Biomechatronic Hip Exoskeleton Team (BHET)
Final Report

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DISCLAIMER

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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 requirements and their respective weights.

Table 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 assisted in extension/flexion but needs to be passive in all other directions. The team's design also needs to sense the torque 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 must ensure that 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 will 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 the 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 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 currently a priority.

After we have met with our client this semester regarding the Customer Requirements, the client approved all of them except the following: Sense Torque, Minimize Metabolic Cost, and Untethered. These are not relevant anymore and are now out of the scope of the current design.

2.2 Engineering Requirements (ERs)

To meet the customer requirements, they must be translated into quantitative technical specifications. This allows the team to quantify the customer's needs and measure the designs ability to meet those needs. The following section covers the individual engineering requirements for the Hip Exo project. Some of these engineering requirements have changed since last semester. If this is the case, it is noted in the section heading. All other engineering requirements have remained unchanged since last semester.

2.2.1 ER #1: Torque Applied

This ER quantifies the amount of torque assistance to the wearer. The device provides assistive torque during extension/flexion only. An important detail of this requirement states that the design must be able to deliver the specified torque at any point along the full extension/flexion range of motion (ER #10).

2.2.1.1 ER #1: Torque Applied Target = 12.5 N-m

The target value for applied torque was determined over several steps. The customer initially stated that the design should be able to apply 25% of the wearers natural torque, assuming the average patient has a natural hip joint torque of 1N·mkg. This constitutes the peak torque the design must be capable of delivering, it is assumed that the PWM controlled motors will be capable of torque delivery from 0 to peak. Taking the maximum mass of a patient from the NAU Biomechatronic Lab records (50 kg) and multiplying by the client-stated 25% gives 12.5 N·m

2.2.1.2 ER #1: Torque Applied Tolerance = ±3.5 N-m

This tolerance was specified by the client.

2.2.2 ER #2: Metabolic Cost of Walking (Now out of project scope)

The metabolic cost of walking measures how much energy is consumed by the user during a normal walking cycle. Knowing the metabolic cost of walking with and without the hip exoskeleton allows for an assessment of the hip exoskeleton's effectiveness. Determining the metabolic cost of walking is a difficult process that requires the hip exoskeleton to be fully tested and functioning. Because of this, determining the metabolic cost of walking with the hip exoskeleton is now out of the scope of this project.

2.2.2.1 ER #2: Metabolic Cost of Walking Target = N/A

A target value was not specified by our client. The biomechatronics laboratory currently has no data on this engineering requirement.

ER #2: Metabolic Cost of Walking Tolerance = N/A

Similar to the target value described above, no tolerance value was specified by the client.

ER #3: Time to don/doff

The user must be able to put on and take off the hip exoskeleton within a reasonable amount of time. This makes the device more user-friendly.

ER #3: Time to don/doff Target = [1 minute]

After meetings with our client it was determined that it should take 1 minute to put the device on and 1 minute to remove the device. This value was chosen because it seemed like the most reasonable amount of time for this requirement.

ER #3: Time to don/doff Tolerance = [+/-10 Second]

Similar to the target value above, a tolerance of +/- 10 seconds was chosen because it seemed like a reasonable and achievable amount of time for this requirement.

ER #4: User Comfort Rating

The user comfort rating is a qualitative assessment of individual user's experience while using the hip exoskeleton. Multiple user's will be asked to rate the device's overall comfort on a scale of 1-10.

ER #4: User Comfort Rating Target = [9]

The goal of this capstone project is to produce a hip exoskeleton design that is as comfortable as possible. An average rating of 9/10 fits with this goal while accounting for the fact that a perfect average is not realistic.

ER #4: User Comfort Rating Tolerance = [+/-1]

This tolerance puts the expected user comfort rating average to be between an 8 and a 10. This intuitively seems like a reasonable goal to reach for overall user comfort.

ER #5: Weight

The hip exoskeleton must be as light as possible in order to reduce the user's metabolic cost of walking while wearing the device. A lighter exoskeleton yields a better user experience.

ER #5: Weight - Target = Minimize

The current hip exoskeleton does not have a target weight. The client will talk to us about it when we are manufacturing. Presently, we want to minimize the weight as much as possible with the present materials that have been acquired.

ER #5: Weight - Tolerance = not specified

Presently, there are no tolerances set for the weight. It is our priority to minimize it as much as possible.

ER #6: Operation time/cycle (Now out of project scope)

The hip exoskeleton must operate long enough to allow for a substantial amount of data to be collected from tests with users. Because the hip exoskeleton will now be using a control system from current exoskeletons, operation time is no longer under the control of this capstone team.

ER #6: Operation time/cycle Target = N/A

Original operation time was expected to be 2 hours. Now that the capstone team is no longer responsible for the exoskeleton's control systems, this engineering requirement is out of the scope of this project. The hip exoskeleton will now have an operation time/cycle similar to current exoskeletons at the biomechatronics laboratory. The run time of current exoskeletons is not currently known by the capstone team as it does not apply to this project.

ER #6: Operation time/cycle Tolerance = N/A

No longer applicable to this project.

ER #7: Power Required

This requirement specifies the input power to the device. How much power is needed to operate the motors and control module.

ER #7: Power Required Target = 185 Watts

The target value was determined based on the manufacturer ratings for each component, added together. The motors are rated at 90W each. The power draw for the control module was estimated using the peak power required for an Arduino microcontroller at 2.4W.

ER #7: Power Required Tolerance = ±1W

This number was estimated because the specific power required for the control module will not be known and is beyond the scope of this project.

ER #8: Cycles to Failure

The hip exoskeleton should be able to function for a given amount of cycles before maintenance is required or parts need to be replaced.

ER #8: Cycles to Failure Target = Not yet known

The client of this project was not able to provide a specific target value for cycles to failure. This was because they have not yet tested an exoskeleton of this type before. To compensate for this, fatigue testing will be conducted on the completed exoskeleton. The procedure for this fatigue testing will be described in a below section.

ER #8: Cycles to Failure Tolerance = Not yet known

As described above, tolerances for this engineering requirement are not yet known, but will determined during testing.

ER #9: Cost to Manufacture

A requirement of this project was that hip exoskeleton stay within the allotted budget of $2250.

ER #9: Cost to Manufacture Target = [<$1900]

The total budget for this project is $2250, and it was already known that the motors would cost roughly $1600. This leaves roughly $300 for all other materials required to build the exoskeleton. The extra $350 is being set aside for testing and manufacturing costs. This value has not changed significantly since last semester.

ER #9: Cost to Manufacture Tolerance = [+/-$100]

A tolerance of +/-$100 was factored into the budget for this project. This is to account for any differences in material pricing, or if additional materials are required closer to the completion of the project.

ER #10: Extension/Flexion

This value describes the range in extension/flexion that the hip exoskeleton applies torque to the user's hips.

ER #10: Extension/ Flexion Target = [-30° Extension/45° Flexion]

The target value for this engineering requirement was provided to the team by Leah of the Biomechatronics Lab and from published material on similar devices [1, 2]. This target is important because the primary requirement of the hip exoskeleton is to actuate movement in extension and flexion.

ER #10: Extension/ Flexion Tolerance = [+/-5°]

These tolerances were taken to keep in mind that not everyone has the same range of motion.

ER #11: Abduction/Adduction

This value describes the range in abduction/adduction that the user has full freedom of movement.

ER #11: Abduction/Adduction - Target = [40° Abduction/ 20° Adduction]

The target value for this requirement was taken from the Range of Joint Motion Evaluation Chart [3]. This value is important because our hip exoskeleton requires free range of motion in all other directions besides extension and flexion.

ER #11: Abduction/Adduction - Tolerance = [+/-5°]

These tolerances were taken to keep in mind that not everyone has the same range of motion.

ER #12: Rotation

This value describes the range in rotation that the user has full freedom of movement.

ER #12: Rotation - Target = [45°]

This target value was taken from a report by Sanker et al [1]. This target value is important because, similar to abduction and adduction, the designed hip exoskeleton needs to have free range of rotation when it is powered.

ER #12: Rotation - Tolerance = [+/-5°]

These tolerances were taken to keep in mind that not everyone has the same range of motion.

ER #13: Noise (No longer relevant)

An important requirement of this project is that the hip exoskeleton produces as little noise as possible. Less noise generally results in a better and more comfortable user experience.

ER #13: Noise - Target = Minimize

Previously, the goal was to design a device that reduces noise as much as possible. However, this only applied when the team was weighing between a pneumatic or electric actuation system. Now that the project will utilize an electric actuation system noise is no longer a concern.

ER #13: Noise - Tolerance = Not Specified

No noise tolerances were ever required.

ER #14: Conformability/Compliance

Conformability/compliance measures the range of body types and sizes that the hip exoskeleton can fit.

ER #14: Conformability/ Compliance - Target = Various Sizes

One of the customer requirements for the hip exoskeleton is that it fits small to medium builds. So, it is our priority to make it as adjustable as possible. Since we are testing it on the team, we all have varying hip sizes, which can be translated into the small and medium sizes of the children.

ER #14: Conformability/ Compliance - Tolerance = not specified

There are no tolerances on how adjustable the hip exoskeleton needs to be. The team just wants it to fit various sizes.

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 final 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 (Figure1) 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 1: 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.

