

# **Lerner Robotic Arm**

## **Final Report**

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## **DISCLAIMER**

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

## EXECUTIVE SUMMARY

The Lerner Robotic Arm is a waist-mounted wearable robotic exoskeleton developed by a five-member NAU capstone team for project sponsor Dr. Zachary Lerner at the NAU Biomechatronics Lab. The device is designed to assist stroke survivors with upper-limb mobility impairment by providing active gravity compensation at the elbow joint, allowing users to lift and move their affected arm with reduced effort. The project was funded by a \$4,000 grant from W.L. Gore, with a net working budget of approximately \$3,800 after processing fees.

The team identified five customer requirements (CRs) in collaboration with Dr. Lerner: Comfort, Ability to Sit in a Chair, Accessibility, Durability, and Low-Profile design. These requirements were translated into five measurable engineering requirements (ERs): 3 Degrees of Freedom (DoF), a manufacturing cost below \$2,000, a motor speed exceeding 10 rpm, a battery life greater than 30 minutes, and a total arm weight under 2 kg.

The final design consists of three subassemblies: a passive degree-of-freedom hinge that allows lateral arm movement, two active motor joints that power vertical arm motion, and a padded end effector cuff that secures the user's forearm. The arm links are machined from carbon fiber rectangular tubing, and motor mounts are 3D printed using ONYX material with continuous carbon fiber inlay for reinforced strength. The CubeMars AK45-36 motors were selected based on torque analysis showing a required hip torque of 11.5 N·m.

Testing confirmed that the device met or exceeded all engineering requirements. The arm weighed 1.3 kg, well under the 2 kg target. All 3 degrees of freedom were achieved, with 2 active and 1 passive. Motor speed testing measured 14.91 rpm, exceeding the 10-rpm target. Battery endurance testing projected a two-motor runtime of approximately 34 minutes, meeting the 30-minute requirement. Comfortability testing with multiple users, including Dr. Lerner, confirmed the device was comfortable to wear and did not restrict normal daily movement. The device also successfully passed chair and bump tests, validating key customer requirements. The completed arm will be handed off to the NAU Biomechatronics Lab for continued development, with future plans to implement an advanced control algorithm and multi-user adjustability.

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# 1 BACKGROUND

## 1.1 Project Description

Strokes are the leading cause of upper limb disability; survivors often report loss of mobility in one arm which limits daily use. Our hope is to develop a robotic arm which could assist a client's arm so that they can move their arm with ease of use. The robotic arm will be mounted at the waist, low-profile, lightweight, and provide active gravity compensation. The end effector will be attached to the elbow. The project sponsor is Dr. Zach Lerner.

Our budget is a generous 4000 dollars, and W.L. Gore is largely responsible for the funding. We plan to raise at least 400 dollars as this is the fundraising minimum (10%), however we hope to raise much more.

We believe our project is important as there are over 795,000 people each year in the US who experience a stroke. Around 6.3 million people are living with stroke-related consequences in the US, and some studies suggest 40-70% of survivors are affected by arm paresis (weakness) initially, and among those around half have little function in the following 6 months. We want to help those less fortunate than ourselves and believe that helping survivors regain their independence and ability is a great cause. Additionally, although our design is focused on helping those with upper limb disability from strokes, we hope our design can help anyone with impairment in their arms.

## 1.2 Deliverables

The main deliverables for this project include both physical prototypes and supporting design and analysis work. The outcome should clearly demonstrate a functioning waist-mounted robotic arm that provides active gravity compensation, is low profile and supports the elbow joint.

We plan to create a SolidWorks design for the full robotic arm system, including all parts, linkages, and motors. From there we will make engineering drawings and part lists which will be used for manufacturing and assembly. Working prototypes will be built from this model we will first try to replicate the ability of the arm with a rough mockup using cheaper materials however as we go into later prototypes we will use 3d printed carbon fiber and machined parts to get the best possible product.

Once we have built our first prototype we will see what works and what doesn't through physical testing and analysis, we will then go back to our CAD model to modify anything that needs to be changed and we will reiterate this process until we are happy with our final design and it has met our success metrics.

### **1.3 Success Metrics**

To define our success, we must assess what robotic arm is capable of. The robotic arm must successfully support the user's arm and provide smooth gravity compensation. The robotic arm must be lightweight and should allow the user to comfortably rest their arm by their side.

We will judge success based on how well our final design performs and to what degree they meet our design requirements through analysis and testing. Functionally, the arm should produce enough torque at the elbow to balance the weight of the forearm and the hand. We can check this through engineering calculations from our kinematic model and testing prototype's ability to hold the arm in different positions.

The arm should stay under a specified weight limit to maintain the low-profile description. SolidWorks will be used to measure the weight of the arm by using material properties, and we will verify the strength and stiffness using finite element analysis before we build our parts. Once the first prototype is made, we can weigh it and compare reality to simulation.

Energy efficiency and control are also key. The motors should use as little power as possible while still providing smooth and responsive motion. We can test this by measuring current draw and comparing how different motor setups (direct drive vs. transmission) perform.

Finally, overall comfort and natural movement will be checked by testing the prototypes to see if the elbow cup rests comfortably. If the robotic arm meets these requirements, the project can be considered a success.

## **2 REQUIREMENTS**

### **2.1 Customer Requirements (CRs)**

The primary customer requirements for the wearable robotic arm were identified through discussion with the project sponsor, Dr. Zach Lerner, and analysis of stroke survivors with limited upper-limb mobility. Five core requirements were established: Comfort, Ability to Sit in a Chair, Accessibility, Durability, and Low-Profile design. Ability to Sit in a Chair and Low-Profile are rated highest in importance, as the device must integrate naturally into seated daily activities without obstructing posture or creating bulk. Comfort ensures the device can be worn for extended periods without causing fatigue or discomfort to the affected limb. Accessibility reflects the need for the device to be operable by individuals with limited dexterity or strength, ensuring it can be donned, doffed, and controlled with minimal assistance. Durability ensures the device withstands repeated mechanical loading across therapy sessions and daily use.

These requirements directly reflect the lived experiences of the intended users. The high weighting placed on Ability to Sit in a Chair recognizes that many stroke survivors spend significant time seated, and a device that restricts natural seated posture would limit adoption. Low-Profile design promotes confidence in public use and reduces social barriers to wearing the device regularly. Comfort and Accessibility together ensure that the device does not impose additional physical or cognitive burden on the user. Durability, while lower in relative weight, remains essential for long-term reliability and cost-effectiveness. Collectively, these customer requirements form the foundation for translating user expectations into quantifiable engineering goals.

## **2.2 Engineering Requirements (ERs)**

The engineering requirements translate the customer's needs into quantifiable design targets that can be measured and verified. The robotic arm will feature 3 Degrees of Freedom (DoF) to accommodate the range of motion necessary for functional arm and elbow movements during rehabilitation and daily tasks. To maintain affordability for both research and clinical applications, Manufacturing Cost is constrained to under \$2,000. Motor Speed is targeted at greater than 10 rpm to replicate realistic human arm motion speeds during assisted movements. Battery Life must exceed 30 minutes to support a complete therapy session or typical use period without interruption. To minimize user load and preserve comfort during extended wear, the total system Weight is constrained to under 2 kg.

Manufacturability and key tradeoffs are also captured through the engineering requirement correlations. Increasing Degrees of Freedom introduces negative pressure on both Manufacturing Cost and Battery Life, reflecting the added mechanical and electrical complexity. Similarly, Manufacturing Cost and Speed exhibit a negative correlation, as higher-performance motors carry greater expense. Conversely, Speed, Battery Life, and Weight share positive correlations, as heavier battery systems can support both longer runtimes and faster motor operation. Weight is most strongly tied to Comfort and Low-Profile in the relationship matrix, while Degrees of Freedom is the primary driver of Ability to Sit in a Chair. Manufacturing Cost is the dominant engineering lever for Accessibility. These relationships ensure that each engineering decision is traceable to customer priorities and provides concrete benchmarks for prototype evaluation and future optimization.

## 2.3 House of Quality (HoQ)

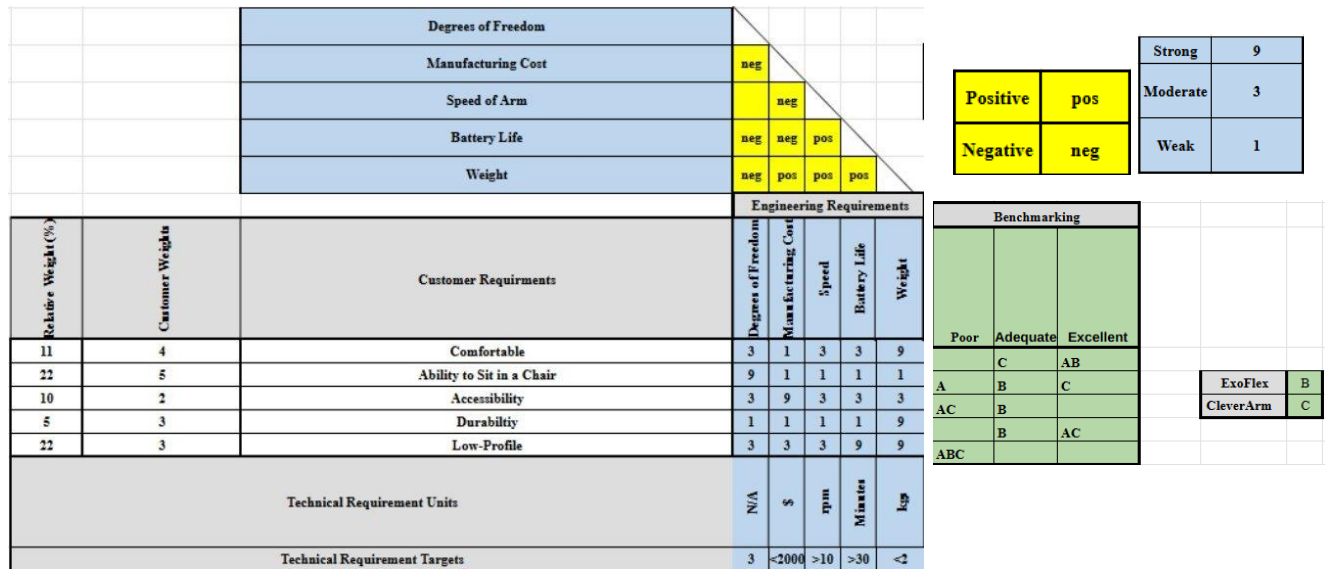


Figure 1: House of Quality relating Customer and Engineering Requirements

## 3 Research Within Your Design Space

### 3.1 Benchmarking

For benchmarking, the group decided to look at four different robotic arms with 3 being stationary and one being a wearable robot. The first benchmark was AGREE's exoskeleton which is made for upper limb rehabilitation. There are multiple different ways it interacts with the user such as passive-assisted, active-assisted, and active-resistive [1]. The interesting part of this design is a spring pulley antigravity system that helps to minimize torque requirements [1]. The next was a robotic arm by CLEVERarm that is again used for upper limb rehabilitation. This design was focused on compactness and having many degrees of freedom [2]. In comparison to AGREE's it is compact as AGREE's is quite bulky while CLEVERarm is sleek and compact [2]. As well as its compactness, it has eight different degrees of freedom to help the rehabilitation with six being active and two being passive [2]. The third arm was also a robot for rehabilitation of upper limbs by ExoFlex. This was a hybrid exoskeleton which means it has both rigid and soft components [3]. This may not be able to replicate in our design as it would be quite difficult to have an almost crane-like robot that is wearable. The last benchmark was a wearable robot but was not designed to be used for upper limb rehabilitation. The design was made by the client Dr Zachary Lerner to do manual tasks [4]. This will help inform the design to see how to acuate an arm from a wearable device.

## **3.2 Literature Review**

### 3.2.1 Colin Donnellan: Evolution of Robotic Arms [5]

This was information about how robotic arms have evolved from the very beginning. The point of this was to show the progression of them to get into robotic surgical arms being used. It stops at what is considered modern robotics, so it will need research for more modern robotics. This will apply to the project to help show where to start from if the history is known.

### 3.2.2 Colin Donnellan: Robotic arm use for upper limb rehabilitation after stroke: A systematic review and meta-analysis [6]

The study was about how upper limb mobility improved with the use of a robotic arm. The report compiles six different studies to get information. It shows that upper limb mobility was improved in stroke survivors with activity in the arm between 30-60 minutes. This will help the project as the goal is to have our design be able to run for 8 hours but knowing that half an hour can improve mobility is helpful.

