Biomechatronic Hip Exoskeleton Team (BHET)

Final Proposal

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DISCLAIMER

EXECUTIVE SUMMARY

The goal of this capstone project is to design and build the mechanical portion of a biomechatronic hip exoskeleton. This hip exoskeleton will be used to reduce the metabolic cost of walking for children with cerebral palsy. The design that this capstone team implements will ultimately be used by the Northern Arizona University Biomechatronics laboratory. Due to this, they are the primary client for this project. Discussions with the biomechatronics laboratory allowed for the primary customer requirements to be established. Key of these requirements are for the design to be as lightweight as possible, comfortable, allow for torque to be applied in the extension/flexion direction linearly, and for the exoskeleton to effectively be able to sense torque at the user's hip joints. With the customer requirements established, corresponding engineering requirements were selected. The combination of these customer and engineering requirements were used to generate a functional decomposition and house of quality. These were used in the process of concept selection, which was described in detail in the previous preliminary report. The concept that was selected at the end of the preliminary report was a dual-belt design that utilized electric motors attached to webbing belts that applied torque assistance during the user's walking cycle. In order to further reinforce and improve this design, testing procedures were established and a risk analysis was conducted. Engineering calculations were also conducted to back up the viability of this design. Finally, a CAD model and low-fidelity prototype were created to conduct basic testing on the dual-belt design. This basic testing, along with discussions with the project's client and the results of the risk analysis led to further improvements on the design. The dual belt design described at the end of the preliminary report was modified to use Bowden cables instead of webbing, this allowed for a more streamlined and lightweight design. This new design is described in detail at the end of the report and it is expected to better meet the customer and engineering requirements for this project. In addition to this, a detailed bill of materials and second semester schedule are provided at the end of this report. The next steps for this capstone team are to further refine the new Bowden cable design, and to begin the manufacturing and testing of the final prototype.

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1 BACKGROUND

The following section will provide an overview of the project and provide background for this project's client, the NAU biomechatronics laboratory.

1.1 Introduction

The goal of the NAU biomechatronics laboratory is to improve mobility for individuals with neuromuscular and musculoskeletal disabilities [1]. To improve mobility, the lab designs exoskeletons for various parts of the body. Exoskeletons are systems placed on a subject's body which are meant to either amplify or assist human action. The lab currently has functioning knee and ankle exoskeletons for testing and research. However, the lab currently does not have a functioning hip exoskeleton for test purposes. The goal of this capstone project is therefore to develop the mechanical elements of a hip exoskeleton for use in the NAU biomechatronics lab. This hip exoskeleton must be lightweight in order to minimize metabolic cost, apply torque in a linear and consistent manner, and be able to measure that applied torque. Designing a hip exoskeleton is critical for furthering research in the biomechatronics lab. Ultimately, the hip exoskeleton designed by this capstone will allow children with cerebral palsy to have greater mobility than they normally would have.

1.2 Project Description

Shown below is the original project description provided by the sponsor:

> Design and build the mechanical aspect of a non-invasive hip exoskeleton for the NAU Biomechatronics Lab. The design must be comfortable for the user, have the degrees of freedom necessary to allow proper movement of the hip joint, and be as lightweight as possible.
>
> NAU's Biomechatronics Lab focuses on developing wearable robotics (exoskeletons) to improve the mobility of people with walking impairment. New devices are tested by comparing the exo-assisted metabolic cost of walking with the unassisted metabolic demand.
>
> The hip exoskeleton will be used to test the optimal amount of joint torque assistance needed at the hip to decrease the metabolic cost of walking in children.
>
> The project will focus only on the mechanical design and movement of the exoskeleton based off hip joint range of motion. Budget of $2,500 - $3,000.

Customer requirements were taken from both this project description and conversations with the project sponsor.

2 REQUIREMENTS

Before creating a design, it is important to cover what is needed to make the design function efficiently. In the following section, the requirements needed to make an effective hip exoskeleton will be covered. Specifically, customer requirements and engineering requirements will be covered. Then those requirements will be compared in the House of Quality. The functional model and black box of our design are also discussed in this section.

2.1 Customer Requirements (CRs)

The instructor of the course and sponsor for the project defined the customer requirements for the exoskeleton. The following table displays the customer needs and weights.

Table 2-1: Customer Requirements and Weights

Customer Requirements	*Weights*
Hip Actuation	5
Full Range of Motion	5
Sense Torque	5
Minimize Metabolic Cost	4
Safe to Operate	4
Untethered	4
Durable	3
Easy to don and doff	2
Comfortable	2
Reliable	2
Within Budget	1
Fit small to medium build	1

The main objective of our design is to actuate movement in the hip. The movement is active in extension/flexion but needs to be passive in all other directions. The team's design also needs to sense the torque that is applied within the system. These three requirements are a priority in the design which is why they are ranked the highest out of all the customer needs.

Another goal is to minimize the metabolic cost of the user's walking. This means that the design cannot be too heavy because then it would require more work to operate. Also, the design needs to be safe and able to be used untethered. The untethered aspect means that the design can be taken anywhere without needing to be plugged into a power source, and the team also want to make sure the device will not harm the user while activated. These requirements are of moderate priority.

The next requirements revolve more around how the exoskeleton interacts with the user. Durability is important in this design because the subject would most likely be using it in their daily lives. It is important, but it is not our priority to make it last for years at this point in our process. The next requirements revolve around it being comfortable, easy to take on and off, and reliable. Exoskeleton's are designed to be an extension of our bodies, so the team wants the final design to be as comfortable and reliable as possible for the user. Though if needed the team will sacrifice some aspects of comfortability to ensure the design works.

The last requirements are that the design needs to fit within budget and fit small to medium builds. They are ranked the lowest since we do not want budget to hinder our design choices. However, this does not mean that we will ignore the budget, we just want to be as open as we can with our choices. Lastly, our design is meant for children, so we want the design to be adjustable. Though when designing we won't be testing on smaller frames, so it is not our priority now.

2.2 Engineering Requirements (ERs)

The following is a list of the engineering requirements derived from the hip exoskeleton's customer needs.

Table 2-2: Engineering Requirements and Tolerances

Requirement	*Tolerances/Target Values*
Torque Applied (∧)	<25% of body weight
Metabolic cost of walking (∨)	0
Time to don/doff	3 min ±2
User comfort rating (0-10)	9 ±1
Weight (∨)	Minimize
Operation time/cycle (∧)	2 hours
Power Required	Minimize
Cycles to failure	2 months
Cost to manufacture (∨)	$1810
Extension/Flexion (∧)	135°
Abduction/Adduction	Free range
Rotation	Free range
Noise (∨)	Minimize
Compliance/Comfortability	Maximize

Each of these engineering requirements are important to the overall project. Maximizing the torque applied is the main goal of the project, and this affects the amount of extension/flexion that results. The team wants to assist only in this direction, so these two requirements must be achieved. Though, the rest of the exoskeleton must promote freedom of movement in abduction/adduction and rotation. This is an aspect of comfort and assisting in those directions is not the goal of this system. Regarding how the system is powered, understanding how much power is required is important to the system. This also affects the operation time/cycle. If the system is taking too much power, the system will not last our desired amount of time. Lastly, in relation to the manufacturing of the system, we want to minimize the amount it costs.

The rest of the requirements relate heavily to the comfort of our subject. Overall, maximizing the compliance and comfortability is important to the team. Minimizing the weight is a priority of the team, since subjects will not like wearing something heavy. Also, if the system is too heavy, it will increase the metabolic cost of walking, which is not wanted. Minimizing noise is important too since wearing a system that is loud is an inconvenience to the wearer and their surroundings.

More information about target values and tolerances of each requirement is provided in Section 2.4.

2.3 Functional Decomposition

The primary objective of this section is to establish our design problems and break the overall function into smaller parts that make it easier to move forward with the concept generation for our project. The black box model helped to determine the subfunctions based on the engineering requirements and the input and output flows based on the materials, energy and signal of the device. Moving forward we created the functional model based on the relationship between input and output flows which we got from the black box model.

2.3.1 Black Box Model

Below is the updated black box model based on the selected current state of the team's design regarding to the customer needs and the engineering requirement. The main goal of our new hip exoskeleton is to actuate the hip joint, so we determine the overall subfunction of the black box model (Figure 2-1) is to actuate the hips. The input flows are human hips under material, human energy and electrical energy under energy and on/off signal under signal. The output flows of the black box model are human hips under materials, torque forward motion under energy and torque data and power level under signal. This black box model helped to develop the functional model.

Figure 2-2: Black Box Model

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

Shown below is functional model generated from the black box model.

