Below the Knee Exo-Skeleton

Team:

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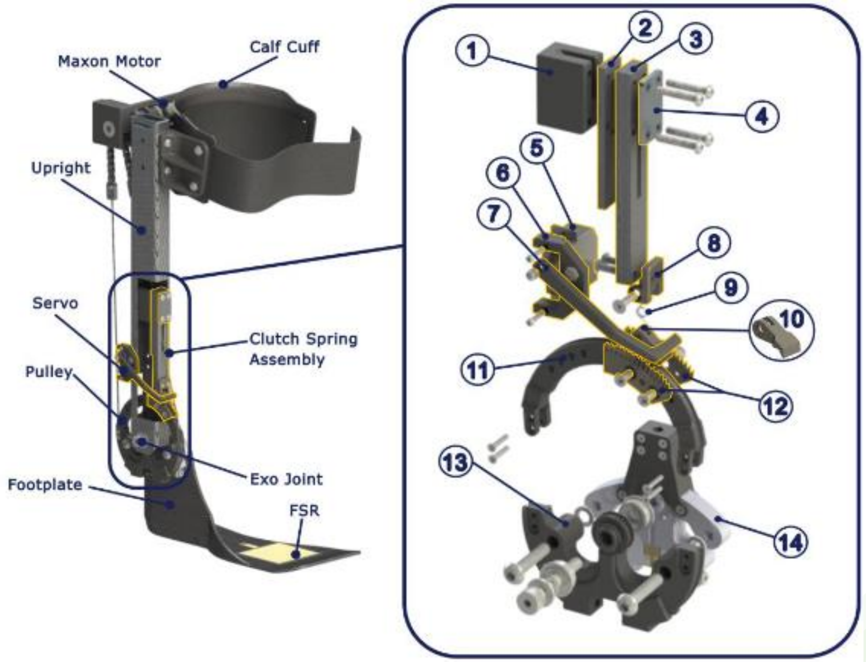
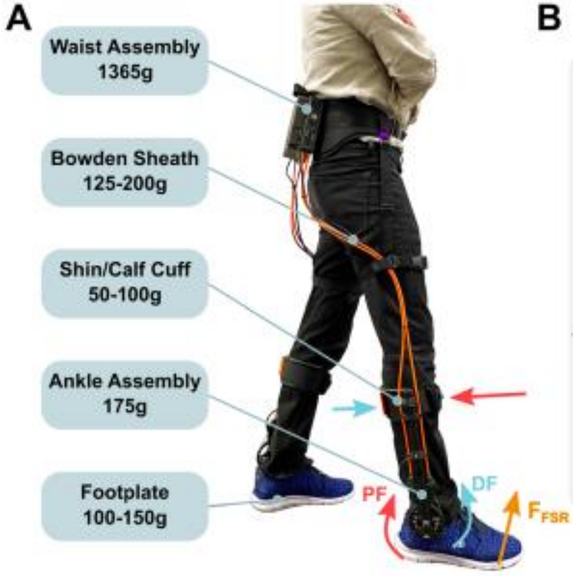
Project Description (Alex)

- The goal of our project is to revise and improve on the design of our existing ankle exoskeleton by creating an enclosed device that incorporates all design elements at the ankle. Our specific elements we will focus on is:
    - the battery
    - The cover and ingress protection design
    - Motor and evaluation of the mounting hardware design

- Our client, Prof. Zach Lerner runs the Biomechatronic Lab at NAU. They develops lightweight wearable robotic exoskeletons to improve the movement of people with walking impairment.
- The sponsor of this project is W.L. Gore.



Background and Benchmarking (Ryan)