### 3.2.3 Colin Donnellan: International Organization for Standardization [7]

These are standards used for human robotic interaction. The standards will help outline the safety to implement while the project is being designed. This will ensure our design meets safety standards.

### 3.2.4 Colin Donnellan: Investigation of the Mounting Position of a Wearable Robot Arm [8]

This was a report talking about the different spots to mount a robot arm. This helped us understand the difficulties in different mounting positions. The robot that the team is designing has been specified from the beginning to be at the hip. This will still help the design process to see what can be done and possible challenges that will involve it.

### 3.2.5 Colin Donnellan: A Review of Robotic Arm Joint Motors and Online Health Monitoring Techniques [9]

The report reviewed commonly used motors for joints in robotic motors. It shows the comparison between several motors to use and how to compare them. This was found before talking to the client Dr Zachary Lerner who then suggested three different motors. Still, this helped explain how to select motors for a robotic arm.

### 3.2.6 Colin Donnellan: Human upper limb and arm kinematics for robot based rehabilitation [10]

The report is an introduction to kinematics and how it was used to help upper limb rehabilitation.

This can be used for the robotic arm that the team will design to help develop an understanding of how to make the arm work. It can be hard using kinematics but may be helpful knowledge to use for inverse kinematics.

### 3.2.7 Colin Donnellan: Effects of two different robot-assisted arm training on upper limb motor function and kinematics in chronic stroke survivors: A randomized controlled trial [11]

The report is background information on how well robot assisted therapy helps in upper limb rehabilitation in stroke survivors. Shows kinematics as well so that they can improve the team's understanding for future parts of the project. Again, it also shows the improvement made by people using robot assisted therapy.

### 3.2.8 Colin Donnellan: LiPo battery energy studies for improved flight performance of unmanned aerial systems [12]

This report shows the studies for LiPo batteries can be improved. These batteries are used for UAVs but can possibly help show how to improve the lifetime of the electrical motors in the device to be close to eight hours of running time.

### 3.2.9 Colin Donnellan: Numerical simulation for the discharge behaviors of batteries in series and/or parallel-connected battery pack [13]

This report shows a simulation to show the discharge rate between batteries being linked in parallel or in series. It shows that batteries in series reach their fully discharged state sooner than those in parallel. Though batteries in parallel have a large change in current when it gets close to a fully discharged state.

### 3.2.10 Colin Donnellan: Design Consideration for Arm Mechanics and Attachment Positions of a Wearable Robot Arm [14]

The report shows the consideration of where to place the attachment position of a robotic arm that can be worn. The first spot that they looked into was mounted on the chest and going forward from the user's body which led to five degrees of freedom. The second spot they investigated was on the shoulder and going over the arm and led to four degrees of freedom, so the chest one was better.

### 3.2.11 Caleb Lamca: Ergonomics and Design: A Reference [15]

This design guide for ergonomics highlights the human factors and limitations that engineers need to understand before designing products meant for human interaction. Included is the rationale

behind engineering for people but also includes references to anthropometry and how to design most efficiently for your target. Common workplace motions, everyday uses and fatigues, and general design considerations are discussed in this handbook.

### 3.2.12 Caleb Lamca: Industrial Maintenance and Mechatronics [16]

Chapter 12 is all about belt drives and gear drives, very useful when determining the drivers behind our motor system. The full discusses the in-depth aspects of the industrial maintenance sphere but has a very relevant correlation to small-scale products such as the robotic arm we are building as a team. The book discusses loads, nominal tolerances, the different applications for different drivers, and all useful information relating to our design space.

### 3.2.13 Caleb Lamca: Understanding Steel Tube and Pipe Metallurgy [17]

If we use piping, this source provides insight into the strength of piping and how to select the right materials for our desired applications. Also discussed heavily is how hardness influences design decisions. From heat-treat to metallurgic properties, hardness has an impact on which products to use. The article also discusses how to measure and apply this knowledge to various applications.

### 3.2.14 Caleb Lamca: Fastener Design Manual [18]

This design handbook from NASA discusses various fasteners including rivets, screws, and adjacent products like washers and flare nuts. The team can use this information to influence design decisions and make strategic use of the resources given. This is our only source as a team on fasteners but holds significant importance when thinking of how we will physically build our prototype and eventually the final design.

### 3.2.15 Caleb Lamca: Mechanisms [19]

This handbook describes kinematics and how they apply to all mechanisms. The team will leverage the in-depth content relating to degrees of freedom and kinematics in the physical design process of our robotic arm. The handbook also dives into motors from AC to air and hydraulics, useful in determining how our system will operate and what drivers will be the most beneficial.

### 3.2.16 Caleb Lamca: Handbook on Polymer Selection for Engineering [20]

Polymer selections, something we should have a source for if we use polymers. We likely will, as polymers are widely used in biomedical applications, and we could use their high strength and low weight properties in our own design. This polymer selection handbook will be useful in the selection

criteria behind each design choice we make in this design sphere.

### 3.2.17 Caleb Lamca: Metal Strength Chart - A Pro Guide 2025 [21]

This article provides hard data and theory behind metal strength and applications. All types of strength are discussed, from shear to bending. If our team decides to use metal in our designs, we will use this article to influence certain design decisions to ensure we have the most robust design for our given application.

### 3.2.18 Caleb Lamca: Composites Material Datasheet [22]

This is a material datasheet that compares material properties for various composites by Markforged including the ONYX carbon fiber reinforced nylon. Includes tables, graphs, and information about all the mixtures and composite materials with their corresponding stress and strength properties.

### 3.2.19 Caleb Lamca: Haddington Dynamics AS PDF Case Study [23]

This PDF is a case study on the ONYX material used in a robotic arm. The case study describes the mechanical properties, how the ONYX material helped, and included information about the production benefits and savings using this material.

### 3.2.20 Caleb Lamca: 6 Steps to Your First SOLIDWORKS Simulation [24]

This article helps walk through the steps of using SolidWorks simulation tools. Using this article will be helpful in the future as the team continues to complete FEA and other related analyses of critical components on the robotic arm. The article also provides information about SolidWorks materials libraries, which is very important when the team is making educated decisions about which materials to use on certain critical components.

### 3.2.21 Kaitlyn Davis: A humanoid robot teleoperation approach based on waist–arm coordination [25]

The report describes the control system of humanoid robots that control waist-arm coordination (WAC). It also introduced dual-arm coordination (DAC). The DAC method focuses more on the relationship between a single controller and a manipulator. The WAC method focuses on the motion of both the arm and hip; this method is used to understand the inverse kinematics that may be needed to calculate the velocity.

### 3.2.22 Kaitlyn Davis: Design and development of a robotic arm [26]

This paper provides information about the kinematics of a 5-degree of freedom (DOF) and how they function. It provides the principles of robotic kinematics, MATLAB, and Arduino. There are also different models for the angle configurations and to prove the kinematics of the robotic arm.

### 3.2.23 Kaitlyn Davis: Progress in Biomedical Engineering [27]

This is a review of biomedical engineering and the exoskeleton systems that they are using for human assistance. It also focuses on the design of wearable robotics; this includes rigid-joint and soft exoskeletons used in pervasive health. It applies to upper limb kinematics and biomechanics of these rehabilitation devices.

### 3.2.24 Kaitlyn Davis: A review on design of upper limb exoskeletons [28]

This report is a review of multiple upper limb exoskeletons used for human-robot interaction, or for neuromuscular rehabilitation. It provides classification and comparisons of multiple exoskeletons. It provides challenges along with some of the systems' pr methods that are needed when designing an exoskeleton for rehabilitation purposes.

### 3.2.25 Kaitlyn Davis: Comparison of material's properties for exoskeletons [29]

This paper provides a list of materials used in an exoskeleton and provides important information such as the pros and cons of each material. It also includes the density, hardness, Youngs modulus, shear modulus, weldability, and machinability of each material.

### 3.2.26 Kaitlyn Davis: Exoskeleton-assisted anthropomorphic movement training for the upper limb after stroke: The EAMT randomized trial [30]

This article analyzes the effects of exoskeletons and physical therapy among stroke patients. Provides figures that relate natural movement, time, and joint angle data, as well as degrees of freedom. This may further our understanding of the mobility of different stroke patients and how to design our exoskeleton.

### 3.2.27 Kaitlyn Davis: Design methodology of portable upper limb exoskeletons for people with strokes [31]

This article provides the mobility and portability of an exoskeleton device, along with its uses and what it can do for stroke patients. The article provides examples of the exoskeleton materials, actuation systems, the three different motors (electric, hydraulic, and pneumatic), and different operation modes (assistive, corrective, and resistive). Discomfort and singularity problems are also mentioned as the exoskeleton may face some issues with accidental collisions with adjacent objects.

### 3.2.28 Kaitlyn Davis: Mechanical Design and Kinematic Modeling of a Cable-Driven Arm Exoskeleton Incorporating Inaccurate Human Limb Anthropomorphic Parameters [32]

Kinematic modeling and control were analyzed of a cable driven upper limb exoskeleton. It also covers uncertainties that may include inaccuracy of human-arm kinematics and errors when wearing the exoskeleton.

### 3.2.29 Kaitlyn Davis: A Systematic Approach for Kinematic Design of Upper Limb Rehabilitation Exoskeletons [33]

Provides the kinematic structure of an exoskeleton that connects to the wrist, it is like our design. It has different methods and conceptual designs that may help with the final design.

### 3.2.30 Kaitlyn Davis: A Test Bench for Evaluating Exoskeletons for Upper Limb Rehabilitation [34]

More kinematic results also include torque in the joints and range of motion. This was an evaluation of an upper body exoskeleton using different parameters. This process is a test bench to evaluate exoskeletons, which may come in handy when the team is testing the prototypes.

### 3.2.31 Joel Gisleskog: Series Elastic Actuators [35]

Pratt and Williamson introduce series elastic actuators and explain why lightweight, efficient designs are needed for better torque control in powered exoskeletons.

### 3.2.32 Joel Gisleskog: Quasi-Direct-Drive Actuation for Shoulder Exoskeletons [36]

Yu, Chen and Liu discuss quasi-direct-drive actuation, highlighting how some bandwidth is traded off to improve compliance and control in shoulder exoskeletons.

### 3.2.33 Joel Gisleskog: Gravity Compensation of an Upper Extremity Exoskeleton [37]

Moubarak et al. compare passive and active gravity compensation methods, giving useful insight for early design choices in how to support arm weight.

### 3.2.34 Joel Gisleskog: Human Arm Weight Compensation in Rehabilitation Robotics [38]

Just et al. compare three different gravity compensation methods and show their effectiveness, which can help guide the control approach for our own system.

### 3.2.35 Joel Gisleskog: Gravity Compensation of an Exoskeleton Joint Using Constant-Force Springs [39]

Hill et al. show how constant-force springs can lower the torque requirements at exoskeleton joints, improving overall mechanical efficiency.

### 3.2.36 Joel Gislenskog: Model-Based Control for Exoskeletons with Series Elastic Actuators [40]

Vantilt et al. describe the kinematic and dynamic modelling steps used in exoskeletons with series elastic actuators, which will be useful for our own model development.

### 3.2.37 Joel Gislenskog: Standard Terminology for Exoskeletons and Exosuits [41]

ASTM International defines the official terminology for exoskeletons and exosuits, helping keep our project language and reports consistent.

### 3.2.38 Joel Gislenskog: ISO 13485:2016 – Medical Device Regulations [42]

Outlines the regulatory and quality management requirements for medical devices, providing a framework to ensure our design meets safety and compliance standards

### 3.2.39 Joel Gislenskog: lightweight upper-limb exoskeleton [43]

A light weight and ergonomic upper-limb exoskeleton designed for stroke therapy, includes useful insights into joint alignment and mechanical design choices.

### 3.2.40 Joel Gislenskog: soft wearable robotics for upper-limb Assistance [44]

Describes soft actuators and wearable robotic systems that assist upper-limb using pneumatic networks.

### 3.2.41 Cole Pace: Survey on Main Drive Methods Used in Humanoid Robotic Upper Limbs [45]

This report outlined the main driving mechanisms used in robotic upper limbs, such as direct drive, tendon drive, and transmission systems. It helped the team understand the trade-offs between torque output, back drivability, and efficiency when determining which actuation method would best fit the wearable arm's design goals.

