Robotic Exoskeleton for Shoulder Complex Assistance

Final Report

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DISCLAIMER

EXECUTIVE SUMMARY

Dr. Zachary Lerner, lead researcher of the Biomechatronic lab, has spent the last decade developing a robotic ankle and hip exoskeleton designed to assist individuals who suffer from stroke, cerebral palsy, and spinal cord injuries (SCI). Dr. Lerner has tasked our team with designing a robotic shoulder exoskeleton by improving upon the MyoShirt, an exo-suit created by ETH Zurich. Our team used a bio-inspired design method to design components of our exoskeleton that would mimic muscular structures in the human body necessary for augmentation. Our project goal is to design a robotic shoulder exoskeleton with the ability to increase the user's shoulder endurance by 15%. The project client, Dr. Lerner, has designated a set of customer requirements which is that the design must:

- Be cable a cable driven system
- Use a pulley to create torque about the shoulder
- Be user operable
- Be lightweight
- Be low-profile
- Assist the shoulder-arm motions of the user

The team discussed the customer requirements with the client and converged on the following list of engineering requirements which will be used to both quantitatively and qualitatively measure the success of the project and satisfaction of the client.

The design will:
- Include Bowden cables to actuate the system
- Revise Dr. Lerner's previous pulley design
- Be controllable by the user independently of any stationary machinery
- Weigh less than 6 lbs.
- Protrude less than 10 cm (3.94 in.) from the body
- Increase the user's timed ability to hold an object by 15%

Through multiple iterations, and lots of design failures, the team was able to design an exoskeleton device that weighs a total of 5.5 lbs., protrudes 4.5 in. at maximum, and incorporates Bowden cables and a pulley into its design. The endurance test is a benchmark created by the team to replace the pull-up test, and the endurance test was used to determine the overall success of the device. From the endurance test the team found that the device did increase the time the user was able to hold a weight in front of them. An average increase of 49% was calculated from the test results although further testing with more trials will most likely change this average.

The device engineered by the team meets the lightweight, cable actuated, and pulley mechanism customer requirements but failed to meet the requirement of being user operable and low-profile. The device successfully increased the shoulder endurance of the user and is therefore deemed as a successful project with results to verify the data collected. The final design presented here will be used as the first iteration of many in a new branch of research for Dr. Lerner's lab at Northern Arizona University.

ACKNOWLEDGEMENTS

The team would like to thank Dr. Zachary Lerner for the guidance of design throughout the project. Graduate student Daniel Colley is acknowledged for his help with design validity and design testing. His contribution to create a code and work with the team to make the design functional aided the final phase of the project. The team would like to thank Professor David Willy and Dr. Tim Becker for further guidance and recommendations during the design process of this project. Lastly, the team thanks W.L. Gore for sponsoring this project with an allotment of $3,750 for the project budget.

TABLE OF CONTENTS

Contents

1 Background

1.1 *Introduction*

The Robotic Arm Exoskeleton project is a new branch of research in Dr. Lerner's Lab where his previous exoskeleton devices are designed to assist the gait cycle of impaired individuals. This project will be the first of many that delve into the area of upper body exoskeletons compared to Dr. Lerner's current lower body exoskeleton research. His interest for the future of this project is to create a device that can be used by technicians or assembly line workers who will be holding their arms above their head or away from their body for most of their work. The goal for now is to reduce the fatigue the user will experience when engaging in these arm motions for prolonged periods of time. This project is not designed to create a rehabilitative device, rather it aims to create a functional device with the ability to meet an initial benchmark set by the client.

Not only will the success of this project benefit the research of Dr. Lerner, but it will be the first step for his lab to attempt an upper body exoskeleton with a baseline for what to improve upon. The other benefiter of the project is the sponsor, W.L. Gore, and although their company has no current use for exoskeletons their gain from this project is the interaction of engineering in their community with a project that has the potential to benefit individuals in the future.

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 impairments. 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 worn DC motors. Successful completion of this project will lead to a design concept and functional prototype".

This was the original description given at the start of the project. Since then, the project's design requirements and benchmarking methods have changed. Rather than assisting the user with a pull-up the benchmark was changed to an endurance test where the user will hold an object in front of their body to actuate the shoulder and back muscles. This was changed due to time constraints, increasing risk of safety, and client interest. This change allowed the team to conduct a simple, but more effective test before moving onto the more complex pull-up test for future iterations. This project is sponsored by W.L. Gore with an allotted budget of $3,750 which will be used for the iterative design process and to purchase high quality materials to construct the final design out of.

2 REQUIREMENTS

The Robotic Arm Exoskeleton project tasked the team with designing, testing, and presenting a functional exoskeleton device with the ability to increase the shoulder endurance of the user. The team discussed with the client specific constraints for the project and decided with the client what reasonable goals the team would be able to deliver on. This section will qualitatively and quantitatively detail the measurement of success of the project as described by the project's design requirements.

2.1 *Customer Requirements (CRs)*

The customer requirements (CRs) for the project are seen in Table 1 with their weight attached to each entry. The weight for each requirement is on a scale from 1 to 5 with 1 being the least important, and 5 being the most important. Many of the requirements are weighed the same due to their impact on the objective of the project. A note worth mentioning is that the customer requirements established during the first semester have since changed and Table 1 reflects the updated requirements. These customer requirements were changed to get rid of outdated requirements but mainly to give the team a clearer understanding of what they should be designing against.

Table 1: Customer Requirements

Customer Requirement	Weight (1 to 5)
CR1 - Cable Actuated System	5
CR2 - Utilize a Pulley	5
CR3 - User Operable	3
CR4 - Lightweight	4
CR5 - Low-profile	4
CR6 - Assist Shoulder Endurance	5

Customer requirements 1, 2, and 6 are weighted the highest since the objective of the project is to engineer a functional device that increases the user's endurance. Although a lightweight and low-profile design would benefit the user in their ability to perform the endurance test effectively, the main components that make the design functional are the cable actuation to drive the pulley, the pulley itself, and the benchmark goal to measure the device effectiveness.

Weighted the second highest are CRs 4 and 5. These are important design aspects and have been considered by the team during each design iteration. For the client, it is important for the device to be lightweight and low-profile so that it doesn't interfere with the user's quality of life when wearing the device, but it is not as important when getting the device to be functional. During the design iterations, all components were designed to be made of lightweight materials such as 3D printing filament, carbon fiber, and aluminum.

The lowest weighted requirement is CR3 which has a weight of 3. This weight was selected to be a neutral measurement of the customer requirement because it is not so unimportant that it can be disregarded in the design process, but it's not the most important component because the device will still function whether it is controlled by a computer or a wireless remote. The client did state for this project that the power system is beyond the scope of the team. This means that the team is not responsible for engineering a way for the device to be powered, rather the client's lab will take care of this portion. Whether this design is met or not is not going to jeopardize the success of the project since it will remain functional one way or another.

2.2 Engineering Requirements (ERs)

The engineering requirements (ERs) created by the team are qualitative and quantitative measurements of the customer requirements. Table 2 lists the targets the team set for the CRs with a tolerance for each ER that the team will use during the testing phase to measure if the ER was met or not.

Table 2: Engineering Requirements

Engineering Requirement	Target	Tolerance
Bowden Cable Actuation	Bowden Cables	N/A
Revise Dr. Lerner's Previous Pulley Design	N/A	N/A
Independently Operable	N/A	N/A
Lightweight	Weigh < 6 lbs.	+ 4 lbs.
Low-profile	Protrude < 10 cm (3.94 in.)	Maximum
Increase Time to Hold an Object	15% Increase	Minimum 12.5%

Many of the ERs for this project are qualitative so they won't have a physical target to meet. ER 2 and 3 will be visually interpreted by the team if the requirement was met. ER 1 can also be a visual measurement but for this project the team specified that Bowden cables will be used for the system and that will be the only measurement of this requirement.

Engineering requirement 4 has a tolerance of plus 4 lbs. Initially, the idea of making a 1-arm or 2-arm exoskeleton was discussed but not answered. The team felt that with the projected design of the exoskeleton device that the weight requirement would be surpassed. The team discussed this concern with the client to which he agreed and specified that a 1-arm system will be the focus for this project, and that the weight requirement can be exceeded by a few pounds while still being acceptable.

Engineering requirement 5 has a maximum tolerance of 10 cm. The current devices in Dr. Lerner's lab utilize concise designs so where a typical subsystem may use 3 components to be complete, Dr. Lerner's lab aims to make that subsystem a 1 component system. This helps eliminate unnecessary parts and reduce overall weight. The team in this project must engineer a low-profile design to match what is created in Dr. Lerner's lab and to be acceptable by the client.

Engineering requirement 6 has a target of a 15% increase and a tolerance of 12.5% at minimum. The team plans to measure this requirement by timing the user so this requirement will either be met or not met by displaying at least a 12.5% increase in measured time. If there is an increase in time greater than 15% then that will be a highlighted accomplishment achieved by the team during the testing section.

2.3 *Functional Decomposition*

The purpose of a flow decomposition diagram is to show the hierarchy of the various subsystems within the final product. There are three main assemblies that the team must design for this project: pulley design and mounting, component mounting to the user, and cable routing. The team utilized this functional decomposition to plan their design process for these subsystems. The most important thing to design first is the pulley design and how it mounts to the user. Once the team can finalize this component then they will move onto the next assembly which is the component mounting to the user. This is how the team will connect the motor, cabling, batteries, and other subsystems to the user to make an independently operable device. The last assembly to be designed is the cable routing. Since the Bowden cables are fluid and can be positioned in any direction, the team is able to add these last. Adding these last gives the team room to change any components at the last minute while still being able to connect cables to them. If the cables are attached and then components are changed then all the cabling will need to be changed.

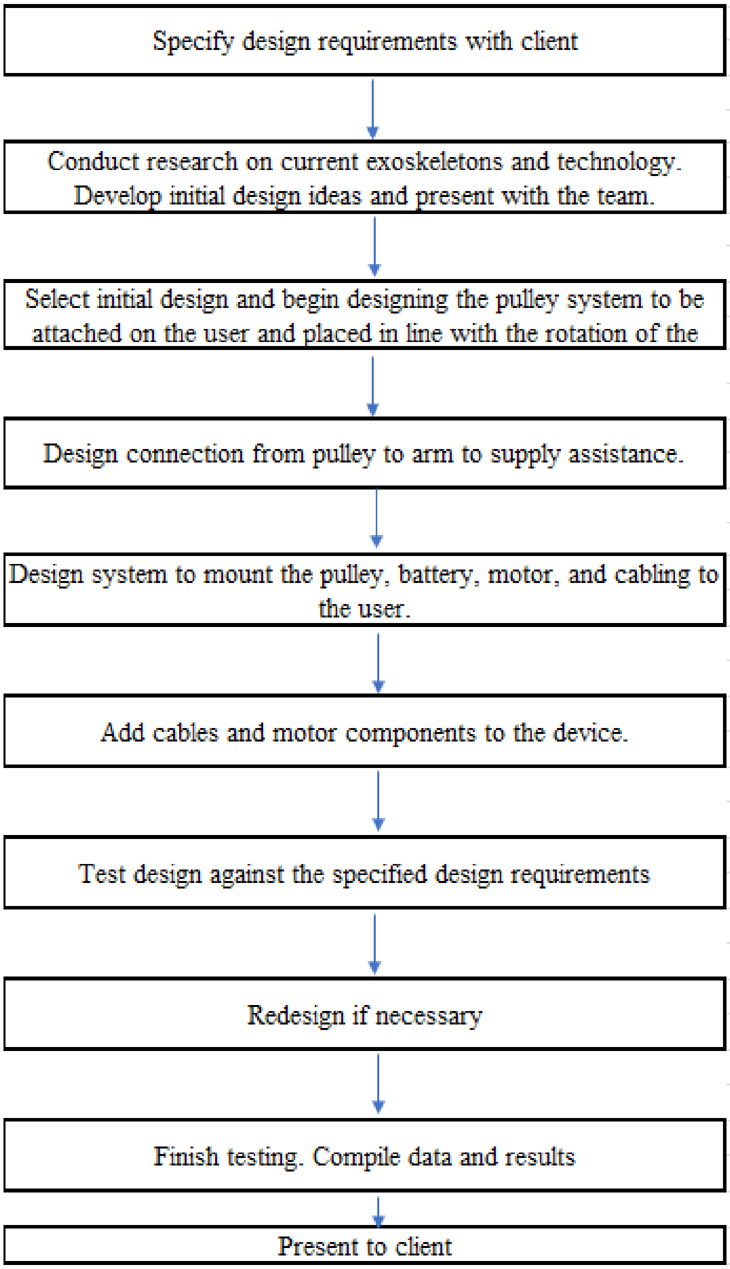


Figure 1: Flow Decomposition

2.3.1 Black Box Model

Below is the Black Box model created by the team at the beginning of the project. It has remained unchanged because it still accurately reflects the inputs and outputs of the exoskeleton system. The Black Box model allows the team to visualize what this exoskeleton design will need to make it functional and what the team can expect to be outputted.

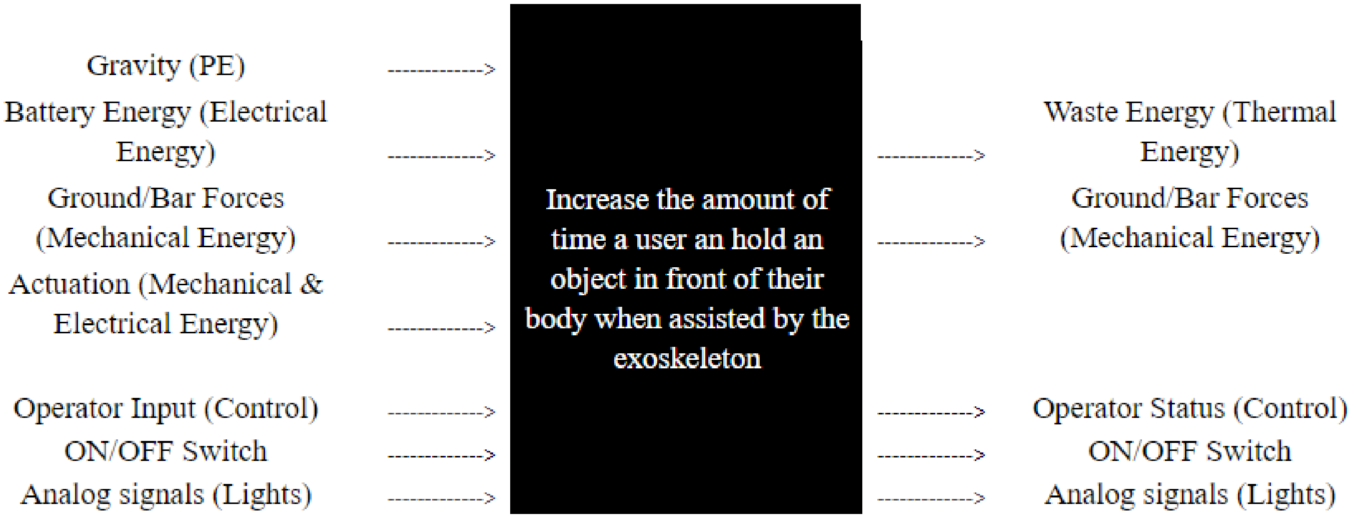


Figure 2: Black Box Model

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

The functional model is a structed representation of the functions presented within the model system or in the case of this project, the exoskeleton shoulder design. The reasoning behind why the team decided to create a functional model was because they wanted to layout and visualize the different subcomponents that would be going into the design and how they would work with one another. By viewing how the device's components would in tantum the team could better assess whether the system makes logical sense, will most likely work, and if anything was to be changed, what it would be and what the system would be changed to. The functional model below also depicts the process at which the team will expect the device to actuate and perform. By looking at the functional model below we can see that the device should and does run as intended by the team. The functional model also provides the team with a reference to use during testing. If the team is unsure of what the next should be, what they planned or if someone not a part of the team is running the device and is unsure of how it operates, they can look at this model as a 'guide,' to how the shoulder exoskeleton works.

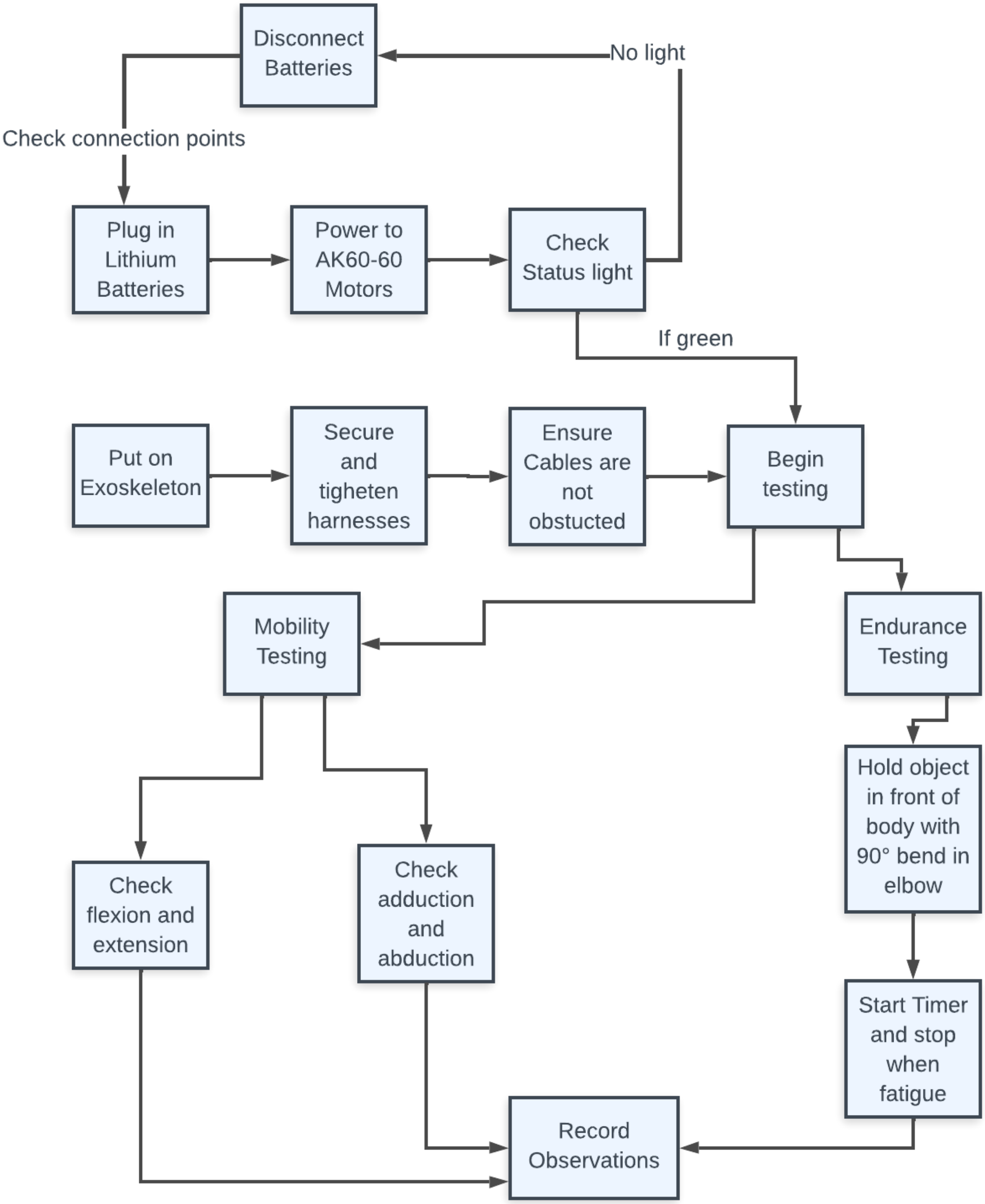
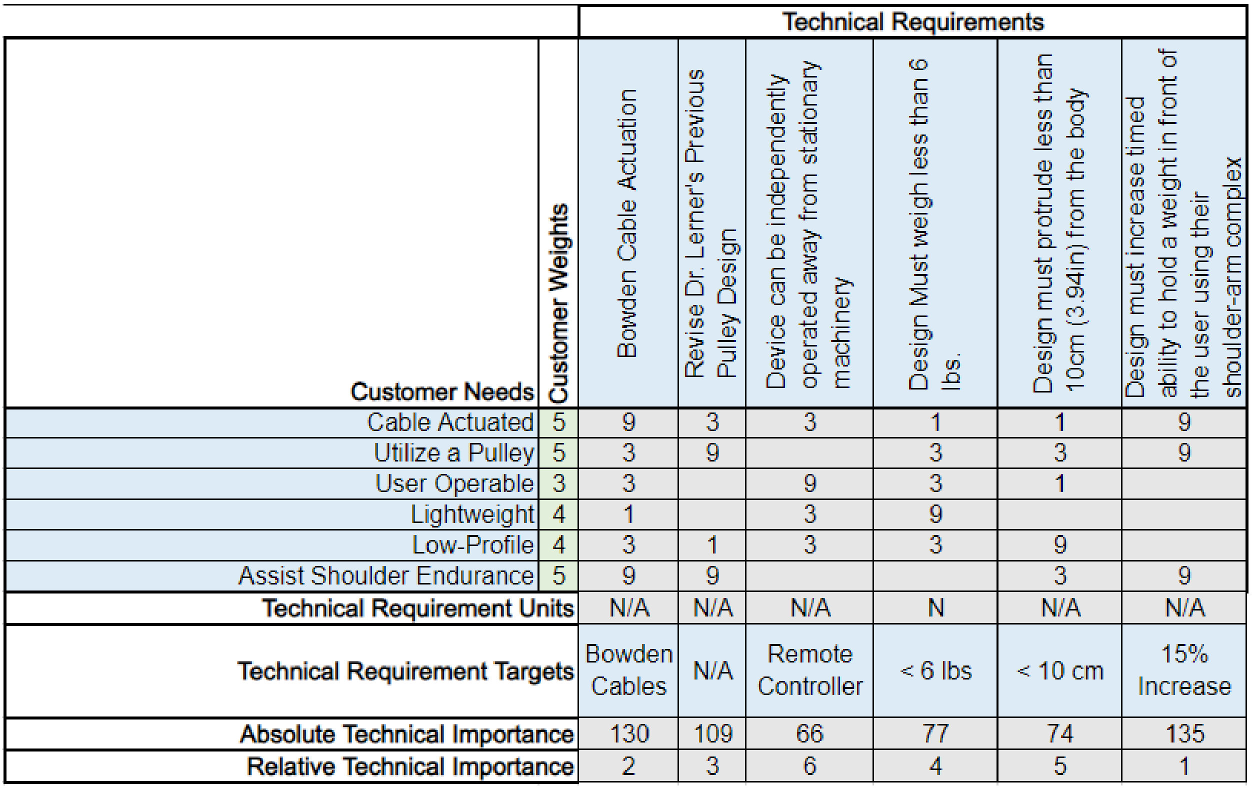


Figure 3: Functional Model

2.4 *House of Quality (HoQ)*

The team created a house of quality (HoQ) to show how the customer requirements relate to the technical requirements. A HoQ is a 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 collectively scored each section as either a 9, 3, 1, or 0 to rank its importance within the project. From an initial meeting with the client, the team found that the most important project aspects for achieving the goal of assisting shoulder endurance is the implementation of a cable actuated system and a pulley mechanism. The team agrees that these components impact the functionality and efficiency of the device the most. Originally, the team wanted to include fail safes for the device such as a kill switch and motor limits, but as the team figured out that the power system design was beyond the scope of this project, the goal to include the fail safes was left alone.

Due to the generation of the HoQ occurring before the team's visit to 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 HoQ gave an initial overview of important design components to focus on which led the team to the next stage of the design process, literature review and benchmarking.



		Technical Requirements					
Customer Needs	**Customer Weights**	Bowden Cable Actuation	Revise Dr. Lerner's Previous Pulley Design	Device can be independently operated away from stationary machinery	Design Must weigh less than 6 lbs.	Design must protrude less than 10cm (3.94in) from the body	Design must increase timed ability to hold a weight in front of the user using their shoulder-arm complex
Cable Actuated	5	9	3	3	1	1	9
Utilize a Pulley	5	3	9		3	3	9
User Operable	3	3		9	3	1	
Lightweight	4	1		3	9		
Low-Profile	4	3	1	3	3	9	
Assist Shoulder Endurance	5	9	9			3	9
Technical Requirement Units		N/A	N/A	N/A	N	N/A	N/A
Technical Requirement Targets		Bowden Cables	N/A	Remote Controller	< 6 lbs	< 10 cm	15% Increase
Absolute Technical Importance		130	109	66	77	74	135
Relative Technical Importance		2	3	6	4	5	1

Figure 4: 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 3. 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 them. 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 to 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 3: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ASNI/AAMI HE 74:2001	Human Factors Design Process for Medical Devices	Helps in the design of how the device with interface with the user in a safe manner.
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 DESIGN SPACE RESEARCH

The following section includes the literature review performed by the team and the benchmarking of existing designs. The team found 3 existing exoskeletons to compare their concept generation to and determine the feasibility of the design. The literature review allows the team to understand how current exoskeletons are functioning and what critical components need to be considered for the design of this shoulder exoskeleton.

3.1 *Literature Review*

From the previous semester, the team felt that the most important exoskeleton components necessary for review were the type of motor used to power the device, the anatomy of the shoulder, back, and arm, the material properties for components considered for the design, the transference of force using Bowden cables, and lastly force coupling in the shoulder. These research topics cover all areas of this project's design requirements. Each of these topics were individually researched by members of the team and the summarized findings are listed below.

The current motor designated for the project is the AK60-6. This lightweight motor produces 80KV which is the number of rpms per supplied volt. Since this project only needs to offer about 15% assistance to the user, the maximum output for this motor is too much for this target. The AK60-6 has plenty of power to reach the 15% assistance target and its design specifications allow the team to meet the lightweight and low-profile design requirements easily. Similar motors from the same company were researched to determine if their capabilities were more fitting to the project than the AK60-6. The AK10-9 and AK70-10 are two motors that output much more power than the current motor. However, they are almost double the weight making them unusable for the team's lightweight design (T-Motor, n.d.) (CubeMars, n.d.) (Robotics, n.d.).

The research on human shoulder, back, and arm anatomy was necessary during the first semester when the team was set on conducting a pull-up test. The anatomy research would help the team understand how the human muscles work and which ones were necessary for augmentation to perform a pull-up. Now, the team has moved on to an endurance test where different muscles are to be used. What remains important is the ball and socket joint that the shoulder utilizes. The mobility of the shoulder is vast and it's due to the two joints of the shoulder. The first being the acromioclavicular joint which connects the scapula to the clavicle. The second is the glenohumeral joint which is the "ball" within the shoulder joint. Correctly replicating these joints with mechanical components has the potential to enhance the strength of the shoulder while retaining the current range of motion. (Orthopedics, n.d.)

The team is determined to design components that can be 3D printed. Normal PLA has inadequate material properties to be used directly in the design. Instead, the team is planning to print their parts out of Onyx or Onyx inlaid with Carbon Fiber. Both printing materials have very high elasticity factors that make them durable and resistant to deformation. The research conducted for this section found that storing and printing the print filaments in different conditions had a big impact on the tensile strength of the material. Printing the material in a dry condition compared to a wet condition had a increase in tensile strength of about 30 MPa. Unfortunately, the client for the project possesses the only available printer for the team that can print Onyx and Carbon Fiber so taking advantage of these printing conditions is unavailable (T-Motor, n.d.) (P. F. Flowers, 2017) (C. Ma, 2021) (A. Aboshio, 2015) (S. Valvez, 2020).

Bowden cables have a unique property to them that the team will benefit from in this project. Bowden cables use a sheath to cover the cable. When a force is applied to the cable, only the cable will move and not the sheath. This allows the team to orient the cable on the user in any direction while still being able to supply the same amount of force without any loss. Although the cable can be placed in any direction, the angle of elevation of the arm will limit the amount of torque applied to the arm. The nature of this project will require assistance to the arm when extended above the head. From an analysis of elevation angle versus torque, the recommended angle for assistance is 90° to 130° and the team will use this recommendation when applying the Bowden cables to the design (Rossini, 2021).

Lastly, it's important for the team to understand the complex motion of the shoulder. Force coupling is used in human anatomy to resist forces creating motion in the other direction. The upper trapezius and serratus anterior force couple is used to produce an upward rotation of the scapula (shoulder blade) when raising a person's arms. This joint is more complicated and is supported by four major muscles: the serratus anterior, lower trapezius, upper trapezius, and levator scapula. These muscles each act in a different direction on the scapula, which allows for upper rotation of the shoulder blade while keeping the glenoid (shoulder socket) in proper positioning (L. E. Osgood, 3.2 Couples). To maintain shoulder stability when raising the arm to the side, the serratus anterior and lower trapezius act as the primary stabilizers (L. E. Osgood, 3.2 Couples).

The team will use all the above information to implement mechanical components into the exoskeleton design to efficiently assist the shoulder-arm complex.

3.2 *Benchmarking*

Benchmarking is the process of measuring the performance of different companies' products, and in the case of this report, benchmarking was used to compare the various state-of-the-art exoskeleton systems specifically designed for shoulder improvement. The team was given a dissertation by Dr. Lerner at the beginning of the project about the MyoShirt where he stated that that design is what the team should improve upon. With the MyoShirt as the baseline design, the team researched 3 other designs that were similar but different enough to provide the team with various ideas and options. Dr. Lerner's initial idea for the project was to create an altered version of the MyoShirt that was portable, lightweight, and low-profile to aid those with shoulder stability impairments.

3.2.1 System Level Benchmarking

After researching state of the art versions of upper body exoskeletons the team selected their top 3 exoskeleton devices to compare the MyoShirt to. The designs were selected because they best fit the previously stated design requirements for the project. Each design will be discussed in detail throughout the sections below.

3.2.1.1 Existing Design #1: ETH Zurich's MyoShirt

The MyoShirt is the current model that the team aims to improve upon. The system involves a soft wearable robotic suit that assists the user with upper limb use in daily life. The goal of the MyoShirt was to improve the mobility of the shoulder for those that have shoulder impairments. The suit is a textile-based assistive device, meaning that it can be worn without any changes to the user's outfit. The bulk of the weight from the MyoShirt, including the motors and batteries, are located off the shirt and are in what ETH Zurich calls 'the box'. Additionally, the MyoShirt can sense the users' movements and can respond intuitively by assisting the user in whatever direction they were trying to move in. Lastly, the MyoShirt stabilizes the shoulder as it engages in movement. The shirt resists the effects of gravity and having only one motor per arm, the suit can support multiarticular movements such as reaching and grabbing (Lab).

The MyoShirt relates to the customer requirements exactly. First off, the MyoShirt is super lightweight, which is one of the main requirements for the team. Going off the lightweight feature of the MyoShirt, it is also very slim and does not protrude far off the user. On top of this, the MyoShirt is a cable-driven system using Bowden cables, which is another requirement for this project. Lastly, the MyoShirt provides extra stabilization to the shoulder joint, which is something the team is striving towards. Below is a photograph of the MyoShirt (Lab).

