Lerner Robotic Arm

Conceptual Design Report

Cole Pace: Project Manager and Prototype Lead

Joel Gisleskog: Design Lead and Testing Lead

Caleb Lamca: Manufacturing Lead and Fundraising Lead

Kaitlyn Davis: Budget Lead and Documentation Lead

Colin Donnellan: Website Developer and Logistics Manager

Fall 2025-Spring 2026

NAU NORTHERN ARIZONA UNIVERSITY

Steve Sanghi College of Engineering

Project Sponsor: Dr Zachary Lerner

Faculty Advisor: Dr. Dante Archangeli

Instructor: Dr David Willy

DISCLAIMER

EXECUTIVE SUMMARY

The Lerner Robotic Arm project aims to design and manufacture a waist-mounted robotic arm that assists individuals with upper-limb mobility impairments, particularly stroke survivors. The device is designed to provide active gravity compensation at the elbow joint, enabling smoother, more natural arm motion while remaining lightweight, compact, and comfortable for everyday use.

Throughout the Fall 2025 semester, the team established key customer and engineering requirements, created detailed CAD models in SolidWorks, and performed mathematical modeling to determine torque demands, optimal link geometry, and battery capacity. Benchmarking and literature reviews guided material and motor selection, emphasizing safety, ergonomics, and efficiency. The AK45-36 motor was selected for its torque output, while ONYX carbon-fiber nylon was chosen for its strength-to-weight ratio in 3D-printed components. Finite Element Analysis confirmed a significant improvement in the safety factor between initial and revised motor mount designs.

Initial prototypes demonstrated functional motion, comfortable fit, and adequate weight distribution through a wearable rig system. Future work will focus on integrating electronic control, refining the hinge design allowing the arm to rest at one's side, and impact testing to validate long-term performance. The project remains on schedule to deliver a functional, assistive device that combines mechanical reliability, ergonomic design, and user comfort by the end of Spring 2026.

TABLE OF CONTENTS

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 795,00 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 an 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 our happy with our final design and it has met our success metrics.

1.3 Success Metrics

To define our success, we must assess what we want the robotic arm to be cable of the robotic arm must successfully support the users 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 thorough 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 protype 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 the target users (stroke survivors with limited upper-limb mobility. The most critical requirements are Range of Motion and Safety, both rated highest in importance. This device must allow natural arm movement while supporting the elbow through active gravity compensation. Safety ensures that the user is protected from excessive joint torque, pinch joints, or electrical hazards during operation. Comfort and Ease of use are also key factors, as the device will be worn for extended periods and must not restrict the user's daily activities. A Low-Profile design ensures minimal obstruction and promotes confidence in public use, while Durability guarantees long-term reliability under repeated mechanical loading. Lastly, Cost is considered to maintain affordability for both research and potential clinical applications.

These requirements directly reflect the needs and experiences of the intended users. Comfort and usability prioritize user well-being, while safety and range of motion ensure that the device functions as a true assistive aid. By balancing cost and durability, the team aims to produce a lightweight practical prototype that satisfies both the sponsor's research objectives and real-world feasibility. Collectively, these customer requirements serve as 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 allow natural arm and elbow motion while supporting necessary rehabilitation movements. To maintain comfort and reduce fatigue, the total system Weight is constrained to under 2 kg, with mass distributed near the waist to minimize user load. Torque Speed performance will target 60°/s to match realistic human joint motion speeds during lifting tasks. For endurance, Battery Life is specified to exceed 8 hours, ensuring the device can function for an entire therapy session or daily use period without frequent recharging.

Manufacturability and material quality are also defined quantitatively. Manufacturing Cost must remain below $1,000, and both Component and Material Quality are rated at engineering levels suitable for safety and mechanical integrity under load. Additionally, Degrees of Freedom, Weight, and Torque Speed correspond directly to user comfort, range of motion, and ease of use, while Battery Life and Durability influence reliability and long-term satisfaction. These parameters provide concrete targets for design validation and testing, ensuring each engineering decision supports the primary customer objectives. The quantified metrics serve as performance benchmarks for prototype evaluation and future optimization.

2.3 House of Quality (HoQ)

Degrees of Freedom						
Quality of Components	pos					
Quality of Materials		neg				
Manufacturing Cost	pos		pos			
Torque Speed		pos				
Battery Life	neg	pos		neg	pos	
Weight	pos	pos	pos	pos	pos	pos