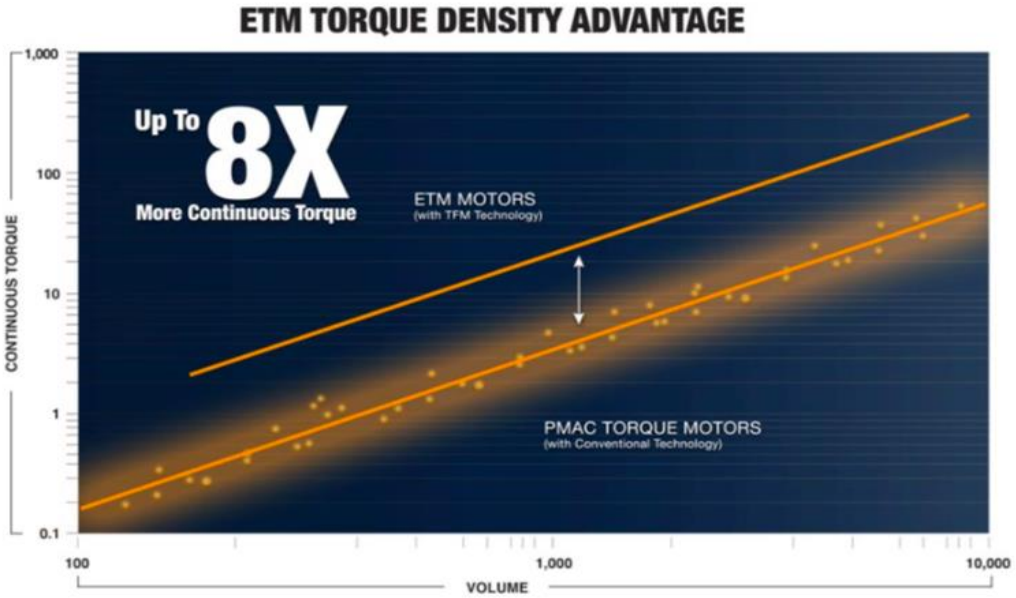


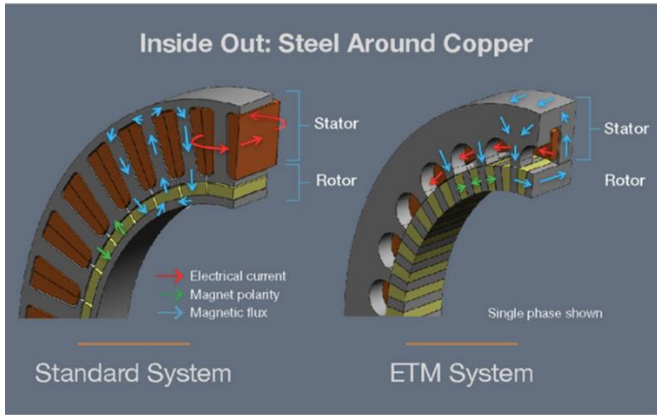
PARTICIPANT CHARACTERISTICS

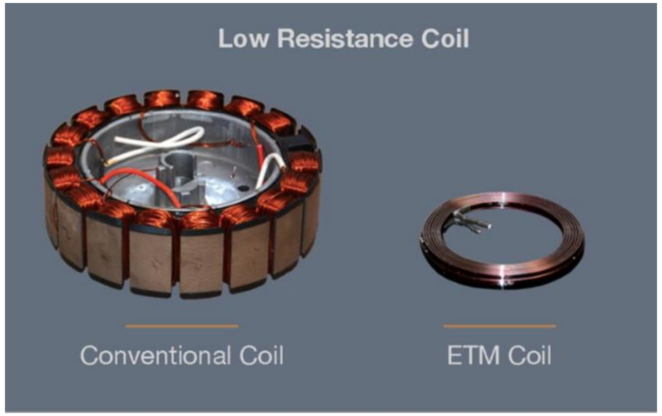
Participant	Sex	Age [years]	Mass [kg]	Peak Prescribed Torque [Nm]	No Spring vs Spring Mean Torque Difference[1] [Nm]		
					0.75 m/s	1.0 m/s	1.25 m/s
P1	F	25	50.0	15.0	0.04	0.90	0.07
P2	M	21	68.2	20.5	-0.21	-0.44	-0.08
P3	M	33	68.0	20.0	0.79	-0.35	0.95
P4	M	23	66.0	20.0	-0.04	-0.36	0.01
P5[2]	M	27	90.9	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**

- 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

ETM | Electrifying Torque™







The Motor: (Ryan)

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.

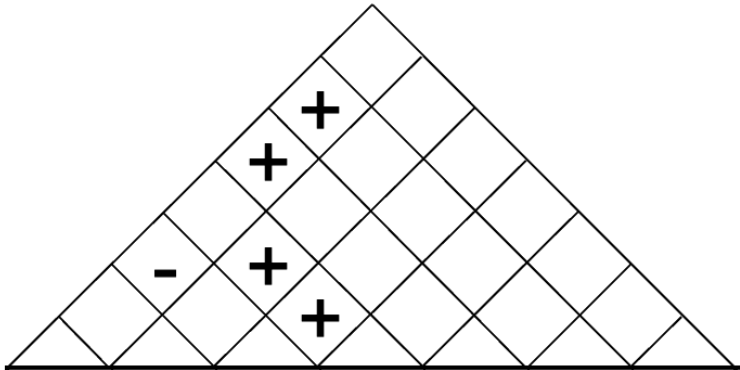
Utah Knee (Alex)

- 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

Benchmark: Humotech Caplex EXO-001(Nick)

- 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.)