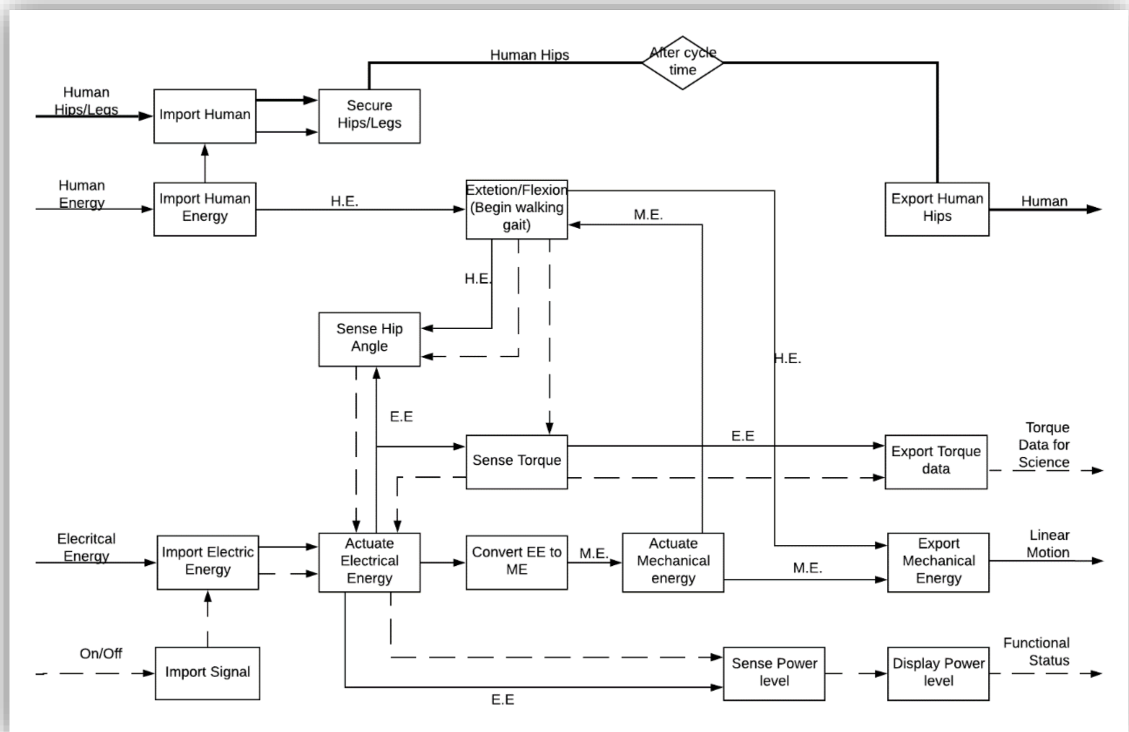

Figure 2-3: Functional Model

After we determined our updated black box model, we started to look at activities, actions, processes, operations of our system. We also looked at what could be done by using the functional model diagram for the selected current state of the team's design regarding to the customer needs and engineering requirements (Figure 2-4). We started from the input flows that we got from black box model and we identified the functions that provide the output flows of the system. First, we will turn the signal (on/off) of the device and then import human hip, human energy, electrical energy into the device. After that the device will start the walking cycle in the linear direction, and then we'll get the loop of the hip actuation which will export the human hip. For the human energy the device will export the torque data and mechanical energy in a linear motion and lastly the device will convert the EE to ME and display the power level of the device.

2.4 House of Quality (HoQ)

The House of Quality related the customer needs to develop engineering requirements. Refer to the House of Quality in Appendix D for more detail on each customer needs versus engineering requirements. The tool showed us which relations would play the largest role in the design.

For our exoskeleton, according to the RTI (Relative Design Importance) making sure the design can actuate extension/flexion effectively is highly important, while keeping the design passive in all other degrees of movement. This also means we want to maximize the output of torque that is applied to the system, specifically it is stated that less than or equal to 25% of the subject's body weight would be torque applied. Though, while of maximizing torque, the team needs to also minimize the metabolic cost of walking. This can be measured later in our design process, but for now the team can ensure that this aspect is minimized by lowering the weight of the system. There is no target weight the design needs to reach, but it is imperative that it is as low as it can be. The design also needs to operate at the full cycle time and last for certain time period. This showed the team that we must think about how the device will actuate movement for two hours long and last for two months without breaking. As result, this also made us consider how different actuation methods will draw our more power from the source. The last aspects of the design the team needs to consider is how comfortable it is for the user, which will be measured by a user comfort rating. The user comfort rating would ideally be an average of 9 with a tolerance of ±1. There are other aspects that go into comfort, such as compliance and how easy it is to don and doff. It regards to donning and doffing, ideally, we want to reach 3 minutes with a tolerance of ±2.

The testing procedures numbered at the bottom of the House of Quality will be described in Section 3.

2.5 Standards, Codes, and Regulations

The BHE will be attached to and interact directly with a human. This fact increases the importance of safety. Standardized practices and methods have been published that inform this type of design and the BHE team has identified a list of relevant publications Table 2-1.

The American Society for Testing and Materials (ASTM) has recognized the need for standardization in the field of exoskeleton development and developed committee F48 that is focused on creating standard practices for exoskeleton designs. This has been a recent development and to date F48 has only published one standard focused on labeling practices [2, 3].

Table 2-3: Standards of Practice as Applied to this Project

Standard Number or Code	Title of Standard	How it applies to Project
ASNI/AAMI HE 74:2001	Human Factors Design Process for Medical Devices	Helps in the design of how the device with interface with the user in a safe manner.
HFDS – ch.14	Human Factors Design Standard – Anthropometry and biomechanics	Provides aggregated statistical data for body measurements; Offers standard practices when designing for human ergonomics

3 Testing Procedures (TPs)

The capabilities of the device will need to be evaluated to ensure that each design requirement is satisfied. This will require a testing under conditions that reflect the actual use-case of the exoskeleton. The following sections provide an overview of test procedures which will evaluate the design. These procedures are presented in the order which they are planned to occur.

3.1 Testing Procedure 1: Extension to Flexion Ratio

Hip joint ROM includes three types of movement: extension/flexion, abduction/adduction, and external/internal rotation. The hip exoskeleton must not limit the wearer in any of these types of movement during the walking cycle. The device will apply assistive torque in extension/flexion, over the entire range of the wearer's normal gait.

3.1.1 Testing Procedure 1: Objective

This test is intended to observe the functionality of the torque delivery system on the BHE. The test will evaluate peak torque capability through the expected extension and flexion of the hip (30 degrees/100 degrees, respectively). The test will also evaluate the BHE ability to apply torque on-demand through the entire ROM. The test fixture will be restricted to extension/flexion to control for unexpected motion which could change peak torque characteristics.

3.1.2 Testing Procedure 1: Resources Required

The procedure requires simulation of cyclic hip extension/flexion, which will require a model of the hips. Tissue will not be simulated for this test as it is beyond its scope, the intent of the model is to simulate the human hip joint ROM during walking gait cycle.

3.1.3 Testing Procedure 1: Schedule

This will be the first test run on the final prototype because it is evaluating the top technical requirements of the design. The test is intended as a validation of components, so it will be run on all iterations of the design. The team would like to test the final prototype in December pending availability of members, if this is not possible, then the test will be scheduled for the first week of the spring 2020 semester.

3.2 Testing Procedure 2: Displacement Testing

Exoskeletons have presented a unique design challenge for engineers. Dynamics of the walking gait are difficult to precisely replicate, and the interaction points are made of tissue, meaning the design cannot be rigid. This implies that the harness and leg straps may shift their position on the wearer during operation, which can affect the data being collected and the assistance torque vector. The team must be able to quantify displacement to evaluate the efficacy of the harness design.

3.2.1 Testing Procedure 2: Objective

To evaluate the frame and harness of the BHE, if they can support the reaction forces generated during normal operation. The test will also test the compliance required of the harness material, as the team believes there will be an inverse relationship between compliance and displacement.

3.2.2 Testing Procedure 2: Resources Required

This test will occur in stages, first utilizing a test rig to evaluate reaction displacement under controlled conditions. Further testing will incorporate simulated soft tissue, to model the real use-case. This will require two separate test fixtures be constructed. Instruments to measure displacement can be fairly simple, either electronic (linear and rotary encoders) or a manual means of quantifying a change in position, like a graduated ruler and goniometer.

3.2.3 Testing Procedure 2: Schedule

This test will occur early in the spring 2020 semester with a target of the last week of February. This date is intended to allow for completion of test procedure 1, which will validate the components and allow for testing of the actual configuration.

3.3 Testing Procedure 3: User Comfort

Some of the technical requirements are focused on the BHE components which interact directly with the wearer (user comfort, passive DOF range, time to don/doff). These requirements will be tested through a focus-group type method. This is due to the subjective nature of some of the requirements.

3.3.1 Testing Procedure 2: Objective

To evaluate the user experience when wearing the BHE, including comfort, time to don/doff, and range of motion

3.3.2 Testing Procedure 2: Resources Required

This test will likely require the most planning, as the team will need human test subjects. Volunteers will be gathered and observed donning the device, walking around, and removing it. Procedures will need to be carefully developed for each phase, including a detailed list of standardized questions and acceptable body measurements of the subjects. The test will require use of a facility with open space as well

3.3.3 Testing Procedure 2: Schedule

This test will be performed mid-spring 2020, target is first week of march and planning will be ongoing throughout the semester. Beginning in January, the team will seek test subjects to perform the test and the procedure will be developed by mid-February.

4 Risk Analysis and Mitigation

The below sections discuss the FMEA of this project. This includes the top ten projected critical failures of the design and a discussion on risks and trade-offs analysis.

4.1 Critical Failures

The following sections will cover the top ten critical failures that could result from our current prototype. To categorize the failures, we split the system into four subsystems: the soft harness, rigid frame, actuation system, and control systems. These failures were recorded and ranked in the FMEA sheet which was done by the team. It can be referenced in Appendix C.

