Below-the-Knee Exoskeleton

Final Design Report Template

Ryan Oppel: Budget Lead

Alexandra Schell: Team Lead

Nicholas Watkins: Design Lead

Fall 2023-Spring 2024

Project Sponsor: W.L. Gore
Faculty Advisor: Prof. Zachary Lerner
Instructor: David Willy

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

For our team's capstone project, we are tasked to improve upon a previous capstone design for an Ankle Exoskeleton through our client Dr. Lerner. Dr. Lerner's previous capstone team had built a working Ankle Exoskeleton that consists of a mechanical boot that consists of a boot-like frame that houses a motor and gearbox, which provides leverage to the ankle joint. The motor located on the frame of the ankle draws power through wires running up the user's leg, connected to a battery pack and microcontroller situated on a belt located on the waist of the user.

Our task as a team is to take all the components of the previous design and situate them below the knee of the user. On top of making the design below the knee, we will be upgrading the motor, microcontroller, and battery. To fit all these components below the knee, we will need to work through a couple of different steps. First, we need to redesign the frame of the boot. Doing this will give us more space to work on the battery and microcontroller below the knee. Some constraints we need to consider when making this design are not to limit the range of motion, a universal design that fits all users, and lightweight not to fatigue the user. Second, our design needs to have ingress protection for our electrical components. Our electrical components need to be resistant to dust and water to ensure they do not incur any damage while the user is operating the Exoskeleton. Some constraints that we need to consider while implementing ingress protection are not limiting the range of motion and a lightweight design. Our last step in our implementation is thermal and stress testing our design under strain. As the Exoskeleton is in use, the motor, microcontroller, and battery will heat up, which might be uncomfortable for the user if we don't properly insulate each electrical part. To do this, we have to find out how hot each component gets and then properly insulate each part so as not to reduce the effectiveness of the exoskeleton.

Our first task was installing a new motor, the Maxon ECX flat 32L. For this upgrade, we redesigned the motor mount and bracket to accommodate the larger motor, rebuilt the chain and sprocket housing, and manufactured a new sprocket welded to the motor axle. Additionally, we moved the Printed Circuit Board and battery onto the exoskeleton. This required designing and producing a case to house and mount the PCB and battery to the exoskeleton, while providing a high enough ingress protection for normal use. CAD models and images of our design can be found further down within this report.

TABLE OF CONTENTS

Contents

1 BACKGROUND

This chapter outlines the key deliverables, project goals, and success metrics essential for the redesign of the below-the-knee exoskeleton. The project focuses on eliminating the need for a waist-mounted battery and Arduino, with all components integrated below the knee. The design is aimed at supporting individuals with walking impairments, enhancing both daily function and physical therapy outcomes.
The chapter is organized into the following sections:

1. **Project Description** – This section discusses the overall description and background of the project. It included the intended goal, the sponsors, and funding/fundraising requirements.
2. **Deliverables** – This section discusses the critical outputs expected for the project, including the evaluation of motor specifications, battery analysis, motor mount design, and cover with ingress protection. These deliverables ensure the exoskeleton meets both the functional and environmental protection requirements.
3. **Success Metrics** – The criteria for project success are defined and linked to major technical milestones. This section highlights the importance of motor and battery performance, the structural integrity of the motor mount, ingress protection testing, system integration, and budget management. Each phase of the project will be rigorously assessed through calculations, simulations, and physical testing to ensure compliance with design requirements and functional efficiency.

1.1 Project Description

Our sponsor currently has a version of a below-the-knee exoskeleton, but it has an Arduino, and the battery is stored in a pack at the waist. It was designed to aid in the gait of people with a walking impairment and can be used as a physical therapy method or in daily use. Our goal was to redesign the exoskeleton to incorporate all the aspects needed below the knee so that we can discard the belt portion. Our client is the head of the NAU Biomechatronic lab, Professor Zachary Lerner. Their lab develops lightweight wearable robotic exoskeletons to improve the movement of people with walking impairments. According to our client, our focus for the duration of this capstone was to evaluate the motor specifications and the mounting hardware design for the motor. We were also to research and calculate the needs for a new battery selection and create a mount for said battery and Arduino. Finally, we were to create a new cover and ingress protection design for all the above-listed parts: Arduino, motor, and battery.
For this project, we had a budget of $4,000 dollars provided to us by WL Gore. On top of this funding, we had a fundraising goal of $400. We began a GoFundMe with the intent to raise our goal.

1.2 Deliverables

The key deliverables for this project have several critical aspects that need to be taken into consideration for the design and functionality of the system:

1. **Class Deliverables:** This includes all required submissions as per the course outline, ensuring that the project meets the academic expectations and milestones outlined for evaluation.
2. **Motor and Battery Analysis:** A comprehensive analysis of the chosen battery and motor to confirm that they are the optimal selection and configuration. This analysis considers factors such as power requirements, efficiency, weight, and compatibility with the system's operational demands.
3. **Motor, Battery, and PCB Mount Design:** The motor mount design was carefully engineered to securely integrate the motor into the overall structure using the analysis for power requirements

and efficiency. This design ensures stability, proper alignment, and effective transmission of power from the motor to the rest of the system. We also designed a new location for the PCB and battery to ensure all necessary parts are below the knee, do not inhibit movement, and create a cohesive design.

4. **Cover and Ingress Protection Design:** The cover design focuses on safeguarding internal components while providing ingress protection (IP rating) against debris and water. This ensures durability and compliance with environmental protection standards, critical for the longevity of the system.

Together, these deliverables contribute to the overall functionality, safety, and durability of the project, ensuring that all mechanical and electrical components work cohesively and reliably.

1.3 Success Metrics

Success for this project is assessed by meeting the key design requirements and ensuring the functionality of the exoskeleton without the waist belt, while keeping it lightweight and durable. The motor and battery must support daily usage for individuals with walking impairments. Each design phase will involve specific testing: calculations for power and torque requirements, finite element analysis (FEA) for mechanical components, and ingress protection tests for environmental safety. The overall design must be user-friendly and ergonomic, capable of functioning in a variety of real-world scenarios without compromising on safety or comfort. Budget management is also a key success factor, ensuring resources are allocated effectively. Table 1 breaks down the success matrix used for the semester.

Objective	Definition of Success	Assessment Methods	Timeline (Weeks)
Motor and Battery Analysis	Identify a motor and battery combination that meets the power, torque, and endurance requirements for daily use.	Success will be measured through detailed motor specifications analysis, power output calculations, and battery endurance tests. Battery life must meet the operational requirements for daily physical therapy sessions (at least 30 minutes of use).	1-3
Motor, Battery, and PCB Mount Design	Develop a durable, lightweight motor mount that securely houses the motor, PCB, and battery below the knee, without adding excessive weight or hindering movement.	Success is determined by CAD designs, stress analysis (FEA), and testing for vibration resistance and impact testing. This allows the team to ensure full daily use without the location of the mount inhibiting motion.	5-9
Cover and Ingress Protection Design	Design a cover that protects the motor and electronics, ensuring no environmental damage (debris, moisture) while maintaining easy maintenance access.	Success is defined by creating a cover that passes ingress protection tests (e.g., IP standards) and is easy to assemble/disassemble. Material selection must be lightweight and durable.	9-12
System Integration (Motor, Battery, and Electronics)	Integrate the motor, battery, and electronics below the knee, ensuring smooth operation without the need for a waist belt.	Success is measured through functionality testing in real-life or simulated conditions. The system must operate for at least 30 minutes without malfunction, and overall weight must remain below a defined limit.	12-15
Budget and Fundraising	Complete the project within the $4,000 budget and raise $400 through external funding.	Regular budget reviews and successful fundraising will indicate success. No budget overruns, and sufficient funds must be available for all necessary components and testing.	15-End of Year

Table 1Definition of Success

2 REQUIREMENTS

This section includes the customer requirements, which were mainly determined from reading research papers on both this and similar designs, partnered with requirements laid out by our client, Professor Lerner. They represent the criteria most important to the individuals using the device, which may be overlooked by the engineers. These criteria allow us to create a design that customers will want to use, rather than one that is simply functional, considering aspects such as comfort and affordability. The engineering requirements are the criteria that will allow us to create a design that will properly function for all intended users, such as the torque and temperature of electric components. The house of quality allows us to determine the correlation between these requirements; by weighing the customer requirements and assigning a value to the correlation between them and the engineering requirements, we can see the technical importance of each engineering requirement. This allows us to prioritize the engineering requirements with strong correlation to the most important customer requirements and compare these targets to existing devices that serve similar functions.

2.1 Customer Requirements (CRs)

The first customer requirement is durability (CR1). This will be important as the device will eventually be used in a customer's everyday life, and when walking outdoors, likely, they may eventually either kick or walk too close to an object and contact the device. Eventually, we will design a protective cover, but along with this, the components need to be stable and close to the leg to avoid damage. A high range of motion (CR2) is important as the device is designed to be assistive rather than simply an ankle brace. This means that the user will be able to use the motion of their ankle freely, and the device should be able to accommodate that full range of motion. Once again, the device will eventually be used for everyday life, such as hiking and recreational walking. Because of this, the system will likely be used for an entire day at a time, thus, both comfort (CR3) and long battery life (CR4), both of which can sustain the user for a full day, are relevant to the product. Both adjustability (CR5) and affordability (CR7) are important as the device is intended to be accessible to a wide range of individuals who need assistance. Because the device is intended for those with cerebral palsy and other muscular deficiencies, it is crucial that the device is lightweight (CR6) and can be easily attached to the user's feet for as long as they need, while still allowing them to walk normally. The customer requirements can be listed as follows:

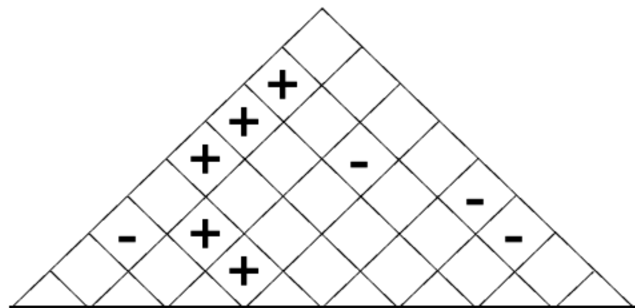
- CR1: Durable
- CR2: High range of motion
- CR3: Comfortable
- CR4: High battery life
- CR5: Adjustable
- CR6: Lightweight
- CR7: Affordability

2.2 Engineering Requirements (ERs)

A lightweight design is our most important design requirement, and based on other similar products, 3kg is the maximum weight that the system should total (ER5). A device that is too heavy will be impossible for certain users with more severe conditions, which is unacceptable, as those individuals are the most in need of the product. The ability to accommodate users of all weights (ER4) as well as different foot sizes (ER2) is significant, as, once again, the device is intended for all users with conditions that require the assistance that this device can provide. High torque (ER3) is closely related to the accommodation of users of all weights. The device is intended to assist users rather than fully support them, however, a motor with a higher torque will provide aid to users with more severe conditions who require the extra assistance. The temperature of the motor (ER6) is an important requirement. The motor, depending on placement, can transfer heat to the battery and the user's leg, which burns the user's skin. It can also cause the battery to overheat due to the covering material and design used, which is what we plan on preventing with our design. Ingress protection (ER8) is very important to the design, as the device will eventually be intended for general use, and the motor, battery, and PCB need to be safe from the environment. The battery capacity (ER7) will be necessary once this device is intended for general use; however, as the design is still a functional prototype and only used within the lab, the battery does not need to last for a full day. Energy efficiency is the lowest rated requirement (ER1), because the current design can operate for about four hours, and selecting a new battery and motor are some of our current tasks. The above engineering requirements can be listed out as follows:

- ER1: Energy efficient (Run for at least 30 minutes before battery hits 25%)
- ER2: Accommodate different shoe sizes (at least .27m)
- ER3: High Torque (at least 10 N-m)
- ER4: Supports users of all weights (at least 90 kg)
- ER5: Lightweight (under 3 kg)
- ER6: Temperature of motor (under 70 °C)
- ER7: Battery Capacity (~1000 mAh)
- ER8: Ingress Protection (at least IP 45)

2.3 House of Quality (HoQ)



Customer Requirements \ Design Requirements	Importance (1-5)	Energy efficient	Accommodate different shoe sizes	High torque	Support users of all weights	Under 3 kg	Temperature of motor	Battery Capacity	Ingress Protection	1 Worst	2	3	4	5 Best
Improvement Direction														
Durable	3		3		6	6	6		9		C	AB		
High range of motion	5			9								B	AC	
Comfortable	4		3		3	3	3						A	
High battery life	3	9		6			9	9					B	
Adjustable	3		3		6								C	A
Lightweight	5			3		9			3				B	AC
Affordability	5							3	3		C	B		
Technical Importance: Absolute		27	30	78	48	75	57	42	57	A	Caplex Exo			
Technical Importance: Relative		7%	7%	19%	12%	18%	14%	10%	14%	B	Utah Knee			
Design Competitive Assessment	Worst: 1							B	C	C	ETM Motor			
	2				C		B	C	B					
	3	AB		B		C	C							
	4			C	A	B			A					
	Best: 5	C	A	A		A								
Target Value		90	0.3	1000	90	2	70	1000	54					
USL		60	0.27		120	3	155		68					
LSL		30	0.22	500	30	1.5		500	52					
Units		mins	m	mNm	kg	kg	C	mAh	IP					

Figure 1 House of Quality

3 Research Within Your Design Space

3.1 Benchmarking

When it comes to benchmarking, we began the research to revise and improve upon the current design. With the goal of a new motor and mounting design in mind, one of our state-of-the-art systems was a motor designed by the Electrifying Torque Motor, ETM. They are a company that has made a DC electric motor that is specifically for applying torque. This Motor could theoretically improve the efficiency of our design by consuming less energy than a brush or brushless motor.

The second state-of-the-art design is a full prosthetic made by the University of Utah. It was a fully prosthetic design made to be lighter and more compact. The AVT system used in the Utah knee project uses adjustable transmission to meet different speed and torque needs. It was made of a bigger DC motor connected to a 4:1 planetary gear, among other design accommodations. This allowed for a reduction in the motor size and allowed for less torque due to low mass and inertia. The only downside was that it could only change transmission levels under minimal load. Overall, the entire prosthetic weighed 1.6 kg vs the average 3.4 kg.

Finally, there was the Humotech Caplex EXO-001. It was an exoskeleton that could be attached to the foot and was developed to aid in ankle injury recovery. It mounts to the user's shoe and is adjustable for multiple different sizes of shoe. It uses a cable system to apply torque with a max torque in Plantarflexion being 180 Nm and in Dorsiflexion being 1.5 Nm. The standard weight of the device was 1.4 kg.

3.2 Literature Review

3.2.1 Ryan Oppel: Proceedings of SYROM 2022 & Robotics 2022 - Chap. 23: Design of an Exoskeleton for Rehabilitation Ankle Joint [1]

Chapter 23 of *the Proceedings of SYROM 2022 & Robotics 2022* focuses on the design of an exoskeleton specifically for ankle joint rehabilitation. This chapter dives into the mechanical design and biomechanics of the ankle joint, highlighting the stresses experienced during movement and the importance of precise joint mechanics for effective rehabilitation. The proposed exoskeleton uses motorized joints and linear actuators to assist in ankle movement, aiming to improve mobility and support recovery for patients with ankle injuries. Learning about this technology can provide valuable insights into how exoskeletons are designed to mimic natural joint movements and enhance rehabilitation processes, which is crucial for anyone interested in biomechanics, robotics, or medical device innovation.

3.2.2 Ryan Oppel: PID Control with Intelligent Compensation for Exoskeleton Robots [2]

PID Control with Intelligent Compensation for Exoskeleton Robots talks about using smart tweaks to make exoskeletons work better. It combines basic PID control, which helps keep things steady, with clever tricks like neural networks to fix issues and improve performance. This helps exoskeletons move more naturally and smoothly, which is super important for helping people in rehab or doing tough jobs. Learning about this can give me a good idea of how these wearable robots are controlled and why that’s important for making them work well.