Figure 5: MyoShirt

3.2.1.2 Existing Design #2: CAREX; a cable-driven arm exoskeleton for neural rehabilitation

Like the MyoShirt the CAREX exoskeleton is an upper arm cable-driven system that aims to aid in shoulder rehabilitation and stabilization. The CAREX exoskeleton also uses a battery and motor system located off the user, but instead of having a box hold all the electronics off to the side, the CAREX uses a system of tracks located on the ceiling. This system allows the user to move around without having the feeling of a cable dragging behind them. Although a very good idea it is not something that the team wishes to improve upon (Design of a cable driven arm exoskeleton (CAREX) for neural rehabilitation, 2012) (Y. Mao, 2015).

The thing that separates the CAREX suit from the MyoShirt is that it does not use a fabric system but rather a cuffing system at each of the major joints in the arm (i.e., the shoulder, elbow, and wrist). The team really liked this idea of a cuffing system and including a soft fabric-like cuff that sits above the elbow is a design that would benefit the team on their design. Below is an image depicting the cuffing described above (Design of a cable driven arm exoskeleton (CAREX) for neural rehabilitation, 2012).

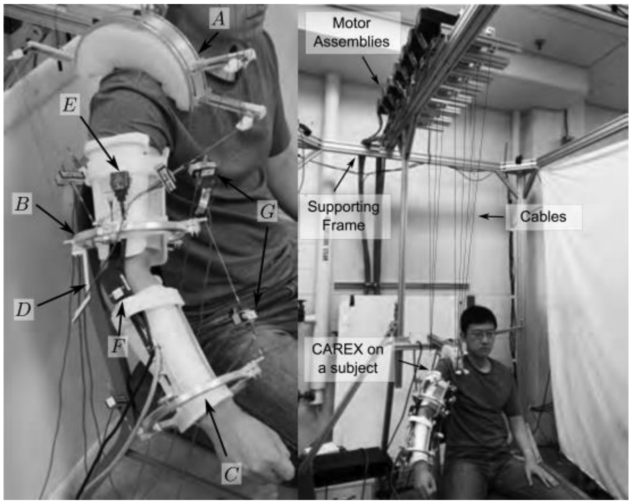


Figure 6: CAREX Cuff System

3.2.1.3 Existing Design #3: SAM: a 7-DOF portable arm exoskeleton with local joint control

The SAM or Sensoric Arm Master is a fully portable exoskeleton with sensors to help aid in the user's movement. The SAM has integrated local joint control, meaning each cuff or joint has its own motor coupled with a sable capstan and gearbox. This design helps improve the overall performance of the device, but at the cost of a high weight. The goal for the team is to have a system that weighs less than 6 lbs., and the SAM device comes with a total weight of 13.23lbs. On top of this increase in weight, most of the mass is located at the shoulder, specifically around 65% of the total weight. While the SAM is the first fully portable device looked at by the team, the additional stress that the additional weight will cause to the user is something that the team is not interested in. With that being said, the SAM does provide the team with some insight on how to make a fully portable device (Rossini, 2021). Below is a diagram showcasing a model of the SAM.

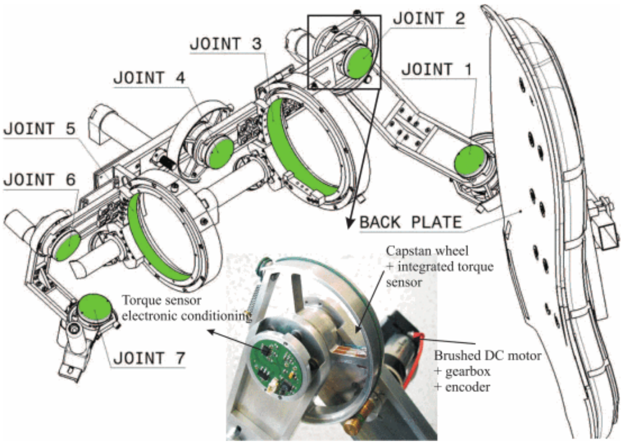


Figure 7: Sensoric Arm Master

3.2.2 Subsystem Level Benchmarking

Arm exoskeletons are complex devices and the design that the team is striving for is no exception. To make things much easier to understand and interpret, the team has decided to break up the main system into three separate subassemblies, which are as follows: the motor location and mounting, the cable routing, and the anchor points along the arm. Each subsystem will be discussed in greater detail below.

3.2.2.1 Subsystem #1: Motor Location and Mounting

The location of the motor assembly is going to prove to be crucial for the overall effectiveness of the design. Having a motor location that is either too low on the back or too high may cause cable routing issues, safety concerns, or comfortability issues. The team is striving to create an exoskeleton that not only works but is also fully portable and low-profile, so having motors lay flush and comfortably along the body is critical. The motor location and mounting process for each existing design will be discussed below.

3.2.2.1.1 Existing Design #1: MyoShirt

The box that the MyoShirt uses is where all the motor and electrical components sit, therefore the shirt is so lightweight and comfortable to wear. The box is not something that the team wants to pursue when determining the motor mounts and location because it goes against the portability requirement for the design.

3.2.2.1.2 Existing Design #2: CAREX

Like the MyoShirt the CAREX uses a motor assembly that sits above the user along a track. While more portable than the MyoShirt, the team still does not want to pursue this idea for the motor mounts and location. The location for the motors is just not what the team had in mind and does not provide that much additional information and aid to the team and their requirements and goals.

3.2.2.1.3 Existing Design #3: SAM Exoskeleton

The SAM is the only existing design that is fully portable so the way that the motors are mounted, and their location was very intriguing to the team. After careful inspection and consideration, the team does want to move forward with this idea but wants to make some changes to it to better fit their goals, requirements, and design specifications. While this SAM system does meet the team’s requirement of being fully portable, it does not meet the requirement of being slim and not protruding more than ten centimeters off the body. To improve the design to better meet the team’s needs, instead of attaching the motors at each joint, the team wants to run cables from the elbow and shoulder joints down the back to the low back where the motors and electrical components will be stored.

3.2.2.2 Subsystem #2: Cable Routing

Having simple yet effective cable routing is critical for overall success. The cables that attach the motor to the actual arm need to be routed in such a manner that it is safe for the user, and it allows for a full range of motion. The cables need to be routed so they help the operator's movement and do not hinder it. The best way to accomplish this task is to go simpler rather than more complex. The team is striving to use just one cable system per arm. This will allow for the most natural movement possible without ‘over-doing,’ it. Below are a few existing designs that route their cables in such a way that is explained above.

3.2.2.2.1 Existing Design #1: MyoShirt

The MyoShirt is extremely sleek and slim, there is almost no protrusion coming off the body. The. The user of the MyoShirt is basically hardwired to a computer. While the shirt is far more comfortable than the other designs presented, the cable routing that the MyoShirt has is not something that the team wants to recreate as it goes completely against the customer requirement of making a fully portable design.

3.2.2.2.2 Existing Design #2: CAREX

The CAREX is a more rigid design than that of the MyoShirt, so the user is not nearly as dependent on the location of the motor mounted system. The CAREX also uses an above head track that allows the user to move wherever they want if there is track available. Again, while this design is effective it is not something that the team wants to proceed with because it goes against the customer requirements of having a portable exoskeleton.

3.2.2.2.3 Existing Design #3: SAM Exoskeleton

While the SAM system is fully portable it protrudes much further than the team would like it to. The SAM has its motors attached at each connection point which causes a very bulky final product. One of the customer requirements set for the team was to not let the system exceed more than ten centimeters off the body and the current SAM system would fail this requirement. Although the team does not like the location of each component, they can be easily moved, and the team does want to improve on this design by implementing a system like this but behind the back of the user making the system much more compact.

3.2.2.3 Subsystem #3: Anchor Points

To have a contraction of a muscle it needs to be anchored along the bone; the anchor point is what connects the tendons from the muscles to the bones. Without an anchor point there will be no contraction, this holds true for the exoskeleton design. To accommodate the existing muscles within the human body, the team plans to add slots along each anchor point to give the user extra room to express their movements. These slots will provide the user with additional freedom to move how they please. The team plans to have two of these types of anchor points for each arm, having a total of four for the entire body. Two points located on a cuff just above the elbow joint, like that of the CAREX system above and the other two points resting along the shoulder joint. Along with the motor attachments along the back, the system will prove to be more than stable and safe enough for the user. Below are a few existing examples of these anchor points being used.

3.2.2.3.1 Existing Design #1: MyoShirt

The MyoShirt does not have any real direct anchor points as the other two designs do because it is a more soft and malleable design rather than a rigid one. With that being said, the MyoShirt does have points at which the Bowden cables meet, and these points are the back and elbow. While this design is unique and does work, the team does not wish to pursue this because the soft fabric will not allow for a fully potable system. To have a fully lightweight and portable design the team needs to have some rigid components for the batteries and motors to attach to.

3.2.2.3.2 Existing Design #2: CAREX

The CAREX exoskeleton uses a cuff system as its anchor points. There are cuffs located at the shoulder, lower bicep, and wrist. These locations for anchor points are exactly what the team needs for their design. Although the team does not wish to pursue the cuff system as CAREX did, they do want to use the locations for their slot and sleeve design along the lower bicep and shoulder joints.

3.2.2.3.3 Existing Design #3: SAM Exoskeleton

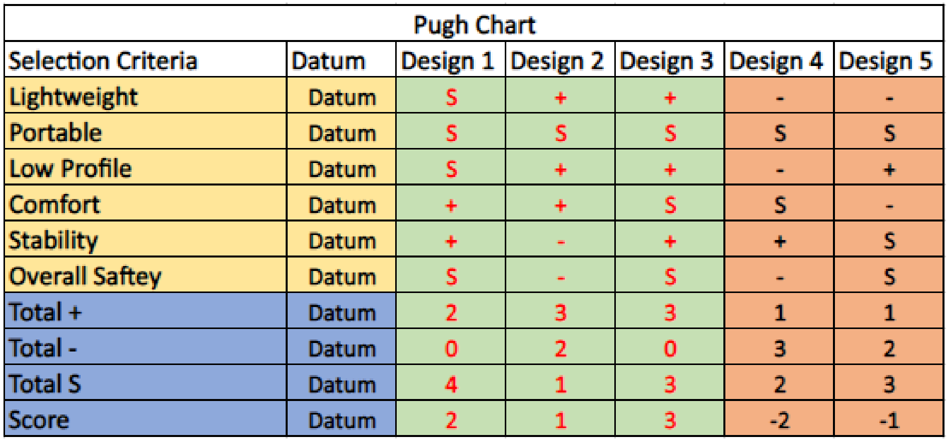
Like the CAREX the SAM system has three anchor points, the difference being on the location. The SAM system has these anchor points located on the biceps, forearm, and the wrist. When it comes to effectiveness and comfort the CAREX system seems to have a better design. Having anchor points along the bicep, especially within a cuff, restricts the movement of the user. Putting the bicep anchor point at a lower region, like the CAREX does which is just above the elbow seems like a better solution. The requirements for the team are to create an exoskeleton that aids in shoulder mobility, so the only anchor point that needs to be considered are those that are along the shoulder itself and the elbow joint. The SAM systems anchor points and locations are something that the team does not wish to pursue.

4 CONCEPT GENERATION

The concept generation discussed in the following sections occurred during the first semester, but the second semester is when the team redefined the customer requirements. The design requirements in the figures are different than the current design requirements, but the team did not update the figures since the original concept generation was developed on the old design requirements.

The team's concept generation was a process that went on for about a week. The team came together with many designs and through discussion chose the first designs to put into a Pugh Chart which is seen in Table 4. The Pugh chart scored only the designs that the team thought best represented the design requirements. The designs that did not meet the initial customer requirements were immediately voted out and were not considered for further design evaluation.

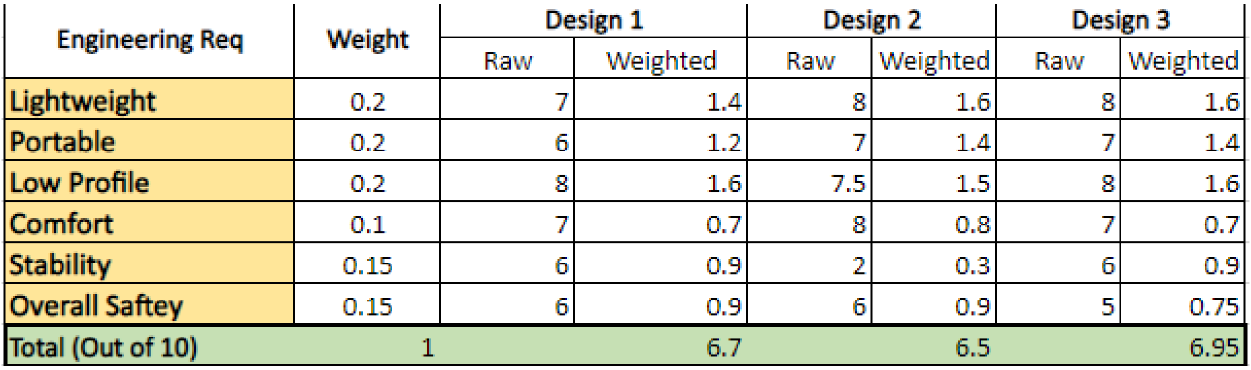
Table 4: Pugh Chart



Pugh Chart						
Selection Criteria	Datum	Design 1	Design 2	Design 3	Design 4	Design 5
Lightweight	Datum	S	+	+	-	-
Portable	Datum	S	S	S	S	S
Low Profile	Datum	S	+	+	-	+
Comfort	Datum	+	+	S	S	-
Stability	Datum	+	-	+	+	S
Overall Saftey	Datum	S	-	S	-	S
Total +	Datum	2	3	3	1	1
Total -	Datum	0	2	0	3	2
Total S	Datum	4	1	3	2	3
Score	Datum	2	1	3	-2	-1

From the Pugh Chart the team decided that designs 1, 2 and 3 were the best as seen from their total score. These designs were then put into a decision matrix which evaluated the designs on individual components instead of general components. Seen above in Table 5: Decision Matrix is

Table 5: Decision Matrix



Engineering Req	Weight	Design 1		Design 2		Design 3	
		Raw	Weighted	Raw	Weighted	Raw	Weighted
Lightweight	0.2	7	1.4	8	1.6	8	1.6
Portable	0.2	6	1.2	7	1.4	7	1.4
Low Profile	0.2	8	1.6	7.5	1.5	8	1.6
Comfort	0.1	7	0.7	8	0.8	7	0.7
Stability	0.15	6	0.9	2	0.3	6	0.9
Overall Saftey	0.15	6	0.9	6	0.9	5	0.75
Total (Out of 10)	1		6.7		6.5		6.95

the decision matrix that the team created to evaluate the remaining designs and choose a final one.

The design that was chosen from the decision matrix was design 3. All the designs evaluated in the decision matrix are listed below with the selected design being labeled in Figure 8 as “final design”. After the team selected their design from the decision matrix, they discussed it with the client. Although this design is not entirely what the client was looking for, the guidance he offered the team led them to what is now the “final design”. This design includes a chest harness for mounting motors, uses the existing chain drive system provided by the lab, and uses an anchor point on the upper arm to assist with the planar motion as requested by the client.

4.1 *Full System Concepts*

Below is a review of the designs entered into the decision matrix with a description of each and why it was scored the way they were. The final design created after speaking with the client is presented here with a reason as to why it is better than the design selected from the decision matrix.

4.1.3 Full System Design #1: Shoulder Specific Design with Chain Drive

The design shown in Figure 8 is the design that the team came up with after talking to the client about the design that was chosen from the decision matrix and redirected onto a different path. This design will be able to interface with the other suits that the client is currently working on and use the same drive system. Pictured in red is where the motors will mount. The motor uses a chain that mounts onto a Bowden cable which is seen in blue. The chain allows the motor to apply 2 directions of force which allows the design to apply force in two directions. This will allow the Bowden cable to assist and lift as well as lowering the arm of the person wearing the suit. A negative to this design is the mounting situation. The team will have to mount two different motor-chain interfaces on the back which will make it hard to stay under the weight requirement given for this project, however, the client has stated that the weight can be surpassed if needed for prototyping purposes.

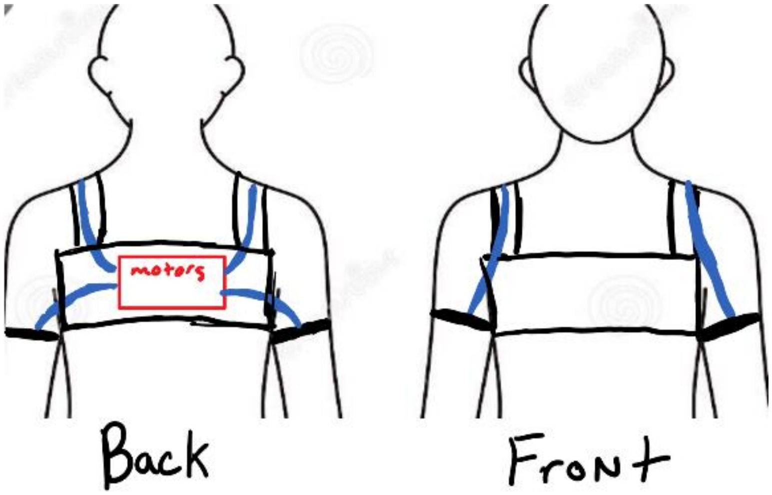


Figure 8: Final Design

4.1.4 Full System Design #2: Single Arm Winch

This design is seen in the design matrix as ‘Design 1’. This was created when the team was tasked with making a design for the whole arm which was before the client meeting which gave us redirection. Pictured in black is the vest which the motors and the pully assembly mounts to. This design has BOA hubs for the ability to resize which is a big pro for this design. A con is the fact that this would be much more difficult to convert into a two-arm design with geometry.

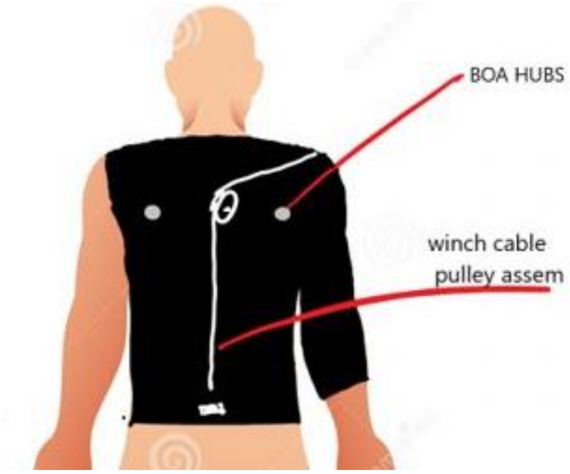


Figure 9: Original Design 1

4.1.5 Full System Design #3: Dual Shoulder-Mounted Motors

This next design is seen as ‘Design 2’ in the design matrix which was the lowest scoring design from the original concept generation. This design has two motors mounted at each shoulder which would be able to coil each arm separately. This design was made for full arm assistance not just assistance for the shoulder. This means that this design would interfere with what we are trying to interface with. Pros to this design are the fact that the mounting on the back is very simple and can give different degrees of assistance to either arm. The cons to this design are the weight increase from having two motors mounted to the back of the user and being able to operate the motors separately based on the needs of the user.

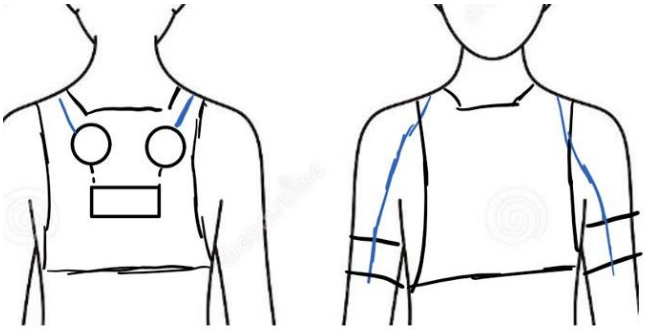


Figure 10: Original Design 2

4.1.6 Full System Design #4: Single Coiling Motor on the Back

This design is seen as 'Design 3' in the design matrix and came out with the highest awarded score among the 3 designs in the design matrix. This design has a single motor mounted on the back with two cables (seen in blue) coiling in opposite directions to pull the arms. The pros to this design were that a single motor greatly reduces the weight of the design, one motor coiling both arms allow us to reduce the complexity of the design as we do not need to code the two motors to move simultaneously. Cons to this design are that one motor may not have the strength required to help the user, and there is no variation in the assistance for different arms.

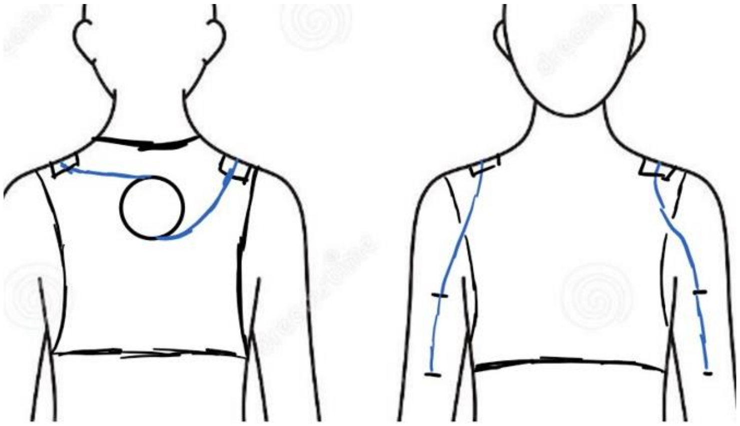


Figure 11: Original Design 3

This is the design brought to the client with the intention of this being the final design. As previously stated, the client wanted to offer more direction as they felt we were misled with what was wanted. The result of this meeting is seen in *Figure 24* with the new final design.

4.2 *Subsystem Concepts*

To create the final design, the team broke the problem into 3 subsystems: The motor mounting, the arm mounting, and the cable routing. These are the 3 main components that must go into the design for it to work properly.

4.2.3 Subsystem #1: Arm Mounting

One of the main subsystems is arm mounting. This determines how the Bowden cables will mount onto the arm. There were two designs that the team was going back and forth on.

4.2.3.1 Design #1: Tube Arm Mount with horizontal Track

This first design is like a flexible, rigid tube that will be placed onto the arm which will give the Bowden cables a surface to mount to. As seen in the below figure the tube will have a rail which will keep the force acting in the correct plane as to move the arm vertically in the plane perpendicular to the body.

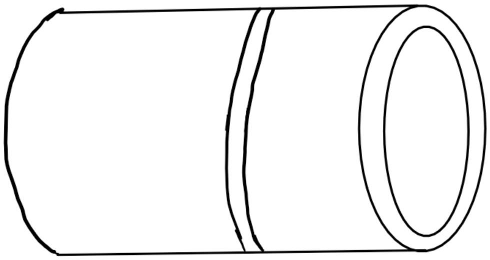


Figure 12: Arm Mounting Design 1

This design has the advantage of being rigid enough as to where great force can be exerted, and this arm mounting design will be able to withstand the force being exerted. The groove in the center is used for mounting the Bowden cable with a track what will allow the cable to self-correct when the user turns their arm. This means no matter what orientation the user's arm is in the force will be applied vertically. A con to this design is the bulkiness and lack of adjustability between users. This specific design will not be able to be adjusted for someone with a larger or smaller arm meaning that a new arm mount will have to be made for different users.

4.2.3.2 Design #2: Adjustable Arm Mount

Design 2 used a similar design for mounting the Bowden cables with a mounting strap seen in blue. The Bowden cable will attach to this and be able to self-orient like design 1. Where this design differs is the actual mounting system on the arm. This design is like a strap that can be adjusted around the arm using Velcro like a blood pressure arm cuff where the strap can be changed based on the size of the user's arm. The pros to this system are the self-orienting Bowden cable attachment, and the adjustability for users with different arm sizes. However, this leads to the cons as the arm mount is not made from a rigid material. This gives it adjustability but takes away some of the stability and subsequently this design will not be able to withstand the same forces as design 1.

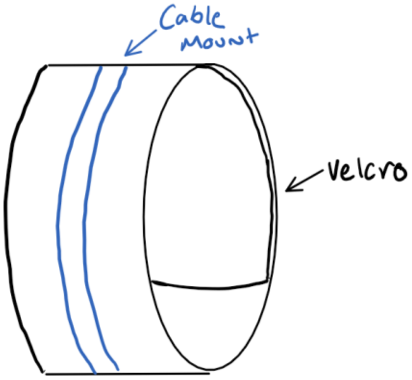


Figure 13: Velcro-Based Arm Mount with Self-Orienting Cable Attachment

4.2.4 Subsystem #2: Cable Routing

Cable routing is another subsystem that we have made a subsystem. This is one of the most important aspects of the design as it determines how force is transferred from the motor to the arm.

4.2.4.1 Design #1: Over Shoulder Cable Routing

The main design that we made is having 2 Bowden cables per arm. One cable for movement up and another for downward movement. Having the cable anchored at the top of the shoulder will give the arm the moment required to help lift the arm up. The trouble with this is making sure that the top of the arm is receiving enough force to adequately assist with upward movement. That would be a con to this design. It will be more difficult on the motor to lift the arm from this configuration. A pro to this is the simplicity in mounting the Bowden cables as they are directly connected to the mount on the arm.

4.2.4.2 Design #2: Force Transfer Over Shoulder

A second design for the cable routing includes a transfer system to help transfer some of the force to adequately lift the arm. This will act as a lever to help transfer the pull from the motor to the mount on the arm. A con of this design is that this will protrude more than allowed in the requirements if done incorrectly. This will also make everyday movement more cumbersome as this will get caught on hair, clothes, and any similar objects. The green in the figure below is the cable coming from the motor, while the red is that cable mounting to the arm.

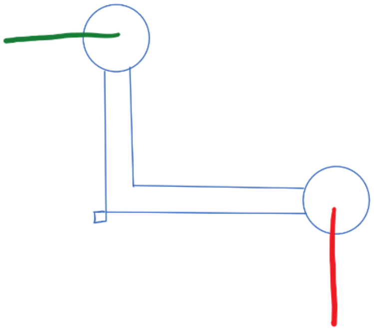


Figure 14: Lever for Transferring Force to Arm

4.2.4.3 Design #3: Under Arm Cable Mounting

The last design for this subsystem is the under-arm cable mounting. The specification of the revised design needs assistance while lifting and lowering the arm. This is where the under-arm mounting comes in. The motor is interfaced with the chain and Bowden cables for a force in two directions, this second direction will be mounted under the arm and onto the same arm mount which will be able to pull the arm down along with keeping the cable properly oriented.

4.2.5 Subsystem #3: Motor Mounting

The last subsystem that we defined was the motor mounting which completes the three main components of the design. It has already been discussed that we will be using a motor-cable interface that the client has already made to simplify the number of parts needed in their total project. This is just discussing how we would mount the motor assembly on the back.

4.2.5.1 Design #1: Belt Attachment for the Motors

The first design that was talked about is using a belt made of leather around the chest which will give the motor an appropriate place to mount and a rigid base to exert force from. The pros to this include being very lightweight as all that will be needed is the belt to mount, another pro is a belt offers a stable base for mounting and operating the motors. The cons of this would be restricting the breathing of the user, the belt is not a flexible material meaning if tightened the user may not be able to expand their chest to breath or it will be significantly harder. A second con is the possibility of the belt to slide down the body while in use. Without shoulder straps the belt may fall which could possibly hurt the user or break the motors.

4.2.5.2 Design #2: Posture Corrector for Motor Mount

The other design that we had for motor mounts would be using something like a posture corrector. Pros to this design are having a common geometry for the shoulders and back. A posture corrector will correct the geometry of the back and shoulders of people of all sizes meaning we can design to the consistent geometry the design will have more consistency with people of different sizes. The posture corrector will also provide a stable place for the motors to mount and pull from. The cons are that we would have to design a posture corrector that can be sized to multiple people with different body types or buy one online which we would then have to design a motor mount to work specifically with that design. Both cons can be worked around and will have to be discussed further with the client.

5 DESIGN SELECTED – First Semester

The goal of this project is to design and manufacture a device to actuate shoulder movement. The project client is currently working on an elbow exoskeleton for muscular assistance for everything below the elbow. The device engineered in this project should be able to seamlessly integrate into the existing elbow design. 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.

Design Description

The following sections show the engineering process behind the Arm Exoskeletons current design and where this design will progress to 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. The figure presented below shows the preliminary design.

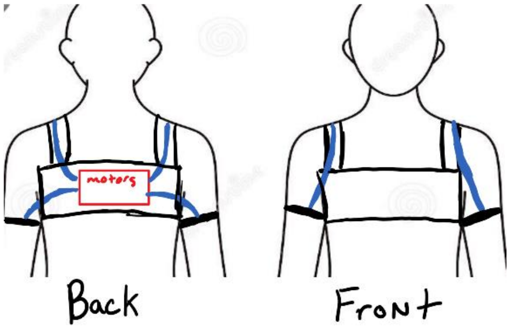


Figure 15: First Design Iteration

One of the fundamental drawbacks to this design was its use of non-standard parts within the Biomechatronic 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 below.

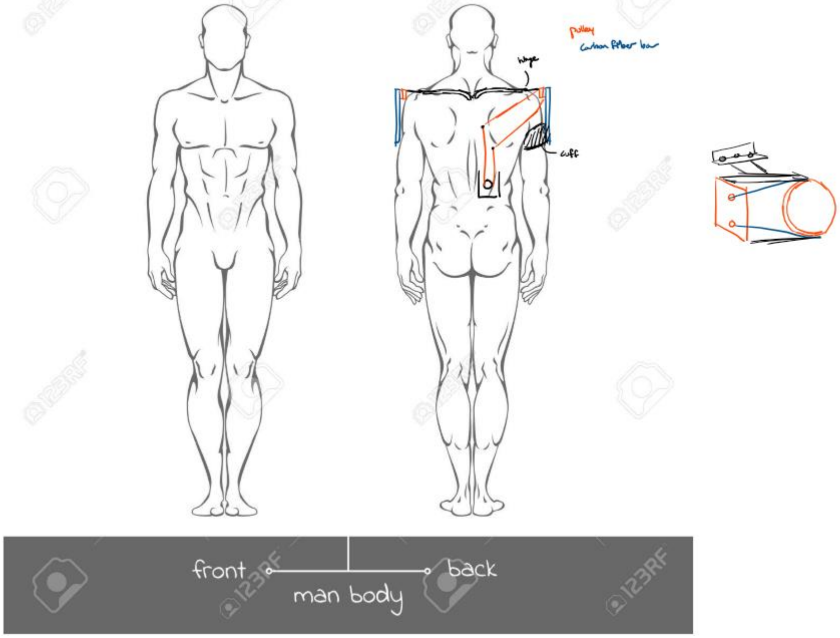


Figure 16: Second Design Iteration

The Final approved design corrects many of the 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 Biomechatronic lab. This allows for easier adaptation of the design into the existing devices within the mechatronics lab, while also providing 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. During the first semester the pulley was going to directly interface into the upper bicep structure of Dr. Lerner’s elbow exo-muscle using a custom lever arm. The idea behind this was to effectively eliminate the need for any bicep mounting cuff as the exo-elbow design has the cuff included. A figure of this elbow design can be seen below. Later, this idea was abandoned, but the idea and goal were to effectively simplify the designs and lower the component list allowing for significant weight reduction with both designs assembled and worn. The shoulder exo-muscle will no longer be interacting directly with the arm itself and rather with the secondary device. However, for the purpose of testing this feature the upper half of the elbow exo-muscle with be used to simulate the integrated designs.

