Robotics and Automation – Arm Exoskeleton

Final Proposal

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This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

According to various sources and population surveys, shoulder pain and discomfort affects anywhere from 18-26% of modern adults. This makes shoulder pain one of the most common regional pain syndromes. To combat this drastic statistic, Dr. Zachary Lerner at Northern Arizona University formed a capstone team consisting of senior mechanical engineering majors and asked them to design, create and improve upon the MyoShirt exoskeleton. Through careful consideration and thought, Dr. Zachary Lerner had provided the team with a set of requirements and goals he wanted to meet as a part of this project. The requirements set out for the team were as follows:

1. Safety
2. Comfort
3. Portable
4. Stability
5. Low profile
6. Lightweight

Based on these customer requirements, a set of engineering requirements needed to be set to have smooth and successful design process. The list of engineering requirements are as follows:

1. Implement a DC (direct current) motor to aid the pull-up.
2. Implement a cable driven system.
3. The entire exoskeleton must be less than 6lbs.
4. Components of the design cannot protrude more than 10cm from the body.
5. The exoskeleton must provide around 15-20% assisted force.

With all the customer and engineering requirements set, Dr. Lerner had one more request for the team and that was to try and integrate this shoulder exoskeleton system into an elbow one that he already had. Knowing all this information and after many trials and errors, the team decided on a final design.

The final design that the team opted for features a pulley system with Bowden cables located on the outer shoulder. These cables then route down the back to the motors which are located on the low back. The design also features a hinge system that allows for the lateral movement of the shoulder without any interference. The motor will either rotate clockwise or counterclockwise depending on the movement that is desired. To interface this Bowden cable system, with the already established elbow exoskeleton, the team decided to implement a universal bicep cuff that will allow for easy attachment of the elbow subsystem. Combining the shoulder and elbow systems will provide the operator with a full arm exoskeleton allowing for movement in all directions. Future iterations of this design will be tested for increases in strength and comfort among the users and will be discussed in further detail within this memo. The team is planning to have many testing cycles over the winter break to flesh out their prototyping design and have the best possible design in all aspects, ready to go for the upcoming spring semester.

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1 BACKGROUND

1.1 Introduction

The scope of this document is to explain and discuss an arm exoskeleton that will be capable of assisting a person with shoulder and upper arm impairments by allowing them to accomplish tasks throughout everyday life. The ability to complete an overhand pull-up will be used as a benchmarking tool to evaluate the strength of the design. The goal of this project will be to create a successful and lightweight design capable of completing the requirements above. Once this goal has been achieved Professor Lerner and NAU's biomechatronic laboratory plan to further expand on this project, with an end goal to have a wide variety of exoskeleton limbs to aid those in need. In addition to the benefits that the biomechatronic lab will receive, the project's sponsor, W.L. Gore, will be thrilled to see a fully functional system helping those in need.

1.2 Project Description

The following is the original project description provided by the sponsor. "Professor Lerner's NAU (Northern Arizona University) Biomechatronic Lab (biomech.nau.edu) develops lightweight wearable robotic exoskeletons to improve the movement of people with walking impairment. In this project, talented students with an interest in robotics/mechatronics will be tasked with creating an arm exoskeleton capable of assisting someone when doing a pull up. The project will involve designing a cable driven actuation system powered by body warn DC motors. Successful completion of this project will lead to a design concept and functional prototype.

This project will have the following deliverables:

- Select appropriate motors and transmission system
- Design and fabricate the body attachment points
- Assemble the arm exoskeleton prototype
- Work with the NAU Biomechatronic lab team to complete pull up tests

Budget: $3,750 (Pending W.L. Gore Approval).

1.2.1 Original System Structure

Due to the lack of commercial exoskeleton systems, it is difficult to find free research articles. We began our research from a dissertation from ETH Zurich provided by Professor Lerner about the MyoShirt. The MyoShirt is the state-of-art upper arm exoskeleton that this project is based off. It is a compact and lightweight system using cable driven DC motors to power the suit. While the MyoShirt was a phenomenal step in the correct direction, it does leave room for improvement, with the biggest downside being portability. The MyoShirt requires the user to be connected to a station housing all the electrical and computer components sit. A major goal for this team and project is to make a design like the MyoShirt but be fully portable allowing the user to roam freely.

As stated before, arm exoskeletons and exoskeleton limbs in general are a very new and niche area of work. With the MyoShirt being an excellent guide and example, the system structure can be broken down in a simple manner. Being constructed of mostly fabric will allow for a comfortable and lightweight design. Due to weight constraints, there will be limited metal components on the system. A sub-system of Bowden cables connected to a small, yet powerful DC motor located on the back, is going to drive the movement of the extremities. To ensure the safe and fluid travel of these cables, a channel

allowing for smooth flow without interfering with the user or any other sub-system will need to be implemented.

1.2.2 Original System Operation

Although the human body seems straightforward and simple, it is quite complex and calculating forces as well as determining 'tendon' or Bowden cable location will prove to be a challenge. Researchers at ETH Zurich were able to accomplish this task and explained their system as follows: "Forces are generated in a motor unit and transferred to the shoulder via tendons, inducing assistive torques that support shoulder elevation and external rotation. Using motion and force sensors, the user's movements are detected and followed without any additional user inputs" (ETH Zurich). Including the exceptional cable routing that went into the MyoShirt, motion sensors were implemented to detect the movement of the user and then aid them with force in whichever direction was desired. The MyoShirt also supports the users arm against gravity allowing them to be able to move smoothly and effortlessly throughout their daily life.

1.2.3 Original System Performance

The MyoShirt performed exceptionally well in all its tests. The suit was able to increase muscular endurance while holding an object, which can be seen below. Going hand in hand with an increase in muscular endurance, a decrease in muscle activity was also achieved. Having an increase in muscle endurance and a decrease in muscle activity shows the true effectiveness of the system. A concern with an exoskeleton system like one of this nature is that it may restrict the range of motion and flexibility of the user, but the MyoShirt had no effect on any participants range of motion. To power and operate the MyoShirt a sub-system coined, 'The box,' needed to be implemented. The box can be seen in the diagram below. A 24V to 5V battery system was used and should supply more than enough power for both the MyoShirt and future designs to come. Issues with this are again portability. The overall goal is to improve on these statistics while also creating a fully portable system (1).

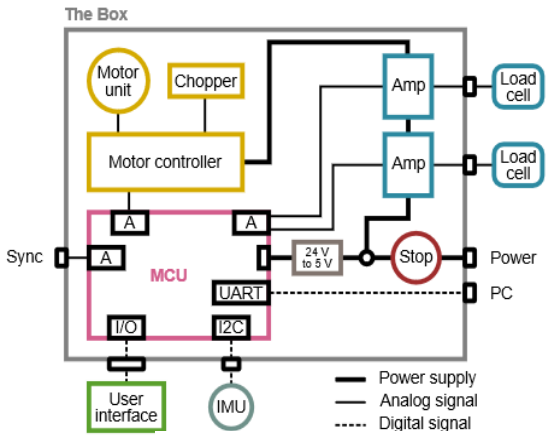


Figure 1: "The Box"

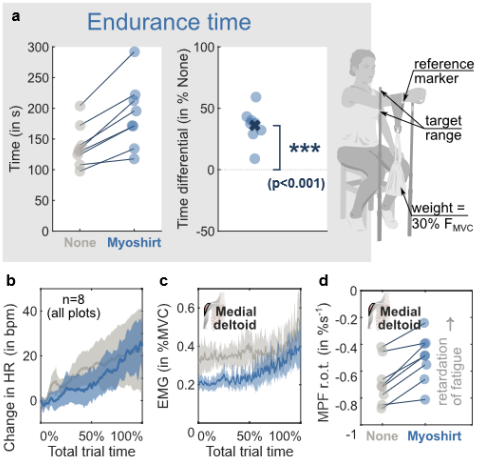


Figure 2: Trial Graphs

1.2.4 Original System Deficiencies

Although the MyoShirt is a groundbreaking invention and discovery for the world of exoskeleton design and development, it does fall short in a few distinct areas. Firstly, and most importantly the user is fixed in a radius determined by the cable length attaching them to the batteries. Creating a design that is

fully portable but just as strong as the MyoShirt is going to be a challenge but is certainly possible. With the main objective set on creating a fully portable system like that of the MyoShirt, the team set out to accomplish this task.

2 REQUIREMENTS

Dr. Zachary Lerner's NAU Biomechatronic Lab (biomech.nau.edu) develops lightweight wearable robotic exoskeletons to improve the movement of people with walking impairment. For this project the capstone team is assigned to create a shoulder driven exoskeleton capable of assisting someone when doing a pull up. The exoskeleton will provide support to both shoulder joints and will aid in overhead pushing and pulling movements. This device needs to use a cable driven system powered by body warn DC motors used in Dr. Lerner's other projects. Additionally, the team discussed a possible collaboration with some of Dr. Lerner's students who are developing an elbow joint exoskeleton. We aim to create a design that can complement his other projects and create a sturdy base for future research.

2.1 Customer Requirements (CRs)

Given the requirements listed above, the capstone team and Dr. Lerner produced multiple customer requirements to begin our design process.

- Safety
- Comfort
- Portable
- Stability
- Low profile
- Lightweight

The two highest rated customer requirements are a lightweight system, and a low profile. Dr. Lerner commented during team meetings that the device should not be limiting any range of motion or weighing down the person. Instead, he wants a design that sits close to the body and is made from lightweight materials. The team decided the best way to approach these requirements is by 3-D printing our larger components to reduce weight.

The second highest rated customer requirements are stability and safety. These requirements are complementary, as a stable system will reduce the risk of injury to the user. The shoulder is a complex unit, controlled by the glenohumeral and clavicular joint. The designs will have multiple anchor points to secure these joints and implement a few mechanical fail-safes to shut down the device if needed. By making safety and stability a priority, we recognize the potential dangers of our design and improve them to make it as secure as possible.

The lowest rated customer requirements are portability and comfort. These requirements may be scored lower; however, they are still especially important to the design process and selection. Portability was chosen as a customer requirement because Dr. Lerner wanted to avoid the MyoShirt's dependency on an external control system. The exoskeleton needs to have motors, battery, and wiring all mounted to the body. Comfort is also an important requirement, however Dr. Lerner mentioned he is willing to sacrifice a little bit of comfort to increase mechanical assistance. The design will make sure to keep all the wiring off the body, to avoid abrasion and irritation of the skin.