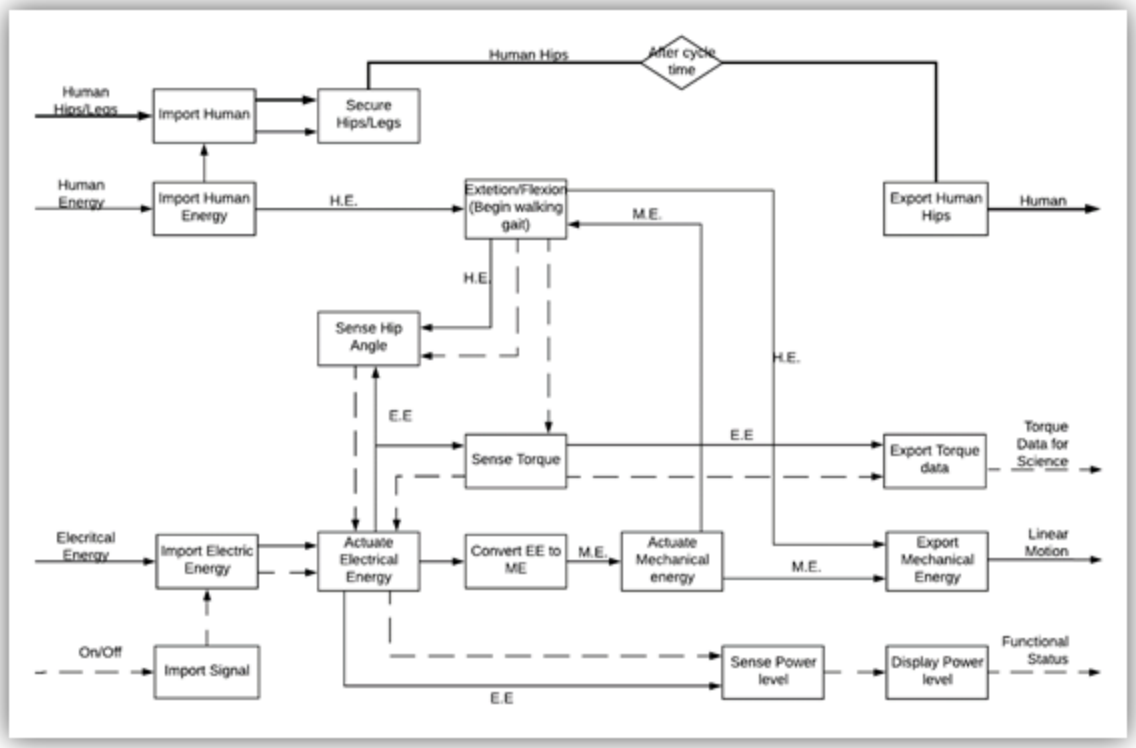

Figure 2: Functional Model

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*). 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

Engineers have an ethical responsibility to ensure a design is safe for the stakeholders. It can be difficult to know when designing a new product exactly how to measure the inherent safety of a design. Industry standards and legal requirements exist to ensure a design is safe before it reaches the end user. The team is obligated to identify relevant documentation and ensure compliance of the Hip Exoskeleton design. The following section is included to summarize the standards, codes, and regulations that apply to their project.

Standards applied to project

Table 2.1 Applicable standards

Ref. #	Standard Identifying Code	Title of Standard	How it applied to Project
1	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.
2	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	ASTM F3323	Standard Terminology for Exoskeletons and Exosuits	Provides a reference for common applicable terms that will be used in the final documentation of the project.

4	ASTM F3392	Standard Practice for Exoskeleton Wearing, Care, and Maintenance Instructions	Specifies minimum information to be conveyed in user documentation.
5	ASTM F3427	Standard Practice for Recording Environmental Conditions for Utilization with Exoskeleton Test Methods	Establishes what environmental conditions to consider need to be specified and potential performance impacts.

Committee F48 was established by ASTM International to develop a collection of standards specific to the exoskeleton and exosuit industry. As of the date of this memo, the committee has published three standards (Table 2.1, Ref # 3,4,5), though they have numerous proposed new standards still in development. Future work on the Hip Exoskeleton will be affected by the implementation of the proposed standards.

3 Testing Procedures (TPs)

This semester the team had various tests planned, but due to present circumstances they were not able to be completed. Overall, many of our tests involve wearing the exoskeleton and moving around with it. The team wants as much input on the comfortability and conformability of the exoskeleton since it will be worn by many people. Also, we needed to test the cycles of failure for certain parts of the exoskeleton since they ranked high in our original FMEA testing.

3.1 Testing Procedure 1: Torque/Power Output

This test is to evaluate the output torque and power of the hip exoskeleton. The test will be able to quantify the torque that is applied and overall power delivery. This test satisfies the engineering requirement for testing torque applied to the system and the power required by the device. Overall, a week was allotted for this test and another test in the following sections.

3.1.1 Testing Procedure 1: Objective

The objective is to use a test fixture, manufactured by the BHET team, to test the torque and power output. The motor mount assembly, which includes the final speed reduction pulley and actuation cables, will be attached to the testing fixture. To test the torque, the cables will be secured to load cells. An Arduino microcontroller will be programed to record the load cells output and control the motor speed controllers. Each level will be fun three times and results averaged.

The power deliver will be tested using the same motor mount assembly and test fixture. Though, the load cells will be replaced by pulleys. The cables will be routed the pulleys, then weights will be attached to the ends of the cables. Test assembly will then be placed at the end of the table, motors will be programmed to run, and the time taken to move the weight will be recorded. Using this data the power delivery can be calculated.

3.1.2 Testing Procedure 1: Resources Required

The resources required for the torque/power output test can be referenced below.

The main resource required for this test is the test fixture. It's a frame designed to contain the motor mount and load cells so that they are aligned. Displacement of the load cell occurs colinear with the cord. This frame can easily be made with off the shelf materials and tools. Figure 1 shows what the completed assembly would have looked like.

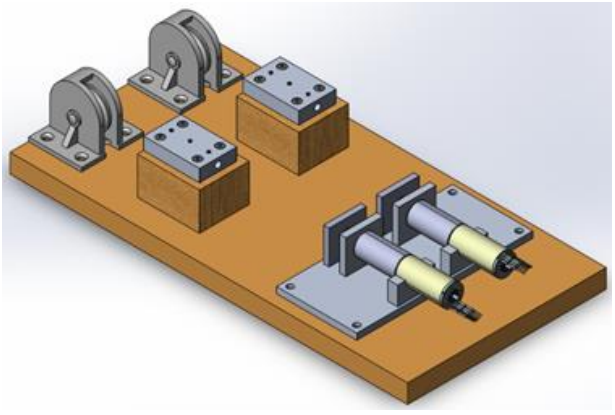

Figure 3-1 Test Fixture in Power Output Test

The next required item is the motor mount assembly, which included: motors, cables, hardware, and power source. The individual components have been manufactured in the Machine Shop or 3D printed.

Two load cells are required, the Wheatstone bridge is affixed to an aluminum member, and comes with a 24-bit analog-to-digital converter. This was already owned by one of the team members, but they can easily be purchases online.

The Arduino microcontroller is an open source programable microcontroller and can interpret and record the load cells output. This was also already owned by a team member, though it can also be ordered online or rented out from the university. Coding will be done in MATLAB.

To use all of these devices we would also need a computer or laptop, this test would have been done in the Biomechatronics Lab of NAU.

3.1.3 Testing Procedure 1: Schedule

The time we had allotted to this test was about a week, it would have been done the same week as fatigue testing since they use the same testing fixture. Actual testing time would only take a day since they are not long tests. Extra time would have been used to create the testing fixture, and also the code. Though since the testing fixture is relatively simple, we believe a week would be sufficient time.

3.2 Testing Procedure 2: User Comfort Rating/Survey

The exoskeleton is going to be worn by various people so understanding their opinion on the device is important. Random people would be chosen to wear the device and then they would complete a survey afterwards. This satisfies the user comfort rating engineering requirement, and this test was going to be done in a week. This gives a flexible schedule depending on the volunteer's schedules.

3.2.1 Testing Procedure 2: Objective

The primary goal is to receive feedback on the exoskeleton's design. Ten people would have been chosen at random to try on the exoskeleton. We would let them walk around in a set path, it would not be powered, and then ask them to complete a survey after. The survey questions would be given to the testers by the BHET team.

3.2.2 Testing Procedure 2: Resources Required

The main resources required is the completed hip exoskeleton, a testing room, test subjects, and the survey. The hip exoskeleton would be completed by the BHET team. The testing room would be the Biomechatronic lab, and the test subjects would have been gathered by the members of the team. The created survey can be referenced below. The rating would be on a 1-5 scale, one being the worse rating.

Table 3-1 Survey Questions

Survey Qusetion	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9	User 10	Total
User comfort(Hip Belt)											
User comfort(Knee Brace)											
Time to don/doff											

3.2.3 Testing Procedure 2: Schedule

This test can be completed quick, but it depends on if ten people can be gathered on time and their schedule. Ideally, the test would be scheduled for one week but try to gather people beforehand so that way their schedules can be worked with.

3.3 Testing Procedure 3: Fitment Tests

This test procedure tests the fit and conformability of the hip exoskeleton. It would be run by the members of the BHET team. This test satisfies the engineering requirements for weight, conformability, and testing the various range of motions. The exoskeleton needs to be able to have free range of motion in all directions besides extension and flexion, while being as lightweight as possible. Overall, this test was allotted a week time and it would've been done the same week as the user comfort rating test. Though, this test would only take a day, it would be dependent on the user comfort ratings schedule.

3.3.1 Testing Procedure 3: Objective

The objective of this test it to see if the hip exoskeleton can fit a variety of people, is lightweight, and supports free movement in all ranges of motion besides extension and flexion. The hip exoskeleton would have been worn by the members of the BHET team since we have varying body types. Each member would also move their legs in the specified direction: adduction, abduction, and rotation. Afterwards, the exoskeleton would be weighed by itself on a high accuracy scale.

3.3.2 Testing Procedure 3: Resources Required

The only resources required for this test is the hip exoskeleton, measuring tape, goniometer, and a scale. The measuring tape is already owned by a member and it would be used to measure what hip sizes the exoskeleton can fit comfortably on. A goniometer is a special ruler that is used to specifically measure range of motion, this was purchased by a BHET member and can easily be found online. The scale would ideally be high accuracy and would have been borrowed from or used at the Engineering Building at NAU.

3.3.3 Testing Procedure 3: Schedule

This test was would be done during the same week at the user comfort rating test. Since it is just the four members of the BHET team, the actual test time would take only about a day. Though, extra time might need to be required depending on who the team is borrowing the scale from.

3.4 Testing Procedure 4: Fatigue Failure Modes

This testing procedure is focused on testing the critical failure modes of the hip exoskeleton. Fatigue in certain components will result from the exoskeleton being used frequently. This test satisfies the engineering requirement regarding cycles to failure. The test would be completed during the same week as the torque/power output test.

3.4.1 Testing Procedure 4: Objective

The objective of this test is to test the aspects of the design with the highest failure potential. These failures were taken from the risk analysis and mitigation the team has conducted. The top points of failure were creep deformation in the motor mounts, and high cycle fatigue in the Bowden cables/housing. Overall, we want to understand when these types of failure will occur.

The exoskeleton would be mounted to the test fixture in Figure 1 and will be powered in a manner similar to when it is assisting the user's walking cycle. The test will run until there is wear being shown on either the Bowden cable or the motor mounts. When wear is present, the amount of cycles will be recorded. The amount of cycles until failure will be implemented into the maintenance plan for the hip exoskeleton.

3.4.2 Testing Procedure 4: Resources Required

The resources required for this test are a testing area, test fixture, test program, and the completed hip exoskeleton. The testing area would have been the Biomechatronics Lab. The test fixture is the same used in the torque/power output test. The test program is one of the more important resources since it is needed for the hip exoskeleton to run. This program would also be used to record the cycles until failure.

3.4.3 Testing Procedure 4: Schedule

This test would occur during the same week as the torque/power output test. A week should be an efficient amount of time since most of the time taken during the test will be set up and creating the code. Also, the team would have to wait and observe the wear on the cables and motor mounts.

