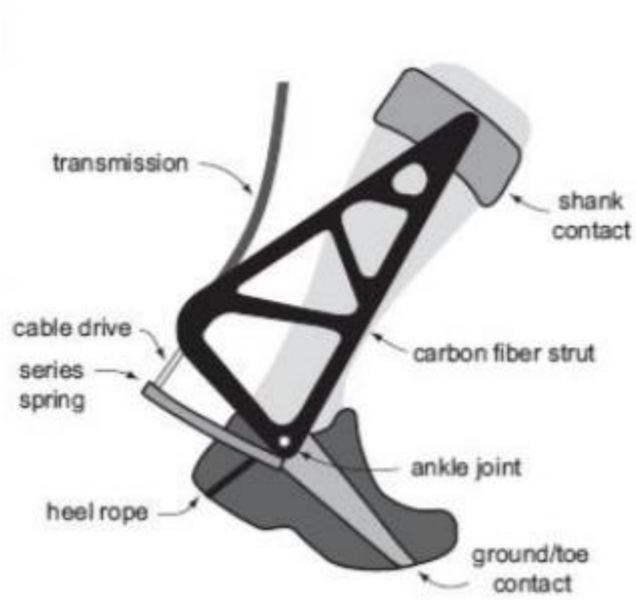


Figure 16. Schematic of exoskeleton used by CMU [9]

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 [9]. 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: Versatility and Innovation

The designs focused in this section are targeted towards providing versatile designs that are also innovative.

The following design shown in Figure 17 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.

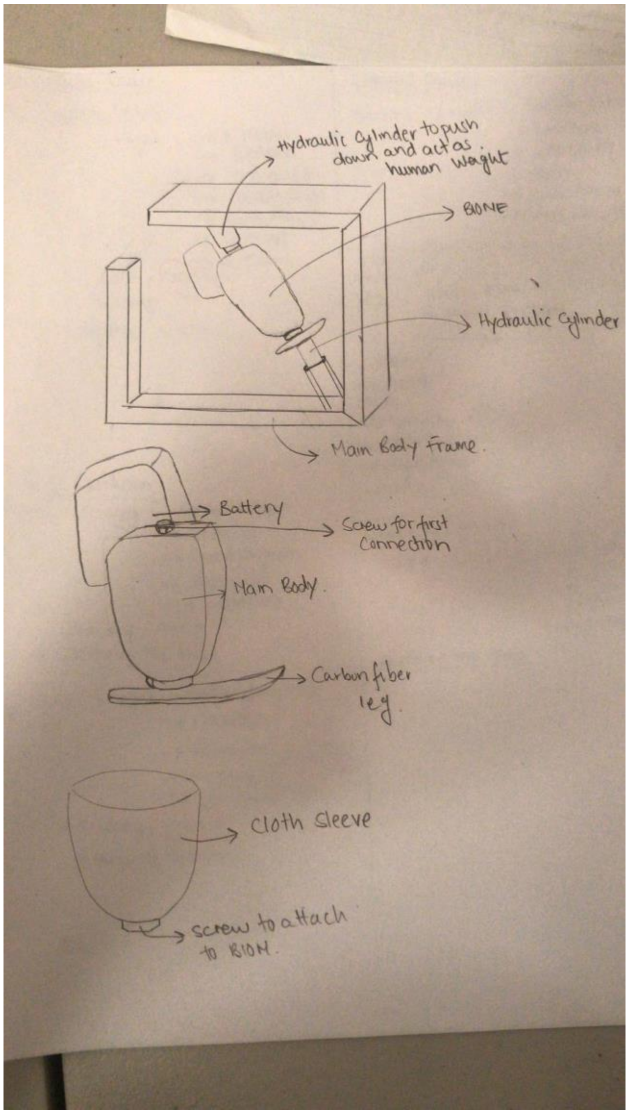


Figure 17. Design-1 considered by the team

The next design shown in *Figure 18* 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.

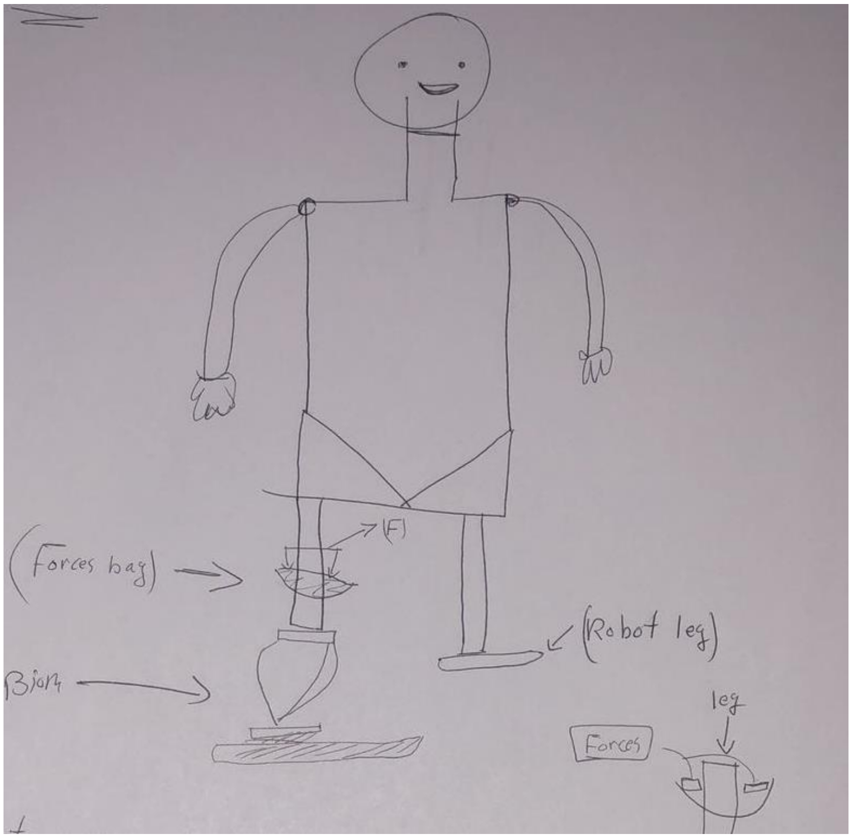


Figure 18. Design-2 considered by the team

The next design shown in Figure 19 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.

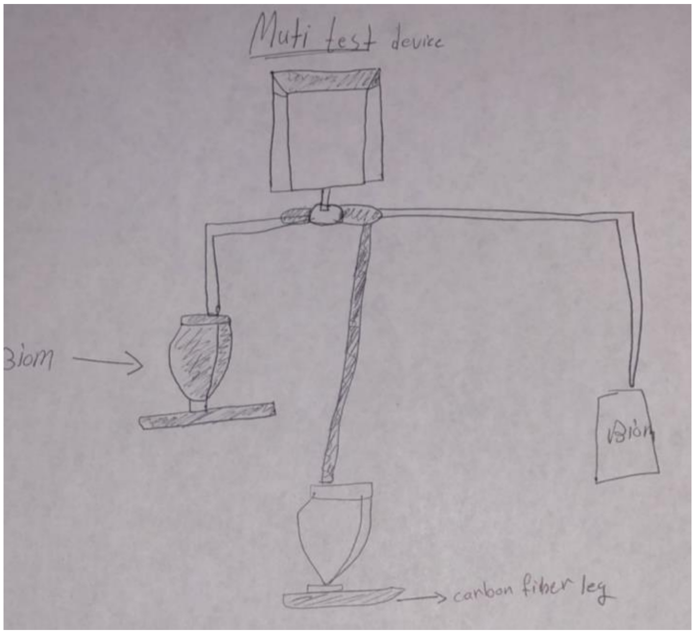


Figure 19. Design-3 considered by the team

The next design shown in *Figure 20* 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

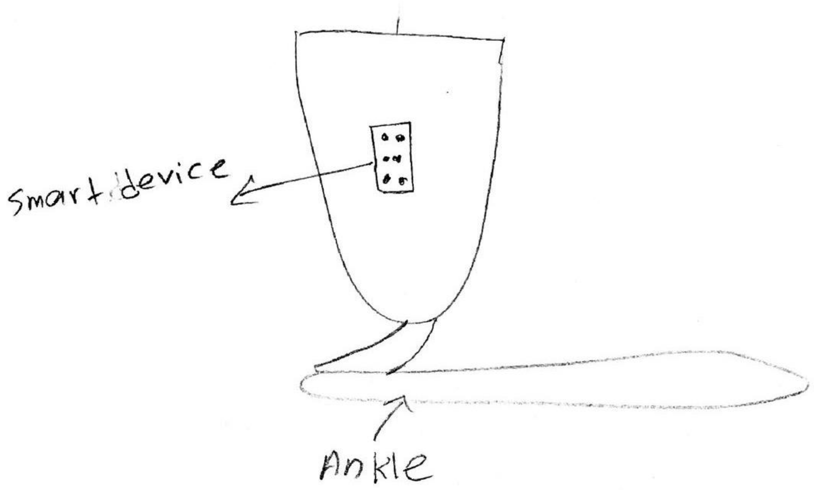


Figure 20. Design-4 considered by the team

The next design shown in *Figure 21* 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

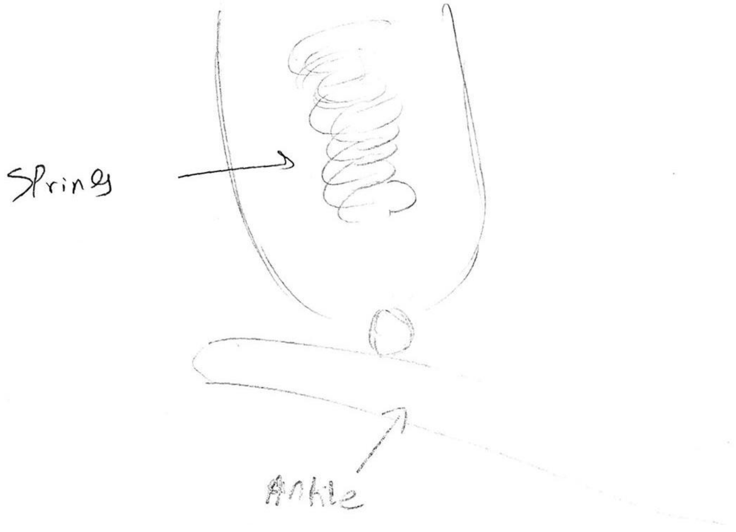


Figure 21. Design-5 considered by the team

4.2 Design #2: 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 22, 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

