Wearable Upper-Limb Robotic Arm

with Active Gravity Compensation for Stroke Rehabilitation

Presented by: Caleb Lamca · Cole Pace · Colin Donnellan · Joel Gisleskog · Kaitlyn Davis

Client

Dr. Zach Lerner
NAU Mechanical Engineering

Sponsor

W.L. Gore

NAU | Steve Sanghi College of Engineering

Background

Project Description Deliverables Success Metrics

Project Description

THE PROBLEM

Stroke is the leading cause of upper limb disability. Over 80% of survivors lose arm mobility. Clinical robotic rehabilitation devices remain prohibitively expensive and restricted to clinical settings.

OUR SOLUTION

A belt-mounted active gravity compensation mechanism with two powered joints controlling upward motion and forward reach, plus a free-moving hip hinge. Pressure sensors detect arm weight to drive brushless DC motors providing real-time gravitational assistance — enabling functional independence without muscle fatigue.

Client: Dr. Zach Lerner, NAU Mechanical Engineering

Sponsor: W.L. Gore

80%+
of stroke survivors affected

10 RPM
target operating speed

$4,000
project budget & fundraising target

Deliverables & Success Metrics

Deliverables

COURSE

- Fully designed and manufactured device with one motor functioning and accurate pressure sensing.
- Technical documentation, CAD models & engineering drawings.
- Final symposium poster and presentation.

CLIENT

- Documented analysis on each assembly part to ensure feasibility.
- Integration with OpenExo software/hardware.
- Design package for future iteration or manufacturing.

Success Metrics

1 **Speed Performance**

The device must move the user's arm at a natural speed (≥10 RPM), verified via timed motion testing.

2 **Gravitational Assistance**

Device must actively compensate gravity on the arm. Pressure sensors detect load intent; motors respond in real-time.

3 **User Comfort & Posture**

Users maintain neutral seated posture and allow their arm to rest naturally by their side during operation.

4 **Intuitive Operation**

Device must be easy to be taken on, off, and operate without extensive training.

Requirements

Customer Requirements   Engineering Requirements   House of Quality

Requirements

Customer Requirements

CR1 Comfortability
Wearable for extended periods without pressure points, skin irritation, or restricted blood flow.

CR2 Ability to Sit
Hip mechanism must not prevent the user from sitting in standard chairs.

CR3 Low Profile
Device stays close to the body, suitable for everyday environments without excess protrusion.

CR4 Accessibility
Able to be integrated into OpenExo

CR5 Durability
Withstands repeated daily use and accidental bumps typical of home environments.

Engineering Requirements

ID	Requirement	Target	Tolerance
ER1	**Degrees of Freedom**	3 DOF	±0
ER2	**Weight of Arm**	<2 kg	+0.25 kg
ER3	**Speed of Arm**	≥10 RPM	−2 RPM
ER4	**Battery Life**	30 min	±5 min
ER5	**Mfg. Cost**	<$2,000	+$250

House of Quality

Engineering Requirement	Degrees of Freedom	Manufacturing Cost	Speed of Arm	Battery Life
Degrees of Freedom				
Manufacturing Cost	neg			
Speed of Arm		neg		
Battery Life	neg	neg	pos	
Weight	neg	pos	pos	pos

Positive	pos
Negative	neg

Strong	9
Moderate	3
Weak	1

Relative Weight (%)	Customer Weights	Customer Requirments	Degrees of Freedom	Manufacturing Cost	Speed	Battery Life	Weight
			Engineering Requirements				
11	4	Comfortable	3	1	3	3	9
22	5	Ability to Sit in a Chair	9	1	1	1	1
10	2	Accessibility	3	9	3	3	3
5	3	Durabiltiy	1	1	1	1	9
22	3	Low-Profile	3	3	3	9	9
		Technical Requirement Units	N/A	$	rpm	Minutes	kg
		Technical Requirement Targets	3	<2000	>10	>30	<2

The House of Quality shows the relation between our Customer and Engineering Requirements as well as target values for the ERs.

Design Space Research

Benchmarking   Literature Review   Mathematical Modeling

Benchmarking

Three state-of-the-art upper-limb exoskeleton systems were benchmarked at the system level to inform the design of our gravity compensation mechanism.

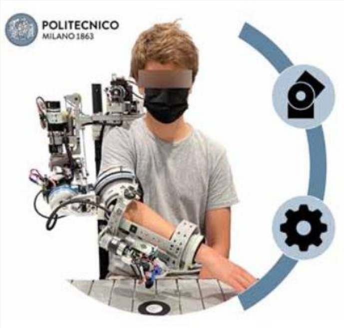


Figure 1 **Agree Exo Exoskeleton [1]**

Uses a spring-pulley antigravity system to minimize joint torque requirements, enabling lightweight passive assistance during arm elevation.

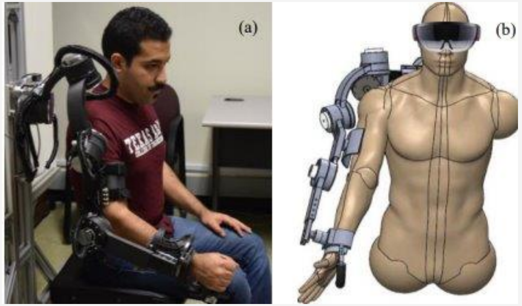


Figure 2 **CleverArm Exoskeleton [2]**

Focused on compactness and versatility, featuring 8 degrees of freedom to closely replicate the full range of natural human arm motion.

Figure 3 **ExoFlex Exoskeleton [3]**

A hybrid exoskeleton combining both rigid structural components and soft actuators, balancing support strength with user comfort and conformability.