4 DESIGN SPACE RESEARCH

4.1 Literature Review

The team performed research to identify current solutions to the design problem. Walking gait has been studied for many years and has presented a challenge to researchers because of the difficulty in developing a kinematic model from observation. In recent years computer tracking and simulation has allowed for more accurate modeling. The published results of the most recent studies provided the technical specifications concerning range of motion. Further technical papers were found that detailed the design of exo devices, which were used for benchmarking the problem.

4.2 Benchmarking

Multiple sources were identified that related to development of exoskeleton devices intended for lower-body application. The team found that there were virtually no consumer products that met the design requirements, though a few concept demonstrations had been developed by commercial entities. Much of the existing design space literature was provided by academic studies and projects which were focused on data collection and analysis. With a few exceptions, many of these published technical papers explored the use of exo-suits for strength enhancement, in contrast to the BHET's goal for rehabilitative assistance. Despite this, the team was able to learn a lot from all sources because the fundamental research was consistent throughout, i.e. human walking gait analysis.

4.2.1 System Level Benchmarking

The following sections describe the full-system designs that were used to guide the team's approach to the project.

4.2.1.1 Existing Design #1: Harvard Soft Exosuit

The following figure shows the Harvard soft exosuit:

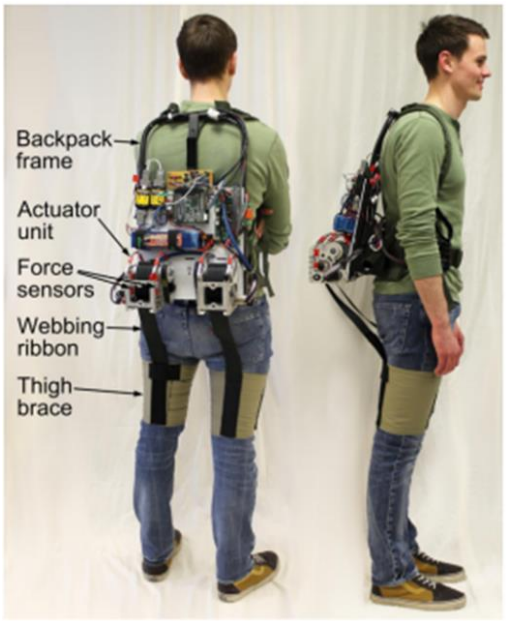

Figure 4-1- Harvard soft exosuit [2]

This design is very promising, and it meets a lot of the customer requirements for this capstone project. In this design, the entire control and actuation system is contained within a wearable backpack. Webbing is spooled around the pullies at one end and attached the user's legs at the other end. This means the design allows for a significant amount of comfort for the user. The design also uses force sensors within the pulleys to calculate applied torque.

4.2.1.2 Existing Design #2: Honda Stride Management Assist (SMA)

The following figure shows the Honda Stride Management Assist:

Figure 4-2- Honda Stride Management Assist [3]

Of the three system level benchmark designs selected, the Honda SMA is the most commercially viable and user-friendly design. However, Honda has not released a significant amount of information about this device. Despite this, the Honda SMA is a good example of a lightweight and ergonomic design that may aid in the design of this team's exoskeleton.

4.2.1.3 Existing Design #3: Bowden Cable Design

The following figure shows a Bowden Cable Design taken from literature review:

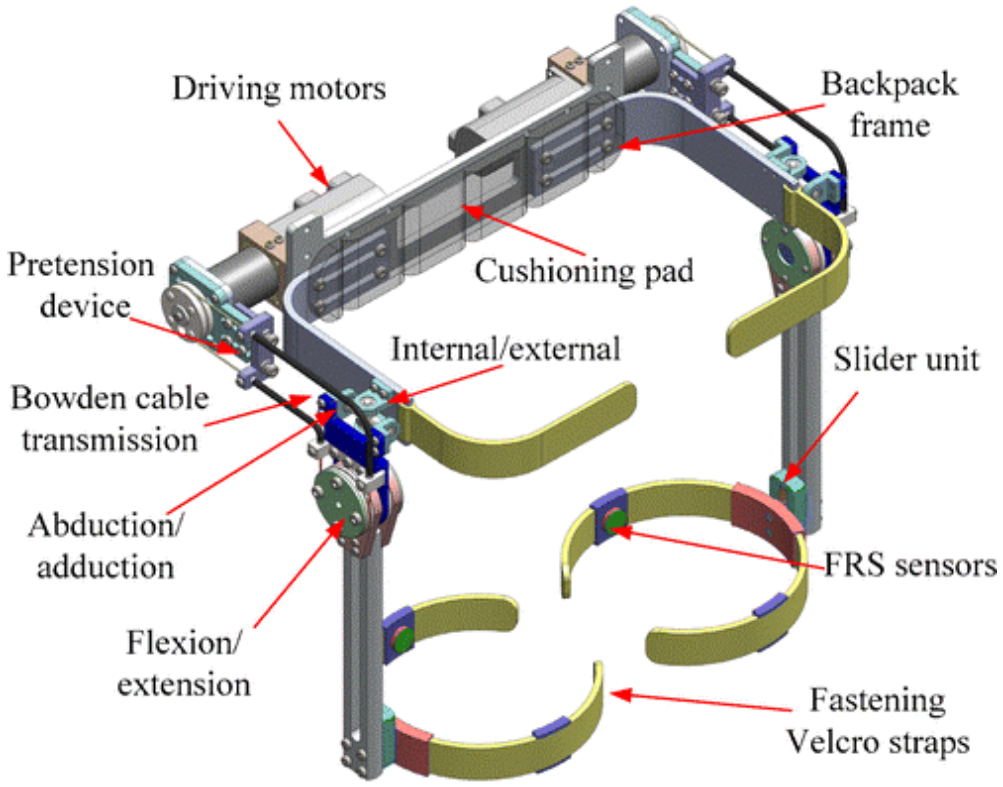

Figure 4-3 - Bowden cable design [4]

This design is very similar to existing designs already in use at the biomechatronics lab. This is a good example of a simple design that could be manufactured by the capstone team with relative ease. The combination of Bowden cables and electric motors could easily implement the existing electronics and control systems already in use by the biomechatronics lab.

4.2.1 Subsystem Level Benchmarking

The team organized the project into different subsystems that will function together to fulfill the project requirements. The following sections cover the subsystem descriptions and the existing designs which could fulfill the function of the subsystem.

4.2.1.1 Subsystem #1: Soft Harness

The soft harness allows for an interface between the user and the rigid frame and actuation system of the hip exoskeleton.

4.2.1.1.1 Existing Design #1: Spandex leg loops with metal frame backpack

This is the soft harness used by the soft exoskeleton discussed in previous sections. The below figure shows this harness.

Figure 4-4 – Leg-loop harness with rigid hip belt [2]

This harness is very good for freedom of movement, but it falls short on applying force linearly in the extension/flexion direction.

4.2.1.1.2 Existing Design #2: Semi-rigid hip belt

The following figure shows the semi-rigid hip belt used on the Honda stride management assist device.

Figure 4-5 – Semi-rigid hip belt [3]

This design utilizes a soft hip belt in conjunction with a rigid framework that houses all the battery and control components. This is a good example of a low-profile and ergonomic design. However, its small form factors mean that it's not as load bearing as the soft exoskeleton design that utilizes a backpack frame.

4.2.1.1.3 Existing Design #3: Soft hip belt

The below design uses a soft hip belt that conforms well to the user's body.

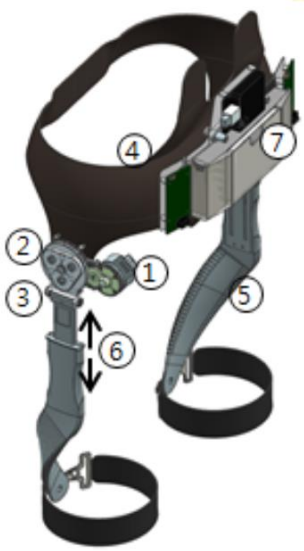

Figure 4-6 – Soft hip belt [5]

This harness design has the advantage maximizing the user's comfort, particularly at the hips. It also seamlessly integrates with the frame and actuation system, further improving ergonomics and comfort.

4.2.1.2 Subsystem #2: Rigid Frame

The rigid frame serves as a connection point between the actuation system and the soft harness.

4.2.1.2.1 Existing Design #1: Conformable Rigid Design

Shown below is a design that utilizes a rigid strut that conforms to the user's body.

Figure 4-7 – Conformable rigid design [5]

This design excels in having a low profile and user comfort. However, the complex geometry of the frame may be difficult for the team to manufacture with the available resources.

4.2.1.2.2 Existing Design #2: Single Straight Pivot

The below figure shows a single straight pivot used in the Bowden cable design discussed earlier.

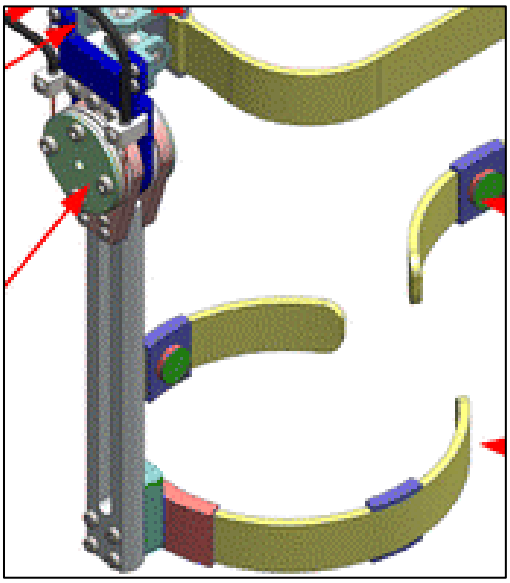

Figure 4-8 – Single straight pivot [4]

This is a good example of a very easy to manufacture design. Although, its inherent simplicity may also cause it to limit the user's movement, particularly in abduction/adduction.

4.2.1.2.3 Existing Design #3: Dual Pivot

The design shown in the below figure is taken from the Honda stride management assist device.

Figure 4-9 – Dual pivot [3]

This frame design utilizes pivot points in both the extension/flexion and abduction/adduction directions. This is a lightweight and robust design that allows for full range of motion for the user. However, this type of design may limit rotation of the hip.

4.2.1.3 Subsystem #3: Actuation System

The actuation system is the source the forces generated by the hip exoskeleton. These forces are usually transmitted through the rigid frame to the user.

4.2.1.3.1 Existing Design #1: Webbing spool

Shown below is a webbing spool design used by the soft hip exoskeleton discussed earlier.