2.2 Engineering Requirements (ERs)

The engineering requirements are based off the customer requirements provided by Dr. Lerner. These requirements are goals that the team must aim for the design to be successful.

- Implement a DC (direct current) motor to aid the pull-up.
- Implement a cable driven system.

- The entire exoskeleton must be less than 6lbs.
- Components of the design cannot protrude more than 10cm from the body.
- The exoskeleton must provide around 15-20% assisted force.

The first two engineering requirements are the required materials we must use in the design. The Biomechatronic lab uses AK Series Dynamic Modular motors that are specifically designed for use in exoskeleton designs. To assist the lab in their research, the team will be using the same type of motors. This will allow future teams to build upon the design, as they are already familiar with the type of motors the team is using to power the exoskeleton. Similarly, Dr. Lerner wants to implement a cable driven system to provide power and support to the shoulders.

The last three engineering requirements focus on the mechanical properties of the exoskeleton and set realistic quantitative goals for our design. The weight and protrusion of the system must stay below the required limit to meet the customer requirements of lightweight and portability. The reason behind this is to have a design that can be worn in everyday tasks. Eventually, a design with assisted shoulder movement can be used by warehouse workers, construction workers, and other jobs that require continuous lifting and pulling movements throughout the day. This design needs to be able to handle repeated loads over time, which is why the initial assisted force is set at a lower goal. Fifteen to twenty percent assisted force will be measured in our second semester of testing and may be modified to provide more assistance if the design is successful.

2.3 Functional Decomposition

The purpose of a functional decomposition diagram is to show the hierarchy of the various subsystems within a final product. When breaking down the subsystems of an arm exoskeleton, three main assemblies come to mind, the motor mounting system, cable routing system and the various anchor points that are required to build a stable product. To aid in the decomposition process, the team opted for two different yet effective routes. Firstly, a black box model was constructed which can be seen in the section below. The black box model allowed the team to brainstorm ideas and pull useful information about the design process without revealing or diving too deep into the design phase. The model was able to depict the various forces that will be acting on the system and user, which allowed the team to take these ideas into account when completing their concept generation. After a black box model was constructed and discussed the team wanted to further expand on this idea and go further in depth. To accomplish this a functional flow chart was developed. The flow chart can be seen below and is within section 3.3.2. The flow chart that was constructed went along with the black box model but just went further into detail on what actions needed to be done by the user, and how they are going to be accomplished.

With two different forms of decomposition completed it was time for the team to discuss the three subsystems listed previously and how they should be integrated into an effective exoskeleton. Mounting the motors is a safe and effective location is step one when designing an exoskeleton. The team went through many trials on motor location but eventually decided on a low to mid-back location. Following the motor location, the cable routing was going to prove to an issue. The team decided on routing cables from the back, to over the should and down to the front of bicep. Lastly anchor points. Without a strong and sturdy hold on the cable the motor could not move anything. Putting an anchor point just above the inside of the elbow will mimic the tendons within the arm exceptionally well and will provide a stable connection point for the system. The reasoning behind all the decisions above will be discussed in greater detail in section 3.3.2.

2.3.1 Black Box Model

Below is a snapshot of the black box model the team used when developing their arm exoskeleton. The model was constructed before any designs were discussed and it allowed the team to better visualize a rough outline of the forces and inputs that would be acting on the system and its operator.

Inputs:		Function:		Outputs:
Pull-up Bar (Solid)	---------->	Increase the amount of pull-ups someone can do by 20% when wearing the exomuscle suit	---------->	Pull-up Bar (Solid)
	---------->		---------->	
Gravity (PE)	---------->		---------->	
Battery Energy (Electrical Energy)	---------->		---------->	Waste Energy (Thermal Energy)
Ground/Bar Forces (Mechanical Energy)	---------->		---------->	Ground/Bar Forces (Mechanical Energy)
Actuation (Mechanical & Electrical Energy)	---------->		---------->	
	---------->		---------->	
Operator Input (Control)	---------->		---------->	Operator Status (Control)
ON/OFF Switch	---------->		---------->	ON/OFF Switch
Analog signals (Lights)	---------->		---------->	Analog signals (Lights)

Figure 3: Black Box Model

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

Depicted below is snapshot of the flow chart that the team used when developing their arm exoskeleton. The flow chart was constructed after the black box and continued the ideas presented within it. With all the forces discussed from the black box, the team came up with the three main subsystems within an arm exoskeleton and created a flow chart around them to get a better understanding of their operation. On top of this the discussion on each subsystem's role, location and function was brought to our attention. In the section below each subsystem is described in greater detail explaining their purpose, function, and role within the entire system.

1. Motor Mounting – When thinking about where to attach the motors to the body, many challenges start to arise. Putting the motors on the hip would allow for a much more stable and potentially more comfortable experience, the issue with this is that having motors along the hip will inevitably cause the cables to be much longer which can in turn cause many cables routing issues. The team wanted to avoid as many issues with the cable as possible so putting the motors on the hip was out of the question. It was then thought that maybe the motors should be mounted on the upper trapezius muscle group. This would allow for shorter cables solving the issues depicted above but it is not the ideal location. This is because having the motors so high on the back may interfere with the way a pull-up is performed. Usually, the latissimus dorsi or more commonly known lats, aid the most in a pulling motion that brings the elbows closer to the body. The goal of this project is to mimic the way the human body moves and support that movement with an exoskeleton, and the benchmark test to see any strength increases will be a pull-up which is exactly why the team opted for a mid to low back location for the motors.
2. Cable Routing - Creating a cable system that is simple yet effective and efficient is going to prove to be the hardest part of this project. Given a motor location of the mid to low back the best route for the cables to travel is from the motor to the top of the shoulder and down the front of the arm and attaching at some point along the bicep. This system will be mirrored along both sides of the body. The routing of these cables will allow for fluid motion of the shoulder joint assisting the user in shoulder mobility. The shoulder being a ball and socket joint allowed for almost 360° of motion. The way that the cables are depicted above will allow for assistance in the frontal raise region of movement but will not accommodate for any movement in the lateral or rear planes. If the team decides to further improve on this design, additional cables in these planes will be implemented.

3. Anchor Points - Now that the motor location and the cable channels have been discussed, the points at which the cables connect to will be determined. Although the biceps' main purpose is to aid in elbow flexion, the biceps are also responsible for forearm and wrist rotation. The team does not want to implement a fixed anchor point at the bicep because one of these ranges of motion will be compromised. The idea of a slot along the bicep anchor point was brought up and is what the team plans to implement into their design. This will allow for a simplistic design but will not interfere with any actuation or comfort for the user. Again, this system will be mirrored across the body.

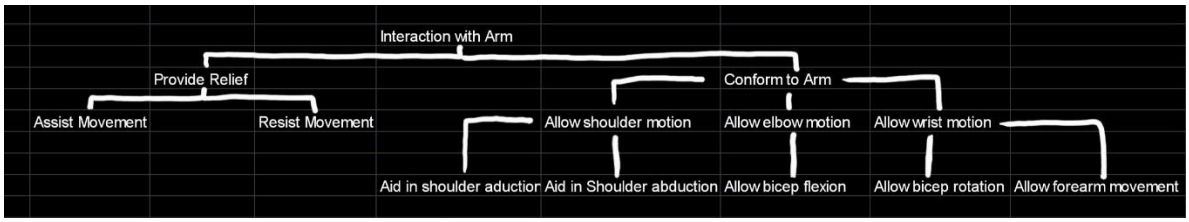
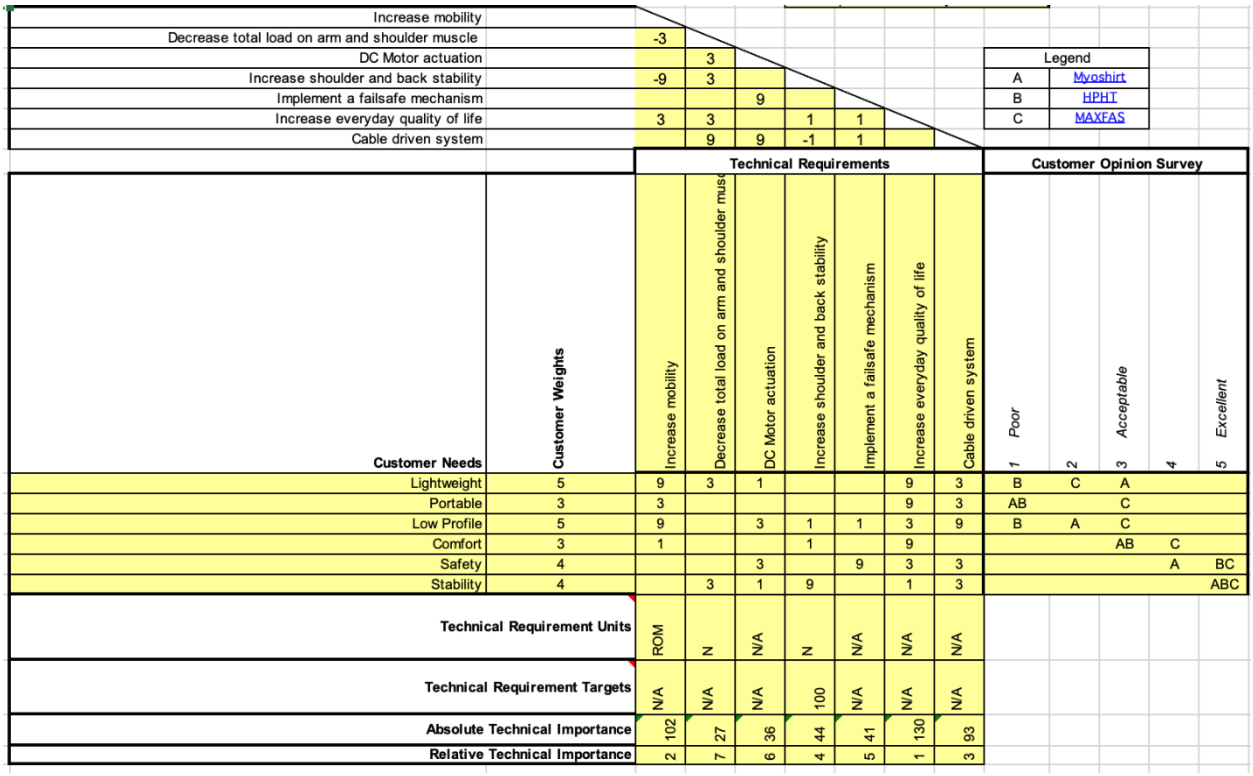