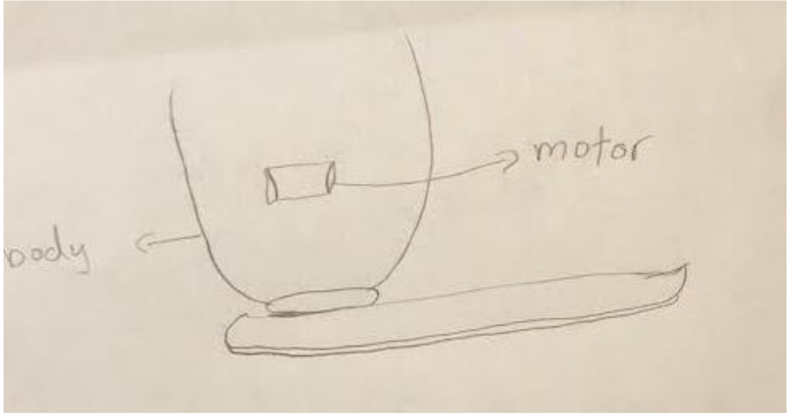


Figure 22. Design-6 considered by the team

The next design shown in Figure 23 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

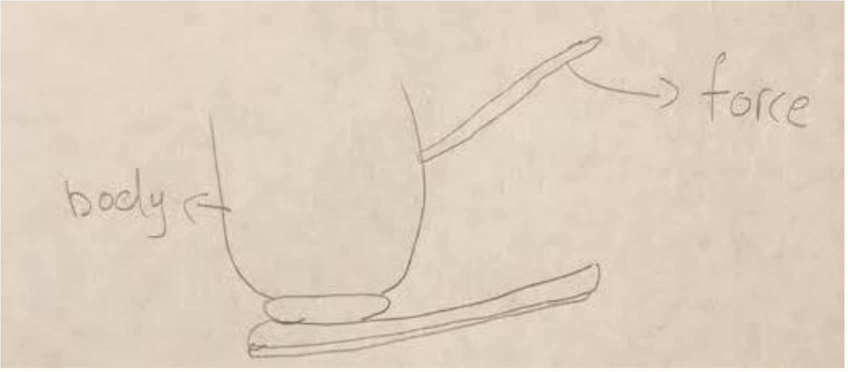


Figure 23. Design-7 considered by the team

4.3 Design #3: Economics

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

The following design shown in Figure 24 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.

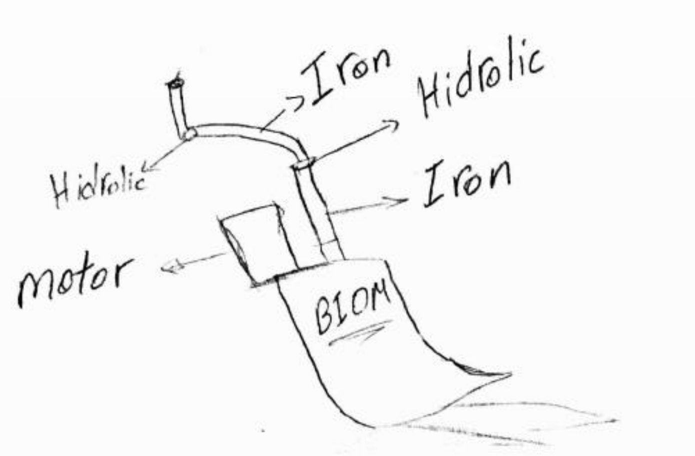


Figure 24. Design-8 considered by the team

The following design shown in Figure 25 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

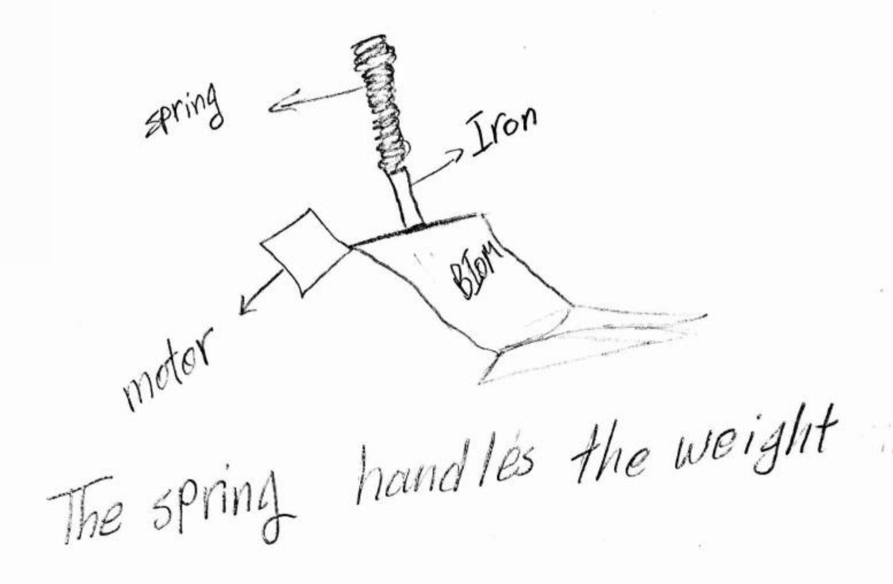


Figure 25. Design-9 considered by the team

5 DESIGN SELECTED – BiOM Test Fixture

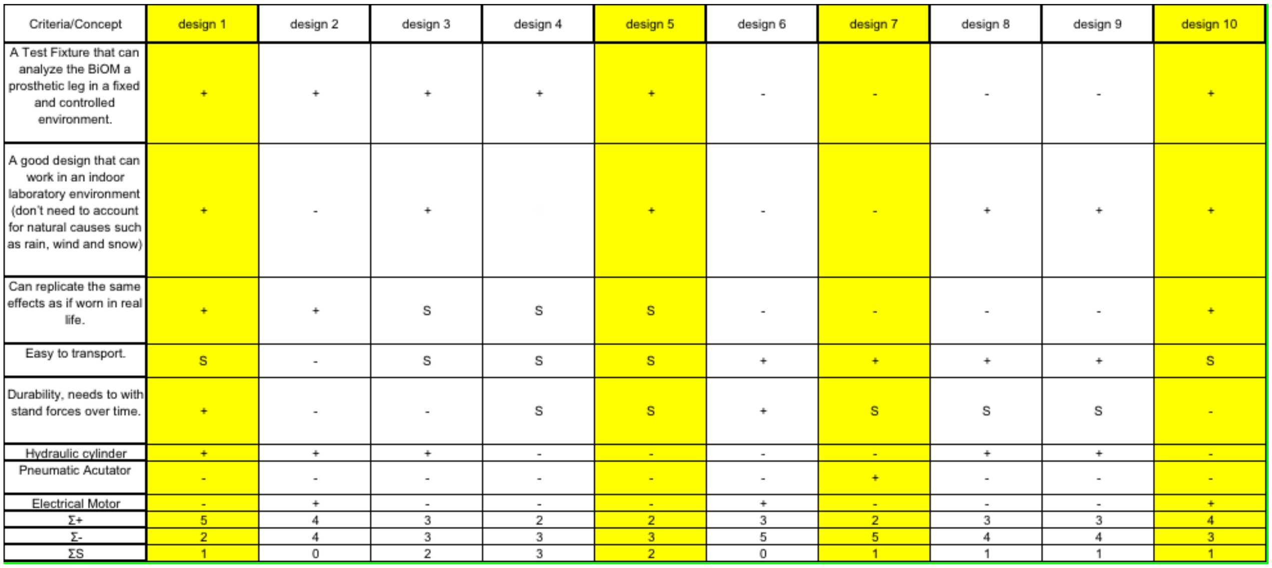
Based on the various designed proposed in the previous section, every device has its own pros and cons and hence it is very difficult to select a final design for implementation. However, given that design a BiOM required a thorough understanding of the algorithms in order to program the microprocessor 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.



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 26 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.