4.1.1 Potential Critical Failure 1: Creep in the Chassis

This failure relates to creep deformation on the chassis, which is the main metal bar in the rigid frame. The failure can be caused by the rigid frame material being too thin, which makes it more susceptible to deformation when is being used. When this happens, the rigid frame will no longer fit close to the user's body. To mitigate the failure the material of the metal can be switched out to something with a higher cycle life.

4.1.2 Potential Critical Failure 2: High Cycle Fatigue in the Spool Holder

High cycle fatigue in the spool holder is caused by the stresses from the spool moving. The reason it is high cycle is because the spool will be moving a lot while the system is active. This failure can be caused by the material of the spool holder not being robust enough. When this happens, fracture can occur which makes the spools unable to operate. This results in the system not working. The failure can be mitigated by using a stronger material and using FEA analysis to understand where the spool holders are experiencing the most stress.

4.1.3 Potential Critical Failure 3: Creep in the Spool Holder

Creep is deformation in the spool holder and is also caused by the stress from the moving spool. This failure can also be caused by the material not being robust enough. When this happens, there may be space in the mount between the spools and bracket. This failure is like the high cycle fatigue failure, and it can also be mitigated by using a stronger material and using FEA analysis to understand the forces.

4.1.4 Potential Critical Failure 4: Combined Creep and Fatigue in Motor Mount

Combined creep and fatigue in the motor mount is a result from the stresses on the component as the motor is running. This can result in deformation or fracture. The failure can be caused by the brackets in the mount being too thin. If this failure happens, motor mount failure will occur which would be a serious failure in the system. It can be mitigated by using a stronger episode in the bracket and using FEA analysis to see the forces acting on the brackets.

4.1.5 Potential Critical Failure 5: High Cycle Fatigue in the Motors

High Cycle Fatigue in the Motors is happening by overstressing and overheating the motor parts. Also, the high vibration can result many issues with motor. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is motor will be Unable to operate. Thus, the Recommended Action to this failure to be mitigated is to provide Preventative maintenance checks and services (FMEA) to avid this failure.

4.1.6 Potential Critical Failure 6: Abrasive Failure in the Spools

Abrasive Failure in the Spools can be caused by Poor Maintenance and Assembly error to the spools. Also, overstressing in the spools can result Abrasive Failure in the Spools. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is erratic operation in the system will happen. Addition to that, the spools might run into noise and heat that will cause effects to other parts in the system. Thus, the Recommended Action to this failure to not happen is to provide Preventative maintenance checks and services (FMEA) to avoid this failure.

4.1.7 Potential Critical Failure 7: Abrasive Wear in Timing Belts

The main issue that will cause the failure of Abrasive Wear in Timing Belts can be caused by Poor Maintenance and Assembly error to the Timing Belts. Another thing causes this failure is overload into the motor will lead high fraction (Abrasive Wear) in the timing belts and that will lead to back it in certain time. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is noise in the system will happen. Addition to that, the Timing Belts might run into noise and heat that will cause effects to other parts in the system. Thus, the Recommended Action to this failure to not happen is to provide Preventative maintenance checks and services (FMEA) to avoid this failure.

4.1.8 Potential Critical Failure 8: Abrasive Wear in Pulleys

Abrasive Wear in Pulleys is can be caused by Poor Maintenance and Assembly error to the pulleys. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is noise in the system. Addition to that, as the abrasive wear in pulleys increase this will lead to the system to be more lose and not safe to use. Thus, the Recommended Action to this failure to be mitigated is to provide a stronger material and Preventative maintenance checks and services (FMEA) to avid this failure.

4.1.9 Potential Critical Failure 9: Fatigue Failure in Shafts

The primary issue that will cause the Fatigue Failure in Shafts is result from Assembly error to the shafts. Also, choosing the low-quality shafts with short cycle life during the assembly of the system another reason of this failure. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is breaking the shafts in the system. Thus, the Recommended Action to this failure to be mitigated is to provide Preventative maintenance checks and services (FMEA) to avid this failure.

4.1.10 Potential Critical Failure 10: Corrosion Wear in Wiring

Corrosion wear in the wiring is when the metal in the wiring will start to corrode due to its chemical reaction with its environment. Though, this failure would most likely be cause by assembly error. Once the material corrodes, it would result in a bad electrical connection which would hinder how the system transfers electricity. Overall, to mitigate this error, checks would need to be made during assembly to make sure there is not exposed wiring. Also, maintenance checks to see if all the wiring are up to our standard.

4.2 Risks and Trade-offs Analysis

Overall, most of the failures present in our design were in the rigid frame subsystem and the actuation system. Only one high ranking failure was present in the control system. This specific control system failure does not relate heavily to the rigid frame and actuation system. Especially since this failure is caused by an assembly error. Though, the actuation system and rigid frame rely heavily on each other. Changes made can affect the entire design.

The entire exoskeleton relies on the chassis. If the chassis fails, the whole system will not work without that structure. Though, changing the design of the chassis will affect the spool holders and motor mounts, which are directly related to components in the actuation system. Though, it can be argued that the changes made to the chassis, spool holders, and motor mounts will not need to result in changing dimensions. Since to mitigate the failures in these components, only changing the material of the part is needed.

Even if changes were made to the material in the rigid frames, it would not affect the susceptibility of fatigue and abrasive failure in the actuation system. The timing belts are the second highest ranked potential critical failure, and it is also a critical part of the system. Also, many of these failures besides the high cycle fatigue in the motors are either a result of an assembly error or poor maintenance. Assembly error can be controlled within manufacturing, but it is difficult to encourage users to take their exoskeletons in for maintenance.

These failures make it difficult to truly understand how to mitigate each failure. Especially when some of the highest-ranking critical errors can only be prevented by user maintenance. In conclusion, there were too many key components in the actuation system and rigid frame that were at risk for failure. As a result, due to these risks and a meeting with the client, certain changes have been made to our design which will be referenced in later sections.

5 DESIGN SELECTED – First Semester

This chapter will describe changes to the design made after the preliminary report. The current state of the design will also be discussed, and an implementation plan will be established.

5.1 Design Description

The following section will describe the current state of the team's design as well a detailed account of changes made since the preliminary report.

5.1.1 Design at the Time of Preliminary Report

Shown below is the design described in the preliminary report.

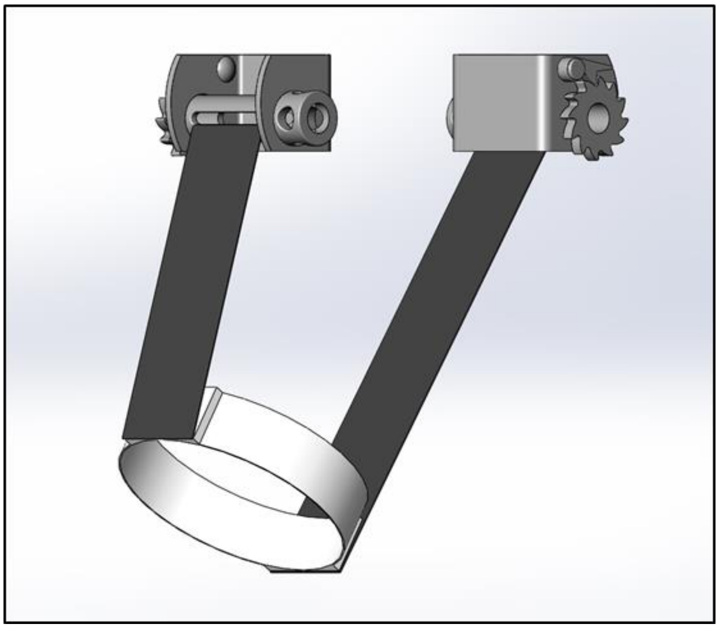

Figure 5-1: Design as of the preliminary report

This design from the preliminary report demonstrated the concept of a dual belt design as a basic CAD model. A dual belt design was selected because it was projected to be the most lightweight, and because it best fit the needs of the project's client. Engineering calculations conducted to reinforce the selection of this design over other concept variants is detailed in Appendix A. To get a better understanding of how a full system like this would function, a more detailed CAD model was made. This CAD model is shown in the below section.

5.1.2 Detailed CAD of Dual-Belt

Once the dual belt design was selected in the preliminary report, a more detailed cad model was produced, this is shown in the below figure.