Correlation	
Positive	pos
Negative	neg

			Engineering Requirements							Benchmarking		
Relative Weight (%)	Customer Weights	Customer Requirments	Degrees of Freedom	Quality of Components	Quality of Materials	Manufacturing Cost	Torque Speed	Battery Life	Weight	Poor	Adequate	Excellent
11	4	Comfortable	3	3	3	1	3	3	9		C	AB
22	5	Range of Motion	9	3	3	1	1	1	1	A	B	C
10	5	Safety	3	9	9	1	9	1	3			ABC
10	2	Cost for Consumer	3	9	9	9	3	3	3	AC	B	
5	3	Durabiltiy	1	9	9	1	1	1	9		B	AC
5	4	Ease-of-use	9	3	3	1	9	3	3	BC	A	
22	3	Low-Profile	3	1	3	3	3	9	9	ABC		
Technical Requirement Units			N/A	$	$	$	°/s	Hours	kgs			
Technical Requirement Targets			4	<1400	<1000	<1000	60	>8	<2			

Figure 1: House of Quality

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 bateries 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 looked into 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 deign 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. Inlcued are tables, graphs, and information about all of 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 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 Gisleskog: 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 Gisleskog: Standard Terminology for Exoskeletons and Exosuits [1]

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

3.2.38 Joel Gisleskog: 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 Gisleskog: 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 Gisleskog: 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 robotiv 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 Battery Capacity for One Motor - Colin Donnellan

Dr Zachary Lerner gave the team three motors to possibly consider for the project. The team decided to use those motors in our calculations as Dr Lerner is a client and knows more about wearable robotics. The motors given were AK40-10 KV170, AK45-10 KV75, and the AK45-36, which are all suitable for humanoid robotic joints. Using the product comparison from the website, the next step was to find the capacity needed to power the motors.

$$Capacity = \frac{Rated\ Power}{Rated\ Voltage} \cdot 8\ hours \qquad (1)$$

AK40-10: 20 Ah

AK45-10: 13 Ah

AK45-36: 11 Ah

The rated power and rated voltage were used as those are the values for each motor that are at a safe usage to not overheat or damage the motor. It was next multiplied by eight hours as that is the time that the group wants the product to last. Lastly, the equation above only gives the capacity of one motor and the design that will be used will have two motors, so the found value will need to be doubled to find the true capacity needed.

3.3.2 Cross Sectional Geometric Selections – Caleb Lamca

One important aspect of the design process is determining the beam geometry, specifically the cross-sectional geometry. For this application, there were two leading ideas; a rectangular tube and a circular tube. Both of these designs are easy to find cheap prototype alternatives, exist in abundance in the open market, and can be 3D printed with relative ease [21]. For the remainder of the calculations in this section, we will focus on these two designs. When comparing the cross-sectional geometry, we use equations for the Moment of Inertia, which are crucial in determining the maximum stress in each beam in comparison to the maximum allowable stress in our design as a whole.

$$\sigma_{max,c} = \frac{(M_{max} \cdot c)}{I_c} = 15.4\ [MPa]$$

$$\sigma_{max,s} = \frac{(M_{max} \cdot c)}{I_s} = 69.4\ [MPa]$$

As we can clearly see from equations 2 and 3, the circular cross-section carries a significantly lower stress, roughly 4 times less. This lower stress will allow the team to have a higher factor of safety, which is important when designing a medial-adjacent product with dynamic forces. We can also extract that the moment of inertia directly determines the output for maximum stress per beam. A higher moment of inertia will contribute to lower maximum stress.

$$I_c = \frac{\pi}{64}(D^4 - d^4) = 9 \cdot 10^{-6}[m^{-4}]$$

$$I_s = \frac{HW^3 - hw^3}{12} = 2 \cdot 10^{-6}[m^{-4}]$$

Equations 4 and 5 show this principle. The circular cross-section has a much higher moment of inertia and will therefore contribute to a lower stress in any beam it will be utilized. If the geometries for the square tubing and circular tubing are comparable- as they would both need to have similar sizes to fit the same application, the circular cross-section will always have the higher moment of inertia. The team used these calculations and principles to determine that the circular cross-sectional geometry will be best suited for our design applications. Along with other factors, such as cost, ease of acquisition, ease of prototyping, etc.

3.3.3 Link Motion Analysis-Joel

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.

link 2=248mm= link 1

distance from elbow to waist=70mm

$$\sin(\theta) = sin^{-1}\left(\frac{70}{248}\right) = 16.4°$$

$$90 - 16.4 = 73.6°$$

$$90 + 73.6 = 163.6°$$

$$l_1x_1 = lcos(\theta) = 248 \cdot \cos(163.6°) = -237.9mm$$

$$l_1y_1 = lsin(\theta) = 248 \cdot \sin(163.6°) = -70mm$$

$$B_{x1} = -237.9 + 248 = 10.1mm$$

$$B_{y1} = -70 + 0 = -70mm$$

$$A_s = (-238mm, 70mm)$$

$$B_s = (10mm, 70mm)$$

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.

$$l_1x_2 = lcos(\theta) = 248 \cdot \cos(45°) = 175.36mm$$

$$l_1y_2 = lsin(\theta) = 248 \cdot \cos(45°) = 175.36mm$$

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

$$B_{y1} = 175.36 + 175.36 = 350.7mm$$

$$A_s = (175.36mm, 175.36mm)$$

$$B_s = (350.7mm, 350.7mm)$$

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.

$$\theta_1 = 163.3 - 45 = 118.6°$$

$$\theta_2 = 0 + 45 = 45°$$

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

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

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.