### 3.2.42 Cole Pace: Upper Limb Soft Robotic Wearable Devices: A Systematic Review [46]

This study reviewed soft robotic exosuits and wearable upper limb devices designed to restore motion and assist movement. It helped demonstrate the importance of lightweight and flexible materials for user comfort, guiding material and design choices for the prototype.

### 3.2.43 Cole Pace: Human Weight Compensation with a Backdrivable Upper-Limb Exoskeleton [47]

This paper discussed weight compensation control strategies for backdrivable exoskeletons. It provided insight into how gravity-compensation algorithms can reduce user fatigue and improve safety when supporting the weight of the arm.

### 3.2.44 Cole Pace: 3D Printing Continuous Fiber Reinforced Polymers [48]

This article covered the manufacturing process and benefits of printing parts with continuous fiber reinforcement. It supported design decisions on how to fabricate lightweight, high-strength parts for the robotic arm using fiber-reinforced materials.

### 3.2.45 Cole Pace: Robots and Robotic Devices — Safety Requirements for Personal Care Robots [49]

This ISO standard defines safety protocols for physical assistant robots that interact directly with humans. It ensures that the team's design process follows established international safety guidelines for wearable robotics and physical human–robot interaction.

### 3.2.46 Cole Pace: A Simplified Inverse Dynamics Modelling Method for a Novel Rehabilitation Exoskeleton [50]

This report provided a simplified inverse dynamics model for calculating the torque required at each joint of a rehabilitation exoskeleton. It helped determine the necessary motor output and control strategies for the elbow and shoulder joints in the team's design.

### 3.2.47 Cole Pace: Upper Limb Motor Impairment After Stroke [51]

This study reviewed common upper-limb impairments experienced by stroke survivors, including weakness, spasticity, and loss of coordination. It justified the need for an assistive robotic arm by outlining how gravity-compensation and motion assistance can improve functional recovery.

### 3.2.48 Cole Pace: Overall Structure for a Light-Weight Robotic Arm [52]

This paper presents a parametric structural optimization method for minimizing mass while maintaining stiffness and dynamic performance in robotic arm links and joints.

### 3.2.49 Cole Pace: Design and Structural Analysis of a Robotic Arm [53]

This report details the mechanical design and structural analysis of a three-joint robotic arm, focusing on link sizing, joint stresses, and manufacturable cross-sections.

### 3.2.50 Cole Pace: Compact Joint Mechanisms for Wearable and Assistive Robots [54]

This article reviews the design of compact, wearable joint actuation mechanisms, including cable-driven, quasi-direct-drive, and hybrid compliant joints, specifically for exosuits and assistive robotic limbs.

## 3.3 Mathematical Modeling

### 3.3.1 Link Motion Analysis- Joel Gisleskog

Part of the design requirement is for the client's arm to be able to comfortably rest by their side, I would like to work out what angular velocity the robotic links would have to move to go from resting to extended in front of the client in a specific amount of time. To figure this out, I first needed to know what angles the robotic links would start at rest. To do this, use the Pythagoras theorem. Assumptions made is that both links are the same at 248 mm and the distance from elbow to waist is 70 mm.

$$\begin{aligned}\sin(\theta) &= \sin^{-1}\left(\frac{70}{248}\right) = 16.4^\circ \\ 90 - 16.4 &= 73.6^\circ \\ 90 + 73.6 &= 163.6^\circ \\ l_1x_1 &= l\cos(\theta) = 248 \cdot \cos(163.6^\circ) = -237.9mm \\ l_1y_1 &= l\sin(\theta) = 248 \cdot \sin(163.6^\circ) = -70mm \\ B_{x1} &= -237.9 + 248 = 10.1mm \\ B_{y1} &= -70 + 0 = -70mm \\ A_s &= (-238mm, 70mm) \\ B_s &= (10, 70mm)\end{aligned}$$

Now we have the co-ordinates of the links at the rest position; to work out the angular velocity we must pick a time for the arm to reach the desired position in. I measured myself naturally lifting my arm out to the fully extended position multiple times and got an avg of 1.28s. I assumed that for the desired position the robotics arm must both be at an angle of 45 degrees.

$$l_1x_2 = l\cos(\theta) = 248 \cdot \cos(45^\circ) = 175.36mm$$

$$l_1 y_2 = l \sin(\theta) = 248 \cdot \sin(45^\circ) = 175.36 \text{ mm}$$

$$B_{x2} = 175.36 + 175.36 = 350.7 \text{ mm}$$

$$B_{y2} = -70 + 0 = 35.7 \text{ mm}$$

$$A_s = (175.36 \text{ mm}, 175.36 \text{ mm})$$

$$B_s = (350.7 \text{ mm}, 350.7 \text{ mm})$$

Here are the final co-ordinates at the end position. Each of the links must turn through a unique angle, so the links must move at different angular velocities.

$$\theta_1 = 163.3 - 45 = 118.6^\circ$$

$$\theta_2 = 0 + 45 = 45^\circ$$

$$\omega_1 = \frac{\Delta\theta_1}{1.28} = \frac{-2.07}{1.28} = -1.6171 \text{ rad/s}$$

$$\omega_2 = \frac{\Delta\theta_2}{1.28} = \frac{\frac{\pi}{4}}{1.28} = 0.6136 \text{ rad/s}$$

So therefore, the maximum required velocity is 1.6171 rad/s. This is helpful as this informs us of our decision when picking motors based on the required torque.

### 3.3.2 Torque Evaluation at Joints-Cole Pace

Using the angular velocity from the previous calculations, the torque at the hip and elbow was calculated for a direct drive and a remote transmission system. The next equation is for the direct drive system.

Hip:

$$\tau_1 = g \left( m_1 r_1 + (m_2 + m_{m2})(L_1 + r_2) + m_p(L_1 + L_2) \right) + \alpha_1 (m_1 r_1^2 + m_2(L_2 + r_2)^2 + m_p(L_1 + L_2)^2)$$

$$\tau_1 = 11.5 \text{ N} \cdot \text{m}$$

With this torque value, we were able to select the motor that can produce this torque.

### 3.3.3 Velocity for Shoulder Flexion at the Elbow - Kaitlyn Davis

Velocity of the arm at the elbow when the shoulder is undergoing forward flexion, where the arm starts from hanging straight down at 0 degrees and moves upward to a 90-degree angle. Here, the velocity of the arm at the elbow is observed. According to research, the average shoulder to elbow length is about 330mm (13in) in an adult. Average angular velocity equations:

$$\omega_{avg} = \frac{\Delta\theta}{t}$$

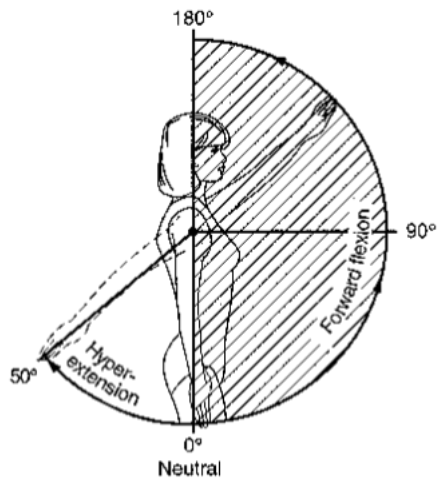
To reach 90 degrees from shoulder flexion (delta theta = 90 degrees) it took 1.28 seconds. We plugged our known values into the equation below.

$$\omega_{avg} = \frac{\Delta\theta}{t} = \frac{90^\circ \cdot \left(\frac{\pi}{180}\right)}{1.28s} = 1.227 \text{ rad/s}$$

The average angular velocity of the arm from 0 to 90 degrees is 1.227rad/s. Turning this into RPM so that it is easy to find the value through the motor specification and when testing.

$$\omega_{avg} = 1.227 \frac{\text{rad}}{\text{s}} \cdot \frac{60}{2\pi} = 11.72 \text{ rpm}$$

Our results show that the velocity of our arm design needs to move around 11.72 rpm for safety and comfort when the device needs to move upward and downward.



*Figure 2: Anthropometry of Range of Motion*

## 4 Design Concepts

### 4.1 Functional Decomposition

A functional decomposition for the team's robotic arm is shown below. This functional decomposition highlights the most important features of the design, along with the subsequent functions that accompany them. For instance, the "Support Arm" branch header is an essential function, and within that function, the support needs to hold the weight of the user's arm and allow them to comfortably rest at their side. This branch highlights the ER of supporting minimum weight, and the CR of comfortably resting. The team has referenced this functional decomposition extensively throughout the course of the last two semesters, and it has been paramount in keeping the team on track. See Figure 3 below.

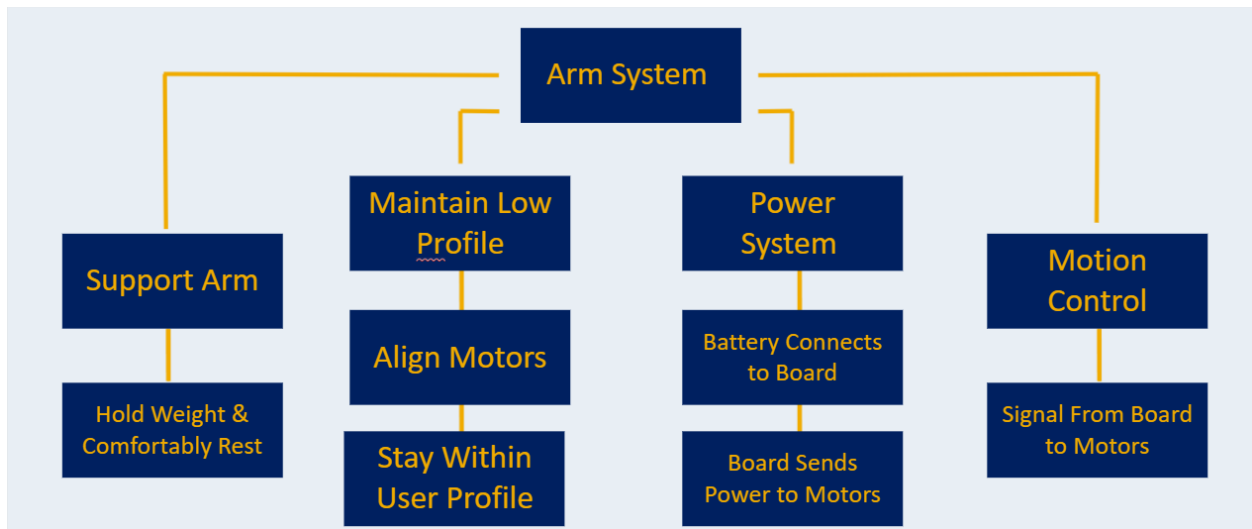


Figure 3: Functional Decomposition

### 4.2 Concept Generation

The team decided on three major criteria to evaluate the design of our device early in the design stage. The three major criteria were the motors, joints, and the link geometry. To evaluate each motor, the team considered rated voltage (V), rated power (W), rated torque (Nm), rated current (A), rated speed (RPM), peak torque (Nm), peak current (A), No-load speed (RPM), reduction ratio, weight (G), size (diameter \* length), driver board, and encoder.

For motor selection, the team was given three different motors by the client to evaluate.

- AK40-10 KV170
  - Pros: Lightest weighing motor and highest rated speed.
  - Cons: Lowest torque and will not be able to provide the torque needed for our device.
- A45-10 KV75
  - Pros: Lightweight, and good rated speed
  - Cons: Low torque will not be able to provide the torque needed for our device.
- AK45-36 KV80
  - Pros: Handles needed torque for each joint in both transmission and direct drive.
  - Cons: Heaviest option which will increase device weight and has the lowest rated speed.

For joints, the team considered the degrees of freedom (DOF) for the device and whether a certain joint may be suitable to achieve the required DOF. The team determined that the top three options were ring joints, ball joints, and revolute joints.

- Ring joint (2 DOF)
  - Pros: Finer movement of the hand / arm is allowed.
  - Cons: transmitting power to two different axis increases cost and complexity.
- Ball joint (3 DOF)
  - Pros: Smoother movement of the arm is allowed.
  - Cons: Requires three motors for each DOF
- Revolute joint (1 DOF)
  - Pros: Simple transmission and requires only one motor.
  - Cons: Limited DOF causes less smooth movement and motion.