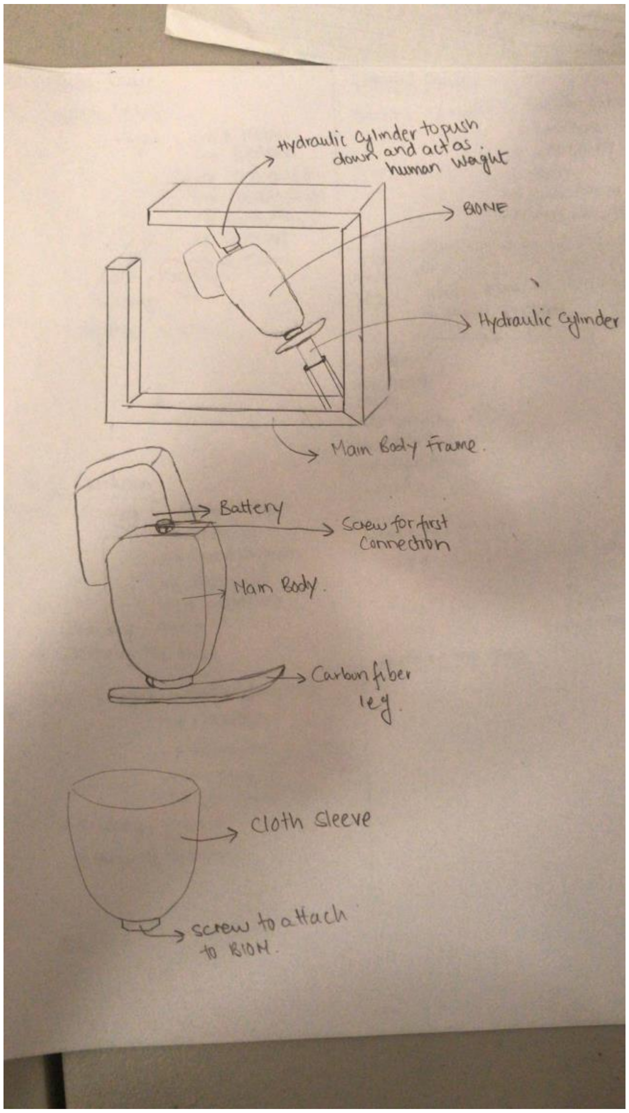


Figure 26. Design selected (Design-1) by the team

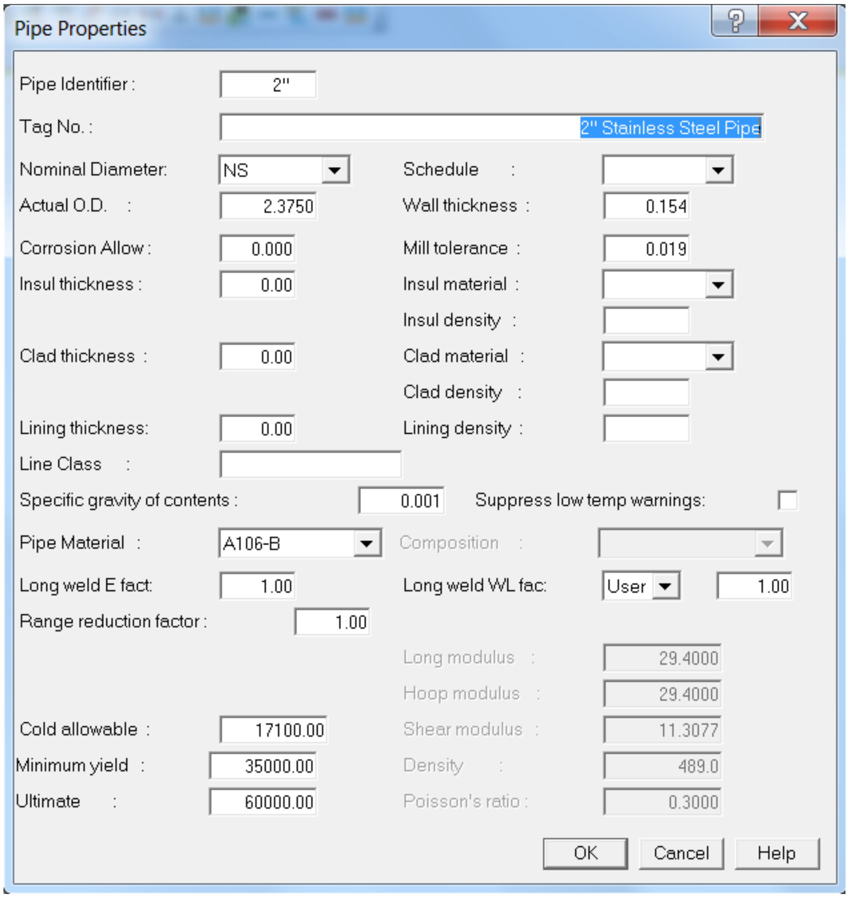
6 PROPOSED DESIGN

DESCRIPTION OF THE MODEL

The proposed design is tested using the software Bentley Autopipe 11.01.00.23. Autopipe provides a comprehensive and advanced software tool specialized in pipe stress analysis. As shown in results below, the hydraulic cylinder used to act as human weight is represented 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 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.

MATERIAL USED IN THE MODEL

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 27.



Pipe Identifier : 2"
Tag No. : 2" Stainless Steel Pipe
Nominal Diameter: NS
Schedule :
Actual O.D. : 2.3750
Wall thickness : 0.154
Corrosion Allow : 0.000
Mill tolerance : 0.019
Insul thickness : 0.00
Insul material :
Insul density :
Clad thickness : 0.00
Clad material :
Clad density :
Lining thickness: 0.00
Lining density :
Line Class :
Specific gravity of contents : 0.001
Suppress low temp warnings: ☐
Pipe Material : A106-B
Composition :
Long weld E fact: 1.00
Long weld WL fac: User 1.00
Range reduction factor : 1.00
Long modulus : 29.4000
Hoop modulus : 29.4000
Cold allowable : 17100.00
Shear modulus : 11.3077
Minimum yield : 35000.00
Density : 489.0
Ultimate : 60000.00
Poisson's ratio : 0.3000

Figure 27. 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).

The line diagram of the Autopipe model used for stress analysis is shown in Figure 28 below.

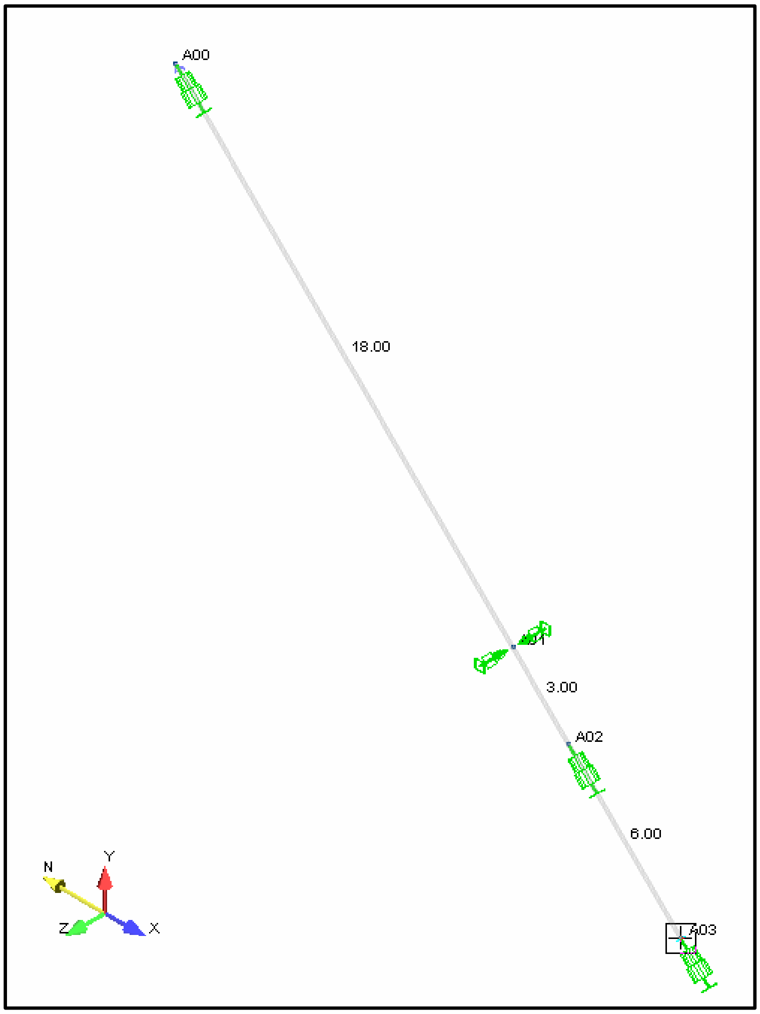


Figure 28. Snapshot of the BiOM modeled using Bentley Autopipe software for stress analysis.

A zoomed version of the different components of the model is shown in Figure 29, Figure 30 and Figure 31. As shown in Figure 29, the concentrated load of 287 lb is shown at point A00. Figure 30 and Figure 31 show the guide support and the anchor at the bottom end of the model to represent the fixed frame.

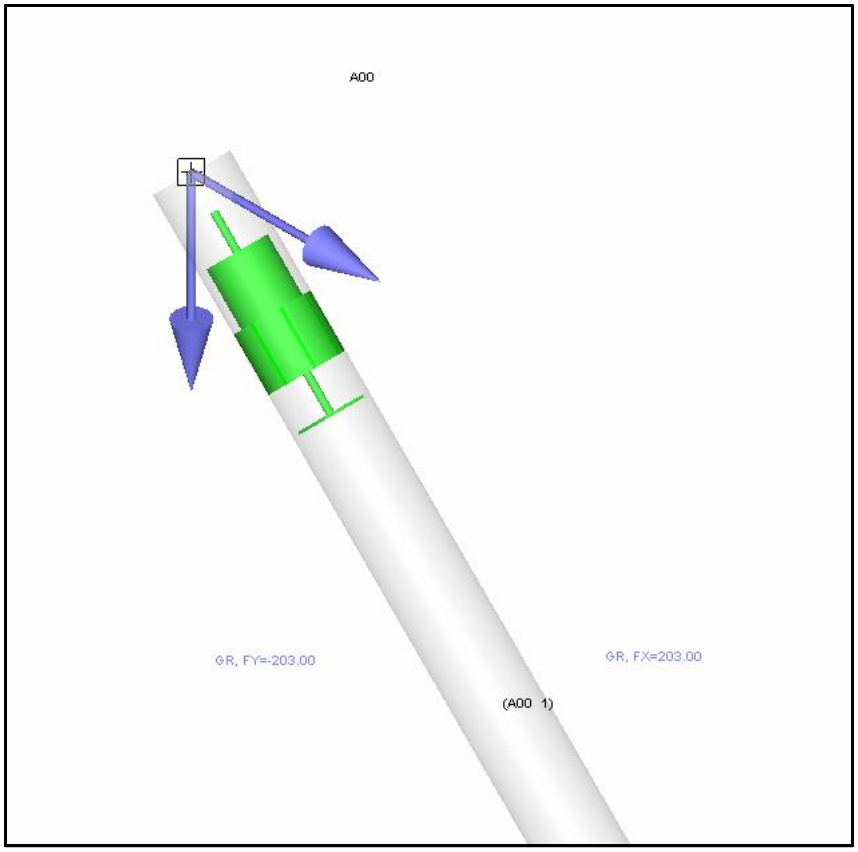


Figure 29. Zoomed portion of the top segment of the stress analysis model using Bentley Autopipe

