Below the Knee Exoskeleton

Team:
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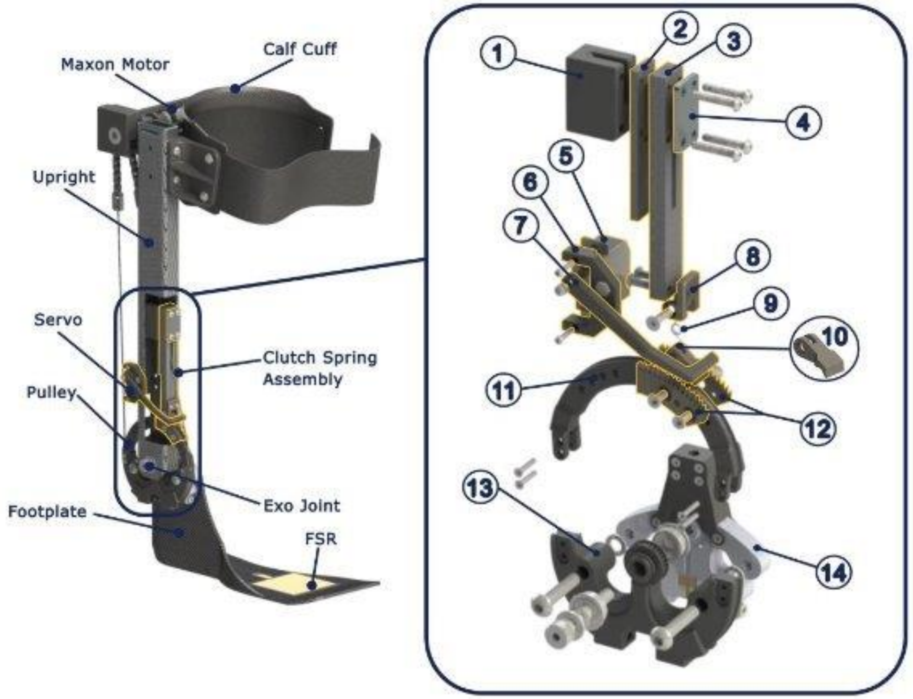
NAU NORTHERN ARIZONA UNIVERSITY

Project Description

Goal:

Change existing design to encompass the following items completely below the knee rather than on the waist

- Battery selection
- Cover and ingress protection design
- Motor evaluation and mounting hardware design.



Our Client:

•Prof Zach Lerner, head of Biomechatronic Lab. They develop lightweight wearable robotic exoskeletons to improve the movement of people with walking impairment.
•W.L. Gore

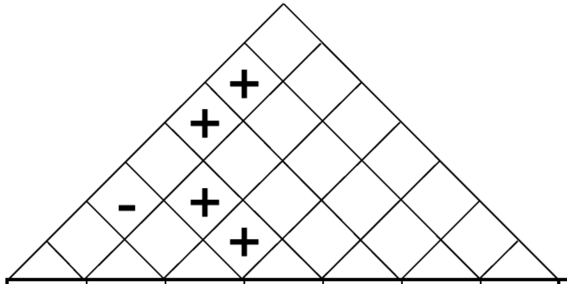
Design Requirements

CR's

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

ER's

- •ER1: Energy efficient
- •ER2: Accommodate different shoe size
- •ER3: High Torque
- •ER4: Supports users of all weight
- •ER5: Under 3 kg
- •ER6: Temperature of motor
- •ER7: Battery Capacity
- •ER8: Ingress Protection



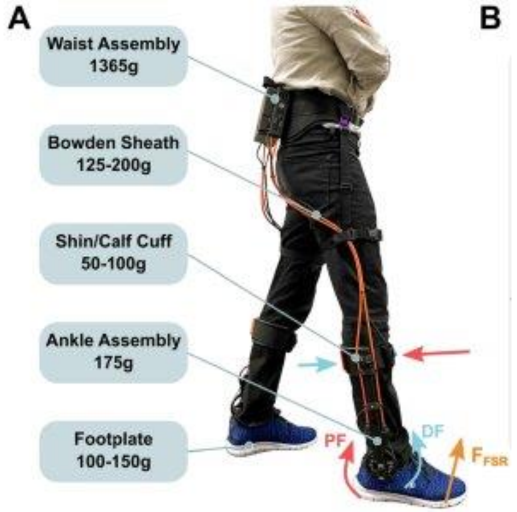
Design Requirements / Customer Requirements	Importance (1-5)	Energy efficient	Accommodate different shoe sizes	High torque	Support users of all weights	Under 3 kg	Temperature of motor	Battery Capacity	1 Worst	2	3	4	5 Best
Durable	3		3		6	6	6			C	AB		
High range of motion	5			9							B	AC	
Comfortable	4		3		3							A	
High battery life	3	9					9					B	
Adjustable	3		3		6							C	A
Lightweight	5					9						B	AC
Affordability	5							9		C	B		
Technical Importance: Absolute		27	30	45	48	63	45	45					
Technical Importance: Relative		9%	10%	15%	16%	21%	15%	15%					
Design Competitive Assessment	**Worst: 1**							B					
	2				C		B	C					
	3	AB		B		C	C						
	4			C	A	B							
	Best: 5	C	A	A		A							
Target Value		90	0.3	100	90	2	70	1000					
USL		60	0.27	150	120	3	155						
LSL		30	0.22	60	30	1.5		500					
Units		mins	m	mNm	kg	kg	C	mAh					

Improvement Direction

Customer Competitive Assessment

A	Caplex Exo
B	Utah Knee
C	ETM Motor

Background and Benchmarking



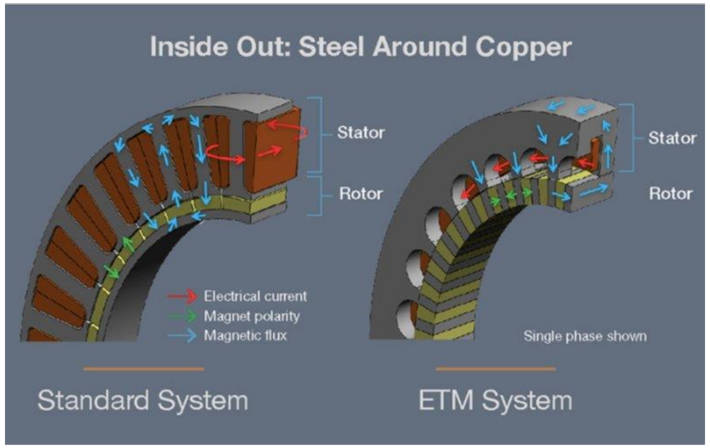
Our client wants us to revise and improve upon an already functional Ankle Exo-Skeleton. The previous design was tested of 6 test subjects which showed improvements in slower speeds but did not help in faster speed