3.3.4 Torque Evaluation at Joints-Cole

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 following equations are for the transmission design.

Hip:

$$\tau_1 = g\big(m_1 r_1 + m_2(L_1 + r_2) + m_p(L_1 + L_2)\big) + \alpha_1(m_1 r_1^2 + m_2(L_2 + r_2)^2 + m_p(L_1 + L_2)^2$$

$$\tau_1 = 6.78\ N \cdot m$$

$$\tau_{1S} = 10\ N \cdot m$$

Elbow:

$$\tau_2 = g\big(m_2 r_2 + m_p L_2\big) + \alpha_2(m_2 r_2^2 + m_p L_2^2)$$

$$\tau_2 = 2.94\ N \cdot m$$

$$\tau_{2S} = 4.5\ N \cdot m$$

The next equation is for the direct drive system.

Hip:

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

$$\tau_{1S} = 11.5\ N \cdot m$$

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

3.3.5 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:

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

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.

$$w_{avg} = \frac{\Delta\theta}{t} = \frac{90° \cdot (\frac{\pi}{180})}{1.28\ s} = 1.227\ {rad}/{s}$$

The average angular velocity of the arm from 0 to 90 degrees is

1.227rad/s

The linear velocity of the elbow can be solved by using the equation below. For the radius r value, 330mm =0.33m is used, because the velocity of the elbow is being solved.

v= wavg∗r=1.227rads∗0.33 m=0.405ms *v= wavg∗r=1.227rads∗0.33 m=0.405ms*

$$v = w_{avg} \cdot r = 1.227 \cdot .33 = .405 \frac{m}{s}$$

Our results show that the velocity of our arm design needs to move around

0.405 m/s for safety and comfort when the device needs to move upward and downward.

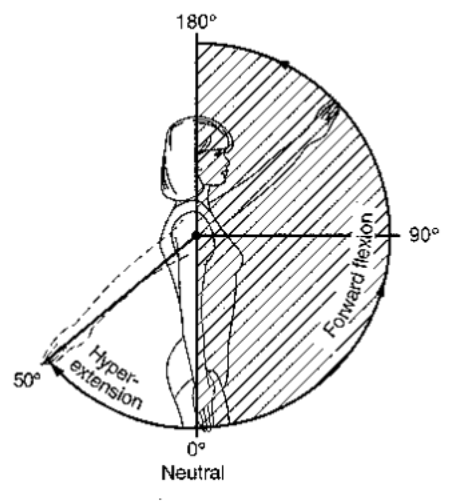


Figure 2: Anthropometry of Range of Motion

4 Design Concepts

4.1 Functional Decomposition

Figure 3 depicts the functional decomposition the team will use as a reference for the remainder of this project. Through this chart, we will be able to easily identify the next step at each stage in design and determine where to direct the most attention. This chart will act as an outline to ensure we have delivered every aspect of our design for each project deliverable.

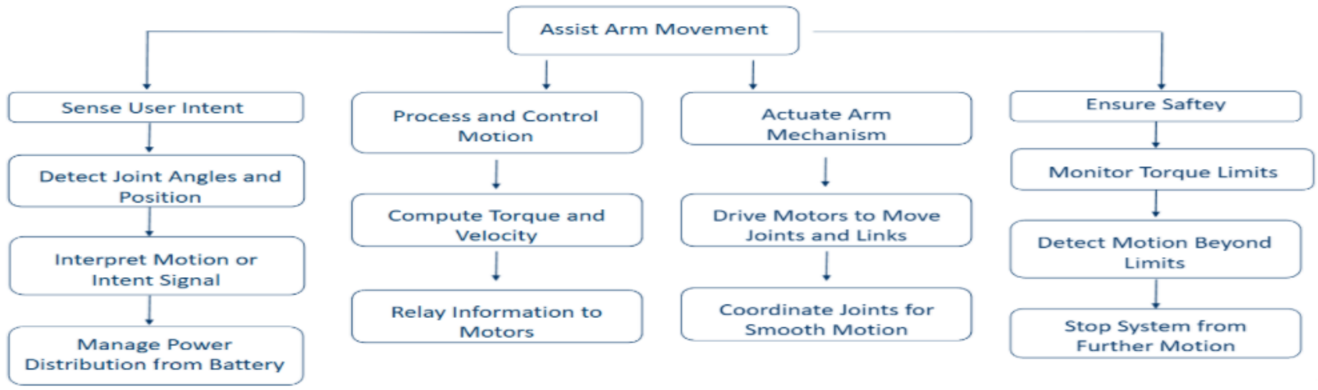


Figure 3: Functional Decomposition

The functional decomposition is especially important for our project as there are many elements that are dependent on one another. Understanding which components and features affect others before the extensive design and prototype phases will streamline our processes and limit fatigue and frustration.