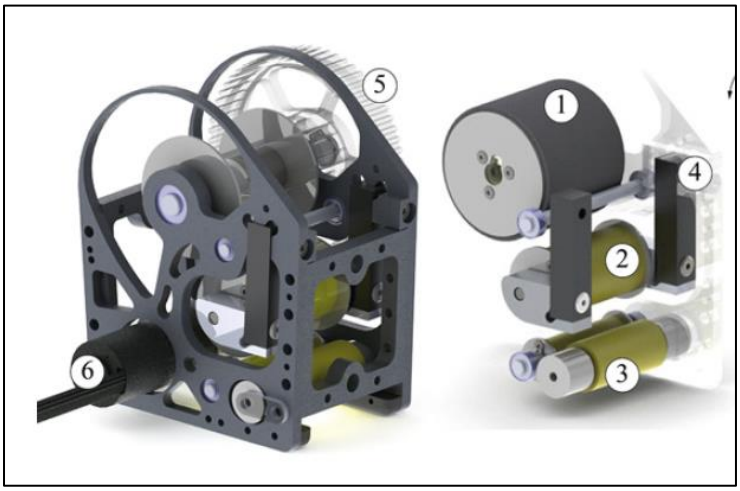

Figure 4-10 – Webbing spool design [2]

This system allows for the webbing to be extended and contracted in a controlled manner. Additionally, it contains force sensors that allow for the calculation of toque applied at the hip. The main disadvantage of this system is its complexity. Manufacturing and testing a system of this nature may be difficult with the time allotted and budget of this project.

4.2.1.3.2 Existing Design #2: Hydraulic Servo Rotary Drive

Shown in Figure 4-11 below is a hydraulic servo rotary drive taken from literature review.

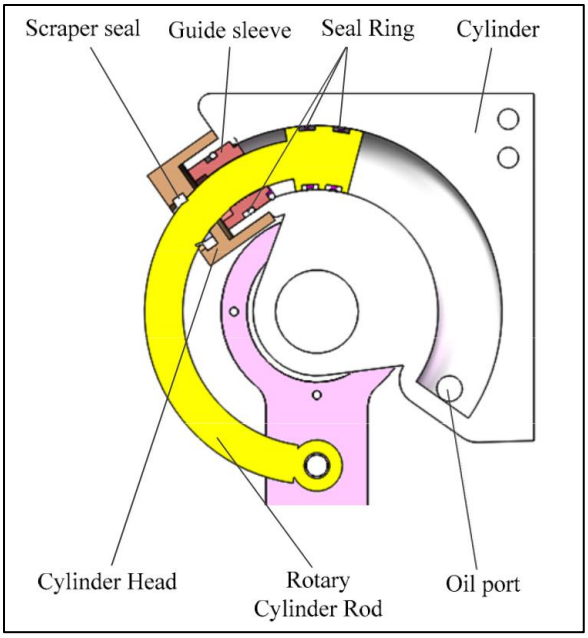

Figure 4-11 – Hydraulic servo rotary drive [6]

This is a very robust design that allows for toque to be applied directly at the hip. However, an untethered hydraulic system could be difficult to implement. Due to the proprietary nature of this design, it's likely that it will also be very difficult to manufacture.

4.2.1.3.3 Existing Design #3: Soft Passive Design

Shown below is a passive design designed by the Harvard bio-designs lab.

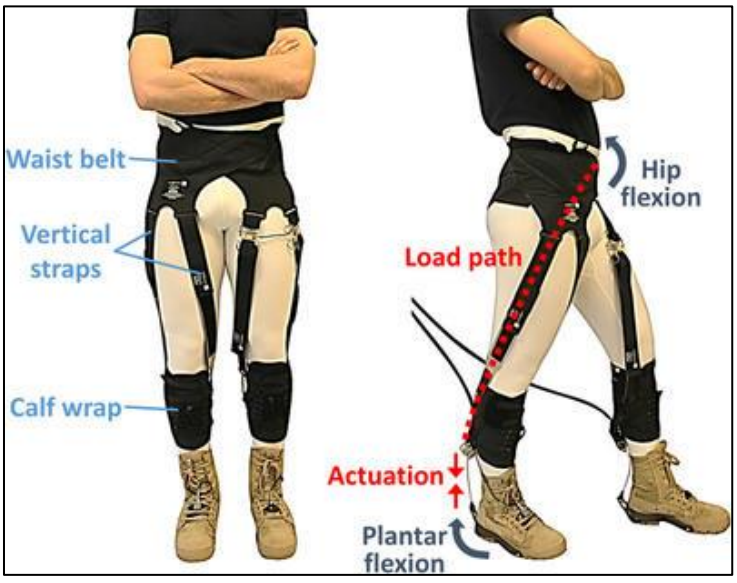

Figure 4-12 – Soft passive design [7]

While this design is an example of an ankle exoskeleton, it is a good example of using webbing wraps for loadbearing. This design is low-profile and comfortable as well. However, implementing this design to a hip exoskeleton may be difficult. It also may be difficult for this type of design to apply toque at the hips in a linear fashion since the support structure isn't rigid.

5 CONCEPT GENERATION

This chapter will briefly detail the early design stages of the project. What is not shown, for simplicity, is the very initial concept generation. These initial concepts are no longer relevant to the scope of the project.

5.1 Design Description

The following section will describe the state of the team's design up until the end of the fall 2019 semester.

5.1.1 Design at the Time of Preliminary Report

Shown below is the design described in the preliminary report.

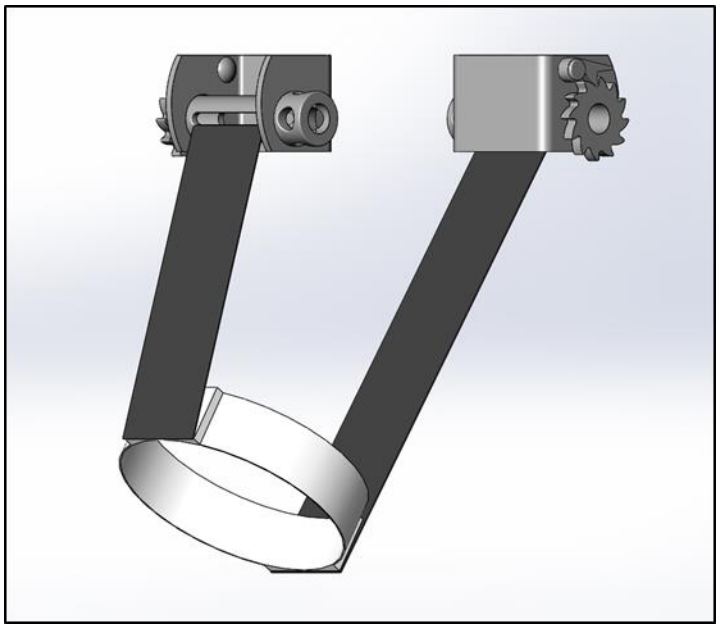

Figure 5-1: Design as of the preliminary report

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. 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.

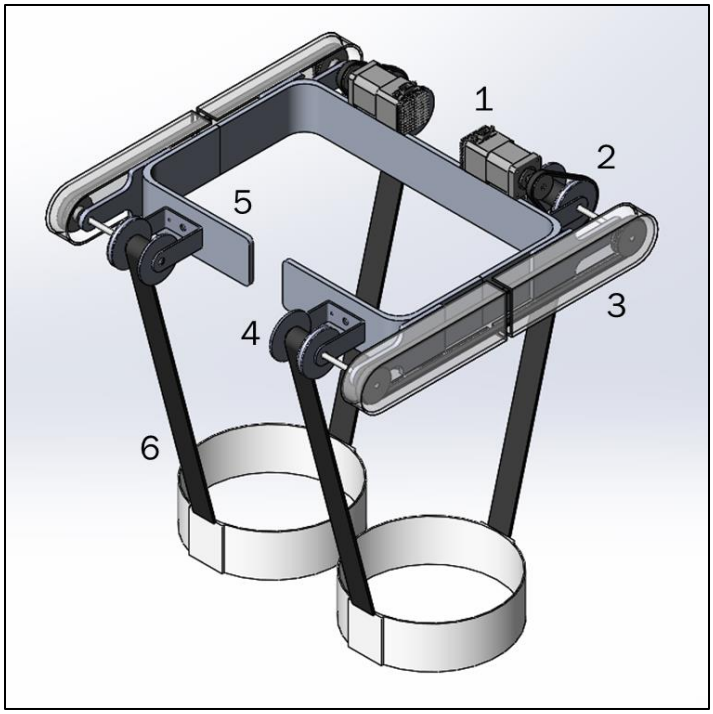

Figure 5-2: Detailed CAD of dual-belt design

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.

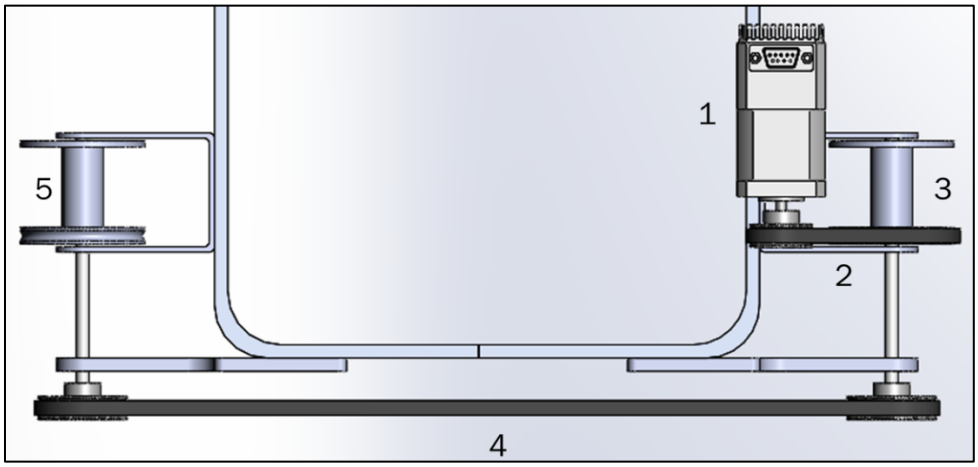

Figure 5-3: Drive system from CAD model

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 next section.

6 DESIGN SELECTED – First Semester

After the dual-belt design was chosen in the fall 2019 semester, a prototype was made to test the viability of this design. This chapter will discuss the conclusions and design changes made based off of the performance of the prototype. The final design that was selected at the end of the spring 2020 semester will also be discussed in this chapter.

6.1 Design Description

This section will cover the design changes made to the Bowden cable iteration of the hip exoskeleton design.

6.1.1 Prototype

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

Figure 6-1: Prototype Constructed for Dual-Belt Design

There were a few takeaways from the construction of the 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 addresses this issue.

6.1.1 Revision Post-Prototype

Based off FMEA, discussions with this project's client and analysis of the prototype, changes of the original dual-belt design were made. The below figure shows this change of design.