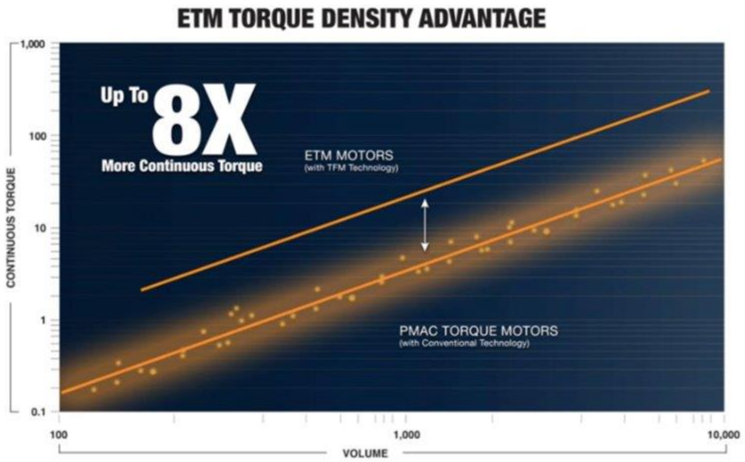
PARTICIPANT CHARACTERISTICS

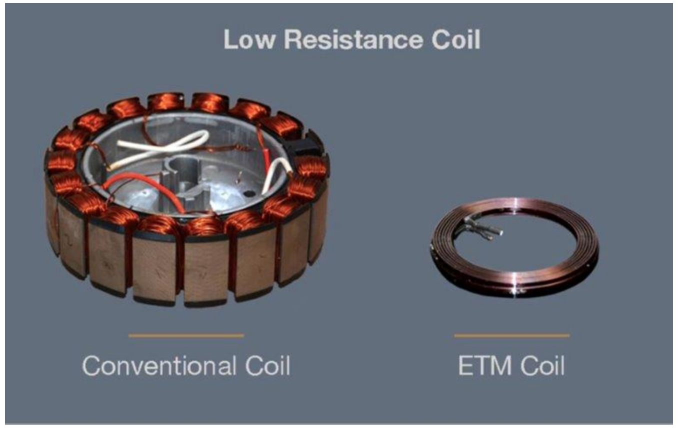
Participant	Sex	Age [years]	Mass [kg]	Peak Prescribed Torque [Nm]	No Spring vs Spring Mean Torque Difference[1] [Nm]		
					0.75 m/s	1.0 m/s	1.25 m/s
P1	F	25	50.0	15.0	0.04	0.90	0.07
P2	M	21	68.2	20.5	-0.21	-0.44	-0.08
P3	M	33	68.0	20.0	0.79	-0.35	0.95
P4	M	23	66.0	20.0	-0.04	-0.36	0.01
P5[2]	M	27	90.9	22.0	-0.92	-0.16	-0.66
P6	M	29	72.7	22.0	0.18	-0.30	0.83
Mean	**-**	**-**	**69.3**	**19.9**	**-0.03**	**-0.12**	**0.19**

Benchmarking

ETM | Electrifying Torque™







Electrifying Torque motor (ETM)is a company that has made a DC electric motor that is specific for applying torque. This Motor could improve Efficiency to our design by consuming less energy than a brush or blushless motor.

Benchmarking

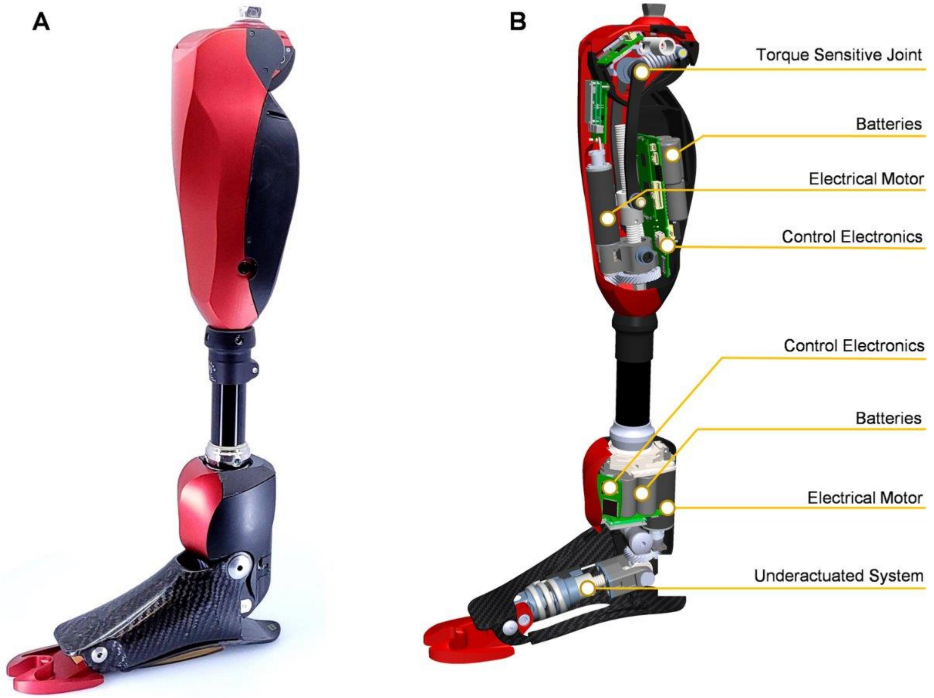
Humotech Caplex EXO-001

- Exoskeleton to assist in ankle injury recovery
- Mounts to user's shoes – adjustable for various leg & shoe sizes
- Requires a cable system to apply torque
- Max Torque: Plantarflexion: 180 Nm -Dorsiflexion: 1.5 Nm
- Standard Device weight: 1.4 kg (3 lb.)

Benchmarking

Utah Knee

- AVT system used in the Utah knee project uses adjustable transmission to meet different speed and torque needs.
- Made the prosthetic lighter and more compact. Uses a bigger DC motor connected to a 4:1 planetary gear among other design accommodations.
- Allows for reduction in motor size and requires less torque due to low mass and inertia.
- Downside: it can only change transmission levels under minimal load.
- Total weight: 1.6 kg



Literature Review

- *Proceedings of SYROM 2022 & Robotics 2022 - Chap. 23: Design of an Exoskeleton for Rehabilitation Ankle Joint*
- ➢ A motorized ankle exoskeleton was developed to aid rehabilitation by mimicking natural joint mechanics for better recovery.
- *PID Control with Intelligent Compensation for Exoskeleton Robots*
- ➢ The paper improves exoskeleton control using PID and AI-based compensation to enhance movement precision and responsiveness.
- *The design, validation, and performance evaluation of an untethered ankle exoskeleton*
- ➢ A compact, battery-powered ankle exoskeleton was tested and shown to reduce energy use and improve mobility.
- *Adaptive control strategies for lower-limb exoskeletons to assist gait*
- ➢ Real-time adaptive control techniques help exoskeletons better assist users' walking by adjusting to motion changes.
- *A New Approach of Minimizing Commutation Torque Ripple for Brushless DC Motor Based on DC–DC Converter*
- ➢ A new method using a DC–DC converter smooths out motor torque to improve exoskeleton motion control.
- *ASTM F48 Formation and Standards for Industrial Exoskeletons and Exosuits*
- ➢ ASTM F48 sets safety and performance standards for designing and using exoskeletons in industrial and healthcare applications.

Literature Review

- *Opportunities and challenges in the development of exoskeletons for locomotor assistance*
  - ➢ This article discusses current advancements and difficulties in developing effective walking-assist exoskeletons.
- *Aerospace specifications metal data sheet for Aluminum Alloy 7075 – O (ss)*
  - ➢ Material properties of Aluminum 7075–O are provided for calculating safety factors in exoskeleton motor mounts.
- *3D printing strength: How to 3D print strong parts*
  - ➢ This guide explains how infill density and pattern choices affect the strength of 3D-printed parts.
- *Introduction to SOLIDWORKS simulation - finite element analysis*
  - ➢ SOLIDWORKS FEA tools were used to analyze and ensure the strength and safety of exoskeleton motor mounts.

Literature Review

- *Kinematics and Kinetics of the Foot and Ankle during Gait*
- ➢ This article analyzes foot and ankle mechanics during the gait cycle, highlighting their importance in loadbearing and how this data informs exoskeleton design and simulation.
- *Cadaveric Gait Simulation*
- ➢ Dynamic Gait Simulation (DGS) using cadaver models offers detailed insights into foot biomechanics and helps improve exoskeleton modeling and design accuracy.
- *Developments and clinical evaluations of robotic exoskeleton technology for human upper-limb rehabilitation*
- ➢ Advancements in upper-limb exoskeletons use sensors like EEG and EMG for better joint control and feedback, though challenges remain with bulk, power, and cost.
- *Toward High-Performance Lithium–Sulfur Batteries: Efficient Anchoring and Catalytic Conversion of Polysulfides Using P-Doped Carbon Foam*
- ➢ Lithium–sulfur batteries offer high energy density and long life, with carbon-based materials improving conductivity and discharge rates for robotic applications.
- *A Lightweight, Efficient Fully Powered Knee Prosthesis with Actively Variable Transmission*
- ➢ A knee prosthesis using actively variable transmission (AVT) improves energy efficiency and reduces motor size, offering insights for weight reduction in exoskeleton design.