3.2.3 Ryan Oppel: The design, validation, and performance evaluation of an untethered ankle exoskeleton [3]

The design, validation, and performance evaluation of an untethered ankle exoskeleton is about making a small, battery-powered device to help people move their ankles better. This exoskeleton helps people walk more easily and uses less energy, which is great for both healthy people and those with movement issues like cerebral palsy. This can give me knowledge on how these devices are made to help people move better and recover faster, which is useful for biomechanics and robotics.

3.2.4 Ryan Oppel: Adaptive control strategies for lower-limb exoskeletons to assist gait [4]

This scientific paper explores how advanced control methods help exoskeletons support walking. These strategies adjust in real-time to the user's movements, making the exoskeletons more effective and comfortable. This shows how technology can enhance mobility for people with walking difficulties.

3.2.5 Ryan Oppel: A New Approach of Minimizing Commutation Torque Ripple for Brushless DC Motor Based on DC–DC Converter [5]

The article is about making brushless DC motors run smoother by reducing the jerky movements (torque ripple) they can have. This is done using a DC–DC converter to better control the motor's current. This improves the movement of the exoskeleton and makes it more controllable for the user.

3.2.6 Ryan Oppel: ASTM F48 Formation and Standards for Industrial Exoskeletons and Exosuits [6]

These are the industry standards for making an exoskeleton and ensure that exoskeletons are safe, effective, and reliable. This committee, formed in 2017, develops standards for the design, performance, and use of exoskeletons in various fields like industry, healthcare, and the military. Learning about these standards is important because it helps me understand the best practices and safety measures needed to develop and use exoskeletons. This knowledge is crucial for making these devices, as it ensures they meet high-quality standards and are safe for users.

3.2.7 Ryan Oppel: Opportunities and challenges in the development of exoskeletons for locomotor assistance [7]

This article looks at the progress and hurdles in making exoskeletons that help people walk. It talks about how these devices can improve movement for people with walking difficulties and the technical and clinical challenges that come with it. Learning about this helps me understand the real-world applications and obstacles in developing exoskeletons, which are important for biomechanics and robotics. It shows how far we've come and what still needs to be done to make these technologies more effective and accessible.

3.2.8 Ryan Oppel: Aerospace specifications metal data sheet for Aluminum Alloy 7075 – O (ss) [8]

This is a materials data sheet for specifically Aluminum Alloy 7075 – O (ss), a high-strength-to-weight ratio alloy which we will be using for our motor mounting brackets. "A material data sheet (MDS) is an important document that provides key information about a material's properties, like its strength, durability, and how it behaves in different conditions (temperature, moisture, etc.)." this information is important for us to know because this info will help us calculate the factor of safety's we need for our mounting hardware and anything else we might use this material for within the build.

3.2.9 Ryan Oppel: 3D printing strength: How to 3D print strong parts [9]

The article explains how to make 3D prints stronger by choosing the right infill settings. Infill is the internal pattern inside the print, and it affects how strong the final object is. The article says that a denser (more filled) infill makes the print stronger, but it also uses more material and takes longer to print. Different patterns, like grid or honeycomb, can also change how strong the print is.

3.2.10 Ryan Oppel: Introduction to SOLIDWORKS simulation - finite element analysis [10]

This source was used to help better understand how to operate SolidWorks to help find out specifically how to operate its FEA feature. We used the FEA feature to help us calculate the loads being presented on the motor mount and surrounding brackets to make sure that the material we were using would hold the motor and not hurt the user in any way. The SolidWorks tool also helped us to find any weak points in our design by showing potential breakpoints in our design.

3.2.11 Alex Schell: Kinematics and Kinetics of the Foot and Ankle during Gait [11]

This article discusses the role of the foot, ankle, and joint in the gait, as well as the phases within the cycle of the gait. It goes over how this is considered when building braces and exoskeletons. It begins by breaking up the stages of the gait as well as the importance of different joints in the forces applied to the foot. This analysis on the forces and applying it to the control of the robotics system to accomplish a simulation of the gait. It concluded that the most important aspect of load-bearing in the lower body focuses on the foot. Its importance in this demonstrates that we need to understand its function and analyze the mechanics of the foot allows us to look at opportunities to alter or correct the gait through robotics. New motion capture technology allows us to better analyze these measurements and advance modeling approaches. This article allows us to better understand the importance of the foot during the different stages of the gait and aided in calculations.

3.2.12 Alex Schell: Cadaveric Gait Simulation [12]

This article outlines the way Dynamic gait simulation, DGS, can simulate the full kinetics and kinematics of gait, making it more useful for modeling walking dynamics. It takes calculations and imaging done on an actual gait and applies it using cadaveric models. It allows for a greater understanding of the forces, tendons, and otherwise, degrees of freedom, and kinematics. It allows scientists to replicate the dynamics of the foot. This article allows us to get a better idea of the modeling techniques used in our calculations and thus the design of our exoskeleton.

3.2.13 Alex Schell: Developments and clinical evaluations of robotic exoskeleton technology for human upper-limb rehabilitation [13]

This article describes exoskeleton advancements and focuses on improving joint control and muscle activity for rehabilitation using EEG, EMG, and other sensors to enhance accuracy and motor stability. This allows scientists to provide real-time physiological measurements. However, challenges remain with weight, power consumption, limited torque, bulky designs, and high costs, which hinder practical usability. This article allows us to get a better idea of the current sensors used in the creation of prosthetics for joint control.

3.2.14 Alex Schell: Toward High-Performance Lithium–Sulfur Batteries: Efficient Anchoring and Catalytic Conversion of Polysulfides Using P-Doped Carbon Foam [14]

This article discusses the benefits and downsides of Lithium-Sulfur Batteries. This includes high energy density and good energy storage. On the downside, the insulating sulfur can limit operation. It offered a few options to increase efficiency, including limiting porous carbon, which enhances conductivity but reduces battery life and charge efficiency. PCF can also have high discharge and a good life cycle. The microporous nature makes it good for high-performance LSBs. This article helps us get a better idea of the types of batteries that can be used for our specific goals of high energy storage and high battery life.

3.2.15 Alex Schell: A Lightweight, Efficient Fully Powered Knee Prosthesis with Actively Variable Transmission [15]

This article describes a group of roboticists at the University of Utah who worked to develop a lower-weight, fully powered prosthesis, equivalent to a passive prosthesis. It used Active Variable Transmission (AVT), which adjusts transmission to meet different speed and torque needs. This prosthetic used a DC motor, a planetary gear, leadscrews, bearings, and an incremental encoder for position feedback. This allowed for a reduction in motor size because it required less torque due to low mass and inertia. The downside, though, is that it can only change transmission under minimal load. The AVT system was a logical choice to lower the overall weight of a machine and could be applied to lower the weight of our prosthetic since we are already adding weight in the form of the battery pack and Arduino.

3.2.16 Alex Schell: F3527 Standard Guide for Assessing Risks Related to Implementation of Exoskeletons in Task-Specific Environments [16]

This article highlights the risk assessments that must be considered for creation of exoskeleton. It also mentions the guide to not override existing laws and regulations.

3.2.17 Alex Schell: The Essential Guide to Selecting Batteries for Robotics [17]

This article describes the usage of different types of batteries for certain necessities in robotics, including powering sensors, microprocessors, and motors. The battery must match power, voltage, and current specifications, determining that $LiFePO_4$ batteries stand out for long cycle life and reliability. This allows us to look at more options for batteries, which is one of our team's deliverables.

3.2.18 Alex Schell: Batteries for Electric Vehicles [18]

This article discusses the different types of batteries used in electric vehicles. They are preferred due to the high power-to-weight ratio, as well as high energy efficiency. This allows us to gain a better idea of a battery that offers high efficiency, since it is used to power a car. The downside is the size, but if we can find a battery that emulates these factors, it would be a beneficial choice for our design.

3.2.19 Alex Schell: Convection Heat Transfer [19]

This article discusses the properties of heat transfer through convection. It discusses the difference in air flow over a flat plate versus a cylindrical object. It also contains an in-depth overview on the formulas that go into calculating heat transfer across the different types of objects. This was useful to the project to allow us to do an in-depth thermal analysis on different parts of our design. 6.3.1 and 6.3.2 shows said thermal analysis on our motor cover design, and we also plan to perform an analysis on the PCB mounting as well.

3.2.20 Alex Schell: Properties of Air at atmospheric pressure - The Engineering Mindset [20]

This article goes over the different properties of air at different temperatures. This covers density, ρ, dynamic viscosity, μ, specific heat capacity, cp, thermal conductivity, k, and Prandtl number, Pr. This was useful to my project for the thermal analysis conducted in sections 6.3.1 and 6.3.2.

3.2.21 Alex Schell: IP Ratings [21]

This article discusses the standards assigned to different levels of ingress protection. This is useful to our project because one of the main tasks assigned to us is to create a cover for the motor, PCB, and battery. As of right now, we are estimating a 5 on the level of solid foreign objects, or protected against dirt, and a 1-4 on the scale of water, or protected against water drops to light splashing water.

3.2.22 Nick Watkins: Prosthetic forefoot and heel stiffness across consecutive foot stiffness categories and sizes [22]

This article focuses on prosthetics and the ideal stiffness based on the user's weight and activity level. Our design is not a prosthetic; however, this can help us to determine the ideal flexibility for the foot plate for the user's comfortability as well as assistance in walking.

3.2.23 Nick Watkins: Robotic Emulation of Candidate Foot Designs May Enable Efficient, Evidence-Based, and Individualized Prescriptions [23]

This article is also focused on prosthetics, explaining a system used to emulate the sensation of wearing prosthetics to aid in fitting. This can be used for the exoskeleton when researching gaits and walking patterns.

3.2.24 Nick Watkins: F3528-21 Standard Test Method for Exoskeleton Use: Gait [24]

This standard is incredibly relevant to our design, as it outlines the methods of evaluating the safety and performance of exoskeletons, specifically those assisting in a user's gait, including medical rehabilitation, recreational hiking, and military use. The tests include an endurance test, a speed test, and a balance test, and can be used to provide manufacturers with information about the usefulness of their designs.

3.2.25 Nick Watkins: G-Exos: A wearable gait exoskeleton for walk assistance [25]

This article explains the process of creating an ankle exoskeleton designed for stroke patients to assist dorsiflexion, plantarflexion, and ankle stability.

3.2.26 Nick Watkins: The Mechanical Functionality of the EXO-L Ankle Brace [26]

This article analyses the functionality of an elastic ankle brace, designed for sprains, to limit only the motion of combined inversion and plantar flexion.

3.2.27 Nick Watkins: Pilot evaluation of changes in motor control after wearable robotic resistance training in children with cerebral palsy [27]

This article discusses a prior stage of our device; however, rather than usage as an assistive device, the system was used for resistance training on users with cerebral palsy.

3.2.28 Nick Watkins: Does Ankle Exoskeleton Assistance Impair Stability During Walking in Individuals with Cerebral Palsy? [28]

This article is about the state of the device we are working on, from several years ago. It discusses the stability and gait analyzed from testing an exoskeleton designed to assist plantarflexion in individuals with cerebral palsy.

3.2.29 Nick Watkins: F3323-24 Standard Terminology for Exoskeletons and Exosuits [29]

These standards cover terminology associated with exoskeletons and exosuits, including labeling, test metrics, and test methods.

3.2.30 Nick Watkins: F3474-20 Standard Practice for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics [30]

This standard explains recommended approaches and variables for assessing the function of exoskeletons. Variables include joint movement, posture assessment, and functional movement.

3.2.31 Nick Watkins: Ankle Exoskeleton Assistance Can Affect Step Regulation During Self-Paced Walking [31]

This article discusses the effect of exoskeletons on gait. Unimpaired individuals were recorded walking with and without exoskeleton assistance, with their step width, walking speed, and cost of transport analyzed.

3.3 Mathematical Modeling

3.3.1 Center of Mass – Alex Schell: To begin our calculations, we did a simple Center of Mass calculation. The main position was in the end stage of the gait, where the foot is just pushing off the ground and beginning the swing stage. The calculations were based on the measurements of a teammate's foot, with the assumption that the ankle and foot make up about 6.5% of the weight of the human body. Figure 2 demonstrates the diagram of the foot on a grid system, marking the center of mass with a red dot at point (-3.95, 8.91). This calculation of the center of mass can be used to determine where to place the payloads, aid in stability, and predict motion, such as angular velocity, Potential Energy, and Kinetic Energy.

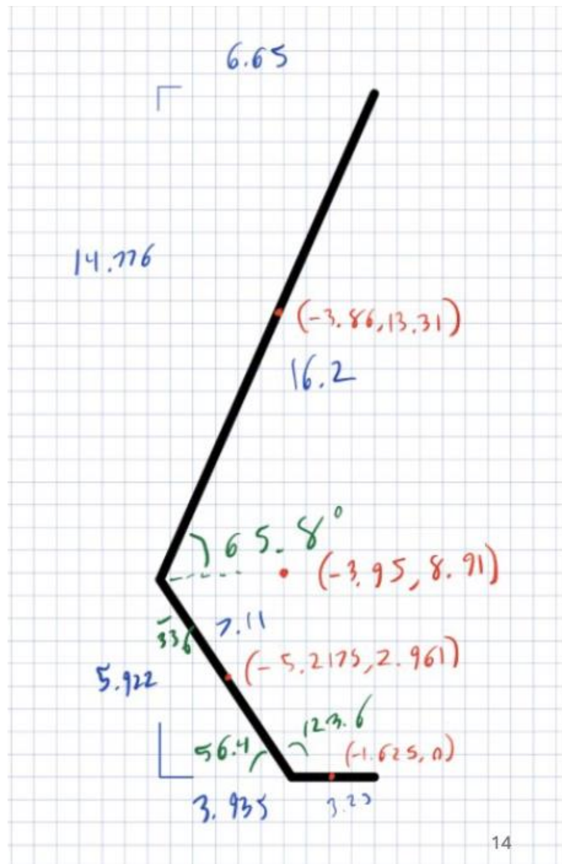


Figure 2 Center of Mass

3.3.2 Mathematical Modeling of the Foot – Nick Watkins: The next calculation was to model the forces of the foot at the location where the force is the greatest. We assumed a weight of 200 lbs (90kg) and a shoe size of 10.5. Figure 3 demonstrates the free body diagram of the forces below the ankle. We were able to calculate ground force, 1068N, force at the ball of the foot, 958N, and the work, -45.12J. Figure 4 demonstrates the method with which we found the above values. The calculations for work were then used for the next set of calculations, 3.3.2.