For Link geometry, the team had considered simple cross-sectional geometry links, to where they would be evaluated. It was decided that the best simple options were a hollow rectangular cross-section and a hollow circular cross-section.

- Hollow Rectangular
  - Pros: Strong directional stiffness and low weight.
  - Cons: Weak torsion and off axis bending.
- Hollow Circular
  - Pros: Resists twisting
  - Cons: Less stiff per unit weight in one direction

### **4.3 Selection Criteria**

The selection criteria for the robotic arm included a high factor of safety (above 4 for

biomechanics applications) and a torque capacity higher than that of the motors' applied output. These selection criteria are relevant to engineering requirements 2 and 3, as torque and speed are inversely proportional, and a high factor of safety can only be justified while staying below the target weight for the device. Below is a FoS table for multiple critical parts using FEA to validate design minimums and ensure the most at-risk parts can handle the applied torque output from the motors on top of the robotic arms own weight.

Both motor mount concepts for the first and second prototypes were strong enough to handle the application. However, the motor mounts in the first semester prototype were over engineered for strength without consideration for electronics routing, heat transfer, bulk, and material cost. More comparisons between the first and second semester prototypes can be found in section 4.4 Concept Selection.

Next, the motors needed to be compared across three different client recommendations. A chart from the CubeMars website can be found below that summarizes the characteristics of each.

Model	Rated Voltage (V)	Rated Power (W)	Rated Torque (Nm)	Rated Current (A)	Rated Speed (RPM)	Peak Torque (Nm)	Peak Current (A)	No-load Speed (RPM)	Reduction Ratio	Weight (G)	Size (diameter *length) MM	Driver Board	Encoder
AK45-36 KV80	24	33	8	2	40	24	6.5	52	36:1	340	φ55*54	Yes	Single
AK45-10 KV75	24	39	2.5	2.1	150	7	5	180	10:1	260	φ53*43	Yes	Single
AK40-10 KV170	24	59	1.3	2.7	370	4.1	7.3	435	10:1	200	φ53*37	Yes	Single

Figure 4: Client-Recommended CubeMars Motor Characteristics

## 4.4 Concept Selection

The concepts selected for this project were from the second prototyping phase in January 2026. The decision matrix for the project can be found below.

Criteria	Weight	Prototype 1		Prototype 2 ✓	
		P1 Rating	P1 Score	P2 Rating	P2 Score
Links	2	2	4	5	10
Motor Mounts	1	3	3	4	4
Hinge	2	2	4	5	10
Electronics Access	3	1	3	4	12
Low Profile	5	1	5	5	25
Weight	2	2	4	4	8
<b>Total</b>			<b>23</b>		<b>69</b>

Figure 5: Decision Matrix for Prototype Phases

The decision matrix highlights a few critical factors pertaining to the performance and function for the arm. The links chosen are rectangular tubes made from machined carbon fiber. Although the math supports circular cross sections, our clients recommended these links, and with the strength of carbon fiber, they are perfect for this application. Additionally, rectangular geometry allows the links to attach to other components much easier than circular links. The motor mounts utilize this rectangular geometry to slip into the links for high strength connections. The mounts chosen easily to attach to small sections of the motors and use the existing threaded holes on the motors to achieve high connection strength while letting the heat from the motors escape to the ambient air. Furthermore, the improved motor mounts do not interfere with the electronic connections that must be made and are significantly smaller to maintain the low profile the team desired.

Below is a FoS table that summarizes critical parts of the design. Please note that these FEA simulations are meant to help rationalize the relative strength of the parts and have been tested extensively to ensure they are able to perform the required tasks. Also note that although RF-DET002 falls below the required 4 minimum FoS, this study neglects the use of carbon fiber infill, and the parts are significantly stronger than this study shows once the rigidity of the carbon fiber is implemented.

Part No.	Description	Material	Location	Allowable	Stress	FoS
RF-DET001	Link	Machined Carbon	B	6.00E+08	1.87E+07	32.1
RF-DET001	Link	Machined Carbon	D	-	-	-
RF-DET002	Mount 1	ONYX	A	2.00E+08	5.51E+07	3.6
RF-DET003	Mount 1-2	ONYX	C	2.00E+08	8.75E+06	22.9
RF-DET004	Mount 2	ONYX	C	2.00E+08	8.55E+06	23.4
RF-DET005	Fastener Plate	ONYX	A	2.00E+08	6.37E+06	31.4
RF-DET005	Fastener Plate	ONYX	C	-	-	-
RF-DET006	Motor Mount	ONYX	A	2.00E+08	1.70E+07	11.8
RF-DET006	Motor Mount	ONYX	C	-	-	-

*Figure 6: FoS Table for 6 Critical Parts at Varying Locations Along the Arm*

Below is the current state of the CAD for this design. Minor revisions have been made to the originally selected parts for higher strengths and optimized for 3D printing and carbon fiber inlay. The FoS table reflects these revisions and is up to date as well.

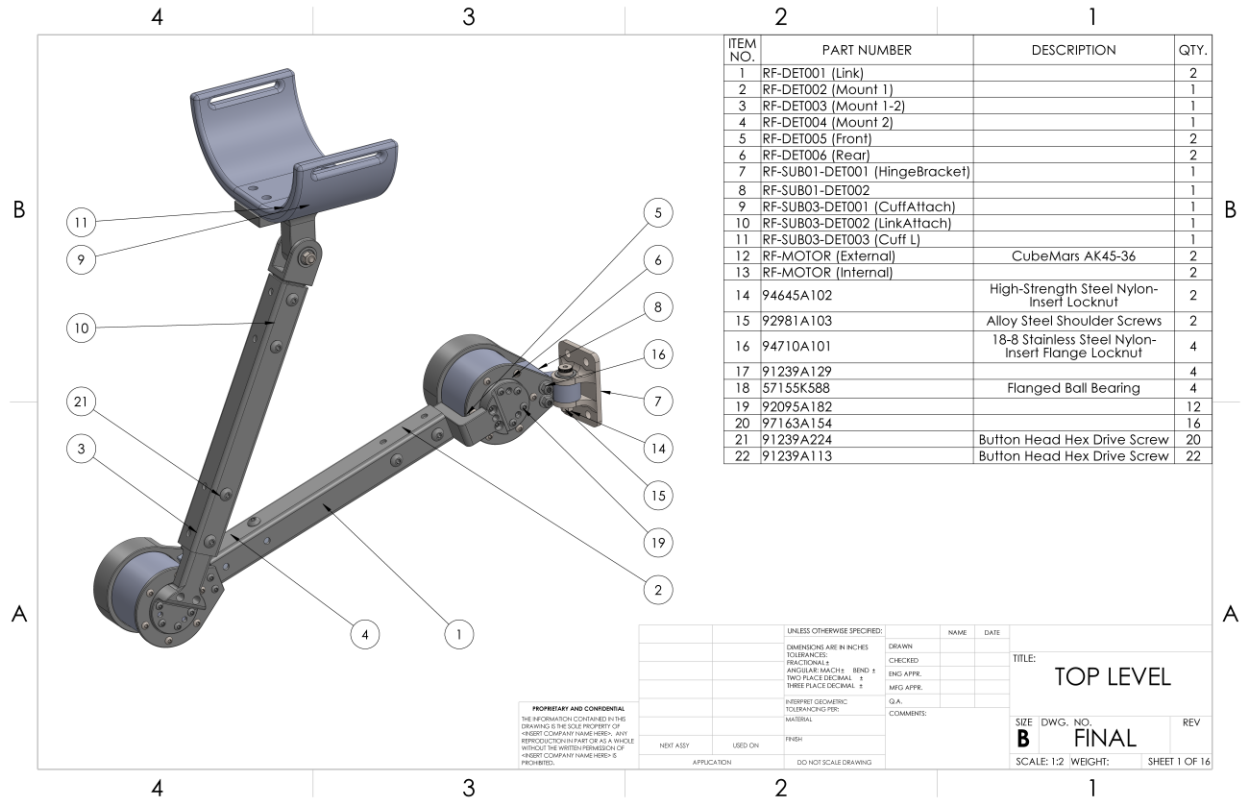


Figure 7: Top Level CAD After Second Prototyping Phase

# 5 Schedule and Budget

## 5.1 Schedule

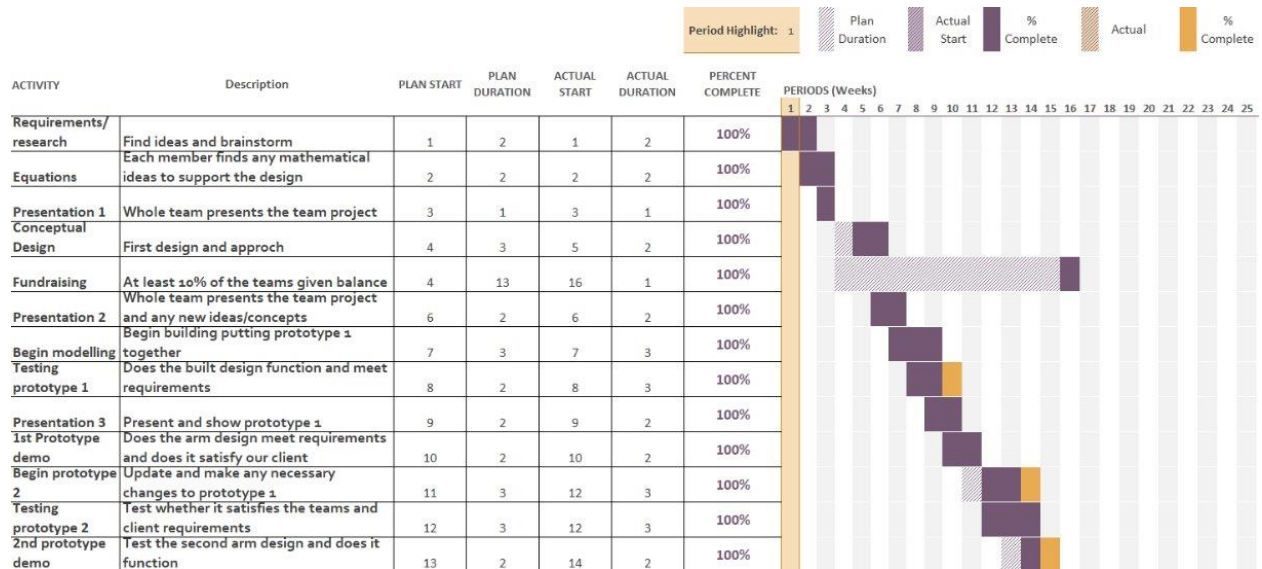


Figure 8: Semester 1 Schedule

Throughout the first semester, the team concentrated on research, design, and prototyping of the device, ensuring a strong foundation for the project’s development. They dedicated time to exploring relevant technologies, evaluating design options, and iterating early concepts to refine their approach. By maintaining consistent communication and effective time management, the team was able to address challenges as they arose and keep progress aligned with their planned timeline. As a result, we successfully met all of our goals for the semester while building momentum for the next phase of the project.



### 5.3 Bill of Materials (BoM)

Bill of Materials					
Category	Description (Includes Vendor)	Quantity	Cost	Status	Make/Buy
Motors	CubeMars AK45-36	2	\$598.35	Purchased/Received	Buy
3D Filament	Sunlu PLA 3KG Spool, MarkForged 800cc Onyx and 150cc Carbon Fiber CFF	1 Each, 2 CF CFF	\$1,197.70	Purchased/Received	Buy
Battery	Amazon LiPo Battery XT60 Plug	1	\$67.12	Purchased/Received	Buy
Hip Belt	Atlas Hiking Grade Belt (Black/LRG-XL), Amazon Foam Padding	1	\$160.64	Purchased/Received	Buy
Lerner Provided	AK board, Hinges, JLCPCB	1 Each, 2 CF CFF	\$308	Donated/Received	Make/Buy
Capstone	Brackets, Arm Links, Motor Mounts, Elbow Attachment	1 Bracket, Elbow Attachment, 2 Arm links, Motor Mounts	\$0.00	Donated/Received	Make
Fasteners	McMaster-Carr Screws, nuts, bolts (includes all fasteners used in all prototypes)	1 Each, 2 CF CFF	\$313.67	Purchased/Received	Buy
Electrical	Amazon PAWBOSE Lipo Safe Bag, PUSLA KO Lipo Battery Charger, Arduino Nano 33 BLE, Cord Protector, Resistors, INLAND Micro Center, Sparkfun Electronics Teensy 4.1, Luxonis OAK-D Pro	1 Each, 2 Arduino Nano, Teensy	\$694.24	Purchased/Received	Buy
Other	Belt supports, PVC Piping, other small items	1 Each	\$40.31	Purchased/Received	Buy
		<b>TOTAL</b>	<b>\$3,379.85</b>		

Figure 10: Bill of Materials for Final device

The table outlines all components required for the final build, organized into clearly defined categories. This structure allows for easy reference and helps ensure that each part of the system is accounted for during assembly. By grouping components based on their function, the team can more efficiently manage materials, track progress, and verify that all necessary elements are included in the final design.