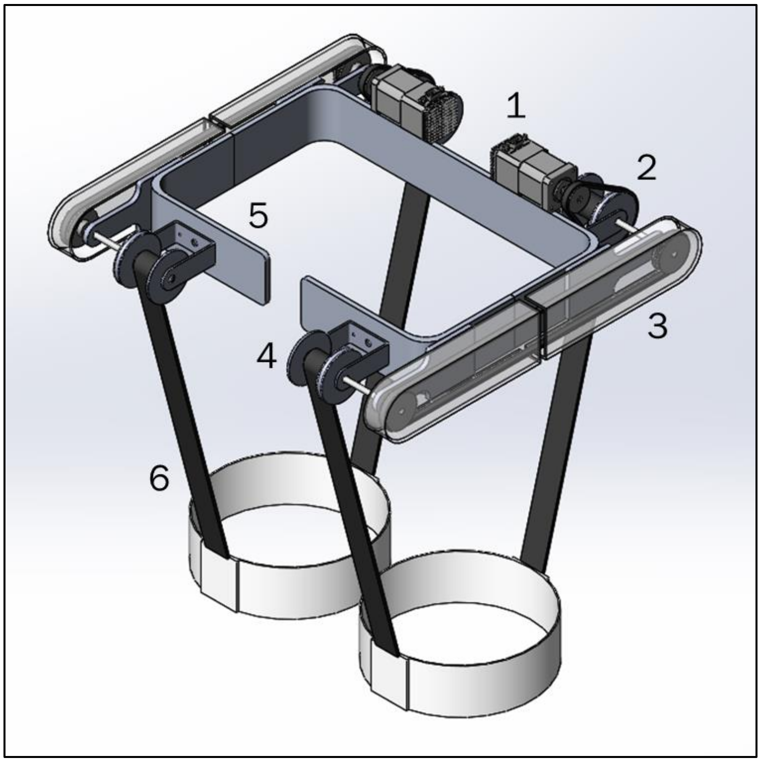

Figure 5-2: Detailed CAD of dual-belt design

Referring to the numbers displayed in the above figure, 1 is an electric motor connected to a rear spool (2) which is connected to a drive belt with cover (3) which is then connected to the front pulley (4). Numbers 5 and 6 highlight the rigid frame and belts connected to leg loops, respectively. This detailed CAD includes small improvements made from the original concept variant. Most notably is the use of 2 motors instead of 4, this was done to reduce cost as motors are the most expansive component in this system. The belts were also reduced from 2 inches to 1.25 inches in width to reduce weight. To accommodate for only 1 motor per side instead of a motor on all four pulleys, a drive belt (3) is used to transfer the energy from the rear spools to the front spools. A detailed view of this drive system is shown in the below figure.

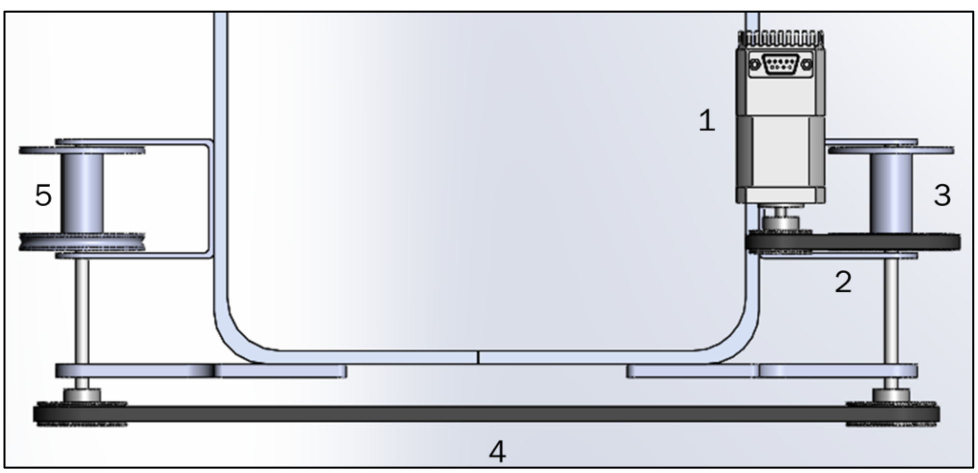

Figure 5-3: Drive system from CAD model

Components shown in the above figure are as follows, electric motor (1), drive belt I (2), rear spool (3), drive belt II (4), and front pulley (5). This system utilizes timing belts for accurate positioning of the spools. Additional images of this CAD model can be found in Appendix B. This CAD model was used to create the prototype that will be described in the below section.

5.1.3 Prototype

Shown below is a photo of the prototype constructed for the dual-belt design.

Figure 5-4: Constructed prototype of dual-belt design

There were a few takeaways from the construction of a low-fidelity prototype. Firstly, the use of a soft military-style belt with MOLLE webbing proved to be a comfortable and effective mounting solution for the rigid structure of the exoskeleton. However, the prototype did reveal some issues with the design for the rigid frame. As shown in previous images of the CAD model, the frame must be rectangular in shape to accommodate for a timing belt system. This creates an issue in that the rigid frame causes interference in the natural movement of the user's arms during the walking cycle. To solve this issue, the rigid frame needs to be brought closer to the user's body in order to allow for better freedom of movement in the arms. The design described in the below section attempts to address this issue.

5.1.4 Revision Post-Prototype

Based off FMEA, discussions with this project's client and analysis of the prototype, changes of the original dual-belt design have been made. The below figure shows this change of design. Preliminary sketches and additional views of this design can be found in Appendix B.

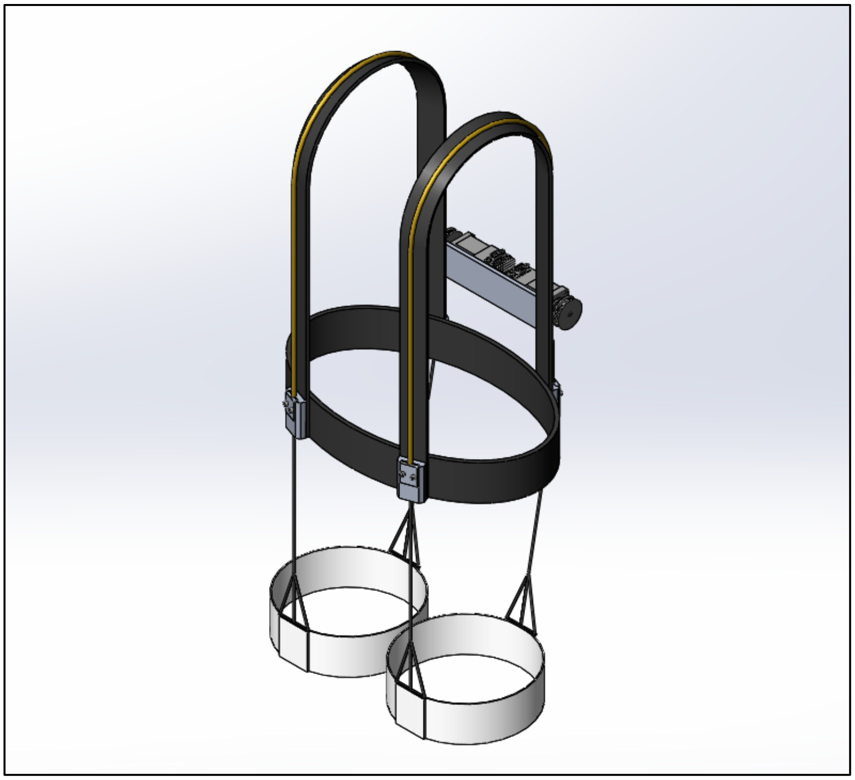

Figure 5-5: Change of design after FMEA and Discussions with client

It was established with the previous design that the rigid frame would interfere with the natural movement of the user's arms, impeding the natural walking cycle. To solve this issue, the above revision to the design was made. This new design utilizes Bowden cables in the place of a timing belts to transfer the energy generated by the electric motors to the user's hips. Like the previous design, the new design only utilizes two motors, one per leg. The Bowden cable will run down to a knee brace fastened to the user's knees. A spool will be attached to the Bowden cable, allowing the cable to be drawn in as the motor rotates. The biggest engineering challenge for this design is accounting for differences in the rate of cable being brought in at the front versus the rate of cable being let out at the back. These rates may not be consistent with each other so running tests in both CAD and on the prototype will be critical in understanding this behavior.

It is likely that the final prototype presented at the end of the first semester of capstone will closely resemble the design described above.

5.2 Implementation Plan

This section will describe how the current design will be implemented. This includes a bill of materials, resources required (information, people, materials, facilities, etc.) and schedule.

5.2.1 Design Implementation

It was established in previous sections that the biggest design challenge of the most recent design is potential differences in Bowden cable rates between the front and the back of exoskeleton. To test for this, the current prototype will be used to measure the differences in cable-in versus cable-out. Further verification of the results gathered from prototype testing will be conducted in SolidWorks. When the CAD model of the most recent design is developed further, a motion study will be conducted to understand the difference between cable-in versus cable-out. When a front/back cable ratio is obtained from both test methods, the ratio will be accounted for with gear reductions on the electric motor and with variable spool diameters.

5.2.2 Bill of Materials (BOM)

Shown below is the exploded view of the current design and a corresponding bill of materials. Note that the numbers displayed on the exploded view correspond to part numbers listed in the BOM. Also note that not all part numbers in the BOM are present in the exploded view due to this iteration of the design being recent to within a week of this report.