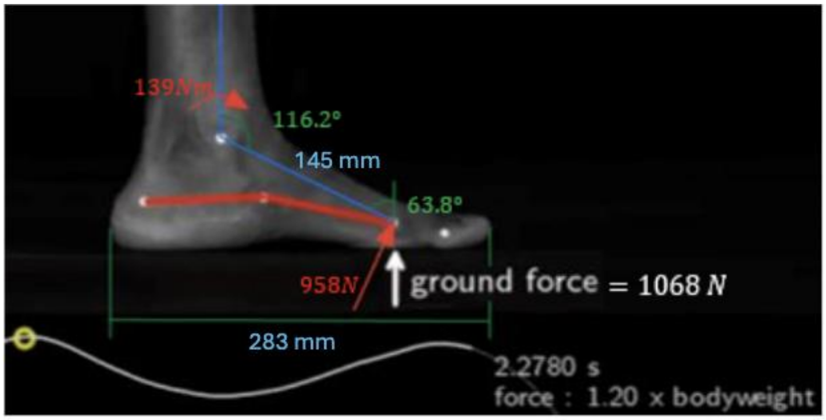


Figure 3 Free Body Diagram

(Yale Biomechanics and Control Lab, 2020)

Assuming: 200 lbs (90 kgs)
Shoe size men 10.5 (283 mm)

Calculating the peak torque produced by the ankle

$$F_g = 1.2 * 90\,kg * 9.81\,m/s^2$$
$$F_g = 1068\,N$$

$$F = 1068\,N * \sin 63.8°$$
$$F = 958\,N$$

$$\tau = 958\,N * \frac{145\,mm}{1000}$$
$$\tau = 139\,Nm$$

$$W = \tau * \Theta$$
$$W = -139\,Nm * (116.2° - 97.6°) * \frac{\pi}{180}$$
$$W = -45.12\,J$$

Equation 1 Mathematical Modeling Calculations

3.3.3 Torque Output by Motor onto motor mount – Ryan Oppel: For this Analysis of the motor mount, what we are looking to find is the stresses applied from the motor to the mount and all other components. We are working with an ECX FLAT Maxon motor, so to start with this analysis, we must define the amount of force that this motor will have on the mount. Our mount for the motor consists of two parts that will be screwed on to the motor, a carbon fiber tube, and each other. These two parts that create the mount of the motor will also hold a cover for the motor which will also be screwed into each other. Another variable which is important to know when doing a stress analysis is the type of material used for the mounts and other components attached to the motor and or mounts. For these mounts, our client, Dr. Lerner, picked out the material that we will use. The material for these mounts is 7075-O (ss) Aluminum alloy. This is the type of material that he has used in the past for his exoskeleton projects, and it has shown that this material is the perfect balance between strong, lightweight, and thermally conductive, which will help us with thermal management of the motor later down the line. The last criterion to understand to perform a stress analysis will be the physical dimensions themselves. Because our parts are dimensionally complex, I will be using SolidWorks software to visually show the stresses on the material. I believe it is important to bring up this variable because in the design phase of the project, the team made sure that we design parts to have as little of few weak points as possible. We did this by filling holes and edges and creating connecting parts where we can ensure structural integrity. While we are doing some of these calculations through SolidWorks, we are still doing a considerable number of calculations by hand. In this analysis, we will ultimately find the factor of safety of our motor mount (FoS). In this, we must calculate many things, starting with the force the motor will displace onto the mount. Since the motor has an attached gearbox, we will be finding the torque that the gearbox will apply. Then we must find the mounting points on the mount and find the forces that will be applied to each of them. After that, we will find the weakest point in the mount and do a force analysis there, where we will then be able to calculate our factor of safety with our known material.

To start with our calculations, I must first find the amount of torque that the motor will apply to the motor mount. I found this information on the manufacturer's website. For the ECX FLAT Maxon motor, we find that the nominal torque that this motor will provide at maximum power will be 103 mNm. With this information, I will then calculate how much torque will be applied to the motor mount by using a simple gear-ratio equation with our gearbox, which is a 1:35 gear ratio.

$$\text{Output Torque} = \text{Input Torque} \times \text{Gear Ratio}$$

$$\text{Output Torque} = 103\,\text{mNm} \times 35 = 3605\,\text{mNm}$$

$$3605\,\text{mNm} = 3.605\,\text{Nm}$$

Equation 2: Torque Output Equation

With this value, I must conceptually understand how these forces will be applied to the mount itself. Now that I know the value at which the motor is applying torque to the rest of the mount, I must find out what points are being displaced on the mount, find their distance from the displaced torque, and how many points of contact there are.

The motor is mounted to the bracket by four screws that are 3mm in diameter which are situated exactly 13mm away from the center of the motor shaft. With this information, I can calculate how much force each mounting point will experience with a simple torque equation.

$$T = F \cdot r \implies F = \frac{T}{r}$$

$$T = 3.605\,\text{Nm} \qquad r = 13\,\text{mm} = 0.013\,\text{m} \qquad F = \frac{3.605}{0.013} = 277.31\,\text{N}$$

Equation 3 Torque Stress Equation

With this number, I then divided the total force by 4 to find out how much each mounting force will experience, which gave me a final number of 69.33N. The only other stresses applied to the mounts are the downward force of the weight of the motor cover and mounted motor, which is attached to a chain that comes out to approximately 2N of force.

Now, with the torques known on each mounting point for the motors to mount onto the brackets, I then did a finite element analysis in SolidWorks of all the forces applied to the motor mounts.

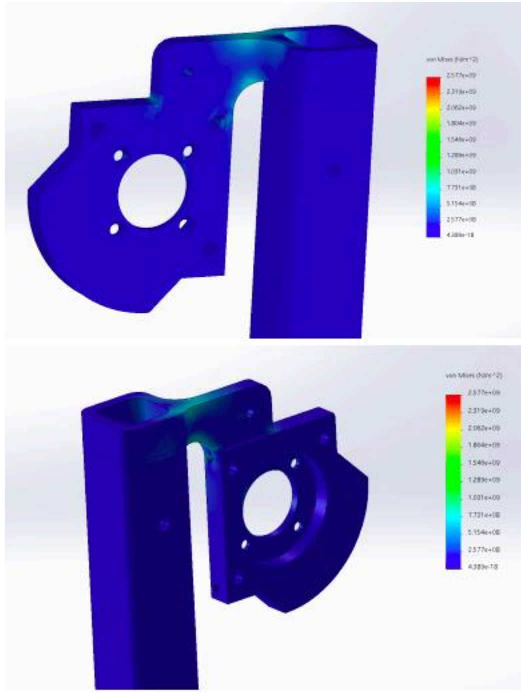


Figure 4-5 Visuals of the FEA applied to the motor mounts with known variables.

As we can see, where the connection is between the motor mount and the carbon fiber tube, the design comes to a bottleneck which is where we can see where our biggest calculated force peaks. according to SolidWorks, the max amount of stress that was applied to our design was 1.042*10^7 N/m^2 which comes out to approximately 10.42MPa.

According to the ASM Material data sheet, 7075-O (ss) Aluminum alloy has a yield strength of approximately 145MPa. With these new values, I can now calculate the factor of safety for our motor mounts.

The equation for the Factor of Safety is:

$$\text{FOS} = \frac{\sigma_{\text{yield}}}{\sigma_{\text{applied}}}$$

$$\text{FOS} = \frac{145}{10.42} \approx 13.91$$

Equation 4 Factor of Safety

$$T_{\text{output}} = T_{\text{input}} \times \text{Gear Ratio}$$

Equation 5 Torque Output Calculation

$$\text{Total Efficiency} = (\text{Stage Efficiency})^{\text{Number of Stages}}$$

If we assume a 2% loss per stage and a multi-stage gearbox with 3 stages to achieve the 89:1 ratio:

$$\text{Total Efficiency} = (0.98)^3 \approx 0.94$$

Equation 6 Total Efficiency Calculation

3.3.4 Gear Ratio and Stress and the Motor – Alex Schell: If torque output is labeled as the torque needed at the ankle and torque input is measured at the motor, both calculations were solved in the previous presentation. Input was calculated at 3.7 Nm due to the specs of the motor, and the output was 139 Nm. Due to these numbers, we can assume we need a gear ratio of 38:1. With the equations listed in equation 7 and the torque being 3.7 Nm and the radius of the shaft, as designed in SolidWorks, being 3 mm, the stress is calculated at 8.74 E7 MPa

Stress at the motor

$$\tau = \frac{T * r}{J}$$

τ = Stress

T = Torque

r = radius of the shaft

$$J = \frac{\pi r^4}{2}$$

J = Polar moment of inertia

Equation 7 Stress Calculations

3.3.5 SolidWorks Simulation – Alex Schell: We performed a simulation to show the stresses and the life cycle of the current motor mount, which is one of the items we are tasked with redesigning. The current location is at the back of the model, prone to being bumped by surrounding objects. There is no water resistance or protection against debris, which is another customer requirement. The current placement is prone to high stress and fracture. Figure 6 demonstrates the Von Mises stresses based on a force of 15N. Figure 7 demonstrates the Life Cycle based on 15N after 1000000 cycles.

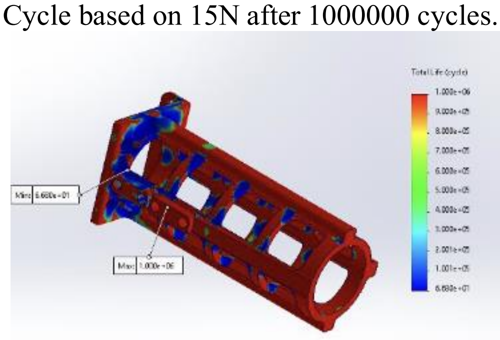


Figure 6 Von Mises Stress

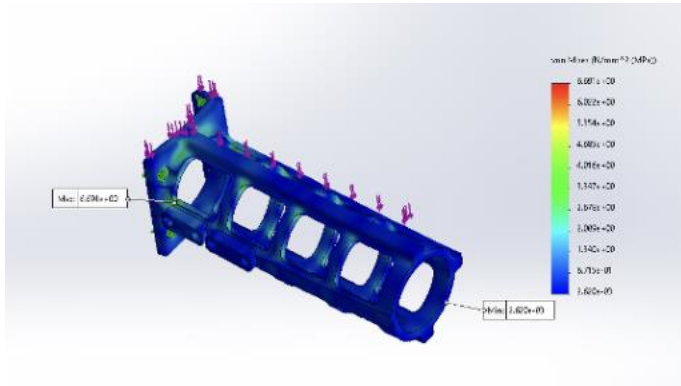


Figure 7 Life Cycle

4 Design Concepts

4.1 Functional Decomposition

Figure 8 depicts the functional decomposition our team followed throughout the year. It breaks up the deliverables needed and analyzes the route that we took to ensure that our deliverables were up to the standards of our client's requirements and successful with the overall design.

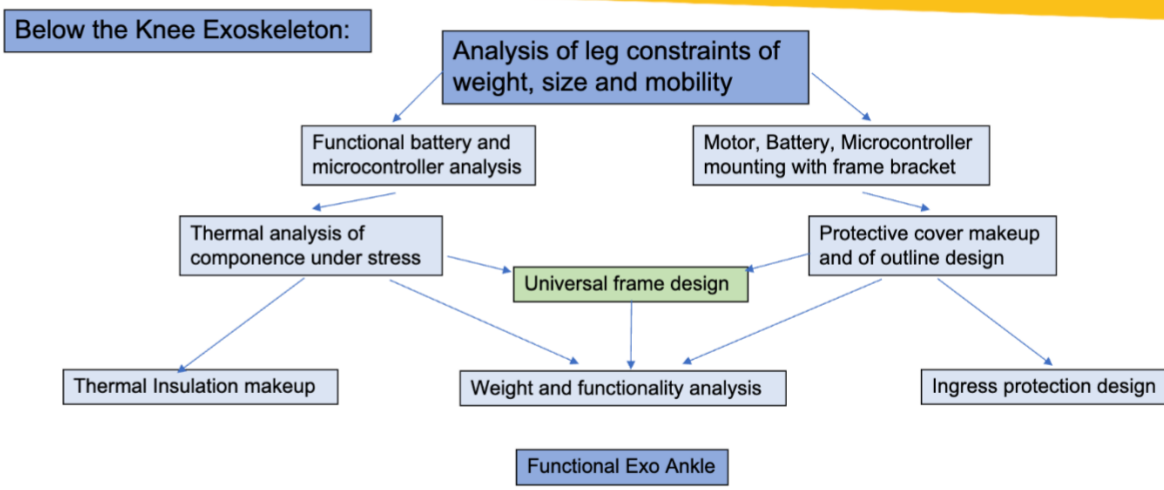


Figure 8: Functional Decomposition

4.2 Concept Generation

Our goal was to move both the battery and PCB onto the exoskeleton itself. Currently, the battery, microcontroller, and PCB controlling the exoskeleton are mounted on a belt that the user must wear while operating. This system is sufficient for a physical therapy or testing environment, but the final design will need to be capable of operating under everyday use. A new battery had to be selected as well. The new motor has a higher power draw, and the power life of the system needed to be extended.

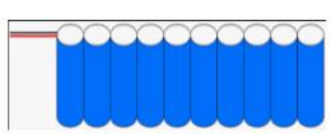
 *Figure 12: 3500mAh 10A Protected Lithium Ion*	
 *Figure 12: Li-Ion 21700 Battery*	 *Figure 13: 2p3s 10.8v 6400Mah Lithium Battery Pack*

Figure 9: Battery Selection

After careful consideration, our team chose the E-Flight 22.2V battery. The first concept placed the battery on the frame of the exoskeleton. This separates the battery from other electronics as well as the user's skin, which will prevent the components from overheating and the battery from burning the user.

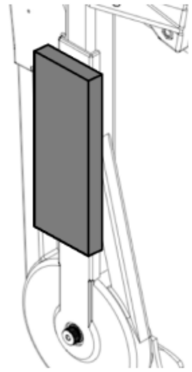


Figure 10 The battery is mounted on the frame.

This concept, Figure 11, has the battery mounted on the back of the motor, which will keep the center of mass as high as possible and will not contact the user's leg.

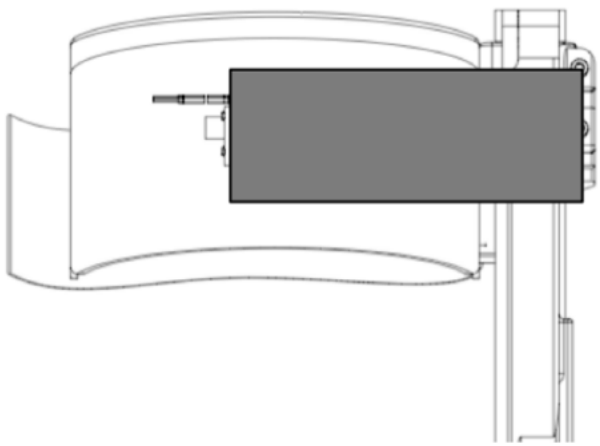


Figure 11 The battery is mounted on the motor.

Figure 12 requires multiple battery cells instead of a single battery and holds these cells on the outside of the cuff. In addition to the placement away from the user's leg, the center of mass of the battery is at the highest possible point.

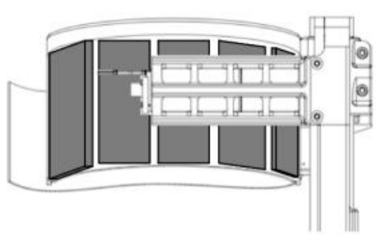


Figure 12 Battery cells are mounted on the cuff.

The final concept mounts the battery cells in a heat-resistant sleeve under the cuff. The cells are far from the motor while also keeping the center of gravity high.

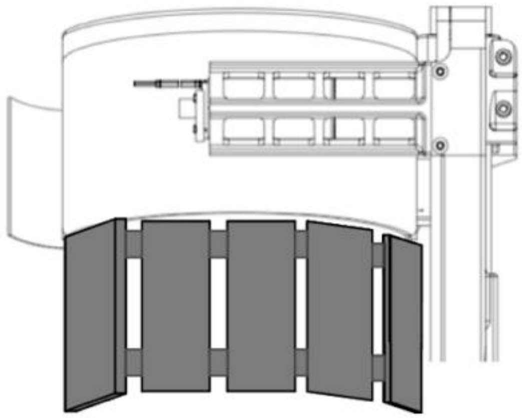


Figure 13 Battery cells are mounted under the cuff.

4.3 Selection Criteria

Our team's selected parts consist of the motor, the battery, and the frame, for how we will compile the parts. Each part had its own weight system depending on its purpose and how they were used in the exoskeleton.
While our team was analyzing the motor and the specifications, our client (Professor Lerner) had already picked out a motor for us to use. So instead of comparing motors quantifiably, I will rather show through calculations why this motor is a better fit for our exoskeleton than the previous motor.

Old: EC-4pole

Nominal voltage	36 V
No load speed	16300 rpm
No load current	109 mA
Nominal speed	14900 rpm
Nominal torque (max. continuous torque)	43.7 mNm
Nominal current (max. continuous current)	2.16 A
Stall torque	612 mNm
Stall current	29.1 A
Max. efficiency	88 %

Figure 14 Factory Specifications of the old motor without gearbox

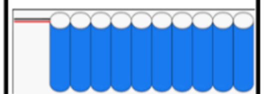
Nominal voltage	24 V
No load speed	10600 rpm
No load current	179 mA
Nominal speed	8100 rpm
Nominal torque (max. continuous torque)	103 mNm
Nominal current (max. continuous current)	4.24 A
Stall torque	438 mNm
Stall current	51.6 A
Max. efficiency	89 %

Figure 15 Factory Specifications of the new motor without a gearbox

As shown in the motor spec sheets (Figures 14 and 15), our new motor is specified for torque. The ECX Flat has roughly 2.4 times more continuous torque than the EC-4pole. This allows us to increase our applied force from the Exoskeleton, or we could keep the same amount of torque but drastically boost our efficiency. The ECX-Flat does, however, take approximately 2.16X more continuous current to run, which is one downside, but does not outweigh the good. This is the reason why we are using a different battery to adjust to these new parameters.