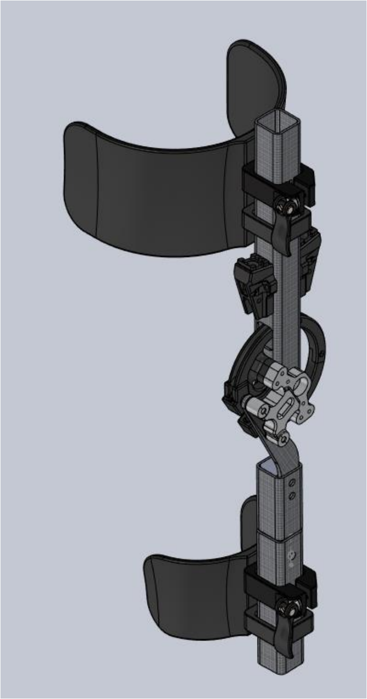


Figure 17: Biomechatronics Lab Elbow Design

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 shoulder exoskeleton 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 user's 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 user's back. These forces will be transferred 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 aids 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 below.

Figure 18: Example Harness (3M Science Applied to Life, n.d.)

A harness that attaches around the legs provides adequate resistance against the tensional force that is 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 Fall 2022 Prototype

-See Appendix A for all sketches of the 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 discuss 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 device's form factor as well as the device's 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 are listed in Table 6.

Table 6: Analysis Assumptions

Variable	Value
Length: L	90mm
Thickness: t	2.67mm
Height: h	19mm
Onyx Flexural Modulus: E	51GPa
Pulley Moment: M	8.5Nm

$$I_y = \frac{ht^3}{12}$$

Equation 1: Moment of Inertia

$$F = M/L$$

Equation 2: Resultant Force

$$\delta = \frac{FL^3}{3EI}$$

Equation 3: Cantilever Beam Deflection

Using the dimensions from Table 6, the moment of inertia is 30.13mm^4 and the force on the beam is 94.4N. From Equation 3, the final deflection of the beam is equal to 14.9mm downwards. In English units this is .58in. This result seems to be deflecting too much which can be an issue for the design, but Onyx is very flexible so the component won't necessarily break, but it could create discomfort on the user's arm. This much bending may not make the bar rigid enough to cause movement on the user's arm.

Using the equations above but changing the beam thickness to 12mm from 2.67mm (.47in from .1in), the moment of inertia becomes 2736mm^4. If all other factors remain the same the deflection of the beam becomes .164mm downwards which is roughly .006in. This slight increase completely changes the amount of bending that the beam will experience. This is what the team wants for the design. If the deflection becomes so small that it can be negligible then the safeness of the device is immensely greater since the part has a very low chance of breaking.

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 N/m.

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 produces must be integrated 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 in the figure below is the adapted lever arm the team was planning to use.

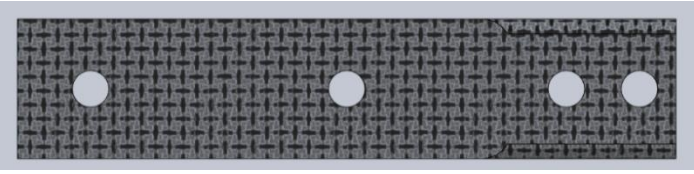


Figure 19: CAD Adaptation for Integration

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 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 designs 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 (Physiopedia, n.d.) (Physiopedia, n.d.).

For the motor to deliver the maximum assistance to the shoulder, the cables and pully must work in 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.

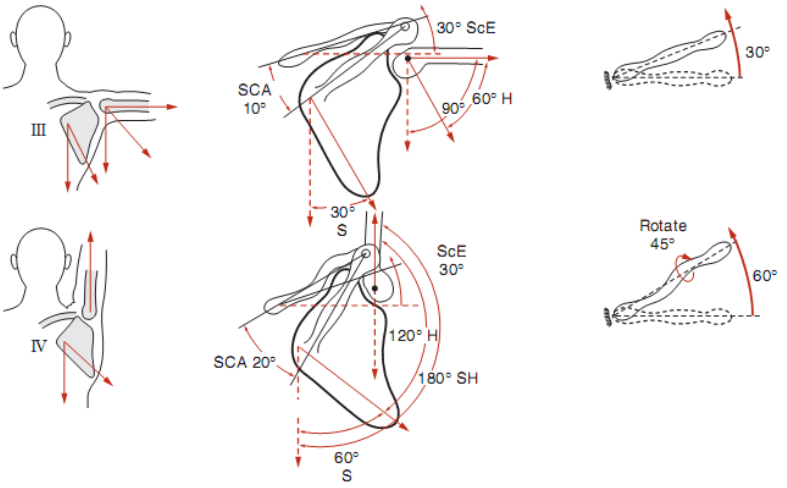


Figure 20: Scapulohumeral Rhythm of the Shoulder (Garofalo, 2009)

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 using 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 out when it has been decided that fitment, comfort, and functionality have 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 specialized equipment needed to manufacture carbon fiber and Onyx printed parts. The team has also foreseen the possibility that key parts may need 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 accept 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. The chart below shows the Spring semester plan.

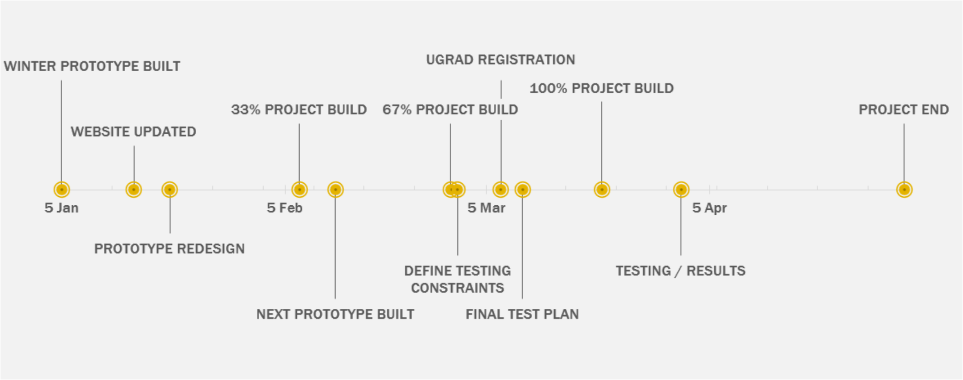


Figure 21: Timeline

To conclude the Fall 2022 prototyping, two SOLIDWORKS assemblies of the final prototype for the semester, one with an exploded view and one without, will be provided below.

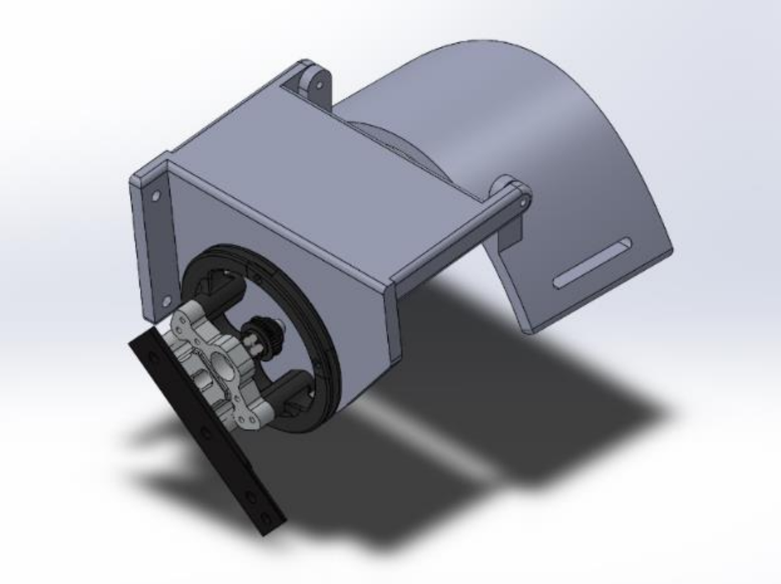


Figure 22: First Prototype

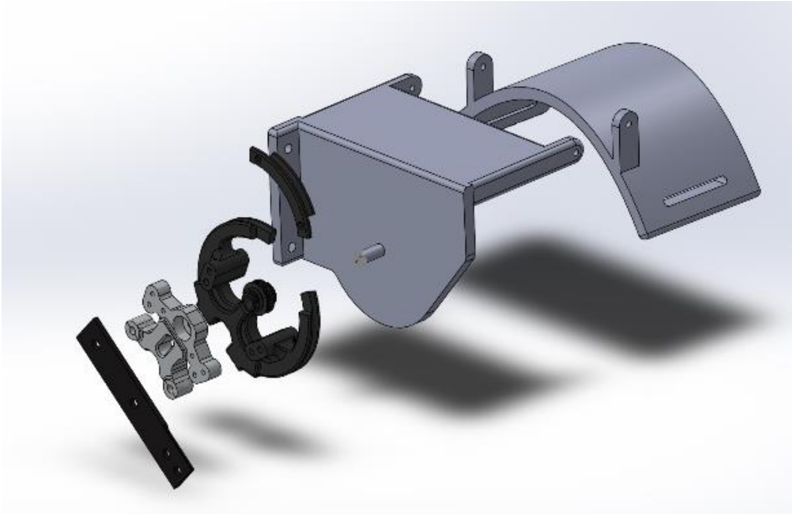
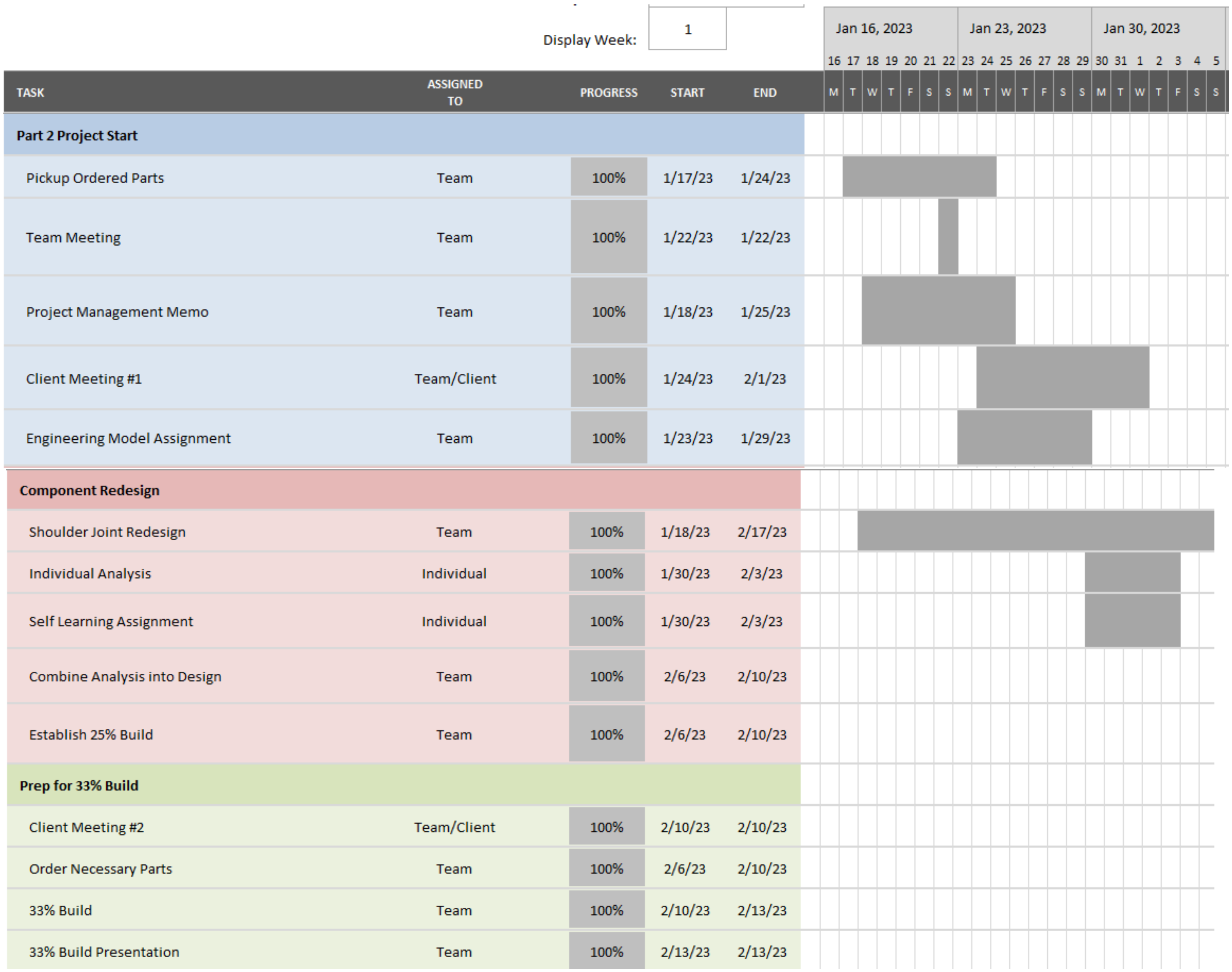


Figure 23: First Prototype Exploded View

6 Project Management – Second Semester

6.1 *Gantt Chart*

The team planned out the second semester according to the hardware status updates. 3 updates were used throughout the semester where the team was required to have 33%, 67%, and 100% of their build finished by a certain deadline. Figure X displays the start of the second semester up to the 33% build. In this timeline, the team tried to meet with their client as often as possible to present the most current design iteration. The team initially planned for the 33% build to be the heaviest in design iteration and the following builds to be slight revisions, but that's not how this semester played out. The team was able to meet their 33% build but felt that the prototype they

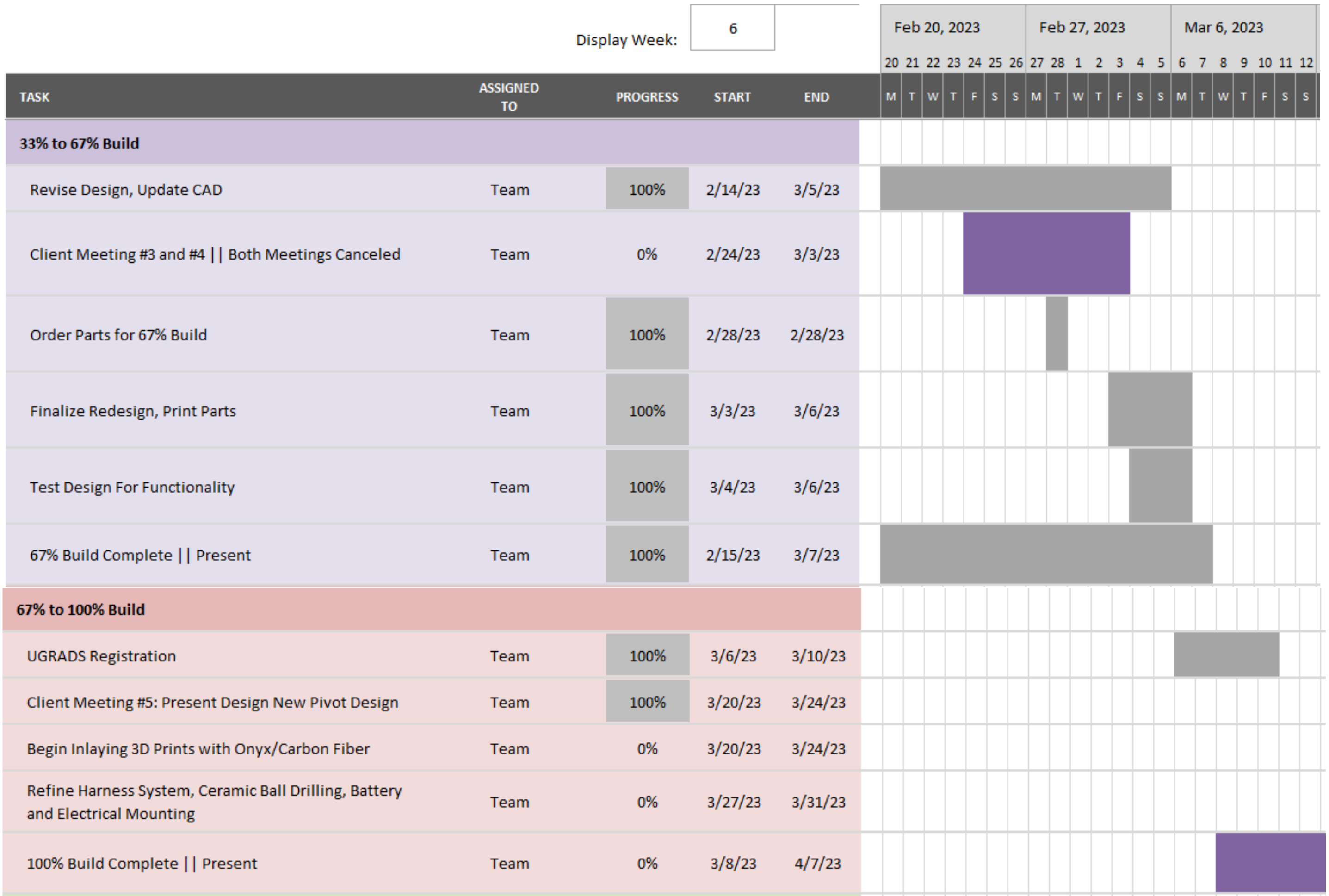


TASK	ASSIGNED TO	PROGRESS	START	END
Part 2 Project Start				
Pickup Ordered Parts	Team	100%	1/17/23	1/24/23
Team Meeting	Team	100%	1/22/23	1/22/23
Project Management Memo	Team	100%	1/18/23	1/25/23
Client Meeting #1	Team/Client	100%	1/24/23	2/1/23
Engineering Model Assignment	Team	100%	1/23/23	1/29/23
Component Redesign				
Shoulder Joint Redesign	Team	100%	1/18/23	2/17/23
Individual Analysis	Individual	100%	1/30/23	2/3/23
Self Learning Assignment	Individual	100%	1/30/23	2/3/23
Combine Analysis into Design	Team	100%	2/6/23	2/10/23
Establish 25% Build	Team	100%	2/6/23	2/10/23
Prep for 33% Build				
Client Meeting #2	Team/Client	100%	2/10/23	2/10/23
Order Necessary Parts	Team	100%	2/6/23	2/10/23
33% Build	Team	100%	2/10/23	2/13/23
33% Build Presentation	Team	100%	2/13/23	2/13/23

Figure 24: Gantt Chart 33% Timeline

delivered was not up to the standards that the team would have liked.

Figure 24 is from the 33% build to the 67% build. In this phase, the team began feeling behind schedule due to the amount of design iterations they were performing. At this point, there was no clear design being focused on and multiple major components were being changed within each iteration.



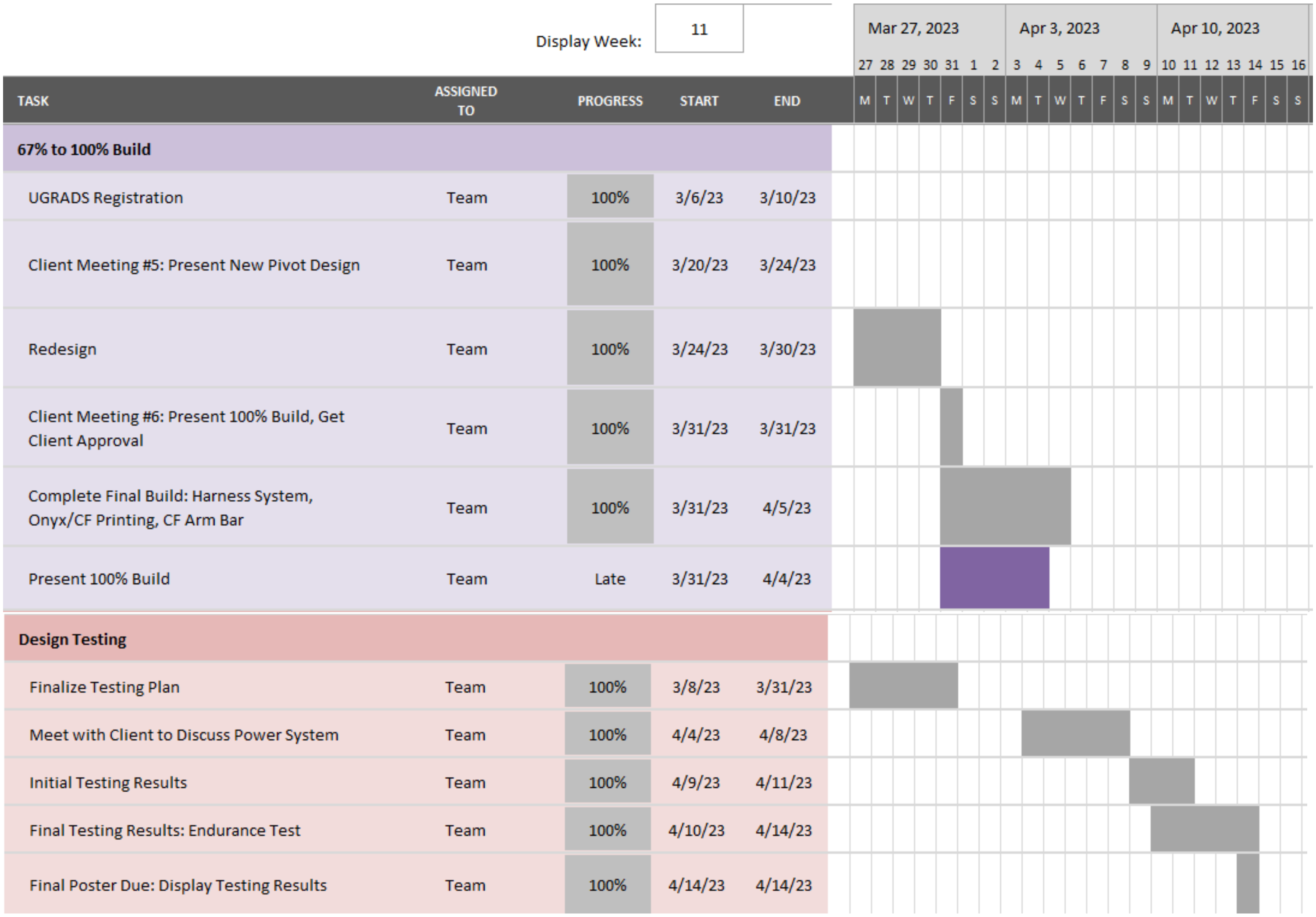
Display Week: 6

TASK	ASSIGNED TO	PROGRESS	START	END
33% to 67% Build				
Revise Design, Update CAD	Team	100%	2/14/23	3/5/23
Client Meeting #3 and #4 || Both Meetings Canceled	Team	0%	2/24/23	3/3/23
Order Parts for 67% Build	Team	100%	2/28/23	2/28/23
Finalize Redesign, Print Parts	Team	100%	3/3/23	3/6/23
Test Design For Functionality	Team	100%	3/4/23	3/6/23
67% Build Complete || Present	Team	100%	2/15/23	3/7/23
67% to 100% Build				
UGRADS Registration	Team	100%	3/6/23	3/10/23
Client Meeting #5: Present Design New Pivot Design	Team	100%	3/20/23	3/24/23
Begin Inlaying 3D Prints with Onyx/Carbon Fiber	Team	0%	3/20/23	3/24/23
Refine Harness System, Ceramic Ball Drilling, Battery and Electrical Mounting	Team	0%	3/27/23	3/31/23
100% Build Complete || Present	Team	0%	3/8/23	4/7/23

Figure 25: Gantt Chart 67% Timeline

Included in this timeline of the project were the plans for the 67% to 100%. The 67% prototype strayed away from the design requirements the team should have been focusing on. Although it was a feasible concept that the team was very excited to move forward with, the client explained that it did not meet the customer requirements and that he would like to see the design use a pulley along with some other changes. This is the point in the project where the customer requirements were refined from the first semester to what they are now.

The team was very behind entering the 67% to 100% build phase. Multiple design iterations were performed during this phase and multiple times the team got denied approval of the design. Closer to the 100% presentation due date is when the team was able to fulfill the customer requirements with their proposed design and they gained client approval. The team was late on the 100% presentation due date since they were waiting for their final 3D printed components to



Display Week: 11

Mar 27, 2023 | Apr 3, 2023 | Apr 10, 2023

TASK	ASSIGNED TO	PROGRESS	START	END
67% to 100% Build				
UGRADS Registration	Team	100%	3/6/23	3/10/23
Client Meeting #5: Present New Pivot Design	Team	100%	3/20/23	3/24/23
Redesign	Team	100%	3/24/23	3/30/23
Client Meeting #6: Present 100% Build, Get Client Approval	Team	100%	3/31/23	3/31/23
Complete Final Build: Harness System, Onyx/CF Printing, CF Arm Bar	Team	100%	3/31/23	4/5/23
Present 100% Build	Team	Late	3/31/23	4/4/23
Design Testing				
Finalize Testing Plan	Team	100%	3/8/23	3/31/23
Meet with Client to Discuss Power System	Team	100%	4/4/23	4/8/23
Initial Testing Results	Team	100%	4/9/23	4/11/23
Final Testing Results: Endurance Test	Team	100%	4/10/23	4/14/23
Final Poster Due: Display Testing Results	Team	100%	4/14/23	4/14/23

Figure 26: Gant ChartFigure 27: Gant Chart 100% Timeline

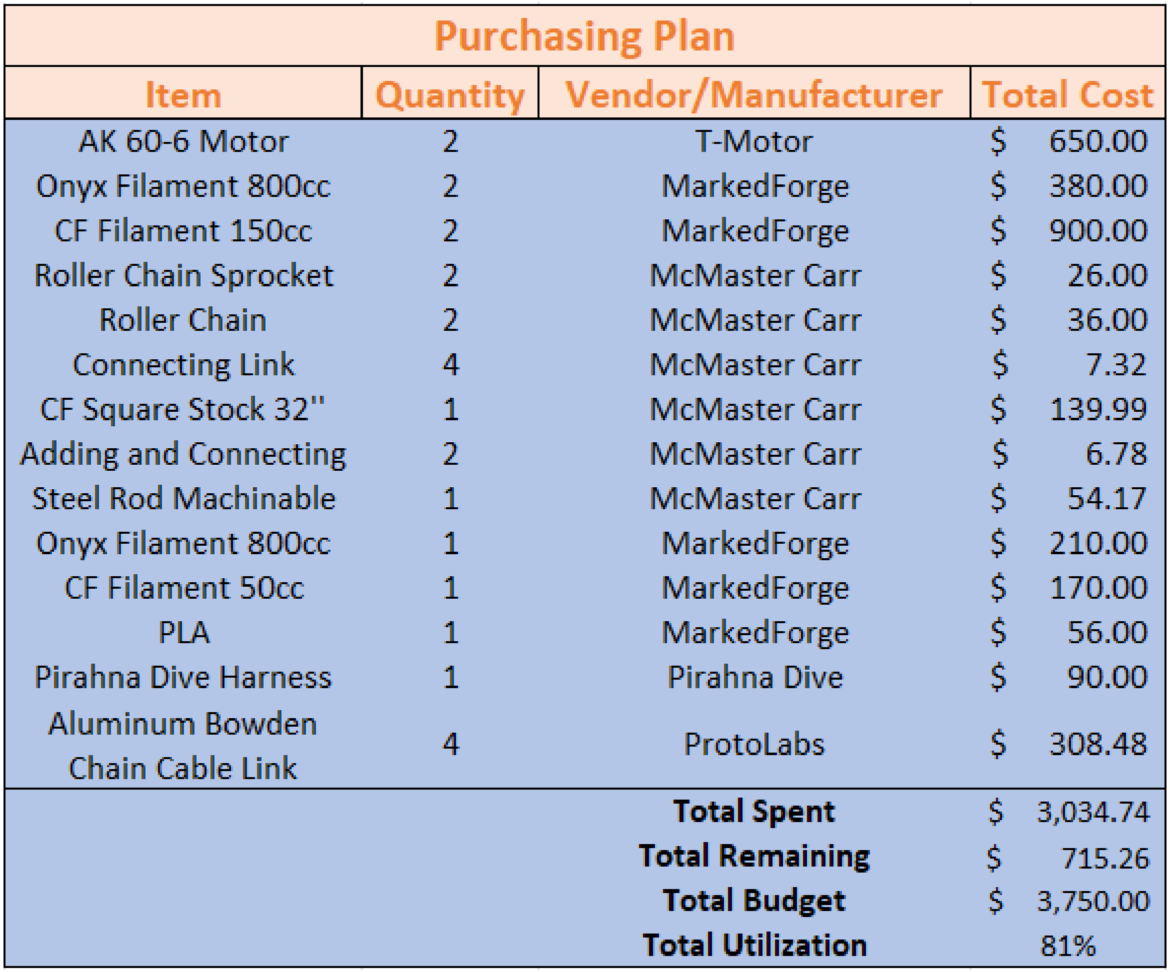
be printed with Onyx. Onyx and Carbon Fiber parts take a longer time to print which hurt the team during this time crunch. The patience paid off though as the team was able to present a quality final exoskeleton design that both the team and the client were proud to have made.

Looking back on the way the team handled the tasks given to them, it would have been better for the team to meet more often with the client and to get direct answers. The team struggled with receiving vague design suggestions from the client that made the team overthink what he was trying to convey. Also, if the team worked harder during the 33% build to ensure their design was on the right track, then they realistically could have been done by the 67% build. The team is not upset at missing a deadline or two because they would rather deliver a quality product than rush it and deliver something that still was unfinished.

6.2 *Purchasing Plan*

The team utilized a high percentage of the budget given for the project. The initial budget utilization prediction from semester 1 was that the final product would use about $2,000 of the total budget. This included a room for emergency parts, testing, etc. The team ended up using $3,034.74 out of the total $3,750 allotted for the project. The highly iterative design process performed by the team accounts for a lot of the purchasing. There was a high anticipation for 3D printing of a lot of components, so the team ordered extra Onyx and Carbon Fiber filaments. Other high-quality parts such as the Carbon Fiber square stock and very small, machined aluminum chain links ate a lot of the budget.

If the team was on track with their design phase they would not have had to utilize as much of the budget, but since there were so many designs changes the team had to act fast to get the necessary parts ordered. There was less time to figure out the exact number of materials necessary, so the team had to make better judgement and order extra in case they ran out.