Customer and Engineering Requirements (Nick)



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	Low production cost	1 Worst	2	3	4	5 Best
Improvement Direction													
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		4	0.3	70	90	2	35						
USL		8	0.27	140	120	3	70						
LSL		2	0.22	20	30	1.5							
Units		hr	m	Nm	kg	kg	C						

Customer Competitive Assessment

A	Caplex Exo
B	Utah Knee
C	ETM Motor

Research: Ryan Oppel

Proceedings of SYROM 2022 & Robotics 2022

Chap. 23: Design of an Exoskeleton for Rehabilitation Ankle Joint

- *This book focuses on the joints and the stresses each experience during movement*

PID Control with Intelligent Compensation for Exoskeleton Robots

- *This book shows the allowable range of motion in every facet an exoskeleton could be used while also providing visuals of how to build an Exo in different areas with minimal compromises to range of motion.*

The design, validation, and performance evaluation of an untethered ankle exoskeleton

- *This paper dives into the neuromuscular impairments such as cerebral palsy and how Exo-skeleton technology can be made to help These problems.*

Adaptive control strategies for lower-limb exoskeletons to assist gait

- *This paper talks about the different Strategies that a knee/ankle Exo-skeleton could implement to perform a positive force*

Research: Ryan Oppel

A New Approach of Minimizing Commutation Torque Ripple for Brushless DC Motor Based on DC–DC Converter

- *This paper talks about how brushless dc motors still suffer from commutation torque ripple, which would affect how we intend to use the motor*

ASTM F48 Formation and Standards for Industrial Exoskeletons and Exosuits

- *This paper provides an overview of a new consensus standards committee for exoskeletons, ASTM International F48, and describes the organization and current activities of this committee.*

Opportunities and challenges in the development of exoskeletons for locomotor assistance

- *This online article outlines the history, patents, developments, and challenges of Exo-skeleton technology.*

Brushless & DC Servo Motor Used in Biomedical Exoskeletons

- *This website provides lists and details of the outlines of a motor that is ideal for using within exo-skeleton technology.*

Research 2 (Alex)

- Kinematics and Kinetics of the Foot and Ankle during Gait [1]
  - Discusses role of foot, ankle, and joint in the gait, as well as the phases within the cycle of the gait and how this is considered when building braces and exoskeletons.
- Cadaveric Gait Simulation [2]
  - Outlines the way DGS can simulate the full kinetics and kinematics of gait, making it more useful for modeling walking dynamics.
- Developments and clinical evaluations of robotic exoskeleton technology for human upper-limb rehabilitation [3]
  - Exoskeleton advancements focus on improving joint control and muscle activity for rehabilitation, using EEG, EMG, and other sensors to enhance accuracy and motor stability. However, challenges remain with weight, power consumption, limited torque, bulky designs, and high costs, which hinder practical usability.
- Toward High-Performance Lithium–Sulfur Batteries: Efficient Anchoring and Catalytic Conversion of Polysulfides Using P-Doped Carbon Foam [4]
  - Discusses benefits and downsides to Lithium-Sulfur Batteries, including high energy density, good energy storage, but the insulating sulfur can limit operation.

Research 2 (Alex)

- A Lightweight, Efficient Fully Powered Knee Prosthesis With Actively Variable Transmission [5]
  - Worked to develop a lower weight fully powered prosthesis, equivalent to a passive prosthesis. Actively Variable Transmission (AVT): adjusts transmission to meet different speed and torque needs. Uses DC motor, planetary gear, leadscrew, bearings, and an incremental encoder for position feedback.
- F3527 Standard Guide for Assessing Risks Related to Implementation of Exoskeletons in Task-Specific Environments [6]
  - Highlights risk assessments that must be considered for creation of exoskeleton. Also mentions the guide to not override existing laws and regulations.
- The Essential Guide to Selecting Batteries for Robotics [7]
  - Describes usage for different types of batteries for certain necessities in robotics, including powering sensors, microprocessors, and motors. Battery must match power, voltage, and current specifications, determining that $LiFePO_4$ batteries stand out for long cycle life and reliability.
- Batteries for Electric Vehicles [8]
  - Discusses the different types of batteries used in electric vehicles, because they have high power-to-weight ratio, and high energy efficiency.