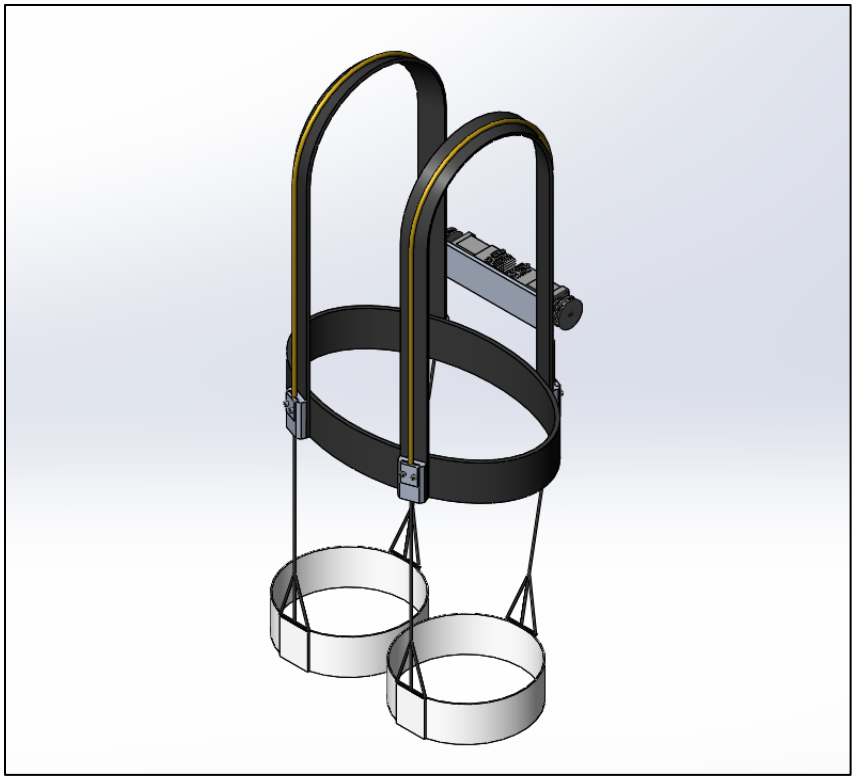

Figure 6-2: Change of design after FMEA and Discussions with client

It was established with the dual-belt 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. The new design utilized 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 challenges established for this design was accounting for the differences in the rate of cable being brought in at the front versus the rate of cable being let out at the back.

6.1.2 Final Design

Shown below is the finalized deign at the end of the spring 2020 semester.

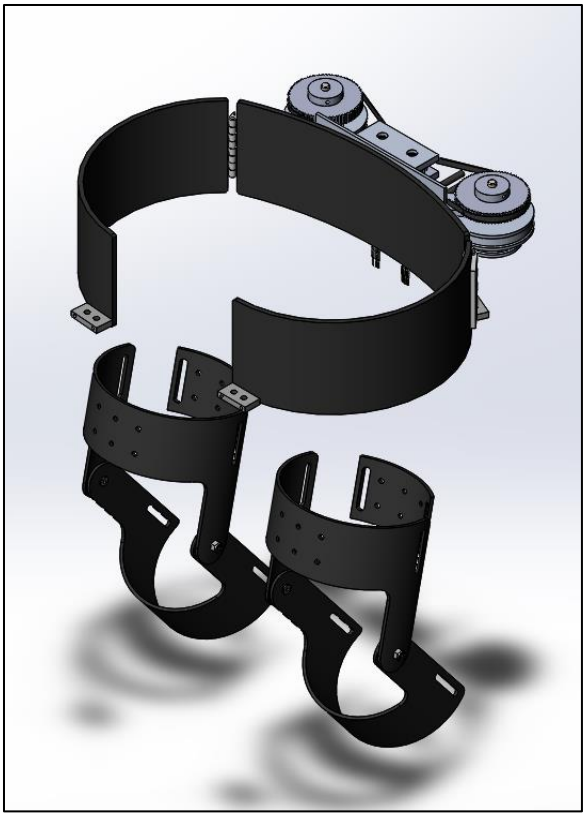

Figure 6-3: Front View of Final Design

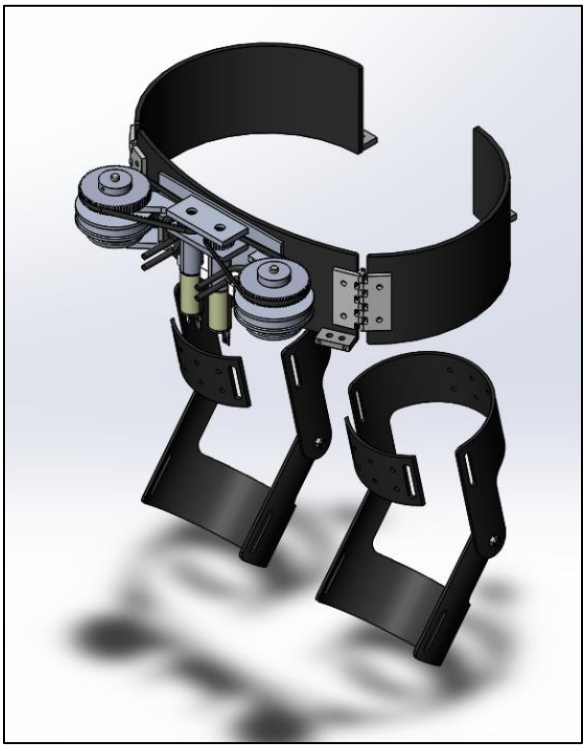

Figure 6-4: Rear View of Final Design

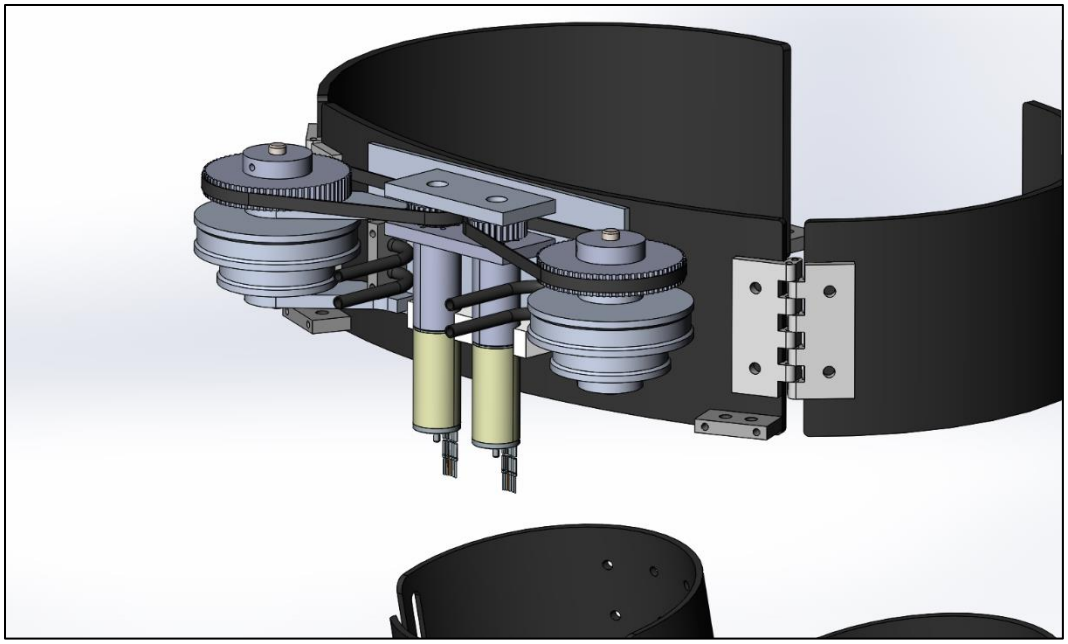

Figure 6-5: Detail View 1 of Motor Assembly

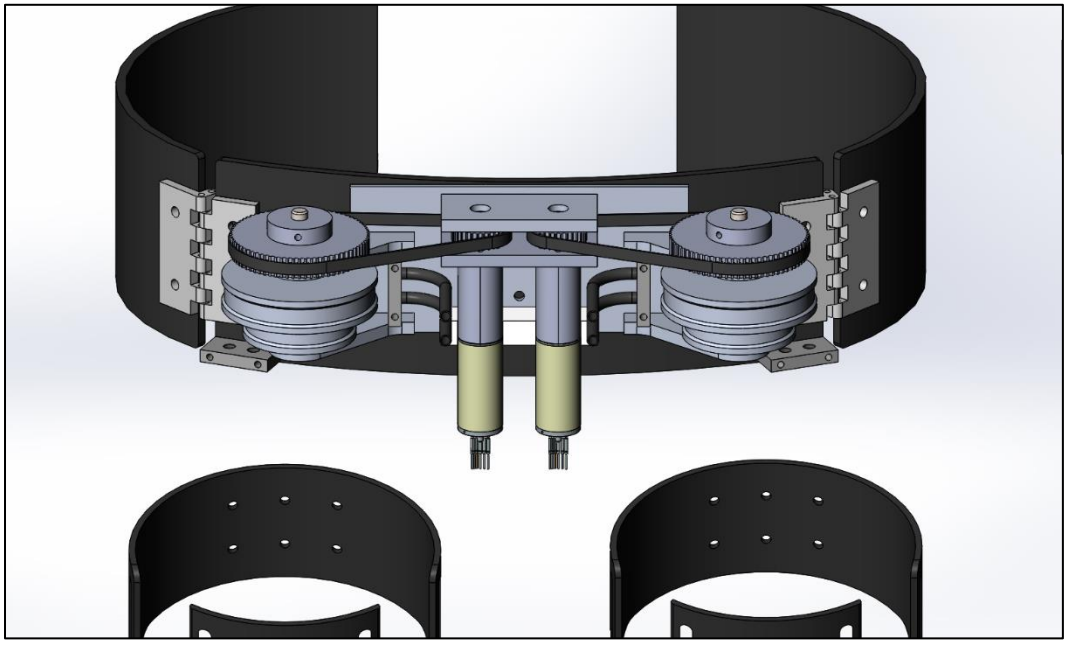

Figure 6-6: Detail View 2 of Motor Assembly

This most recent design has a few key improvements over the initial concept for the Bowden cable design. Firstly, this design has a much higher fidelity CAD model so this project can be more easily picked up by future parties. This design also moves the motors to a vertical position for better use of limited space. The pulleys that actuate the Bowden cable also have two different diameters to accommodate for different amounts of cable take-up in extension/flexion. The timing belts in this design also add further gear reduction off of the motors to better accommodate for the power requirements for this project.

6.2 Implementation Plan

This section will cover the resources required to complete this project.