Literature Review

- *F3527 Standard Guide for Assessing Risks Related to Implementation of Exoskeletons in Task-Specific Environments*
  - This standard outlines risk assessment procedures for safe exoskeleton use, emphasizing compatibility with existing regulations.
- *The Essential Guide to Selecting Batteries for Robotics*
  - The article compares battery types for robotics, recommending LiFePO4 for long cycle life and stability, aligning with exoskeleton power needs.
- *Batteries for Electric Vehicles*
  - EV batteries are praised for energy efficiency and power-to-weight ratio, inspiring potential use in robotics if size constraints are addressed.
- *Convection Heat Transfer*
  - This article explains how heat transfer varies across different geometries and flow types, aiding in the thermal analysis of motor covers and PCB mounts.
- *Properties of Air at atmospheric pressure - The Engineering Mindset*
  - The article provides essential air property values like density, viscosity, and conductivity, which are critical for thermal calculations in design.
- *IP Ratings*
  - This article breaks down ingress protection (IP) standards, helping guide the waterproof and dustproof design of the exoskeleton's electronics housing.

Literature Review

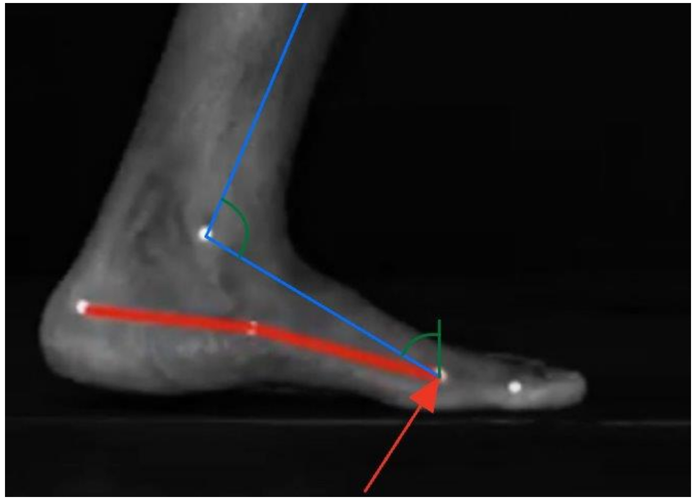
- *Prosthetic forefoot and heel stiffness across consecutive foot stiffness categories and sizes*
  - ➢ This article investigates optimal prosthetic stiffness based on user characteristics, offering insights into designing comfortable and supportive footplates for exoskeleton users.
- *Robotic Emulation of Candidate Foot Designs May Enable Efficient, Evidence-Based, and Individualized Prescriptions*
  - ➢ A robotic emulation system helps simulate prosthetic foot behavior, providing a useful method for testing and tailoring exoskeleton designs to match natural gait dynamics.
- *F3528-21 Standard Test Method for Exoskeleton Use: Gait*
  - ➢ This standard outlines specific gait-based performance and safety tests for exoskeletons used in medical, recreational, and military contexts, guiding our design evaluations.
- *G-Exos: A wearable gait exoskeleton for walk assistance*
  - ➢ This study presents an ankle exoskeleton that supports key ankle movements in stroke patients, serving as a design reference for lower limb support mechanisms.
- *The Mechanical Functionality of the EXO-L Ankle Brace*
  - ➢ The EXO-L brace selectively restricts harmful ankle motions like inversion with plantarflexion, showing how passive devices can aid in joint protection.

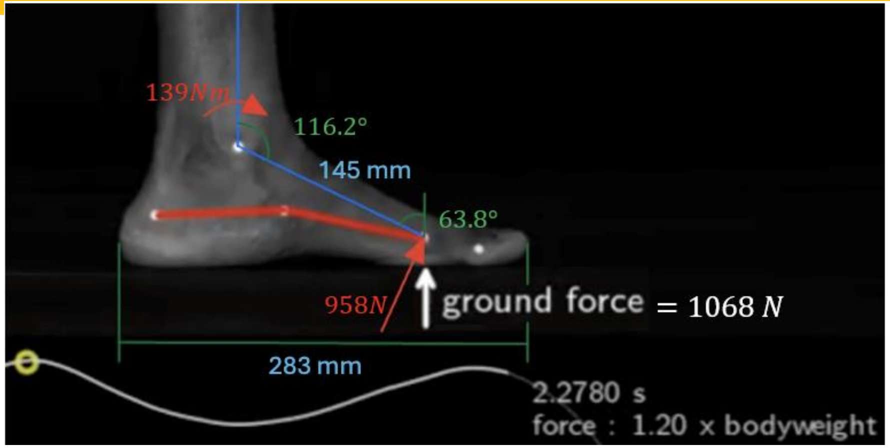
Literature Review

- *Pilot evaluation of changes in motor control after wearable robotic resistance training in children with cerebral palsy*
   - This article details earlier iterations of our device used for resistance training, not assistance, and its impact on motor control in children with CP.
- *Does Ankle Exoskeleton Assistance Impair Stability During Walking in Individuals with Cerebral Palsy?*
   - This study analyzes how an exoskeleton assisting plantarflexion affects balance and gait in users with CP, directly informing the stability aspects of our current project.
- *F3323-24 Standard Terminology for Exoskeletons and Exosuits*
   - This standard defines key terms, labeling practices, and testing language used in the field of exoskeleton development.
- *F3474-20 Standard Practice for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics*
   - This guideline provides a framework for evaluating ergonomic performance in exoskeletons, focusing on posture, joint motion, and functional assessments.
- *Ankle Exoskeleton Assistance Can Affect Step Regulation During Self-Paced Walking*
   - The article evaluates how ankle exoskeletons alter gait characteristics like step width and speed, using data from unimpaired users to study control implications.

Mathematical Modeling

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





(Yale Biomechanics and Control Lab, 2020)

Calculating the peak torque produced by the ankle

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

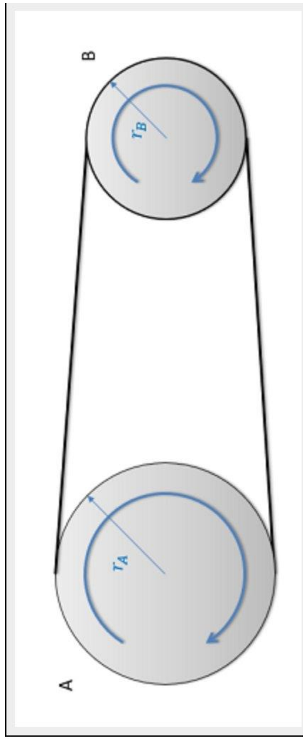
$$F = 1068\ N * \sin 63.8°$$
$$F = 958\ N$$

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

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

Mathematical Modeling

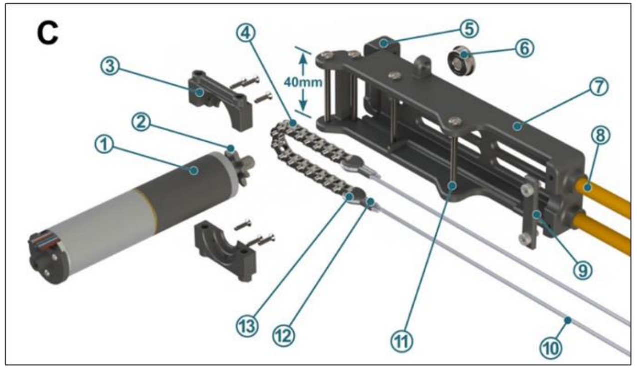
Gear Ratio and Stress at the Motor



Gear Ratio

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

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 is 139 Nm. Due to these numbers, we can assume we need a gear ratio of 38:1.