Purchasing Plan

Item	Quantity	Vendor/Manufacturer	Total Cost
AK 60-6 Motor	2	T-Motor	$ 650.00
Onyx Filament 800cc	2	MarkedForge	$ 380.00
CF Filament 150cc	2	MarkedForge	$ 900.00
Roller Chain Sprocket	2	McMaster Carr	$ 26.00
Roller Chain	2	McMaster Carr	$ 36.00
Connecting Link	4	McMaster Carr	$ 7.32
CF Square Stock 32"	1	McMaster Carr	$ 139.99
Adding and Connecting	2	McMaster Carr	$ 6.78
Steel Rod Machinable	1	McMaster Carr	$ 54.17
Onyx Filament 800cc	1	MarkedForge	$ 210.00
CF Filament 50cc	1	MarkedForge	$ 170.00
PLA	1	MarkedForge	$ 56.00
Pirahna Dive Harness	1	Pirahna Dive	$ 90.00
Aluminum Bowden Chain Cable Link	4	ProtoLabs	$ 308.48
		Total Spent	$ 3,034.74
		Total Remaining	$ 715.26
		Total Budget	$ 3,750.00
		Total Utilization	81%

Figure 28: Purchasing Plan

6.3 *Manufacturing Plan*

The team feels there is no necessary change from the first semester manufacturing plan to the one presented now. All the manufactured parts were free to the team due to who made them. The only parts that were manufactured by the team were the 3D printed parts and the 2 machined parts. All 3D printing was done in house either at the personal printer of a team member or through the printer found in the Biomechatronic lab. The metal parts were machined by team members with purchased materials in the machine shop at NAU. The manufacturing aspect of this project costing the team $0 really helped them remain under budget.

Manufacturing Plan

Item	Quantity	Vendor/Manufacturer		Total Cost
Shoulder Plate	1	Team	3D Print	$0.00
Hinge Plate	1	Team	3D Print	$0.00
Large Pulley	1	Team	3D Print	$0.00
Large Pulley Bridge	1	Team	3D Print	$0.00
Pulley Flat Anchor	1	Team	3D Print	$0.00
Tube Spacer	1	Team	3D Print	$0.00
Bicep Cuff	2	Team	3D Print	$0.00
Bicep Mount Upper	1	Team	3D Print	$0.00
Bicep Mount Lower	1	Team	3D Print	$0.00
Ball Joint Bar	2	Team	3D Print	$0.00
Ball Joint	1	Team	3D Print	$0.00
Pivot Point	1	Team	3D Print	$0.00
Socket Mounting Plate	1	Team	3D Print	$0.00
Corner Hinge	1	Team	3D Print	$0.00
Motor Mount Plate	1	Team	3D Print	$0.00
Motor Mount	3	Team	3D Print	$0.00
Onyx Pulley	1	Team	3D Print	$0.00
Onyx Corner Hinge	1	Team	3D Print	$0.00
Aluminum Shaft	1	Team	Machine Shop	$0.00
Sprocket Shaft Weld	1	Team	Machine Shop	$0.00

Figure 29: Manufacturing Plan

6.4 *Major Changes Applied during Second Semester and Justifications – as needed*

During the spring semester the team applied many major changes to the project with multiple complete redesigns. These redesigns took many different forms. While initially these designs drew inspiration from the prototype that was produced first semester. The design then quickly moved away from a common hinge mechanism and towards replicating an external shoulder joint with the use of a ball joint. Many of these designs were not viable due to their lack of providing necessary torque to the user's arm. Ultimately the team began to take a deeper dive into the joints used in first semester however relocating these joints and eliminating the over shoulder mount for a more stable, comfortable, and ultimately functional design. The following is the process which was taken throughout the second semester and the reasoning behind the decisions that were made.

The first major change that was implemented to the design in second semester was the adaptation of a soft harness to mount the device to the user body. This took the form of a standard posture corrector. The methodology behind this decision was that it would provide a consistent body position for the device to attach to. Much of the device was at this stage held to harness with added strapping which was sewn onto the device or parts that were directly riveted onto the device. The harness was being used for not only mounting points for certain components but also attaching the device to the user's body. The idea of a soft harness provided a comfortable and flexible platform, however, ultimately was flexible during the wrong point in user motion. This allowed for an improper fitment to the user during much of the swing of the arm. Ultimately this harness system was swapped for addition of a rigid back plate.

Throughout the second semester, the project underwent a series of major changes, including complete redesigns. The team initially drew inspiration from the prototype produced during the first semester, but soon realized that a common hinge mechanism was not sufficient for their goals. Instead, the team opted to replicate an external shoulder joint, utilizing a ball joint. However, many of these designs were deemed unfeasible due to their inability to generate the necessary torque to assist the user's arm.

The team ultimately decided to take a closer look at the joints used in the first semester and repositioned them, eliminating the over-shoulder mount in favor of a more stable and comfortable design. To accomplish this, the team implemented a soft harness to mount the device to the user's body, like a standard posture corrector. However, the harness proved too flexible during much of the arm's swing, resulting in improper fitment. The team then a-made the decision to switch to a rigid backplate.

Through research, the team discovered that SCUBA diving backplates are commonly used to mount tanks to divers. The Piranha Dive MFG. dog bone style SCUBA plate was ultimately selected due to its many pre-drilled holes, allowing for easy and rigid mounting of the device. This product also features a specialty harness for secure attachment to the user's body. This new design proved superior to the posture corrector variant and allowed for greater stability and functionality of the device.

The team discovered that rigid attachment points were necessary to prevent losses and allow for efficient translation of tensional forces to the pulley. The SCUBA plate was ultimately selected for its pre-drilled holes and the accompanying specialty harness, providing secure and rigid attachment points for the various components.

During the iterations that followed, the team made several changes to address the issue of losses. These changes are listed in order, beginning with the addition of a ball and socket joint. Although this joint provided a great range of motion, it resulted in significant losses around the pulley. The team then removed the shoulder-mounted joint and opted for a backplate-mounted joint, simplifying the design, and providing a more secure joint relative to the motor's position.

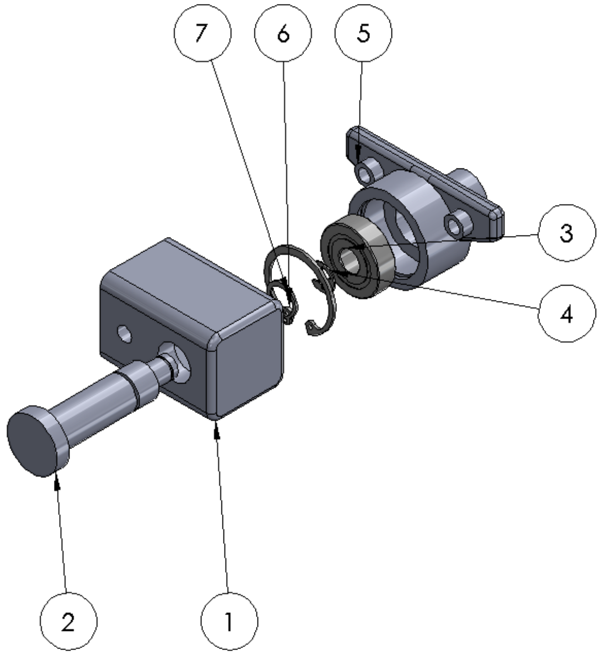
However, this back-mounted joint created problems, as the optimal joint placement was closer to the user's actual shoulder joint to achieve the desired range of motion. To address this issue, the team generated the idea of moving the ball joint to the hip and using a long, thin member - a piece of 5/16" all-thread - to create a highly mobile bar with a pivot point. An ordinary cable was used instead of Bowden cables, which reduced losses within the system. This design was based on the concept of a cantilever, with the cable providing force on either side of the pivot point, translating into assistance in both arm raise and lower directions. However, this design did not conform to the client's requirement of using Bowden cables, so it was promptly changed.

The final iteration moved the ball joint to the back and utilized a series of all-thread and carbon fiber tubes to hold the pulley on the outside of the arm. Smaller iterations were also made on this design, including the removal of the ball joint. This design achieves a proper balance between range of motion and minimized losses, with all lateral motion provided by a ball bearing placed on a rigidly mounted shaft. This design was tested and is currently in use.

7 Final Hardware

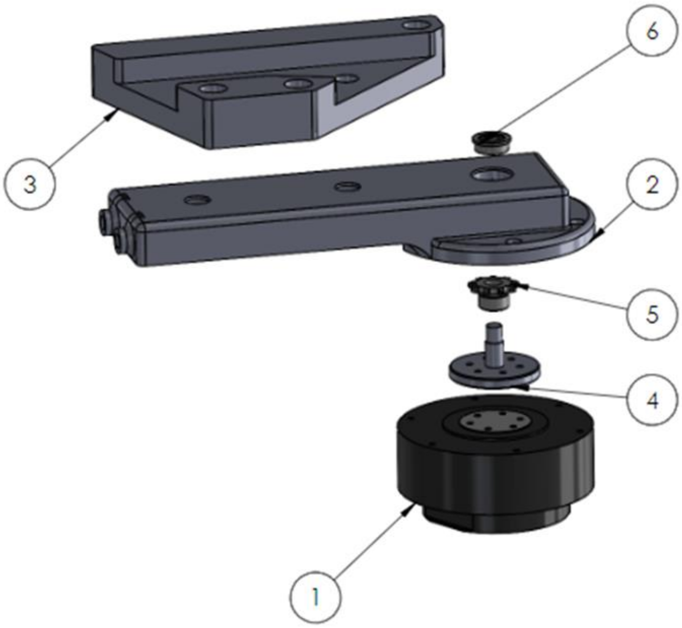
7.1 *Final Hardware Images and Descriptions*

The final design of this project has met nearly all the customer and engineering requirements and has been a successful design the team is proud of. The design features a plethora of different components, the main components present within the design will be listed out below. The figures placed below will showcase the components that are present within the whole design but are separated by subassembly for ease of understanding and simplification.



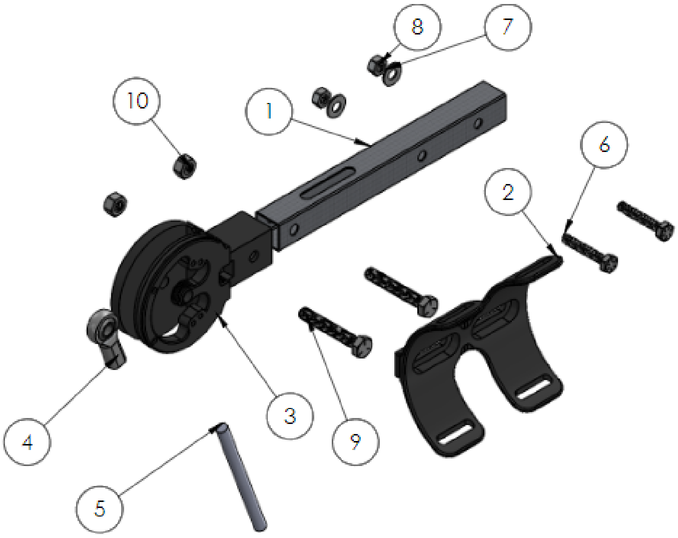
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	A-01	Tube Cap	1
2	A-02	Shaft	1
3	A-03	Ball Bearing	1
4	A-04	Side-Mount External Retaining Rings	1
5	A-05	Termination Block	1
6	A-06	Internal Retaining Ring	1
7	A-07	External Retaining Ring	1

Figure 30: Subassembly A: Termination Block



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	B-01	MOTOR AK60-6	1
2	B-02	MOTOR MOUNT	1
3	B-03	MOTOR ADAPTER PLATE	1
4	B-04	SPROCKET PLATE	1
5	B-05	CHAIN SPROCKET 2302K68	1
6	B-06	MOTOR BEARING 780K143	1

Figure 31: Subassembly B: Motor



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	C-01	Ultra-Strength Lightweight Carbon Fiber Tube	1
2	C-02	ARM CUFF	1
3	C-03	PULLEY	1
4	C-04	ROD END	1
5	C-05	ALLTHREAD	1
6	C-06	HEX BOLT 1/4-20	2
7	C-07	1/4in Steel Washer	2
8	C-08	1/4-20 NUT	2
9	C-09	5/16-20 HEX BOLT	2
10	C-10	5/16-20 HEX BOLT	2

Figure 32: Subassembly C: Pulley

7.1.1 Hardware Present

The hardware components used within the final design of the shoulder exoskeleton include:

- Dog-bone scuba back plate: This back plate, originally manufactured for scuba diving, provided a perfect mounting system. With the back plate parts could be attached to the back of the person and come around the front if needed. This plate allowed for an easy to wear and comfortable design that was simple to assemble.
- Dog-bone harness: In addition to the back-plate the team bought the respective harness to go along with it. This way the team could ensure that there was a secure, comfortable, and sturdy fit.
- Carbon fiber square stock: Within this design there are two square tubes of carbon fiber. Both tubes are the same size, just different lengths. These tubes are used to mount the system to the back and come around to the front as well as connect the pulley to the bicep cuff. The reason for the carbon fiber stock was because of its mechanical properties. Carbon fiber was the strongest and lightest material available to the team, which is why it was used.
- Onyx and carbon fiber filament: Some of the components within the design were too

difficult to manufacture, to make these pieces while maintaining strength, Onyx (a nylon-based filament) and carbon fiber filament were used to 3D print these parts. The parts that were manufactured this way consisted of the carbon fiber tube end cap, the Bowden cable termination block, the bicep arm cuff, and the pulley.

- 10mm Bearing: A 10mm bearing with additional hardware such as the retaining rings and c-clips was used inside of the Bowden cable termination block to accommodate for the lack of movement in the lateral direction. The bearing was placed on the aluminum shaft manufactured by the team and can be seen in the description below.
- Aluminum shaft: The aluminum shaft on the final design comes through the carbon fiber end cap and attaches inside the Bowden cable termination block. This shaft is used to hold the bearing subsystem presented above while maintaining strength and a lightweight design.
- All-thread: A small ~3inch piece of all-thread was used to connect the hiem joint present inside of the pulley, to the Bowden cable termination block. The Heim was pre-threaded, but to connect the 3D printed termination block the team used heated inserts and put them inside of the block. This was the all-thread could attached to both ends.
- Elastic Velcro: To hold the bicep cuff to the users arm in a safe and secure fashion, the team opted to use an elastic Velcro that wraps around the arm and attaches back to the cuff. This allowed for a lightweight and comfortable attachment system.
- Bowden-cables: Bowden cables were used to connect the motor directly to the pulley. These cables run inside of a sheath and are attached to the motor which is attached to a sprocket and chain system manufactured by the team. The cables attached to the chain via components provided by Dr. Lerner and Protolabs. With this subsystem the chain can rotate these cables, and when the cables are tensioned to be tight around the pulley, torque is created moving the arm up.
- AK60.1 Motor: To power the exoskeleton the team decided to use the AK60.1 motor provided by T-Motor. This motor provides plenty of torque to the shoulder. On average the team used about 5N/m from the motor and the maximum output of this motor was around 7N/m. The motor had plenty of power for what the team needed.
- Battery: A 1800mAh LiPo battery is used to power the device. This battery is plenty strong enough without being overly big. It is attached to the back of the scuba plate via Velcro and with the battery on the device only weighs in at around five and half pounds.
- Additional hardware: The team used a variety of bolts, washers, and nuts to finish this design. Although many different sizes were used throughout the design, the main size bolt that the team used for construction was a 5/16’.

A snapshot of the final design with all the hardware components mentioned above can be seen at the end of section 12.2.

7.2 *Design Changes in Second Semester*

Following the Fall 2022 semester the team knew lots of iterations and prototyping was going to encompass a majority of the Spring semester. At the conclusion of this project the team completed over ten different designs with their own specific components and changes, including the Fall 2022 prototype. Within this section of the report, the Fall prototype will be excluded and only eight of those iterations from the Spring 2023 semester will be discussed to highlight major component and subsystem changes as well as complete design overhauls.

7.2.1 Design Iteration 1: Initial Ball and Socket Design

The original design for this system was the Fall 2022 prototype. The main issue the team saw with this design was the lack of movement that the hinge joint gave the user. To fix this the team created a ball and socket to attach to the pulley and a sliding shoulder cuff to replace the hinge. These two components in conjunction allowed for a better range of motion and more comfortability. Up to this point, the team has yet to power any designs so the lack of torque that this design and the designs following would provide were yet to be discovered.

Figure 33: First Ball and Socket Iteration

7.2.2 Design Iteration 2: Revised Ball and Socket Design

The second iteration that the team had was very similar to the ball and socket design presented above in figure 19. The main difference between the two is the shaft that the ball connects to. In the initial iteration of this design this shaft was far too thick and rectangular. This geometry inhibited the complete movement of the shoulder because the shaft would hit the housing of the socket. To combat this, the shaft was redesigned at this location to be narrower allowing for better range of motion and movement.

Figure 34: Second Ball and Socket Iteration

7.2.3 Design Iteration 3: Revolute Joint

After showing the second iteration to our client, Dr. Lerner expressed that the design was good and we were heading in the right direction, but he was concerned that with the addition of this ball and socket design we would not be applying enough torque. His recommendation was to add a revolute joint below the ball to receive the actuation from the Bowden cables. This way we could keep this range of motion from the ball and socket without compensating for the power output. In addition to the revolute joint, the team decided to scrap the uncomfortable shoulder plate. In this design the system will mount from the back and come out to the side of the shoulder. This change is something that is still present in the final design.

Figure 35: Revolute Joint with Ball and Socket

7.2.4 Design Iteration 4: Revised Revolute Joint

To better improve the previous revolute design the team decided that mounting the pulley directly in line with the shoulder joint was the best option moving forward. Doping this would provide a more natural and conformable feeling when the system is actuated. To accomplish this, the ball and socket needed to be moved to the back. In this design the pulley sits on the outside of the shoulder with the ball behind it.

Figure 36: Second Revolute Joint Iteration

7.2.5 Design Iteration 5: Full Design Overhaul

This design was constructed at about 67% of the way through the semester. The reason for this design was that the team was concerned with the torque being applied through the pulley. To try and fix this, the team decided that a complete overhaul of the design was necessary. First, a backplate was purchased to be worn with a harness, and all the components could attach to it. Next, the ball and socket were moved to sit just above the hip. This would still provide the user with the range of motion that the team wanted. Attached to the ball was a stock of all-thread. This all thread would travel all the way up to a Heim joint hinge subsystem. This subsystem would allow for actuation in the frontal plane. Lastly, this Heim was attached to the cuff. The team was too fixated on trying to get an effective torque from the motor that the customer requirements were lost. This design failed to implement pulley and Bowden cables, and although fixed in the following iterations, this failure was a much-needed step for the team. It allowed them to see the importance of the Bowden cable and pulley subsystem.

Figure 37: Mobility Prototype

7.2.6 Design Iteration 6: Reimplement Bowden Cables

After talking with Dr. Lerner and seeing the issues with the previous design, the team decided that combining the two previous designs into one was the best course of action. The team decided to keep the back plate from the previous design and although the ball joint was no longer an active part, it was replaced with a Heim joint. The team still wanted to ensure as much mobility as possible without sacrificing power. Additionally, the team decided that instead of having a bar come from the back to the side of the shoulder, that another hinge should be placed there to allow for extra range of motion. A pulley and Bowden cables were reintroduced into this design to meet the customer requirements.

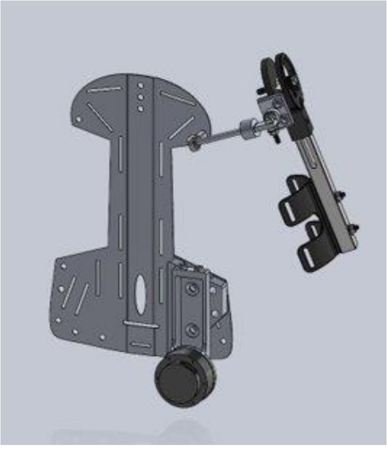


Figure 38: Bowden Cable Reimplementation

7.2.7 Design Iteration 7: Fixed Supports

During this iteration the team was going in the correct direction and were getting closer to the results. The issue the team found when testing the previous design was that with all the DOFs (degrees of freedom) present, it was nearly impossible to apply an effective torque to the pulley. With all the moving pieces the torque would not transmit in the way that the team envisioned. To combat this, although hard, the team decided that they needed to reduce the amount of motion present within the device to get the torque they were seeking. The Heim joint on the back, all thread and hinge system were all redesigned and replaced. The Heim was scrapped in favor of a carbon fiber square stock. The hinge was changed to a bearing and shaft system. This new bearing system would still allow for some movement in the lateral direction without causing any unwanted rotation from the motor. With these changes, adequate torque was applied to the pulley and the team was able to get successful tests and results.

Figure 39: Carbon Fiber Square-Stock instead of All thread

7.2.8 Design Iteration 8: Final Design

With a successful previous design, the team needed to now address smaller components that were issues. During testing of the previous design, the shaft from the end cap that held the bearing broke. This shaft was initially made from PLA. Since this component was small the weight difference between Onyx and aluminum for this specific piece was negligible, so the new shaft was created by the team out of aluminum on a lathe. Another component that needed to change was the Bowden cable termination block. In the previous design, the block was printed out of Onyx vertically. Meaning that the print lines were in line with the direction of the torque. Following this failure, the team decided to fillet and sharp corners on the termination block, print the piece horizontally so the lines went perpendicular the forces and to add additional layers of carbon fiber filament throughout the Onyx for additional strength. With these changes, the design worked as intended with no breaks. A successful design was established, and it is still the design that the team has today.

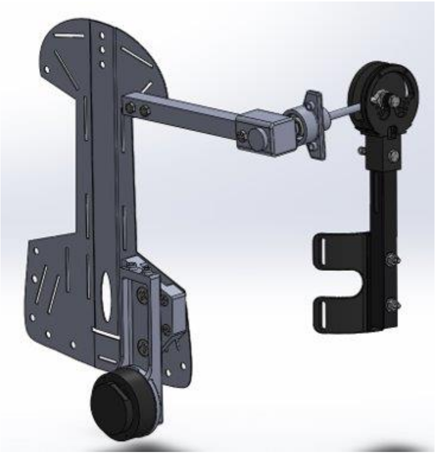


Figure 40: Final Design

7.3 *Challenges Bested*

Getting hardware on time and completing a project is crucial to any project. Doing this effectively without any errors or having any challenges arise is next to impossible and this project was no different. The team had their fair share of challenges, issues, and failures come up. To have a successful project is not to completely avoid these problems because they will almost always arise no matter the planning, thought or execution but rather how you and your team responds to these problems and what happens moving forward. Within this section of the report, the team will showcase the challenges that they faced when completing this project and what they did to overcome them.

1. Miscommunication: The biggest challenge that the team had to face throughout the duration of this project was miscommunication between the team and the client. The team was not clear with their client for a while and vice versa, this led to designs made by the team that didn't fit the client's wishes and goals. During the beginning stages of the project, it felt like the team was throwing anything at the wall and hoping it stuck, rather than just being clear with the client and figuring out what needed to be done. To fix this, eventually the team and client had a very productive meeting after the 67% build to discuss what went wrong and what needed to be done moving forward. It was after this meeting that all miscommunication ended, and the team was able to produce a design and product that not only fit the client's needs but was something that they were happy with. No one was at fault for this challenge, it was bound to happen because the team did establish a clear communication strategy but now knows what to do in the future.
2. 3D Print Time: A challenge that arose that was very hard for the team to combat was the time it took to 3D print a component. Being a design that was highly iterative, 3D printing was a necessity. This challenge was especially hard for the team because it involved a lot of waiting, and when you're pressed for time waiting is the last thing you want to do. So, to combat this, the team had implemented a three-rule system when it came to 3D printing.
    a. Only print at night if possible. By doing this the team was able to maximize their time while awake during the day and could print at night to get the full days' worth of time.

    b. Utilize more than one printer: Using one printer versus two was no competition. Luckily for the team, two of its members had a 3D printer available for use and this basically halved the print time and doubled the productivity.
    c. Print multiple parts when possible: This rule is self-explanatory. When able we needed to print as many things as we could to reduce the printer setup time and overall print time.

3. Software Issues: Software issues almost always arise due to coding errors, and it was no different during the initial tests for this project. The team was not getting the desired movement from the device during the initial testing. The device would move sporadically and quickly. This movement was surely caused within the code and was fixed during the second and third rounds of testing, but not before it caused a break in some of the mechanical components of the design.
4. Structural Issues: Another issue that arose during the testing phase of this project was the lack of structural integrity in components of the design. As stated above, the initial testing round broke some of the components in the design. To combat this the team needed to manufacture new parts, redesign old ones, and fix any coding issues. This was done by implementing a careful planning strategy and role assigning. Team members were given certain tasks to accomplish by a specific date. This was done to reproduce the design as quickly as possible efficiently and effectively so another round of testing could begin. It was because of this careful and well-thought-out plan that allowed the team to iterate the design, improve upon their failures by learning from them and create a project that they are most certainly proud of.

In conclusion, challenges are part of almost any project and are unavoidable. The team was able to overcome the issues and challenges faced throughout this project, not because they avoided them all together, but because their response to the challenges was well planned, thought out, and well executed.

8 Testing

8.1 *Testing Plan*

When it came to testing the design, the team knew that they needed to create their tests around the customer requirements. When doing the experiments, the team took the customer and engineering requirements and made six different experiments to accommodate all of them. The six experiments that the team conducted are as follows:

1. Ensure a cable actuated system.
2. Ensure a pulley driven system.
3. Is the device user operable?
4. How much does the device weigh?
5. How far does the device protrude out?
6. Does the device provide at least a fifteen-percentage increase in endurance and muscle fatigue?

The six experiments will be discussed in further detail below, as long as the results received from the testing.

8.1.1 Design Requirements Summary:

The Robotic Arm Exoskeleton project has been tasked by Dr. Zachary Lerner to design and test a robotic arm exoskeleton that is able to assist the user with pull-ups. The overall goal of the project is for the team to engineer an exoskeleton that increases the number of pull-ups an individual can perform by 15%. The design specifications as outlined by the client are very minimal. Since this project is a new branch of study in Dr. Lerner's Biomechatronic's lab he is not as worried about engineering a sleek, highly efficient device rather he has instructed the team to focus on engineering a functional exoskeleton that can accomplish the project goal. Through constant discussion with the client, the team generated the following engineering requirements respective to their customer requirements.

Table 7: Design Requirements Summary

Customer Requirements	Engineering Requirements
CR1 – Be cable actuated	ER1 – Use Bowden cable actuation
CR2 – Use a pulley to create torque	ER2 – Utilize Dr. Lerner's previous pulley design
CR3 – Be low-profile	ER3 – Will protrude less than 10 cm (3.94 in.) from the user's body
CR4 - Be lightweight	ER4 – Will weigh less than 6 lbs.
CR5 – Operate independently of stationary machinery	ER5 – Will operate only from the user's body
CR6 – Assist the shoulder endurance of the user	ER6 – Will increase the timed ability of a user to hold a weight in front of them

Testing Summary:

Table 8:Testing Summary Table

Test Name	Relevant DRs
Cable Actuation	ER1
Pulley Utilization	CR1, ER2
Protrusion Limit	CR3, ER3
Weight Limit	CR4, ER4
User Operation	CR5
Pull-up Test	CR3, CR4, ER6

8.1.2 Detailed Testing Plans:

Cable Actuation –

Summary:

This simple test is a physical demonstration that the engineered device incorporates cables into the design to actuate the pulley. No test subject is required but a fully constructed device is required to be present. This test will be answered with a simple yes or no as to whether the device uses Bowden cables and whether the device is functional based on the actuation of the Bowden cables.

Procedure:

1) Present the fully constructed exoskeleton device
2) Decide, as a team, whether Bowden cables were used in the design
3) Power on the device and evaluate, as a team, if the pulley rotates due to the tension and compression of the cable system
4) Conclude test

Results:

The team knows this test will be fulfilled because Bowden cables have been the only cable system considered while designing this project. The custom motor sprocket and chain system will connect to the cable at one end and will be looped through the pulley and back to the other ender of the chain creating a connection between the pulley and motor through Bowden cables. When the motor is powered, the device will create tension and compression in the cables enacting a moment of the pulley and making the device functional.

Pulley Utilization –

Summary:

This test is nearly identical to the Cable Actuation test. This test will require the same, fully constructed robotic exoskeleton and will be evaluated by the team whether the device used a pulley in its design. There are no variables being tested besides the yes or no evaluation of the device including Dr. Lerner’s pulley.

Procedure:

1) Present the fully constructed exoskeleton device
2) Decide, as a team, whether Dr. Lerner’s pulley design was incorporated into the device
3) Conclude test

Results:

The team expects this test to be successful since the final design being tested does already has a pulley on it. Dr. Lerner’s pulley design was altered to fit the specifications of the design so it is not the original pulley design that could have been used but this does not necessarily trump the main purpose of this test which is to evaluate if the device uses a pulley or doesn't.

Protrusion Limit –

Summary:

The protrusion test is a quantitative test where the team will be measuring the protrusion of the biggest components of the device. This evaluates customer requirement 3 which is that the device needs to be low profile. The team will be testing against engineering requirement 3 which specifies that the device must protrude less than 10 cm from the user's body. This test requires a test subject, a fully constructed device, and a tape measurer. The team will only measure protrusion in the X or Y plane and will not be measuring at an angle from the test subject's body.

Procedure:

1) Make sure all components of the device are attached and secure
2) Place the device onto a test subject
3) Use a tape measurer to document how many centimeters extruding parts of the device protrude off the user
4) Compile all data into a table and evaluate if it meets or exceeds the engineering requirement

Results:

The team expects all components of the design to meet engineering requirement 4. The design process always included minimally sized components to ensure that the ability to protrude over 10 cm would never be met. If the design protrudes less than 10 centimeters from the test subject's body, then the design requirement and client acceptance will be marked as "Met". In the final presentation, the devices' low-profile characteristics will be highlighted as a major achievement for this exoskeleton project.

weighs 6 pounds or less lightweight and

Weight Limit –

Summary:

The weight limit test requires only the fully constructed device and a scale to measure the total weight of the device. This determines if engineering requirement 4 is met, which is one of the more important aspects to the project. A tolerance of 0 is set for this test since the team's design incorporates only a 1-arm exoskeleton and does not utilize both arms.

Procedure:

1) Make sure all components of the device are attached and secure
2) Place the device onto the scale
3) Record the number displayed by the scale in pounds
4) Reset the scale and conduct 2 more times
5) Conclude test

Results:

The team is unsure of the expected results from this test however the device does feel close to the 6-pound limit set by the client. Each member of the team has held, and some members have worn the device, and although it does not feel uncomfortably heavy the weight of the device is noticeable. If this engineering requirement is met (<6lbs.) then the team will highlight its lightweight characteristics during the final presentation as a major accomplishment of the project.

User Operation –

Summary:

This test is a simple visual test demonstrating whether the device can be operated entirely from the test subject, or if the device needs the assistance of stationary machinery to operate it. This would include a large stationary battery to supply power to the motor, or a specific test area in which the loose cables or components will be held up by some other device. This test will evaluate customer requirement 5 and will only require a test subject and a fully constructed device.