Our frame configuration is mainly based on the battery and PCB, and how we will implement them. Our criteria for our frame design are a high center of gravity, heat transfer to the user and other electrical components, and protection for our cell batteries. The reason for a higher center of gravity is that the higher we can get all the weight up the leg, the less of a moment force the exoskeleton will have on the user's hip and knee joint. To quantify each criterion, we gave each a weighted value of importance based on the customer requirements that the client gave us, with protection of the cell batteries. After calculating our weighted values, our best design came out to be battery cells mounted just above the PCB within the same container. This design is the best of all the criteria, being high up, away from the user, and separate from other electrical components, and in a low-risk area for damage.

4.4 Concept Selection

		1	2	3	4
		3500mAh 10A Protected Lithium Ion 	Dantona L148A26-4-18-3WA3 Lithium-Ion Battery Pack 	Li-Ion 21700 Battery 	E-Flite 22.2V 910 mAh Lithium Battery 
Output power	2	S	-	+	+
Weight and size	3	-	+	-	S
Ease of use	2	+	+	-	+
cost	2	+	-	+	S
TotalΣ		1	1	-1	2

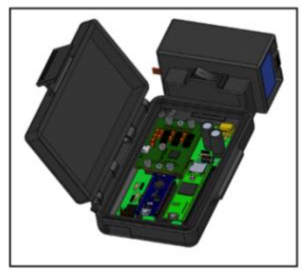
Pugh Chart for PCB Cover Design		
Protection	+	S
Ease of use	-	+
Weight and Size	-	+
Cost	S	+
Total:	-1	3

Table 2 Concept selection for battery and PCB cover

For the four battery placements, we had four selection criteria: high center of gravity, heat transfer to skin, heat transfer to electronics, and protection, in order from least to most important. Keeping the center of gravity closer to the knee will make it easier for the user to move their leg, as the work required increases with distance from the center of rotation. This is relevant as the clients will have existing muscular deficiencies; however, the importance is low since the weight of the battery is minor compared to the weight of the entire system. Heat transfer to skin is a consideration as batteries can get hot with extended use, and the device is intended to be used for hours at a time, although this can be negated with insulation. Heat transfer to electronics refers to the proximity to the motor, as both components get hot with use, and one has the likelihood of causing the other to overheat. Batteries, when exposed to excessive heat consistently, can lose function, swell, and eventually explode. Lastly, "protection" is rated the highest. As stated in Concept Generation, eventually, a protective shroud will be designed and installed to cover the components, so the system needs to be low profile to fit under the cover. Additionally, because this device will eventually be used in real life, likely outdoors, the design needs to avoid parts sticking out far from the assembly, which would make damage more likely if walking too close to any obstacles. Based on these criteria, the design that places the battery under the cuff and the Arduino on the frame ranked the highest. This design has a neutral center of gravity, maintains distance between battery and motor, and keeps the battery as close to the leg as possible. The only criterion this design failed was heat transfer to skin, however, this can be resolved by placing the battery within a heat-resistant sleeve. This design assumes the power source will be several battery cells; however, since the battery selection has already been made, the design may need to be reworked to accommodate different-sized and shaped batteries.

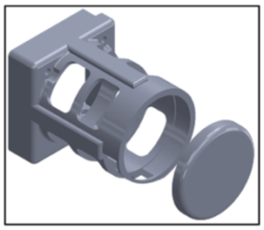
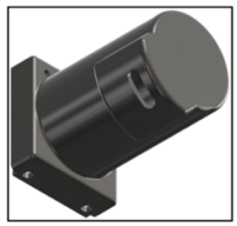
Pugh Chart for Motor Cover Design			
Protection	-	+	S
Ease of use	+	-	+
Weight and Size	+	-	+
Cost	S	S	S
Total:	1	-1	2

Table 3 Selection Criteria for Motor Cover

Based off our selection criteria, our team has compiled our first prototype. Through the selection process we were able to rule out some designs which could cause us issues.

Figure 16 Assembly of our prototype

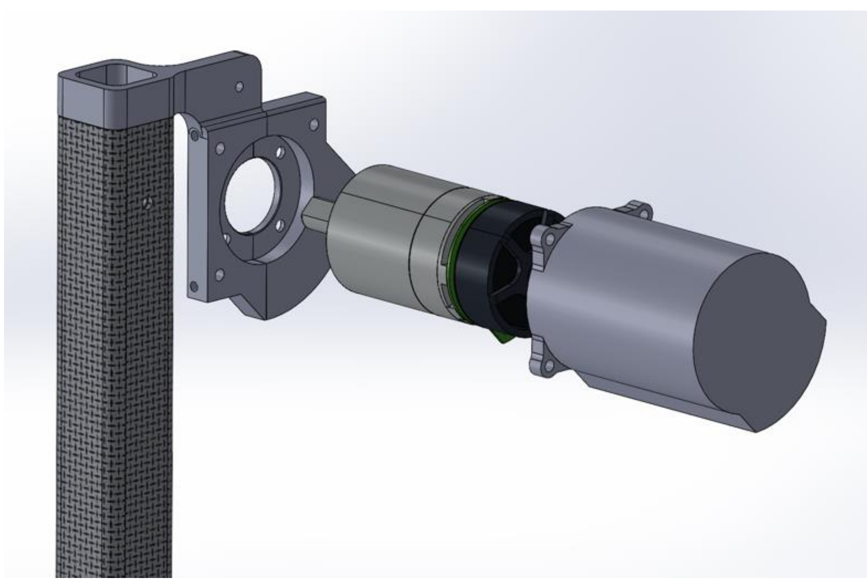


Figure 17 Assembly of our motor mount and protective covering

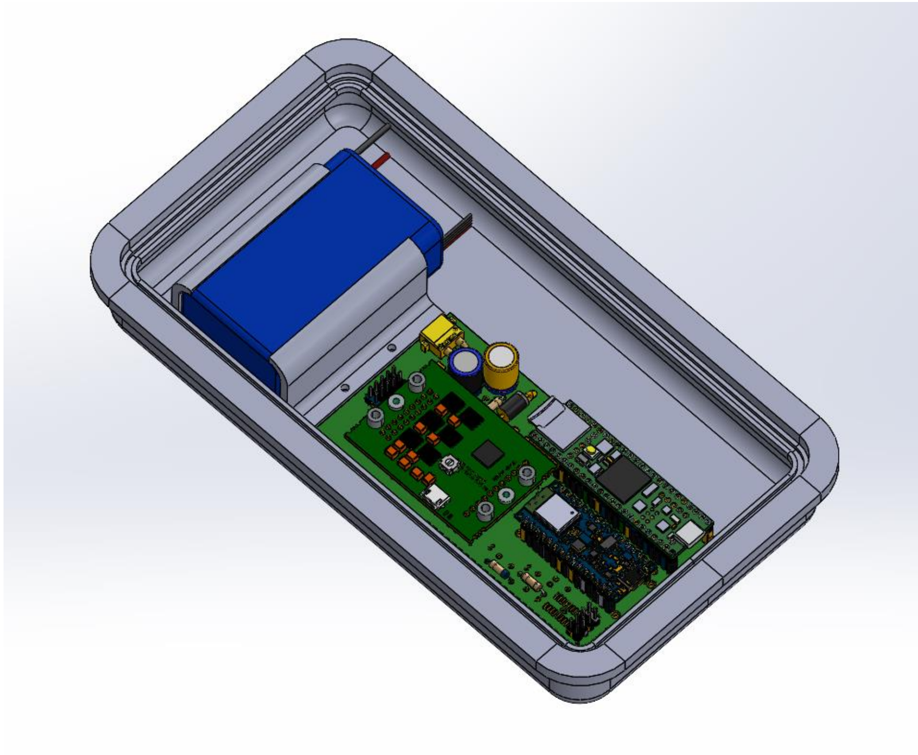


Figure 18 Assembly of our Battery/ PCB Protective Covering

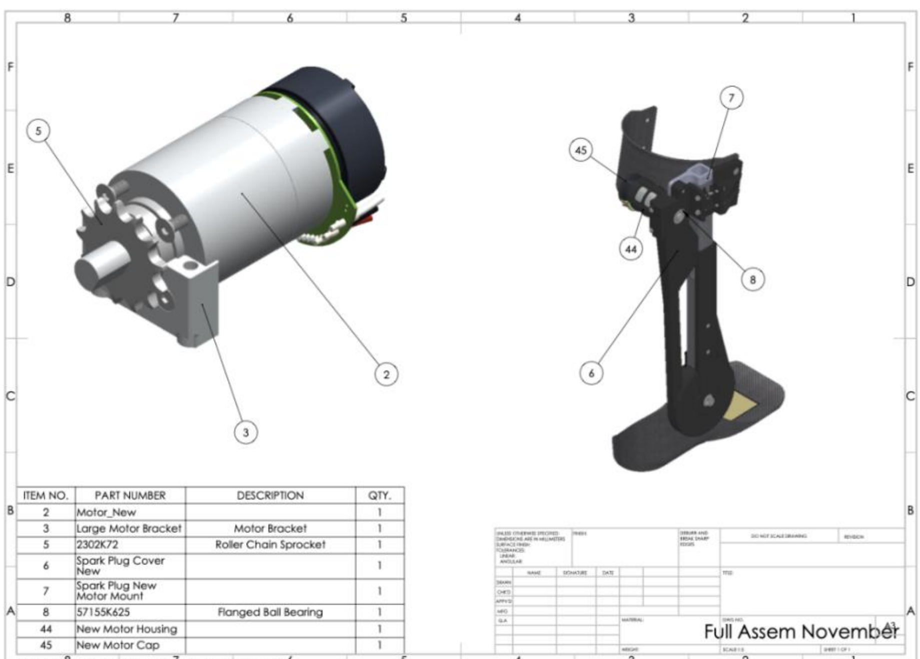


Figure 19 Final Concept Drawing and BOM

5 Schedule and Budget

5.1 Schedule

As the schedule for this semester ends, the team compiled a combination of the Gantt charts from both semesters. The team is on track to be able to complete the final design, where we ended up with tests. With only a little over a week until our final presentation, the team will be able to easily complete the final steps. Figure (20) shows the Gantt chart with the status of the team for the first semester, while Figure (21) shows the schedule for the second semester.

2	Major Deadlines 1st Semester																				
WBS Number	Task Title	Task Owner	Start Date	End Date	Duration	% Done	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2.2	Initial CAD Design	Nick W	9/30/24	10/28/24	28	100%															
2.1	1st Protype Demo	Alex S	10/28/24	11/13/24	15	100%															
2.2	Final CAD and BOM	Nick W	10/11/24	12/3/24	52	100%															
2.3	2nd Protype Demo	Alex S	10/11/24	12/4/24	53	100%															
2.4	Analysis of Prototype	Team	12/4/24	12/7/24	3	100%															
2.5	Purchase of Parts	Ryan O	10/11/24	10/26/24	15	100%															
2.6	Test 1st Prototype	Alex S	11/13/24	11/24/24	11	100%															

Figure 20 Gantt Chart of Semester 1

3	Major Deadlines 2nd Semester																				
WBS Number	Task Title	Task Owner	Start Date	End Date	Duration	% Done	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
3.1	Engineering Model	Team	1/13/25	1/23/25	10	100%															
3.2	Test 2nd Prototype	Alex S	12/13/24	1/20/25	37	100%															
3.3	Analysis of 2nd Prototype	Alex S	1/13/25	2/1/25	18	100%															
3.4	Hardware Status Check 1	Team	1/13/25	2/13/25	30	100%															
3.5	Order all parts	Ryan O	1/13/25	2/13/25	30	98%															
3.6	Website check	Nick W	1/13/25	2/27/25	44	100%															
3.7	Testing Plan	Ryan O	3/1/25	3/27/25	26	100%															
3.8	Hardware Status Check 2	Team	2/13/25	3/6/25	23	100%															
3.9	Final CAD	Ryan O	3/6/25	4/3/25	27	100%															
4	Final Hardware Status and Prototype	Team	3/6/25	4/3/25	27	98%															
4.1	Website check	Nick W	2/28/25	4/17/25	47	80%															
4.2	Test and Analyze Protype	Alex S	4/3/25	4/17/25	14	50%															
4.3	Final Report	Team	4/1/25	4/17/25	16	40%															

Figure 21 Gantt Chart of Semester 2

As for the breakdown of the individual tasks over the year. We mostly followed the guidelines set forth by the class, completing major prototypes by the deadlines. But we have separated our tasks and therefore the semester into three different tasks. They are battery selection, motor analysis, and cover and ingress protection for the motor, PCB, and battery. This covers the location they are to be placed on the overall exoskeleton, as well as how it will be protected against debris and water, as well as protection from heat production. Figure 22 demonstrates the work breakdown structure throughout the year, as well as an overview of the budget and time for each section. These three tasks are again broken up between CAD designs, prototype creation, analysis, and repeated to create a final working product.