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

With the above equations 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

Mathematical Modeling

Thermal Analysis

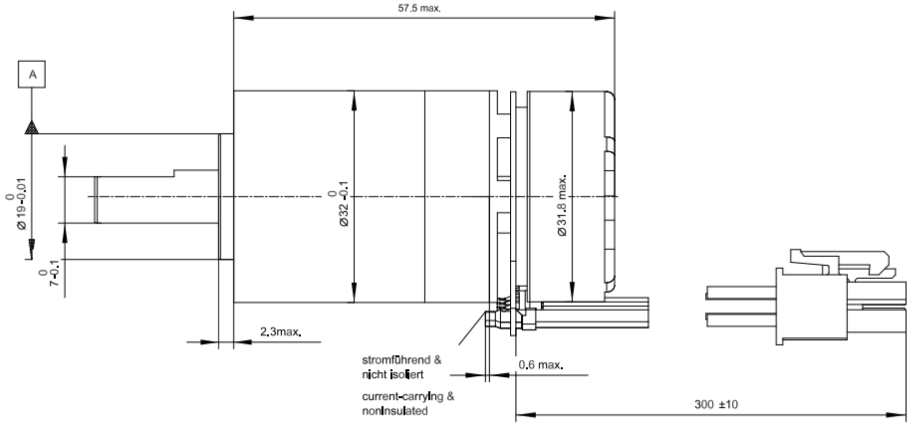
I began with a thermal analysis of the motor with no cover. Since the efficiency is 82.7%, and there is no additional materials to add resistance, rate of heat dissipation = the loss of power. This equals 11.3 W, using the below equations. Can add fins, insulation, fan. Assumptions: Nominal Speed (184.3rpm) and Torque (2811.9mNm); Aluminum; Heat transfer coefficient = 5W/m^2K

$$P_{\text{mech}} = T \cdot \omega$$

Mechanical Power
T = Torque
ω *= angular velocity*

$$P_{\text{loss}} = \frac{P_{\text{mech}}}{\eta} - P_{\text{mech}}$$

Loss of Power
η *= Efficiency*



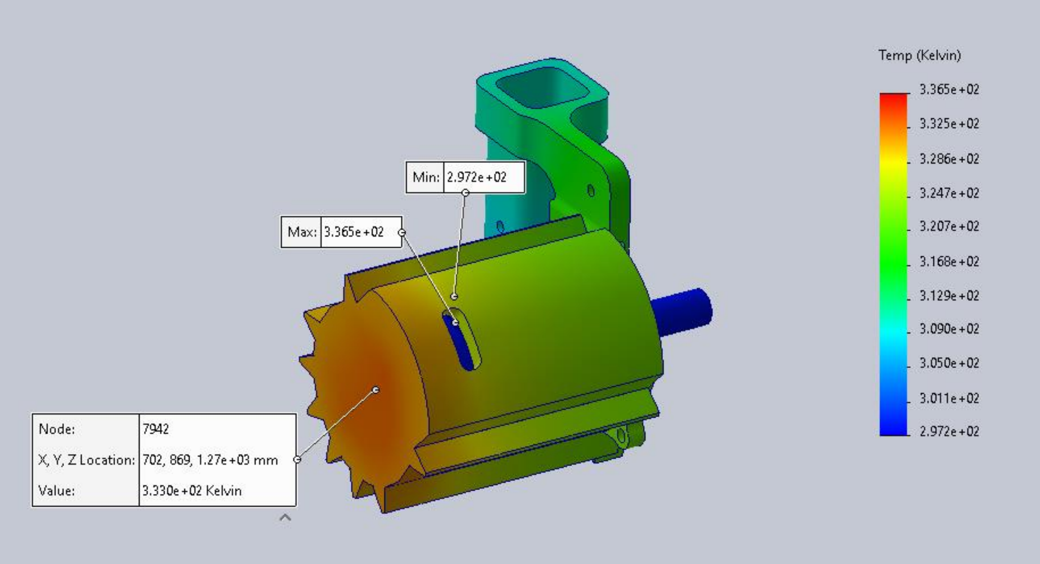
$$Q = h \cdot A \cdot (T_{\text{motor}} - T_{\text{ambient}})$$

Rate of Heat Dissipation

$$\Delta T = \frac{P_{\text{loss}}}{h \cdot A}$$

Change in Temperature
h = convective heat transfer coefficient
A = Area

Mathematical Modeling



$$Re = \frac{\rho * u * L}{\mu}$$

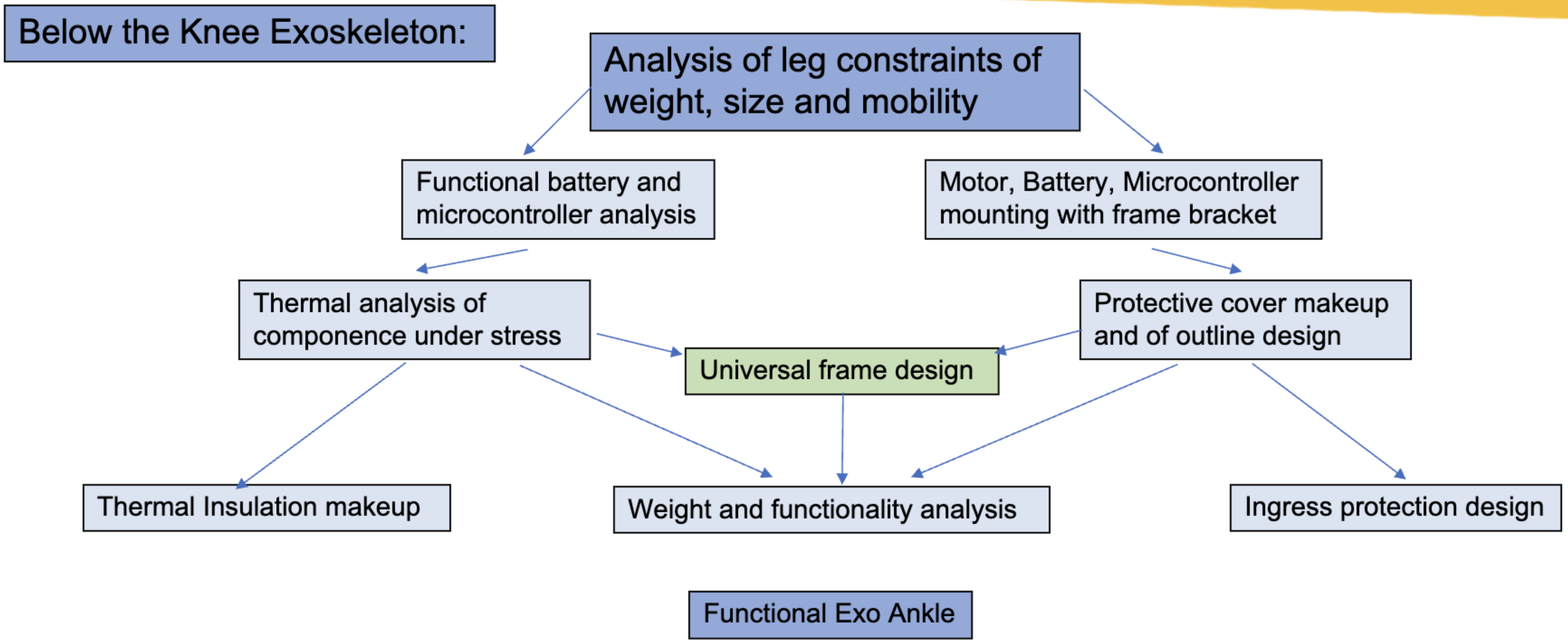
$$Nu = 0.3 + \frac{0.62 Pr^{1/3}}{[1+\left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}]^{1/4}} Re^{1/2}[1 + \left(\frac{Re}{282000}\right)^{\frac{5}{8}}]^{4/5}$$