Figure 4: Functional Model

2.4 House of Quality (HoQ)

The team created a house of quality to show how our customer requirements relate to our technical requirements. A HoQ is a powerful tool used in the initial stages of the design process to organize and prioritize certain functions to meet the demands of the customer. The team met to score each section as either a 9, 3, 1, or 0 to rank its importance. From an initial analysis they found that the design must primarily focus on decreasing the load directly onto the shoulder joint. Additionally, the use and understanding of the type of DC motor the design will be using will be crucial to the design process. After the HoQ meeting, the team made sure to research the technical aspects and connection points of the motor, to incorporate them in their concept generation. Additionally, the team agreed that a mechanical failsafe will be crucial to each design, as the shoulder can be a delicate joint. The team discussed multiple different failsafe's, such as locking systems, limiters, and kill switches to make sure the design is as safe as possible. Stability of the shoulder was another focus and will be key for the success of the exoskeleton design. This ties into the use of a cable driven system, as anchor points will be needed to secure the cable as well as provide points of stability. Due to the generation of the house of quality occurring before the teams visit the biomechatronic lab, they were not as focused on everyday quality of life and mobility. However, after meeting with Dr. Lerner, he explained that he wants full upward and downward mobility and gave specific movements to focus on assisting. The design is no longer completely focused on everyday quality of life, but instead focused on assisting tension and compression of the shoulder joint. The house of quality gave guidance and support for the next stage of the design process, literature review and benchmarking.



Increase mobility																
Decrease total load on arm and shoulder muscle		-3														
DC Motor actuation			3													
Increase shoulder and back stability		-9	3													
Implement a failsafe mechanism				9												
Increase everyday quality of life		3	3		1	1										
Cable driven system			9	9	-1	1										
		Technical Requirements							Customer Opinion Survey							
Customer Needs	Customer Weights	Increase mobility	Decrease total load on arm and shoulder mus	DC Motor actuation	Increase shoulder and back stability	Implement a failsafe mechanism	Increase everyday quality of life	Cable driven system	1 Poor		3 Acceptable		5 Excellent			
Lightweight	5	9	3	1			9	3	B	C	A					
Portable	3	3					9	3	AB		C					
Low Profile	5	9		3	1	1	3	9	B	A	C					
Comfort	3	1			1		9				AB	C				
Safety	4			3		9	3	3				A	BC			
Stability	4		3	1	9		1	3					ABC			
Technical Requirement Units		ROM	N	N/A	N	N/A	N/A	N/A								
Technical Requirement Targets		N/A	N/A	N/A	100	N/A	N/A	N/A								
Absolute Technical Importance		102	27	36	44	41	130	93								
Relative Technical Importance		2	7	6	4	5	1	3								

Legend	
A	Myoshirt
B	HPHT
C	MAXFAS

Figure 5: House of Quality

2.5 Standards, Codes, and Regulations

The team will be continuing the design of the robotic arm exoskeleton with the listed standards and codes found in Table 1. The Engineering Code of Ethics is a useful set of standards regarding engineering practice. For this project, it is the team's responsibility to engineer a device that has zero potential to harm an individual or their property while it is being tested on an individual. Human testing follows a strict set of requirements for it to be an ethical process so the team will be abiding by these requirements when the testing procedure begins.

The ANSI and ISO standards for wearable medical devices will guide the team ethically design a device to be worn by an individual. These standards outline what Good Clinical Practice looks like when testing on individuals. The ISO standard 14971 specifically identifies risks in the device throughout its life, so these standards provide maintenance procedures and what those should look like for wearable medical devices.

Table 1: 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.
Engineering Code of Ethics Section II-1-a	Engineers shall hold paramount the safety, health, and welfare of the public.	"Engineers' judgement is overruled under circumstances that endanger life or property; they shall notify their client as may be appropriate." Helps authenticate safety of device operating from user.
ANSI ISO 14971	Application of risk management to medical devices	Helps identify and control risks through device life for wearable medical devices.
ANSI ISO 14155	Clinical investigation of medical devices for human subjects -Good clinical practice (GCP)	Provides guidance to manufacturers on how to implement GCP for clinical investigations. Protection of patient rights, ethical considerations for trials on humans, etc.

3 Testing Procedures (TPs)

The components necessary for testing the design are listed in the House of Quality as being Lightweight, Portable, Low Profile, Comfort, Safety, and Stability. The project goal is to increase the number of pullups an individual can complete while wearing the assistance device. The result the team is measuring is the effectiveness of the design to increase the user's pullup number while wearing the design, so this will be considered along with measuring the completeness of the Engineering Requirements. Each requirement will be listed from 1 through 5, respectively. Some of the engineering requirements do not require a repetitive testing procedure like other components need, so the measurement will be an observation on whether it fulfills the requirement rather than a numerical statistic to be recorded.

3.1 Testing Procedure 1: Design Weight and Portability

This test will analytically measure the designs weight which must remain under 6 pounds. For the design to be portable it must fully remain and operate from the user's body and cannot be attached to any stationary machinery or objects.

3.1.1 Testing Procedure 1: Objective

This testing procedure only needs 3 steps. Begin by weighing each component of the design on the scale. Next have a team member record the data. Lastly, repeat the process one more time to ensure accurate measurements.

Alternatively, if the design components cannot be weighed individually, the design can be worn by the user, weighed, and then subtracted from the user's initial weight.

This test measures the weight of the design to see if it falls within the weight range established by the client. The portability of the design is measured by observation. This portability test is likely unnecessary since the client stated it must be operated from the user's body, and that is how the design was created.

3.1.2 Testing Procedure 1: Resources Required

Resources required for this test include at least 2 members from the team to be present to record data, a scale to weigh the design, and a computer spreadsheet to input the results. This test can be performed anywhere if the required tools are present as well.

3.1.3 Testing Procedure 1: Schedule

This test will occur once the team has a final design built. The team could test more completed prototypes to get an idea if the weight requirement is on track, but it would be most accurate weighing the final design. This will happen before the other tests that require a user to wear the design and operate it.

3.2 Testing Procedure 2: Design Mobility

This test will be an observational measurement where the team will see if the design of the shoulder plate, hinge, and pulley hinder the mobility of the user while wearing the design. This test will fulfill the Low-Profile Engineering Requirement and is beneficial to the testing process since it will partially test the comfortability of the design.

3.2.1 Testing Procedure 2: Objective

This test is important for the team to see if the design can be operated unhindered by the user. Since the design should be worn daily the user needs to retain full mobility in their arms, rotation of the torso, and movement that will cause the design to shift while on the user.

3.2.2 Testing Procedure 2: Resources Required

The resources necessary for this test is a final design that is fully functional. This part of the testing procedure will be tested first on the team members, so all 5 members of the team need to be present for this test. Having all members there to test the design will provide results that may differ from different body structures. Lastly, a data collector will also be necessary for documentation of the results from this test.

3.2.3 Testing Procedure 2: Schedule

This test is expected to occur after the team has developed a final design and before the test that measures the increase in pullups. The team wants to be sure that the design is fully wearable, comfortable, and functional before testing it on a select group of individuals outside of the members in the team.

3.3 Testing Procedure 3: User Comfort Level

This test is another observational recording. The design should be worn daily for extended periods of time so it is important to the team to know that a person can wear the device continuously without discomfort. This test will answer the Engineering Requirement of Comfortability.

3.3.1 Testing Procedure 3: Objective

The goal for this test is to have an individual wear the device for a longer period. This will most likely include members from within the team to test the design. Testing for this procedure will range from 15 to 30 minutes of wearing the device, performing a multitude of tasks, and ranking comfort levels before, during, and after completing each task. The in-depth testing of this component allows the team to have an exact knowledge of when the design may be uncomfortable for the user and what to change for the final design.

3.3.2 Testing Procedure 3: Resources Required

This test requires a 90% complete build which means a design that is almost what the final design will look like with enough room to add or subtract components if the comfortability test is not passed. A list of tasks will be developed by the team that reflects daily tasks anyone may encounter, and this list will be used to test an individual's comfortability. A comfort scale will be created and used to measure the individual's comfort level. All members of the team will be present for this test, along with a computer and software to collect data.

3.3.3 Testing Procedure 3: Schedule

The test for comfortability will occur just before a final design is made. This will allow the team time to add or subtract components if the design is uncomfortable for users. Once the pullup test begins the team will reevaluate this component on the individual being tested to ensure the design is wearable for testing procedures and other extended periods of time.

3.4 Testing Procedure 4: Design Safety

To test the design on any individual the design must be safe for the user to wear and operate. The team plans to ensure safety through this list of components on the design:

- A single on/off switch to enable the device. The user must turn this switch on, so there will be no accidental device enabling it to cause discomfort for the user.
- The motors and cabling used will both have dimensional tolerances set so that these components will not have the ability to overextend any of the user's natural movements.
- The Bowden cables used will remain sheathed until they reach the pulley which ensures no snapping of the cable.
- The pulley and hinge will have a cover over their components so that if any parts snap or break they will not be able to injure the user.

3.4.1 Testing Procedure 4: Objective

This testing procedure will measure the safeness of wearing and operating the device. The test will proceed by having the team turn the device on while it is unworn by any individual to see if the contraction and extension of the cable and pulley are able to move past their set tolerance. Once this test results in success, the device will then be placed on a team member with device off where the team will then measure their level of comfort and mobility range to see if it is hindered in any way. The device will be turned on where the team members will then move their arms and see if the mobility tolerances are exceeded in any way. Once this results in success the team member wearing the device will proceed to attempt pullups to ensure that the device works in the way its design intended.

After this testing is complete the team will inspect the design to see if there is any wear, damage, overheating, or faults anywhere on the device. If in perfect condition the team will deem the device safe for the user where the team will then move onto the next process in the testing procedure.