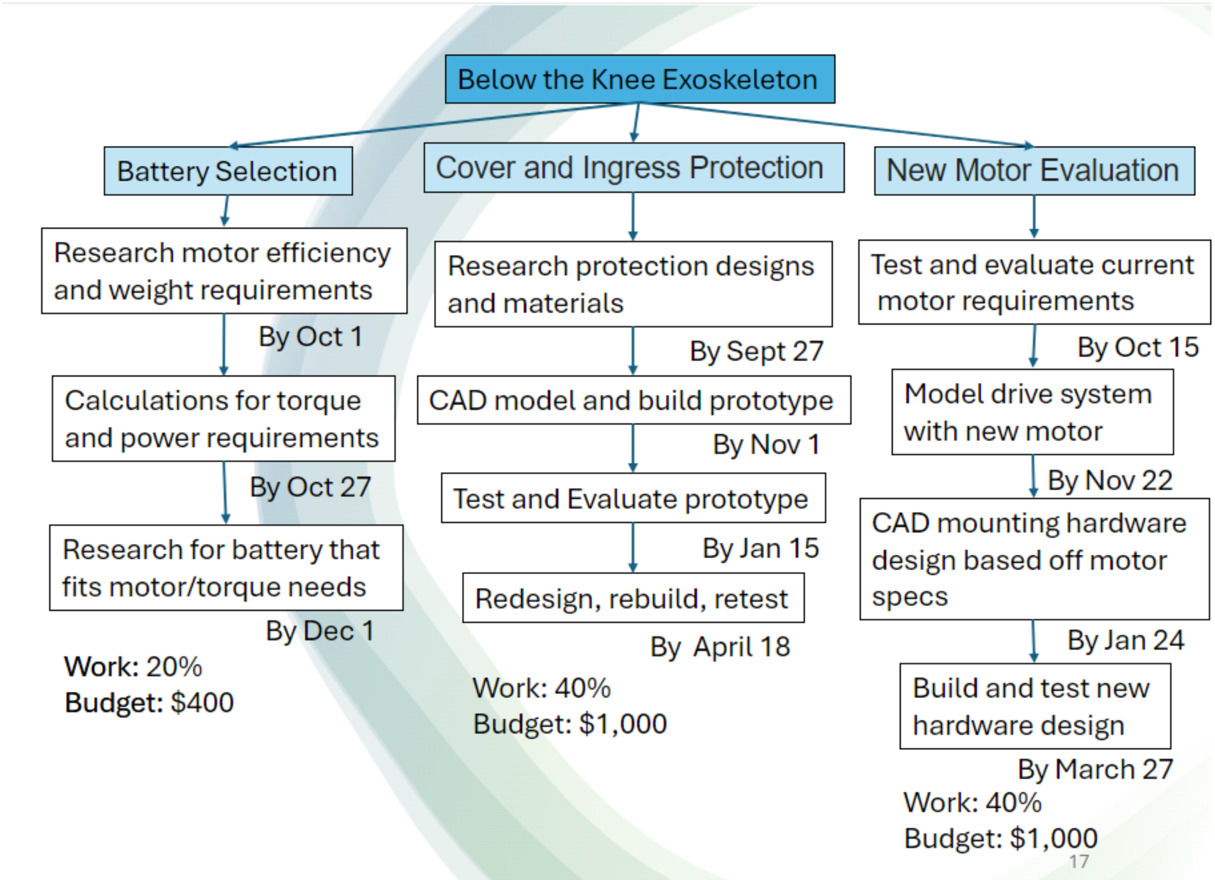


Figure 22 Work Breakdown Structure

5.2 Budget

Table 4 Budget for all parts of the build

Part:	Cost:	Materials:	Purchased or Manufactured:	Vender:	Part #:	Lead Time/ Part Statues:
8mm Steel Ball Bearing	Donated	-	Provided by Client	McMaster	49DD43	On Hand
Medium-Strength Steel Nylon	Donated	-	Provided by Client	McMaster	38DA12	On Hand
Stainless Steel Button Head Torque Screws	Donated	-	Provided by Client	McMaster	49DD88	On Hand
Alloy Steel Socket Head Screw	Donated	-	Provided by Client	McMaster	38DH71	On Hand
Big Gear Modified	Donated	-	Provided by Client	N/A	811X86	On Hand
Bondable Flex Circuit	Donated	-	Provided by Client	McMaster	5GUD5	On Hand
Bracket Bolt	Donated	-	Provided by Client	McMaster	5KY28	On Hand
Cable Chain Interface	Donated	-	Provided by Client	McMaster	808A65	On Hand
Cable Crimp	Donated	-	Provided by Client	McMaster	16X825	On Hand
Clearance Cable	Donated	-	Provided by Client	McMaster	38DH70	On Hand
Cover Bolt	Donated	-	Provided by Client	McMaster	811X86	On Hand
Cuff Locknut	Donated	-	Provided by Client	N/A	38DH70	On Hand
E-flite - EFLB910	53.29	N/A	Purchased	Prop Shop Hobbies	EFLB9106S30	Arrived
FSR Sensor	Donated	-	Provided by Client	McMaster	FSR01CE	On Hand
Inner Link clamp	Donated	-	Provided by Client	McMaster	B1293497	On Hand
M3 Nut	Donated	-	Provided by Client	McMaster	6CA66	On Hand
Motor Cover Cable Clamp	Donated	-	Provided by Client	McMaster	6CE47	On Hand
Motor Cover	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Manufactored
Maxon Motor	599.91	N/A	Purchased	Maxon	B7FFC8204F6C	On Hand
Outer Link clamp	Donated	-	Provided by Client	N/A	811YK3	On Hand
PCB Housing	518.5	PLA Carbon Fiber Filament	Manufactured	Markforged	F-FG-0005	Arrived
PCB	Donated	-	Provided by Client	N/A	N/A	On Hand
Pogo Pin Connector	Donated	-	Provided by Client	McMaster	B1293497	On Hand
Pulley w/ Washer	Donated	-	Provided by Client	McMaster	4EFZ9	On Hand
Quick Connect Footplate	Donated	-	Provided by Client	McMaster	811YK3	On Hand
Roller Chain	Donated	-	Provided by Client	McMaster	2TAA1	On Hand
Motor Motor - Upright	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Manufactored
Motor Mount - leaf	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Manufactored
STTR Upright	Donated	-	Provided by Client	CarbonParts	6CA66	On Hand
Slider Spacer	Donated	-	Provided by Client	N/A	6CE47	On Hand
Small Motor Cover Cable Clamp	Donated	-	Provided by Client	McMaster	811X87	On Hand
Calf Cuff Adjuster	Donated	-	Provided by Client	McMaster	826K20	On Hand
Strain Gage	Donated	-	Provided by Client	McMaster	38CZ28	On Hand
Terminal Pads	Donated	-	Provided by Client	McMaster	1MVP8	On Hand
Motor O-ring	16.91	Fluorine Rubber	Purchased	Amazon	38DE72	Arrived
PCB Housing O-ring	16.9	Rubber	Purchased	Amazon	26LG26	Arrived
Torque Sensor Quick Connect	Donated	-	Provided by Client	N/A	808A65	On Hand
M3 25mm w/ Bolt	Donated	-	Provided by Client	McMaster	38CV95	On Hand
M5 12mm w/ Bolt	Donated	-	Provided by Client	McMaster	5KY28	On Hand
Motor Bracket	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Manufactored
motor cap	254.97	PLA Carbon Fiber Filament	Manufactured	Markforged	F-MF-0001	Arrived
Cuff assembly	Donated	-	Provided by Client	N/A	N/A	On Hand
All Other screws	Donated	-	Provided by Client	McMaster	N/A	On Hand
Hi-temp Gasket	12.97	-	Purchased	Tractor supply	I21744599	Arrived
Flanged Ball Bearing	41.44	-	Purchased	McMaster	148-2Z	Arrived

5.3 Bill of Materials (BoM)

Table 2 contains a short bill of materials for new parts, purchased and manufactured. A complete bill of materials can be found in the appendix.

Table 5: Budget of Purchased Parts

Item Description:	Material:	Part #:	Vendor:	Price:
800cc Onyx Filament Spool	Carbon Fiber Filament	F-MF-0001	Makerforge	$254.97
150cc Carbon Fiber CFF Spool	Carbon Fiber Filament	F-FG-0005	Makerforge	$518.50
E-Flite 22.2v 910mAh li-po battery	-	EFLB9106S30	Home Hobbies INC.	$53.29
ECXFL32L motor with a 1:35 Gear Ratio X2	-	B7FFC8204F6C	Maxon Motors	$599.51
Fluorine Rubber O-Rings, 42mm OD, 38mm ID, 2mm Width (pack of 10)	Fluorine Rubber	N/A	Amazon	$16.90
10 PCS O Rings Nitrile Rubber Round O-Rings Seal Grommets 185mm OD 181mm ID 2mm Width	Nitrile Rubber	N/A	Amazon	$16.91
SUNLU PLA 3D Printer Filament PLA Filament 1.75mm	PLA	N/A	Amazon	$27.27
Creality PLA Carbon Fiber Filament 1.75mm	Carbon Fiber PLA	N/A	Amazon	$39.28
Carbon Fiber upright	Carbon Fiber	C25502	Rockwest	$173.99
Small gear cog	-	2302K69	McMaster	$94.66
Flanged 8mm Bearings	-	5717K623	McMaster	$41.44
Aluminum Brackets	Aluminum 7075	N/A	Shenzhen Yuanhuijin Technology Co. LTD	$90.00
Aluminum Mount	Aluminum 7076	N/A	Shenzhen Yuanhuijin Technology Co. LTD	$139.00
Aluminum Rack and Picket	Aluminum 7077	N/A	Shenzhen Yuanhuijin Technology Co. LTD	$1,352.00
			Total Cost:	**$3,417.72**

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

Some of the biggest aspects of our project involved open wiring with no insulating properties or protection. Our job was to design parts for these assemblies that would withstand an outdoor environment. We designed these parts with thermal management and ingress protection in mind. Some of our critical potential failures could come from the protective covering of the motor and the Battery/ PCB compartment. We designed an O-ring fitting for each compartment to ensure a watertight seal. If that seal were ever to be broken and water made its way into the motor or PCB, then we could have damaged a component, which would be a costly lesson to us. We design our parts with a tight tolerance to leave no gap for foreign material to enter the system and to reduce our chances of failure.

Another way we, as a team, had to be cautious was when it came to thermal management. The electrical components that we deal with have the potential to get very hot during extreme stress, which could damage the part or at least reduce its life of the part. So, in designing our protective covering, we had to keep in mind how we will disperse the heat that these parts create while protecting the rest of the system. Our team designed parts with the hope that we could use heat transfer through the protective material to disperse the heat. Using heat syncs and small DC fans, we have situated ourselves on our conductive protective covering (Aluminum Alloy 7075 – O (ss)), and we hope to transfer that heat coming from our electrical components.

Most of our parts are brackets and our only concern with the brackets is the possibility of being too heavy for the user. The risk to trade off we have here is the balance between making them strong enough to hold up and light enough for the user to comfortably operate.

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
Maxon Motor	Exessive force	Motor is less functional or broken	System is mishandled	200	Add more protection to cover
	Thermal deformeatipon	Motor can sieze	Improper termal management	30	Add more thermal management
	Abraisive wear	Motor is less functional or broken	Regular use	500	Add more protection to cover
	Corrosion from outside elements	Motor won't work with other components	Improper ingress protectiont	50	more ingress protection
Motor support	Exessive force	Motor could sag	Regular use	500	brace suppot
	Tempurature induced deforation	Support could break or become brittle	Used out in freezing weather	50	Add more thermal management
	Cycle fatigue	Support could wear	rubbing from cloths	200	Add more protection to cover
Motor ingress protection	Tempurature induced deforation	O-ring could go bad	extreme temperatures	300	different design
	Exessive force	Cover can fracture	System is mishandled	200	Add more protection to cover
	Thermal fatigue	Cover can become brittle	extreme temperatures	50	Add more thermal management
	Impact wear	Cover can fracture	Regular use	500	Add more protection to cover
PCP	Impact fracture	PCP can break	System is mishandled	200	Add more protection to cover
	Thermal fatigue	PCP can overheat	not enough thermal management	30	Add more thermal management
	Cycle fatigue	Small parts can wear	Regular use	500	different design
	Corrosion from outside elements	PCP can overheat or short circuit	left in weather for extended period	50	add more ingress protection
Battery	Cycle fatigue	Battery can loose power	Regular use	500	different design
	Tempurature induced deforation	Can compromise battery life	overloading the battery	300	Add more thermal management
	Corrosion from outside elements	Can kill the battery	water seeps in	30	add more ingress protection
	Stress Rupture	Can break protective seal	overloading the battery	50	different design
	Exessive force	Can break protective seal	System is mishandled	100	Add more protection to cover
PCP/ Battery ingress protection	Exessive force	Cover can fracture	System is mishandled	100	Add more protection to cover
	Tempurature induced deforation	O-ring could go bad	Improper termal management	300	different design
	Thermal fatigue	Cover can become brittle	extreme temperatures	50	Add more thermal management
	Impact wear	Cover can fracture	System is mishandled	100	Add more protection to cover
Themal management of PCP/ Battery	Adheisive wear	Loose effective dissipation	misclaculated shifting of parts	100	fix it's mounting
	Exessive force	Can brittle the material	System is mishandled	300	Add more protection to cover
	Corrosion from outside elements	Loose effective dissipation	water seeps in	50	add more ingress protection
	Cycle fatigue	Can brittle the material	Regular use	500	Add more thermal management
Themal management of Motor	Adheisive wear	Loose effective dissipation	misclaculated shifting of parts	100	fix it's mounting
	Exessive force	Can brittle the material	System is mishandled	300	Add more protection to cover
	Corrosion from outside elements	Loose effective dissipation	water seeps in	50	add more ingress protection
	Cycle fatigue	Can brittle the material	Regular use	500	Add more thermal management

Table 5: FMEA Chart

Our recommended actions consist of adding more protection or more thermal management properties. What we had to do as a team was find the balance point between making the Exo-Ankle bulletproof and lightweight. The risk trade-off for our recommended actions was to better brace the motor, PCB, Battery, and cover, which allowed it to be better accessed when testing of Ankle-Exo.

6.2 Initial Prototyping

6.2.1 Physical Prototype

Due to the nature of our project, until receiving the final say from Dr Lerner to buy the new parts, we did not know the exact specifications of our redesigns until later in the year. With a new motor, new battery, and a task to move the PCB to the leg, a partial re-design of the exoskeleton was necessary. The new motor required most of the drive system to be rebuilt. Before we received the actual specifications, we only had the full CAD model of the existing exoskeleton and a general idea of the sizes and specifications of the new parts. Using the CAD model, we 3d printed a full-size model of the exoskeleton, sans the footplate and cuff, which are thin carbon fiber parts that were very difficult to print. The purpose of this prototype was to create a way to analyze the model outside of the CAD. Because the actual exoskeleton couldn't leave the biomechatronic lab, and the new parts had not been finalized at the time, this would be our only way to modify a real model for the time being. Because this prototype served only for design, we printed subassemblies together, meaning that the model could not be disassembled and reworked. We printed the model using Nick's printer, which ran into several issues throughout the process. First, the nozzle jammed, and replacements had to be purchased. Then the thermistor, which monitors the extrusion temperature, died, and the heating block was replaced. Lastly, the printer motherboard shorted and could not connect to the print server, needing to be replaced as well. The printer began running again close to the deadline, so several parts were fast, low-quality prints.
We then printed a new prototype, this time printing each part individually, so that we could rebuild the model for alternate designs. In the prototype, some parts cracked from the screws as well as stress from the inaccurate tolerances from low-quality parts. In addition to adding tolerances to the part models, we used PLA carbon fiber filament rather than PLA, due to its high strength.

6.2.2 Virtual Prototype

Our working CAD model included mounts for both the PCB and battery, and a new motor housing designed to protect the motor from moisture, debris, and damage. Most of the drive system and some of the frame had been redesigned, including the full motor subassembly, the motor mount, and the front cover. The motor has an open back, leaving the coils exposed. Because of this, the motor housing prioritizes protection from overheating diffusion, enclosing the entire motor and using an O-ring to seal the cover to the mount. As part of our virtual prototype, we conducted a heat transfer analysis on the motor and housing. Figure 23 shows the outcome of this study. Section 4.3 in this report shows the calculations used in this simulation.

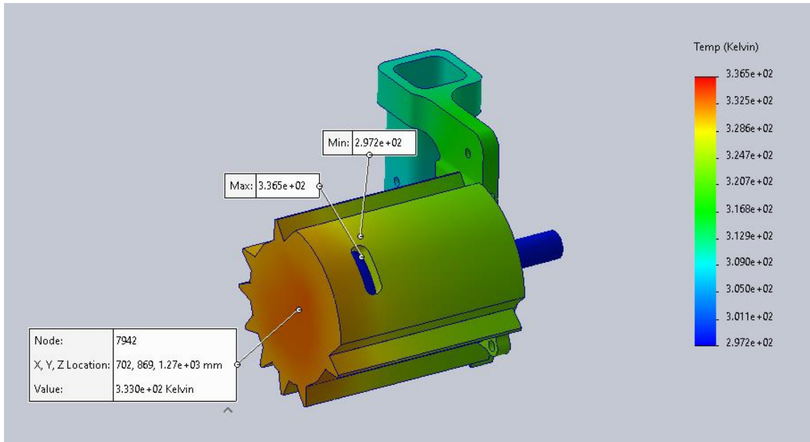


Figure 23Thermal analysis of the motor.

6.3 Other Engineering Calculations

For this study, I decided to rerun an analysis of the thermal dispersal from the motor to the edge of the cover. Our team recently had a design check with our client, where he looked over our designs and gave invaluable insight. One of the main challenges our team faced was preventing heat from the motor from being felt by the user via the dispersal of the heat using a motor cover, as well as preventing it from overheating in the cover. Our previous design was determined to be too costly and difficult to manufacture within the time and costs the client provided. Our current design puts some heat sinks around the perimeter of the cover, using aluminum as the material for the entire shield. Our redesign changed the location of the heat sinks and broke up the material to be easier to manufacture. Given that the motor itself produces the majority of the heat, with the gearbox producing significantly less, the heat sinks were moved to encompass solely the motor. We also broke up the design so that the casing around the gearbox can be produced using 150cc Carbon Fiber, while the heat sinks are produced using the normal aluminum. This will significantly cut the costs of the motor cover. Because of this rather small change, many of the equations remain the same, with a few added equations and a new simulation in SolidWorks.