4.2 Concept Generation

The team decided on three major criteria to evaluate the design of our device. 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 wanted 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.

- o Cons: transmitting power to two different axis increases cost and complexity.
- Ball joint (3 DOF)
    - o Pros: Smoother movement of the arm is allowed.
    - o Cons: Requires three motors for each DOF
- Revolute joint (1 DOF)
    - o Pros: Simple transmission and requires only one motor.
    - o 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 deicide that the best simple options were a hollow rectangular cross-section and a hollow circular cross-section.

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

4.3 Selection Criteria

The team selected motor, link geometry, and the joints for how the design will come together. Each of the parts had its own criteria to find out how each part is selected.

The first was the motor that the design will use. The three motors that Dr. Lerner gave us were evaluated by how the motors can handle the torques that were calculated above.

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: Product Comparison

The motor needs to be able to withstand 10 to 11.5 Nm so that the device can hold the arm up. The peak torque would need to have that requirement as those were the peak torques calculated. From those requirements needed, the motor selected was AK45-36.

The next was the link geometry for how to have the design work. This was found as deciding to be between a rectangular or circular cross section. Deciding between these two was calculated by seeing which area had better bending stress, which can be seen in the modeling section. From that calculation, the cross-sectional area chosen was circular as it can withstand better bending stress.

The last criteria that were needed for the joints and how they will connect with each other. The joint selection that was chosen was a revolute joint. The revolute joint was chosen because of its ability to get the movement that is wanted as well as at the time being there are two modes of actuation one being direct drive and one being transmission drive. For the transmission drive it would need cables and would get in the way of other joints.

4.4 Concept Selection

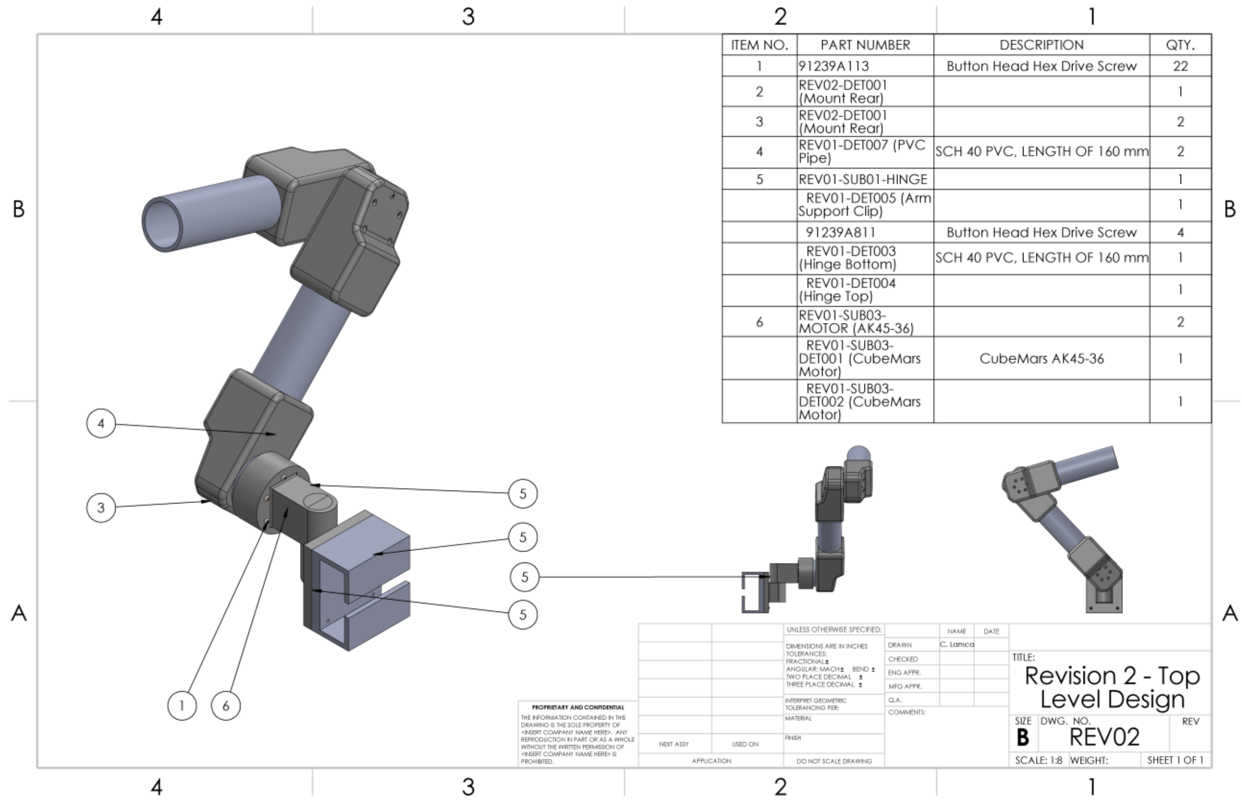
The team developed a new model that incorporates new motor mounts and a new hinge that allows the articulation of the arms and movement about the user. A new material was introduced for consideration by our mentor, Dr. Lerner. This new material is called ONYX and utilizes a carbon fiber/nylon composite for 3D printing. FEA testing was completed in SolidWorks for the first and second motor mount revisions, the results for the Factors-of-Safety and the stresses in each part are shown in Table 1 below.