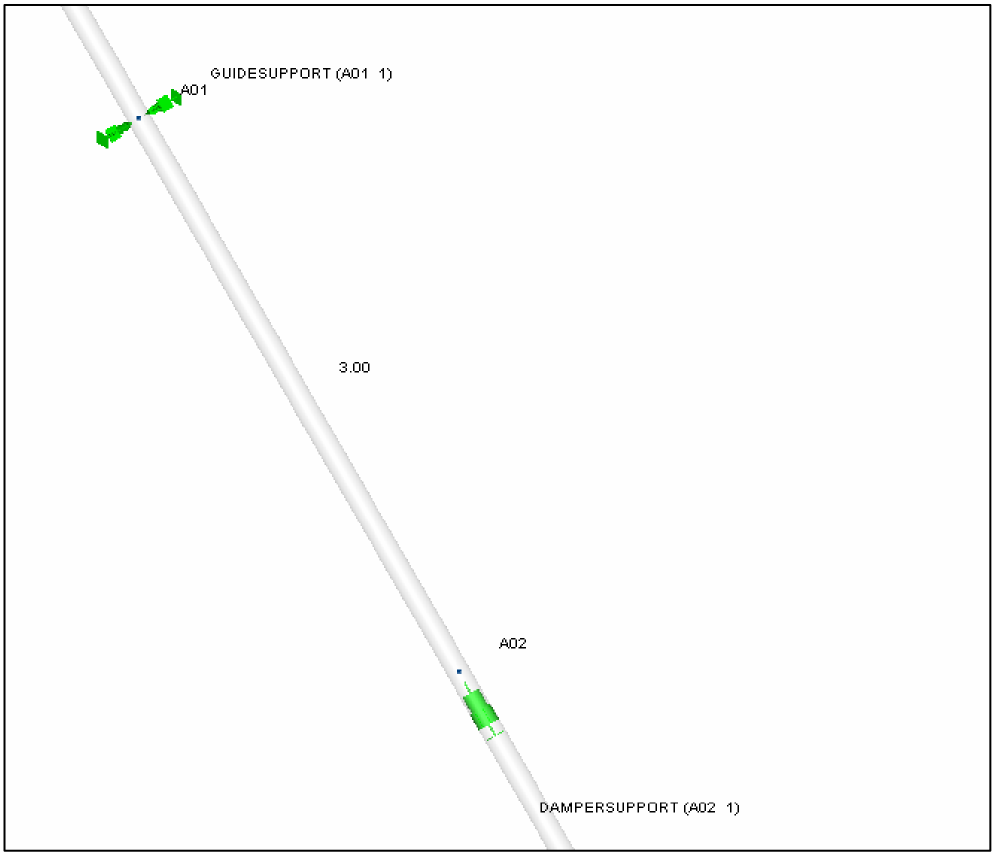


Figure 30. Zoomed portion of the middle segment of the stress analysis model using Bentley Autopipe

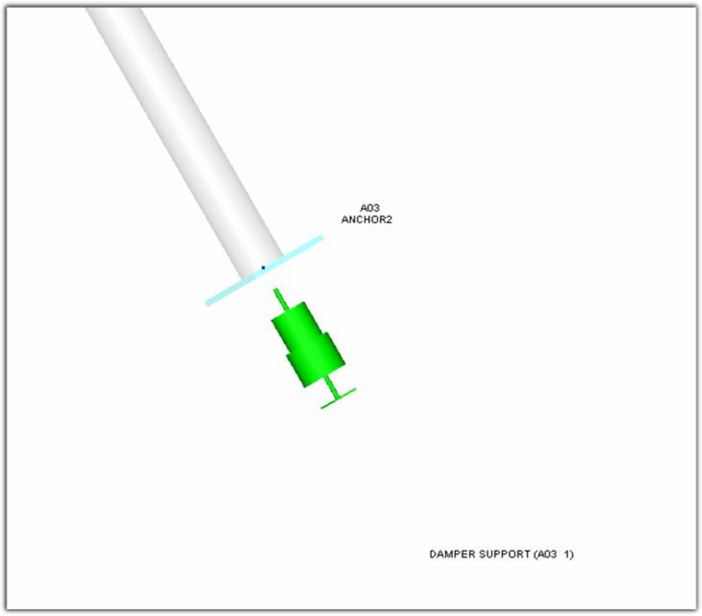


Figure 31. Zoomed portion of the bottom segment of the stress analysis model using Bentley Autopipe

RESULTS OF ANALYSIS:

The results of the stress analysis using Bentley Autopipe [11] 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. 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:

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 32. The values of maximum stresses and force/moment are shown in Figure 33 and Figure 34 respectively.

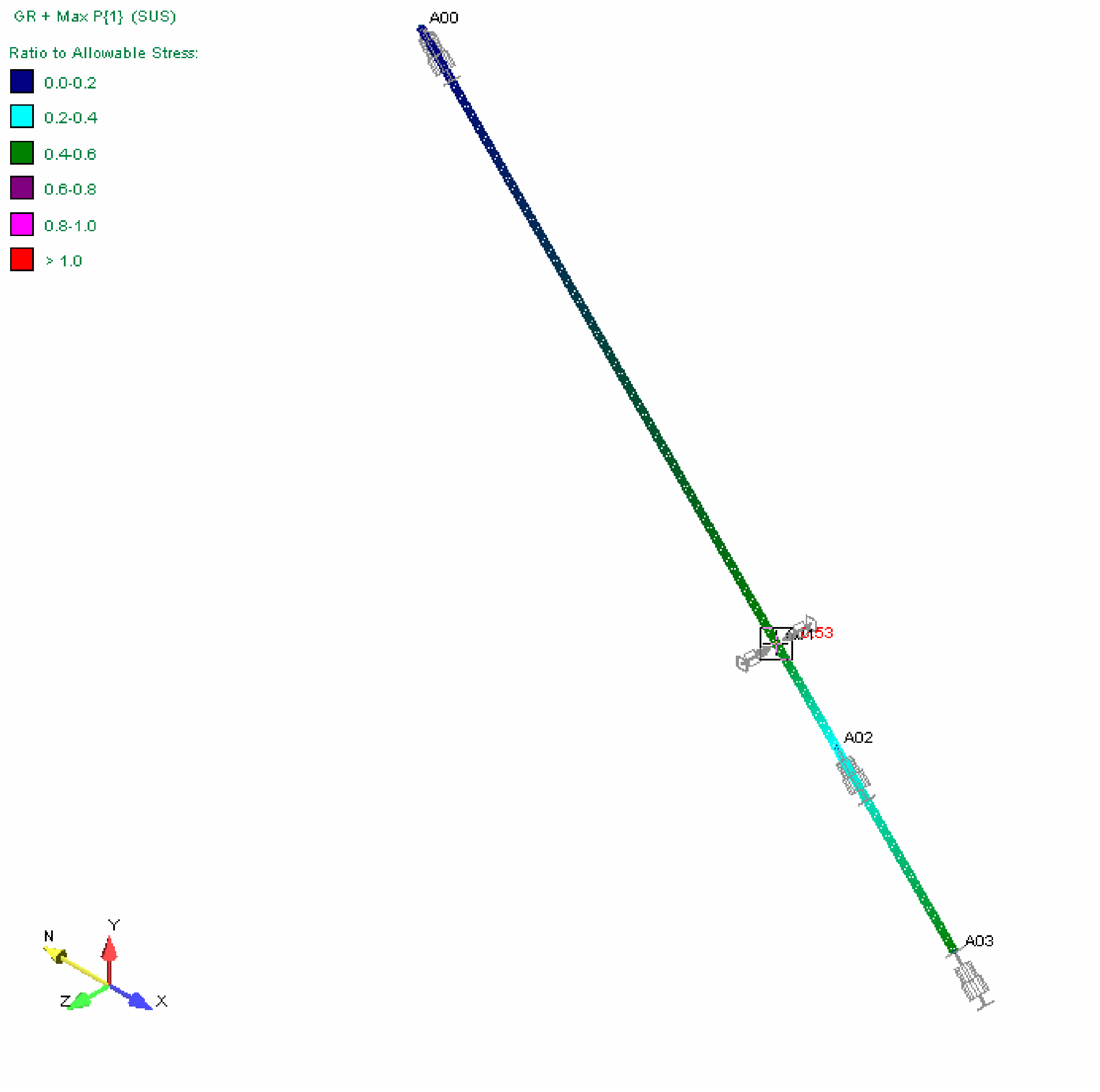
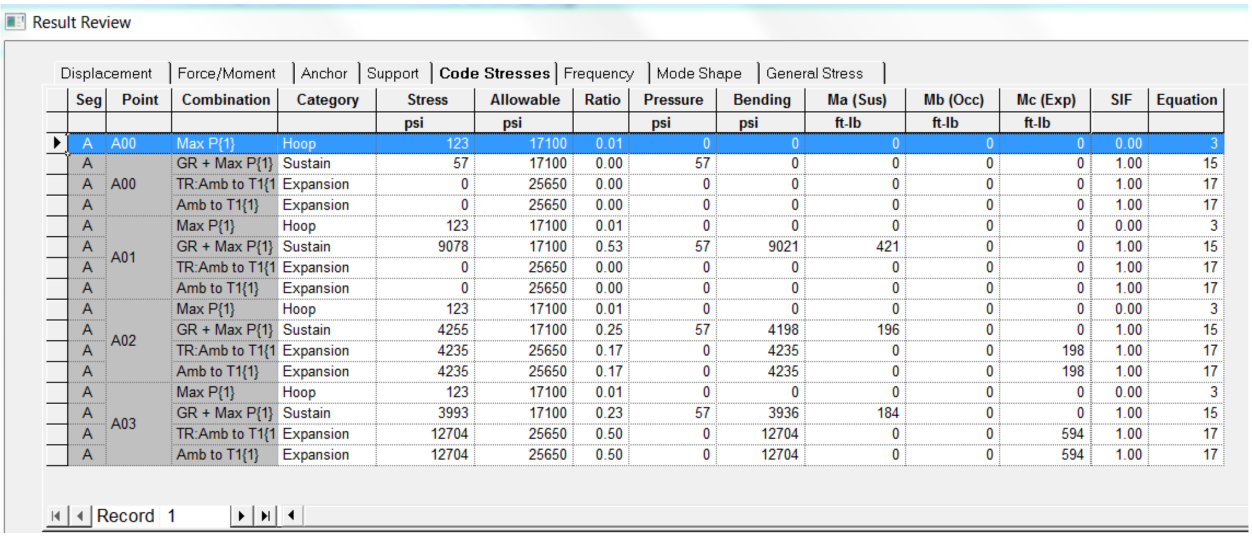
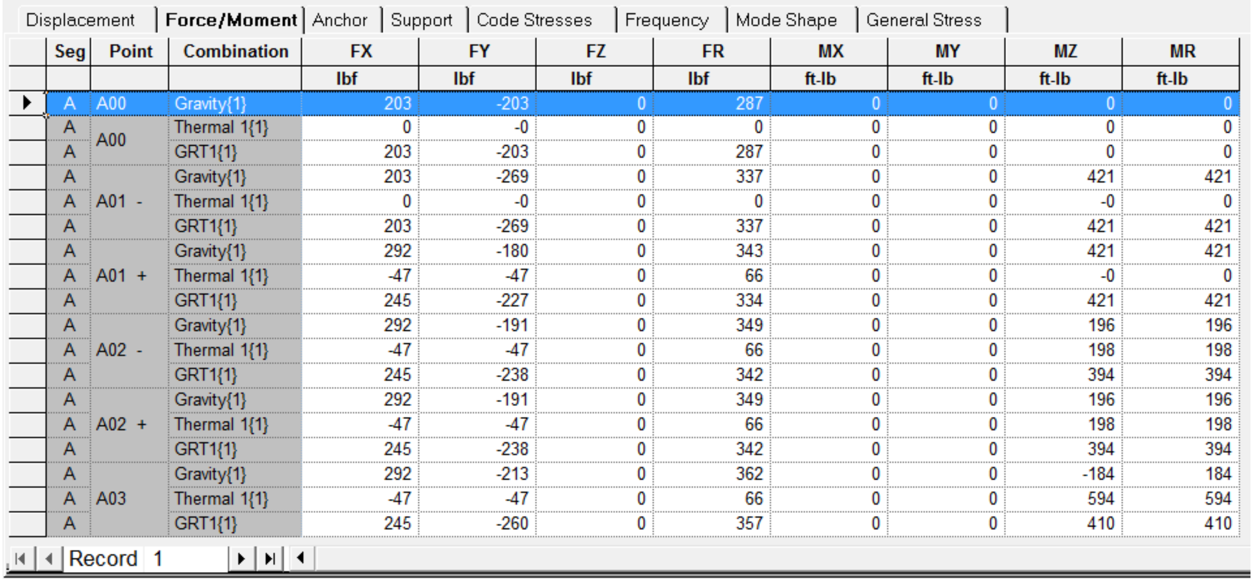