Procedure:

1) Place the device onto the test subject
2) Visually evaluate, as a team, whether the test subject can power the device by themselves and utilize its functionality
3) Document evaluation and conclude test

Results:

The customer requirement that this test evaluates is a prominent design requirement which is also affected by the devices lightweight and low-profile characteristics. The team knows that the device was constructed to hold all power systems and batteries on the user's body which enables the device to be independently operated by the user. The team expects this test to pass with no chance of failure.

Endurance Test –

Summary:

This is the most important test for this project. This test evaluates the amount of assistance supplied from the motor to the user's shoulder complex while performing an endurance/fatigue test. The test subject for this test will be measuring the amount of time that the user can hold various weights out in front of them both unassisted and assisted. For this test, the team plans on having multiple different participants with different levels of strength, size, height, gender, etc.

Procedure:

1) Have the participant put on the exoskeleton device (unpowered).
2) Allow the test subject to get their arm in an L shaped position.
3) Have another person place the weight into their hand.
4) Immediately start the timer.
5) Continue timing until the subject's arm dips passed a 90-degree angle.
6) Immediately stop the timer.
7) Switch subjects and repeat the unassisted test with all participants to allow for adequate rest.
8) Once all participants have performed the unassisted test, begin the assisted one with the same steps as listed above. (Here the device will be on at 7N/m at the motor or 21N/m at the shoulder).

Results:

The team is strictly measuring the time it takes for an individual to fail at holding a specific weight out in front of them. To get a better time while assisted by the device than when they aren't assisted. This will be calculated by taking the percent difference between the two measured values. To find the percentage increase in seconds held, the following equation will be used.

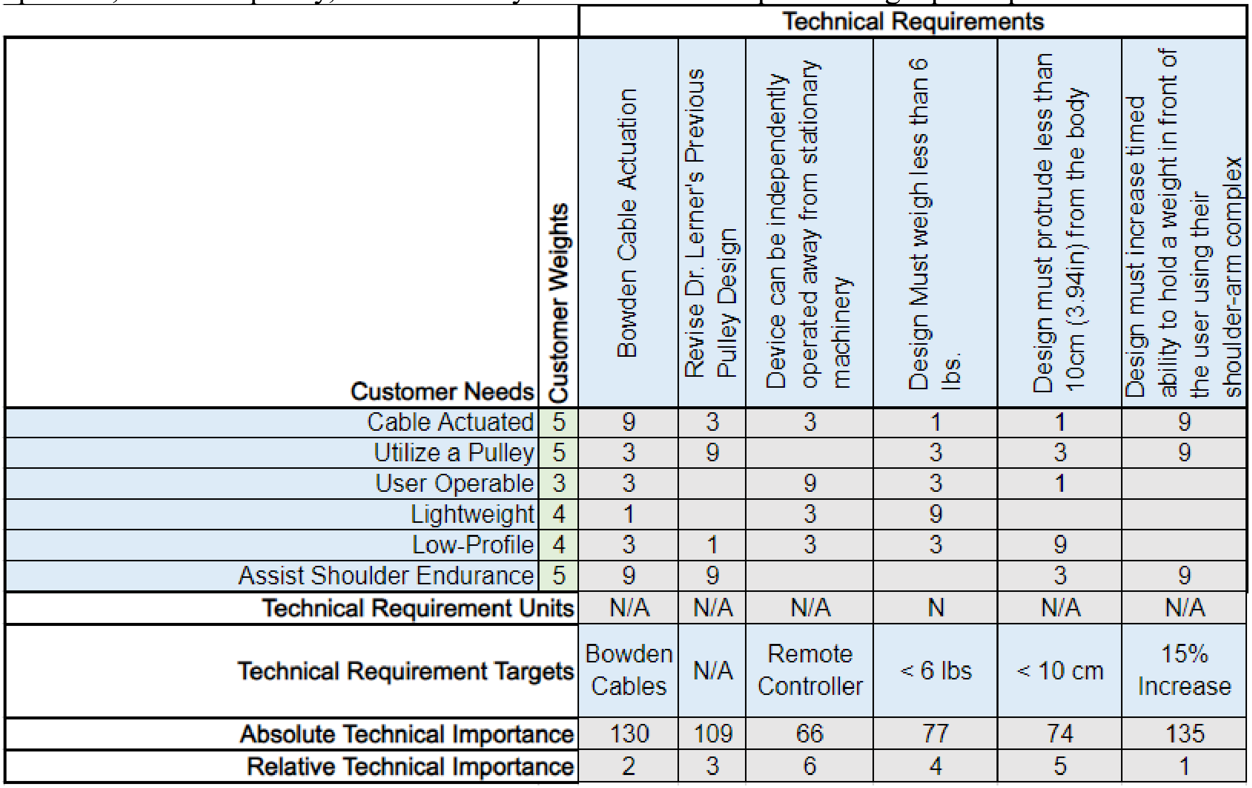
$$I = \frac{P_A - P_{UA}}{P_{UA}} \times 100$$

Equation 4: Percent Difference Formula 4

If the device does increase the number of pull-ups that the test subject was able to complete then the project will be deemed a success, and the team will be able to discuss the results of why the torque actuated on the pulley is sufficient for assisting the user's shoulder complex.

8.1.3 QFD:

The team has updated the customer and engineering requirements since the beginning of the project. The client was able to specify for the team that the design should use his pulley design, as well as that the design will measure the pull-up assistance by calculating the difference between assisted and unassisted pull-ups. The team has since dropped the "Safety" and "Stability" customer requirement and have further defined the "Portable" requirement to be CR5. Figure 1 is a copy of the team's initial quality functional deployment. The weight of each customer's requirement remains as well as the relationship between each customer and engineering requirement. As stated at the beginning of this report, the team is presenting to the client a robotic exoskeleton that is lightweight, low-profile, cable actuated, independently operable, utilizes a pulley, and ultimately aids a user when performing a pull-up.



		Technical Requirements					
Customer Needs	**Customer Weights**	Bowden Cable Actuation	Revise Dr. Lerner's Previous Pulley Design	Device can be independently operated away from stationary machinery	Design Must weigh less than 6 lbs.	Design must protrude less than 10cm (3.94in) from the body	Design must increase timed ability to hold a weight in front of the user using their shoulder-arm complex
Cable Actuated	5	9	3	3	1	1	9
Utilize a Pulley	5	3	9		3	3	9
User Operable	3	3		9	3	1	
Lightweight	4	1		3	9		
Low-Profile	4	3	1	3	3	9	
Assist Shoulder Endurance	5	9	9			3	9
Technical Requirement Units		N/A	N/A	N/A	N	N/A	N/A
Technical Requirement Targets		Bowden Cables	N/A	Remote Controller	< 6 lbs	< 10 cm	15% Increase
Absolute Technical Importance		130	109	66	77	74	135
Relative Technical Importance		2	3	6	4	5	1

Figure 41: QFD

8.2 *Testing Results*

After completing all six experiments, the team and client were both pleased with the results. Four out of the six experiments were completed. Of the two that the team failed to meet, one was extremely close and the other needed more time. Although not all the customer's and engineering requirements were met, they were still client approved and accepted. Below will be the table showing the specifications alongside the tolerances, requirements and if the team had reached their goal for a specific experiment.

8.2.1 Specification Sheet:

Table 9: Specification Sheet

Engineering Requirement	Target	Tolerance	Measured/Calculated Value	ER Met? (Yes or No)	Client Acceptable (Yes or No)
Bowden Cable Actuation	N/A	N/A	N/A	Yes	Yes
Implement a Pulley	N/A	N/A	N/A	Yes	Yes
Lightweight	< 6 lbs.	+ 4 lbs.	~5.5 lbs.	Yes	Yes
Low-Profile	< 10 cm (3.94 in)	Maximum of 10 cm	~ 4.5 in or 11.43 cm From largest protrusion	No	Yes
Independently Operable	Independently Controlled	N/A	N/A	No	Yes
Increase in time to hold an object	15% Increase	Minimum of 12.5%	Average of 49% Increase	Yes	Yes

9 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.

9.1 *Potential Failures Identified First Semester*

9.1.1 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.

9.1.2 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.

9.1.3 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.

9.1.4 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.

9.1.5 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.

9.1.6 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.

9.1.7 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.

9.1.8 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.

9.1.9 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.

9.2 *Potential Failures Identified This Semester*

Most of the new failures this semester originated from the large number of iterations done. Having new iterations every week it is hard to keep track of what will be failing on each design iteration in between last semester and the final design. These few failures are what we expected to fail and what failed our final design in the testing phase.

9.2.1 Bowden Cable Termination Block Failure due to Layer Line Shear

On the shoulder there is a block where the Bowden cables terminate and get anchored into the pully. During our first tests this block had a cylindrical feature which was printed vertically which made the layer lines from the 3D printing concentric with the cylinder itself. This created a weak point in the base (where it inevitably failed) due to the stress concentration on the weaker part of the 3D print Seen in the figure below.

Figure 42: Bowden Cable Termination Block Failure

How this was resolved was increasing the diameter of the cylinder, adding a fillet to reduce the stress concentration, and changing the print orientation to increase the strength. These changes are seen in the figure below.

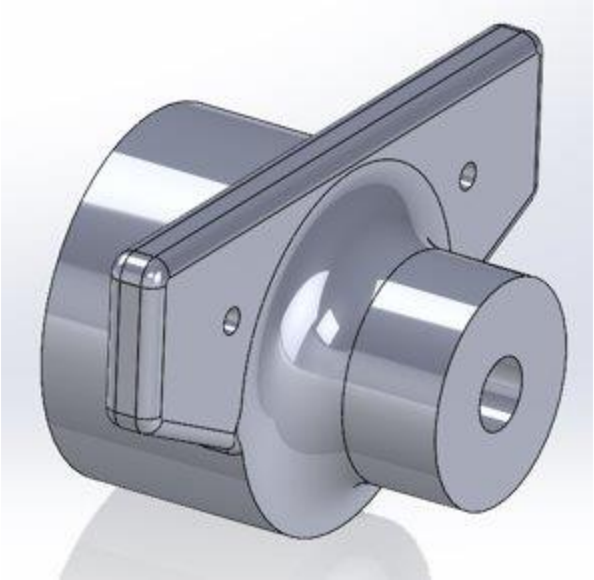


Figure 43: New Termination Block

9.2.2 Plastic Shaft Failure due to Normal Load

The first iteration of the termination block had a Shaft which was 3D printed into the block. When experiencing the force from the motor the shaft immediately snapped. This was due to similar reasoning as the previous failure the shaft was printed in a way where the layer lines were concentric with the shaft leading to the weakest point of the print experiencing the most force. After failure we analyzed the footage and saw that this was the case. To correct this error the entire shaft was made from aluminum to get rid of the weak points that the 3D printing. This was done instead of just changing the print orientation as the shaft would be experiencing by far the most force from the motor and wanted to make sure that the shaft had no way to fail due to the force. We fed the shaft through the back of the termination block and the Carbon Fiber Square stock which ensured that it could withstand the forces. An image of the shaft is seen below.

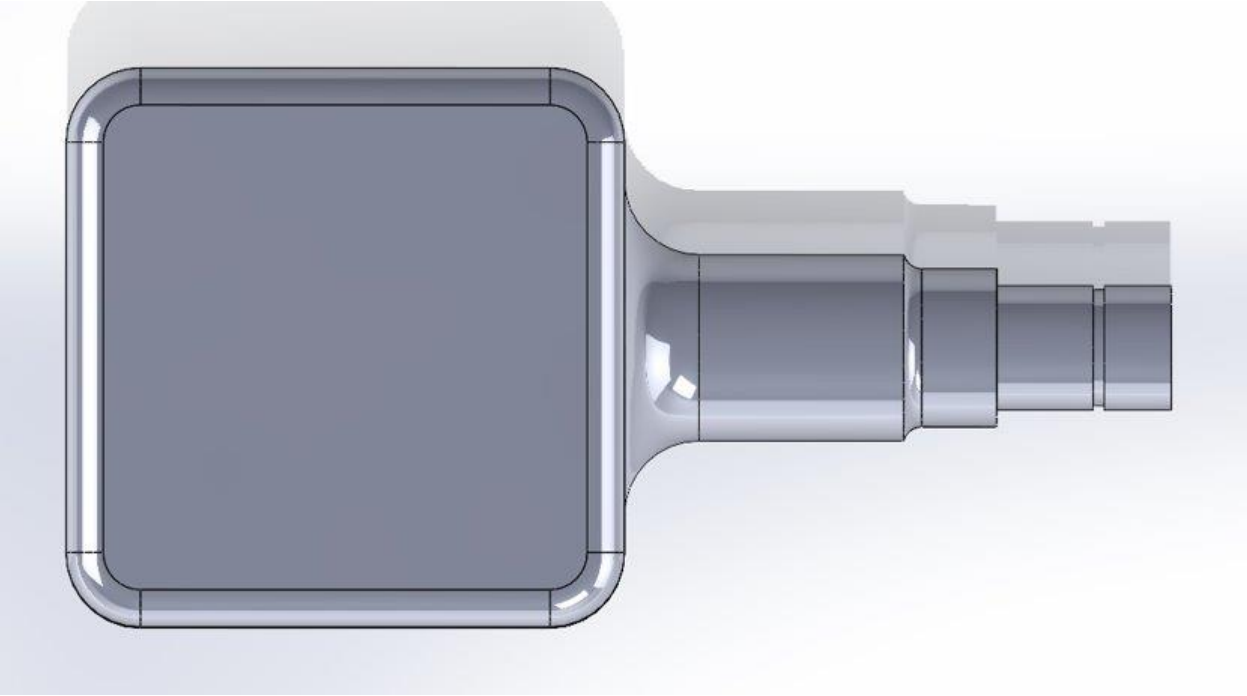


Figure 44: First Plastic Termination Block Shaft

Figure 45: Aluminum Shaft

9.3 *Risk Mitigation*

During the finite element analysis none of the parts failed due to the forces applied by the motor. All these analyses were applied in such a way that any of the deformations were an overestimate to over design the prototype. This was the main way that the failures were prevented. The failure of the Bowden cables failing in tension was a slight worry, however, we up sized the cables to a diameter that they could not possibly break at with the forces the motor was capable of outputting which added no cost as the sizes were standardized. Evidence that we have of major critical failures is mostly in FEA. The image below shows the carbon fiber square stock with a calculated 120N of force. The 120N comes from the 3:1 gear ratio on the motor and the peak output that the motor can give. Assuming all said force is loaded into the proper part of the beam with fixtures around the holes in the side of the square stock (not pictured) the deformation is less than a tenth of a millimeter which is an acceptable deformation that will be negligible with regards to the comfort and structural integrity of the design.

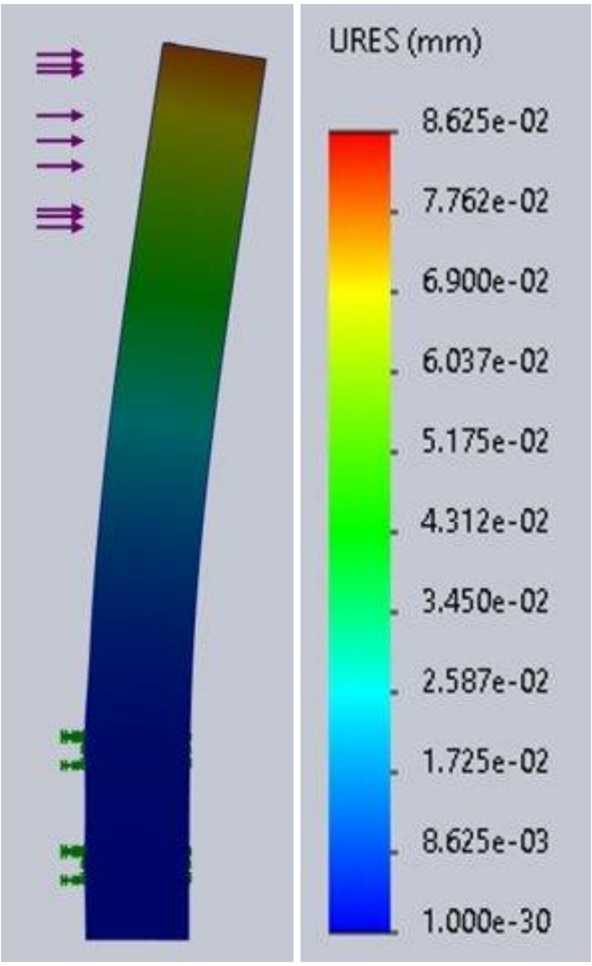


Figure 46: Finite Element Analysis on Carbon Fiber

The next part that could be subject to a major failure is the motor mount. 9Nm was used, which is the peak output torque from the motor and centered it where the force from the motor would experience the torque. This was assuming that all the torque from the motor was being put into deforming the motor mount.

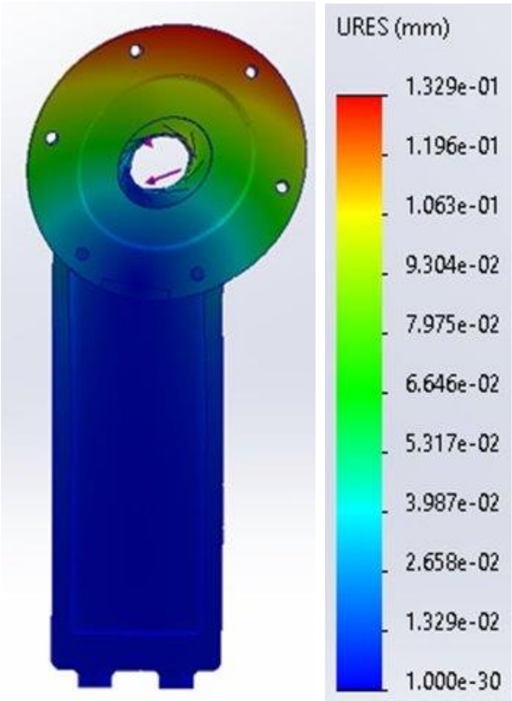


Figure 47: Motor Mount Finite Element Analysis

The last major failure was at the Bowden cable termination block. The 120N force was separated equally between two of the wings. The force was placed where the reaction from the Bowden cables is and was fixed where it is mounted onto the Tube Cap.

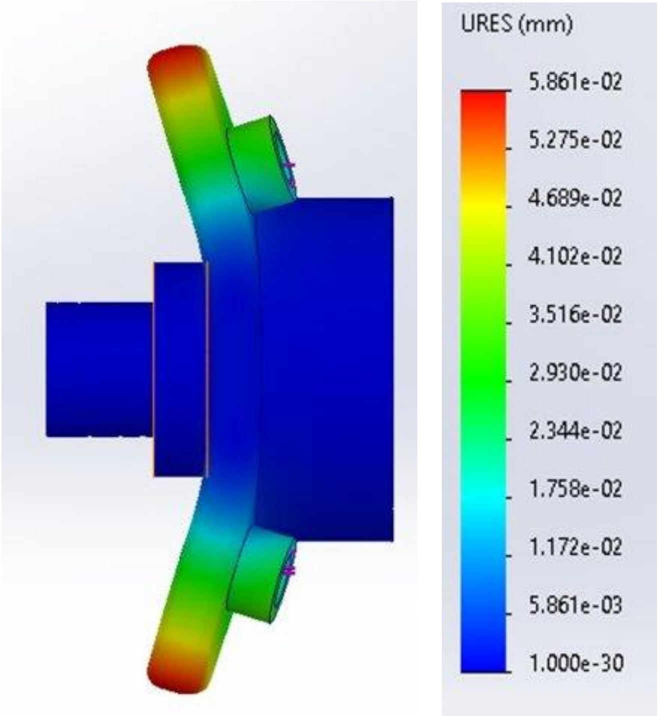


Figure 48: Termination Block Finite Element Analysis

10 LOOKING FORWARD

10.1 *Future Testing Procedures*

10.1.1 Pullup Test

The pullup test will be conducted in the future once the design is mirrored to the second shoulder. This procedure shows both the mobility of the shoulder and the ability to assist in over the head motions. What will be required for this test is a pullup bar that is located close to the desktop setup to control the device. This test can only be conducted with the addition of the second arm into the design.

10.2 *Future Iterations*

A future iteration of this design includes the second arm as mentioned above. This will allow for a more complete testing plan as pullup tests can be added. Future iterations also include the ability to make the design independently operable. What needs to go into this is creating a way for the user to actuate the design independently which is currently lacking. What this will enable us to test is the real-life applications of the design by having users wear the design daily and offer user feedback with a survey on their experience with the exoskeleton.

11 CONCLUSIONS

This report summarizes the work done to design a shoulder exoskeleton for Dr. Lerner and the Biomechanics Lab and includes details on plans for future iterations of the design. We showcased our design process by explaining our QFD, functional decomposition, and an analysis of all our previous iterations of the design. To reiterate, our design has a few requirements that we met. The design must be able to provide a torque to the shoulder using a cable driven system, implemented use of Bowden cables and Dr. Lerner's pulley, allow the user to sustain a load while wearing the device, and provide a low protrusion device under 6 pounds. After multiple reconstructions and failures, the team has settled on a design that will meet these criteria.

The Robotic Arm Exoskeleton team met most design requirements but were unable to engineer a low-profile and independently operable device. The team successfully made a lightweight exoskeleton that increases the endurance of the user when engaging in static arm holds all while remaining under budget. The future work of this project holds a lot of opportunities with immediate improvements being the development of a 2-arm exoskeleton, fail safes, developing an independently operable system, and increasing the range of motion. If future iterations can refine our design, we hope to see it used for rehabilitating patients with damaged shoulder cuffs and torn ligaments.

11.1 *Reflection*

A major part of our design process was designing critical parts out of PLA initially to see where and how they would sheer or fracture. After failure, we would redesign the critical parts of the system and repeat the same procedures. This allowed us to identify the weak points of the design, specifically the joint around the back that allowed for abduction and adduction of the arm. Once we were confident in the integrity of the component, we would reprint out of Onyx and retest. If the component failed again, we would revisit the CAD, redesign, and reprint. The parts that failed with onyx would then be reprinted with carbon fiber filament inlayed with the component to strengthen the part. When it came to testing the device, we kept all initial tests off the body until it was deemed safe to wear. This allowed us to test the code the Biomechanics lab provided to see the ideal range of motion for the device.

11.2 *Resource Wishlist*

If we were tasked to re-attempt the exoskeleton, there are a few areas that would make the design process easier. First is the use of our own filament in the Idea Lab. We spent over a thousand dollars on filament to have the freedom to print multiple prototypes, however the team found out that we would be charged directly for each part from the IDEA lab. Since two of our members were trained in the machine shop, we were able to avoid submitting requests and machined our own parts. The only downside was that we lacked the training to use the CNC machine in the machine shop, if we were able to learn G-Code and practice on the CNC, we could get even closer tolerances on our machined parts.

11.3 *Project Applicability*

The completion of this project has prepared us in multiple different engineering disciplines. First semester, the team began establishing a strong client relationship, begin the design process based on a list of customer requirements and needs, and began prototyping initial iterations of the design. The second semester was focused on the manufacturing and purchasing of new prototypes and the assembly of the final design. Towards the end we faced multiple failures and setbacks, however, were able to stay positive and provide a device that we all are proud of. This past year has tested our abilities as engineers and prepared us to join the industry. We want to thank and acknowledge everybody who has supported us on this journey and are excited to see the future iterations through the Biomechanics Lab at Northern Arizona University.

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13 APPENDICES

13.1 *Appendix A: Fall Semester Prototype, Parts, and Drawings*

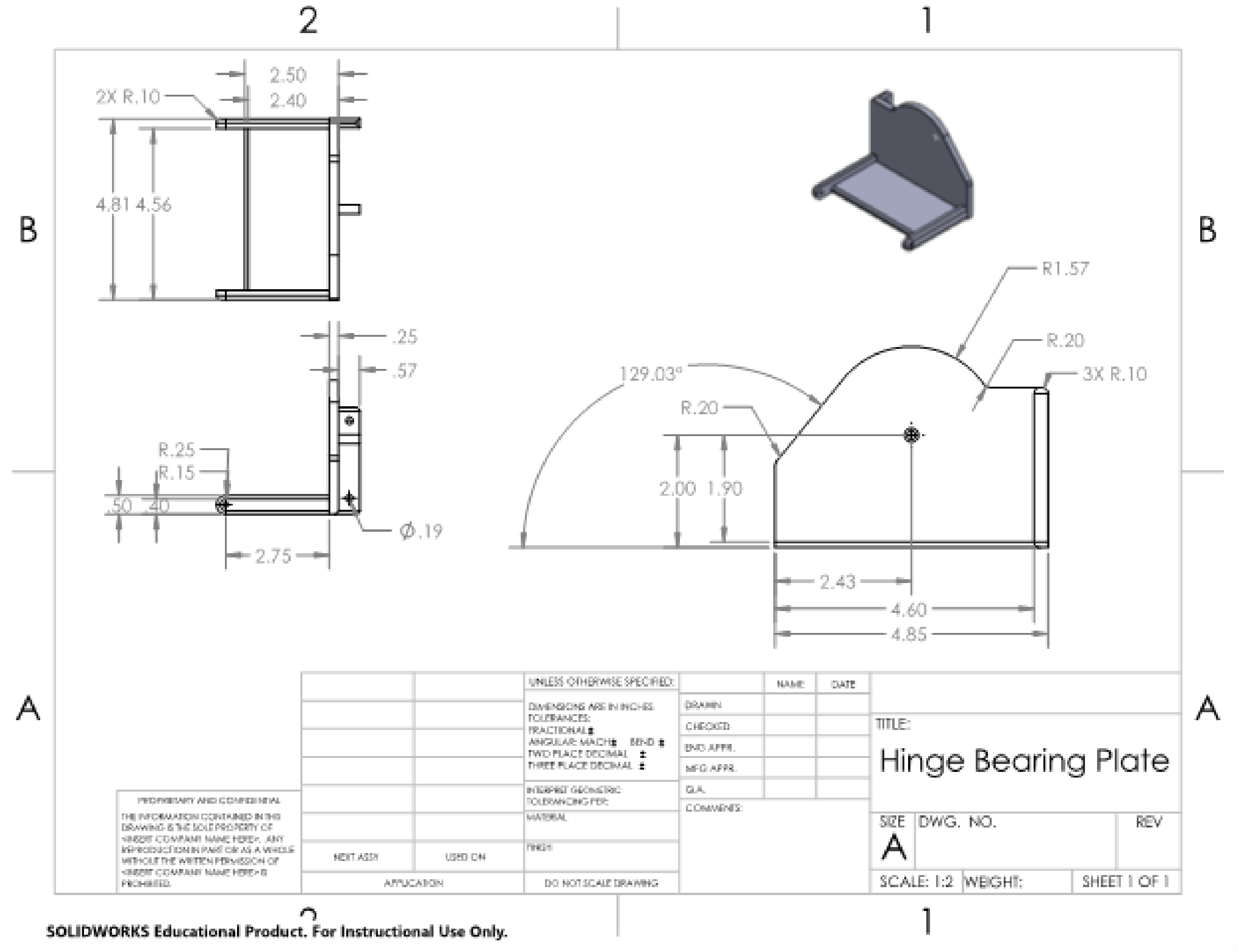


Figure 49: Hinge Bearing Plate Drawing

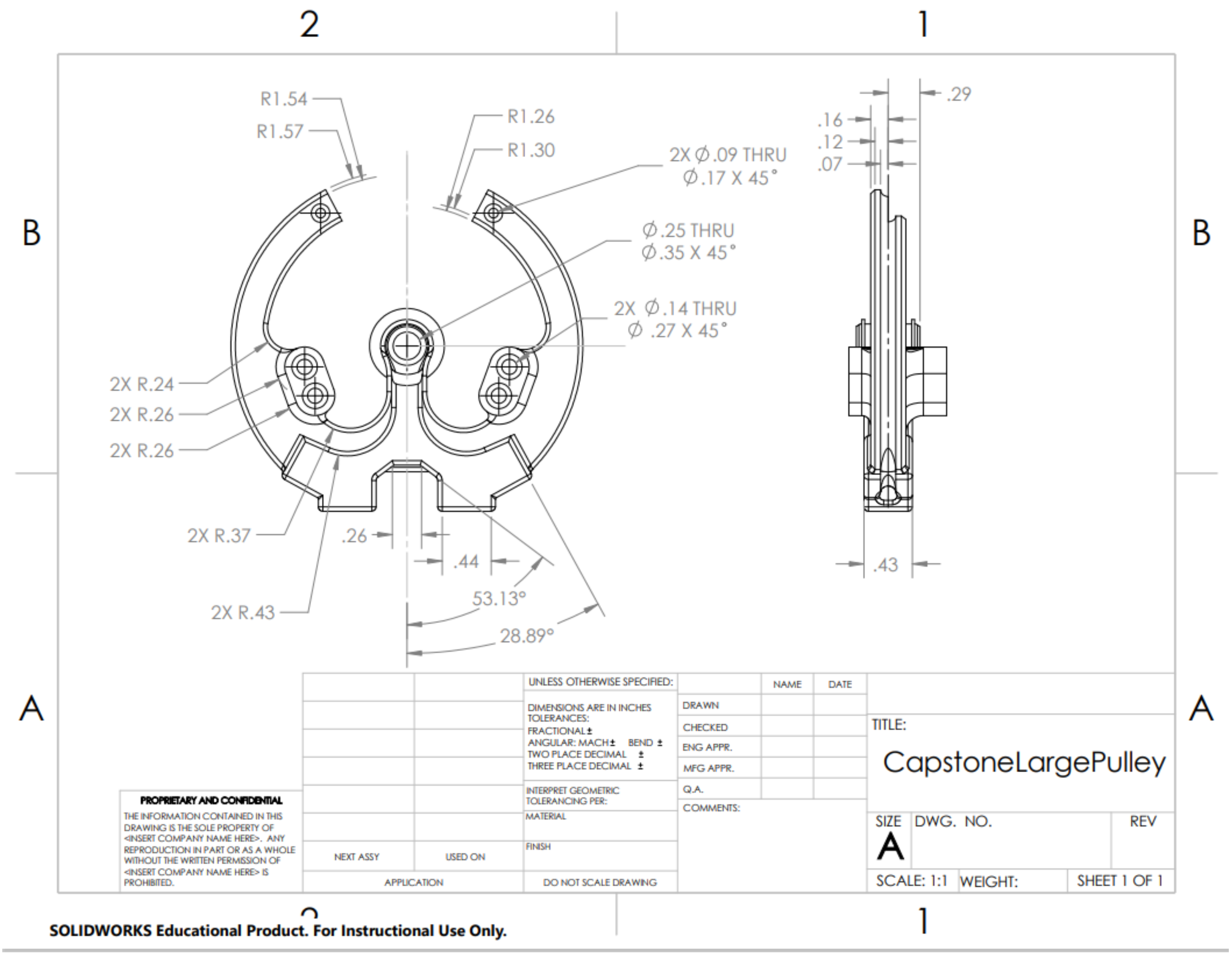


Figure 50: Pully Drawing

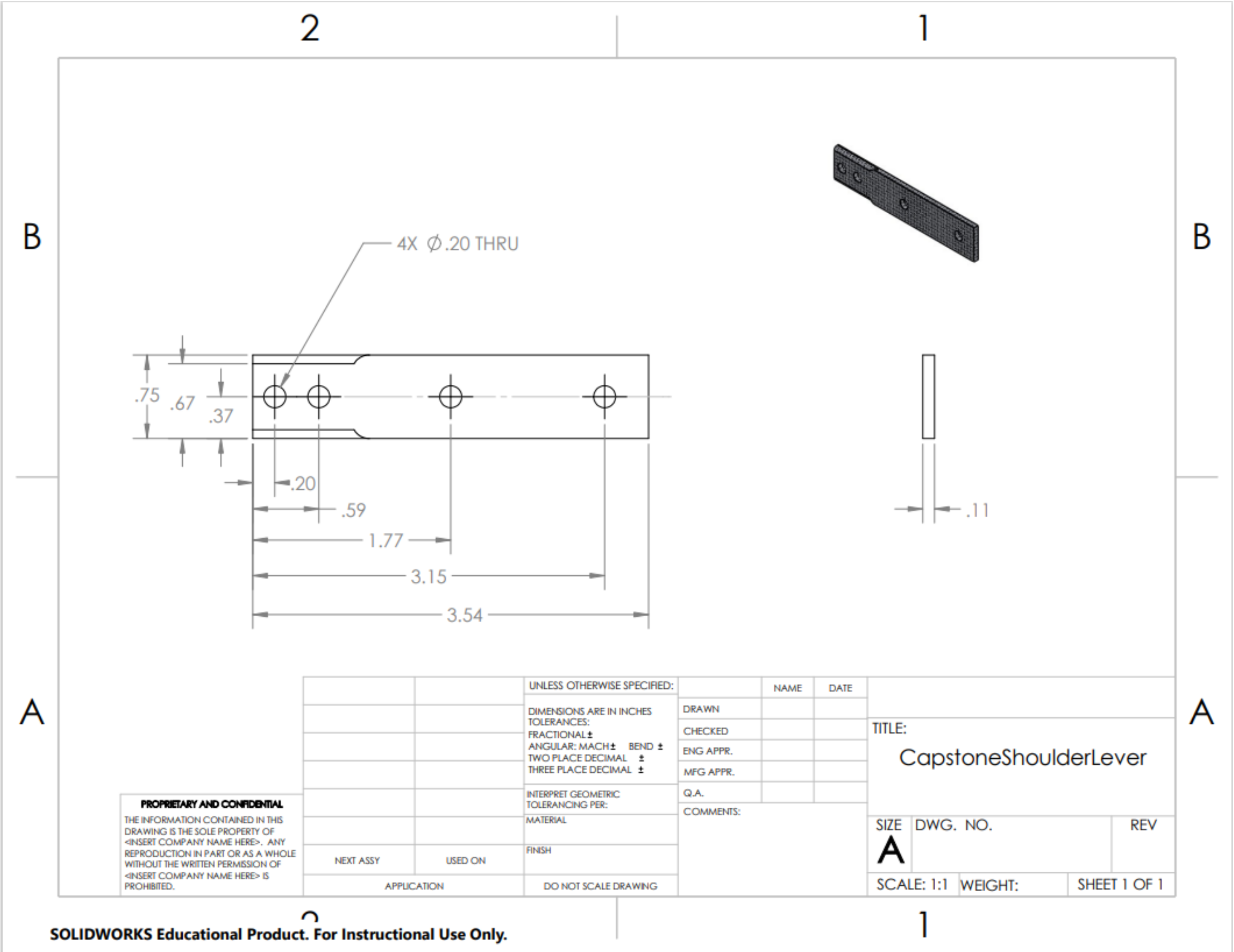


Figure 51: Shoulder Lever Drawing (Not in Final Design)