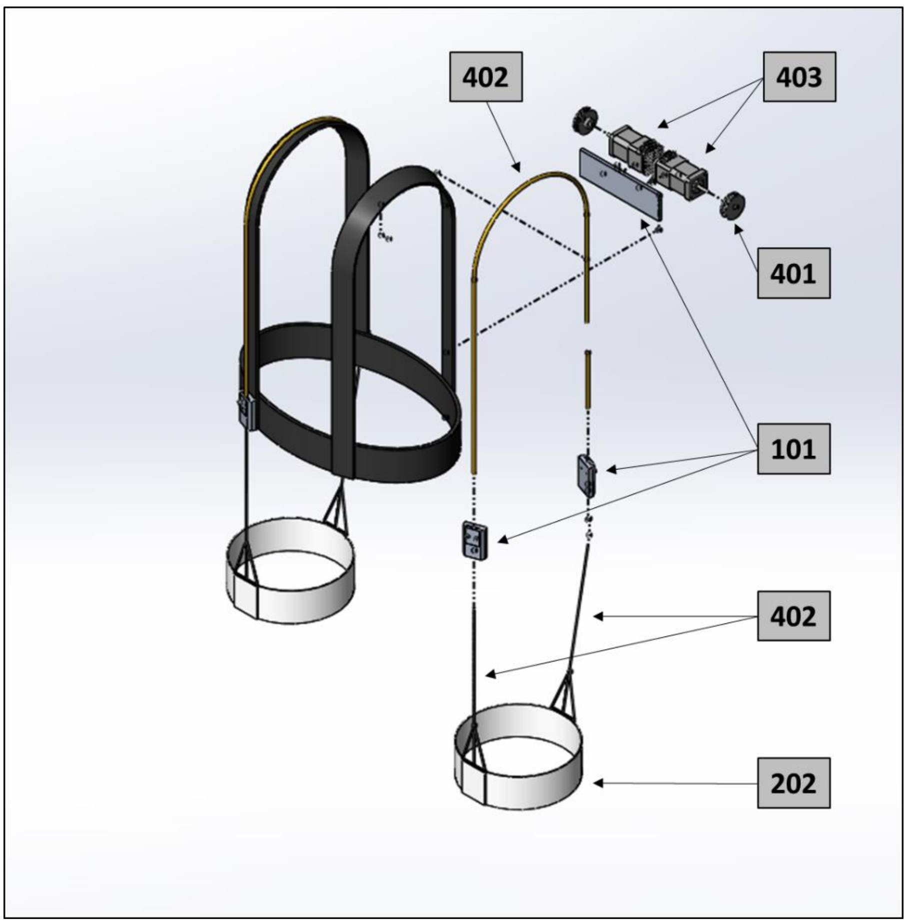

Figure 5-6: Exploded view with part numbers

Table 5-1: Bill of materials for the current design

Dual-Belt Design			
Subsystem	**Part #**	**Component**	**Price (Total)**
1. Rigid Frame	**101**	Aluminum Stock (Frame	$75.00
2. Soft Harness	**201**	Harness	$50.00
	202	Knee Brace x 2	$35.76
	203	Buckles	$5.00
3. Power System	**301**	Power Supply	$50.00
	302	Battery	$50.00
	303	Wiring/Controller	$50.00
4. Actuation System	**401**	Bearings and Gearing	$100.00
	402	Bowden Cable/Webbin	$12.63
	403	Electric Motor x 2	$1,200.00
	404	Spools	$100.00
5. Sensors	**501**	Sensors	$100.00
		Total	**$1,828.39**

The above BOM breaks down the required raw materials for each subsystem. The most significant expense in this project will be the motors, as they will likely need to be made custom by a manufacturer. Bearings, gearing, custom spools and a custom rigid frame will also be a large expense. Note that the custom spools and rigid frame components may need to be produced by a machine shop and labor will also factor into their cost. These labor costs and other related resources will be described in the below section.

5.2.3 Resources

The below table provides an overview of the resources required to build and test the exoskeleton design.

Table 5-2: Anticipated resources for completion of project

Resources		
Name	**Service Provided**	**Cost (If any)**
NAU Biomechatronics Lab	Testing facilites, knowledge on previous exoskeleton designs. Some electrical componentry including control systems.	0
Protolabs	CNC machining of frame components.	Dependant on parts manufactured. Expected service fee per part.
NAU Machine Shop	CNC machining of frame components.	0
3D Printer (Sean's personal printer)	Rapid prototyping for final prototype.	Less than $20 in print material
	Max Total	**$100.00**

Most of the resources required for the completion of this project are already available at little to no cost. The only resource that may incur any manufacturing costs is machining smaller, more complicated parts in the assembly. There are a few resources available for machining parts. The first is Protolabs, which is an online resource that will manufacture components based off CAD drawings. The other option is the NAU machine shop, which can manufacture parts at little to no cost, but turnaround time may be much slower compared to Protolabs. Whichever option is used for machining will depend on available budget and how quickly parts will be needed. Ideally, parts will be sent to NAU machine shop for manufacturing well ahead of time so the team doesn't need to pay Protolabs extra costs in labor and shipping. However, a budget for manufacturing from resources like Protolabs is accounted for in the above table.

5.2.4 Comparison between BOM and Resources

Most of the budget for this project will go to raw materials due to the custom nature of the electrical components and rigid frame. Most of the manufacturing of this project will be done by the capstone team in the Biomechatronics laboratory. This will reduce labor costs and allow the team to put more of the budget into high quality materials.

5.2.5 Schedule

An overview of the schedule for the second semester of this project can be found in Appendix E. The most significant deadlines of the second semester are the hardware summary (January), midpoint report and individual analysis II (February), final poster, presentation and report (April). This capstone team is constantly planning ahead of time to ensure that these deadlines are met. It is the goal of this team to have a significantly refined design at the end of the first semester to ensure the second semester progresses quickly and effectively.

6 CONCLUSIONS

The process for designing a hip exoskeleton for the NAU Biomechatronics lab has been an extensive process. Overall, the team wants to create a hip exoskeleton that can assist individuals with neuromuscular and musculoskeletal disabilities, which is the main goal of the lab. The hip exoskeleton is meant to assist movement in extension/flexion. Other critical requirements heavily relate to applying the required torque to assist this movement while also being comfortable and safe for the user. To maximize comfortability for the user, minimizing weight and keeping freedom of movement in other degrees of motion is another priority.

Our final solution was a soft exoskeleton which is run by a belt drive. The movement is actuated by webbings which are attached at the front and back of the leg. Two motors power the movement of the webbings to actuate the extension/flexion movement. The motors are placed on a rigid frame which is attached to a soft frame. This design was initially liked by the team and client due to the lightweight design.

Though, this solution will be changed in the future due to a recent meeting with our client. There were aspects of the design that had difficult problems to solve in the amount of time we had. Instead, we will be moving forward with a design based on high strength cords and Bowden cables.

7 References

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[10] Federal Aviation Administration, *HF-STD-001B: Human Factors Design Standard,* U.S. Department of Transportation, 2016.

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8 APPENDICES

Shown below are the appendixes for this report.

8.1 Appendix A: Engineering Calculations

The below sections describe engineering calculations used to reinforce concept selection.

8.1.1 Calculations for Cycles Until Failure

In order to understand how each material of each design compares to one another it is important to calculate how much fatigue they can withstand until failure. Our design will be working with the human body which is constantly in motion so seeing how that can affect each material is important.

To estimate the cycles until failure, equation relations to S-N curves were implemented. The equations used will be referenced below.

$$N = \sqrt[b]{\frac{S_f}{a}} \quad \text{6-13 [4]}$$

$$a = \frac{(f*S_{ut})^2}{S_e} \quad \text{6-14 [4]}$$

$$b = -\frac{1}{3}\log(\frac{f*S_{ut}}{S_e}) \quad \text{6-15 [4]}$$

In the following table values used for S_{ut} (ultimate tensile strength) and f will be shown.

Table 8-1 Values for equations

Material	S_{ut}(MPa)	f
Carbon fiber	600 [5]	0.86 [4]
Polyurethane	44.1 [6]	0.9 [4]
Nylon	82.7 [7]	0.9 [4]

For the value of S_f which is the stress the material is going through. The force was assumed to be around 2 kN which was derived from research done by Wenbin [8]. It is the force that is going through specially the iliopsoas (hip muscle). Then using the garage area of a leg, Stress was found using $\frac{F}{A}$.

The stress we used for every part was around 0.726 MPa. S_e is equal to $0.5S_{ut}$. [4]

Next, the following table will reference an excel sheet which solved the equation above.

Table 8-2 Results

a	b	Sut	Se	N (cycles until failure)
887.52	-0.07851	600	300	2.11496E+39
71.442	-0.08509	44.1	22.05	3.61176E+22
133.974	-0.08509	82.7	41.35	3.42615E+25

The last value N is the cycle time until failure for each material. The numbers are large most likely due to the estimated force being rather low compared to the ultimate tensile strengths. Detailed force analysis has not been done yet but once it is the team can most likely use these equations again to find new cycle times. Overall, it is shown that in general carbon fiber would last the longest out of all these materials, which makes sense due to its higher tensile strength. Though each material has different roles in their specific design, so it is difficult to judge based off longevity of materials along. In general, we can assume that all these materials are long lasting on their own, but further testing needs to be done one how they interact with the entire system.

8.1.2 Mass Calculations

Weight estimates were conducted based off the initial CAD designs produced for the preliminary report. Below is a table showing the projected weights for the top 2 concept variants in the preliminary report and the constructed prototype.

Table 8-3: Projected weights of concept variants vs weight of constructed prototype

Concept Variant	Weight (lbs)
Hamstring	14.53
Dual Belt	5.89
Dual Belt (Prototype)	4.41

The above table demonstrates that the dual belt design is projected to be significantly lighter than the next highest-ranking concept variant. The table also shows that the weight of the dual belt design was confirmed with the construction of the prototype. This justifies the use of the dual belt design as weight reduction is one of the most important customer requirements for this project.

8.2 Appendix B: Design Details

This appendix provides additional images of designs described in the main body of the report.

8.2.1 Dual-belt Design

Below are additional photos of the refined version of the design selected in the preliminary report.