## 6 Design Standards

Design standards play a critical role in this project by ensuring both safety and alignment with modern engineering practices. By adhering to established guidelines and industry benchmarks, the team can reduce potential risks, improve reliability, and create a device that meets professional expectations. These standards also help guide decision-making throughout the design and development process, ensuring that materials, components, and system integrations are appropriate for their intended use. Ultimately, following design standards not only protects users but also supports the creation of a high-quality, dependable device.



The most important feature on this part is the circular cut extrude, datum A, located on the bottom right of the page. This datum is accompanied by a geometric tolerance of cylindricity plus or minus 0.01 mm on a 35 mm radius cut. Cylindricity controls how “circular” the cross section of the extrude is down its length. This part is only cut in this location to allow a relief housing for the motor, so it was important that the cylindricity did not misalign down the length of the part.

This standard was used to ensure that all parts were drawn in accordance with ASME Y14.5 GD&T Standards. All parts were designed and drawn with these in mind.

## **7 Design Validation and Initial Prototyping**

### **7.1 Failure Modes and Effects Analysis (FMEA)**

We ran an FMEA on all major components of our robotic arm: both linkages, both motors, the motor mount, the waist belt, the battery pack, the wiring and the elbow cup. Most components only had one failure mode, however we added an extra one to the battery pack, waist belt and for the first motor as these components could clearly fail in more than one way.

The wiring came out with the highest RPN (162). This is because of electrical shortage, sudden power loss, or overheating. Any of these outcomes could leave the users' arm unsupported during movement and in the worst case could cause a fire hazard. To reduce this, we will use thicker insulated wires and route the cables through the linkages in a way that can avoid sharp bends.

The next highest RPN was the waistbelts in its second failure mode (144). If the belt slips or breaks, the entire arm could detach from the user and swing/fall unexpectedly. This could be especially dangerous for a stroke patient who may not have the reflexes to react. To fix this, we upgraded to a rated belt with a harness to prevent slippage.

The linkages and the motor mounts both scored RPN(140). A fracture in either of these structural components could result in the arm not being able to support the load, which could then cause the mechanism to collapse. We addressed this by using stress analysis and FEA to find a safe thickness for our 3d printed components to avoid any chance of failure.

The motors had the next highest RPN with the first failure mode of each motor scoring (112) and the second failure mode of motor 1 scoring (108). Motor failure can be a problem as if the motor overheats, or there is a software problem the motor could stall or unexpectedly move. If the motor applies the wrong torque, this could be dangerous for someone with limited control and may cause discomfort or pain. We therefore plan to add torque limits and use ventilation for the heating problem.

### **7.2 Initial Prototyping**

#### **7.2.1 Rig Prototype**

The project describes that the arm will be mounted at the hip, which means that some type of device must be made to be worn by the user so that the arm can attach to them. The question that was trying to be answered was, is the rig comfortable to be worn by the user, and does it help distribute the weight of the arm?



*Figure 12: Caleb Wearing the Rig Prototype*

The answers to these questions were both yes. As seen above, the prototype was comfortable to wear and was able to help distribute the weight from the concentrated area that the arm will go to. This informed us that this would be a good path to go down to help the user not experience the full weight of the device at one hip. Future iterations will focus on even better weight distribution with batteries or other aspects of the device being mounted to also help counteract the concentrated weight of the arm.

### **7.2.2 Motor 1 Assembly**

The question that was wanted to be answered was can the motor plates fit onto the motor. This is important as the design built around the motors, so if it does not fit over the motors, the design will need to be adjusted.



*Figure 13: Motor 1 prototype*

Through this it was answered that the design fits over the motors. Future iterations of this will have the top plate be adjusted to have better concentration of carbon as well as to better protect the motor from damage.

### **7.2.3 Motor 2 Assembly**

The question that was wanted to be answered was can the device fold up to have the desired motion that the team wants. This is important as the design needs to be low profile to stay out of the user's way.



*Figure 14: Motor 2 prototype*

Through this it was answered that the design does not get into the fully folded the way that is wanted. To fix this, the arm gap was extended to get over the mount plate so that the arm can fold up on itself.

## 7.2.4 Hinge Assembly

The question that was wanted to be answered was does the desired motion of the passive degree of freedom reached and does the hinge fit into the motor assembly.



*Figure 15: Hinge prototype*

Through this it was answered that the motion is reached in the passive degree of freedom, but the hinge does not actually fit into the motor assembly. This was due to previous changes due to previous prototyping resulting in the hinge not fitting anymore. This was fixed by adjusting the block dimensions so that it would fit into the motor assembly.

## 7.3 Other Engineering Calculations

### 7.3.1 Battery Evaluation - Colin Donnellan

Dr Lerner, our client, recommended a specific battery which was bought to start as a battery for the project. One HRB 1800mAh 6S 22.2V 50C LiPo Battery and they will be used together in parallel to see how much time the motors can get from them.

$$\text{Run Time} = \frac{\text{Battery Voltage} \cdot \text{Battery Capacity}}{\text{Number of motors} \cdot \text{Rated Voltage} \cdot \text{Rated Current}}$$

$$\text{Run Time} = \frac{22.2 \text{ V} \cdot 1.8 \text{ Ah}}{2 \cdot 24 \text{ V} \cdot 2 \text{ A}} \approx 25 \text{ minutes}$$

Using the equations above, it was found that the motors can only run for 25 minutes, which is below what we would want to run for 30 minutes. The biggest drawback of these types of devices is that batteries are limiters. This will be checked in testing as also the battery may be able to be charged above that value.

#### ***7.4 Future Testing Potential***

There are several tests that will be done in the future to see how well the design and construction of the project has been done. The first test that can be done is a battery endurance test to test how long the battery can last with the arm not being in constant use like how it would be used by the user. The next test is an impact test to make sure the device can withstand falling or other impacts that an average person would experience. The last two tests are linked to each other with a mobility test and activity test. These would be done to make sure the device can reach all degrees of freedom as well as be able to do simple tasks that the user would normally do in their daily life.

# 8 Final Hardware

## 8.1 Final Physical Design

The final design of the robotic arm consists of three subassemblies, with configurations 2A and 2B, and eleven unique parts. Below are the drawing images of the top-level design, followed by those three subassemblies.

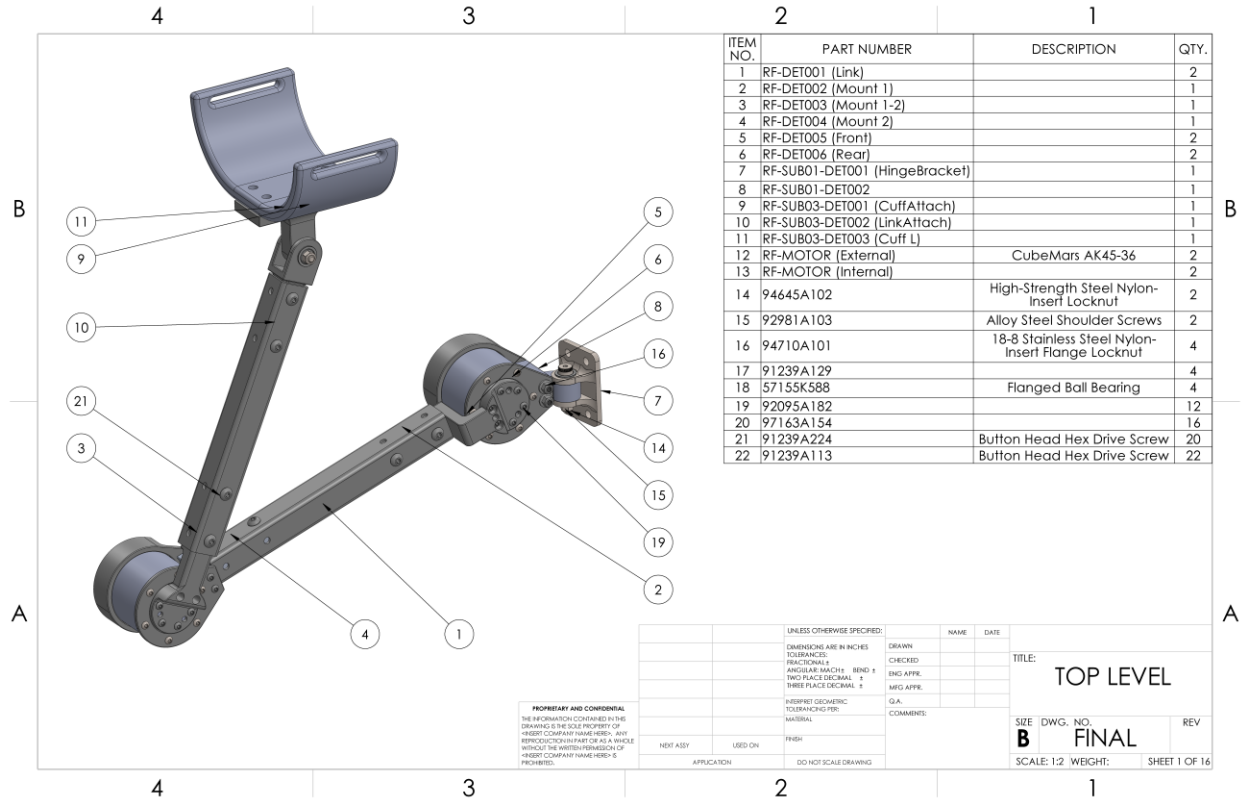


Figure 16: Top Level Design

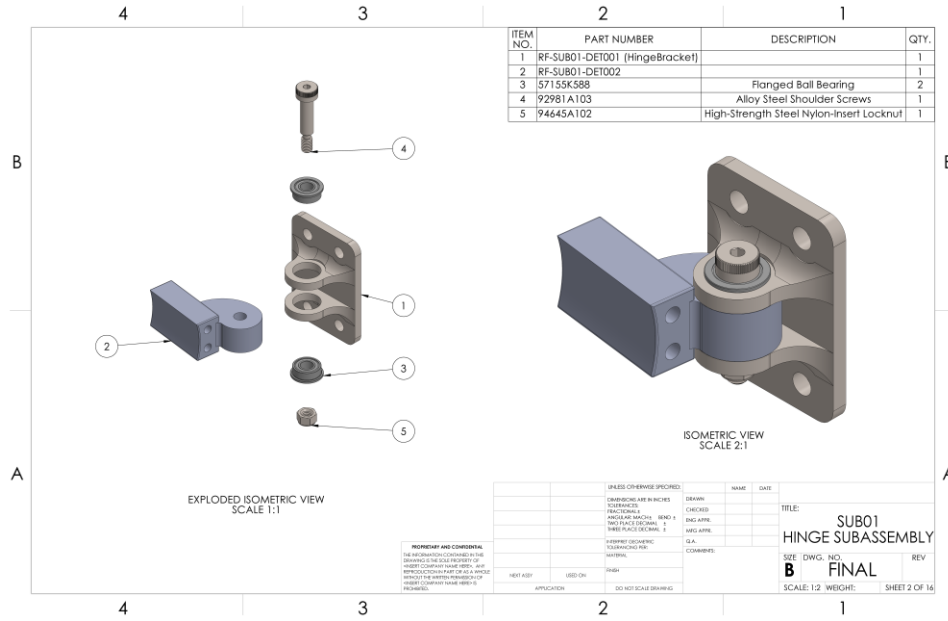


Figure 17: Subassembly 1, Passive DoF Hinge

This subassembly allows for the movement of the arm from one side to one front. This DoF is passive, meaning that it is not powered through this movement and relies on the user. The hinge subassembly utilizes flanged ball bearings to make this movement smooth, and a cammed part to optimize the rotation.