Research 3: Nick

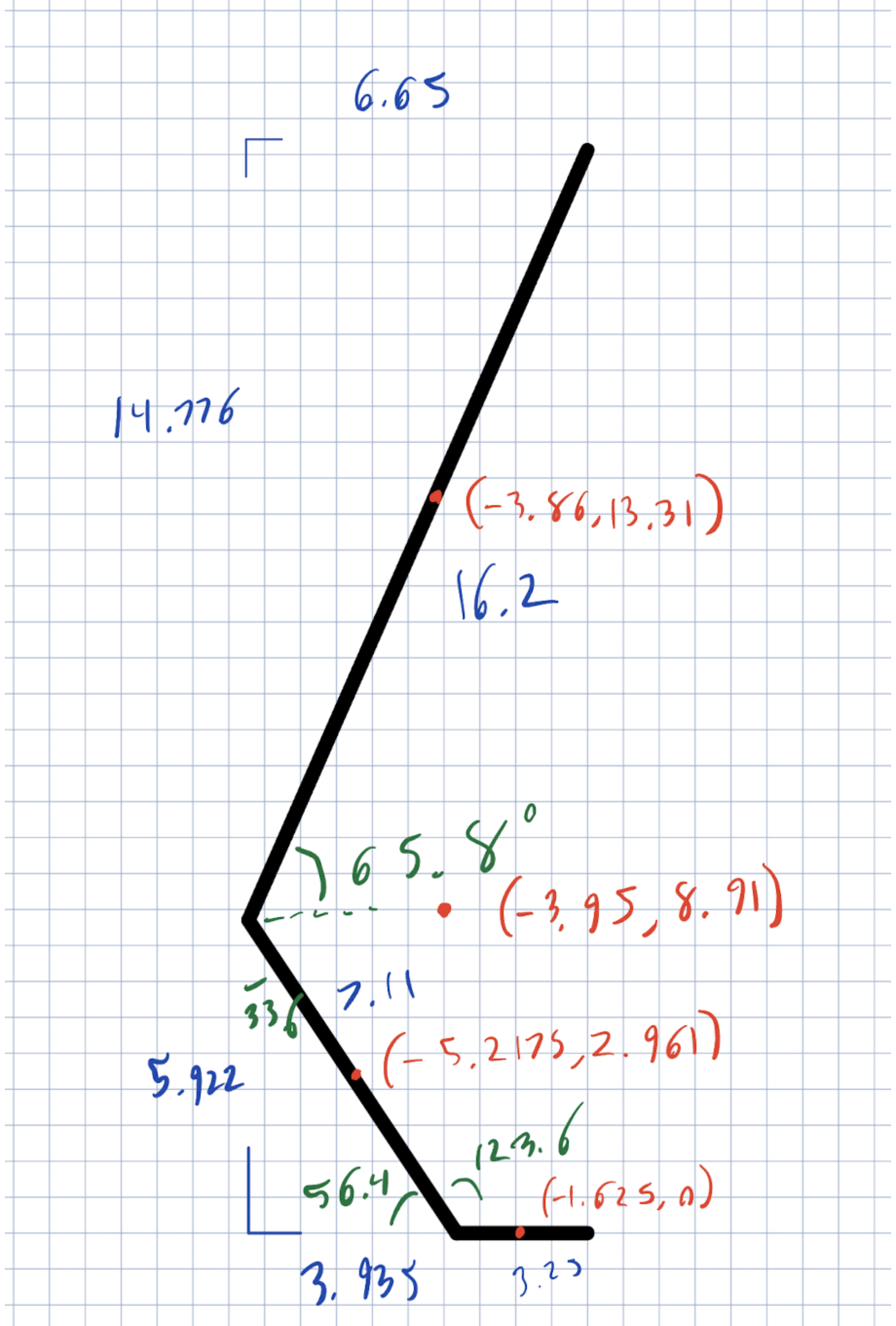
- F3528-21 Standard Test Method for Exoskeleton Use: Gait [11]
  - Outlines the methods of evaluating the safety and performance of an exoskeleton for gait
  - Exoskeleton operations include
- Robotic Emulation of Candidate Foot Designs May Enable Efficient, Evidence-Based, and Individualized Prescriptions [10]
  - Explains a system used to emulate the sensation of wearing prosthetics to aid in fitting
- Prosthetic forefoot and heel stiffness across consecutive foot stiffness categories and sizes [9]
  - Tests prosthetics to determine ideal stiffness based on the customers weight and activity level
- G-Exos: A wearable gait exoskeleton for walk assistance [12]
  - Development of a wearable exoskeleton designed to assist dorsiflexion, plantarflexion, and ankle stability