	REV01		REV02	
Material/Value	PLA	ONYX	PLA	ONYX
Von Mises	2.819e+06	-	7.29e+05	7.43e+05
FoS	17.74	-	68.6	269.1

Table 1: FoS Table

This Factor of Safety table highlights the main differences between the first revision and the second revision of the motor mounts. The stress concentrations due to sharp corners and severe tapers were removed, and more material was added at the critical locations. Additionally, a new material was virtually tested, the ONYX carbon fiber-reinforced nylon. This material has significantly better material properties pertaining to yield stress and flexural strength. For this new mount, a 90/10 nylon/carbon fiber split was tested using custom material property creation via SolidWorks. These changes are tracked above with their results at each stage and contribute to a significant factor of safety for this design. The results of this redesigned mount clearly show that the motor mount subassembly will not be the point of failure in the design of the robotic arm.

The redesigned hinge was also tested using SolidWorks FEA using common PLA 3D printer filament. The hinge was found to have a FoS of 50 and proved that this component/subassembly will not be a weakness in the revised prototype. More work is required to find a reliable method to attach the hinge subassembly and the greater robotic arm to the user. Figure 5 shows the most recent model that will be used in the second phase of prototyping and includes the aforementioned subassemblies.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	91239A113	Button Head Hex Drive Screw	22
2	REV02-DET001 (Mount Rear)		1
3	REV02-DET001 (Mount Rear)		2
4	REV01-DET007 (PVC Pipe)	SCH 40 PVC, LENGTH OF 160 mm	2
5	REV01-SUB01-HINGE		1
	REV01-DET005 (Arm Support Clip)		1
	91239A811	Button Head Hex Drive Screw	4
	REV01-DET003 (Hinge Bottom)	SCH 40 PVC, LENGTH OF 160 mm	1
	REV01-DET004 (Hinge Top)		1
6	REV01-SUB03-MOTOR (AK45-36)		2
	REV01-SUB03-DET001 (CubeMars Motor)	CubeMars AK45-36	1
	REV01-SUB03-DET002 (CubeMars Motor)		1

Figure 5: CAD Model with Bill of Materials

Figure 5 shows the most recent CAD model. This top-level model shows the main components and subassemblies necessary for the next prototyping phase. These subassemblies include the hinge that allows for movement about the user, the joints which house the motor and allow the arm to articulate, the arm links that connect the critical components to one another and protect the wiring. The waist belt is not shown here to maintain the scale. However, the waist belt routes simply though the arm support clip shown as part of subassembly 5 in the bottom right of the model.

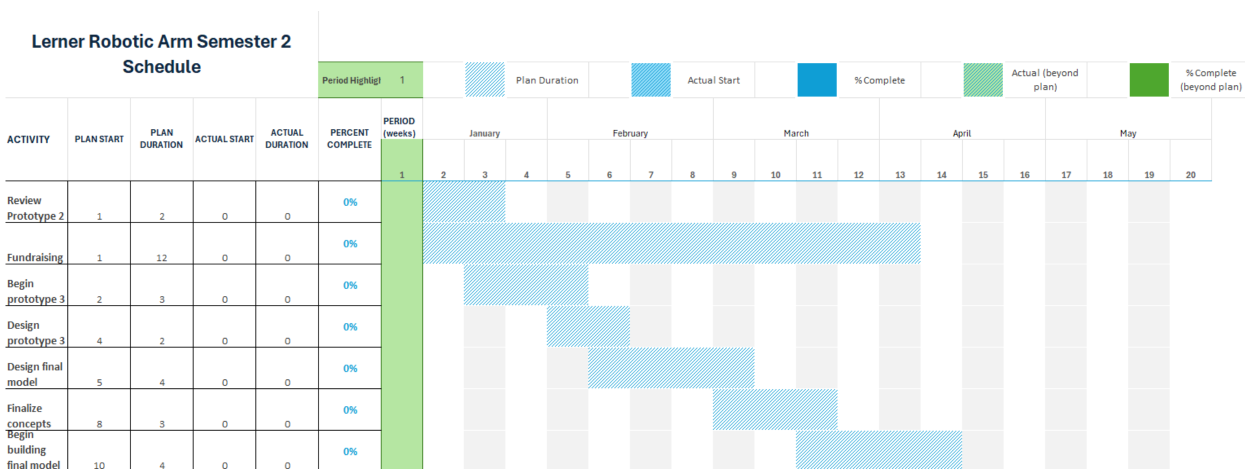
5 Schedule and Budget [Kaitlyn]