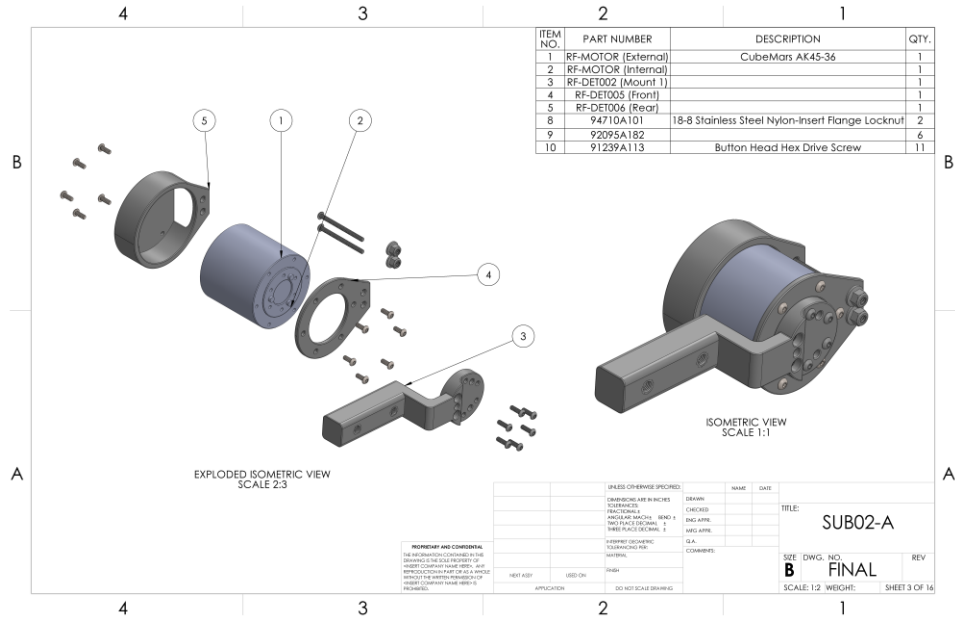
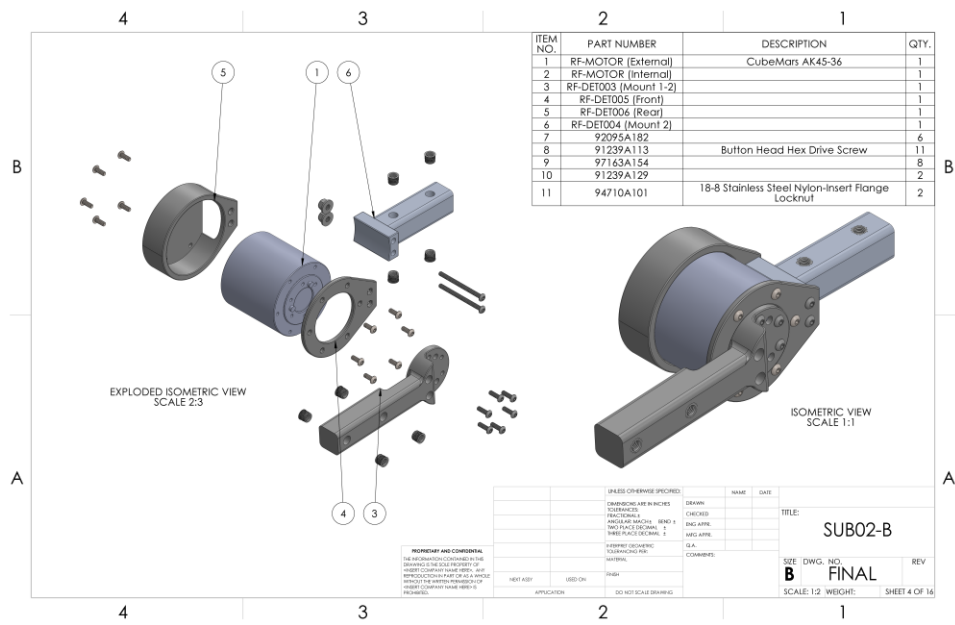


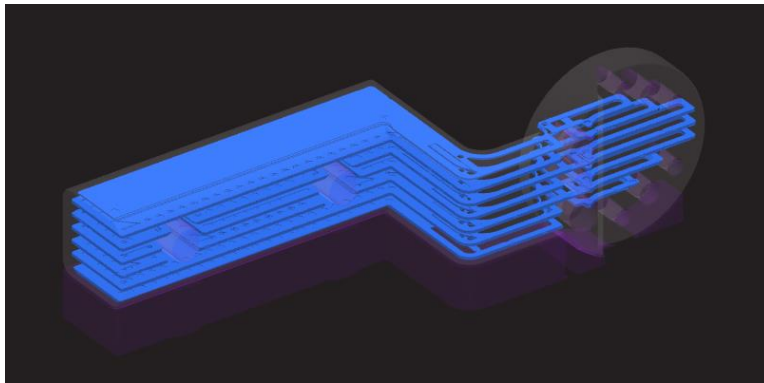
Figure 18: Subassembly 2A, First Motor Joint





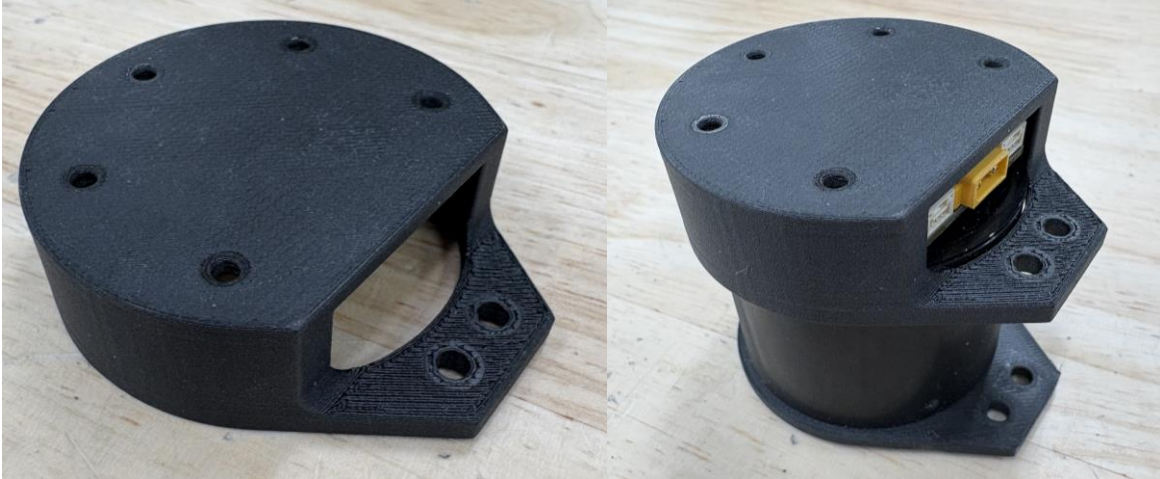


*Figure 21: DET002, Link Mount 1*

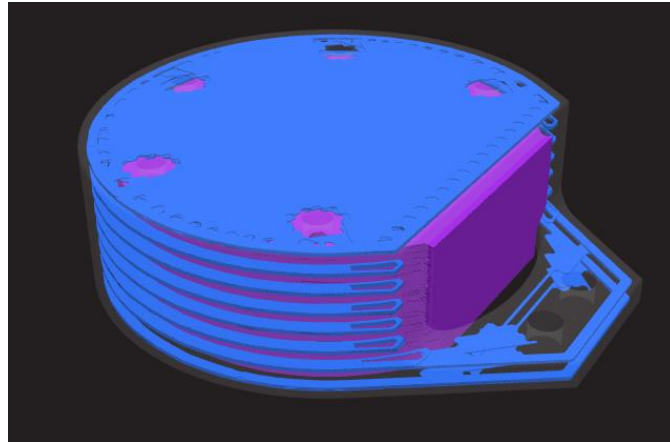


*Figure 22: Eiger Carbon Visualization for DET002*

DET002 is a link connection to the motor and features two 90-degree angle turns to avoid contact with the motor. This design decision was made to keep the two motor subassemblies aligned with each other to maintain a low profile and keep the mass of the arm close to the body of the user. This decision came with a cost, as now the part is susceptible to significant shear stresses. To mitigate these stresses, the team implemented the use of carbon fiber inlay within the ONYX 3D printer material. The carbon content increases the rigidity of the part. This material helps to strengthen the part but increases material cost per part. To reduce the cost, the carbon content was layered rather than applied in a solid fill. Figure 22 is an image from Eiger, and 3D slicer software that allows for the visualization of this carbon content in blue. The next part highlight, DET006, is pictured below.



*Figures 23 & 24: DET006 & DET006 on CubeMars Motor*



*Figure 25: Eiger Carbon Visualization for DET006*

DET006 is a motor mount featuring a partially encapsulated design for motor breathability. It attaches to the other motor mount, DET005, via a spacer and through bolts. This allows the mounts to handle the force of the connections rather than the motor itself. Additionally, the opening on the right-hand side of the images is to accommodate electronic connections from the battery and control board. The tab on this same side is a clear failure point of the part due to bending stresses. This is why the spacer was implemented, but for strength purposes, the same carbon inlay was added to this part. Following this same logic, all parts outside of the end effector subassembly were inlayed with carbon for safety.

## 9 Final Testing

### 9.1 Top level testing summary table

Table 1: Test Summary Table

Experiment/Test	Relevant DRs	Testing Equipment Needed	Other Requirements
Endurance Test	ER4-Battery Life	Device A User Battery Timer Camera	Battery is fully charged
Range Test	ER1-Degrees of Freedom	Device A User Camera	N/A
Weight Test	ER2-Weight of Arm	Scale Device Camera	The device will be disassembled so that the arm is being weighed by itself
Comfortability Test	CR1-Comfortability CR3-Low Profile ER2- Weight of Arm	Device Multiple Users Camera	N/A
Chair Test	CR1- Comfortability CR2-Ability to Sit CR3-Low Profile	Multiple Chairs Multiple Users Device Camera	N/A
Controller Test	ER1-Degrees of Freedom	Device User Camera Timer	Ability to read sensors
Speed Test	ER3- Speed of Arm	Device User Camera Timer	Average time it takes to lift an arm.
Bump Test	CR5-Durability CR3-Low Profile	Device Camera	N/A

## 9.2 Detailed Testing Plan

### 9.2.1 Endurance Test

#### 9.2.1.1 Summary

The test will answer the question of how long the battery will last in the device. The design requirement that this will be testing is ER4, which is battery life. The variable that will be tested is the battery itself to see how long it will last while powering one motor. The battery will consistently be at full charge to see how long a full battery can last in the device.

#### 9.2.1.2 Procedure

- Make sure Battery is fully charged
- Have correct command on the motors so that it is constantly spinning at a safe speed.
- Connect all components to the board to control the start time of the test.
- Have motor run a total of 6 minutes recording data after 45 second intervals for a total of 9 data points
- Using the data, a projection was found through extrapolation to see how long it would take to reach the lowest voltage.

#### 9.2.1.3 Results

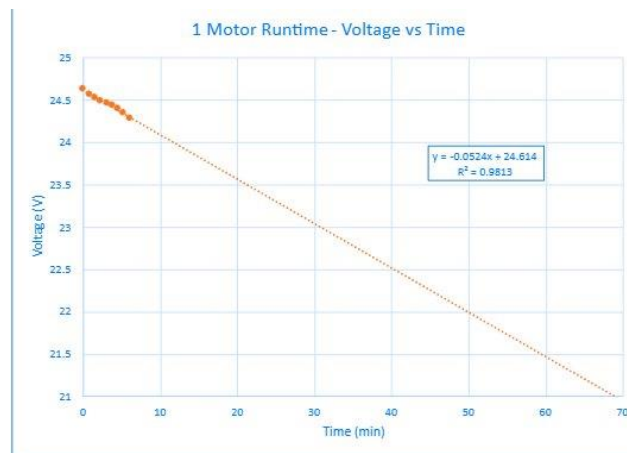


Figure 26: Motor runtime Graph

The graph is only one motor running from a fully charged battery and extrapolated to go until 21 v as that is lowest; the battery should be based on a minimum of 3.5 v per cell in a 6-cell battery. From that it was found that one motor would be 68 minutes, so two motors would be 34 minutes.