$$h = \frac{Nu * k_{air}}{L} \qquad \omega = \frac{2\pi * RPM}{60}$$

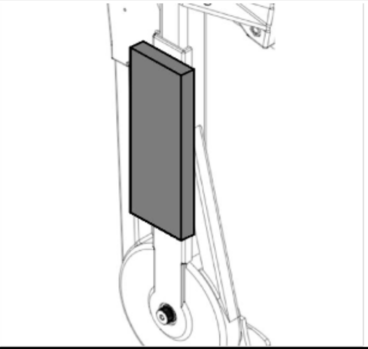
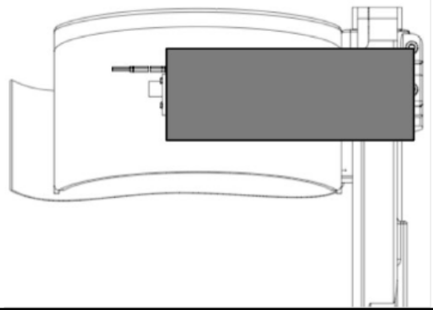
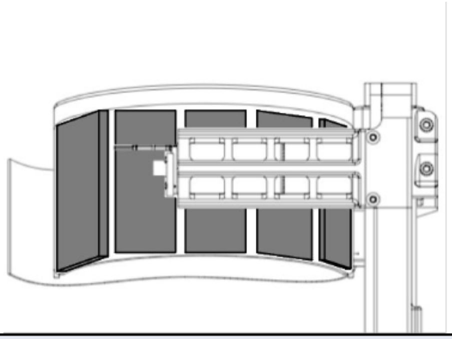
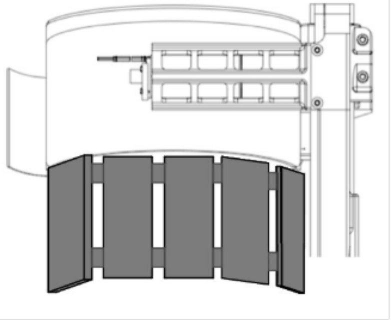
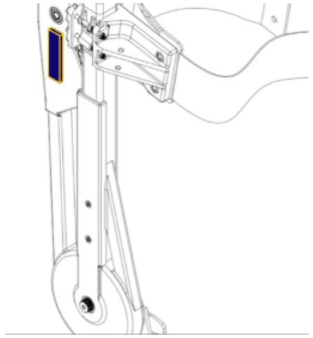
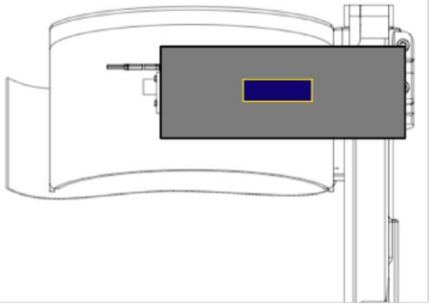
$$H_{dissipated} = P_{input} * (1 - efficiency)$$

Using the formulas to the right, I was able to calculate heat dissipation of the motor to be 10.7 W, while the actual gear box had a dissipation of 4.37 W. Assuming the above design for the motor cover, after a SolidWorks simulation, we calculated the maximum hottest temperature within the case sits at 431 K.

Functional Decomposition



Concept Generation

	1	2	3	4
Battery Placement				
Controller Placement				

Selection Criteria

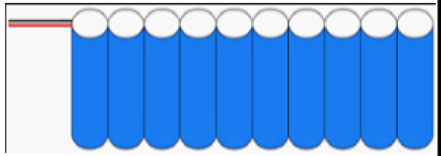
Old: EC-4pole

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 %

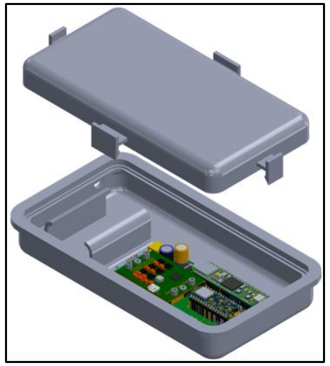
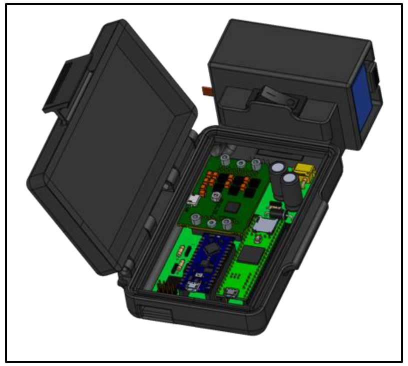
New: ECX Flat

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 %

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

Concept Selection

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

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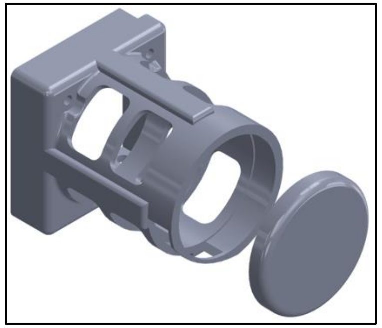
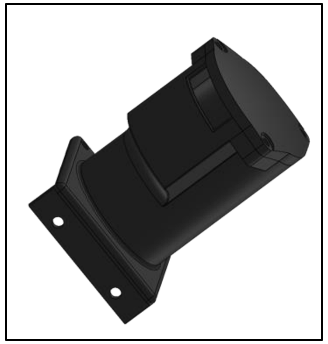
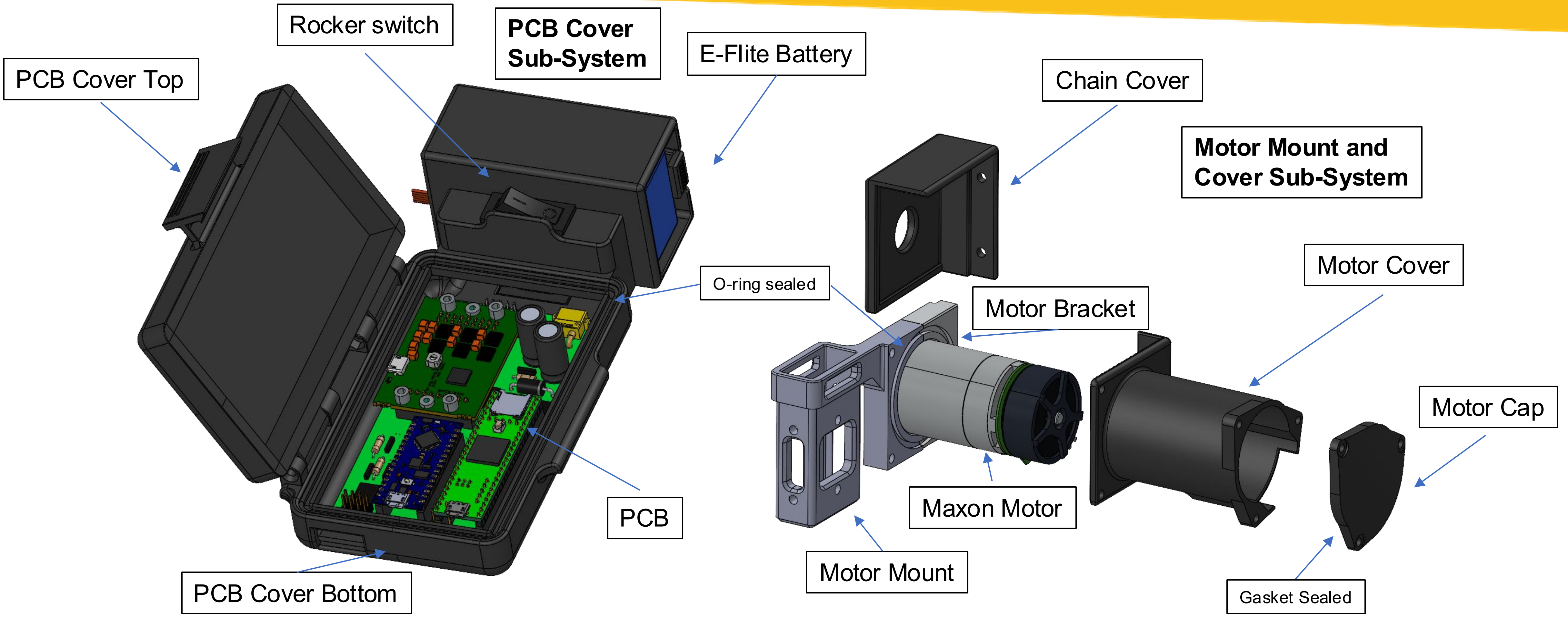
Concept Selection