6.2.1 Bill of Materials

As shown in the below table, a bill of materials was constructed for the most recent design iteration. The new biomechatronic hip exoskeleton design will be made of aluminum (6061 T6) and Kydex. We have determined to use Aluminum (6061 T6) based on its low cost, low weight, and appropriate strength. Also, our client agrees with using this type of aluminum snice the current exoskeletons in the biomechatronics lab use 6061 T6 with no issues. The aluminum has been purchased in the form of rectangular bar stock so it can be machined into the appropriate components in the machine shop (98C). Kydex was selected for the hip belt and knee brace for its low weight, low cost, and it comes in flat sheets that can be easily cut and molded to the shape of the user's body. Our client provided us with the Kydex so we did not have to purchase it for ourselves (this is why it is highlighted yellow in the BOM).

Table 6-1: Bill of Materials

PART (SOLIDWORKS PART NAME)	MATERIAL	DIMENSIONS (in.)	SUPPLIER	QTY.	COST/UNIT	COST
Base_Plate_V1	6061 T6 AL	0.25 x 3 x 12	OnlineMetals	1	$6.30	$6.30
Bearing_Block_V1	6061 T6 AL	0.25 x 1.5 x 48	OnlineMetals	1	$10.05	$10.05
Housing Clamps (At motor assembly)						
Housing Clamps (At cable termination)						
Face_Plate_V2						
Mounting_Bracket_V5	6061 T6 AL	0.5 x 1.5 x 24	OnlineMetals	1	$12.06	$12.06
KneeBraceTop_V2	Kydex	0.125 x 12 x 12	McMaster-Carr	2	$10.16	$20.32
KneeBraceTop-Back_V2						
KneeBraceBottom_V2						
Motors	N/A	N/A	Maxxon	2	$815.73	$1,631.46
					Total	$1,680.19

HARDWARE	MATERIAL	DIMENSIONS (in.)	SUPPLIER	QTY.	COST/UNIT	COST
M4 x 20mm (100 pack)	SS A2-70	N/A	Copper State	1	$8.76	$8.76
M4 x 10mm (100 pack)	SS A2-70	N/A	Copper State	1	$6.20	$6.20
M3 x 10mm (100 pack)	SS A2-70	N/A	Copper State	1	$4.09	$4.09
M3 x 20mm (100 pack)	SS A2-70	N/A	Copper State	1	$5.77	$5.77
Shoulder screw	316 SS	0.25 Shoulder, 10-32	McMaster-Carr	2	$5.32	$10.64
Nylon Insert Locknut (50 Pack)	316 SS	10-32 Thread Size	McMaster-Carr	1	$4.71	$4.71
Bearings for Bearing_Block_V1	Steel	3mm W, ID 6mm, OD 10mm	McMaster-Carr	2	$12.06	$24.12
					Total	$64.29

Alternative Part Materials	MATERIAL	DIMENSIONS (in.)	SUPPLIER	QTY.	COST/UNIT	COST
Bearing_Block_V1	7075 T6	0.25 x 1.5 x 48	OnlineMetals	1	$40.24	$40.24
Housing Clamps (At motor assembly)						
Housing Clamps (At cable termination)						
Face_Plate_V2						
					Total	$40.24

Legend
Already Purchased
Aquired w/out Purchase
No longer needed

Shipping - Online Metals	$21.92
Amount Purchased	$1,681.79
Amount to Purchase	$64.29
Budget	$2,250.00
Funds Available	$568.21

The total budget that was provided to the Biomechatronic Hip Exoskeleton Team (BHET) for this new design is $2250. Total cost of the hip exoskeleton at the time of this memo is roughly $1681.79. This leaves roughly $568.21 to cover shipping, manufacturing, testing, and any additional materials. Items that still need to be purchased by the team is hardware (nuts and bolts) and Bowden cables. Hardware is projected to cost roughly $65 or less, and the Bowden cable system is projected to cost roughly $60. This would still leave roughly $450 remaining after those items are purchased. Manufacturing costs should be relatively low since the exoskeleton will be produced by the capstone team. At this point the project is well below the allotted budget.

The only facilities required to complete this project are the Biomechatronics lab and the NAU machine shop. Both facilities have the resources to complete the remainder of the required manufacturing and testing.

7 IMPLEMENTATION

The following chapter will discuss the manufacturing required for this project and how implementing the design in CAD resulted in design changes.

7.1 Manufacturing

The below sections describe the manufacturing processes required for the completion of this project.

7.1.1 Manufacturing Processes

There are two main manufacturing process used for this project, these being machining and forming. 3D printing was also used for non-critical components. Machining applies to most of the components included in the motor mount assembly. Forming applies to the hip belt and knee brace components of the design. Machining was done with both a manual vertical mill (Bridgeport mills in 98c) and a CNC vertical mill (Tormachs in 98c). The manual vertical mill was used for roughing the outer dimensions of the parts, as setup time on these machines was significantly shorter than the CNC mill. The below figure demonstrates a part being roughed on the manual mill.

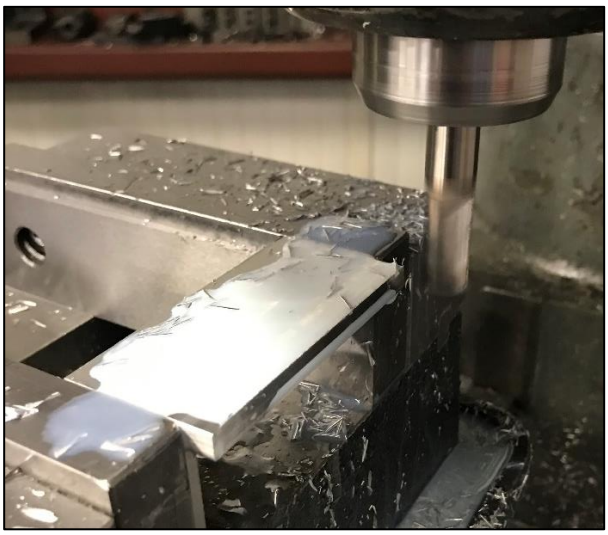

Figure 7-1: Roughing a Part on a Manual Mill

The CNC mill was used to finish parts and to cut the more complicated features that could not be cut on the manual mill. The below figure shows this process.

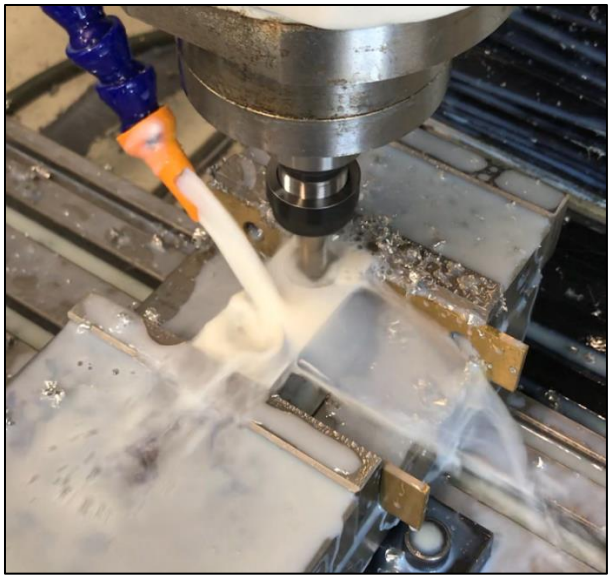

Figure 7-2: Finishing a Part on a CNC Mill

Both of these processes proved to be effective as a means of production for all of the aluminum parts required for this project.

Forming was required for all components made of Kydex, which includes the knee braces and the hip belt. When forming, the component was first cut from a flat sheet of Kydex using a stencil printed from CAD. After the Kydex was cut to shape, the component was then heated with a heat gun until it became flexible. At this point the component was molded over the user (who was wearing a towel to insulate from heat). The Kydex would set after 5-10 minutes and then the part was ready for hardware and finishing work.

3D printing was used for all non-critical components in the design. This included support pieces in the motor mount assembly that wouldn't experience any significant stress during the hip exoskeletons operation. 3D printing will also be used for prototyping and any additional non-critical components.

7.1.2 CAM (Computer Assisted Machining)

For all work done on the CNC mills, CAM was generated from SolidWorks parts to ensure that the parts were machined effectively. All CAM was generated in Autodesk Fusion 360. Shown below is a CAM program generated for this project.

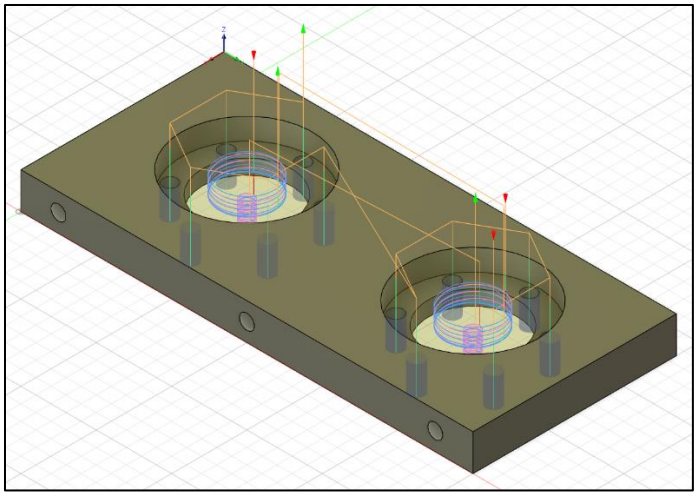

Figure 7-3: CAM generated in Fusion 360

The CAM program details all of the specific steps in the machining process required to cut a part. This was then used to export g-code (the programing language used by CNC mills) to load on a Tormach CNC mill. This program aided in calculating the required speeds and feeds for the CNC mill.

7.1.3 Remaining Tasks

Most of the forming processes required for this project have been completed, all that remains is forming the second knee brace. Most of the remaining manufacturing is CNC machining components of the motor assembly. The below figure highlights in orange the remaining components to be machined.