Figure 32. The stresses for 2-inch pipe are shown using the stress ratio that is color-coded using the colors denoted in the legend



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	A00	GR + Max P{1}	Sustain	57	17100	0.00	57	0	0	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	A01	Max P{1}	Hoop	123	17100	0.01	0	0	0	0	0	0.00	3
A		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	A02	Max P{1}	Hoop	123	17100	0.01	0	0	0	0	0	0.00	3
A		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	A03	Max P{1}	Hoop	123	17100	0.01	0	0	0	0	0	0.00	3
A		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

Figure 33. The table shows the stresses for the 2" schedule 40 stainless steel pipe used for the BiOM



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	A01 -	Gravity{1}	203	-269	0	337	0	0	421	421
A		Thermal 1{1}	0	-0	0	0	0	0	-0	0
A		GRT1{1}	203	-269	0	337	0	0	421	421
A	A01 +	Gravity{1}	292	-180	0	343	0	0	421	421
A		Thermal 1{1}	-47	-47	0	66	0	0	-0	0
A		GRT1{1}	245	-227	0	334	0	0	421	421
A	A02 -	Gravity{1}	292	-191	0	349	0	0	196	196
A		Thermal 1{1}	-47	-47	0	66	0	0	198	198
A		GRT1{1}	245	-238	0	342	0	0	394	394
A	A02 +	Gravity{1}	292	-191	0	349	0	0	196	196
A		Thermal 1{1}	-47	-47	0	66	0	0	198	198
A		GRT1{1}	245	-238	0	342	0	0	394	394
A	A03	Gravity{1}	292	-213	0	362	0	0	-184	184
A		Thermal 1{1}	-47	-47	0	66	0	0	594	594
A		GRT1{1}	245	-260	0	357	0	0	410	410

Figure 34. 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:

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 35 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 36 and Figure 37 respectively.

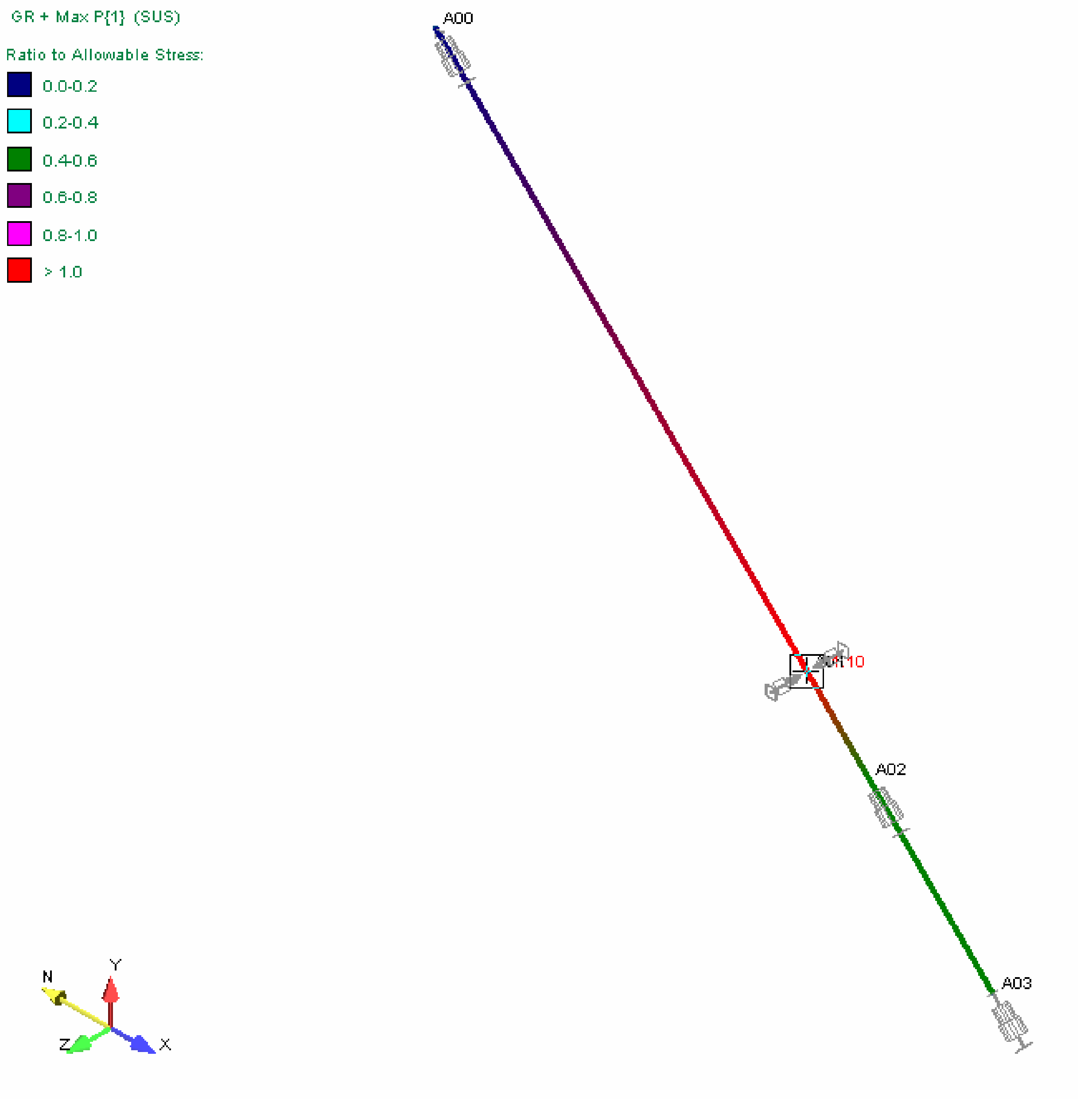
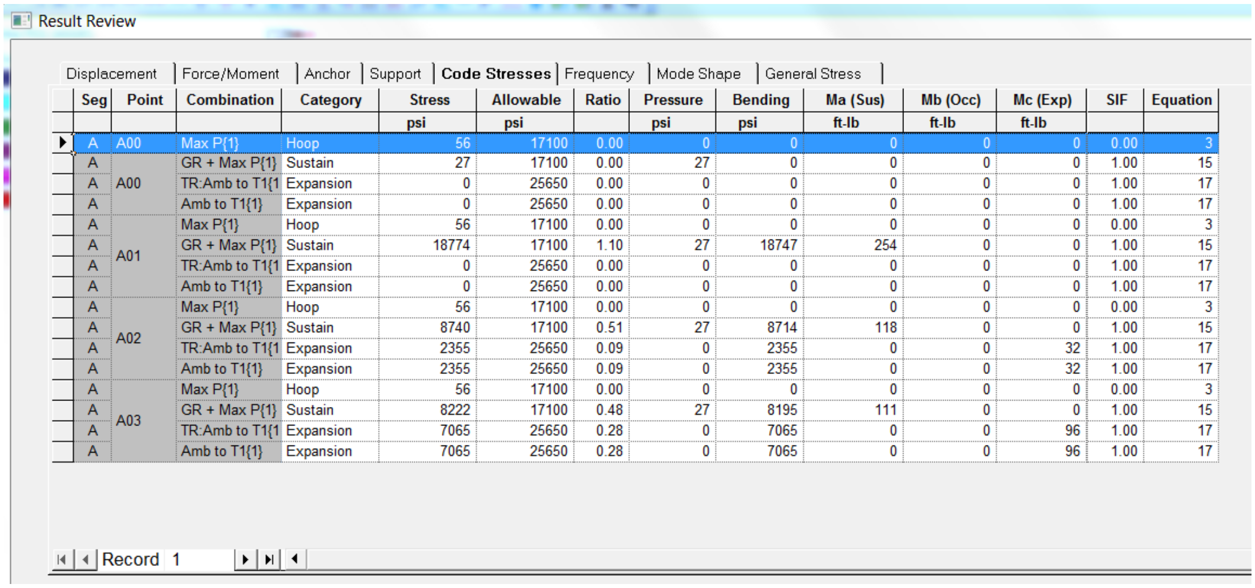
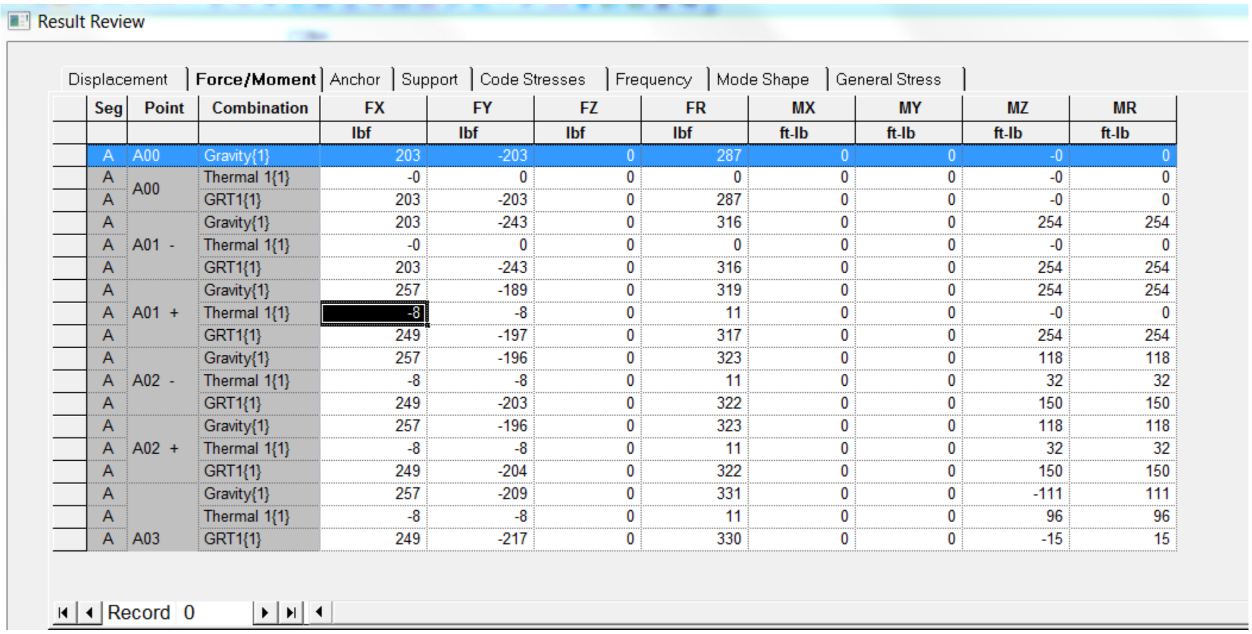