5.1 Schedule

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Requirements / research	1	2	1	2	100%
Equations	2	2	2	2	100%
Presentation 1	3	1	3	1	100%
Conceptual Design	4	3	5	2	100%
Fundraising	4	13	0	0	0%
Presentation 2	6	2	6	2	100%
Begin modelling	7	3	7	3	100%
Testing prototype 1	8	2	8	3	100%
Presentation 3	9	2	9	2	100%
1st Prototype demo	10	2	10	2	100%
Begin prototype 2	11	3	0	0	0%
Testing prototype 2	12	3	0	0	0%
2nd prototype demo	13	2	0	0	0%

Figure 6: Semester 1 Gantt Chart

The first semester, the Lerner Robotic Arm team is on time with all tasks and activities. The team finished the necessary requirements/research, conceptual design for prototype 1. Prototype 1 material was covered in the first demo and partially in presentation 3. The team will start prototype 2 near the beginning of December and present it to the class.



ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Review Prototype 2	1	2	0	0	0%
Fundraising	1	12	0	0	0%
Begin prototype 3	2	3	0	0	0%
Design prototype 3	4	2	0	0	0%
Design final model	5	4	0	0	0%
Finalize concepts	8	3	0	0	0%
Begin building final model	10	4	0	0	0%

Figure 7: Semester 2 Gantt Chart

Above is a draft of what semester 2 may look like for the Lerner Robotic Arm team. The team will review prototype 2 to get a general idea of the next prototype. The team will also begin to finalize any concepts and designs. The budget team will also plan on making purchases for the final model and focus on fundraising more money to make these necessary purchases.

5.2 Budget

The Lerner Robotic Arm team began with a starting budget of $4000 from W.L. Gore, minus $200 for NAU's processing fee, so the team is left with at least $800. The team also plans to fundraise at least %10 of the funding from Gore, so the estimated budget for the team to use is at least $4200.

Budget		
Category	Items	Cost
Tools and materials:	3D Printer Parts	$100
	3D Printer Filament (PLA for prototyping)	$35.99
	3D Printer Filament (ONYX for final build)	$200
	3D Printer Filament (Carbon Fiber for final build)	$450
Manufacturing:		$300
Parts:	Motors (2x CubeMars)	$371.80
	Battery	$67.12
	Miscellaneous Parts	$700
Prototyping:	1st	$205.20
	2nd	$900
TOTAL:		$3330.11

Table 2: Budget and Cost

Table 2 shows an estimated budget and cost for the items the team plans on purchasing. Taking away the estimated cost of about $3331, the team will have a remaining balance of about $869. To achieve this, the team must start fundraising to begin prototyping the second model.

For prototype 1, the team was split into two teams, a team for the rig and a team for the arm.

Rig Prototype 1	
Item	Cost
Waist Belt	$107.74
Universal Sliding Rig Tool Belt Support	$34.34
Total:	$142.08

Table 3: Prototype 1 Rig Cost

Arm Prototype 1	
Item	Cost
22 M-3X50 Screws	$16.50
3kg PLA Filament	$35.99

PVC	$10.63
Total:	$63.12

Table 4: Prototype 1 Arm Cost

Table 3 and 4 show the materials and items used to create prototype 1, the total cost for prototype 1 was $205.20. This total cost includes both the rig and arms total cost. The team is financially on track to create any future prototypes and if needed, to make any more upcoming purchases.

5.3 Bill of Materials (BoM)

Table 5: BoM

Bill of Materials						
Item	Quantity	Vendor	Description	Vendor #	Cost	Purchased
1	2	CubeMars	AK45-36 KV80	AK45-36 KV80	371.8	Yes
2	1	Amazon	HRB 2PCS 1800mAh 6S 22.2V 50C LiPo Battery with XT60 Plug Compatible with RC Helicopter Airplane Car Boat Truck	HRB 2PCS 1800mAh 6S 22.2V 50C LiPo Battery with XT60 Plug	67.12	Yes
3	1	Sunlu	High Speed PLA 3KG Large Spool 3D Printer Filament 3KG	High Speed PLA 3KG Large Spool 3D Printer Filament 3KG	35.99	Yes
4	1	Atlas	Atlas Adventure Hiking Grade Hip Belt Black / LRG-XL | 36-44"	Atlas Adventure Hiking Grade Hip Belt	107.74	Yes
5	1	McMaster-Carr	Button Head Hex Drive Screw-Black-oxide alloy steel M3x0.50mm Thread, 8mm long	91239A113	8.77	Yes
6	1		Button Head Hex Drive Screw-Black-oxide Class 12.9 alloy steel, M3x0.50mm Thread, 15mm long	91239A811	6.5	Yes
7	1	Home Depot	Universal Sliding Rig Tool Belt Support	81701N20	34.34	Yes
8	8		22 M-3x50 Screws		16.5	Yes
9	1		PVC piping		10.63	Yes
				TOTAL:	659.39	

The Bill of Materials is shown in Table 5, where all the team's purchased items are listed, along with the quantity, the vendor, a description of each item, the item number if given, and the cost. So far, this is all the team has and there will be more future items added once prototype 2 has begun.