In this analysis, the calculations for the convective heat transfer remain the same since they use the constants of the properties of air and the length of the motor casing, which remained the same. The calculations for heat transfer are as follows:

The first step in calculating the convective heat transfer coefficient, formula (10), is to calculate the Reynolds number (Re) using formula (8). For this formula, I used the following assumptions: density (ρ) is 1.18 $\frac{kg}{m^3}$., flow velocity (u) is 5 m/s, and dynamic viscosity (μ) is 1.64E-5 $\frac{kg}{m*s}$. [32] These assumptions are based on the properties of air at 25 °C.

$$(8) \qquad Re = \frac{\rho * u * L}{\mu}$$

Using this formula, the Reynolds number can be calculated to be 18,598. Next, I calculated the Nusselt's number using formula (9). This formula is based on the idea that the boundary flow is over a cylindrical surface and that the Reynolds number (Re) is less than 10^7.

$$(9) \qquad Nu = 0.3 + \frac{0.62Pr^{1/3}}{[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{\frac{2}{3}}]^{1/4}} Re^{1/2}[1 + \left(\frac{Re}{282000}\right)^{\frac{5}{8}}]^{4/5}$$

Using the Reynolds number from formula (8) and the assumption that the Prandtl number (Pr) is 0.715, the Nusselt's number (Nu) comes out to be 86.08.

From here, I can calculate the convective heat transfer using formula (10). According to the SolidWorks design, the length (L) of the cover is 58 mm.

$$(10) \qquad h = \frac{Nu * k_{air}}{L}$$

Given that the Nusselt's number (Nu) is 86.06 and the constant thermal conductivity for air (k) is 0.026 $\frac{W}{m*K}$The convective heat transfer coefficient is calculated to be 38.59 $\frac{W}{m^2K}$ at 298 K. [32]

It is not only the motor coils that produce heat, but the gearbox also produces heat. To begin, I had to calculate the angular velocity (ω) using formula (11).

$$(11) \qquad \omega = \frac{2\pi * RPM}{60}$$

Using the assumption that the nominal speed (RPM) of 8100 RPM for our Maxon motor, according to the motor specs (the website has sadly been taken down, but our presentation 2 contains the specs). This then causes the angular velocity (ω) to be 848.23 rad/sec.

From here, I calculated the output power of the motor (P_{output}) using formula (12).

$$(12) \qquad P_{output} = T * \omega$$

Using formula (12), I calculated the power of the motor (P_{output}) to be 87.37 W. This uses the assumption from the motor specs that torque (T) is 0.103 Nm and angular velocity from formula (11), 848.23 rad/sec.

From here, I can calculate the input power of the motor (P_{input}) using formula (13).

$$(13) \qquad P_{input} = \frac{P_{output}}{efficiency}$$

According to the motor specs, the efficiency of the motor is 89%. This causes the input power (P_{input}) to be 98.17 W. From here, I can calculate the heat dissipation for both the motor and the gearbox, using formula (14).

$$(14) \qquad H_{dissipated} = P_{input} * (1 - efficiency)$$

For the motor, we use the idea that power input is 98.17 W and efficiency is 89%. This causes heat dissipation for the motor to be 10.7 W. When it comes to the gearbox, the power input is the same as the power output of the motor. Because of this, the power input is 87.37 W, and the efficiency of the gearbox is 95% for the 35:1 ratio gearbox. Because of this, the heat dissipation for the gearbox is 4.37 W.

From here, I used the new design that Nick created on SolidWorks to run a new simulation. This also included different materials and a new layout that is easier to manufacture. Figure 1 shows the heat dissipation from the previous design. From here, we separated the cover into two parts, one a manufactured cover using 150cc Carbon Fiber, and the other was manufactured to have a heat sink manufactured using aluminum.

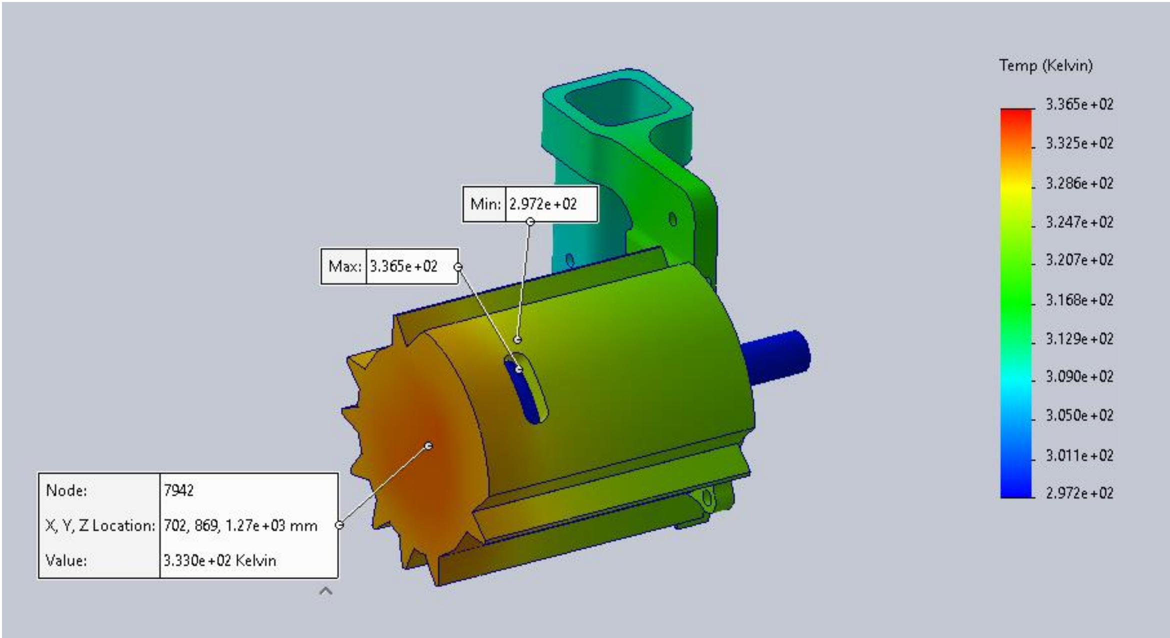


Figure 24 Thermal Analysis of the old motor cover

Because of this change in the cover, the overall cover proves to be more efficient at dispersing the heat. The maximum temperature still lies at the core of the coils on the motor to be 431 K, and the minimum temperature is 297.7 K. Figure 23 shows the thermal dispersion of the new motor cover and proves to be cheaper and more efficient.

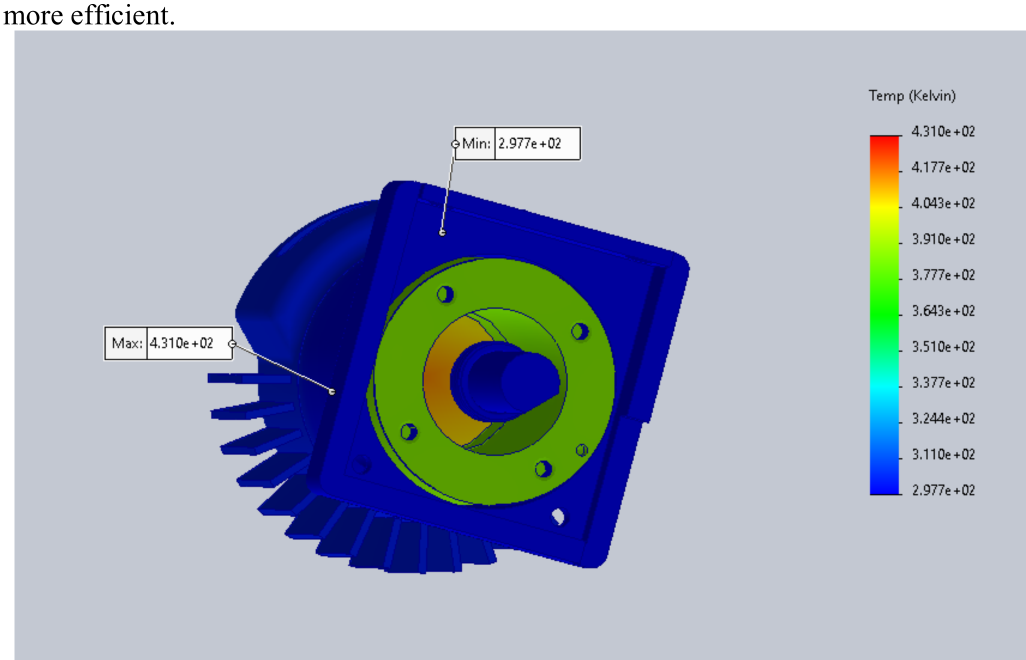


Figure 25 Thermal Analysis of New Motor Cover

Figure 24 shows the motor cover from a different angle to show the new design for the cover, as well as the new materials.

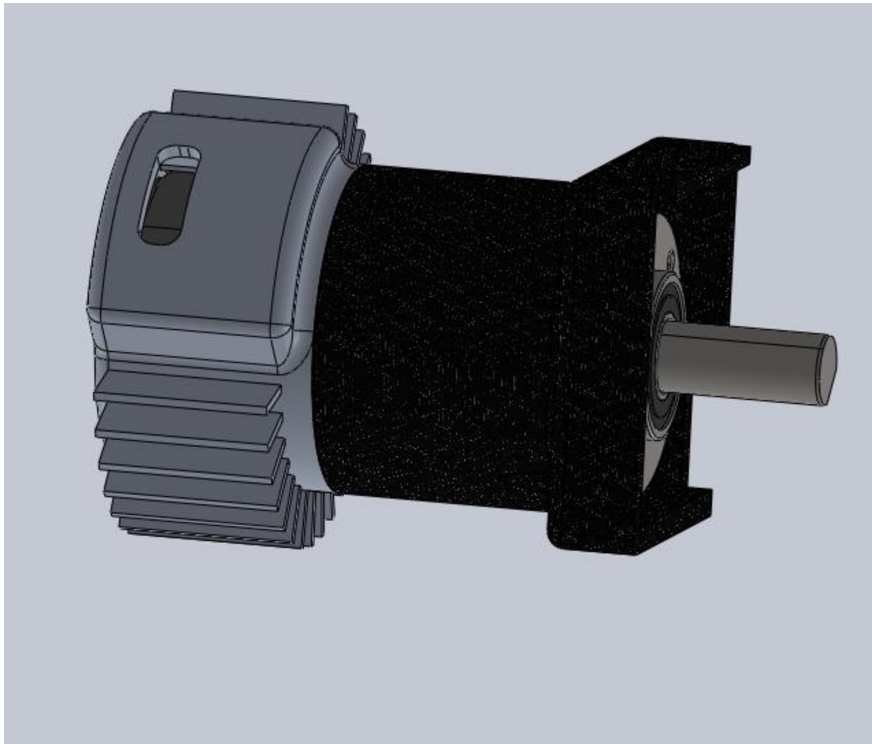


Figure 26 New Motor Cover

6.4 Future Testing Potential

The first new part we needed to install was the motor. Because the new motor has a higher torque than the old one, the effect of torque on the drive system, specifically the cable and crimps, can be analyzed to verify the increase in strain. The battery and PCB had to be moved from a belt onto the exoskeleton itself, enclosed in a protective cover. The main issue that this can cause is the heat produced by these parts. Batteries and PCBs both have a risk of overheating, so a thermal analysis needed to be done to determine if these parts require a cooling system. It is important that the exoskeleton remains lightweight after the new parts are installed, as the target users are individuals with muscular deficiencies, and a system that is too heavy will not allow the user to walk for long periods, if at all. Alternate materials for various parts of the exoskeleton can be researched, and the total and center of mass can be analyzed to decide if the weight of the new parts will make this necessary. Lastly, the heat transfer analysis was performed on the motor within the new cover, and if it is determined that the cover is not adequately diffusing heat, then further steps could be taken. Either a cooling system could be built into the housing, or heat sinks could be either installed or built into the cover. If this is to be done, heat transfer analysis could be performed on different heat sink configurations, and calculations can be made to determine the thermal resistance and heat diffusion of different fin sizes.

7 Final Hardware

7.1 Final Physical Design

Figure 27 The Final CAD of The Full Exoskeleton

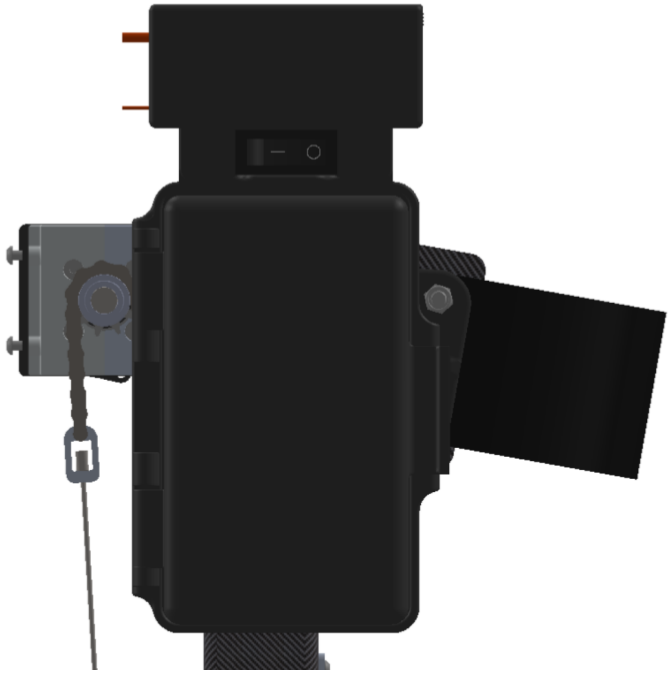


Figure 28 The Chain Sprocket and PCB Case

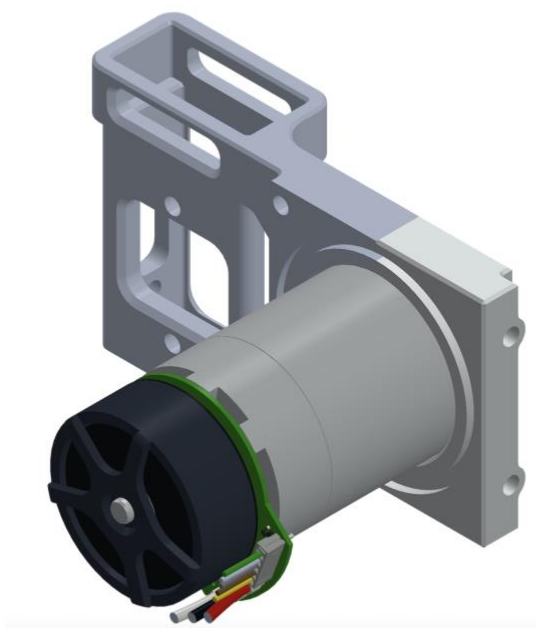


Figure 29 Motor Mount Assembly

8 Final Testing

8.1 *Top-level testing summary table*

The following table, Table 5, demonstrates the main experiments the team ran after the main design was complete. It demonstrates the experiment, the testing materials needed to complete it, and any other resources that were needed.

Experiment/Test	**Relevant DRs**	**Testing Equipment Needed**	**Other Recourses**
Exp1: Weight and COM	ER5: Under 3kg CR6: Lightweight	Scale	Access to device from Lerner's Lab
Exp2: Initial run of device	ER1: Energy Efficient ER3: High Torque ER7: Battery Capacity CR4: High Battery Life	Device, PCB, Battery, Motor	Programmed PCB
Exp3: Ingress Test	ER8: Ingress Protection	Motor and PCB/battery housing, water	Probe, Spray bottle, determined by target IP rating
Exp4: Thermal Test	ER6: Temperature of Motor	Arduino, DAQ, motor & housing	Alternate motor housings
Exp5: Final test on human	ER2: Accommodate Different Shoe Size ER4: Supports Users of All Weight ER1: Energy Efficient ER6: Temperature of Motor CR1: Durable CR2: High range of motion CR3: Comfortable CR5: Adjustable CR6: Lightweight	Assembled device, treadmill	Test Lab

Table 6 Top Level Testing Summary

8.2 *Detailed Testing Plan*

8.2.1 Experiment 1: Weight and COM

8.2.1.1 Summary

The purpose of this experiment is to ensure that engineering requirement 5 and customer requirement 6 are fulfilled. This experiment was relatively simple, ensuring the device in its entirety remains less than 3 kilograms.