Figure 35. The stresses for 1-inch pipe are shown using the stress ratio that is color-coded using the colors denoted in the legend



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	A00	GR + Max P{1}	Sustain	27	17100	0.00	27	0	0	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	A01	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		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	A02	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		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	A03	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		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

Figure 36. The table shows the stresses for the 1" schedule 40 stainless steel pipe used for the BiOM



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	A01 -	Gravity{1}	203	-243	0	316	0	0	254	254
A		Thermal 1{1}	-0	0	0	0	0	0	-0	0
A		GRT1{1}	203	-243	0	316	0	0	254	254
A	A01 +	Gravity{1}	257	-189	0	319	0	0	254	254
A		Thermal 1{1}	-8	-8	0	11	0	0	-0	0
A		GRT1{1}	249	-197	0	317	0	0	254	254
A	A02 -	Gravity{1}	257	-196	0	323	0	0	118	118
A		Thermal 1{1}	-8	-8	0	11	0	0	32	32
A		GRT1{1}	249	-203	0	322	0	0	150	150
A	A02 +	Gravity{1}	257	-196	0	323	0	0	118	118
A		Thermal 1{1}	-8	-8	0	11	0	0	32	32
A		GRT1{1}	249	-204	0	322	0	0	150	150
A	A03	Gravity{1}	257	-209	0	331	0	0	-111	111
A		Thermal 1{1}	-8	-8	0	11	0	0	96	96
A		GRT1{1}	249	-217	0	330	0	0	-15	15

Figure 37. The table shows the stresses for the 1" schedule 40 stainless steel pipe used for the BiOM

COMPARISON USING CARBON FIBER:

The second material considered for the design is carbon fiber [10]. 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.

DIMENSIONS OF THE 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 [12], 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.

SELECTION OF HYDRAULIC CYLINDER

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

Steps followed:

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 38 below for the design options for the hydraulic cylinder.

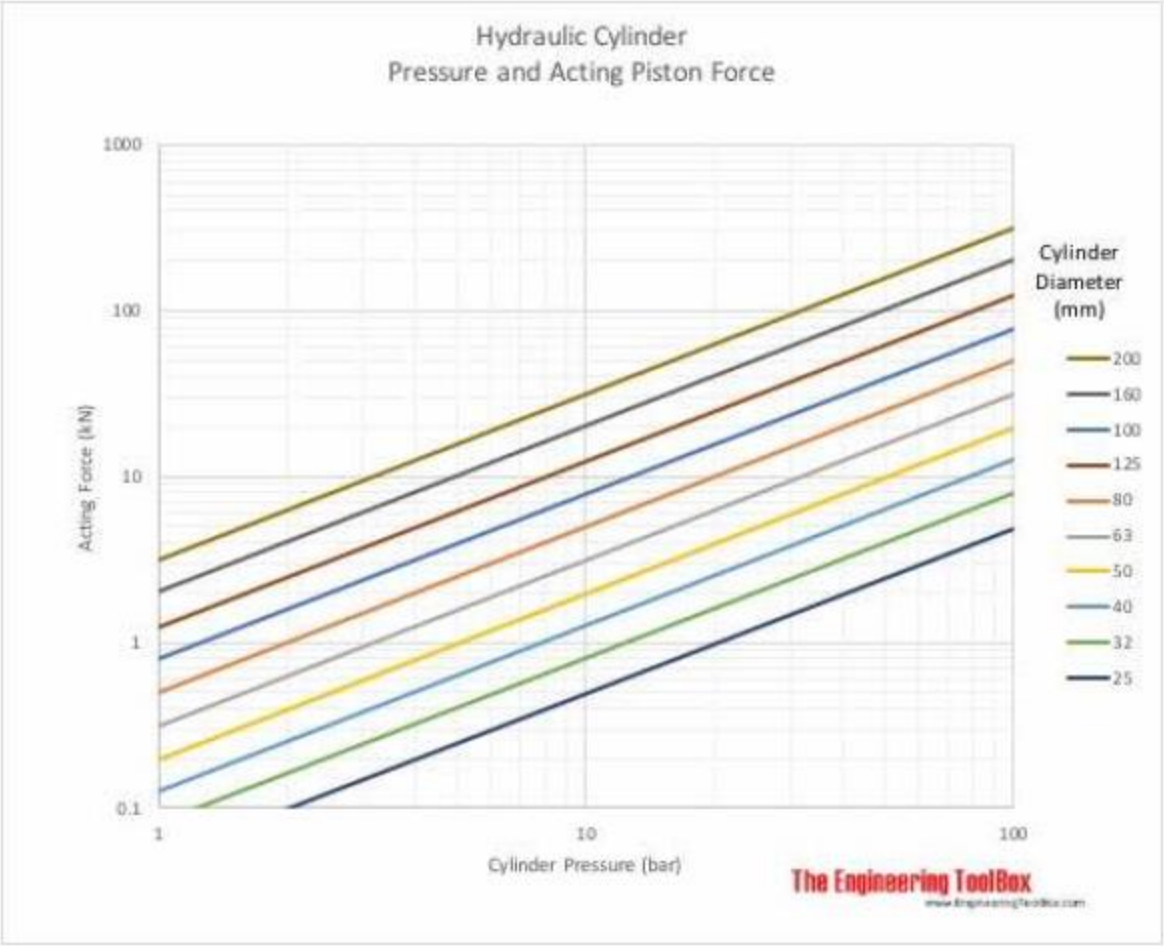


Figure 38. Plot of Acting force of the hydraulic cylinder versus the cylinder pressure

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 [13]

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.

CAD Model

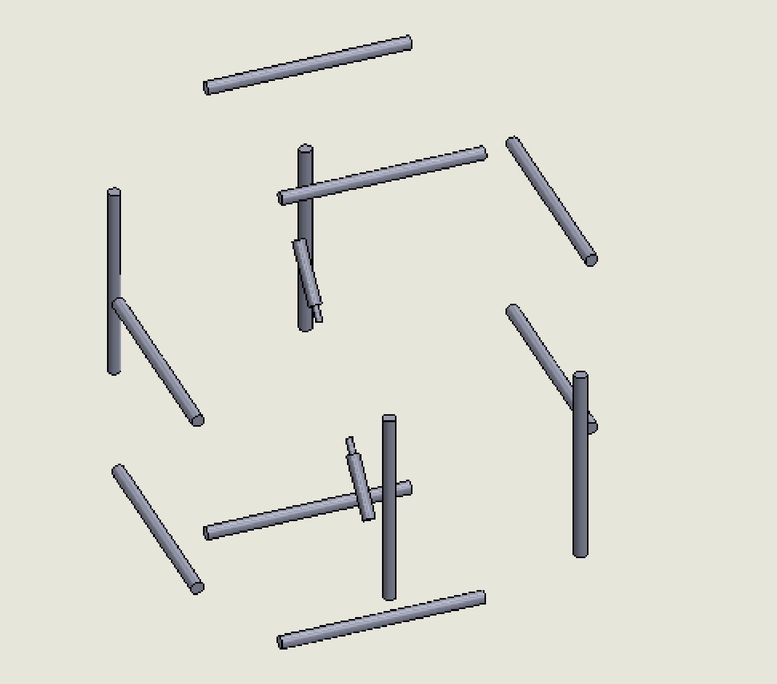


Figure 39. Exploded View

Figure 40.