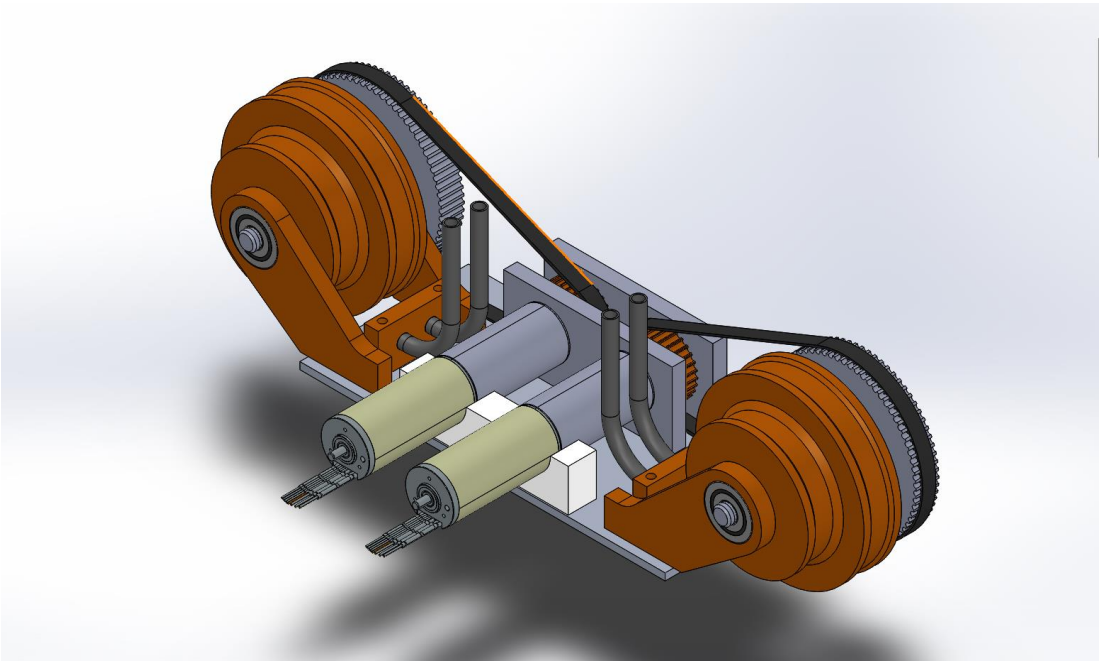

Figure 7-4: Components that still need to be manufactured

Any components not highlighted in the above figure have either already been manufactured or are off-the-shelf parts that can be purchased.

7.2 Design Changes

The design went through many different iterations, as a result of the team's technical analysis of different elements in the design and through the scope of the project being changed. The following sections detail the biggest design changes throughout the project, organized by subsystem.

7.2.1 Component 1: Motor Mount Design Iterations

The Motor Mount subsystem functions to affix the drive components to the harness worn by the user and maintain alignment of the belt drive and cable actuation systems. The previous revision (V3) of the Motor Mount is shown in Figure 7-5 below.

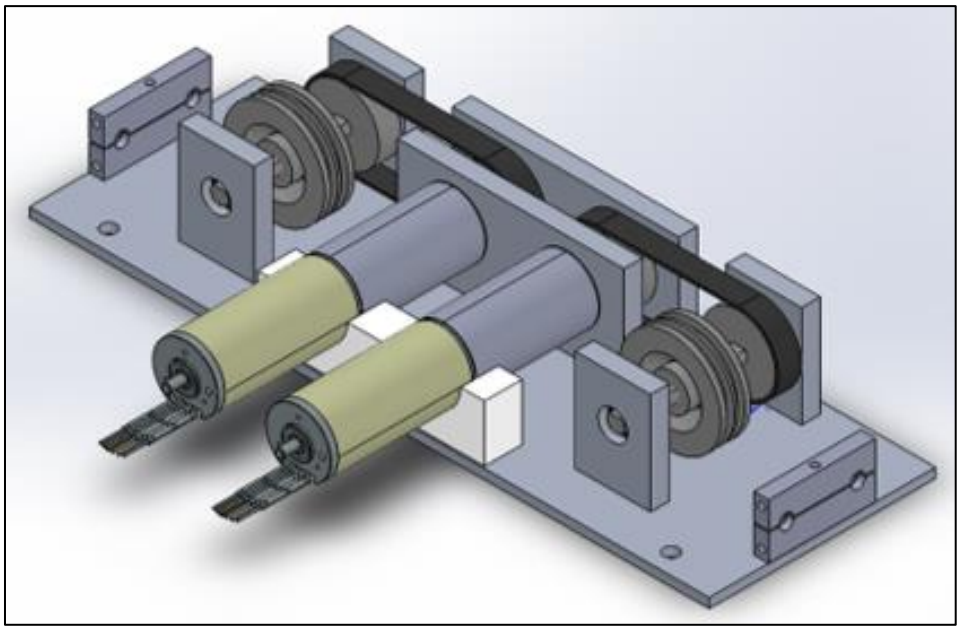

Figure 7-5 V3 Motor Mount subsystem

Changes to the Motor Mount design were required after the team performed a technical analysis on the cable pulley and belt drive. The results of the analysis required the cable pulley to be increased, such that the base plate and bearing blocks supporting the output shaft of the belt drive required modification. V4 of the Motor Mount assembly is shown below, in Figure 7-6. Additionally, the output shaft diameter was increased from 6mm to 8mm, after performing a stress analysis using the larger pulley diameter and applying distortion energy theory ($n = 1.5$), new bearings were selected to match the shaft.

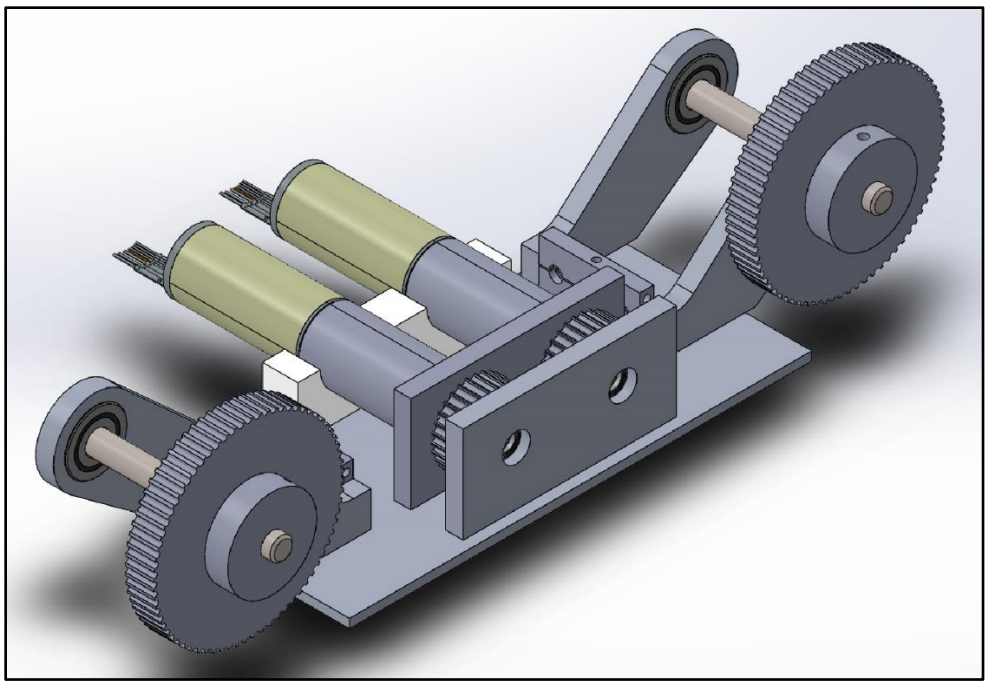

Figure 7-6 Motor Mount V4

The bearing block design had the most significant changes for the V4 Motor Mount. The previous design was a rectangular plate that located the bearing centered between the mounting bolts (Figure 7-7). The need for more clearance for the cable pulley and the timing belt pulley led to the design shown in Figure 7-8. The new part locates the shaft offset from the mounting point. The offset design provides the necessary clearance for the drive system mentioned above, without extending too far which would cause disruption to the wearers arm swing during walking.

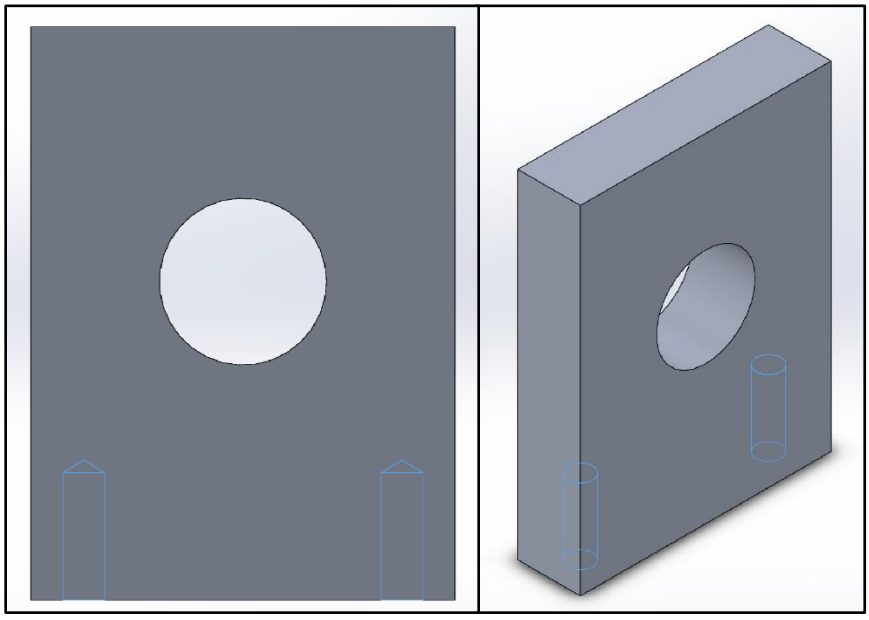

Figure 7-7 Previous Bearing Block design

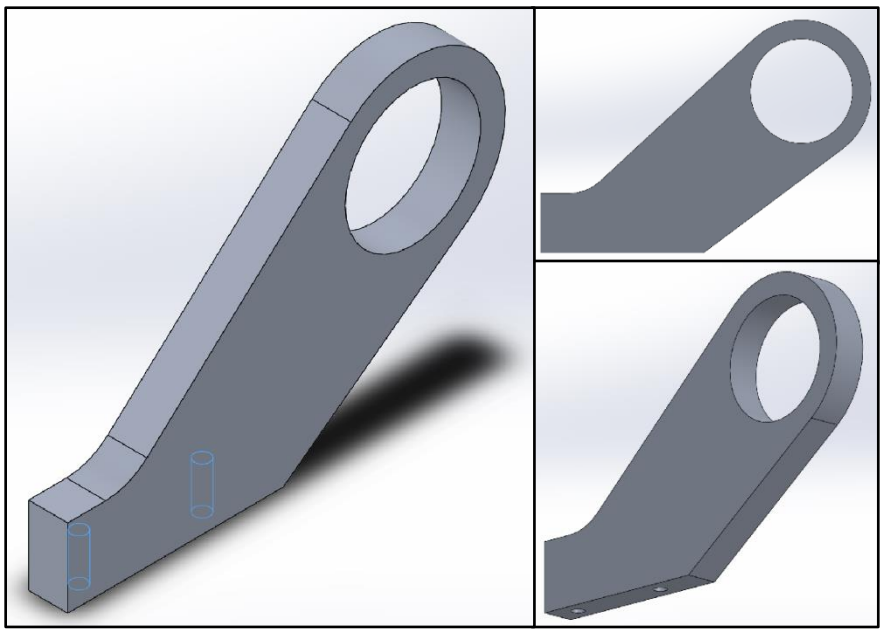

Figure 7-8 New Bearing Block design

The base plate of the Motor mount received minor changes to reduce the overall length and the location of mounting holes to facilitate the new configuration (Figure 7-9).