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)[Joel]

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 an electrical short, 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.

Lower severity components like the hinge and the elbow cup were still reviewed, but there was no real risk of danger, just discomfort. We will use simpler fixes during prototyping to accommodate the user.

In summary, our FMEA helped us identify components which could cause the highest potential impact on user safety, especially for stroke survivors. The FMEA analysis helped guide several design choices: stronger material, insulation, ventilation, and more. It ensured that the final design would prioritize safety and reliability over simplicity

6.2 Initial Prototyping [Caleb and Colin]

6.2a 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 8: Rig Prototype worn by Caleb Lamca

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.

6.2b Arm Prototype

The project is a robotic arm, so the arm needs to do several things to meet the project requirements. There were several questions that were going to be answered with this prototype including: does the arm rest comfortably by your side, does the hinge work, can the joints move without interference, and does the arm reach all three degrees of freedom?

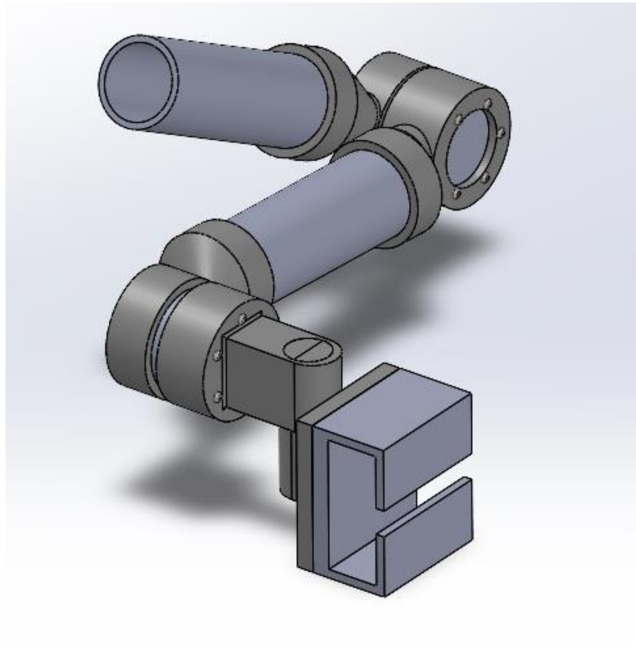


Figure 9: Arm Prototype

These answers were all yes except that the arm does not rest comfortably by the side. Right now, the part of the design that will attach to the rig interferes with where your arm lays naturally by your side and pushes it out, making it uncomfortable to rest your arm. This can be fixed though by moving the location that the device is attached to slightly backward and not directly on the side. Everything else was a success though, which really helps that not much of our design needs to be changed. This informed us that the hinge works in getting the third degree of freedom without it being actuated, the links do not interfere with each other, and the degrees of freedom wanted are reached. Future iterations could improve the placement of the device as well as making slight changes to the design of the device to accommodate electronic devices' needs.

6.3 Other Engineering Calculations

6.3.1 Battery Evaluation - Colin Donnellan

Dr Lerner, our client, recommended a specific battery which was bought to start as a battery for the project. Two 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.

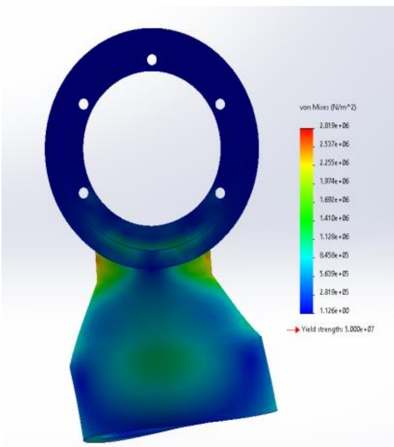
$$Run\ Time = \frac{Battery\ Voltage \cdot Battery\ Capacity}{Number\ of\ motors \cdot Rated\ Voltage \cdot Rated\ Current}$$

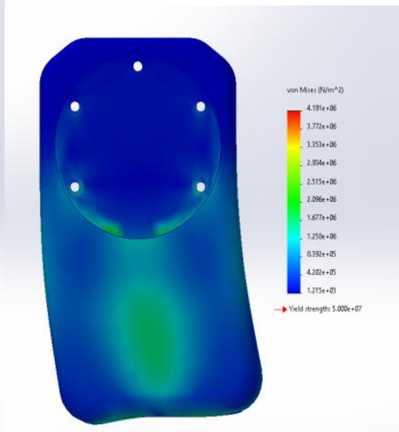
$$Run\ Time = \frac{22.2\ V\ \cdot 3.6\ Ah}{2 \cdot 24\ V \cdot 2\ A} \approx 49\ minutes$$

Using the equations above, it was found that the motors can only run for 49 minutes, which is below the want of 8 hours. There are several ways to improve running time. One is that the running time is only the motors running which will not be running the entire time. Another thing is to add more batteries and adjust how they will be added together so that the running time will be better.