## **9.2.2 Range Test**

### **9.2.2.1 Summary**

The test will answer the question of how many degrees of freedom the device has. This will be testing ER1, the degrees of freedom, so that the entire range of motion desired for the device has been reached. There is not much equipment needed, so it will just be the device itself and a user to wear it and test it. The isolated variable would be the device itself as no changes would be made while the user tests it.

### **9.2.2.2 Procedure**

- Have the user put on device and be fully strapped in.
- Make sure the device is not turned on as electrical components are not being tested.
- Have the user move arm to make sure the device can follow it to make sure the degrees of freedom are reached.

### **9.2.2.3 Results**

The result is that all 3 degrees of freedom were reached with 2 being active degrees and 1 being a passive degree of freedom. With the degrees of freedom reached it also was able to have the desired range of motion set by the client.

## **9.2.3 Weight Test**

### **9.2.3.1 Summary**

The test will answer the question of how heavy the device is. The design requirement that this will be testing is ER2, which is weight of arm. The variable that will be tested is the arm part of the device to see how heavy the arm is as that will be the biggest weight on the user. The arm will be separated from the rig that is worn by the user to get true weight of the arm.

### **9.2.3.2 Procedure**

- Have the arm separated from the wearable rig.
- Lay device on scale to record weight or hung from it to record weight

### 9.2.3.3 Results



*Figure 27: Weight Test Results*

The results that were expected were to be under 2 kg. This was a critical design requirement as the device will be used by stroke survivors, so the device cannot be heavy to impede in their rehabilitation. This was achieved with the result of the arm weight being 1.3 kg

## 9.2.4 Comfortability Test

### 9.2.4.1 Summary

The test will answer the question of whether the entire design is comfortable to wear. The design requirements that this will be testing are CR1, comfortability, CR3, low profile, and ER2, weight of the arm. The variable that will be tested is the device itself to see if a user would be comfortable wearing it. The device will not be changed through testing with different users.

### 9.2.4.2 Procedure

- Have users put the device on.
- Have user give feedback on how they feel in device
- Repeat with multiple different users.

### 9.2.4.3 Results

The consistent feedback about the device was that it was comfortable to wear and go through a range of motion from several people including our client, Dr. Lerner.

## 9.2.5 Chair Test

### 9.2.5.1 Summary

The test will answer the question of whether the user can sit in chairs while wearing the device. The design requirements that this will be testing are CR1, comfortability, CR2, ability to sit, and CR3, low profile. The variable that will be tested is the full device to meet the client's demand of ability to sit in chairs. The device will not be changed while different chairs are tested.

### 9.2.5.2 Procedure

- Have the user put device on
- Have user sit in chair
- Have user give feedback on if they are comfortable
- Repeat with several types of chairs

### 9.2.5.3 Results



*Figure 28: Chair Test Picture*

The result that we received was that it could sit in chairs but was unable to be comfortable in tight chairs with arms. This might vary from user to user, but we will be testing with one user. The device can be adjusted to the location of the arm that can decide how well they can sit in several types of chairs

## 9.2.6 Sensor Test

### 9.2.6.1 Summary

The test will test if the sensors can be read. The design requirement that this will be testing is ER1, the degrees of freedom. All things will be kept the same; it is just a verification of the ability to read sensors.

### **9.2.6.2 Procedure**

- Have all software uploaded to the board
- Connect all components to the board
- Have software running to be able see results
- Add force to FSR to see if it can be read.

### **9.2.6.3 Results**

The sensors read user input. The sensors can detect force input through layers of foam padding. In future work, the sensors will be implemented into the end effector and communicate with the motors for smooth operation

## **9.2.7 Speed Test**

### **9.2.7.1 Summary**

The test will answer the question is the speed of the arm. The design requirement that this will be testing is ER3, which is the speed of the arm. The variable that will be tested is the motor to see if it is fast enough to raise the user's arm. The battery will consistently be at full charge to see how fast a motor is receiving full power. The variables that will need to be calculate is the speed using the time it took and the distance of the final

### **9.2.7.2 Procedure**

- Make sure Battery is fully charged
- Have user put on device
- Connect all components to the board to control the start time of the test.
- Start timer to see how long it takes to lift their arm.
- Repeat to be able to calculate the speed.

### **9.2.7.3 Results**

The average time that it took 1.006 seconds. Moving 90 degrees results in 0.2485 rev/s which is 14.91 RPM. This is also at a low torque output as rated speed is 40 RPM with higher torque output.

## **9.2.8 Bump Test**

### **9.2.8.1 Summary**

The test will answer the question of how strong the device is. The design requirements that this will be testing are CR5, which is durability, and CR3, which is low profile. The variable that will be tested is the arm itself on the full device. The arm will be consistently on the same side as well as the

being strapped to the user the entire time.

#### **9.2.8.2 Procedure**

- Have the user put the full device on.
- Have user bump into tables, walls, and other objects to mimic real life possibility of running into things
- Observe if there are any cracks or defects from the test
- Run motors to see if those were affected at all

#### **9.2.8.3 Results**

The device is not affected by bumping into walls. The device does not break upon impact. The device is low profile to where the user's arm would impact an object before the motors or more sensitive components

## **10 Future work**

There is still significant future work to be completed on the robotic arm. The device will be handed over to Jackson Truitt in the NAU Biomechanics Lab, where development will continue with the goal of transforming it into a fully functional rehabilitation device. Jackson has outlined plans for further improvements, including the implementation of a more advanced control algorithm to enable smoother, more precise motion suitable for rehabilitation use. In addition, the device will be modified to accommodate multiple users, ensuring adjustability and accessibility for a wider range of patients. These enhancements will help move the robotic arm closer to practical, real-world applications in therapeutic settings.

## 11 CONCLUSIONS

The Lerner Robotic Arm project successfully delivered a functional wearable robotic arm prototype designed to assist stroke survivors with upper-limb mobility impairment. Developed over two semesters under the sponsorship of Dr. Zachary Lerner and with funding from W.L. Gore, the team of five engineers designed, analyzed, fabricated, and tested a waist-mounted assistive exoskeleton that provides active gravity compensation at the elbow joint.

The project was guided by five customer requirements: Comfort, Ability to Sit in a Chair, Accessibility, Durability, and Low-Profile design, which were translated into five quantifiable engineering requirements: 3 Degrees of Freedom, a manufacturing cost under \$2,000, a motor speed above 10 rpm, a battery life exceeding 30 minutes, and a system weight below 2 kg. These requirements drove every major design and material decision throughout the project.

The final design features three subassemblies: a passive hinge allowing lateral arm swing, two motor-driven joints providing powered arm elevation and extension, and a padded end effector cuff at the forearm. Carbon fiber rectangular tubing was selected for the arm links, while ONYX material with continuous carbon fiber inlay was used for motor mounts and structural brackets, balancing high strength with low weight. The CubeMars AK45-36 motors were chosen based on torque analysis and client recommendation, providing sufficient torque at both the hip and elbow joints.

Testing validated the design across all major requirements. The arm weighed 1.3 kg, meeting the weight target. All 3 degrees of freedom were confirmed through range testing, with 2 active and 1 passive degree. Motor speed testing measured 14.91 rpm, exceeding the 10 rpm requirement. Battery endurance testing projected a two-motor runtime of 34 minutes, satisfying the 30-minute target. Comfortability and chair testing with multiple users, including feedback from the client Dr. Lerner, confirmed that the device was comfortable, low-profile, and capable of being worn while seated. The bump test confirmed structural durability under real-world impact conditions.

The device represents a strong engineering foundation for a clinical rehabilitation tool. While further development is needed before it can be used in a therapeutic setting, the prototype demonstrates that a lightweight, waist-mounted gravity compensation device is both feasible and practical for stroke survivors. The device will be handed off to the NAU Biomechanics Lab, where Jackson Truitt will continue development with a focus on advanced control algorithms and multi-user adjustability, advancing the design toward real-world therapeutic application.

## 12 REFERENCES

- [1] S. D. Gasperina *et al.*, “AGREE: A compliant-controlled upper-limb exoskeleton for physical rehabilitation of neurological patients,” *IEEE Transactions on Medical Robotics and Bionics*, pp. 1–1, 2023, doi: <https://doi.org/10.1109/tmrb.2023.3239888>.
- [2] R. Soltani-Zarrin, Amin Zeiaee, A. Eib, Reza Langari, N. Robson, and Reza Langari, “TAMU CLEVERarm: A novel exoskeleton for rehabilitation of upper limb impairments,” Nov. 2017, doi: <https://doi.org/10.1109/werob.2017.8383844>.
- [3] I. M. Alguacil-Diego *et al.*, “Validation of a Hybrid Exoskeleton for Upper Limb Rehabilitation. A Preliminary Study,” *Sensors*, vol. 21, no. 21, pp. 7342–7342, Nov. 2021, doi: <https://doi.org/10.3390/s21217342>.
- [4] D. Colley, C. D. Bowersock, and Z. F. Lerner, “A Lightweight Powered Elbow Exoskeleton for Manual Handling Tasks,” *IEEE Transactions on Medical Robotics and Bionics*, vol. 6, no. 4, pp. 1627–1636, Sep. 2024, doi: <https://doi.org/10.1109/tmrb.2024.3464690>.
- [5] M. E. Moran, “Evolution of robotic arms,” *Journal of Robotic Surgery*, vol. 1, no. 2, pp. 103–111, May 2007, doi: <https://doi.org/10.1007/s11701-006-0002-x>.
- [6] B.-O. Lee, Ita Daryanti Saragih, and Sakti Oktaria Batubara, “Robotic arm use for upper limb rehabilitation after stroke: A systematic review and meta-analysis,” vol. 39, no. 5, pp. 435–445, Mar. 2023, doi: <https://doi.org/10.1002/kjm2.12679>.
- [7] ISO - International Organization for Standardization, “ISO/TS 15066:2016,” *ISO*, Mar. 08, 2016. <https://www.iso.org/standard/62996.html>
- [8] A. Kojima, D. T. Tran, and J.-H. Lee, “Investigation of the Mounting Position of a Wearable Robot Arm,” *Robotics*, vol. 11, no. 1, p. 19, Feb. 2022, doi: <https://doi.org/10.3390/robotics11010019>.
- [9] M. Y. Metwly, C. L. Clark, J. He, and B. Xie, “A Review of Robotic Arm Joint Motors and Online Health Monitoring Techniques,” *IEEE Access*, pp. 1–1, Jan. 2024, doi: <https://doi.org/10.1109/access.2024.3447573>.
- [10] S. Parasuraman, Kee Chew Yee, and Arif Oyong, “Human upper limb and arm kinematics for robot based rehabilitation,” Jul. 2009, doi: <https://doi.org/10.1109/aim.2009.5229906>.
- [11] K.-H. Cho and W.-K. Song, “Effects of two different robot-assisted arm training on upper limb motor function and kinematics in chronic stroke survivors: A randomized controlled trial,” *Topics in Stroke Rehabilitation*, pp. 1–10, Aug. 2020, doi: <https://doi.org/10.1080/10749357.2020.1804699>.