3.4.2 Testing Procedure 4: Resources Required

This test requires the fully finished design, a team member to wear the device, and the rest of the team present to record data. This test is observational, but documentation of faults or successes in the safety test can be recorded.

3.4.3 Testing Procedure 4: Schedule

This test will occur after the final design has been built and before the testing on select individuals begins. The team must ensure the design is safe to use and operate before being tested

on volunteering individuals. It will be important to follow humane testing procedures of wearable devices, so the team plans to present all testing procedures, requirements, and restrictions to testing individuals once all requirements are met.

3.5 Testing Procedure 5: Increase, Decrease, or Unchanged Number of User Pullups

This is the final test in the testing procedure. The project goal is to design a robotic arm exoskeleton that assists the user with pullups and other daily activities. The team will be measuring the final Engineering Requirement of increasing the number of pullups a user can accomplish compared to their normal pullup number. Here, the team is expecting the testing individual to record their initial number of pullups completed, rest for a few minutes, and to then wear the device and record their number of pullups completed with the device assistance.

3.5.1 Testing Procedure 5: Objective

This test should display data to the team whether the device designed increases, remains unchanged, or decreases the number of pullups and individual can do while wearing the device.

The team will initiate testing by retesting the previous testing procedures on the user measuring if the device is comfortable, safe, or hinders the user's mobility. Once complete, the user will then perform a pullup test where the team will record the number of pullups completed without the assistance of the device. The user will rest for 5 minutes. The user will then wear the assistance device to perform the same pullup test and the team will record the number of completed pullups. The data will be collected, analyzed, and compiled into graphs and charts that will describe the results from the testing.

3.5.2 Testing Procedure 5: Resources Required

This test will require a pullup bar, volunteer test individuals, and data recorders. The process for testing is more extensive than mentioned here since the team will need to:

- Present all necessary documents for signing to the volunteers.
- Explain how the test will proceed.
- Demonstrate the pullup technique the team is testing.
- Record pullups through multiple iterations.
- Finally confirm results with volunteers and release them from their testing.

3.5.3 Testing Procedure 5: Schedule

This final test will begin 1 to 2 weeks after the final design is built. The team will need time to ensure its safety, comfort, and mobility while wearing the device before it is to be tested on volunteers.

4 Risk Analysis and Mitigation

The FMEA (Failure Modes and Effects Analysis) the team performed is more minimal than expected. There are multiple modes of failure but few sub systems that allow for failure. Most of the subsystem's failure modes pertain to mounting connection and the material the component is made of. The FMEA describes that the best way to detect failure in these components would be to conduct a force analysis. The components with the possibility of breaking or disconnecting have the highest potential of failure and need to be designed with that risk in mind. The critical failures that follow describe in depth the diverse ways each mode can fail and workable solutions to prevent the failure from happening.

4.1 Critical Failures

When looking at the various potential failure points of the final design, there were many things that the team decided to consider. With so many 'potential,' issues possible the team decided that looking at the top ten most likely failures to occur and how to mitigate as well as reducing the possibility of them happening was the best course of action. Below are the ten failure points of the current design and what the team sees happening and how to prevent it.

4.1.1 Potential Critical Failure 1: Bowden Failure Due to Tension

The first potential Failure would be the Bowden Cable failing due to the tension experienced from the motor. The failure will be caused by too much torque output from the motor which will result in the Bowden cable "snapping" which could injure the wearer. This can be mitigated by analyzing the forces output by the motor and designing and selecting a proper thickness Bowden cable to combat this issue.

4.1.2 Potential Critical Failure 2: Twisting on Shoulder Pully

Another mode of failure would be on the shoulder pully. If the force is directed incorrectly there will be a force perpendicular to the pully's turning axis along the structurally weak side. This will cause the pully to break, and the arm will subsequently not be assisted in any movement. To mitigate this the pully can be reinforced in this direction or we can take measures to make sure that the Bowden cable is only exerting force in the proper direction for the pully.

4.1.3 Potential Critical Failure 3: Motor Mount Failure

The motor mounts have the possibility to fail which would mean the tension from the motor and the resistance from the arm will pull the motor off the mounts. This will result in the motor spinning free and possibly injuring the wearer. To prevent this, we would need to analyze the forces experienced by the motor mounts and design their diameter to adequately withstand such forces.

4.1.4 Potential Critical Failure 4: Support Arm Buckling

The current design has a support arm that attaches into the current elbow design being worked on by the biomechatronic lab. The force exerted to lift the arm could instead go into the support arm and cause it to buckle. This would result in the design not having the required support for assisting the arm. To fix this we would need to make sure that the design of the support arm had been properly dimensioned and supported to withstand these forces.

4.1.5 Potential Critical Failure 5: Pully Mount Failure

This is like critical failure 3. If the pully mounts fail the Bowden cable will no longer be able to assist the user with lifting their arm. This can be prevented by making sure that the pully mounts have enough strength to resist the forces and withstand the loading.

4.1.6 Potential Critical Failure 6: Bowden Cable Attachment Failure

The Bowden cables will be routed through the pully resulting in a weak point around the fixtures. These are a thinner piece of the pully which will lead to it failing at a weaker point than the others. This would

lead to the Bowden cables becoming detached from the pulley, not allowing any assistance to take place. Fixing this would require a force analysis of the Bowden cable onto the pully and redesigning the pully fixture to withstand the forces exerted.

4.1.7 Potential Critical Failure 7: Bowden Cable Chain Failure

The system that integrates the motor into the Bowden cable uses a chain to apply both raising and lowering with one motor. An issue that can happen would the chain getting derailed, like what happens with a bike. The effects of this are not too serious as it would likely not break, however we would have to take the system off to re-seat the chain. A solution to this would be to only apply force parallel to the chain which will minimize the failure. Another solution would be to add a guide for the chain so physically restrict its sideways motion.

4.1.8 Potential Critical Failure 8: Mounting Strap Failure

The entire system will be held onto the body by a series of straps and mounts. It is possible that where these are attached to the motor system could lead to tearing on the straps which would cause the whole assembly to not be properly attached to the user. A solution to this would be to reduce the number of sharp edges and sand down the existing sharp corners that could possibly tear the mounting straps.

4.1.9 Potential Critical Failure 9: Hinge Mount Failure

There is a hinge at the top of the shoulder which allows the user to move their arm vertically and still feel assistance from the assembly. It is possible that when the user lifts their arm there will be a combination of directions that would cause binding with the assistance and break the part that mounts the hinge onto the pully and rest of the assembly. This would result in total failure and lead to the pully falling off the arm. This can be fixed by using a universal joint instead of a basic hinge to reduce the binding, or we can limit the hinge to not reach the point at which the binding occurs.

4.1.10 Potential Critical Failure 10: Arm Support to Pully Failure

The arm support will have to be attached to the pully for the motor to move the user's arm. The interface from the support to the pully could shear off and cause the pully to move separately of the arm. This would require a new arm support to be made which would be expensive depending on the material. To reduce the risk, we will have to create the mounts to withstand the forces that the arm will experience.

4.2 Risks and Trade-offs Analysis

Some of the issues that arise when trying to foresee modes of failure in a design is trying to tell which of the modern design changes will clash with each other. Two that directly clash are failures 1 and 6. By increasing the Bowden cable diameter to help reduce the risk of failure 1 it must decrease the material on the sides of the Bowden cable mount. This means that as you try to reduce the risk on failure 1 you increase the risk of failure 2. These two must be balanced as to have a reasonable resistance against both failures. Two more that would clash are failures 10 and 4. As you make the arm safer and more resistant to buckling it becomes harder to mount safely which increases the risk of failure 10. However, making each other riskier is not the only factor there are some failure modes which benefit from making others safer. For example, number 2 and 6 would benefit from each other. Increasing the thickness of the sidewall of the pully will help the torsion from breaking the pully as well as it will make the Bowden cable attachment have some more material to work with and increase the strength of the pully. This will also benefit 1 as we can use a larger diameter Bowden cable. Many of these failure points both positively and negatively impact the design and correction of others. It is important to find a balance in order to get the benefits of all the design changes and minimize the possibility of critical failures in the system.

5 DESIGN SELECTED – First Semester

The goal of this design is to design and manufacture a device to actuate shoulder movement. The form of this design should be a soft structured exo-muscle. This can be accomplished through many different means with specific buildings having a strength in various locations. The client Dr. Lerner is also currently working on an elbow exo-muscle for muscular assistance for everything below the elbow. The device should be able to seamlessly integrate into the existing elbow designs. The following shows the iterations that were involved and the specifications and drawings of the functional prototype. The drawings not shown within this section, or the related appendix are to be assumed to be a non-priority design. These non-priority designs have been specifically designated by the client Dr. Zachary Lerner.

5.1 Design Description

The following sections show the engineering process behind the Arm Exo-Skeletons current design and where this design will progress o in the future. This section includes the rationale behind design changes in the past and the future changes that will be made to the design. The following sections also include a description of the designs current state through prototyping and CAD models, as well as a summary of the various analysis that have taken place and are currently taking place that will shape the designs future.

5.1.1 Design Iterations

The design has changed several times during the design process, these changes were primarily due to changes within the customer requirements. These changes often were centered around the integration of the elbow exo-muscle within the generated design and how this was to be accomplished. Within the preliminary report a design was proposed sharing many traits with the current and final design. Figure 1 (Preliminary Design) shows the preliminary designs presented within the initial proposal.

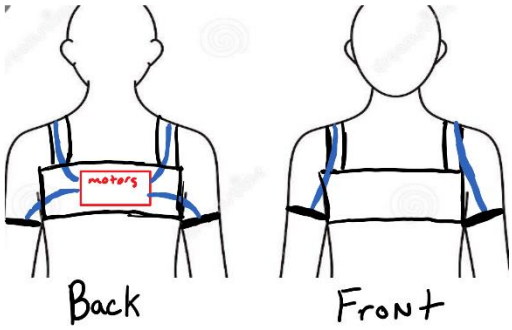


Figure 6: Preliminary Design

One of the fundamental drawbacks to this design was its use of non-standard parts within the biomechatronics lab. This effectively induced more difficulty within manufacturing for future use as new parts would have to be designed and manufactured to implement this. The interface into the existing design of the exo-elbow (Provided to the team by Dr. Lerner,) was also not adequate as the two devices would be effectively separated with no connection between them creating an unnecessary point of instability and strength. There were several concerns listed with the force analysis on this design as well as the direct cable to arm actuation. Due to this the design was determined to be rather inadequate due to the small retraction distance of the cable and the undesirable force vector off the arm. The design was determined to have an unnecessarily high tensional force within the cable, which ultimately caused the

motor mounting plate to be built heavier, putting the design's total theoretical weight above the customer stated weight requirement. The design that ultimately was approved upon is shown in Figure 2.