6.3.2 FEA of 2nd Revision Motor Mounts – Caleb Lamca

The motor mounts worked for prototype 1 and did the job they were designed to do by housing the motors and accepting the arm links. However, these mounts had severe tapers and stress concentrations. The motor mounts were redesigned, taking these factors into account. The second prototype will replace the REV01 motor mounts with the improved REV02 motor mounts, installed in the same orientation as shown in the top-level assembly. The purpose of this analysis is to demonstrate and quantify the increase in strength provided by the revised mount design, as well as the enhanced material performance offered by the ONYX carbon fiber-reinforced nylon. The calculations will consider the strength (measured by the maximum von Mises stress of each component) and the Factor of Safety (FoS) of the REV01 PLA mount, the REV02 PLA mount, and finally, the REV02 ONYX mount.





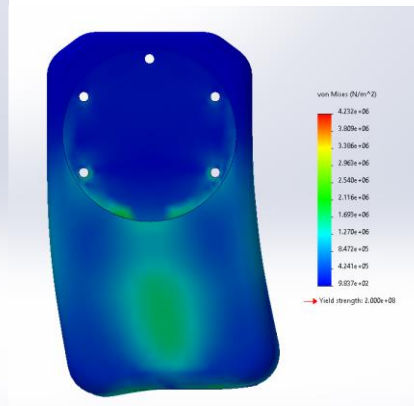


Figure 10: REV01 with PLA | Figure 11: REV02 with PLA | Figure 12: REV02 with ONYX

The figures above highlight the differences in stress concentrations along with a color bar to visualize these concentration locations. The FoS table (Table 1 from section 4.4) was created using the values from these FEA analyses.

To conclude these calculations; a SolidWorks simulation was completed for two revisions of the same part, and the strength of two different materials was evaluated in the process. The purpose of this testing was to guide the team's design decisions by determining whether the first or second revision of the motor mount offered greater strength. The results aligned with the initial hypothesis, showing that the REV02 mount utilizing the ONYX material is significantly stronger. Specifically, the factor of safety increased by 1520.3% when comparing the first revision made from PLA to the second revision made from ONYX. Based on these findings, the team will proceed with the second revision of the motor mount and order ONYX material for prototyping and testing.

6.3.3 Shear Stress on Motor Mount for Prototype – Cole Pace

Before putting our motors in our 3d printed initial prototype, it is important to know whether the Motor mount will be able to withstand the shear stress applied by the motors. A shear stress analysis using nominal values of PLA shear strength was conducted to test this question. The process was as follows:

$$\tau = \frac{F_{bolt}}{t \cdot h}$$

Where,

$$F_{bolt} = \frac{T_{design}}{r \cdot n}$$

With n accounting for the number of bolts securing the motor and h and r representing the shearing area, we found that the minimum thickness we must make the motor mount is 3.55 mm to stay under the shear strength of PLA which was found to be 11.4 MPa.

6.4 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.

7 CONCLUSIONS

The Lerner Robotic Arm project successfully completed its first major design and prototyping phase. The team established quantifiable performance requirements, conducted torque and stress analysis, and validated design choices through FEA and hands-on prototyping. Early prototypes revealed that the hinge mechanism will need to be modified to allow the users' arm to rest by their side but showed that the links can move in the expected fashion.

The current design meets the preliminary success metrics of active elbow support, lightweight structure, and user safety. Upcoming work will include implementing a control system, performing a full kinematic validation, and finalizing joint and link geometries. These continued efforts will ensure the device not only achieves functional performance but also advances the broader goal of developing accessible robotic assistive technology for stroke rehabilitation and daily mobility support.

8 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 nmotor 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/CompositesMaterialDatasheet.pdf. [Accessed: 23-Nov-2025].

[23] Haddington Dynamics AS PDF, Haddington Dynamics AS [Online]. Available: https://www.matterhackers.com/store/l/markforged-onyx-filament/sk/MUJD90ET?srsltid=AfmBOop2G9xXEOvprq4v9Cp-q22Ae8AqqBPLZIovFBkpCFWAUQm58k2B [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," IEEEXplore, 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

[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

[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

[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

[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

[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.