- [12] K. Chang, P. Rammos, S. A. Wilkerson, M. Bundy, and S. Andrew Gadsden, "LiPo battery energy studies for improved flight performance of unmanned aerial systems," *Proceedings of SPIE*, May 2016, doi: <https://doi.org/10.1117/12.2223352>.
- [13] M.-S. Wu, C.-Y. Lin, Y.-Y. Wang, C.-C. Wan, and C. R. Yang, "Numerical simulation for the discharge behaviors of batteries in series and/or parallel-connected battery pack," *Electrochimica Acta*, vol. 52, no. 3, pp. 1349–1357, Aug. 2006, doi: <https://doi.org/10.1016/j.electacta.2006.07.036>.
- [14] L. Drohne, K. Nakabayashi, Y. Iwasaki, and H. Iwata, "Design Consideration for Arm Mechanics and Attachment Positions of a Wearable Robot Arm: 2019 IEEE/SICE International Symposium on System Integration, SII 2019," *Proceedings of the 2019 IEEE/SICE International Symposium on System Integration, SII 2019*, pp. 645–650, Apr. 2019, doi: <https://doi.org/10.1109/SII.2019.8700355>.
- [15] S. Openshaw, E. Taylor, G. Minder, W. Witherow, T. J. Long, and M. Ford, *Ergonomics and Design: A Reference Guide*, Allsteel Inc., Muscatine, IA, April 2006. [Online]. Available: <https://ehs.oregonstate.edu/sites/ehs.oregonstate.edu/files/pdf/ergo/ergonomicsanddesignreferenceguidewhitepaper.pdf> Environmental Health and Safety
- [16] G. R. Ballee, *Industrial Maintenance and Mechatronics*, 2nd ed., Goodheart-Willcox Company, Inc., Tinley Park, IL, 2022. ISBN: 978-1637767115. [Chapter 12]. [G-W+1](#)
- [17] "Understanding Steel Tube and Pipe Metallurgy," *The Fabricator*, Jul. 18, 2019. [Online]. Available: <https://www.thefabricator.com/tubepipejournal/article/tubepipeproduction/understanding-steel-tube-and-pipe-metallurgy> The Fabricator
- [18] R. T. Barrett, *Fastener Design Manual*, NASA Reference Publication 1228, Lewis Research Center, Cleveland, OH, USA, Mar. 1990. [Online]. Available: <https://ntrs.nasa.gov/api/citations/19900009424/downloads/19900009424.pdf> NASA Technical Reports Server
- [19] *Mechanisms*, Lunyax (Wordpress.com), Jun. 2014. [Online]. Available: <https://lunyax.wordpress.com/wp-content/uploads/2014/06/mechanisms.pdf> lunyax's Blog
- [20] *Handbook on Polymer Selection for Engineering*, Google Books. [Online]. Available: <https://books.google.com/books?hl=en&lr=&id=-MB2DhLQ-q0C&oi=fnd&pg=PA421&dq=handbook+on+polymer+selection+for+engineering> ... Google Books
- [21] "Metal Strength Chart - A Pro Guide 2025," PartMFG, 2025. [Online]. Available: <https://www.partmfg.com/metal-strength-chart-a-pro-guide-2025/> partmfg.com

- [22] Morgan Advanced Materials, Composites Material Datasheet, [Online]. Available: [https://s3.amazonaws.com/mf\\_product\\_doc\\_images/Datasheets/Material+Datasheets/CompositesMaterialD atasheet.pdf](https://s3.amazonaws.com/mf_product_doc_images/Datasheets/Material+Datasheets/CompositesMaterialD atasheet.pdf). [Accessed: 23-Nov-2025].
- [23] Haddington Dynamics AS PDF, Haddington Dynamics AS [Online]. Available: <https://www.matterhackers.com/store//markforged-onyx-filament/sk/MUJD90ET?srsId=AfmBOop2G9xXEOvprq4v9Cp-q22Ae8AqqBPLZlovFBkpCFWAUQm58k2B> [Accessed: 23-Nov-2025].
- [24] R. Warren, “6 Steps to Your First SOLIDWORKS Simulation,” GoEngineer, 2024. [Online]. Available: <https://www.goengineer.com/blog/6-steps-first-solidworks-simulation>. [Accessed: 23-Nov-2025].
- [25] X. Fan et al., A humanoid robot teleoperation approach based on waist–arm coordination | emerald insight, doi: <https://www.emerald.com/insight/content/doi/10.1108/IR-12-2022-0306/full/html>
- [26] K. Kruthika, B. M. K. Kumar, and S. Lakshminarayanan, “Design and development of a robotic arm | IEEE conference publication | IEEE xplore,” IEEE Xplore, doi: <https://ieeexplore.ieee.org/abstract/document/8053274/>
- [27] C. Ochieze, S. Zare, and Y. Sun, “IOPscience,” Progress in Biomedical Engineering, doi: [https://iopscience.iop.org/article/10.1088/2516-1091/acc70a/meta?utm\\_source](https://iopscience.iop.org/article/10.1088/2516-1091/acc70a/meta?utm_source)
- [28] M. A. Gull, S. Bai, and T. Bak, “A review on design of upper limb exoskeletons,” MDPI, doi: [https://www.mdpi.com/2218-6581/9/1/16?utm\\_source](https://www.mdpi.com/2218-6581/9/1/16?utm_source)
- [29] Comparison of material’s properties for exoskeletons structure | downloaded scientific diagram, doi: [https://www.researchgate.net/figure/Comparison-of-materials-properties-for-exoskeletons-structure\\_tbl4\\_365212324](https://www.researchgate.net/figure/Comparison-of-materials-properties-for-exoskeletons-structure_tbl4_365212324)
- [30] Z.-J. Chen, “Exoskeleton-assisted anthropomorphic movement training for the upper limb after stroke: The EAMT randomized trial | stroke,” AHAJournals, doi: <https://www.ahajournals.org/doi/10.1161/STROKEAHA.122.041480>
- [31] Y. Zhao, H. Wu, M. Zhang, J. Mao, and M. Todoh, “Design methodology of portable upper limb exoskeletons for people with strokes,” Frontiers, doi: [https://www.frontiersin.org/journals/neuroscience/articles/10.3389/fnins.2023.1128332/full?utm\\_source](https://www.frontiersin.org/journals/neuroscience/articles/10.3389/fnins.2023.1128332/full?utm_source)
- [32] W. Chen, Z. Li, X. Cui, J. Zhang, and S. Bai, “Mechanical design and kinematic modeling of a cable-driven arm exoskeleton incorporating inaccurate human limb anthropomorphic parameters,” Sensors (Basel, Switzerland), <https://pmc.ncbi.nlm.nih.gov/articles/PMC6832992/>

- [33] R. Soltani-Zarrin, A. Zeiaee, R. Langari, and R. Malak, "A systematic approach for kinematic design of Upper Limb", <https://arxiv.org/pdf/1712.02325>
- [34] C. Nguiadem, M. Raison, and S. Achiche, "A test bench for evaluating exoskeletons for Upper Limb Rehabilitation," arXiv.org, <https://arxiv.org/abs/2112.14885>
- [35] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*, 1995, pp. 399–406, doi: <https://doi.org/10.1109/IROS.1995.525827>
- [36] P. Yu, W. Chen, and C. Liu, "Quasi-direct-drive actuation for shoulder exoskeletons: Design and evaluation," *IEEE/ASME Trans. Mechatronics*, vol. 25, no. 5, pp. 2410–2421, 2020, doi: <https://doi.org/10.1109/TMECH.2020.2995134>
- [37] E. Moubarak, K. Pham, R. Moreau, and E. Redarce, "Gravity compensation of an upper extremity exoskeleton," in *Proc. IEEE EMBC*, 2010, pp. 4479–4482, doi: <https://doi.org/10.1109/IEMBS.2010.5626036>
- [38] F. Just *et al.*, "Human arm weight compensation in rehabilitation robotics: efficacy of three distinct methods," *J. NeuroEngineering & Rehabilitation*, vol. 17, Art. 14, 2020, doi: <https://doi.org/10.1186/s12984-020-0644-3>
- [39] C. Hill *et al.*, "Gravity Compensation of an Exoskeleton Joint Using Constant-Force Springs," in *Proc. IEEE Int. Conf. Rehabilitation Robotics (ICORR)*, 2019, pp. 1032–1037, doi: <https://doi.org/10.1109/ICORR.2019.8779422>
- [40] J. Vantilt *et al.*, "Model-based control for exoskeletons with series elastic actuators," *J. NeuroEngineering & Rehabilitation*, vol. 16, Art. 100, 2019, doi: <https://doi.org/10.1186/s12984-019-0526-8>
- [41] ASTM International, *F3323-21: Standard Terminology for Exoskeletons and Exosuits*, 2021. Available: <https://www.astm.org/f3323-21.html>
- [42] ISO, *ISO 13485:2016 - Medical devices — Quality management systems — Requirements for regulatory purposes*, 2016. [Online]. Available: <https://www.iso.org/standard/59752.html>
- [43]
- [44]

- [45] Y. Wang, W. Li, S. Togo, H. Yokoi, and Y. Jiang, "Survey on Main Drive Methods Used in Humanoid Robotic Upper Limbs," *Cyborg and Bionic Systems*, vol. 2021, pp. 1–12, Jun. 2021, doi: <https://doi.org/10.34133/2021/9817487>
- [46] E. Bardi, M. Gandolla, F. Braghin, F. Resta, A. L. G. Pedrocchi, and E. Ambrosini, "Upper limb soft robotic wearable devices: a systematic review," *Journal of NeuroEngineering and Rehabilitation*, vol. 19, no. 1, Aug. 2022, doi: <https://doi.org/10.1186/s12984-022-01065-9>
- [47] D. Verdel, S. Bastide, N. Vignais, O. Bruneau, and B. Berret, "Human Weight Compensation With a Backdrivable Upper-Limb Exoskeleton: Identification and Control," *Frontiers in Bioengineering and Biotechnology*, vol. 9, Jan. 2022, doi: <https://doi.org/10.3389/fbioe.2021.796864>.
- [48] H. Zheng et al., "3D Printing Continuous Fiber Reinforced Polymers: A Review of Material Selection, Process, and Mechanics-Function Integration for Targeted Applications," *Polymers*, vol. 17, no. 12, pp. 1601–1601, Jun. 2025, doi: <https://doi.org/10.3390/polym17121601>
- [49] ISO, "Robots and robotic devices — Safety requirements for personal care robots," ISO 13482:2014, International Organization for Standardization, Geneva, Switzerland, 2014. [Online]. Available: <https://www.iso.org/standard/53820.html>
- [50] Q. Fang, G. Li, T. Xu, J. Zhao, H. Cai, and Y. Zhu, "A Simplified Inverse Dynamics Modelling Method for a Novel Rehabilitation Exoskeleton with Parallel Joints and Its Application to Trajectory Tracking," *Mathematical Problems in Engineering*, vol. 2019, Article ID 4602035, 10 pages, 2019, doi: 10.1155/2019/4602035. [Online]. Available: <https://pdfs.semanticscholar.org/637d/9c65e0053fe6b7fb3adddf370617520c7cd3.pdf>
- [51] P. Raghavan, "Upper Limb Motor Impairment After Stroke," *Physical Medicine and Rehabilitation Clinics of North America*, vol. 26, no. 4, pp. 599–610, Nov. 2015, doi: <https://doi.org/10.1016/j.pmr.2015.06.008>
- [52] H. Yin, S. Huang, M. He, and J. Li, "Overall structure optimization for a lightweight robotic arm," *Robotics and Autonomous Systems*, pp. 1–12, 2024. [Online]. Available: [https://www.researchgate.net/publication/overall\\_structure\\_optimization\\_robotic\\_arm](https://www.researchgate.net/publication/overall_structure_optimization_robotic_arm)
- [53] G. R. Reddy, "Design and structural analysis of a robotic arm," *DIVA Portal*, 2021. [Online]. Available: <https://www.diva-portal.org/smash/get/diva2:1693316>

[54] A. T. Asbeck, S. M. M. De Rossi, I. Galiana, Y. Ding, and C. J. Walsh, "Stronger, smarter, softer: next-generation exosuits and joint actuation mechanisms," IEEE Robotics & Automation Magazine, vol. 21, no. 4, pp. 22–33, Dec. 2014.

doi: 10.1109/MRA.2014.2360283.

[55] "ASME Y14.5 GDT Standard," GD&T Basics. [Online]. Available: <https://www.gdandtbasics.com/asmey14-5-gdt-standard/>

# 13 APPENDICES

## 13.1 Full House of Quality

		Degrees of Freedom								
		Manufacturing Cost	neg				Positive	pos		
		Speed of Arm	neg	neg			Negative	neg		
		Battery Life	neg	neg	pos					
		Weight	neg	pos	pos	pos				
Relative Weight (%)	Customer Weights	Customer Requirements	Engineering Requirements					Benchmarking		
			Degrees of Freedom	Manufacturing Cost	Speed	Battery Life	Weight	Poor	Adequate	Excellent
11	4	Comfortable	3	1	3	3	9		C	AB
22	5	Ability to Sit in a Chair	9	1	1	1	1	A	B	C
10	2	Accessibility	3	9	3	3	3	AC	B	
5	3	Durability	1	1	1	1	9		B	AC
22	3	Low-Profile	3	3	3	9	9	ABC		
Technical Requirement Units			N/A	\$	rpm	Minutes	lbs			
Technical Requirement Targets			3	<2000	>10	>30	<2		Strong	9
								Moderate	3	
								Weak	1	

ExoFlex	B
CleverArm	C