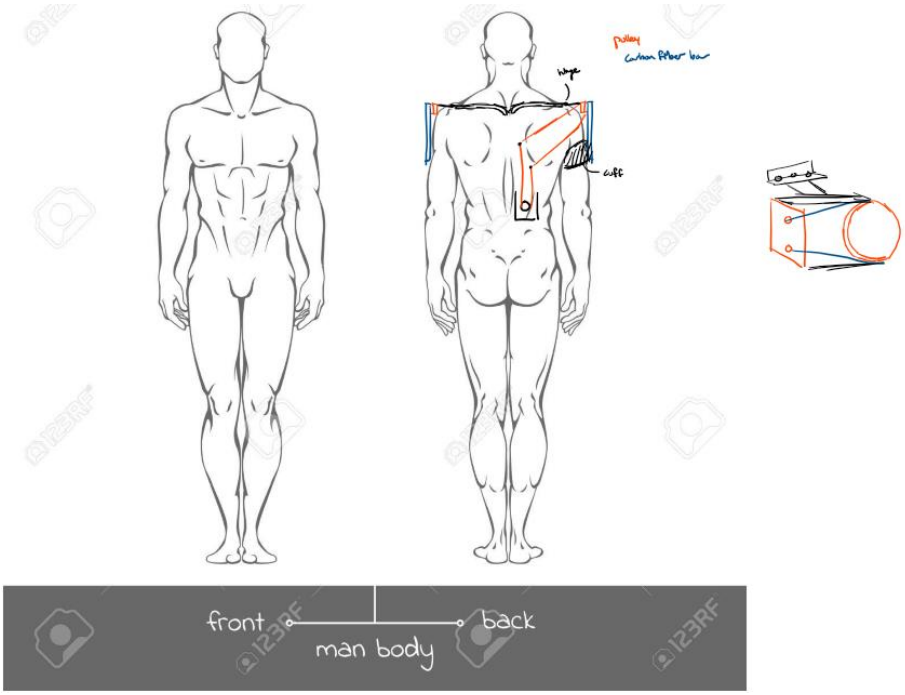


Figure 7: Final Approved Design

The Final approved design corrects many of the aforementioned issues due to its core changes of shoulder actuation. The design rather than using a direct cable to arm interface is translated to a pulley, of which is designed and currently implemented within the biomechatronics lab. This allows for easier adaptation of the design into the existing devices within the mechatronics lab, while also provided a greater length of cable retraction allowing for further reduction within the motor.

5.1.2 Device Structure and Design Concepts

The structure of this design does however require additional bracing to account for the mounting of the pulley itself. To accomplish this a component will be used to replicate the human collar bone. The pulley, which will be acting parallel to the arms position at any given time, must be allowed to move with the arms lateral motion meaning that bearing shaft and the pulley must be supported via hinge plate to account for this. This hinge plate which will be mounting off the external collar bone structure will serve a dual function of maintaining Bowden cable alignment with the pulley to prevent pulley cable derailment. This is accomplished by mounting the sheath of the Bowden cables to the hinge plate in line with the track of the pulley. In the event of lateral arm movement, the cables will move in accordance with the pulley allowing for the free range of motion of the arm without any adverse effects on the function of the device itself. The pulley will directly interface into the upper bicep structure of Dr. Lerner's elbow exo-muscle using a custom lever arm. This effectively eliminates the need of any bicep mounting cuff as the exo-elbow design has the cuff included (seen in Figure 3 below). This effectively simplifies the designs and lowers the component list allowing for significant weight reduction with both designs assembled and worn. The shoulder exo muscle will no longer be interfacing directly with the arm itself and rather with the secondary device. However, for the purpose of test this feature the upper half of the elbow exo muscle with be used to simulate the integrated designs.

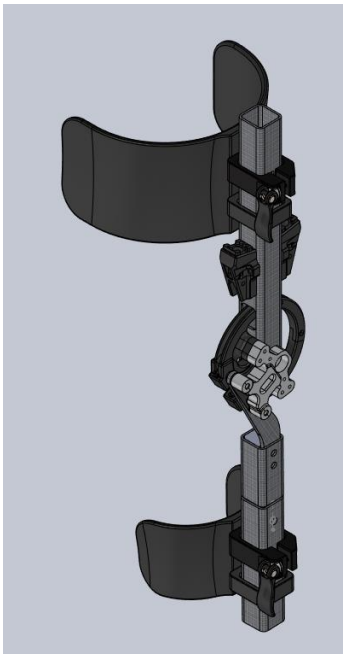


Figure 8: Dr. Lerner's Elbow Exo-Muscle

Due to the individualized structure of the human body from person-to-person custom hinge plates and collar bone structure will likely have to be fitted from person to person. For this reason, the initial CAD package has been generated with the average male in 20 to 30 years of age in mind. Much of the current design is based on the range of motion (ROM) of the human body and where assistance can be applied most effectively with the most impact. For this reason, much of the final device's geometry will be determined by this, to minimize the devices interference within itself and the body to allow for a nearly unaffected ROM.

The exo shoulder device is going to be attached to the body using a harnessing system which all components will be primarily or secondarily attached to. This harness will be responsible for the transfer of all forces applied by the device to the user's body. The primary force concerned in the design of this device being the weight of the users arm plus any weight that may be being carried, and the downward force that may be needed in the action of a pull up for example. Most of the force will be localized to the motor which is located on the users back. These forces will be transfer through the Bowden cables, through the cable motor interface and to the motor mount and harnessing system, which will be seen as a tensional force pulling laterally on the harness. Though the design is aiding both arms it cannot be assumed that an equal and opposite tensional force will be acting on the mount as the device will operate arm actuation independently from one another. Thus, the harness must be able to account for these forces independently and in both directions. The form factor of the harness will be remarkably similar to that seen of a climbing harness shown in Figure 4.

Figure 9: 3M™ DBI-SALA® ExoFit™ XP Tower Climbing Harness 1110301, Medium

A harness that attaches around the legs provides adequate resistance against the tensional force that are expected with design. These anchor points prevent undesired twisting of the harness about the torso of the user, while also providing a secure downward anchor point to prevent lifting of the harness on the user's body.

5.1.3 CAD Package Description and Current Prototype

- See Appendix A for all sketches of CAD design.

Each component of the design has its own purpose. The shoulder plate will be mounted on the shoulder and be connected to the hinge bearing plate. This will provide support for the pulley. The pulley is connected to another bracket which in turn is connected to the arm that connects to the rest of Dr. Lerner's design. These components were all 3D printed for our initial design. After testing the prototype, the team found that the hinge and shoulder plate rotated at an awkward angle, resulting in a loss of force and support. The team will improve upon this design by mimicking the scapulohumeral rhythm of the shoulder and finding a design that fits naturally around the shoulder.

5.1.4 Technical Analysis and Associated Calculations

This section is an overview of the topics deemed to be the most important to the Arm-Exoskeletons success in accomplishing adequate assistance as well proper interfacing with the human body. The following analyses discus critical features and aspects of both the human body and the design itself. This is important to the function of the design as the human body must be considered to properly engineer an effective device.

These calculations will be implemented within the final design of the device and determine the devices form factor as well as the devices overall success in accomplishing the set engineering and customer requirements.

STRUCTURAL ANALYSIS OF RIGID 3D PRINTED BAR

The purpose of this analysis is to measure the force that the material(s) can withstand when different forces are acting on the bar, such as pulling and pushing forces when mounted to the user. Assumptions used for this analysis will include the mechanical properties of the two main materials considered currently for the design: onyx and carbon fiber 3D printing filament. Onyx filament has a tensile stress of 40 MPa, thermal deflection at 145℃, and a density of 1.2 (g/cm^3). Carbon Fiber filament has a tensile stress of 800 MPa, a heat deflection of 105℃, and a density of 1.4 (g/cm^3). Other assumptions not currently set in stone are the shape of rigid bar and its length, but it is assumed that the shape is a rectangular prism, and the length will be at least 8 to 10 inches.

ANALYSIS OF HUMAN FORCE AND FORCE COMPENSATION NEEDED

When determining the average power output for a person and their various muscle groups a couple of different assumptions will need to be made. The team will only consider a 'healthy,' male and female and then based on the values from these statistics, that number can be scaled either way depending on the individual. On average a male can comfortably produce around 200 newtons of force in a pulling motion, with the world record for males being 400 newtons and a female's being 244 newtons. If a normal strength for a man is 200 newtons of pulling force and a female's is around 100 newtons, then we can safely assume that if our machine can successfully and comfortably produce 200 newtons of force, then it should be able to help anyone that needs it. Further analysis of this topic is yet to be conducted but will be continued as it provides the team with great insight into how much power the suit will need for every person of every size and strength.

ANALYSIS OF FORCES EXERTED ON DEVICE AND HUMAN ARM

The device should have the ability to reduce or eliminate the weight of the user's arm plus any added weight of tools or objects held in this position. The human arm was measured to weigh around 2.5 kg on average, adding in the average weight of a hand tool this brings the total to 2.72 kg. Upon calculation of the sum of the moment of the shoulder, offsetting torque required would on average be 8.5 Nm. The motors provide about 3 Nm of torque at normal operation levels with the motor maxing out around 9 Nm.

In accordance with the most recent design a 50 mm diameter sprocket will be used to interface the motor to the Bowden cables. Under normal operating parameters of the motor this produces 120 N of linear force. This force will be translated through the Bowden cables to a pulley system which will be attached via biceps cuffs and Dr. Lerner's elbow exo-skeleton. The pulley located at the shoulder has a diameter of 80 mm. Bringing the torque about the shoulder to 4.8 Nm. Under peak power this jumps to around 14.4 Nm of torque. Thus, what can be assumed about expected forces on the motor mount itself would be only applied by the force of cable retraction from the motor. With an expected force at normal operational output of around 120 N and at peak power a force of around 360 N. With the current harness subsystem which is responsible for attachment of the motor mounts to the user these applied forces will be within the range of what the current designated strapping material can handle.