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

Concept Selection



Schedule

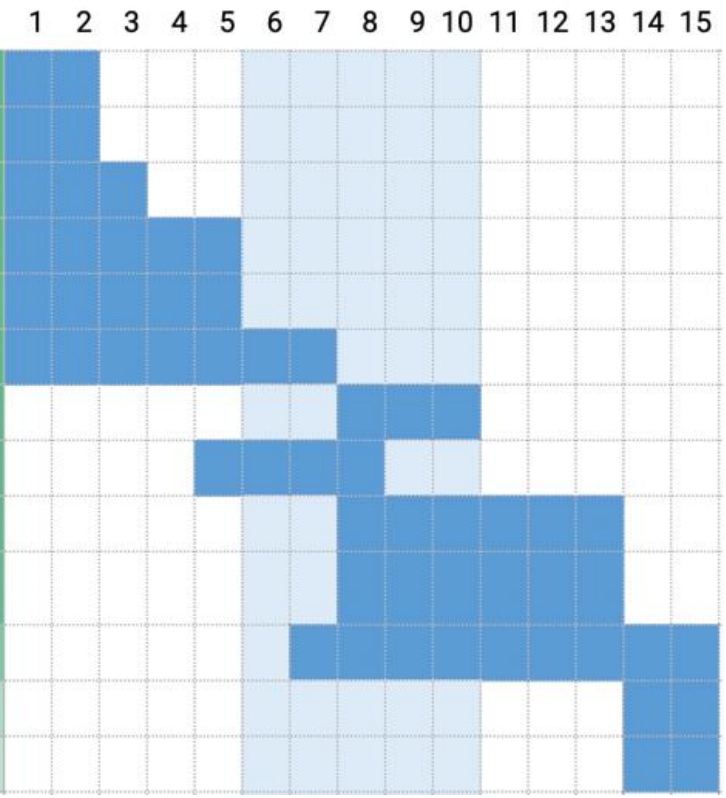
Overview of the first semester:

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	65%															
2.3	2nd Protype Demo	Alex S	10/11/24	12/4/24	53	10%															
2.4	Analysis of Prototype	Team	12/4/24	12/7/24	3	10%															
2.5	Purchase of Parts	Ryan O	10/11/24	10/26/24	15	80%															
2.6	Test 1st Prototype	Alex S	11/13/24	11/24/24	11	75%															

Schedule

Overview of the second semester:

3	Major Deadlines 2nd Semester					
WBS Number	Task Title	Task Owner	Start Date	End Date	Duration	% Done
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%



Budget

Breakdown:

Our team received 4000 dollars from our sponsored W.L. Gore. 5% of the is taken out by NAU and our own fundraising efforts have brought in 275 dollar putting up right back up to 4075 dollars.

Team	Alias	Team #	SubDept Code	Budget Liaison	Email	Primary Budget				Speedchart:
Ankle Exo		F24toSp25_AnkleExo	CP09	Ryan Oppel	rmo88@nau.edu	$ 4,000.00				2920381F25
						$ 809.17	Total Spent			
						$ 3,190.83	**Remaining Balance**			

Purchase Date	HRC #	Vendor	Description	Quantity	Order #	Tracking	Received	Picked Up	Cost	Comments
10/31/2024	Pcard	Markforged	800cc Onyx Filament Spool	1	MF-131611				$ 755.88	
			150cc Carbon Fiber CFF Spool	1						
	Pcard	Prop Shop Hobbies	E-FLIT 22.2 V30C LIPO 6CELL	1	8079				$ 53.29	

W.L. Gore Funding	+4075.00
800cc Onyx Filament	-190.87
150cc Carbon Fiber Filament	-565.01
E-Flight 22.2V battery	-53.29
Maxon ECXFL32L KL A HTQ 24V (X2)	-653.7
Total	+2612.13

The rest of our money will go to further testing and prototyping for future iterations and more carbon fiber material for protective covering.

Bill Of Materials

Parts:	Part#:
Roller Chain sprocket	Manufactured
Big Gear modified Koge	Manufactured
Foot plate	Manufactured
Pully Quick connect	Manufactured
Bridge pulley	Manufactured
PCB sensor case	Manufactured
Calf Cuff adjuster	Manufactured
Cable Cover	Manufactured
Motor Bearing Case	Manufactured
Battery Box Cover	Manufactured
C.F. Upright	Manufactured

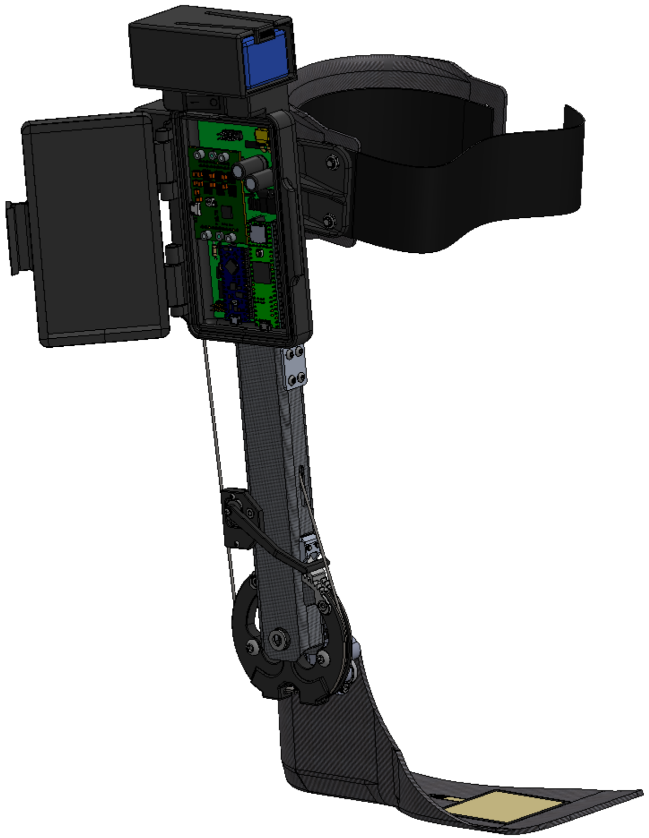
Parts:	Column1
Bondable Flex Circuit	Donated
Cable Chain Linker	Donated
Carbon Fiber square tubing	Donated
Quick Connect torque sensor	Donated
Calibration Magnet	Donated
Sensor cable	Donated
Strain Gage	Donated
Torque Sensor Wires	Donated