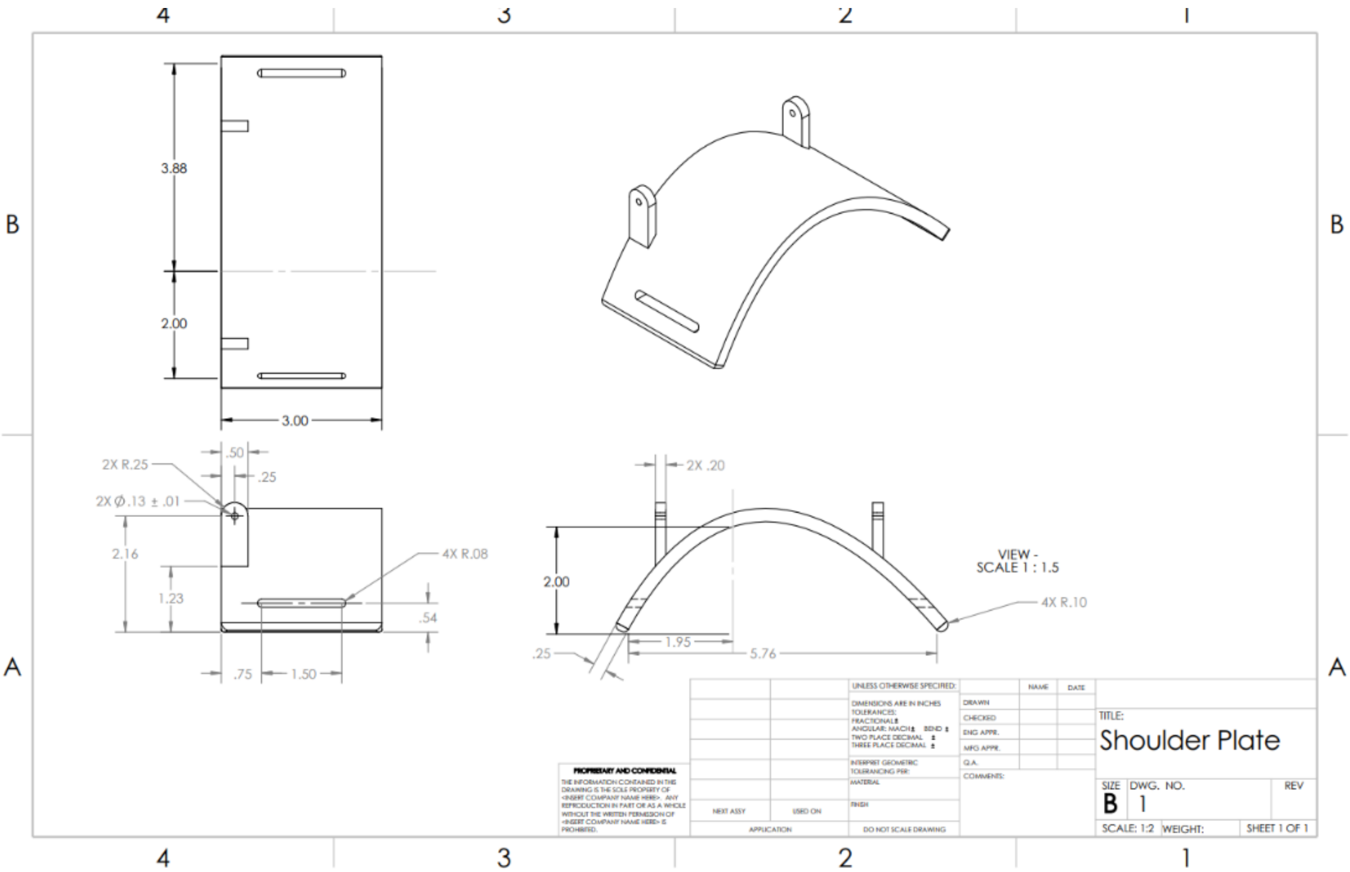


Figure 52: Shoulder Cuff (Not in Final Design)

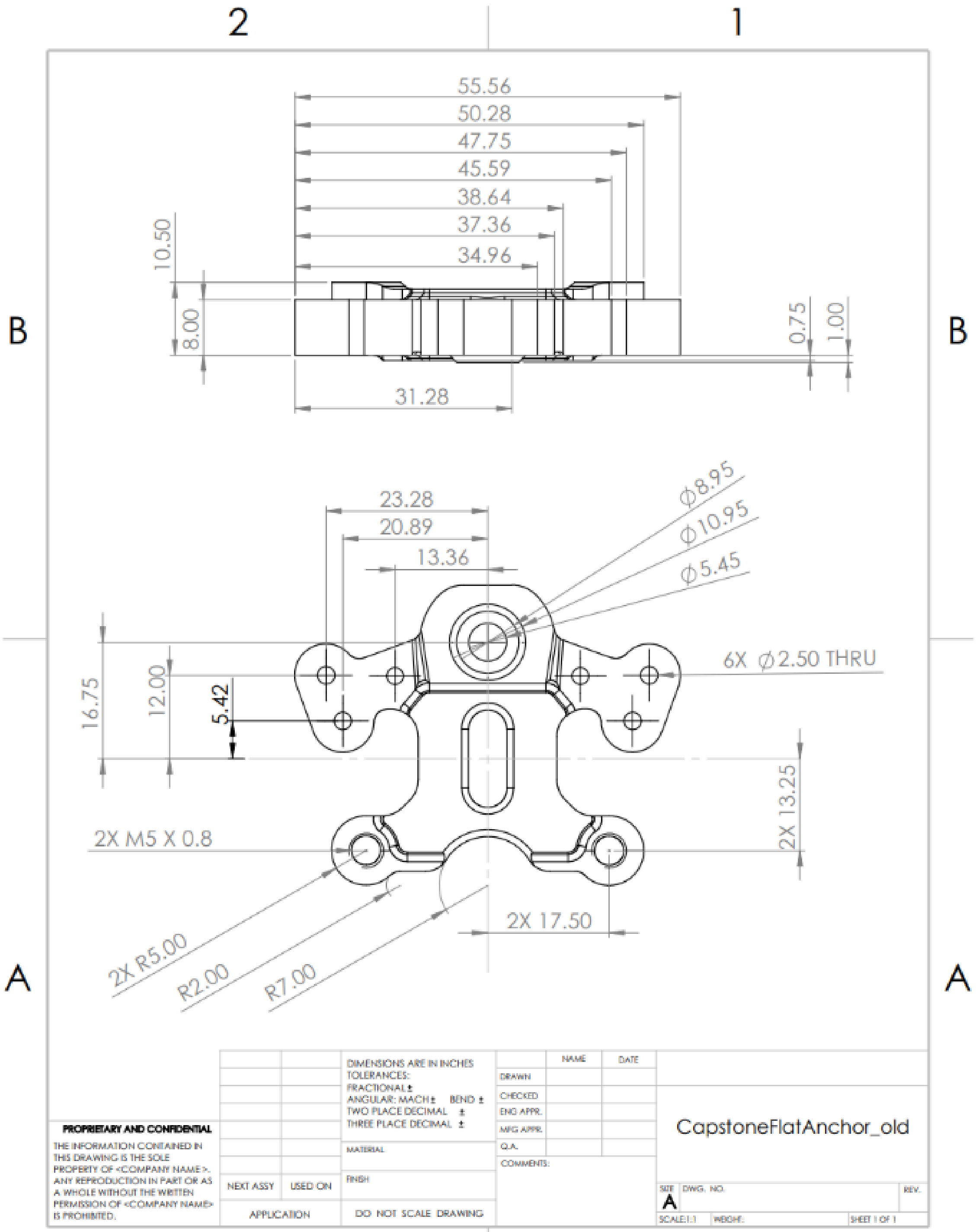


Figure 53: Torque Sensor Drawing (Not in Final Design)

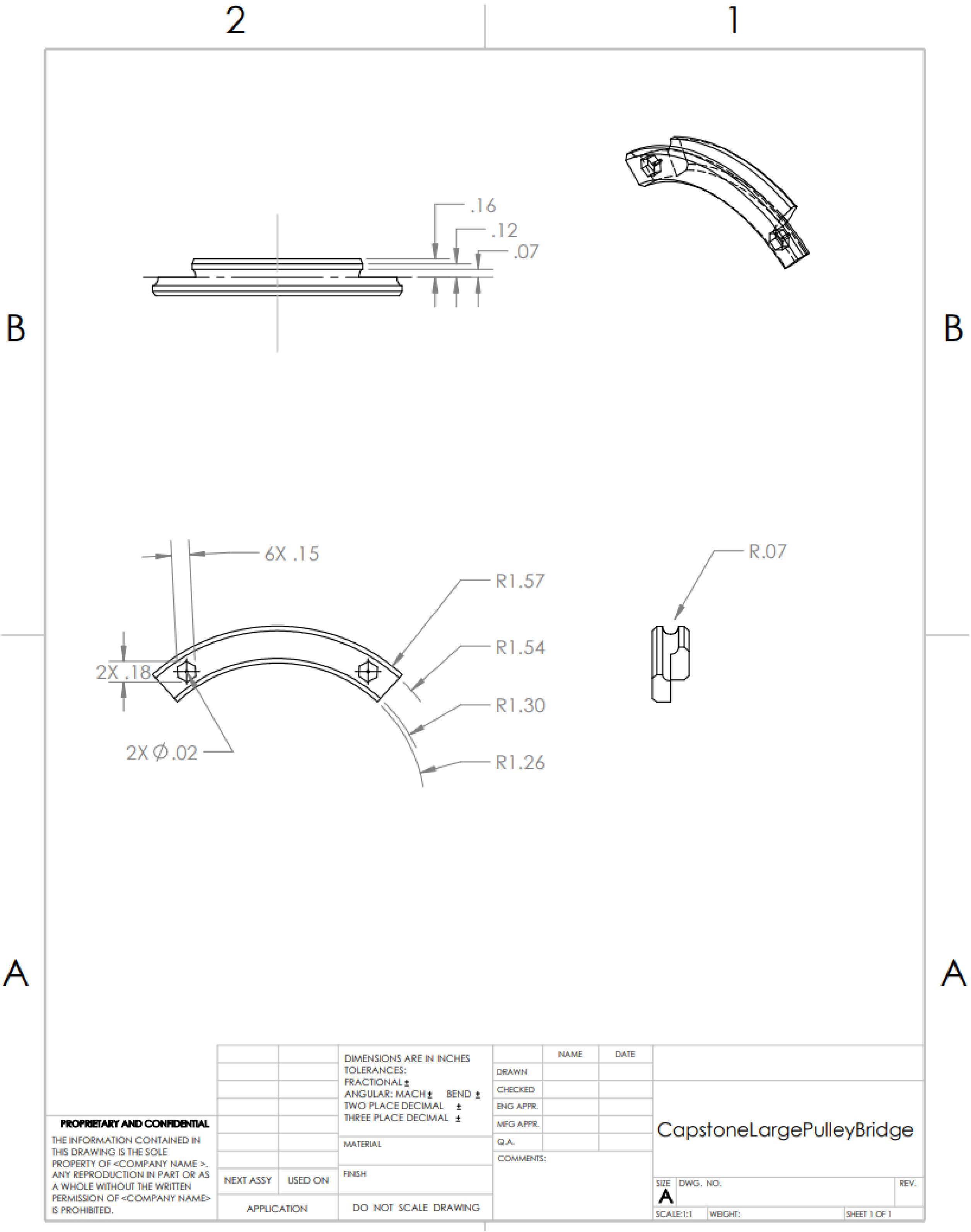
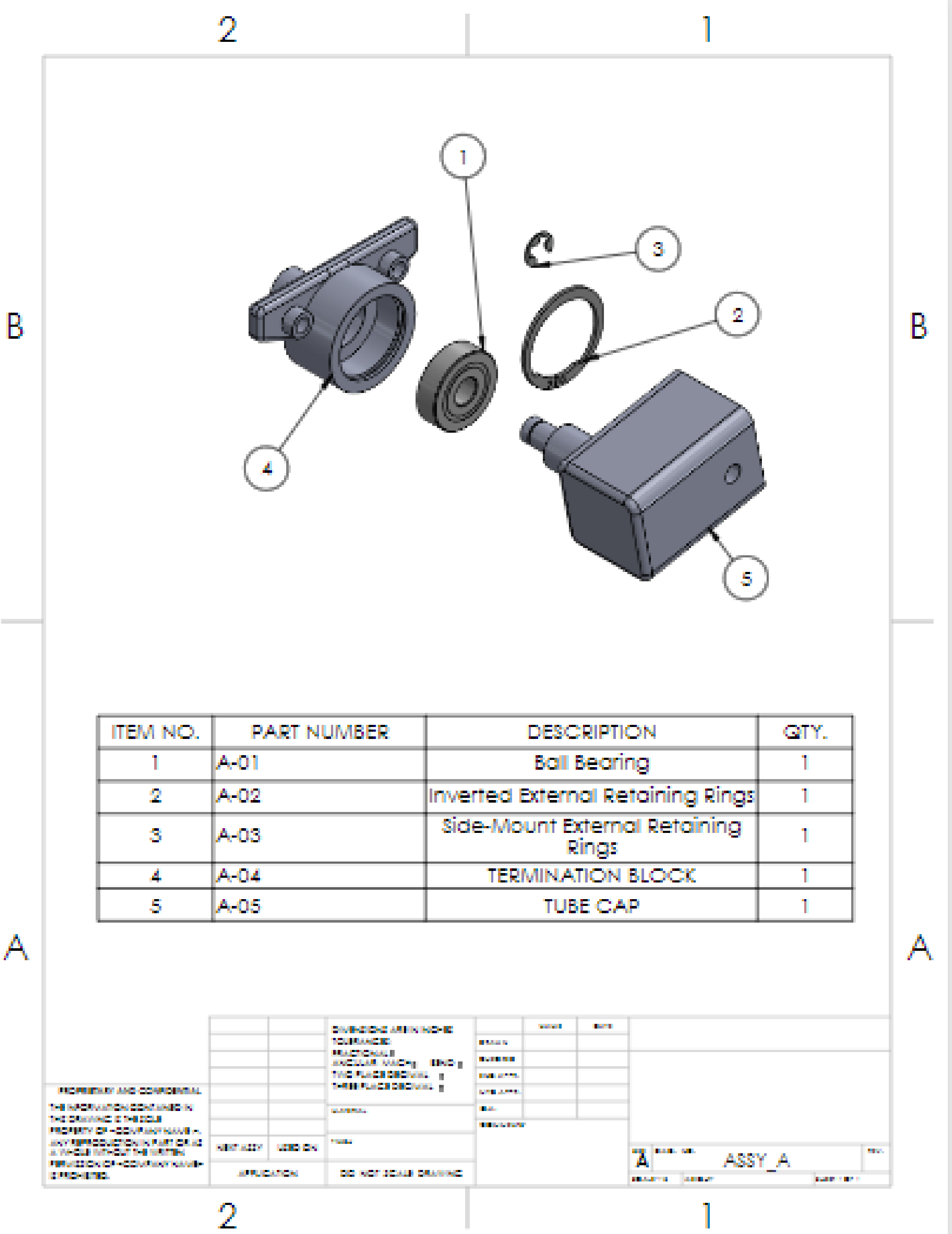


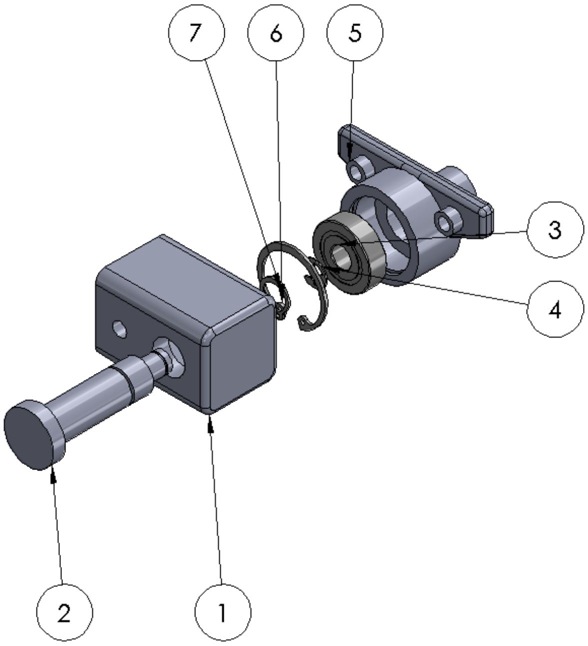
Figure 54: Pulley Bridge Drawing

13.2 *Appendix B: Final Design Drawings*



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	A-01	Ball Bearing	1
2	A-02	Inverted External Retaining Rings	1
3	A-03	Side-Mount External Retaining Rings	1
4	A-04	TERMINATION BLOCK	1
5	A-05	TUBE CAP	1

Figure 55: Termination Block Assembly



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	A-01	Tube Cap	1
2	A-02	Shaft	1
3	A-03	Ball Bearing	1
4	A-04	Side-Mount External Retaining Rings	1
5	A-05	Termination Block	1
6	A-06	Internal Retaining Ring	1
7	A-07	External Retaining Ring	1