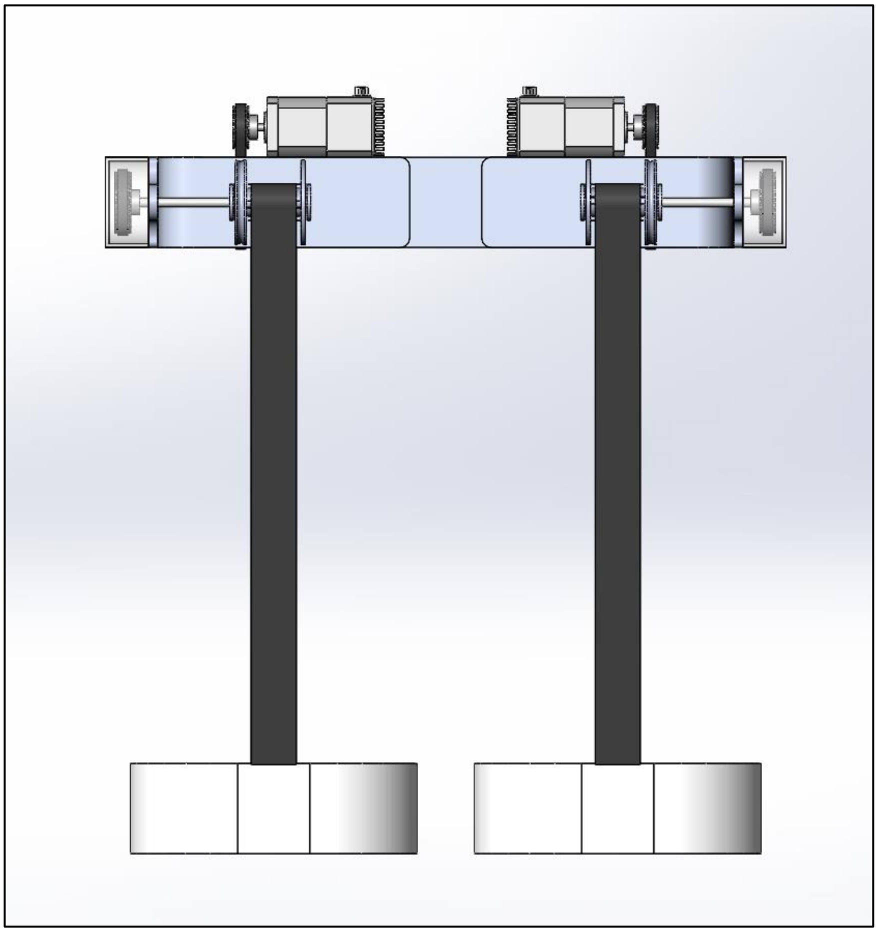

Figure 8-1: CAD of dual-belt design (Front)

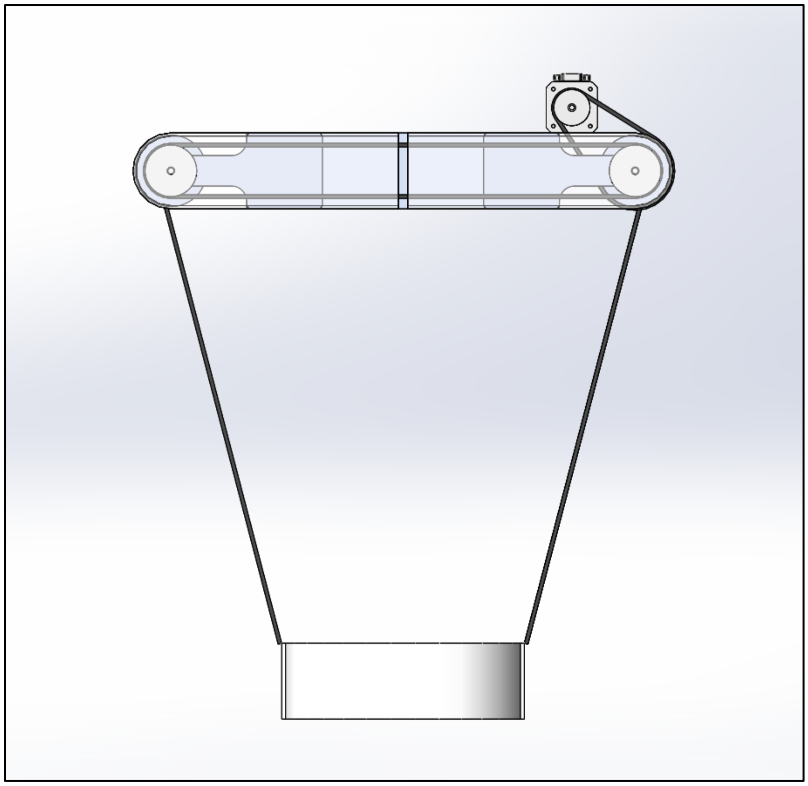

Figure 8-2: CAD of dual-belt design (Right)

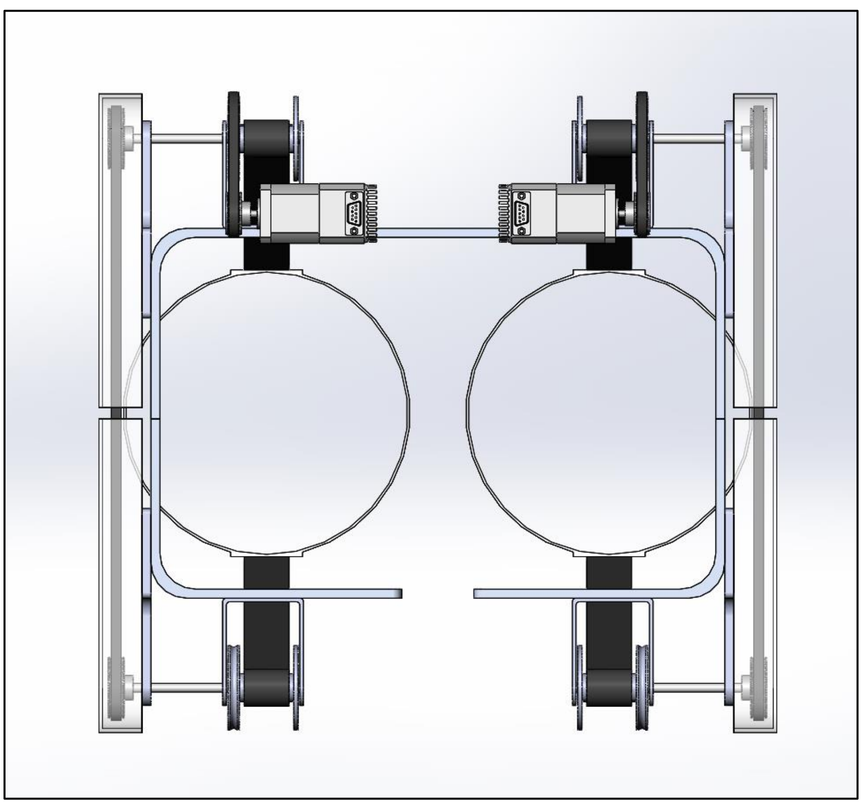

Figure 8-3: CAD of dual-belt design (top)