Research 3: Nick

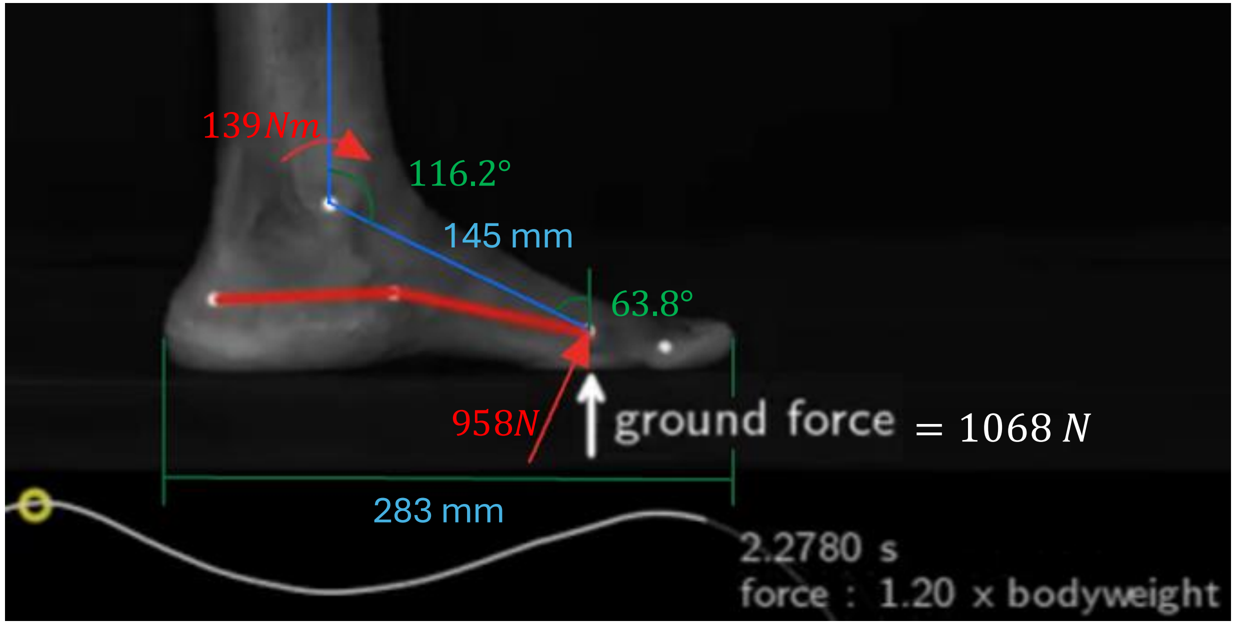
- The Mechanical Functionality of the EXO-L Ankle Brace [13]
  - Evaluates the functionality of a mechanical ankle brace that limits the motion of combined inversion and planter flexion
- Pilot evaluation of changes in motor control after wearable robotic resistance training in children with cerebral palsy [14]
  - Analyzes the effects of resistance therapy using an ankle exoskeleton
- Does Ankle Exoskeleton Assistance Impair Stability During Walking in Individuals with Cerebral Palsy? [15]
  - Assesses the impact of plantar-flexor assistance from an ankle exoskeleton during walking in individuals with CP

Center of Mass (Alex)

- Length of foot based off measurements of team's foot
- Uses:
  - Used to determine where to place payloads for exoskeleton
  - Aids in stability
  - Used to predict motion, angular velocity, P.E. and K.E. etc
  - Use assumption that the foot and ankle is 6.5% the weight of the human body
- Use Matlab to then model velocity and force of the foot at different parts of the gait
- Use of the modeling technologies provided by robotics lab



Mathematical Modeling of the foot (Nick)



(Yale Biomechanics and Control Lab, 2020)