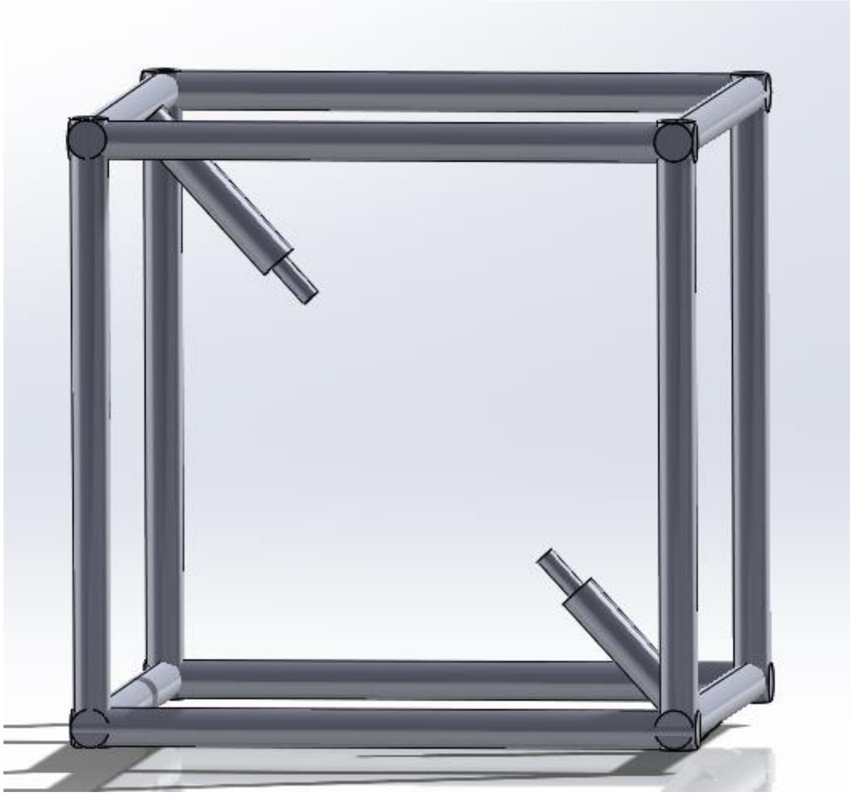


Figure 41. Body frame

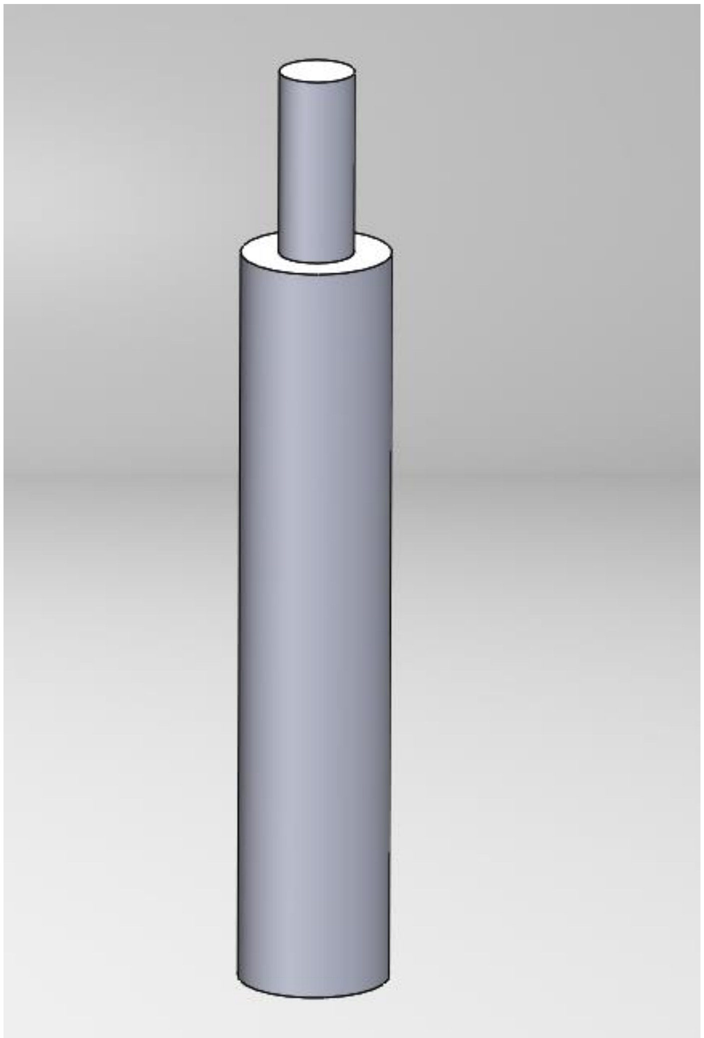


Figure 42. Hydraulic Cylinder

7 REFERENCES

1. Robert LeMoyne, “Advances for Prosthetic Technology: From Historical Perspective to Current Status to Future Application”, Springer, Japan, 2016. (Department of Biological Sciences, Northern Arizona University, Arizona, USA) ISBN 978-4-431-55814-9
2. Jason M. Wilken, “Advances in Prosthetics and Orthotics”, Military health System Conference, Jan. 2011.
3. P. Cherelle, G. Mathijssen, Q. Wang, B. Vanderborght & D. Lefeber, “Advances in Propulsive Bionic Feet and Their Actuation Principles”, Review Article, Advances in Mechanical Engineering, Volume 1, 2014.
4. D. A. Winter, “The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological”, Vol 2, Waterloo Biomechanics, 1991.
5. Smithsonian Magazine [Online]. Available: https://www.smithsonianmag.com/innovation/future-robotic-legs-180953040/
6. BIOM Personal Bionics by Anchor Orthotics & Prosthetics [Online]. Available: http://www.anchorot.com/biom-personal-bionics/ [Accessed Apr 23 2018]
7. J.M. Caputo and S.H. Collins, “A universal ankle-foot prosthesis emulator for experiments during human locomotion”, Journal of Biomechanical Engineering, Vol 136, No. 3, pp. 1-10, 2014.
8. J.K. Hitt, T.G. Sugar, H. Holgate, and R. Bellman, “An active foot-ankle prosthesis with biomechanical energy regeneration”, Journal of Medical Devices, Vol 4, No. 1, Article ID 011003, 9 pages, 2010.
9. Steve Collins, NSF National Robotics Initiative at CMU [Online]. Available: http://biomechatronics.cit.cmu.edu/publications/Collins---NRI---public-update-slides.pdf [Accessed Apr 23, 2018]
10. What is Carbon Fiber, Zoltek, Toray Group, 2018 [Online]. Available: http://zoltek.com/carbon-fiber/what-is-carbon-fiber/ [Accessed Apr 23 2018]
11. Bentley AutoPIPE, Bentley Systems, 2018 [Online]. Available: https://www.bentley.com/en/products/product-line/pipe-stress-and.../autopipe [Accessed Apr 23, 2018]
12. Hydraulic Force Calculation, Engineering Toolbox [Online]. Available: https://www.engineeringtoolbox.com/hydraulic-force-calculator-d_1369.html [Accessed Apr 23, 2018]
13. Festo Hydraulic Cylinder selection Catalogue [Online]. Available: https://www.festo.com/cat/en_us/products_CDC?CurrentIDCode1=CDC-80-100-A-P-A-R&CurrentPartNo=543311 [Accessed Apr 23, 2018]

14. R.J. Casler Jr., ‘BiOM Ankle Architecture’, Sealed-Elastic Actuator (Sealed sMTU), Powerpoint slides, iWalk Inc, Feb 20, 2012.
15. Original system data provided by Client, Stock Stealth TAF trials - BiOM Data, Powerfpoint slides, Oct 10, 2017.

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.