8.2.1.2 Procedure

To test this, the team placed the exoskeleton and all its encompassed parts on a scale provided by the NAU Mechatronics lab. Because the Exoskeleton has a higher COM and is thus difficult to get to lay on the scale, the team had to take apart some of the Exoskeleton and place the individual parts on the scale to get a more accurate weight.

8.2.1.3 Results

The overall weight of the exoskeleton came out to be 1.18 kilograms, which is far below the maximum of 3 kilograms. Figure 25 demonstrates the method used to weigh the Exoskeleton.

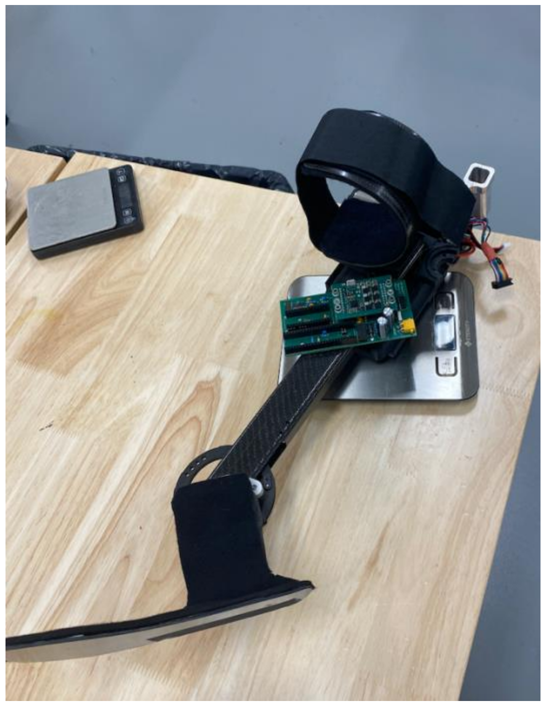


Figure 30 Weight of Exoskeleton

8.2.2 Experiment 2: Initial Run of Device

8.2.2.1 Summary

The purpose of this experiment is to ensure the device can run with the preexisting code provided to us by the other students in the Biomechatronic lab. This test ensures that after a full build of the device, it will continue to run, and that the battery will support the motor and the torque required for the final device. To complete this experiment, the team will need to wire the device, have access to a fully loaded PCB, the battery, and the motor. The team also needed access to the lab.

8.2.2.2 Procedure

To complete this experiment, the team hooked up a rudimentary version of our exoskeleton with a loaded PCB and hooked it to a computer loaded with the necessary code. From here, we ran the code, which confirmed the torque added to the motor was in the correct direction and would move the footplate, ideally forward if the device was hooked up correctly.

8.2.2.3 Results

The results were relatively simple, as the outward check for completion was the movement of the footplate in the correct direction. The code took a few adjustments, especially when the app that controls the movement of the exoskeleton was not working on the initial phone we used, so we had to switch to an iPad to load the program. Overall, the footplate moved in the correct direction, and Figure 26 demonstrates a picture of the team in the process of this experiment.

Figure 31 Initial Run of Device

8.2.3 Experiment 3: Ingress Test

8.2.3.1 Summary

One of the main tasks for this project was ensuring the exoskeleton could withstand being used in an outdoor setting. Because of this, the covers created by the team need to withstand water and debris up to an IP rating of IP44. This experiment allowed the team to prove that our designs could withstand outdoor use.

8.2.3.2 Procedure

The test for ingress protection requires two things: Dust and water testing. The Ingress protection rating (or IP rating) is broken up into these two subjects to understand the protective cases in the different environments that the part would be subject to. The first number in the ingress protection rating is for testing the amount of solid material that can interact with the part. Number 1 through 6, with six being the best, each value corresponds to a different level of material intrusion, our process to test this vale was to submerge our protective casing into finer and finer grit sand, the cover casing held up to level 4 which is material up to 1mm cannot intrude into the casing. The second value of the ingress protection rating was the water test. Numbered 1 through 8, with 8 being the highest value of protection, we did what we did with the dust level by submerging the casing in water. Our casing didn't hold up to being submerged, so we simulated different scenarios. Our casing has a water protective level of 4, which means our casing can withstand moderate levels of a water jet in every direction. In total, our ingress protection rating came out to be an IP:44. This fits our requirement because an IP:44 is considered to be safe for outdoor use, which is our goal with this protective casing.

8.2.3.3 Results

By performing this experiment, the team confirmed that not only does the design pass the requirement set forth by the client, but they surpasses them. We determined the covers have an IP rating of 45, possibly more if the team had access to a dust chamber. Figure 27 demonstrates the procedure taken by the team.

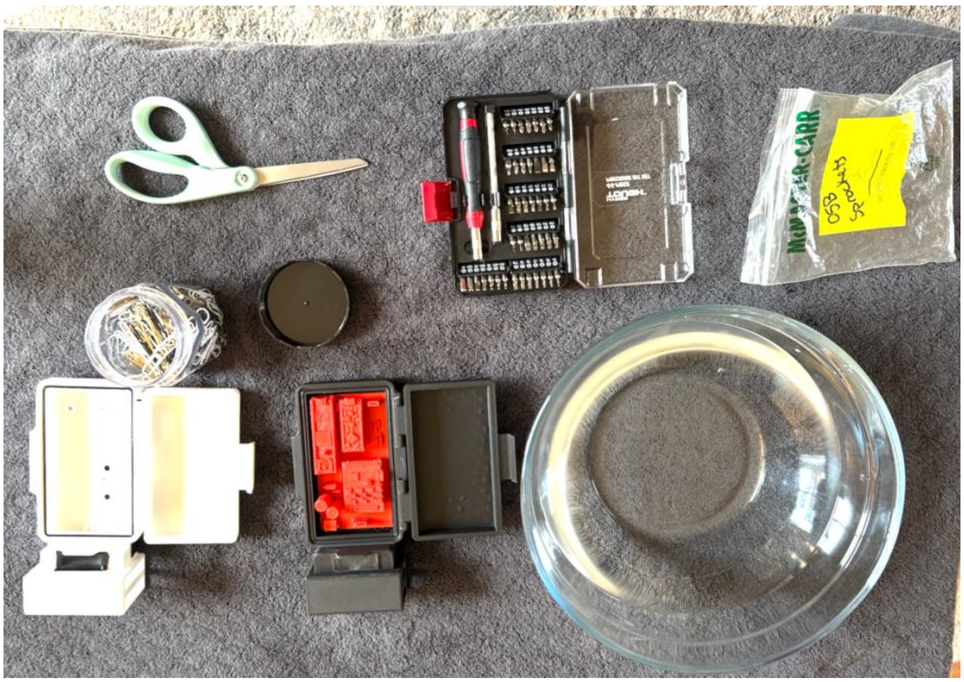


Figure 32: IP tests

8.2.4 Experiment 4: Thermal Test

8.2.4.1 Summary

The purpose of this test was to ensure the motor does not overheat if it were to be placed in a cover. The team had to analyze the temperature of the motor both out of the covering and inside the covering to ensure that it does not hit 70 degrees Celsius or higher.

8.2.4.2 Procedure

This test was performed by running the motor in a normal life cycle and periodically testing the temperature of the motor. For this procedure, the team needed access to the fully functioning exoskeleton, a thermal gun, a thermocouple, and a computer to read the data. We used Professor Lerner's advanced treadmill to run the device continually. We took readings with both the thermocouple and the thermal reading periodically throughout the battery lifecycle.

8.2.4.3 Results

The team was able to confirm that the maximum temperature of the motor never exceeded 54.5 degrees Celsius in either case. This is well below the required temperature limit, meaning that our cover designs are sufficient to moderate thermal readings.

8.2.5 Experiment 5: Final Test on Human

8.2.5.1 Summary

This experiment serves to ensure that the final design is fully functional. This experiment confirms most of our engineering requirements and customer requirements, such as energy efficiency (ER 1) and durability (CR 1).

8.2.5.2 Procedure

This experiment consists of a full run of the device until the battery reaches 25%. From here, the team will take several readings, such as torque, thermal, and voltage. This will be run concurrently with experiment 4. While the user was walking on the treadmill and the readings were being recorded, another member of the team took thorough videos and recorded how the user felt to ensure comfort and the feel of the exoskeleton on the leg.

8.2.5.3 Results

The team was able to confirm that the complete version of the prototype did not prohibit any natural movement of the leg or limit the comfort of the overall device. It allowed for enough torque applied to the footplate, and the team was able to determine the battery would last approximately 53 minutes before it hit a battery life of 25%. With the simple swap of footplate and calf cuff size, it was able to fit and support each member of my team with different foot sizes and weights. Figure 28 demonstrates the final device in action.

Figure 33 Final device in action

9 Future work

While the current design is intended for physical therapy, future iterations will be designed for daily use orthosis. For use in daily life, some features must be improved:

- Lifespan – the working battery will power the device for about an hour during normal use, but for daily use, the battery capacity will need to be significantly improved.
- Device profile – if the device is to be used outdoors, it should be slimmed down, as the working design is liable to get in the way of where the user is walking. Altering the frame to sit closer to the user's leg is one possible improvement regarding the size of the exoskeleton.
- Material strength – when the design can be worn outdoors, the user should be able to use it anywhere, for example, hiking. Making the exoskeleton strong enough so that it can be used off flat ground will allow users more freedom.

From here, the exoskeleton could eventually be advanced to allow users who have limited mobility to walk almost uninhibited throughout daily life. Due to the ingress protection, the exoskeleton could be used on hikes or in town. From here, the possibilities are endless, going so far as to create our very own Iron Man.

10 CONCLUSIONS

For our capstone project, our team was tasked with improving a previous design for a below-the-knee Ankle Exoskeleton, developed by a past capstone team in collaboration with our client, Dr. Zachary Lerner of the NAU Biomechatronic Lab. The original exoskeleton was designed to aid people with walking impairments by enhancing ankle movement through a motor housed in the boot. In this design, the battery and microcontroller were positioned on a waist belt connected by wires running up the user's leg.

Our primary objective is to redesign the system to integrate all components below the knee, eliminating the need for the waist belt. To achieve these goals, several critical requirements needed to be met:

- The redesigned exoskeleton must not restrict the user's range of motion.
- The system must be lightweight to avoid user fatigue.
- The electrical components must have proper ingress protection to safeguard against debris and water.
- The system must pass stress and thermal testing to ensure comfort and safety for the user during extended use.

We selected the Maxon ECX flat 32L motor, known for its stable torque output, paired with a Cell E-Flite battery to power the new system. Our new frame design ideas integrate all components behind the calf muscle and along the upright base of the exoskeleton, offering a more compact and ergonomic configuration. This frame includes paneling to house the battery and microcontroller, while maintaining user comfort and mobility.

In summary, the team's solution features a re-engineered frame to accommodate the new components below the knee, updated motor and battery selections, and protective casing to ensure system durability in real-world conditions. This report details our design choices, calculations, and analysis that led to this solution, laying the foundation for testing and further refinement of the exoskeleton system.

11 REFERENCES

[1] "Proceedings of syrom 2022 & robotics 2022," SpringerLink, https://link.springer.com/book/10.1007/978-3-031-25655-4 (accessed Oct. 20, 2024).

[2] "PID control with intelligent compensation for Exoskeleton Robots," ScienceDirect, https://www.sciencedirect.com/book/9780128133804/pid-control-with-intelligent-compensation-for-exoskeleton-robots (accessed Oct. 20, 2024).

[3] G. Orekhov, Y. Fang, C. F. Cuddeback, and Z. F. Lerner, "Usability and performance validation of an ultra-lightweight and versatile untethered robotic ankle exoskeleton - Journal of Neuroengineering and Rehabilitation," BioMed Central, https://jneuroengrehab.biomedcentral.com/articles/10.1186/s12984-021-00954-9 (accessed Oct. 20, 2024).

[4] R. Baud, A. R. Manzoori, A. Ijspeert, and M. Bouri, "Review of Control Strategies for lower-limb exoskeletons to assist gait - journal of Neuroengineering and Rehabilitation," BioMed Central, https://jneuroengrehab.biomedcentral.com/articles/10.1186/s12984-021-00906-3 (accessed Oct. 20, 2024).

[5] X. Li, H. Yuan, W. Chen, L. Yu, and X. Gu, "Commutation torque ripple reduction strategy of brushless DC motor drives based on boosting voltage of DC-link small capacitor," Micromachines, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8877120/ (accessed Oct. 20, 2024).

[6] B. D. Lowe, W. G. Billotte, and D. R. Peterson, "ASTM F48 formation and standards for industrial exoskeletons and Exosuits," IISE transactions on occupational ergonomics and human factors, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6604650/ (accessed Oct. 20, 2024).

[7] C. Siviy et al., "Opportunities and challenges in the development of exoskeletons for locomotor assistance," Nature News, https://www.nature.com/articles/s41551-022-00984-1 (accessed Oct. 20, 2024).

[8] ASM material data sheet, https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA7075O (accessed Nov. 22, 2024).

[9] "3D printing strength: How to 3D print strong parts," All3DP, https://all3dp.com/2/3d-printing-strength-strongest-infill/ (accessed Nov. 22, 2024).

[10] Inc. Alignex, "Introduction to SOLIDWORKS simulation - finite element analysis," SOLIDWORKS Tech Blog, https://blogs.solidworks.com/tech/2020/01/introduction-to-solidworks-simulation-finite-element-analysis.html (accessed Nov. 22, 2024).

[11,12] Ledoux, W. R., & Telfer, S. (Eds.). (2023). Foot and ankle biomechanics. Academic Press.

[13] Gupta, A., Singh, A., Verma, V., Mondal, A. K., & Gupta, M. K. (2020). Developments and clinical evaluations of robotic exoskeleton technology for human upper-limb rehabilitation. Advanced Robotics, 34(15), 1023–1040. https://doi.org/10.1080/01691864.2020.1749926

[14] Zou, Y., Guo, D., Yang, B., Zhou, L., Lin, P., Wang, J., Chen, X., & Wang, S. (2021). Toward High-Performance Lithium–Sulfur Batteries: Efficient Anchoring and Catalytic Conversion of Polysulfides Using P-Doped Carbon Foam. ACS Applied Materials & Interfaces, 13(42), 50093–50100. https://doi.org/10.1021/acsami.1c16551

[15] Tran, M., Gabert, L., Cempini, M., & Lenzi, T. (2019). A Lightweight, Efficient Fully Powered Knee Prosthesis with Actively Variable Transmission. IEEE Robotics and Automation Letters, 4(2), 1186–1193. https://doi.org/10.1109/LRA.2019.2892204

[16] F3527 Standard Guide for Assessing Risks Related to Implementation of Exoskeletons in Task-Specific Environments. (2021). https://doi.org/10.1520/F3527-21

[17] The Essential Guide to selecting batteries for robotics- Manly Battery. MANLY. (2023, June 2). https://manlybattery.com/the-essential-guide-to-selecting-batteries-for-robotics/

[18] Batteries for Electric Vehicles. Alternative Fuels Data Center: Batteries for Electric Vehicles. (n.d.). https://afdc.energy.gov/vehicles/electric-batteries#:~:text=Lithium%2DIon%20Batteries,-Lithium%2Dion%20batteries&text=They%20also%20have%20a%20high,a%20challenge%20for%20the%20industry.