ANALYSIS OF CAD MODELS ADAPTED FOR INTEGRATION

The client has requested that the design that the team produce must integrate into the current design that his lab has for the elbow. What was required to adapt the same pully design for the shoulder was making the structural member longer and changing the geometry of the adapter that connects the pully to the member. Seen below in Figure 5 is the adapter before and Figure 6 is the adapter after the modification for the new application.

Figure 10: Lever Arm Adapter (Before)

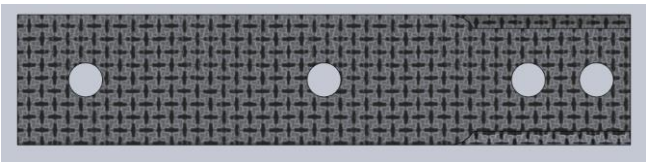


Figure 11: Lever Arm Adapter (After)

This modification permits the ability for the Pully to be mounted onto the same style of bar that it was before without having to change any of the geometry and hardware required. Both plates have the same thickness so they can withstand the same forces applied. The components will be made from the Carbon Fiber 3D printing material that will be inlayed with Onyx Filament. The Carbon Fiber has a Flexural Strength of 540MPa and the Onyx of 71MPa. With these materials and modern design, the two design will be able to integrate seamlessly.

SCAPULOHUMERAL RHYTHM OF THE SHOULDER

Scapulohumeral rhythm defines the kinematic interaction between the scapula and the humerus. For this analysis, the scapulohumeral rhythm of the shoulder will be analyzed to ensure the device does not interfere with the natural movement of the shoulder. This rhythm dictates the timing of movement at these two joints during shoulder elevation and is broken into multiple phases. The first "setting" phase is the 0–30-degree range of motion and is dominated by the glenohumeral joint. After the setting phase the glenohumeral and scapulothoracic joints will move simultaneously, at a respective ratio of 2:1. This ratio can be calculated by dividing the total amount of shoulder elevation (humerothoratic) by the scapular upward rotation (scapulothoracic). If the scapular rhythm is out of balance, there will be a change of normal position of the scapula related to the humerus.

For the motor to deliver the maximum assistance to the shoulder, the cables and pully must work tandem with the natural joints of the shoulder. To mimic the force couples in the shoulder, a full analysis needs to be done to understand the best point to mount the pulley system and where to anchor the support points on the back and shoulder. Positioning of these components will be crucial to not interrupt and off-balance the scapulohumeral rhythm of the shoulder.

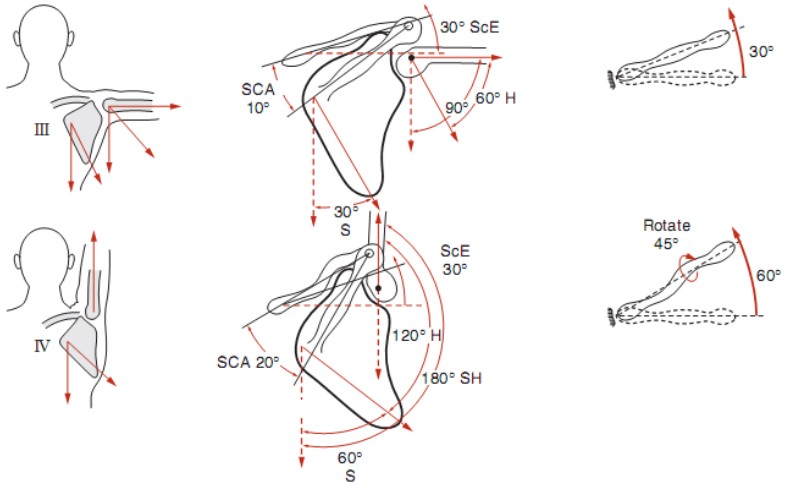


Figure 12: Scapulohumeral Rhythm of the Shoulder

5.2 Implementation Plan

In the upcoming semester the prototype will be transitioned into a complete working design. This will happen through a series of steps as issues and flaws are worked out. One of the primary tools that will be used to aid this process is 3D printers. Two of the team members own 3D printers and plan on use them to help the initial process of designing. This will be essential to the team's final design and budgetary constraint as part can be printed in PLA quickly, and cheaply to test fitment and light duty performance.

As the human body has relatively complex geometry achieving a comfortable and properly fitting device consisting of rigid materials is not an easy task. Printing these parts in the Carbon Fiber and Onyx filaments is not only expensive but takes up valuable machine time. The team will utilize this as much as possible to point when it has been decided that fitment, comfort, and functionality has been effectively maximized and the device is ready for full load testing. Upon this milestone a final device may start to be manufactured using the desired materials. This manufacturing process will require Dr. Lerner's explicit permission to use the Biomechatronics lab and its associated facilities. This will be integral to the production of the final design as the lab holds specialize equipment needed to manufacture carbon fiber and Onyx printed parts. The team has also foreseen the possibility that key parts may be needed to be machined, in this case two of the team members are currently working towards certification in the NAU machine shop.

The Bill of Material can be seen in 8.2 Appendix B which shows the projected materials and associated costs of each. These materials can all be either made or bought from a 3rd party, except for the harness which will be purchased from Enviro Safety Products website and then after being modified to except the various components of the Arm Exoskeleton. The motors will be purchased through tmotor.com. The other Buy-Out products can be purchased directly from The Home Depot. With these purchases in mind the total left-over budget without factoring the small cost of Prototyping supplies there is a total of $1970.62. Allowing plenty of money for potential failures and prototyping.

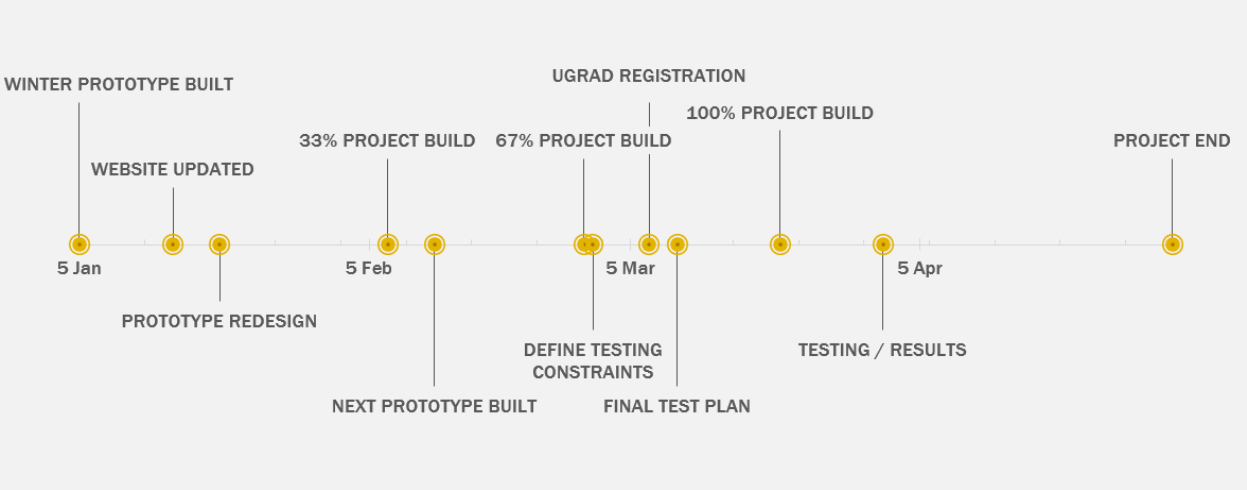


Figure 13: Anticipated Schedule for Spring 2023

The timeline shown above in Figure 8 is for next semester and includes the deadlines of various assignments and milestones. This timeline has much of the building process happening over the course of winter break, outside of the semester schedule. This will allow the team to complete the build process very early on in the semester, allotting time for lower priority tasks including motor control integration and testing with the Elbow Exoskeleton and force optimization. This building process will start with the current prototype and evolve from there. The team's plan for winter break includes identifying weak points within the design and improving on them systematically. The initial prototype is shown below in Figures 9 and 10.

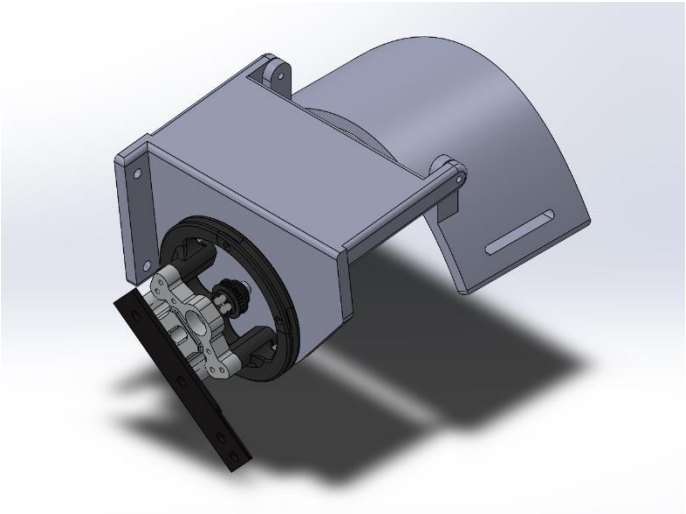


Figure 14: Full Assembly

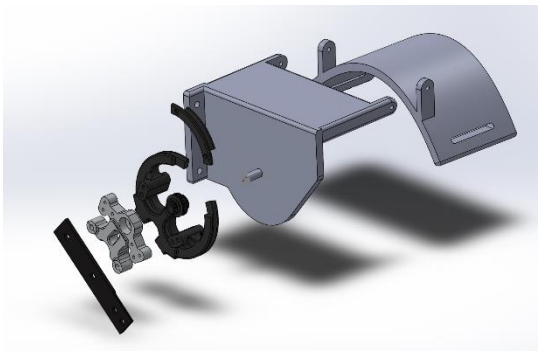


Figure 15: Exploded View

6 CONCLUSIONS

This report summarizes the work done on the preliminary report and includes details on the next step in our design process. We outline the testing procedures, codes and regulations, and a breakdown of our design selection after our initial prototype. To reiterate, our design has a few requirements that we must meet. The design must be able to provide support to the shoulder in tension and compression, allow the user to complete more pull ups that initially desired, integrate seamlessly with Dr. Lerner's elbow exoskeleton, and provide a mobile, lightweight option for upper arm assistance. After many assorted designs, the team has settled on a design that will meet these criteria.