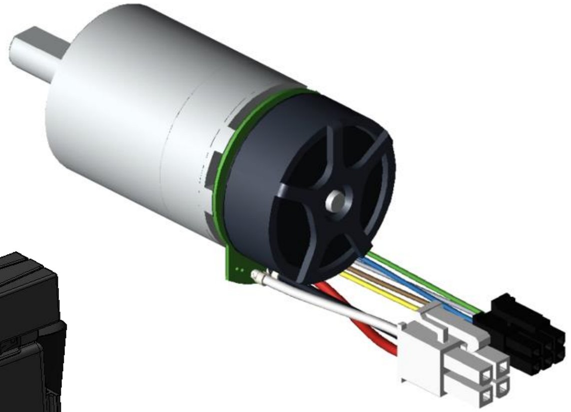
Bill Of Materials

Purchased Items:	Price
800cc Onyx Filament Spool	254.97
150cc Carbon Fiber CFF Spool	518.5
E-Flite 22.2v 910mAh li-po battery	53.29
ECXFL32L motor with a 1:35 Gear Ratio X2	599.51
Fluorine Rubber O-Rings, 42mm OD 38mm ID 2mm Width (pack of 10)	16.9
10 PCS O Rings Nitrile Rubber Round O-Rings Seal Grommets 185mm OD 181mm ID 2mm Width	16.91
SUNLU PLA 3D Printer Filament PLA Filament 1.75mm	27.27
Creality PLA Carbon Fiber Filament 1.75mm	39.28
Aluminum Brackets	75.00
Aluminum Mount	90.00
Aluminum Rachet and Picket	65.00
Aluminum Spacer	249.99
Total:	$2084.56

Parts:	Part #	Price
6mm ball bearing	49DD43	Donated
35 mm button head screw	38DA12	Donated
flanged ball bearing	49DD88	Donated
M8 Steel locknut	38DH71	Donated
M8 steel button head bolt	811X86	Donated
socket head screw	5GUD5	Donated
Hex Head drive screw	5KY28	Donated
M8 bracket bolt	808A65	Donated
Cable Crimp	16X825	Donated
6M Cuff Locknut	38DH70	Donated
FSR	FSR01CE	Donated
small linkage chain.	B1293497	Donated
M3 Nut	4EFZ9	Donated
M3 hex flat screw	811YK3	Donated
Clearance Cable	2TAA1	Donated
Pogo Pin Connector	3RWL9	Donated
M2 flat head screw	6HB56	Donated
M2 nut	6CA66	Donated
M3 sealing socket head screw	6CE47	Donated
M5 button head screw	811X87	Donated
M5 lock washer	826K20	Donated
6mm M5 shoulder screw	38CZ28	Donated
Thermal Pads	1MVP8	Donated
M3 25mm flathead screw	38DE72	Donated
M5 12mm torque screw	26LG26	Donated
M8 bolt	808A65	Donated
6mm Washer	38CV95	Donated
Total:		Donated

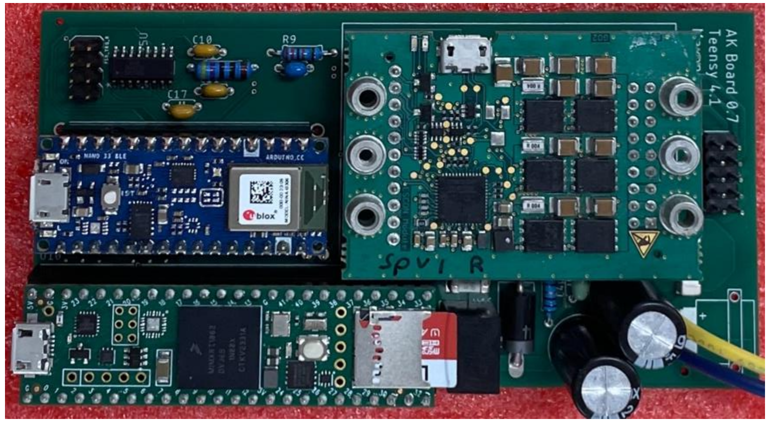
Design Description





CAD

- Motor Cover
- Motor Mount Assembly
- Ingress Protection



Design Validation

FMEA Chart:

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 protection	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

Risk trade-off pieced of our project:

most of our recommended actions consist of adding more protection or more thermal management properties, what we need to do as a team is find the balance point between making the Exo-Ankle bullet proof and light weight.

Design Validation

FMEA Chart:

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
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

Summary: most of our recommended actions are to better brace the motor, PCB, Battery and cover which will be better accessed in testing of the Ankle-Exo.

Design Validation

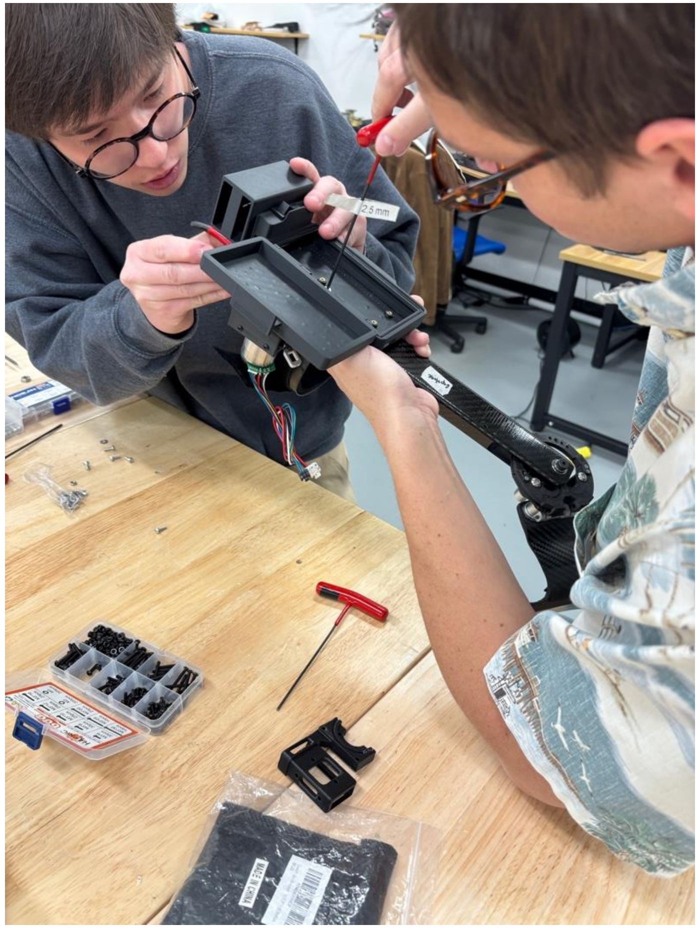
Testing Procedures:

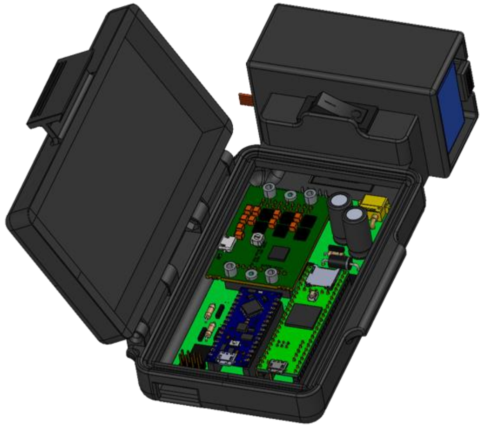
our testing procedures will be done in the robotics lab with our client Zach Lerner in a controlled area where we will be stress testing our prototypes. Once we have a successful prototype, we will then use it around campus to experiment how it handles a non-controlled environment.

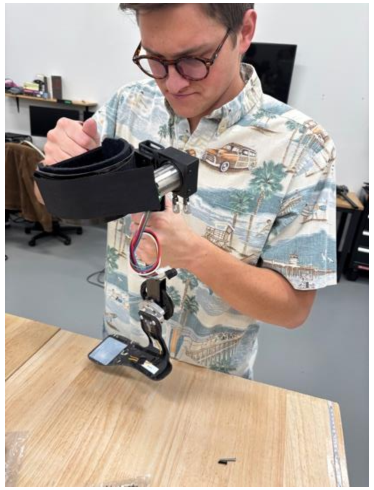
Tools needed for testing:

Zack Lerner’s PCB design is wirelessly controlled by a phone app that has a control panel that calibrates the Ankle-Exo. In the lab there is a in-ground treadmill and a stair stepper which is combined with different systems that can monitor certain variable from the user such as displaced force and fatigue. These tools will help us calibrate our Ankle-Exo and find weak spots within our design.