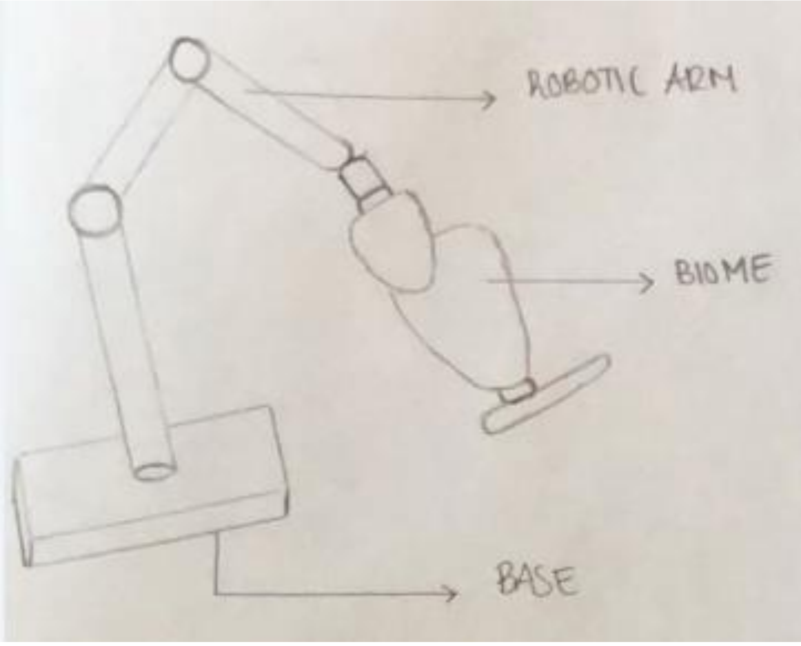


Figure 39. Design-10 proposed by the team

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

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


              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 ***
```

TABLE OF CONTENTS

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-------------------------------------------------------------------------------------------------------------------
-
Biom1-2inSteel
04/25/2018 AUTOPIPE STRESSES                                      BENTLEY
11:23 PM                                                          AutoPIPE Standard 11.01.00.23  RESULT PAGE
1
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-

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

 Point      Load                      TRANSLATIONS (in  )         ROTATIONS (deg  )
 name    combination                   X       Y       Z          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 T   F O R C E S
         ( Force - lbf   , Moment - ft-lb  , Tran. - in  , Rot. - deg   )
  Point/  Connect/    Load                           L O C A L             G L O B A L
 Supp. ID   Type   Combination                Dirn  Force    Deform    Dirn   Force   Deform
 -------- -------- ----------------------     ---- -------- --------   ---- -------- --------


 Tag No.: <None>
 A00                Gravity{1}                forw             0.003     X             -3.159
 A00  1   Damper                                                         Y             -3.163
 Stiff   :RIGID                                                          Z              0.000

                    Thermal 1{1}              forw             0.099     X             -2.930
 Comp.Wt :   0.250                                                       Y             -3.070
                                                                         Z              0.000

                    GRT1{1}                   forw             0.103     X             -6.088
                                                                         Y             -6.233
                                                                         Z              0.000

 Tag No.: GUIDESUPPORT
 A01                Gravity{1}                down      126    0.000     X        -89   0.001
 A01  1   Guide                               left             0.000     Y        -89  -0.001
 Stiff   :RIGID                               forw             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
                                              forw             0.033     Z              0.000

                    GRT1{1}                   down       60    0.000     X        -42   0.024
                                              left             0.000     Y        -42  -0.024
                                              forw             0.034     Z              0.000

 Tag No.: DAMPERSUPPORT
 A02                Gravity{1}                forw             0.001     X              0.074
 A02  1   Damp+Wnd                                                       Y              0.073
 Stiff   :RIGID                                                          Z              0.000

                    Thermal 1{1}              forw             0.022     X              0.497
 Comp.Wt :   0.250                                                       Y              0.466
                                                                         Z              0.000

                    GRT1{1}                   forw             0.023     X              0.571
                                                                         Y              0.539
                                                                         Z              0.000

 Tag No.: DAMPER SUPPORT
 A03                Gravity{1}                back             0.000     X              0.000
 A03  1   Damper                                                         Y              0.000
 Stiff   :RIGID                                                          Z              0.000

                    Thermal 1{1}              back             0.000     X              1.000
 Comp.Wt :   0.250                                                       Y              1.000
                                                                         Z              0.000

                    GRT1{1}                   back             0.000     X              1.000
                                                                         Y              1.000
                                                                         Z              0.000
```

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Biom1-2inSteel
04/25/2018 AUTOPIPE STRESSES                                      BENTLEY
11:23 PM                                                          AutoPIPE Standard 11.01.00.23  RESULT PAGE
3
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                                      R E S T R A I N T   R E A C T I O N S

 Point     Load                         FORCES (lbf   )             MOMENTS (ft-lb  )
 name   combination                 X      Y      Z    Result    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
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Biom1-2inSteel
04/25/2018 AUTOPIPE STRESSES                                      BENTLEY
11:23 PM                                                          AutoPIPE Standard 11.01.00.23  RESULT PAGE
4
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                             G L O B A L   F O R C E S   &   M O M E N T S

 Point     Load                         FORCES (lbf   )             MOMENTS (ft-lb  )
 name   combination                  X      Y      Z    Result    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   ***
```

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Biom1-2inSteel
04/25/2018 AUTOPIPE STRESSES                                      BENTLEY
11:23 PM                                                          AutoPIPE Standard 11.01.00.23  RESULT PAGE
5
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                              ASME B31.1 (2016)  CODE COMPLIANCE
                        (Moments in ft-lb  )             (Stress in psi     )
 Point     Load                      Ma      Mb      Mc            Eq. Load   Code    Code
 name   combination                (Sus.)  (Occ.)  (Exp.)  S.I.F   no. type  Stress  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 to T1{1}                                  594    1.00 (17) DISP   12704   25650

 *** 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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Biom1-2inSteel
04/25/2018 AUTOPIPE STRESSES                                       BENTLEY
11:23 PM                                                           AutoPIPE Standard 11.01.00.23  RESULT PAGE
7
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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}
```

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



     Maximum sustained stress

                              Point            : A01
                              Stress    psi    : 9078
                              Allowable psi    : 17100
                              Ratio            : 0.53
                              Load combination : GR + Max P{1}

     Maximum displacement stress

                              Point            : A03
                              Stress    psi    : 12704
                              Allowable psi    : 25650
                              Ratio            : 0.50
                              Load combination : Max Range

     Maximum hoop stress

                              Point            : A00
                              Stress    psi    : 123
                              Allowable psi    : 17100
                              Ratio            : 0.01
                              Load combination : Max P{1}
```

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Biom1-2inSteel
04/25/2018 AUTOPIPE STRESSES                                            BENTLEY
11:23 PM                                                                AutoPIPE Standard 11.01.00.23  RESULT PAGE
9
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-


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



     Maximum sustained stress ratio

                              Point            : A01
                              Stress    psi    : 9078
                              Allowable psi    : 17100
                              Ratio            : 0.53
                              Load combination : GR + Max P{1}

     Maximum displacement stress ratio

                              Point            : A03
                              Stress    psi    : 12704
                              Allowable psi    : 25650
                              Ratio            : 0.50
                              Load combination : Max Range

     Maximum hoop stress ratio

                              Point            : A00
                              Stress    psi    : 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                                 * * *
```
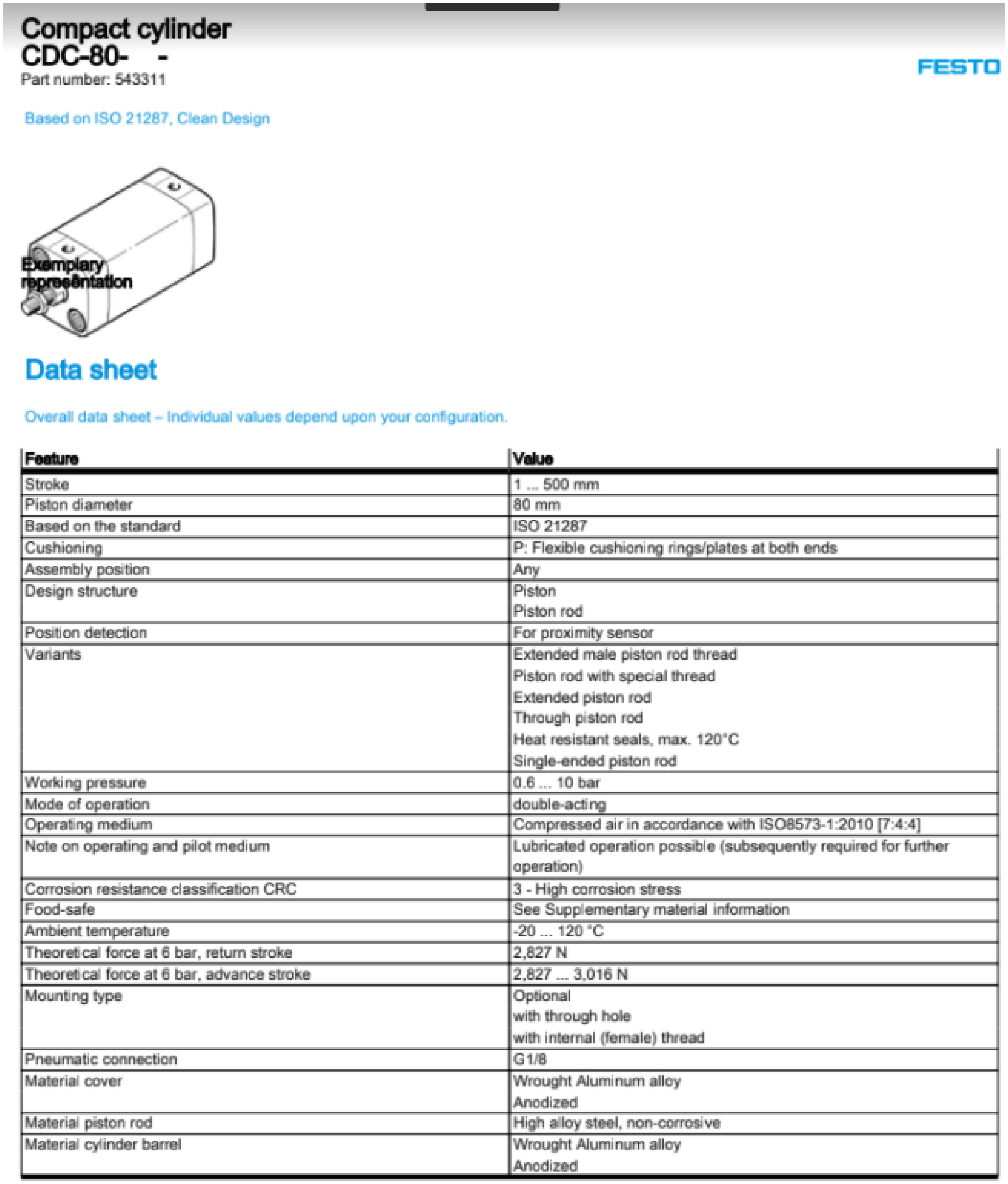

8.3 Appendix C: Datasheet for the selection of hydraulic cylinder



Compact cylinder
CDC-80- -
Part number: 543311

FESTO

Based on ISO 21287, Clean Design

Exemplary representation

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 Piston rod
Position detection	For proximity sensor
Variants	Extended male piston rod thread Piston rod with special thread Extended piston rod Through piston rod Heat resistant seals, max. 120°C 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 with through hole with internal (female) thread
Pneumatic connection	G1/8
Material cover	Wrought Aluminum alloy Anodized
Material piston rod	High alloy steel, non-corrosive
Material cylinder barrel	Wrought Aluminum alloy Anodized