However, the design is open to change depending on how our initial testing unfolds. Each of the five testing procedures has potential modes of failure that may break or damage the device. The team must be prepared to adapt to these failures and modify the design. To deal with the inevitable modes of failure, the team has set apart a significant percentage of the budget to replace any broken components. The team is not afraid of mistakes, rather embracing them as part of the design process and learning from what goes wrong.

The next step for the team is to complete individual analysis on different components to solidify the design, and mathematically verify its structural integrity. Over the next few weeks, the team will also be starting the transition from prototyping to the first build of the "final" design. Once the design is completed, the team can begin its testing procedures and continue with the project. Overall, the team is on track with the deliverables assigned by Dr. Lerner, and plans to complete the next design iteration.

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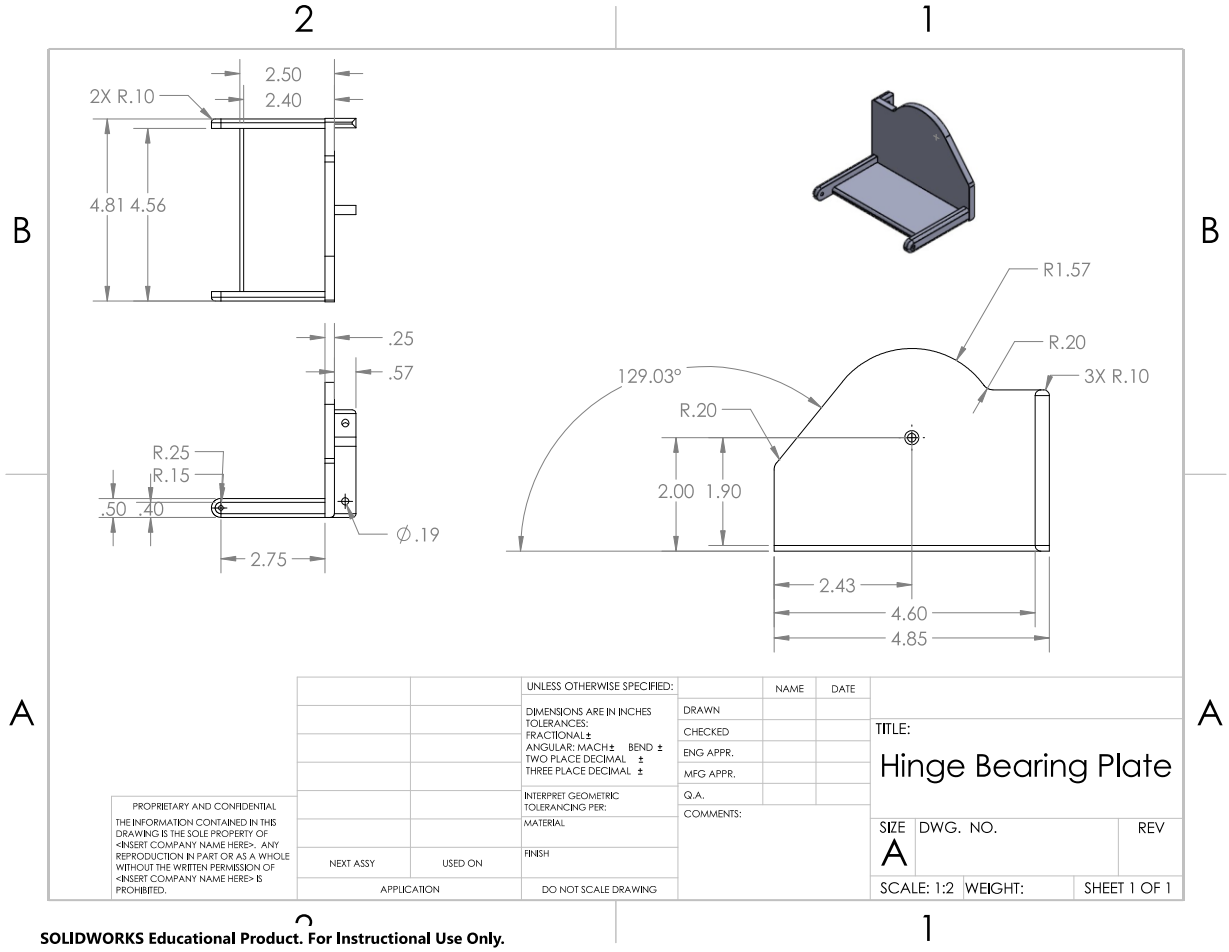
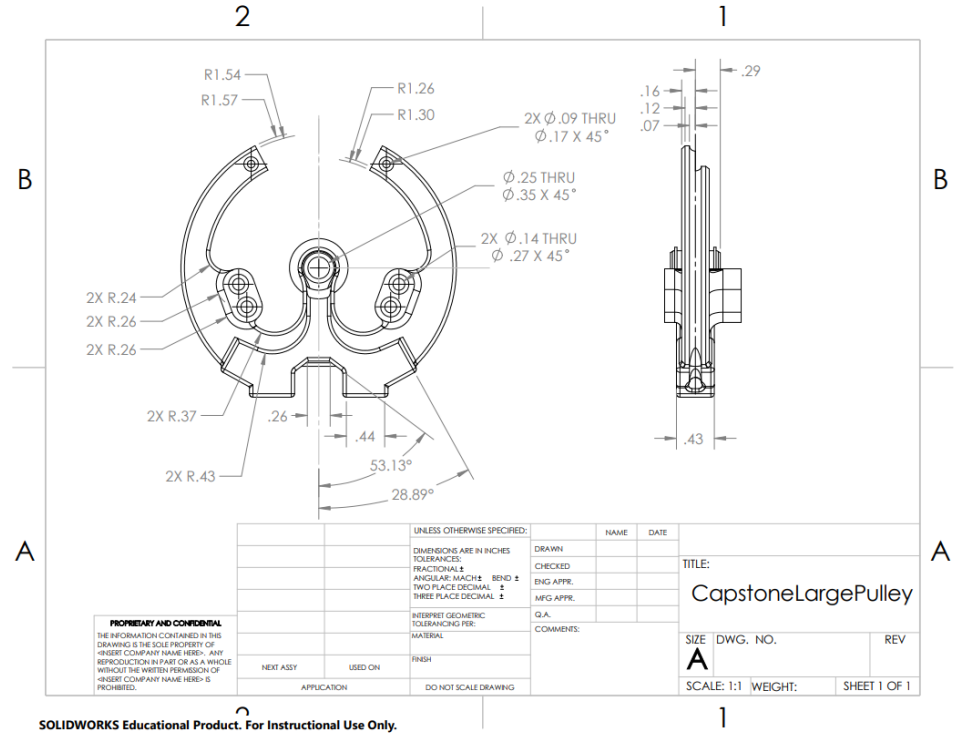
8 APPENDICES

[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.]

8.1 Appendix A: Machine Drawings and CAD Models





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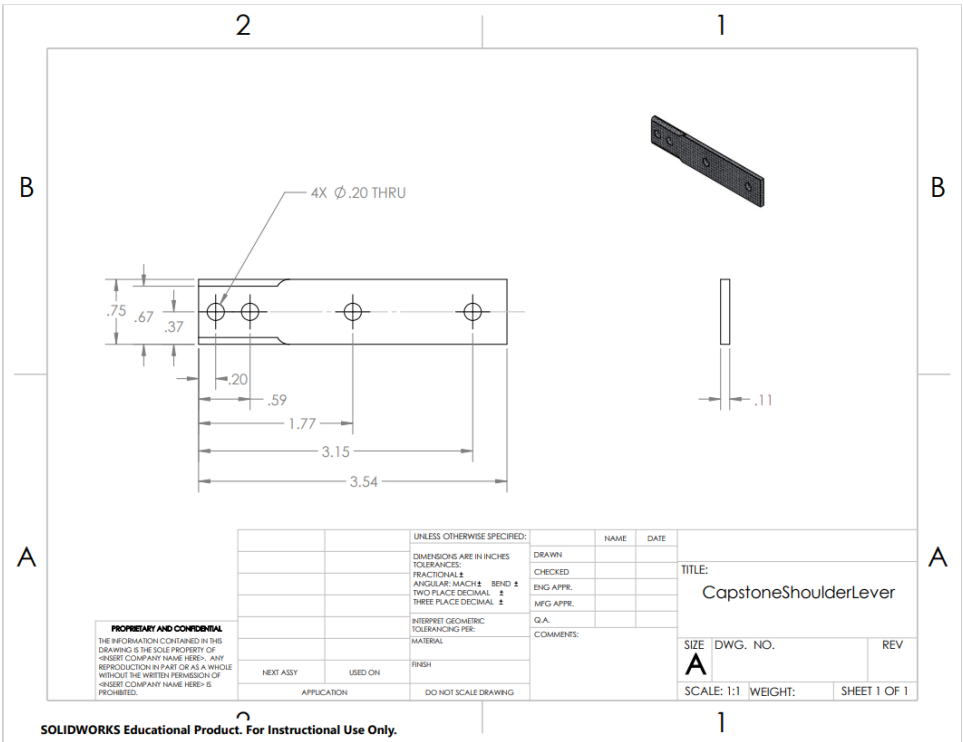