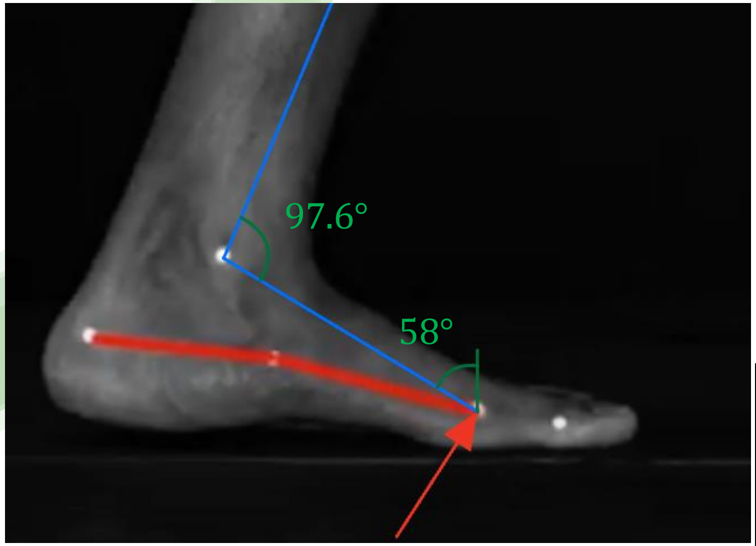
Assuming: 200 lbs (90 kgs)
Shoe size men 10.5 (283 mm)

Calculating the peak torque produced by the ankle

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

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

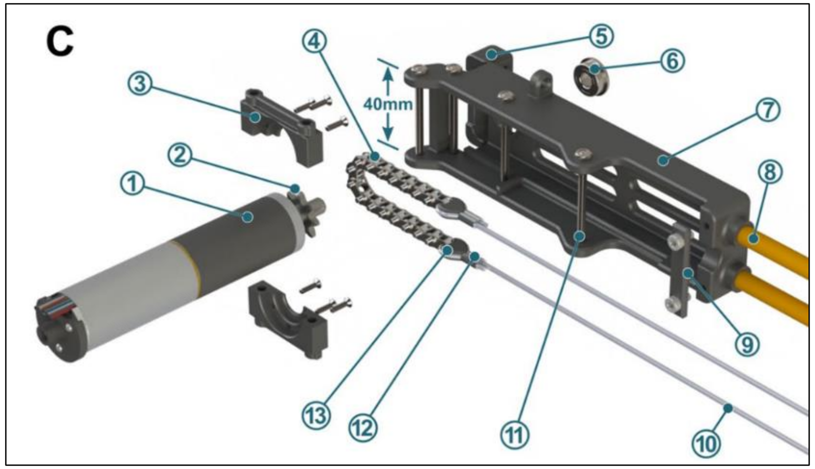
$$\tau = 958\ N * \frac{145\ mm}{1000}$$
$$\tau = 139\ Nm$$



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

Torque output by Motor (Ryan)

Since we are building upon the previous model it's important to know how much torque the original motor could apply to the previous design. Reading through the research paper of the previous design we find that they used a 90 W Maxon motor with an 89:1 gearbox.



The torque input from the motor is only 43.7 mNm. That is hooked up to a gear box with a ratio of 89:1 means that the torque output is approximately 3.7 Nm of force

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

The specs of the motor give an efficiency Rating of 88% at nominal voltage. While giving the gearbox a rough estimate of an efficiency rating of 94%. We calculate that the overall efficiency rating of the system is 82.7%

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

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

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

The previous system had an output torque of 3.7 Nm with an efficiency rating of 82.7%

$$\eta_{\text{system}} = \eta_{\text{motor}} \times \eta_{\text{gearbox}}$$

Schedule (Alex)

Below the Knee Exoskeleton

Battery Selection
- Research motor efficiency and weight requirements — By Oct 1
- Calculations for torque and power requirements — By Oct 27
- Research for battery that fits motor/torque needs — By Dec 1

Work: 20%
Budget: $400

Cover and Ingress Protection
- Research protection designs and materials — By Sept 27
- CAD model and build prototype — By Nov 1
- Test and Evaluate prototype — By Jan 15
- Redesign, rebuild, retest — By April 18

Work: 40%
Budget: $1,000

New Motor Evaluation
- Test and evaluate current motor requirements — By Oct 15
- Model drive system with new motor — By Nov 22
- CAD mounting hardware design based off motor specs — By Jan 24
- Build and test new hardware design — By March 27

Work: 40%
Budget: $1,000

Budgeting (Ryan)

Funding From W.L. Gore =	+$4000
NAU Processing Fee =	-$200
Fundraising Contribution =	+$400
Total Budget =	+$4200

Expenses:	
Tools & Prototyping:	
3_d printer Parts	$250
Filament	$50
Testing Material	$400
Parts:	
Battery	$400
Cover	$500
Hardware	$500
Motor	$1000
Total Expenses:	$3100

As of now, our rough estimate for expenses will leave us with a surplus of approximately $1,100. We are certain as a time that as we get deeper into the project, we will find some additional expected and unexpected expenses

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