[19] "Convection Heat Transfer," Mechatronics Heat Transfer Library, http://www.mhtl.uwaterloo.ca/courses/ece309_mechatronics/lectures/pdffiles/ach6_web.pdf

[20] P. Evans, "Properties of Air at atmospheric pressure - The Engineering Mindset," The Engineering Mindset, Mar. 29, 2015. https://theengineeringmindset.com/properties-of-air-at-atmospheric-pressure/

[21] IEC, "IP ratings | IEC," www.iec.ch, 2024. https://www.iec.ch/ip-ratings

[22] A. T. Turner et al, "Prosthetic forefoot and heel stiffness across consecutive foot stiffness categories and sizes," PLoS One, vol. 17, (5), 2022. Available: https://libproxy.nau.edu/login?url=https://www.proquest.com/scholarly-journals/prosthetic-forefoot-heel-stiffness-across/docview/2686245744/se-2. DOI: https://doi.org/10.1371/journal.pone.0268136

[23] Caputo, Joshua M. PhD; Dvorak, Evan MS; Shipley, Kate CP; Miknevich, Mary Ann MD; Adamczyk, Peter G. PhD; Collins, Steven H. PhD. Robotic Emulation of Candidate Prosthetic Foot Designs May Enable Efficient, Evidence-Based, and Individualized Prescriptions. Journal of Prosthetics and Orthotics 34(4):p 202-212, October 2022. | DOI: 10.1097/JPO.0000000000000409

[24] Standard Test Method for Exoskeleton Use: Gait, 2021, https://doi.org/10.1520/f3528

[25] Zorkot, Mouhamed, et al. "G-EXOS: A wearable gait exoskeleton for Walk Assistance." Frontiers in Neurorobotics, vol. 16, 10 Nov. 2022, https://doi.org/10.3389/fnbot.2022.939241.

[26] Kleipool, Roeland P., et al. "The Mechanical Functionality of the EXO-L Ankle Brace." American Journal of Sports Medicine, vol. 44, no. 1, Jan. 2016, pp. 171–76. EBSCOhost, research.ebsco.com/linkprocessor/plink?id=734bd840-712f-3d8d-99a4-4ce5d14fe723.

[27] Benjamin C. Conner, Michael H. Schwartz, Zachary F. Lerner, Pilot evaluation of changes in motor control after wearable robotic resistance training in children with cerebral palsy, Journal of Biomechanics, Volume 126, 2021, 110601, ISSN 0021-9290, https://doi.org/10.1016/j.jbiomech.2021.110601.

[28] Harvey, Taryn A., et al. "Does ankle exoskeleton assistance impair stability during walking in individuals with cerebral palsy?" Annals of Biomedical Engineering, vol. 49, no. 9, 29 June 2021, pp. 2522–2532, https://doi.org/10.1007/s10439-021-02822-y.

[29] F3323 Standard Terminology for Exoskeletons and Exosuits. (2024). https://doi.org/10.1520/F3323-24

[30] F3474 Standard Practice for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics. (2020). https://doi.org/10.1520/F3474-20

[31] Canete, S., Wilson, E. B., & Jacobs, D. A. (2023). Neural Systems and Rehabilitation Engineering, IEEE Transactions on (Vol. 31, pp. 474–483). IEEE. https://doi.org/10.1109/TNSRE.2022.3226766

[32] Y. A. Çengel and M. A. Boles, "Step by Step Solution," Vaia, 2024. https://www.vaia.com/en-us/textbooks/physics/thermodynamics-an-engineering-approach-8-edition/chapter-2/problem-58-consider-an-electric-motor-with-a-shaft-power-out/

[33] P. Evans, "Properties of Air at atmospheric pressure - The Engineering Mindset," The Engineering Mindset, Mar. 29, 2015. https://theengineeringmindset.com/properties-of-air-at-atmospheric-pressure/

[34] "Electric Motor Output Power | How to measure the power output of an electric motor," www.futek.com. https://www.futek.com/Electric-Motor-Output-Power

[35] "Convection Heat Transfer," Mechatronics Heat Transfer Library, http://www.mhtl.uwaterloo.ca/courses/ece309_mechatronics/lectures/pdffiles/ach6_web.pdf

12 APPENDICES

12.1 Appendix A: Figure Models

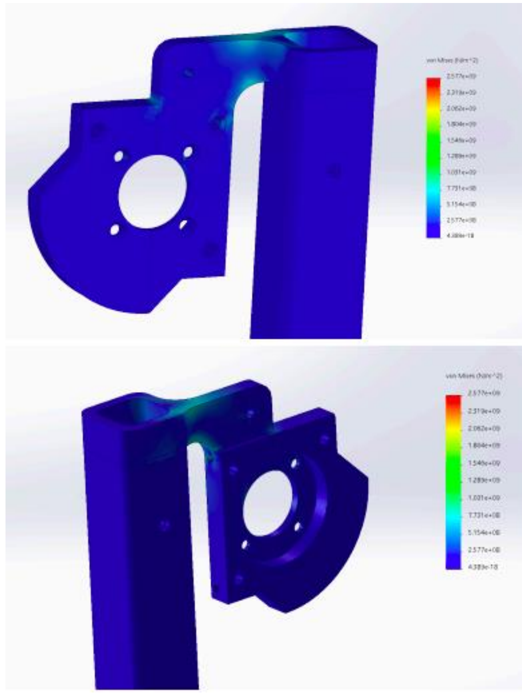


Figure A - 1 Visuals of the FEA applied to the motor mounts with known variables

This FEA analysis shows us our weak points within the design. We can use this new information to help us determine what we as a team need to do to better strengthen our design.

Figure A - 2: Assembly of our initial prototype

Figure A-2 is our completed assembly with the PCB/ Battery compartment mounted onto the Spark Plug Exo-skeleton design.

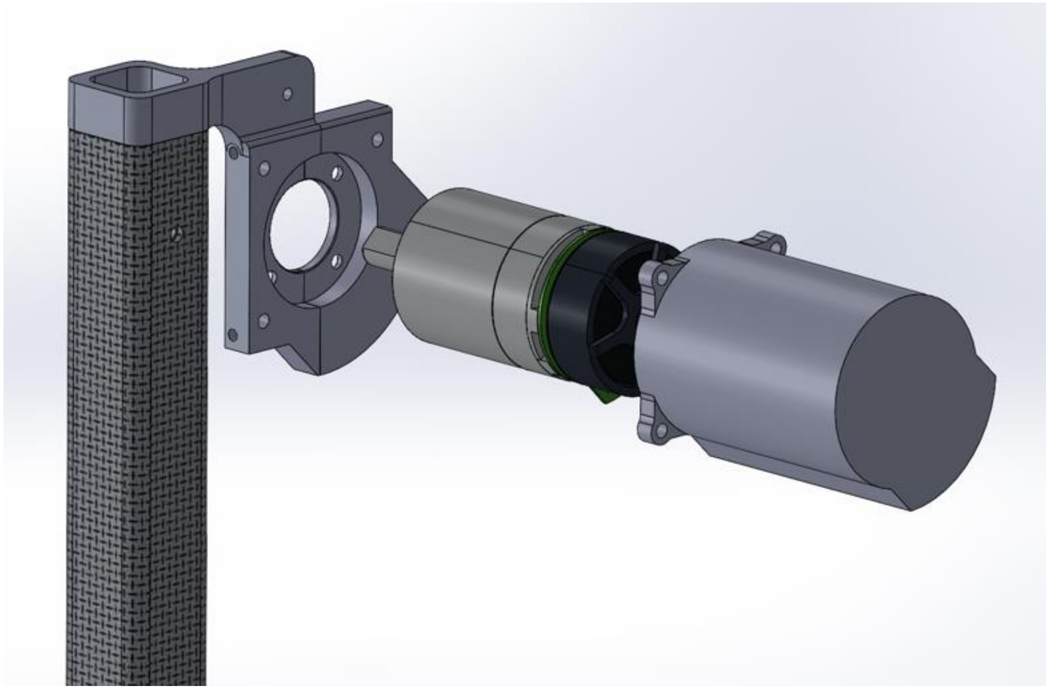


Figure A - 3: Assembly of our motor mount and protective covering

Figure A-3 is our assembly with the aluminum cover over the new motor. This cover is supposed to protect the motor from impact, abrasion, and foreign material, and thermally protect it as well. A heat sync will be mounted onto the flat end of the cover with a small DC fan.

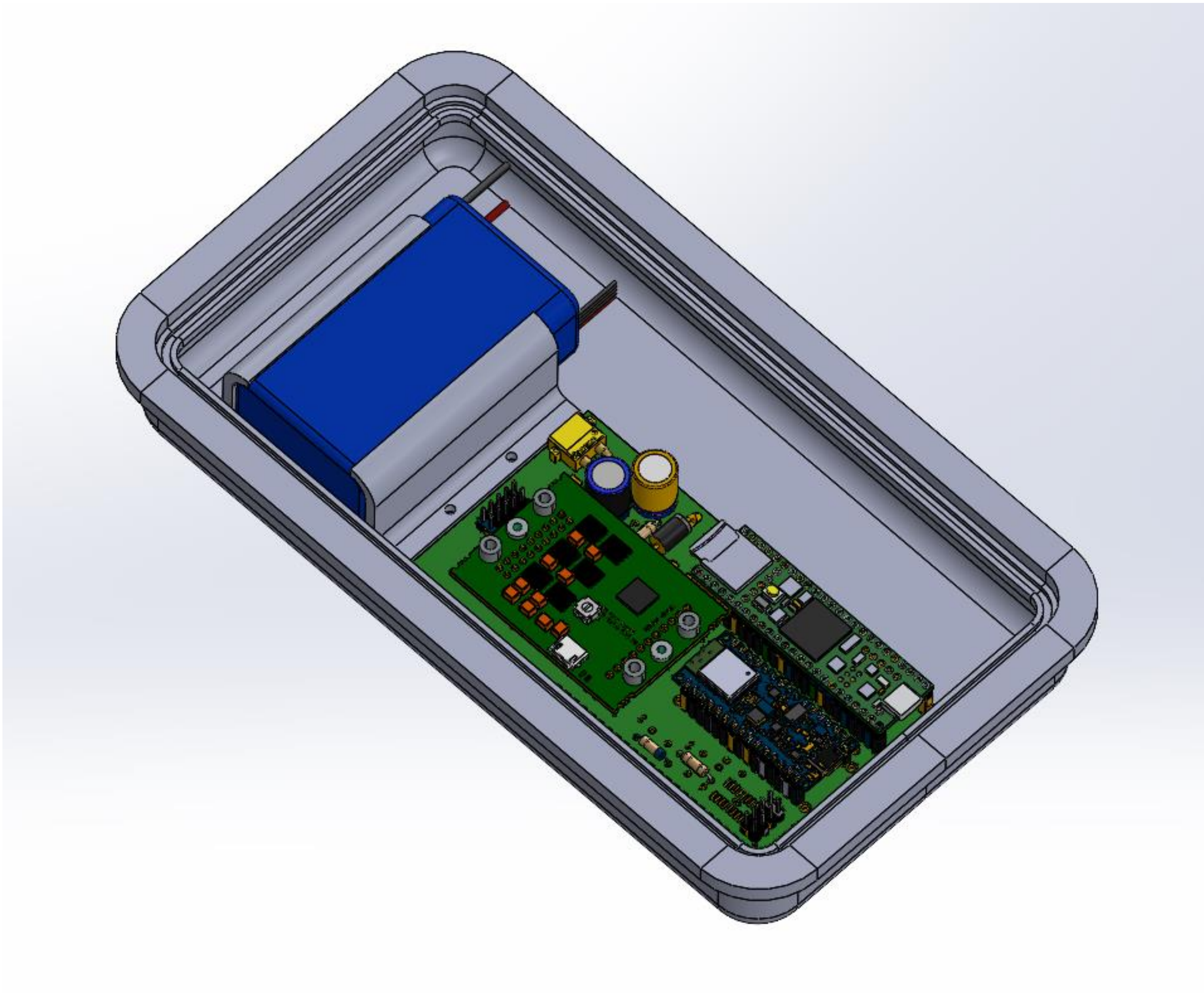


Figure A - 4 Assembly of our Battery/ PCB Protective Covering

Figure A-4 is our PCB/ Battery Compartment. This is to show just how each piece will fit into the compartment and give room for the wires that will be running through here and to the battery.

12.2 Appendix B: Table/Equation Models

Part:	Cost:	Materials:	Purchased or Manufactured:	Vender:	Part #:	Lead Time/ Part Statues:
8mm Steel Ball Bearing	Donated	-	Provided by Client	McMaster	49DD43	On Hand
Medium-Strength Steel Nylon	Donated	-	Provided by Client	McMaster	38DA12	On Hand
Stainless Steel Button Head Torque Screws	Donated	-	Provided by Client	McMaster	49DD88	On Hand
Alloy Steel Socket Head Screw	Donated	-	Provided by Client	McMaster	38DH71	On Hand
Big Gear Modified	Donated	-	Provided by Client	N/A	811X86	On Hand
Bondable Flex Circuit	Donated	-	Provided by Client	McMaster	5GUD5	On Hand
Bracket Bolt	Donated	-	Provided by Client	McMaster	5KY28	On Hand
Cable Chain Interface	Donated	-	Provided by Client	McMaster	808A65	On Hand
Cable Crimp	Donated	-	Provided by Client	McMaster	16X825	On Hand
Clearance Cable	Donated	-	Provided by Client	McMaster	38DH70	On Hand
Cover Bolt	Donated	-	Provided by Client	McMaster	811X86	On Hand
Cuff Locknut	Donated	-	Provided by Client	N/A	38DH70	On Hand
E-flite - EFLB910	53.29	N/A	Purchased	Prop Shop Hobbies	EFLB9106S30	Arrived
FSR Sensor	Donated	-	Provided by Client	McMaster	FSR01CE	On Hand
Inner Link clamp	Donated	-	Provided by Client	McMaster	B1293497	On Hand
M3 Nut	Donated	-	Provided by Client	McMaster	6CA66	On Hand
Motor Cover Cable Clamp	Donated	-	Provided by Client	McMaster	6CE47	On Hand
Motor Cover	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Manufactored
Maxon Motor	599.91	N/A	Purchased	Maxon	B7FFC8204F6C	On Hand
Outer Link clamp	Donated	-	Provided by Client	N/A	811YK3	On Hand
PCB Housing	518.5	PLA Carbon Fiber Filament	Manufactured	Markforged	F-FG-0005	Arrived
PCB	Donated	-	Provided by Client	N/A	N/A	On Hand
Pogo Pin Connector	Donated	-	Provided by Client	McMaster	B1293497	On Hand
Pulley w/ Washer	Donated	-	Provided by Client	McMaster	4EFZ9	On Hand
Quick Connect Footplate	Donated	-	Provided by Client	McMaster	811YK3	On Hand
Roller Chain	Donated	-	Provided by Client	McMaster	2TAA1	On Hand
Motor Motor - Upright	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Manufactored
Motor Mount - leaf	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Manufactored
STTR Upright	Donated	-	Provided by Client	CarbonParts	6CA66	On Hand
Slider Spacer	Donated	-	Provided by Client	N/A	6CE47	On Hand
Small Motor Cover Cable Clamp	Donated	-	Provided by Client	McMaster	811X87	On Hand
Calf Cuff Adjuster	Donated	-	Provided by Client	McMaster	826K20	On Hand
Strain Gage	Donated	-	Provided by Client	McMaster	38CZ28	On Hand
Terminal Pads	Donated	-	Provided by Client	McMaster	1MVP8	On Hand
Motor O-ring	16.91	Fluorine Rubber	Purchased	Amazon	38DE72	Arrived
PCB Housing O-ring	16.9	Rubber	Purchased	Amazon	26LG26	Arrived
Torque Sensor Quick Connect	Donated	-	Provided by Client	N/A	808A65	On Hand
M3 25mm w/ Bolt	Donated	-	Provided by Client	McMaster	38CV95	On Hand
M5 12mm w/ Bolt	Donated	-	Provided by Client	McMaster	5KY28	On Hand
Motor Bracket	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Manufactored
motor cap	254.97	PLA Carbon Fiber Filament	Manufactured	Markforged	F-MF-0001	Arrived
Cuff assembly	Donated	-	Provided by Client	N/A	N/A	On Hand
All Other screws	Donated	-	Provided by Client	McMaster	N/A	On Hand
Hi-temp Gasket	12.97	-	Purchased	Tractor supply	I21744599	Arrived
Flanged Ball Bearing	41.44	-	Purchased	McMaster	148-2Z	Arrived

Table A - 1 Bill of Materials

Since our project is operating on a previous design, we are being provided most of these parts. We decided to add them because even though we do not plan on buying these parts, they are still going to be a part of our final build.