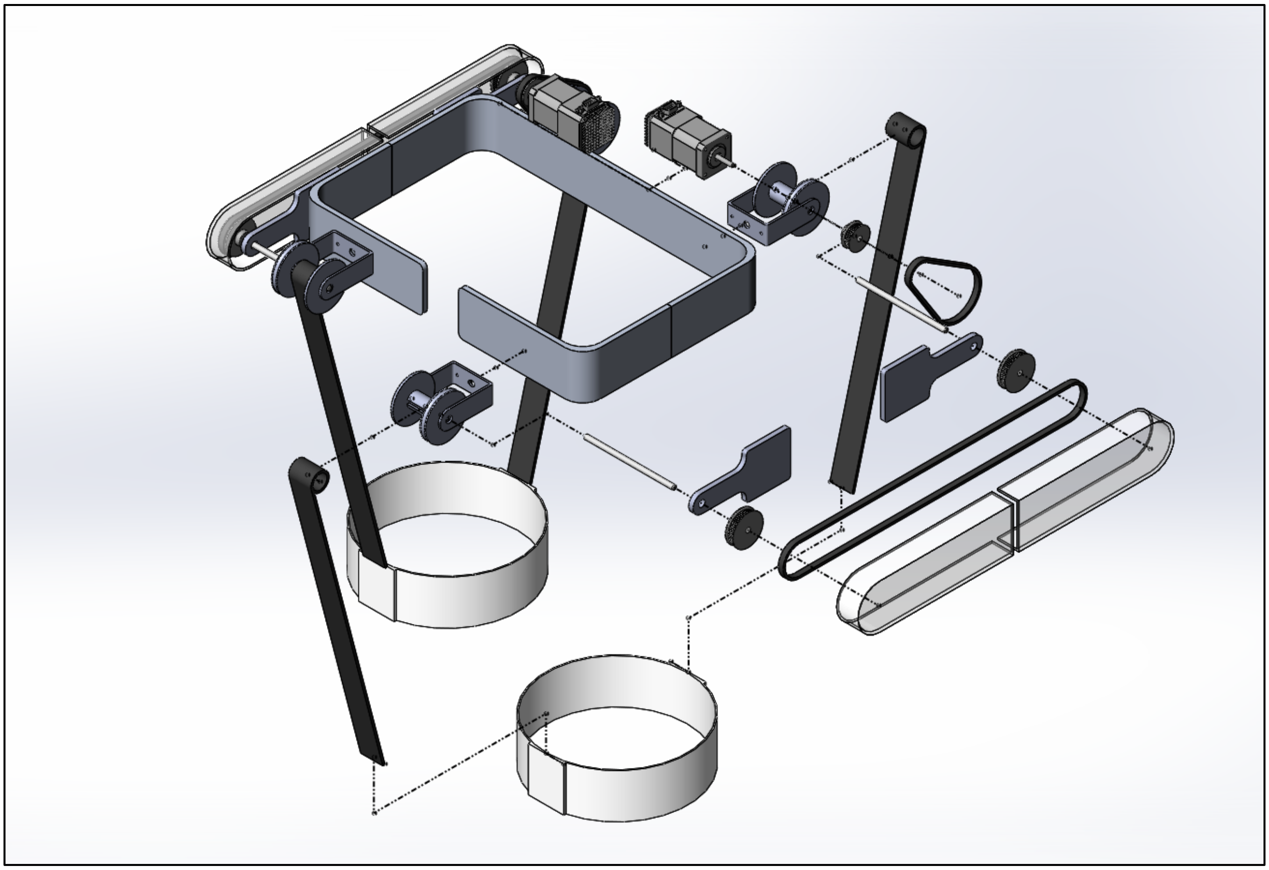

Figure 8-4: Exploded view of dual-belt design

8.2.2 Current State of the Design

Shown below are additional photos of the most current iteration of the design.

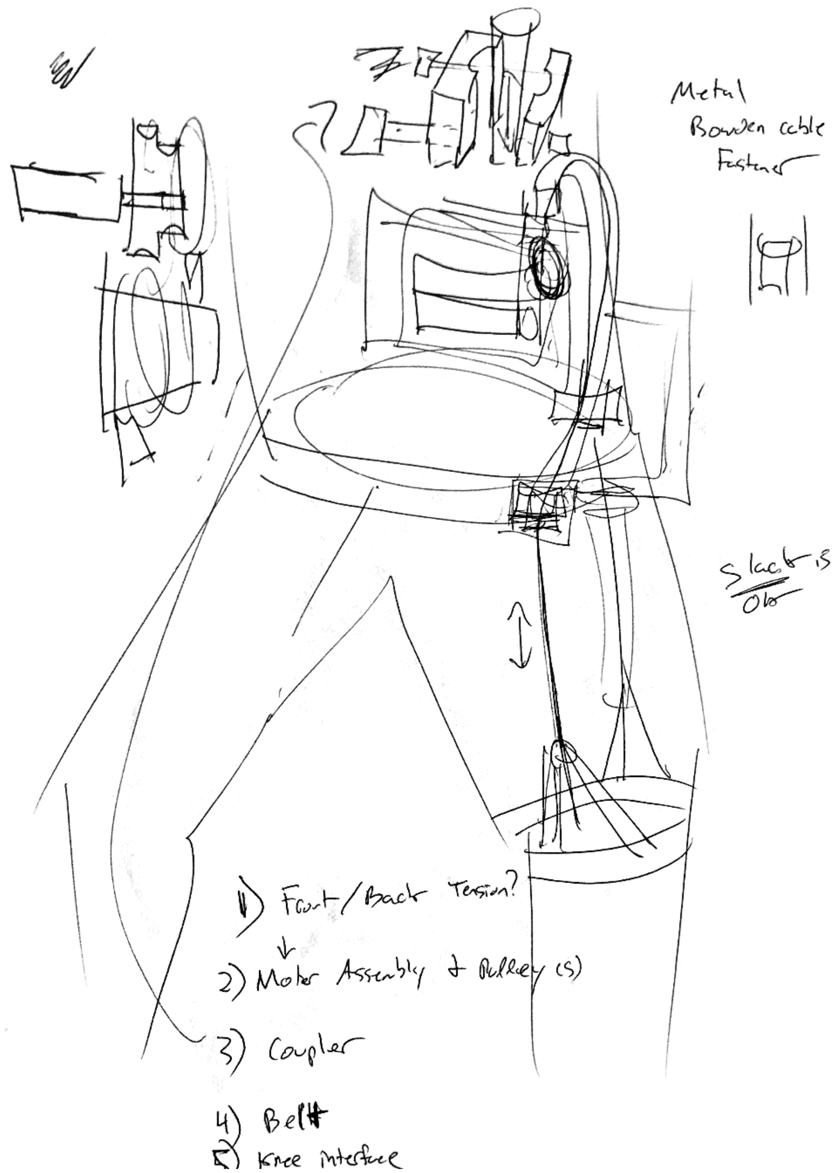

Figure 8-5: Preliminary sketch for most current design

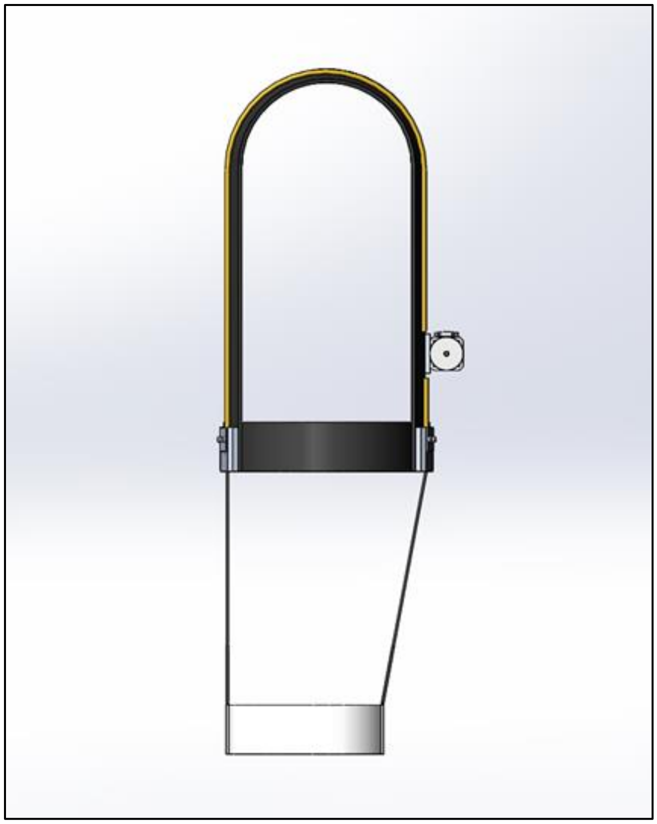

Figure 8-6: Detail view of most current design (right view)

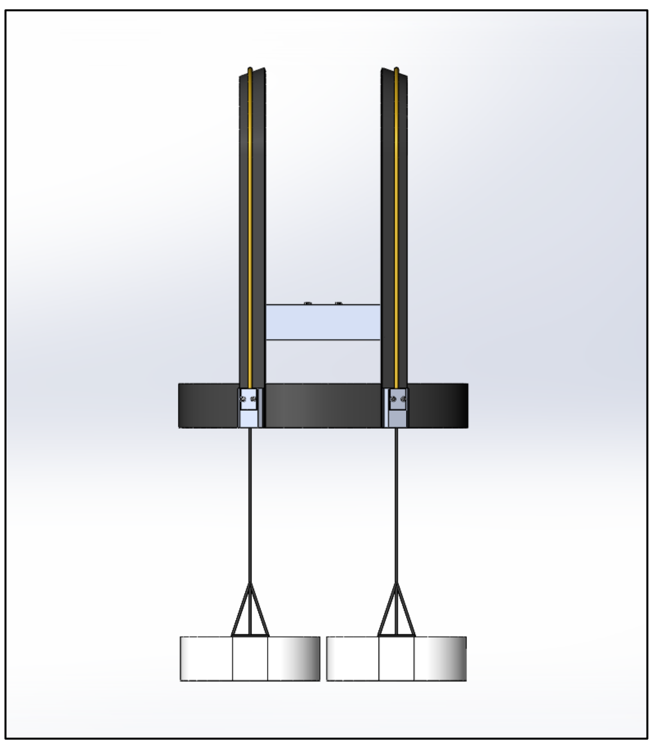

Figure 8-7: Detail view of most current design (front view)