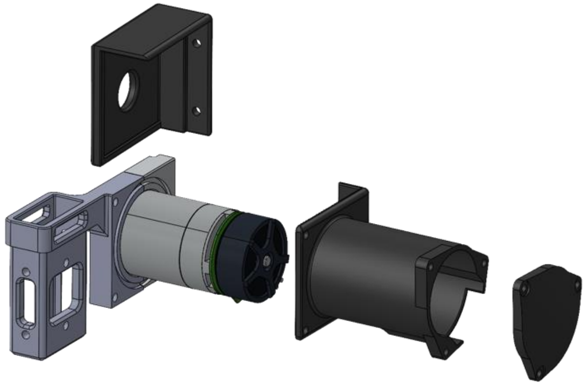
Final Hardware





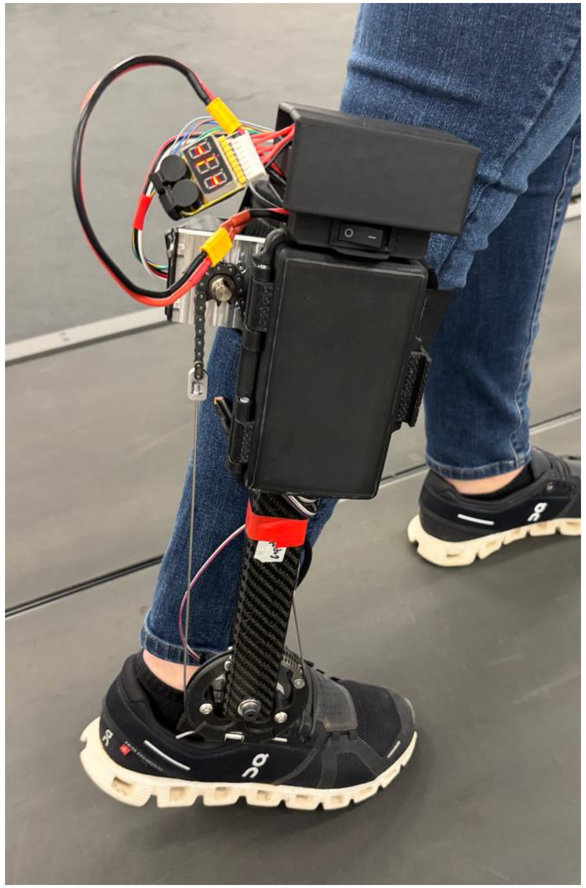


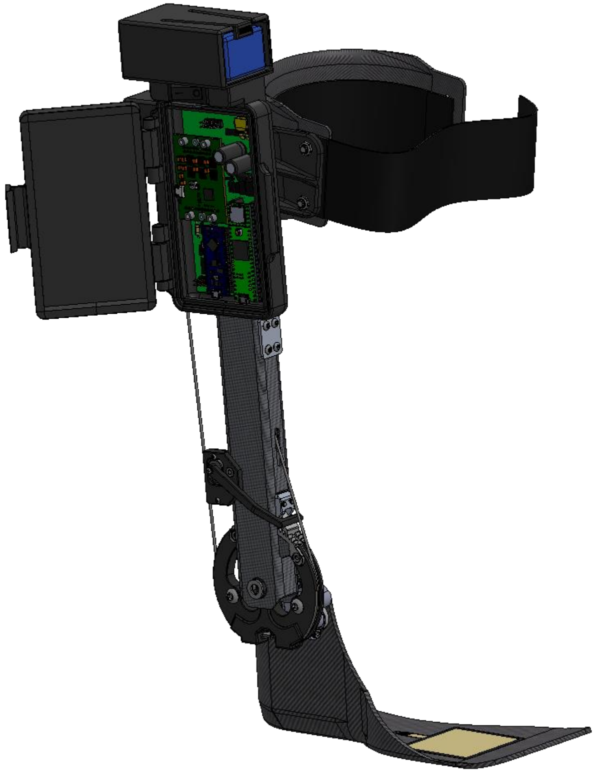
Building and Assembly of
The Exo Skeleton

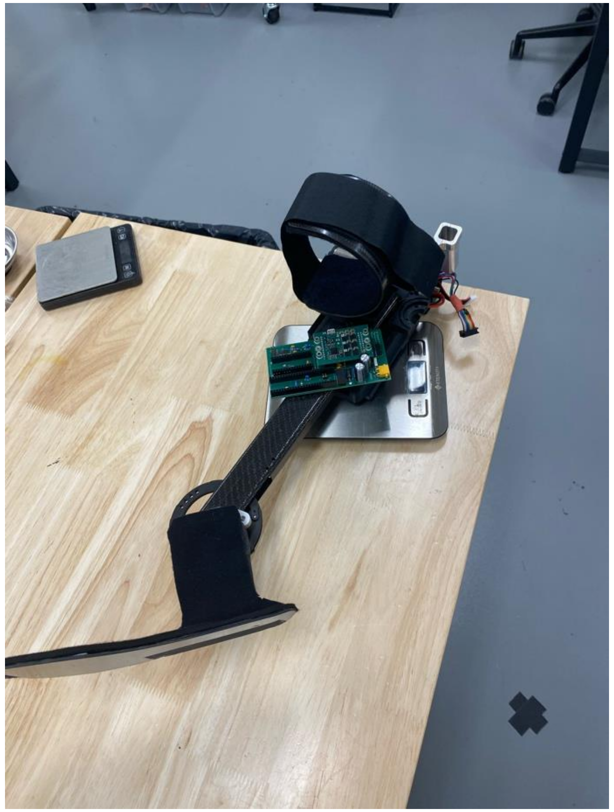


Final Hardware

Final Build of The Exo Skeleton







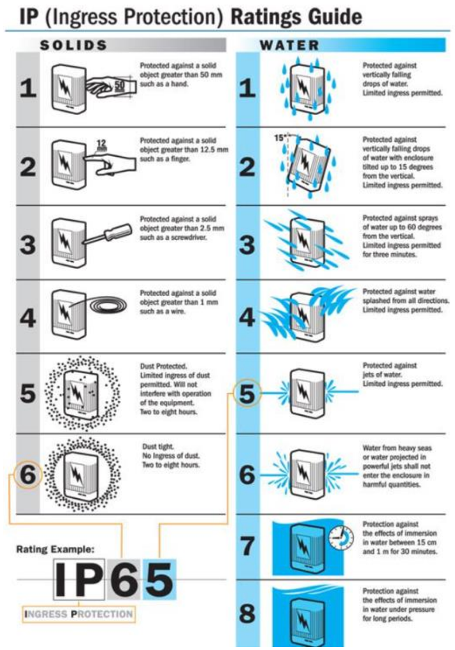
Final Testing

The patient test involved users walking with the exoskeleton on a specialized treadmill in the robotics lab. The equipment measured stride and walking path using a treadmill, a COM detection plate, and multiple cameras. We identified the benefits and limitations by comparing stride data with and without the exoskeleton.

We tested users of different sizes (50–200 lbs. men’s shoe sizes 4–10) to ensure the design was comfortable and adjustable for all.

A stress test pushed the device to its limits. We ran it outdoors multiple times until the battery drained or it operated for over an hour. This helped us measure battery life and check for overheating.

Our goal was for the device to run 20 minutes on one battery, avoid overheating, and be protected against water and outdoor elements.



Future Work

While the current design is intended for use in physical therapy, future iterations will be designed as a 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, 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 users' 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.

Thank You!