Figure 56: Termination Block Assembly

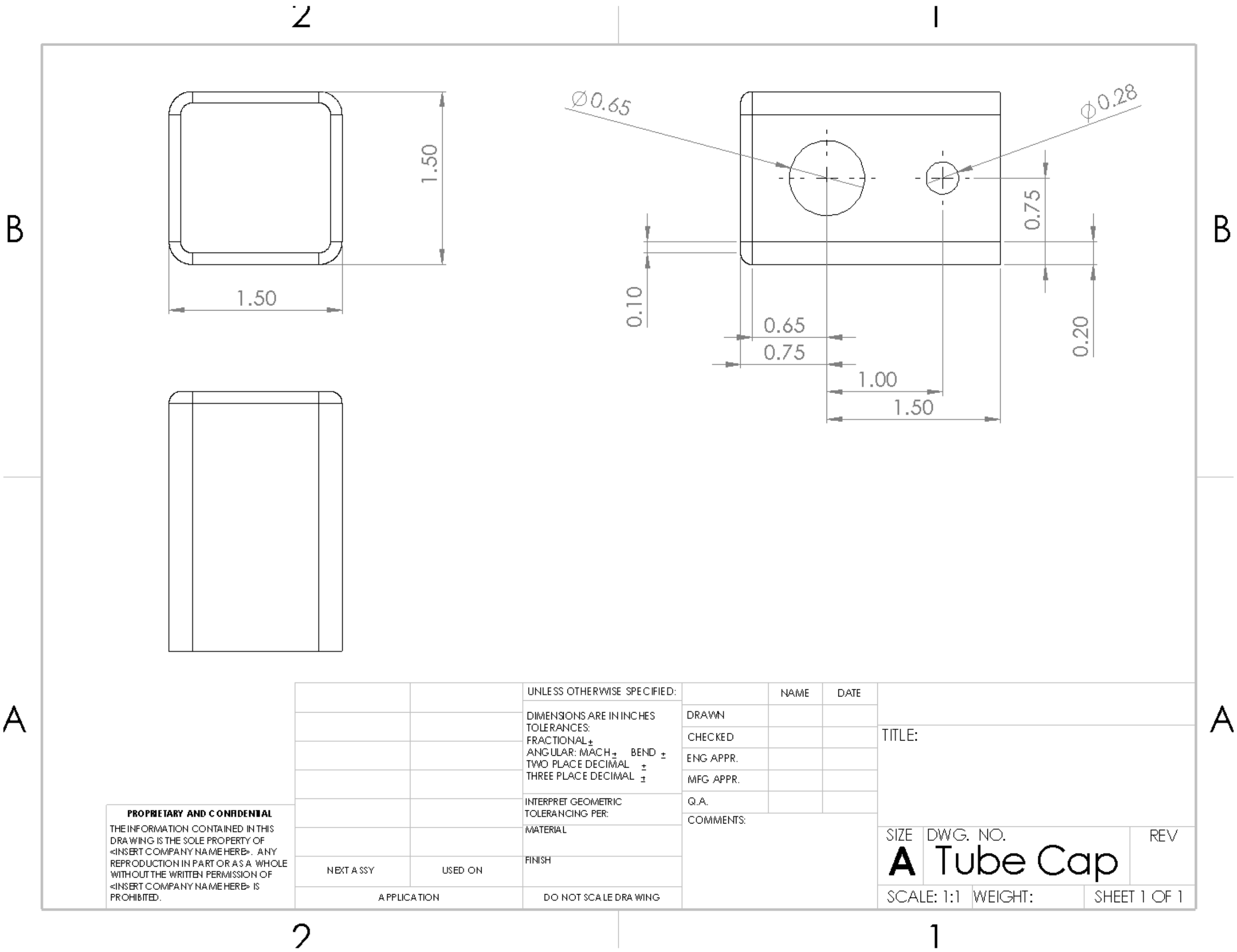


Figure 57: Tube Cap Drawing

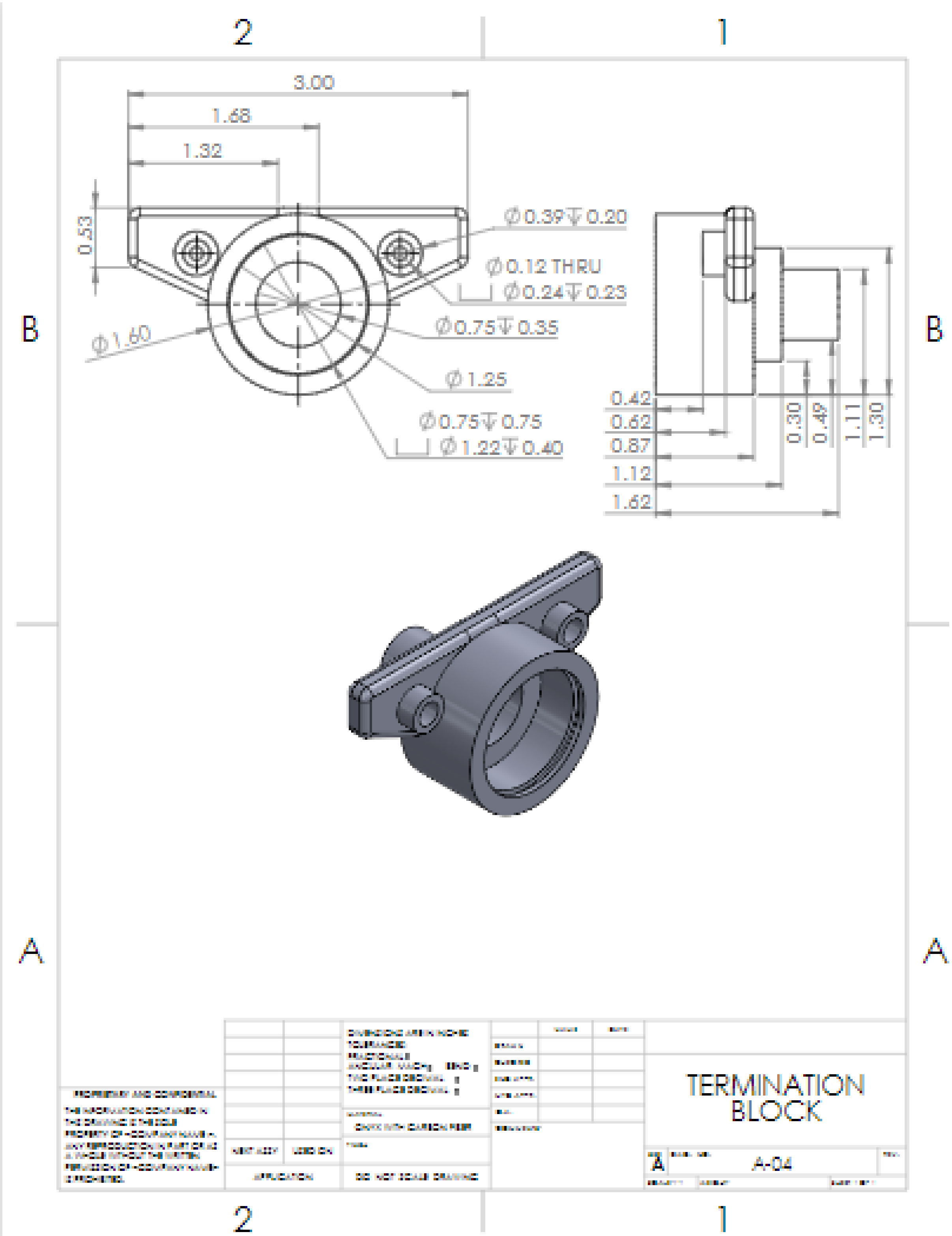


Figure 58: Termination Block

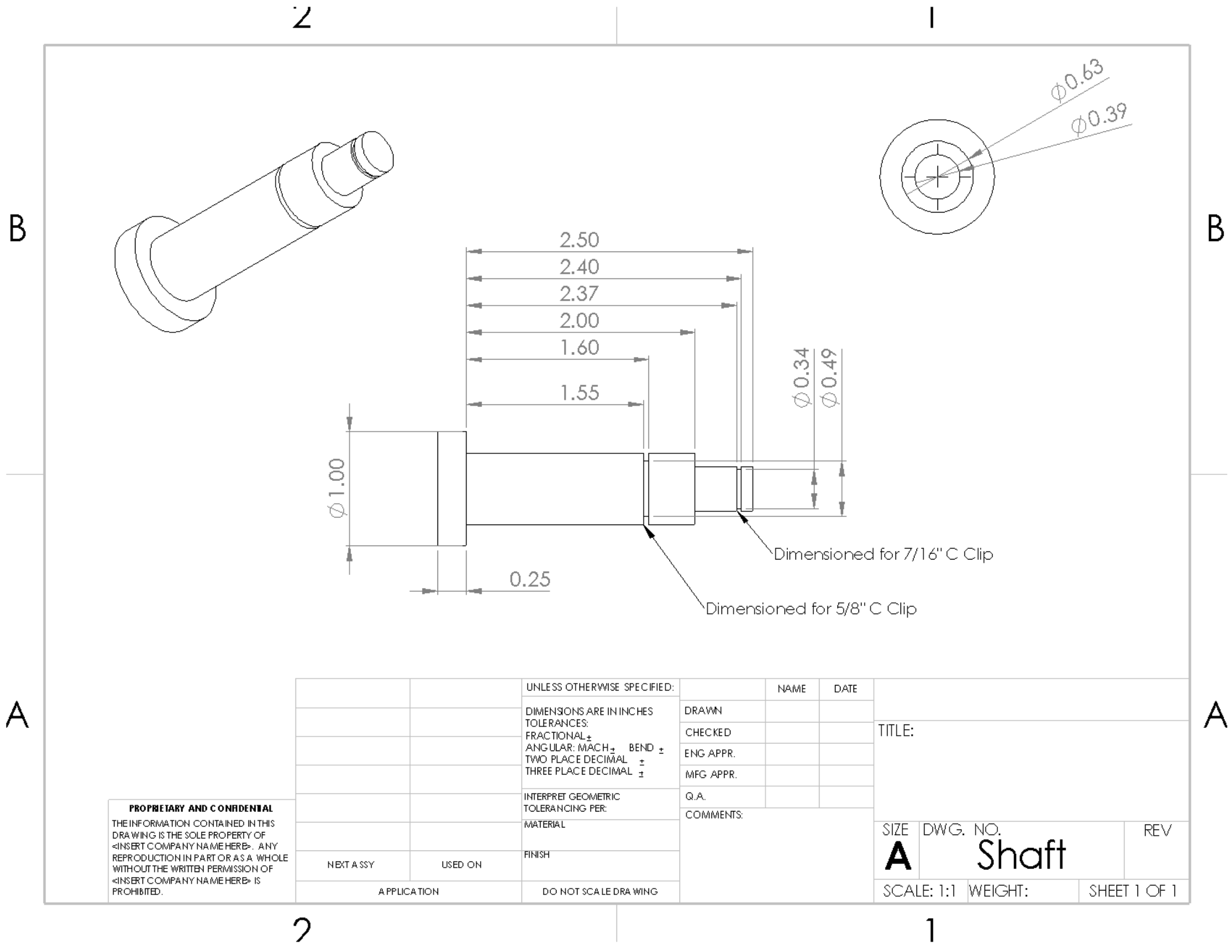


Figure 59: Shaft Drawing

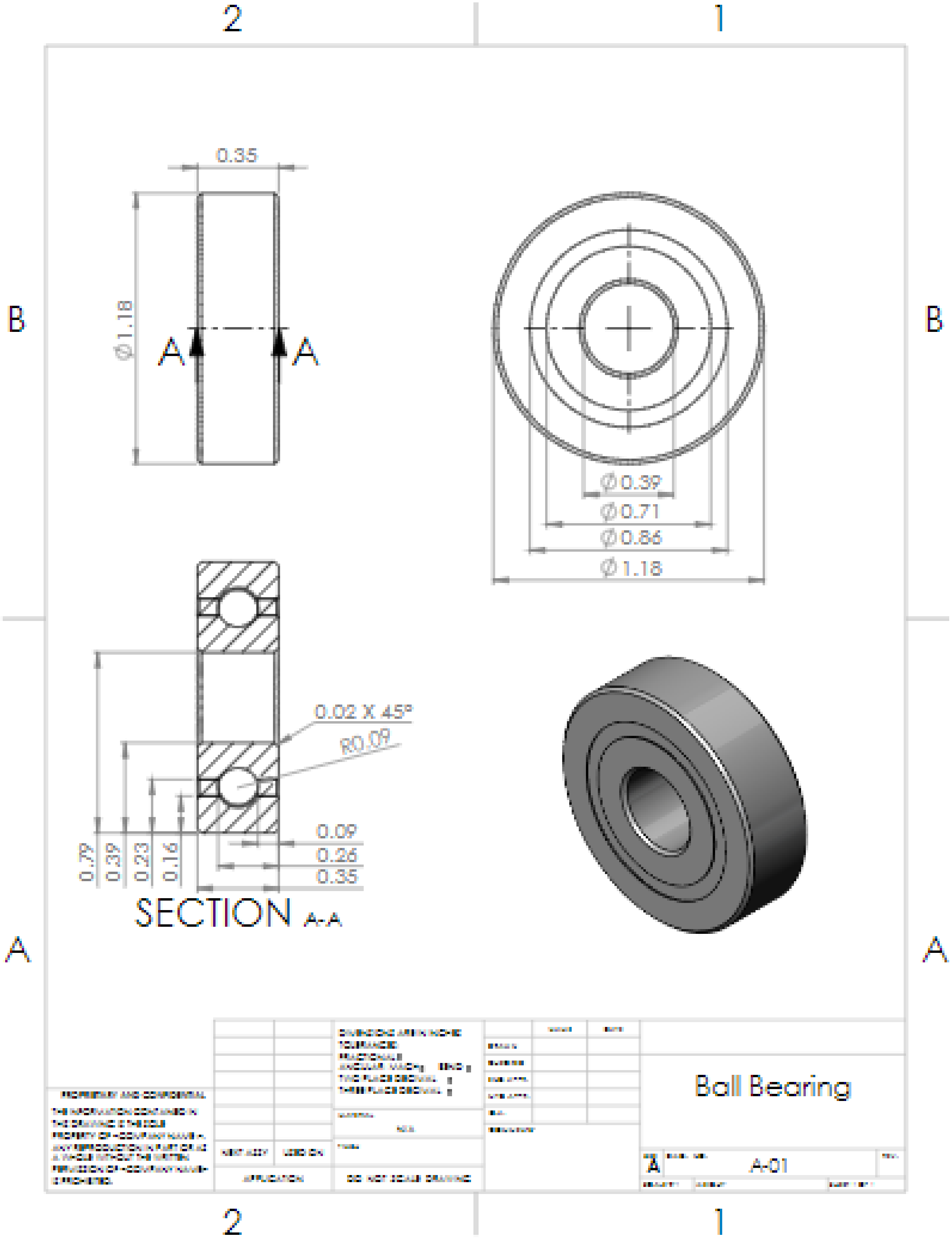
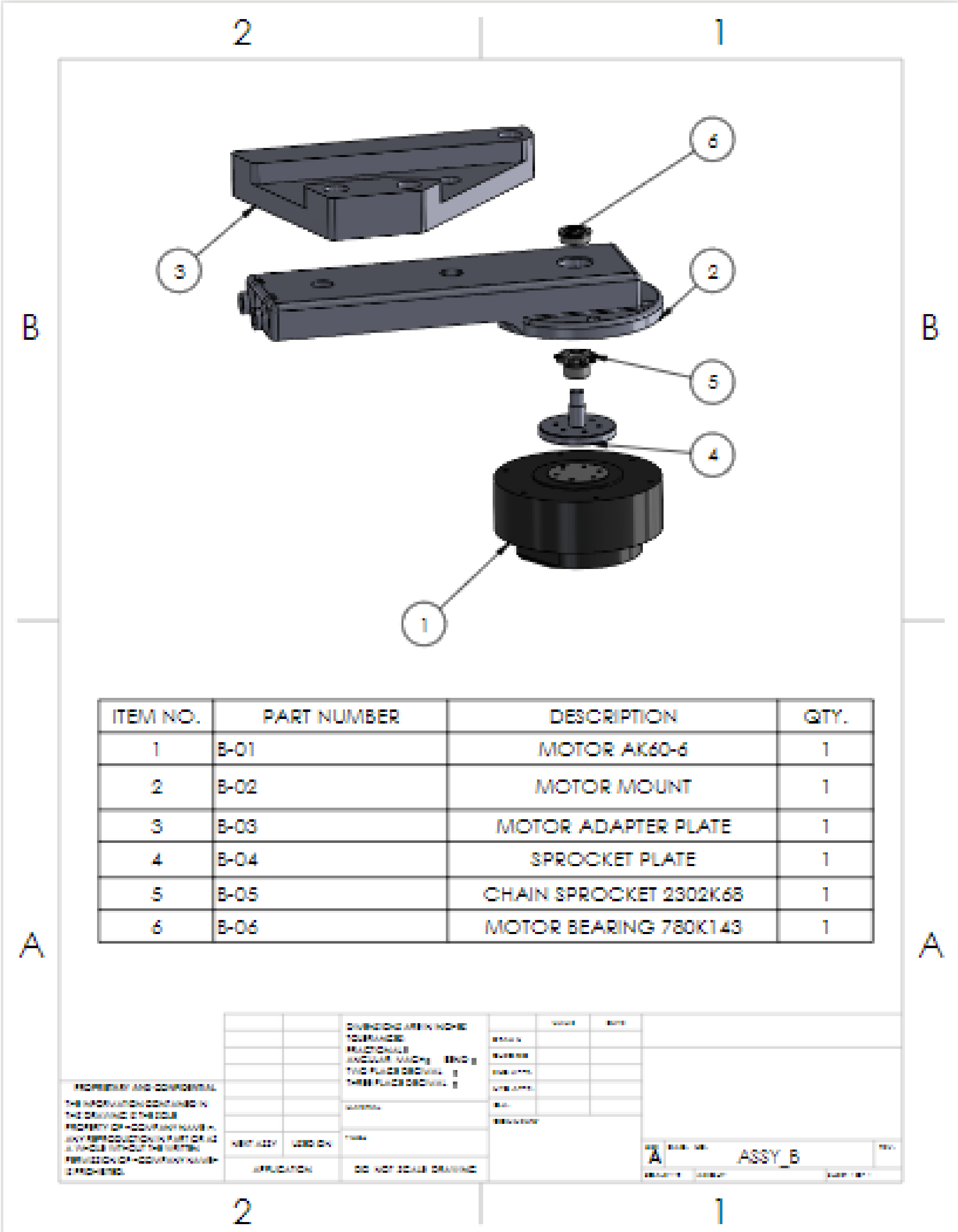


Figure 60: Ball Bearing Drawing



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	B-01	MOTOR AK60-6	1
2	B-02	MOTOR MOUNT	1
3	B-03	MOTOR ADAPTER PLATE	1
4	B-04	SPROCKET PLATE	1
5	B-05	CHAIN SPROCKET 2302K68	1
6	B-06	MOTOR BEARING 780K143	1

Figure 61: Motor Mount Assembly

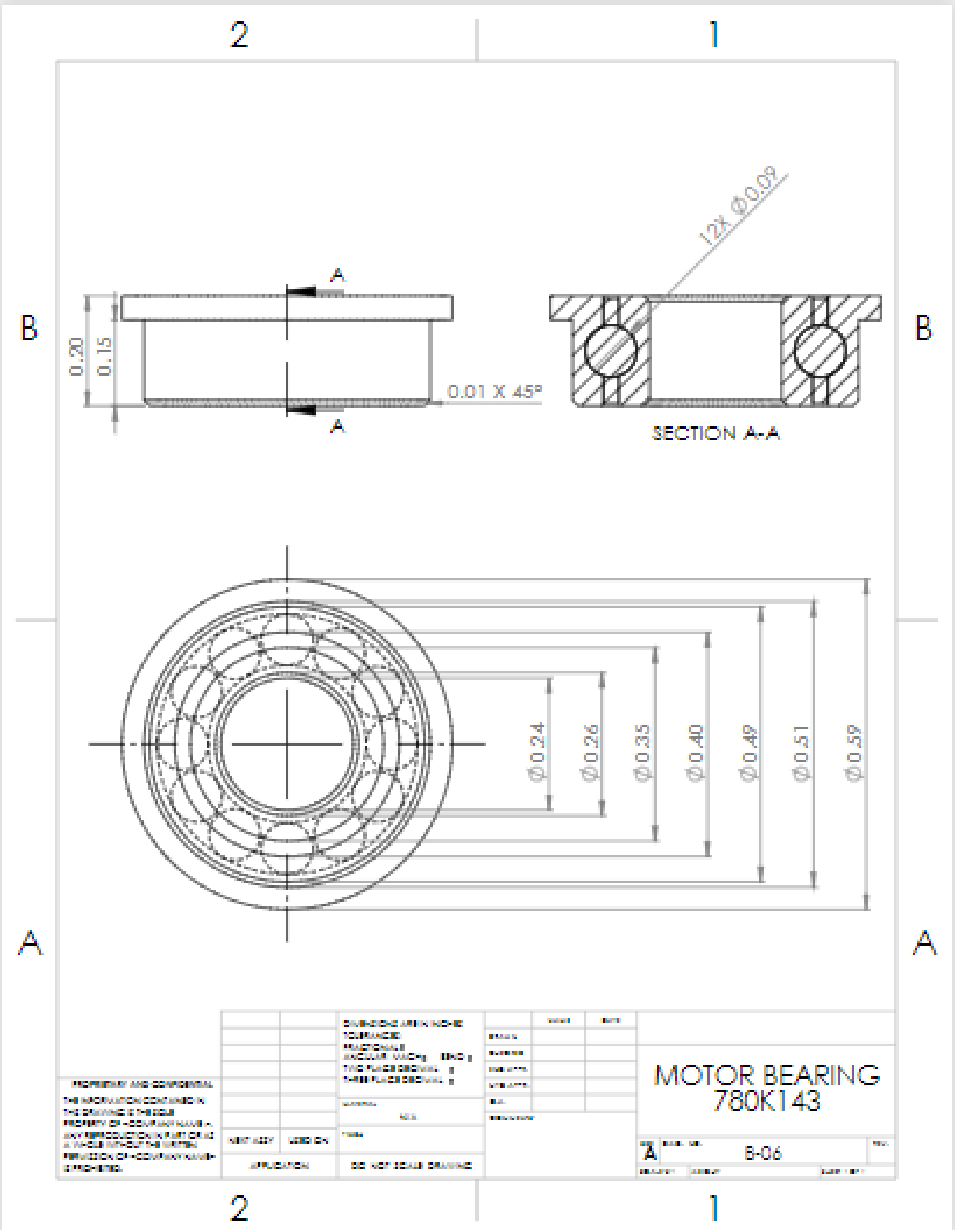


Figure 62: Motor Bearing Drawing

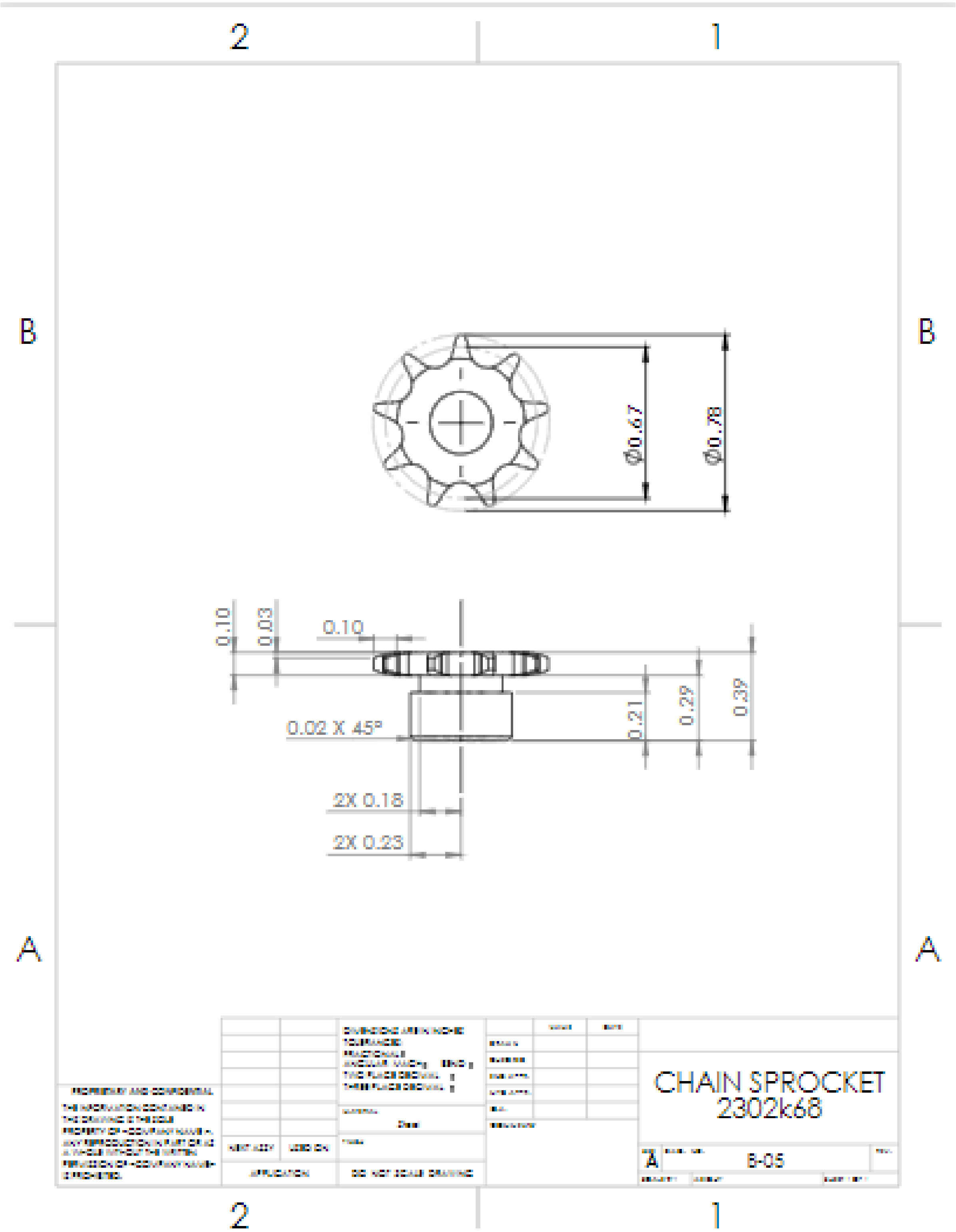


Figure 63: Chain Sprocket Drawing

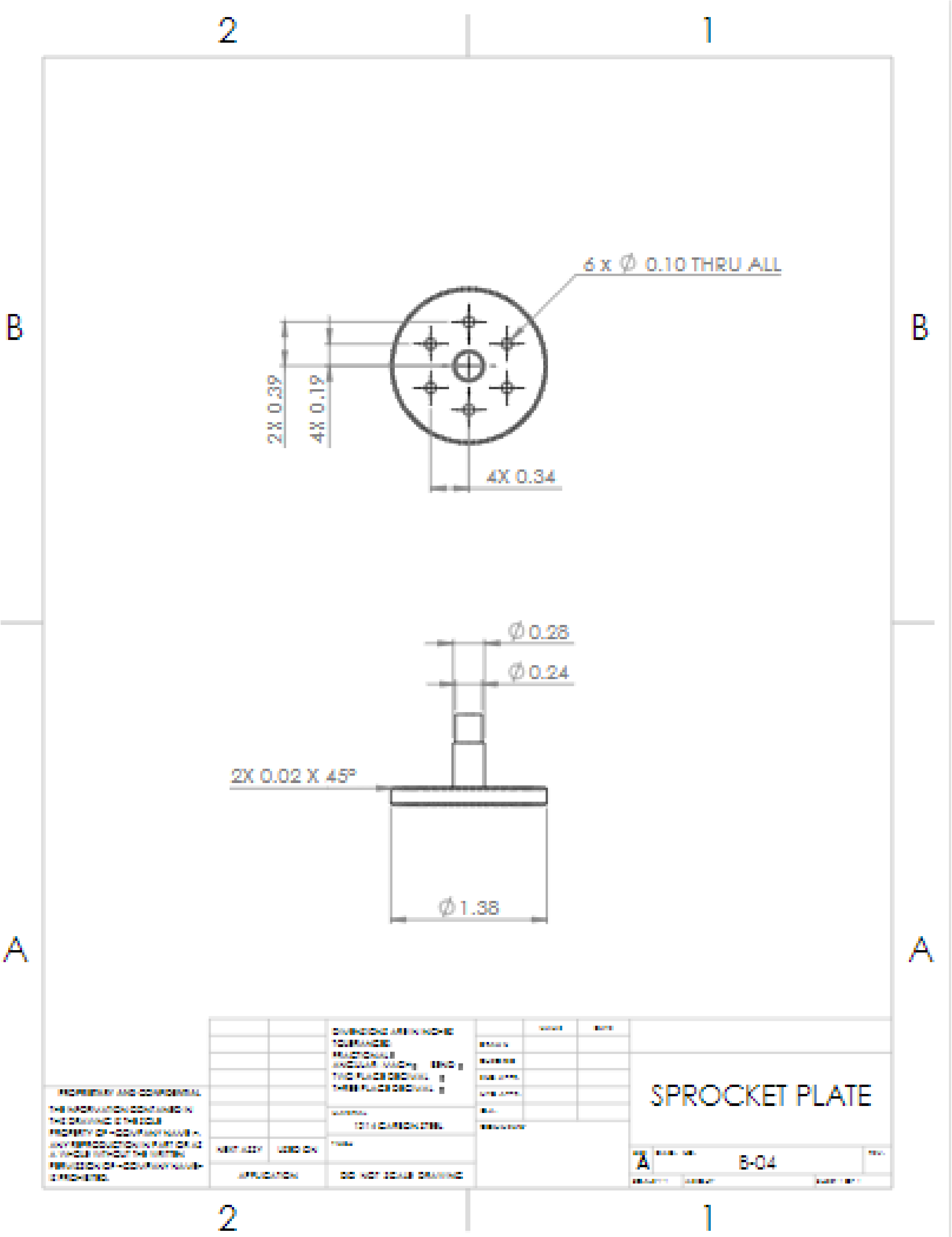


Figure 64: Sprocket Plate Drawing

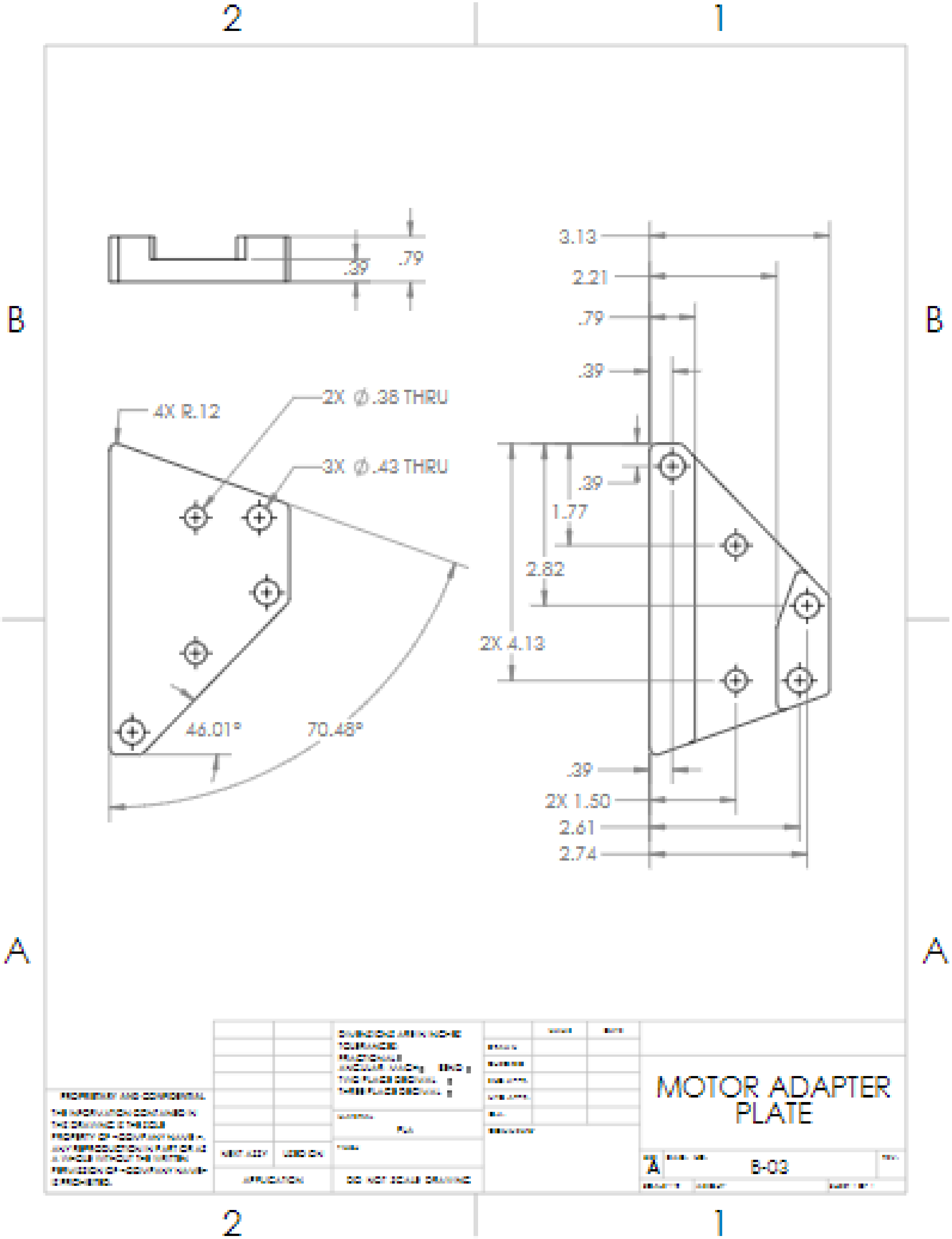


Figure 65: Motor Plate Adapter Drawing

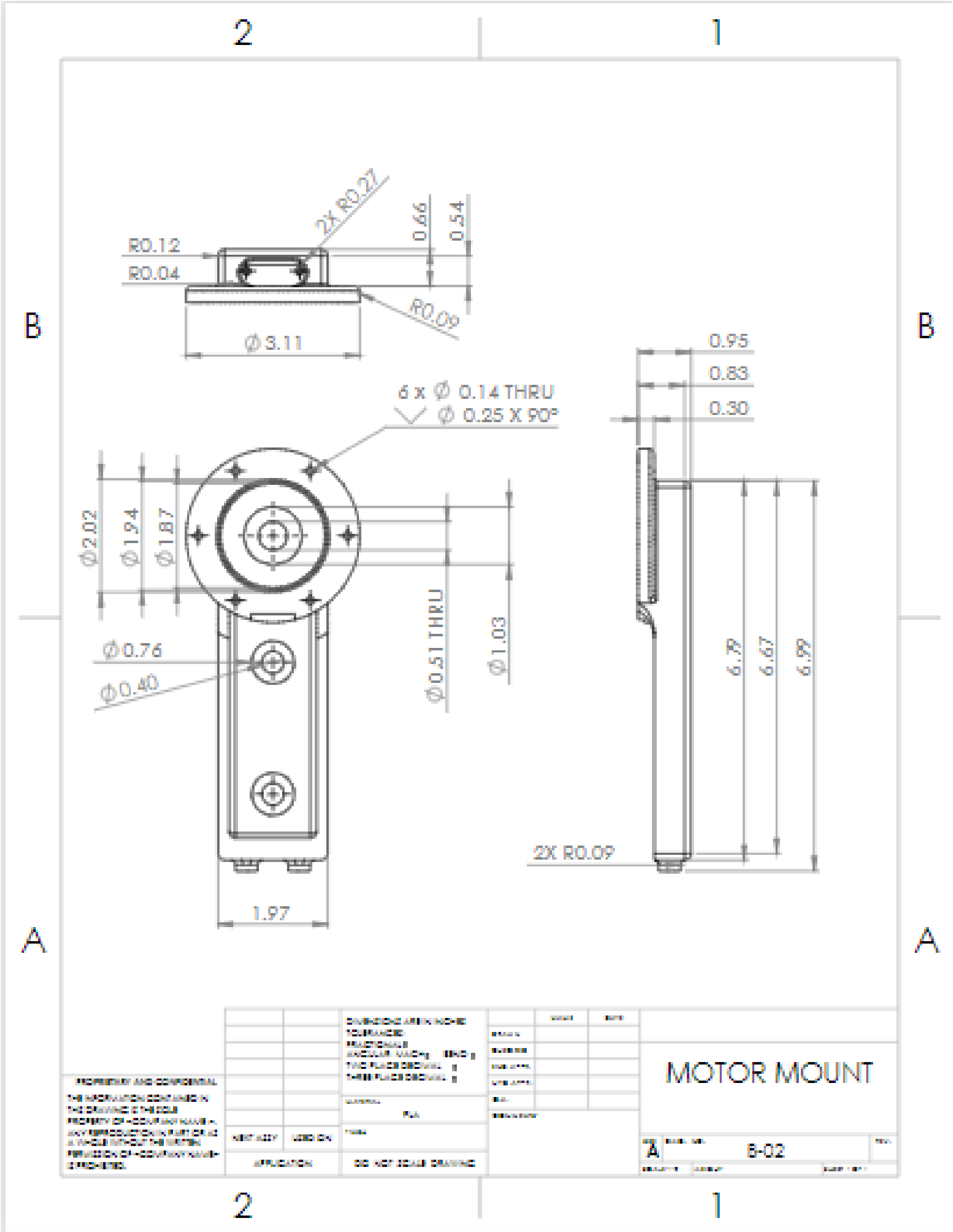


Figure 66: Motor Mount Drawing

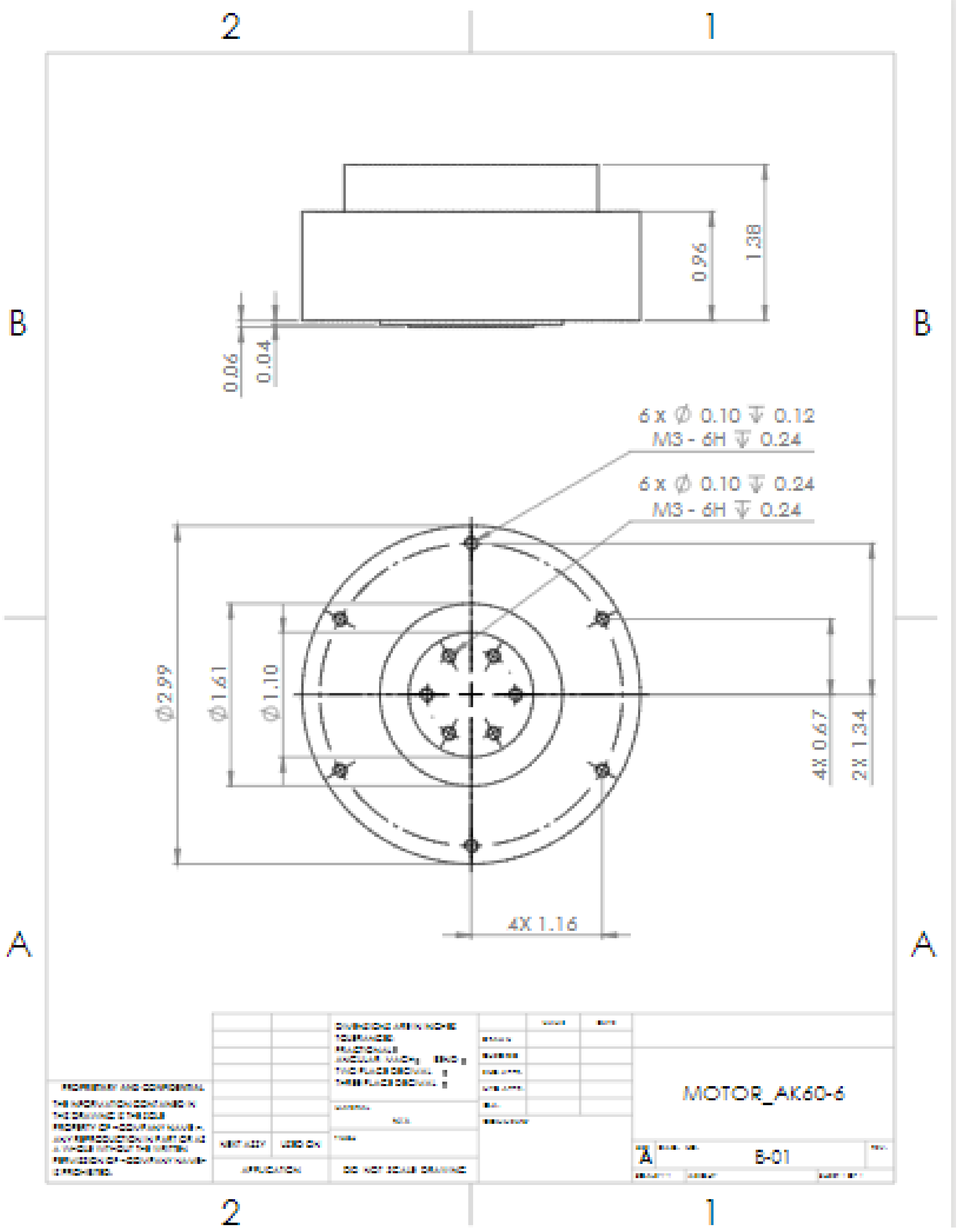
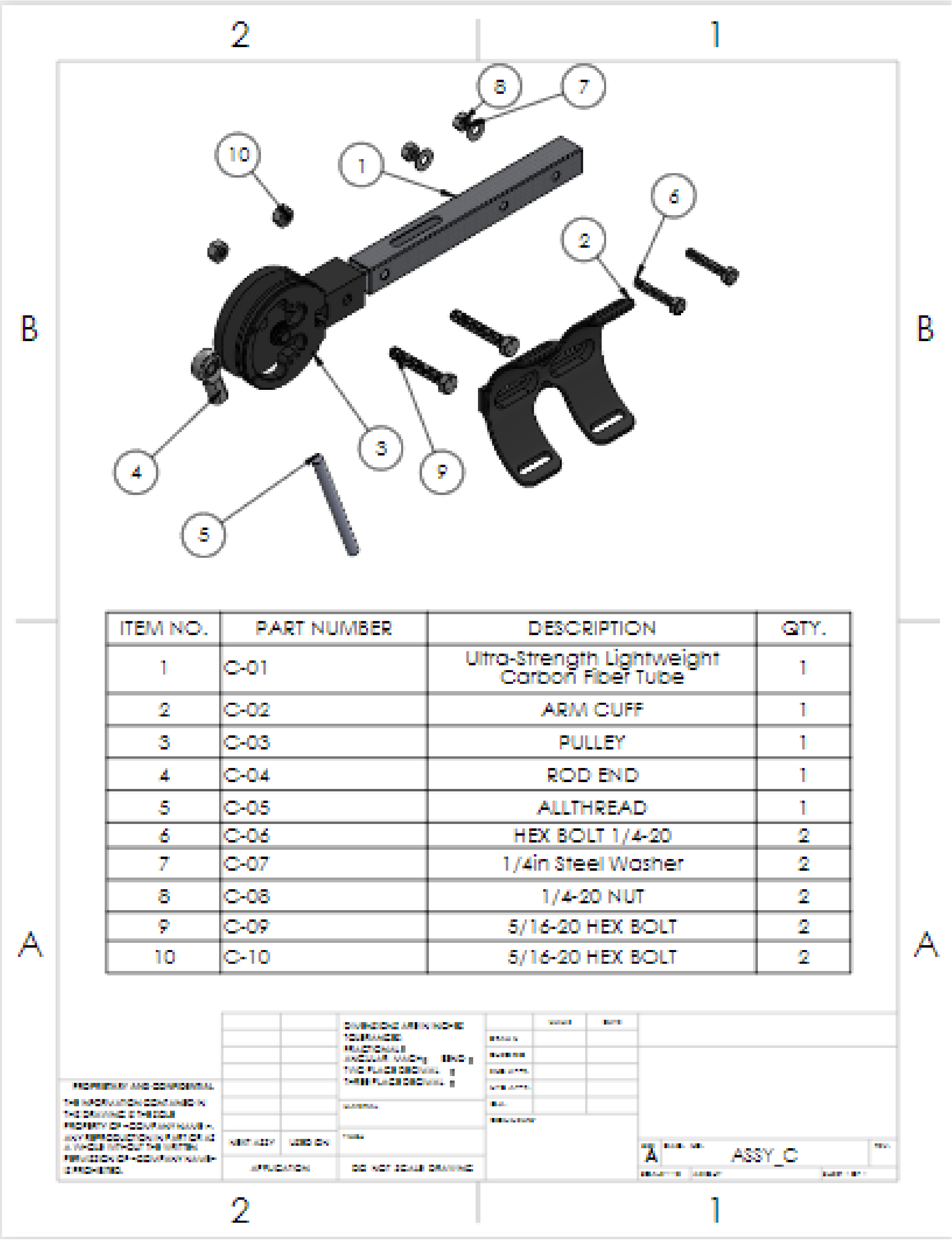