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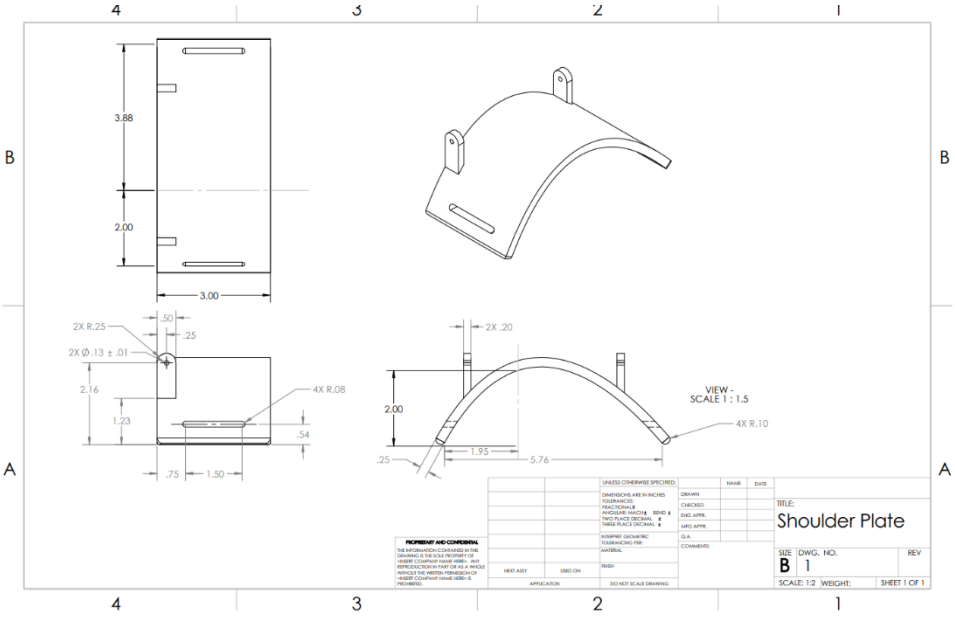
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1.50
2X .20
2.00
.25
1.95
5.76
4X R.10
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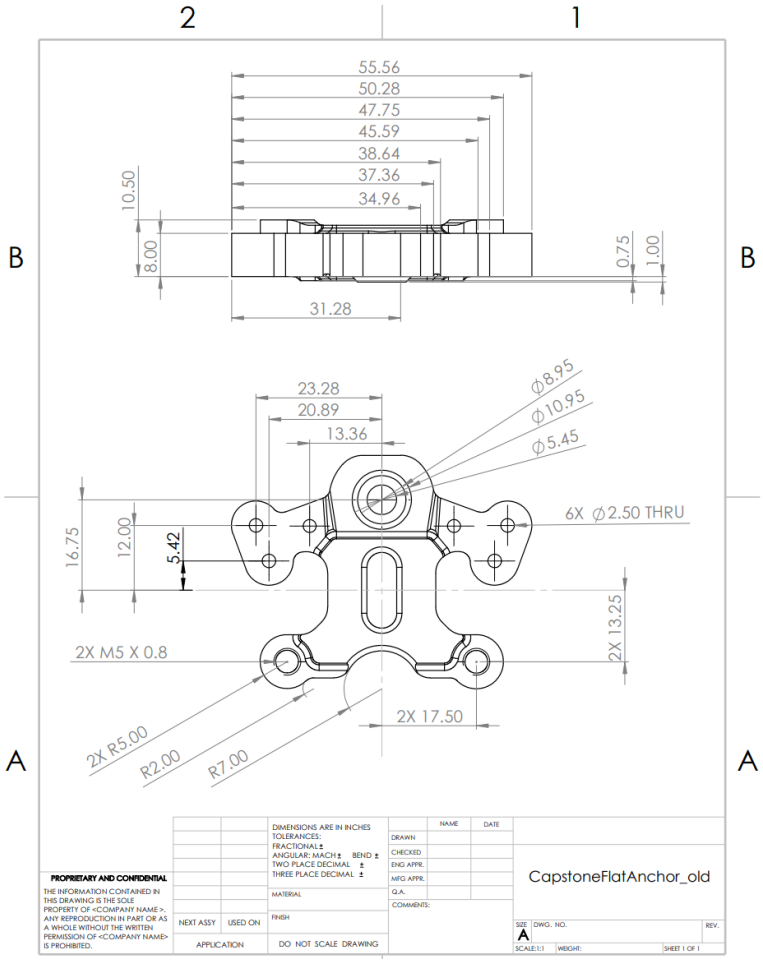
DWG. NO. 1
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1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Ø8.95
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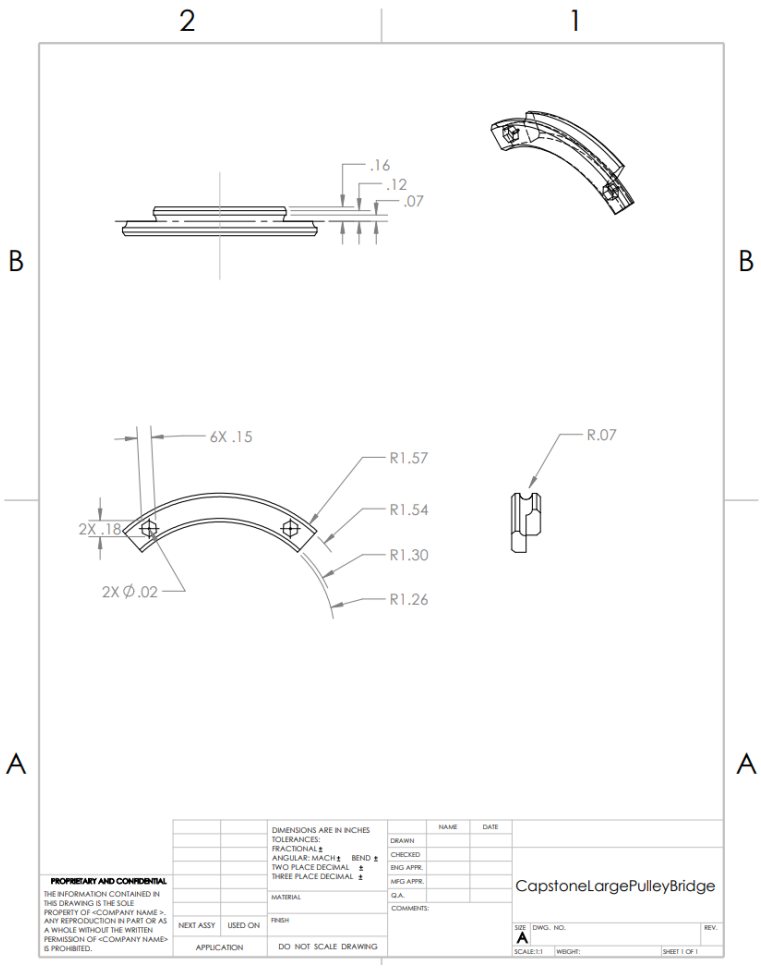
SHEET 1 OF 1



8.2 Appendix B: Bill of Materials

-Bill of Materials

Bill of Materials:	Quantity:		Total Cost:
Shoulder Plate	1	Manufactured	$35.00
Hinge Plate	1	Manufactured	$10.00
Large Pulley	1	Manufactured	$8.00
Large Pulley Bridge	1	Manufactured	$1.00
Pulley Flat Anchor	1	Manufactured	$5.00
Lever Arm	1	Manufactured	$2.00
Tube Spacer	1	Manufactured	$0.50
Shoulder Tube	1	Manufactured	$15.00
Bicep Cuff	1	Manufactured	$25.00
Bicep Mount Upper	1	Manufactured	$1.00
BIcep Mount Lower	1	Manufactured	$1.00
Harness System	1	Modified	$850.00
Motors	2	Buy-Out	$599.00
Bowden Cables 5'	4	Buy-Out	$213.08

6-32 x1in Bolts	8	Buy-Out	$1.38
6-32 Nut	8	Buy-Out	$1.38
#6 Washers	12	Buy-Out	$1.38
6-32 Nylock Nuts	4	Buy-Out	$1.38
4-1 1/2 Sheet Metal Screws	4	Buy-Out	$1.38
8-32 x 1 1/2 Bolts	8	Buy-Out	$1.38
8-32 x 1 Bolts	8	Buy-Out	$1.38
8-32 Nuts	4	Buy-Out	$1.38
8-32 Nylock	4	Buy-Out	$1.38
#8 Washers	12	Buy-Out	$1.38
		Total Cost of Prototype:	$1,779.38

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
Hinge - allows the arm to rotate about the shoulder	hinge breaks	Can injure the user at the shoulder where it connects	8	Material hinge is made from	2	Force analysis on material type	8	128
	range of hinge	Not enough range for mobility, not allowing arm to move in natural motion	5	Type of hinge used	2	Solidworks simulation or real life test	4	40
	Mounting to shoulder plate	Breaks from shoulder plate and no longer assists the user	3	Method of mounting used	1	Force analysis on points of contact between the two components	8	24
Bowden Cable - Assist the user in pulling or pushing motions around the shoulder joint	Attachment failure	Cables can become dettached from pulley removing assistance from the user.	3	Pulley track is too thin	5	Increase inner wall of track to encase cable	3	45
	Chain failure	Chain component of cable can become dettached from its point of contact	3	Motor cable track is too thin	5	Increase inner wall of track to encase	3	45
	Tension failure	Possibility of snapping cable and injuring user	9	Uncontrolled amount of tension in cable	3	Force Analysis on cable material	8	216

Motor - component that enables tension or compression in the cables to provide assistance to user.	Motor disconnects from mount	The motor spins freely and possibly injures the wearer.	8	Overload force on users arm, causing high tensional force on motor mounts.	4	Test when to see the motor disconnects from its mount. Make changes as necessary.	4	128
Support arm - component that interfaces shoulder exoskeleton with elbow exo skeleton	Suport Arm Buckling	Not having required support for assisting arm	3	Force required to lift arm overloads material specifications	2	Force analysis on support arm material	8	48
	Disconection from pulley to suport arm	Breaking the connection point between support arm and pulley requiring new parts	4	Force required to lift arm overloads material specifications	3	Force analysis on spacer material	8	96
Pulley - point where the cable moves around, controlling the user's arm to feel upward or downward force.	Pulley disconnects from cable chain	The chain cable can detach from the pulley which results in no assistance to the user	5	Cable chain track is too thin	2	Test device under different loads and arm positions and Force analysis on pulley material	9	90
Mounting Strap - a series of straps and mounts that fix the system to the user	Strap tears	The entire device is not propperly fixed to the user	5	Tensional Force on motor mount exceeds strength of strap or sharp edges on mount cut strap	2	Test device under different operational loads	5	50