8.3 Appendix C: Failure Mode and Effect Analysis

8.3.1 Full FMEA sheet

Table 8-4: FMEA of each Subsystem, highlighted are top 10

FMEA of each Subsystem, highlighted are top 10

Subsystem	Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Soft Harness	Belt	Abrassive Failure	Poor appearance	2	Overstressing(Contact with subject/frame)	5	Displacement	1	10	Stronger material, larger surface area
		Fretting Wear	Fabric could distress	3	Overstressing	7	Displacement	1	21	Stronger material
	Padding	Abrassive Failure	Poor appearance	1	Poor Quality	5	Displacement	1	5	Stronger material
		Surface Fatigue	Poor appearance	1	Contact with subject	5	Displacement	1	5	Stronger material
	Attachment Point	Fatigue Failure	Breaking, debris	7	Overweight	5	Displacement	1	35	Stronger material, minimize weight on points
		Brittle Fracture	Breaking, debris	7	Overweight	5	Displacement	1	35	Minmize weight
	Knee Brace	Abrassive Failure	Poor appearance	2	Overstressing(Contact with subject)	5	Displacement	1	10	Stronger material
		Fretting Wear	Fabric could distress	3	Overstressing	4	Displacement	1	12	Stronger material
	Buckle	Brittle Fracture	Debris, system can't be worn	7	Overweight, poor quality	3	Displacement	1	21	Minimize weight, high quality material
		Low Cycle Fatigue	Fracture	7	Stress	3	Displacement	1	21	Stronger material
	Adjustments	Abrassive Failure	Ripping	5	Roughly used	2	Displacement	1	10	Stronger material
		Low Cycle Fatigue	Distress in material, stretching	5	Stress	2	Displacement	1	10	Minimize elasticisity
Rigid Frame	Chassis	Creep	Ridid frame no longer fits close to body	5	Rigid frame material too thin	2	Displacement	9	90	Material with higher cycle life
		Deformation Wear	Ridig frame failure	8	Material not hard enough	2	Displacement	2	32	Material with higher cycle life
		High Cycle Fatigue	Ridig frame failure	8	Material not rigid enough	2	Displacement	2	32	Material with higher cycle life
	Spool Holder	High Cycle Fatigue	Fracture, spools unable to operate	8	Material not robust enough	6	Displacement	2	96	Stronger material, FEA analysis
		Creep	Play in mount between spools and brack	5	Material not robust enough	3	Displacement	9	135	Stronger material, FEA analysis
	Coupler	Low Cycle Fatigue	Deformation of braket, no longer fits	5	Coupler experiences unintended stresses	2	User Comfort	3	30	Stronger material, FEA analysis
		Combined Creep and Fatigue	Braket failure, frame detaches from harn	4	Coupler experiences unintended stresses	1	User Comfort	7	28	Stronger material, FEA analysis
	Motor Mount	High Cycle Fatigue	Motor comes free of rigid frame	9	Braket is too thin	4	Displacement	1	36	Stronger material, FEA analysis
		Combined Creep and Fatigue	Motor mount failure	8	Braket is too thin	4	Displacement	9	288	Stronger material, FEA analysis
	Drive Sys Covers	Impact Fatigue	Failure, covers no longer protect user	8	System is dropped	1	User Comfort	1	8	Impact testing
Acuation System	Motors	High Cycle Fatigue	Unable to operate	8	Overstressing	6	Extension/Flexsion	1	48	PMCS
		Thermal Fatigue	Odor, heat,	6	Over Voltage/Current	6	Extension/Flexsion	1	36	PMCS
	Gearbox	High Cycle Fatigue	Noise, erratic operation	5	Overstressing	3	Extension/Flexsion	1	15	PMCS
		THermal Fatigue	Heat	6	Poor Maintenance, Overstressing	3	Extension/Flexsion	1	18	PMCS
		Galling and Seisure	Noise	5	Poor Maintenance, Tolerance stack-up	3	Extension/Flexsion	1	15	PMCS
	Spools	Abrassive Failure	erratic operation, noise, heat	5	Poor Maintenance	4	Displacement	3	60	PMCS
		Stress Rupture	debris, unable to operate	9	Overstressing	1	Extension/Flexsion	1	9	PMCS
	Timing Belts	Abrasive Wear	Noise	7	Poor maintenance	5	Extension/Flexsion	7	245	PMCS
	Pulleys	Abrasive Wear	Noise	7	Assembly error	2	Displacemnet	7	98	PMCS
	Shafts	Fatique Failure	Breaking	7	Assembly error	2	Extension/Flexsion	3	42	PMCS
	Webbing	Fretting Wear	Distress in material, stretching	5	Overstressing	5	User Comfort	1	25	PMCS
Control Systems	Battery	Corision Fatigue	bad connection, no power	9	Assembly error	1	Displacement	1	9	PMCS
		Thermal Fatigue	loss power, chemical may exposed	9	Overstressing	2	Extension/Flexsion	1	18	PMCS
	Wiring	Corision Wear	bad electrical connection	7	Assembly error	1	Extension/Flexsion	6	42	PMCS
		Abrasive Wear	heat	6	Overstressing	3	Extension/Flexsion	2	36	PMCS
	Sensors	Deformation Wear	unaccurate read, erratic operation	7	Assembly error	1	Extension/Flexsion	2	14	Calibration schedule
		Abrassive Wear	Noise, erratic operation	6	Fracture	2	Extension/Flexsion	2	24	PMCS
	Control Module	Corision Wear	Heat	6	Overstressing	1	Extension/Flexsion	6	36	Stronger material, FEA analysis
		Thermal Fatigue	heat	6	Overstressing	3	Extension/Flexsion	2	36	Stronger material, FEA analysis
	Switches	Low Cycle Fatigue	no connection, no power	7	Assembly error,Overstressing,Fracture	1	Displacement	1	7	Stronger material, FEA analysis
		Impact Fatigue	bad quality,noise	5	Assembly error	1	Displacement	1	5	Stronger material, FEA analysis

8.4 Appendix D: House of Quality

Table 8-5 Full House of Quality

Customer Requirement	Weight	Torque applied ↑	Metabolic cost of walk	Time to don/doff	User comfort rating (0	Weight ↓	Operation time/cycle (	Power Required	Cycles to failure	Cost to manufacture ↓	Extension/Flexion ↑	Abduction/Aduction	Rotation	Noise ↓	Compliance/conforma	Benchmarking 1	2	3	4	5
Hip Actuation	5	9	0	1	3	3	9	9	9	9	9	0	0	9	3			B		AC
Full range of motion	5	1	9	1	9	3	3	0	3	1	9	9	9	1	3			B		AC
Sense Torque	5	3	0	0	1	0	9	3	3	9	9	0	0	1	0			A	C	
Easy to don and doff	2	0	0	9	9	9	0	0	1	1	0	0	0	0	9		A	C		B
Comfortable	2	1	9	3	9	9	3	0	1	1	3	3	3	9	9			C	A	B
Minimize medibolic cost	4	3	9	3	3	3	3	3	0	3	9	9	9	0	3		A	C	B	
Within Budget	1	0	0	1	1	3	0	1	1	9	1	1	1	1	0	ABC				
Reliable	2	3	3	3	1	3	9	9	9	9	3	3	3	1	3		C	A	B	
Safe to operate	4	9	9	1	9	3	9	9	3	0	9	9	9	1	3		A		C	B
Untethered	4	3	0	3	9	9	9	9	1	3	0	0	0	0	0					ABC
Durable	3	9	1	1	3	3	9	0	9	3	9	9	9	1	3			AC	B	
Fit small to medium build	1	0	1	3	9	0	0	0	0	1	0	0	0	0	0			ABC		
Absolute Technical Importance (ATI)		160	145	75	206	144	240	163	141	160	247	157	157	83	105					
Relative Technical Importance (RTI)		7.3%	6.6%	3.4%	9.4%	6.6%	11.0%	7.5%	6.5%	7.3%	11.3%	7.2%	7.2%	3.8%	4.8%					
Target ER values		<25% b	0	3 min	9				2 mo.		135°									
Tolerances of Ers				±2	±1						±									
Testing Procedure (TP#)		1	1	3	3	3	1	1	2	N/A	1	1	1	3	3					

8.5 Appendix E: Scheduling

Shown below is the schedule for the second semester of this capstone project.

Table 8-6: Schedule for the second semester of the project

Post Mortum Due	1/6/20	1/15/20	All
Self-Learning	1/13/20	1/22/20	All
Hardware Summary 1 Due	1/22/20	2/11/20	
Start Hardware Summary	1/22/20	2/7/20	All
Edit Hardware Summary	2/10/20	2/11/20	All
Hardware Summary Due	2/12/20	2/12/20	
Peer Eval 1	2/12/20	2/12/20	All
Website Check 1	2/12/20	2/18/20	
Edit Website	2/12/20	2/18/20	Mohanad Fakkeh,Inna Quiambao
Website Check Due	2/19/20	2/19/20	
Midpoint Report	2/24/20	3/3/20	
Start Midpoint Report	2/24/20	2/28/20	All
Edit Midpoint Report	2/28/20	3/3/20	Inna Quiambao
Midpoint Report Due	3/4/20	3/4/20	All
Individual Analysis II	2/24/20	3/10/20	
Choose Topics	2/24/20	2/28/20	All
Compile Research	2/28/20	3/6/20	All
Analysis II Due	3/11/20	3/11/20	
Device Summary	3/11/20	3/25/20	All
Peer Eval 2	3/25/20	3/25/20	All
Postar Drafts	3/25/20	4/1/20	All
Testing Proof	4/1/20	4/8/20	All
Final Poster	4/8/20	4/15/20	All
Operation Manual	4/15/20	4/15/20	Sean Oviedo
Final Presentation	4/13/20	4/22/20	
Compile Information	4/13/20	4/17/20	All
Edit Presentation	4/17/20	4/21/20	All
Presentation Due	4/22/20	4/22/20	
Final Report	4/13/20	4/28/20	
Compile Information	4/13/20	4/22/20	All
Edit Report	4/22/20	4/27/20	Keegan Ragan
Report Due	4/29/20	4/29/20	
CAD Package	4/15/20	4/29/20	Keegan Ragan,Sean Oviedo
Website	5/6/20	5/6/20	Mohanad Fakkeh
Peer Eval 3	5/6/20	5/6/20	All