Figure 67: Motor Drawing



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	C-01	Ultra-Strength Lightweight Carbon Fiber Tube	1
2	C-02	ARM CUFF	1
3	C-03	PULLEY	1
4	C-04	ROD END	1
5	C-05	ALLTHREAD	1
6	C-06	HEX BOLT 1/4-20	2
7	C-07	1/4in Steel Washer	2
8	C-08	1/4-20 NUT	2
9	C-09	5/16-20 HEX BOLT	2
10	C-10	5/16-20 HEX BOLT	2

Figure 68: Arm Assembly Exploded View

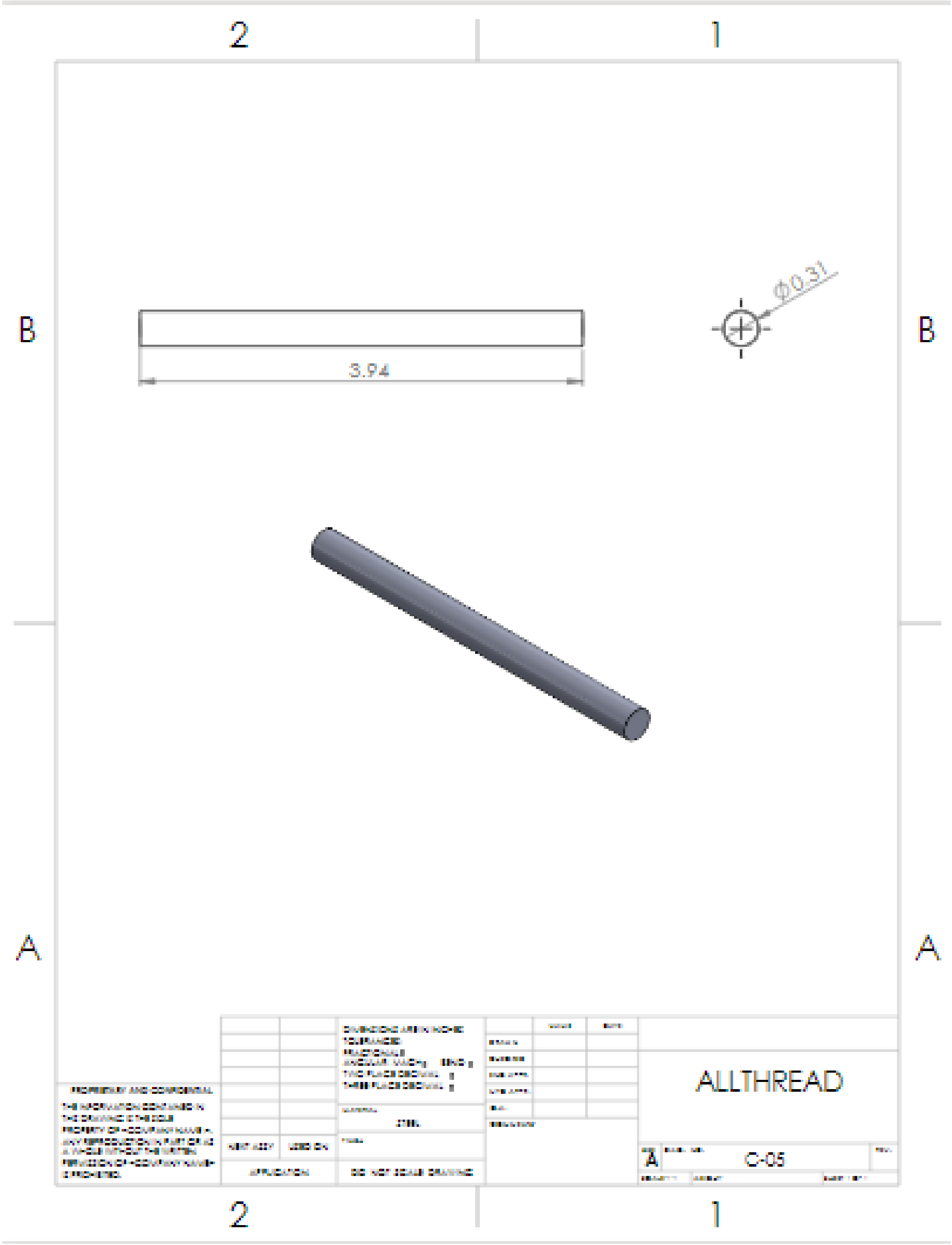


Figure 69: All-thread Drawing

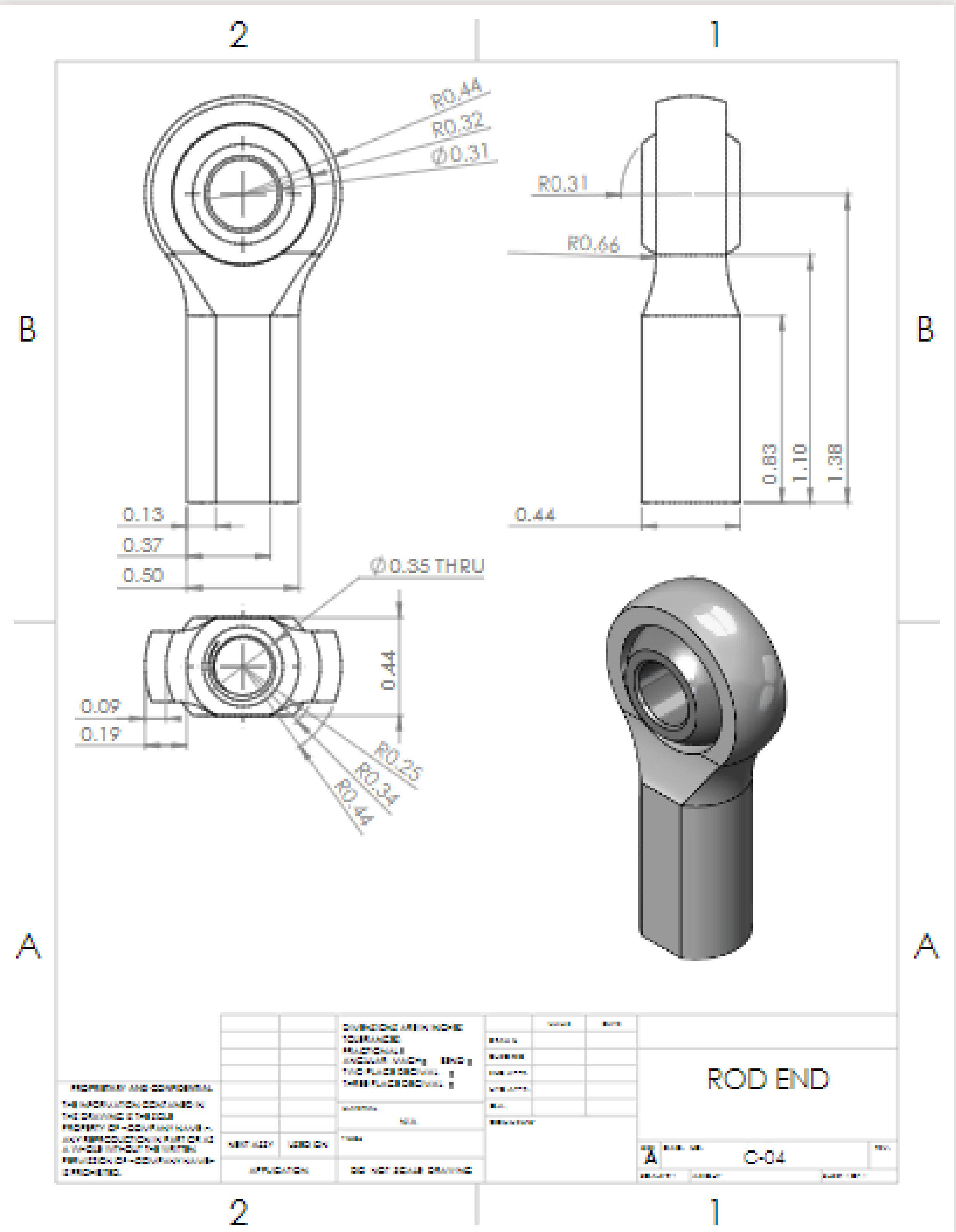


Figure 70: Rod End Drawing

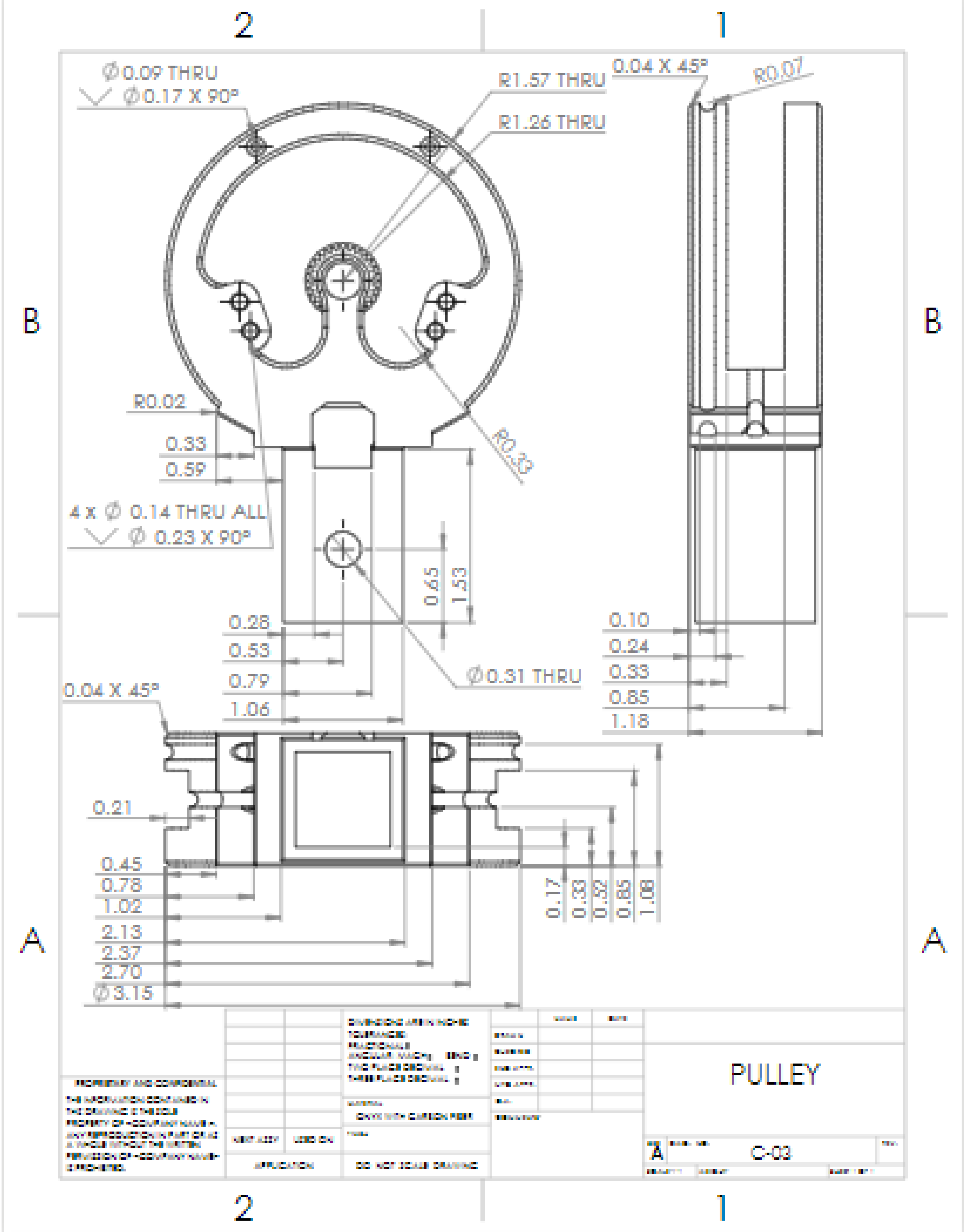


Figure 71: Pulley Drawing

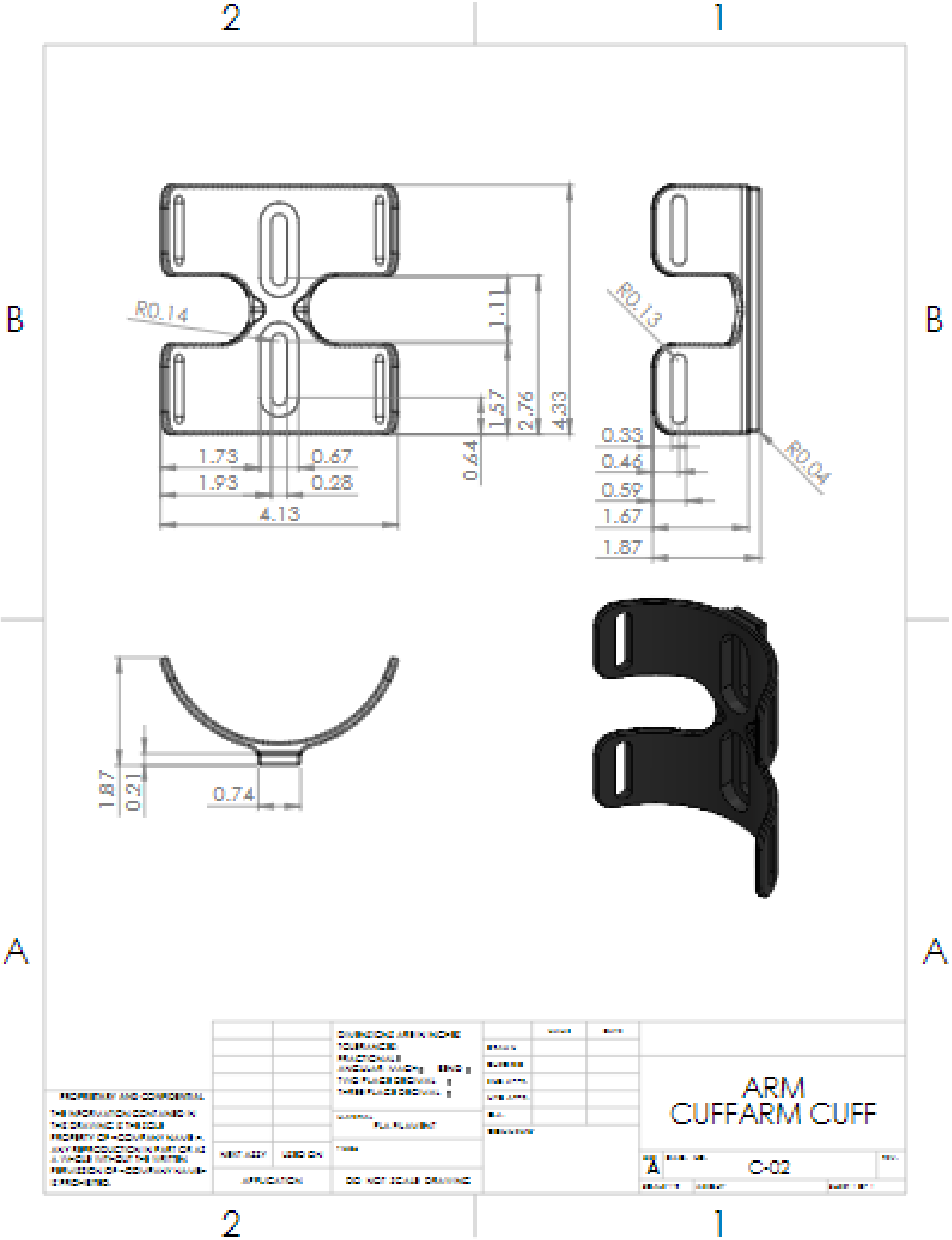


Figure 72: Arm Cuff Drawing

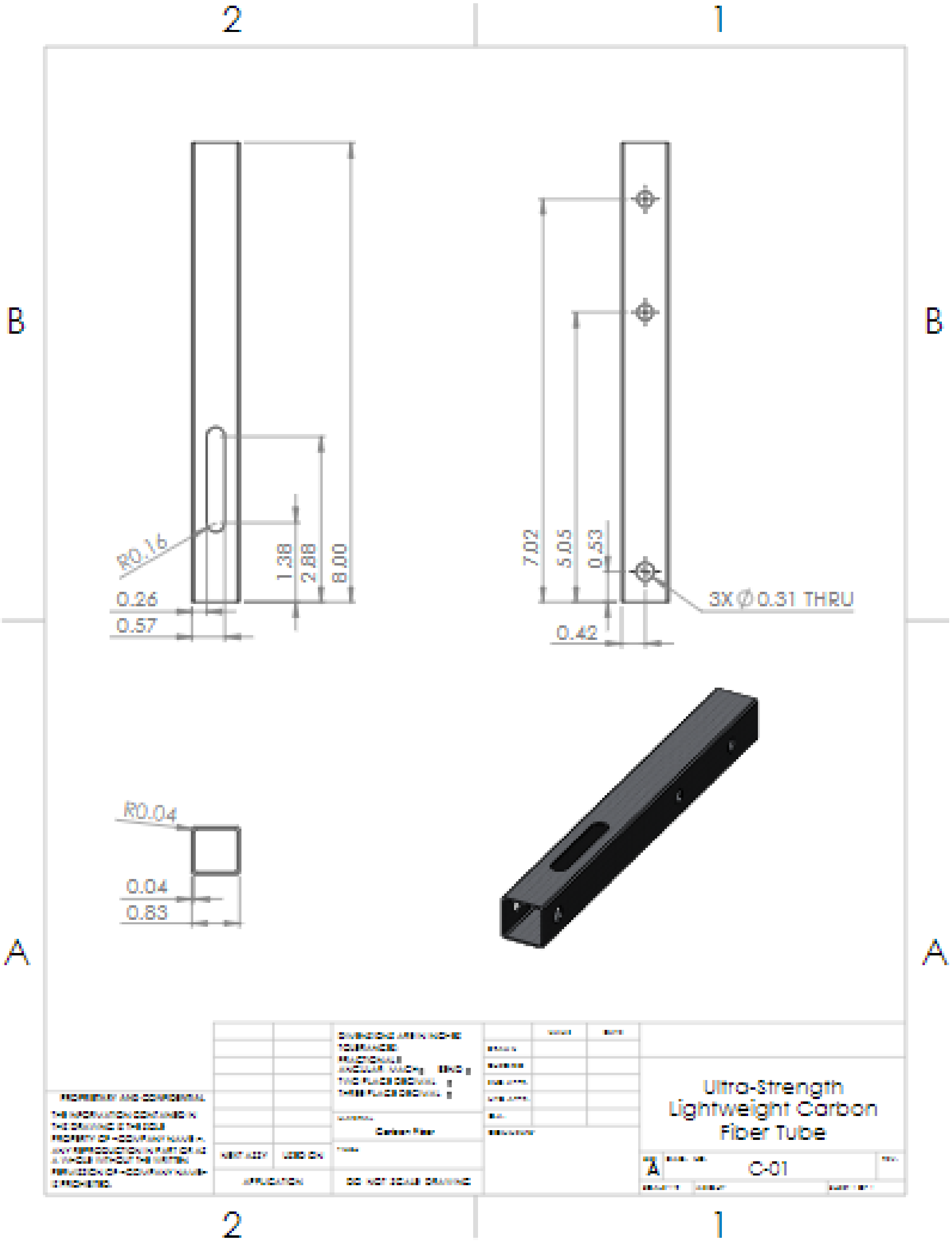


Figure 73: Carbon Fiber Tube Drawing

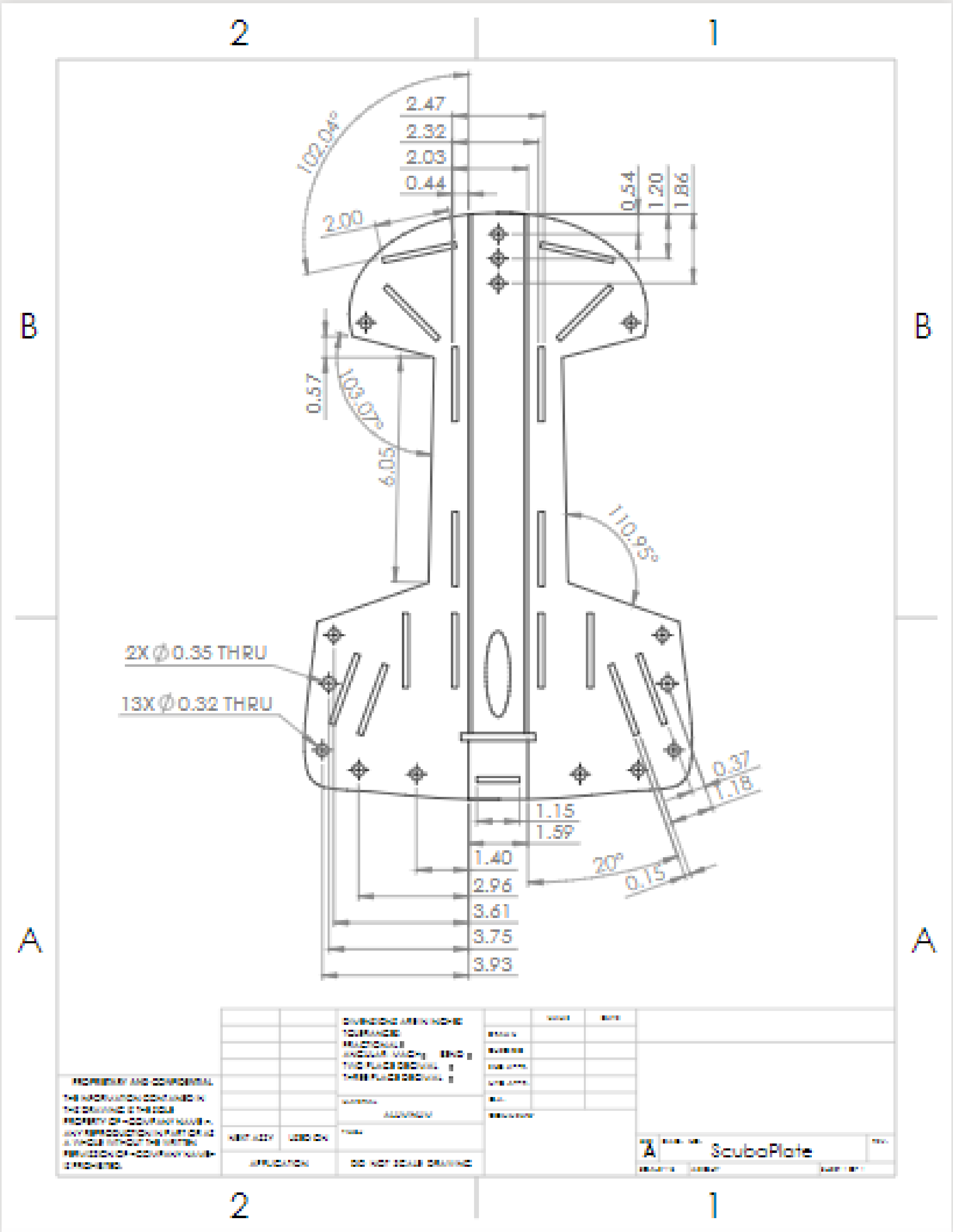


Figure 74: Scuba Backplate Drawing

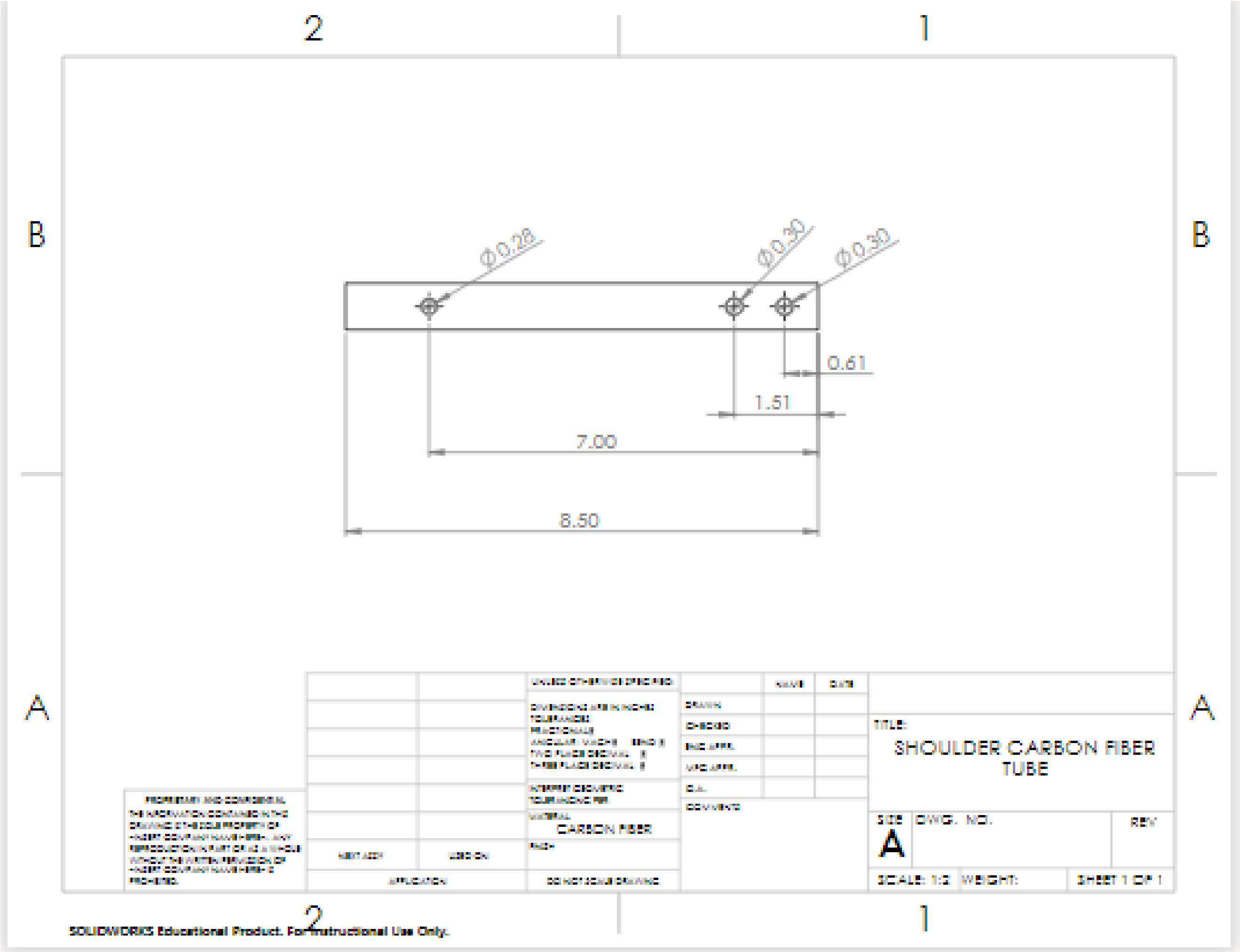


Figure 75: Shoulder Carbon Fiber Tube