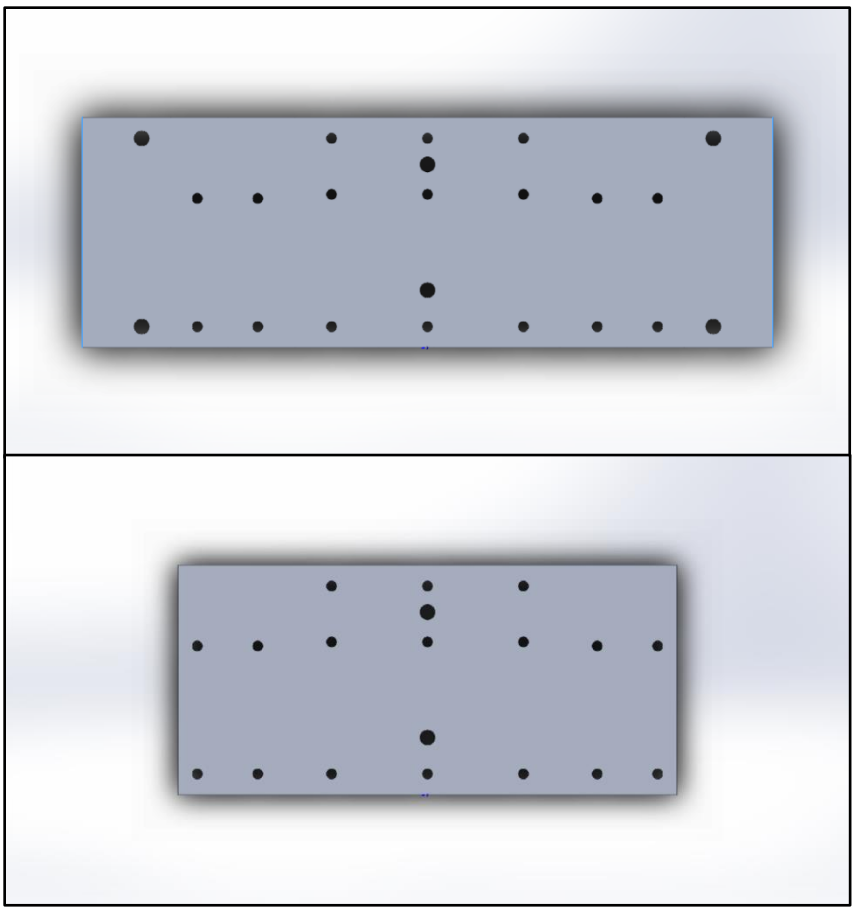

Figure 7-9 Base Plate, previous (top) vs new design (bottom)

7.2.2 Component 2: Pully Design Iterations

Though the pulley design has been relatively simple throughout each iteration of the system, the team needed to get a ratio for the pulley diameters. Our pully design is a dual pulley and each pulley will actuate movement in both the extension and flexion direction. In the original pulley design did not account for slack, so the radii of the pulleys were the same. This is shown below in Figure 7-10.

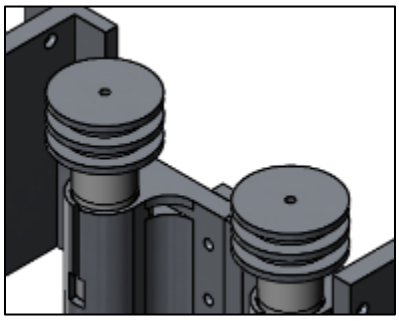

Figure 7-10 Initial Pulley design

This semester the team did tests on how much slack occurred in a length of cord when moving in extension and in flexion, and then Inna was able to derive a ratio from this test. The ratio can be referenced below.

$$1.44r_{back} = r_{front} \quad (7.1)$$

The first iteration of a pulley design using this ratio is also shown below.

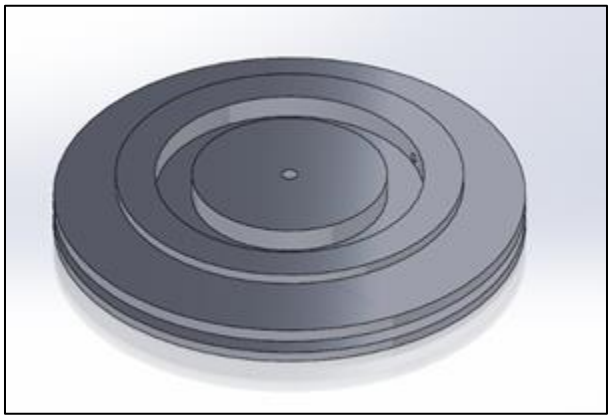

Figure 7-11

Figure 7-12

7.2.3 Component 3: Cable Clamp Design Iterations

The hip exoskeleton transmits torque from the electric motors via tension cables. The cables are routed through a Bowden tube, which terminates at a location coplanar with extension/flexion motion of the user's thigh. It is critical that the termination point of the Bowden tube be maintained at a known position deviation can cause fluctuation in the torque being applied to the user. Design of this component has been changed to favor simple manufacturing. The previous design was a single piece block which secures the tube using set screws. The client was concerned that this design might cause excessive mechanical wear to the cables, as they will rub against the black prior to exiting. The redesigned clamp will hold the outer sheath of the Bowden cable. The inner sheath will extend beyond the clamp, ensuring the cord only directly contact the inner sheathe before exiting the tube. The new design is two pieces that achieve clamping pressure by being bolted together. This design simplifies the manufacturing process, allowing for numerous parts to be made quickly and easily, ensuring an iterative process may occur to refine the design.

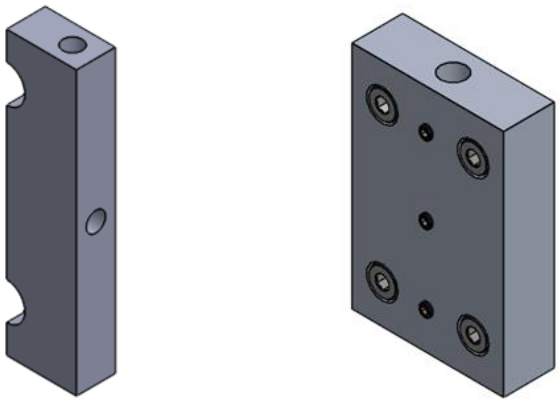

Figure 7-13: Cable clamp design revisions: new (left) vs old (right)

7.2.4 Component 4: Hip Belt Iterations

Shown below is a CAD model of the current state of the hip belt design.

Figure 7-14: Current State of Hip Belt Design

The simplicity of the molded rectangular pieces of Kydex in this design has proven to be effective. However, manufacturing this design has identified some issues with mounting the hinges. Originally the hinges were mounted to the kydex with epoxy, but this proved to not be strong enough. To fix this issue, future iterations of the hip belt design will bolt the hinges to the hip belt, increasing the strength of this part of the design.

7.2.5 Component 5: Knee Brace Iterations

Shown below is the current state of the knee brace design.

Figure 7-15: Current State of Knee Brace Design

This iteration of the knee brace design proved to be very easy to manufacture, however some possible improvements for the manufacturing process were identified. One issue with manufacturing this design was cutting the knee braces by hand. While this was easy to do, it left the part very rough around the edges. Ideally, finalized parts for this component will be cut on a CNC router prior to molding. This will allow for parts to have a better fit and finish. Additionally, the hinge is currently held together with a flush mounted bolt and a nylon lock-nut. While this proved to effective and inexpensive, it could be improved with better hardware.

8 RISK ANALYSIS AND MITIGATION

The Risk Analysis and Mitigation have not been changed from last semester even though we did some changes on the design for more simplicity for the user and the manufactory progress but still all subsystems and components same from last semester. The below sections discuss the FMEA of this current design. This includes the top ten projected critical failures of the design and a discussion on risks and trade-offs analysis.

8.1 Potential Failures Identified Fall Semester

The following sections will cover the top ten critical failures that could result from our current design. 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 A.

8.1.1 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.

8.1.2 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.

8.1.3 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.

8.1.4 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.

8.1.5 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.

8.1.6 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.

8.1.7 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.

8.1.8 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.

8.1.9 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.

8.1.10 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.

8.2 Risk Mitigation

Originally the systems with the highest risk of failure were the actuation system and the rigid frame. For the rigid frame there was specifically a risk of there being creep in the chassis. Though this failure isn't present in the final design since the rigid bar chassis has been removed. The main rigid member of the design is the mounting plate which is on the back of the belt. The belt and knee brace are made of thermoplastic which is susceptible to wear. Especially the knee brace since the cords will be attached to it and it will be subject to consistent movement.

There are no longer any spools in the final design, but we are implementing timing belts to the actuation system along with the pulleys and motors. This means that there is still risk for abrasive wear for both the timing belts and the pulleys.

Overall, the ways we can mitigate the risks in our design is to change the material the systems are made of. Also, depending the wear on the pulleys can be mitigates by possible changing the thickness of the overall pulley.

9 FUTURE WORK

There are a few aspects of this project that will need to be conducted by both the NAU Biomechatronics Lab and future capstone projects. This includes finalizing the manufacturing and testing of the finished design. Currently, the hip belt, 1 knee brace and half the components of the motor mount assembly have been completed. The other knee brace and remaining components of the motor mount assembly will have to be completed by future parties. The focus of this team for the remainder of the semester will be refining the design in CAD and creating a detailed operation and assembly manual for the future parties that work on and improve this design. The goal of this capstone project for the remainder of this semester is to lay the groundwork for future iterations of the hip exoskeleton design.

10 CONCLUSIONS

Following is a conclusion to this report and a reflection on this team's performance.

10.1 Contributors to Project Success

The main contributors to this project's success was constant communication in the form meetings multiple times a week. This allowed this team to plan ahead effectively and stay on top of deliverables. Additionally, organization of all work done for this project aided not only in this teams effectiveness, but also in this teams ability to effectively pass on the work of this capstone project to future parties. It is the hope of this team that the design presented in this report will continue to be improved by both the Biomechatronics lab and future capstone teams.

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12 APPENDICES

[Use Appendices to include lengthy technical details or other content that would otherwise break up the text of the main body of the report. These can contain engineering calculations, engineering drawings, bills of materials, current system analyses, and surveys or questionnaires. Letter the Appendices and provide descriptive titles. For example: Appendix A-House of Quality, Appendix B- Budget Analysis, etc.]

12.1 Appendix A: House of Quality

Table 1 Full House of Quality

		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				
Customer Requirement	**Weight**															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					