Literature Review

References by Team Member (10+ per student)

Caleb Lamca	Cole Pace	Colin Donnellan	Kaitlyn Davis	Joel Gisleskog
S. Openshaw — Ergonomics and Design [4]	Y. Wang, W. Li — Survey on Drive Methods [9]	M.E. Morgan — Evolution of Robotic Arms [14]	X. Fan et al — Humanoid Robot Teleoperation [19]	G.A. Pratt — Series Elastic Actuators [24]
G.R. Ballee — Industrial Maintenance and Mechatronics [5]	E. Bardi, M. Gandolla — Upper Limb Robotic Wearable Devices [10]	B.-O. Lee — Robotic Arm Use for Rehabilitation [15]	K. Kruthika — Design and Development of a Robotic Arm [20]	P. Yu, W. Chen — Quasi-Direct Drive Actuation [25]
R.T. Barret — Fastener Design Manual [6]	D. Verdel — Weight Compensation with Exoskeletons [11]	ISO/TS — Robotics and Robotic Devices [16]	C. Ochieze, S. Zare — Progress in Biomedical Engineering [21]	E. Moubarak — Gravity Compensation of an Upper Extremity Exoskeleton [26]
ASME Y14.5 — GD&T Basics [7]	H. Zheng — 3D Printing Continuous Fiber Polymers [12]	A. Kojima, D.T. Tran — Mounting Position for a Robotic Arm [17]	M.A. Gull, S. Bai — Review on Upper Limb Exoskeletons [22]	F. Just et al — Human Arm Weight Compensation [27]
Lunyax — Mechanisms [8]	Q. Fang — Simplified Inverse Dynamics Modelling [13]	M.Y. Metwly — Review of Robotic Arm Joint Motors [18]	Z.-J. Chen — Exoskeleton-Assisted Anthropomorphic Movement [23]	J. Vantilt — Model-Based Control for Exoskeletons [28]

Torque Analysis

Using our target arm speed and average anthropometric measurements for an adult male, the maximum torque required to lift the arm to shoulder height was calculated by summing moments of the hip joint:

Hip Torque Equation:

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

$$\tau_{Hip} = 11.5\ \text{N·m}$$

VARIABLE DEFINITIONS

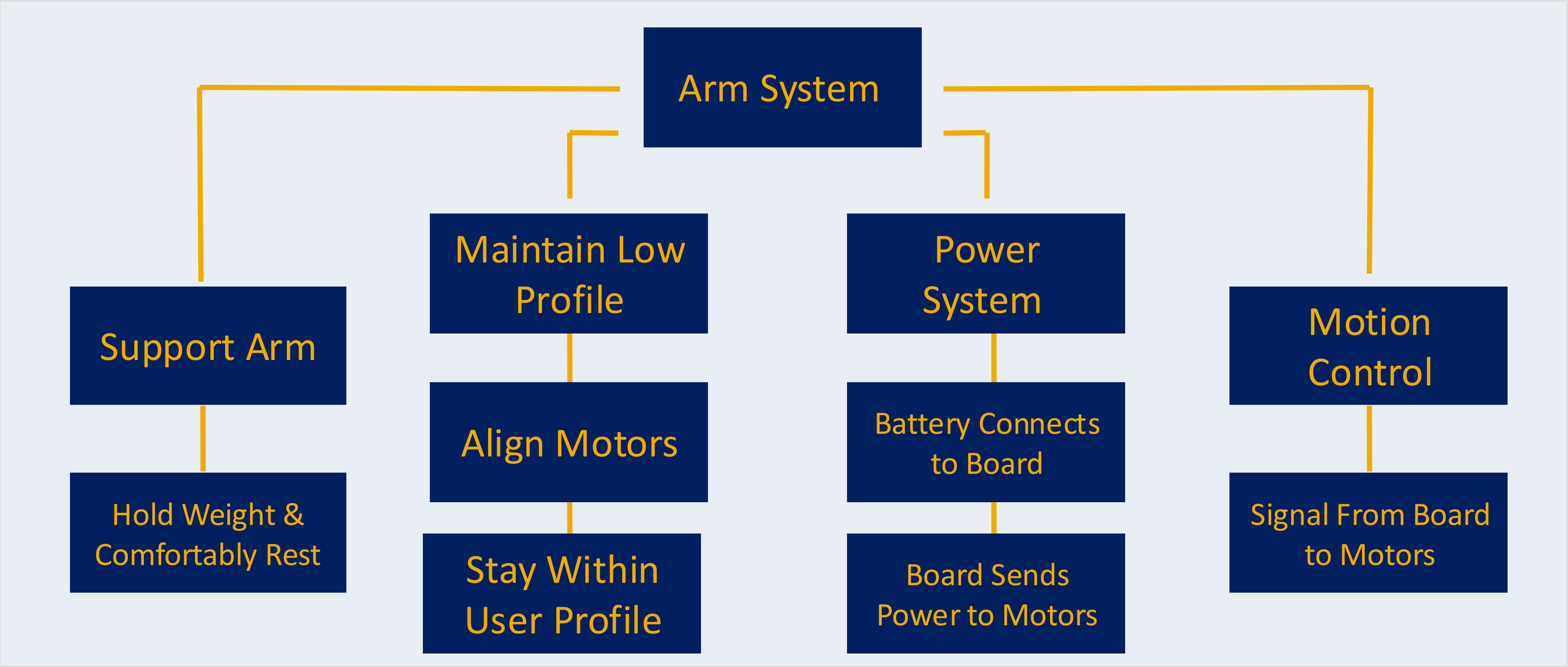
m_1, r_1	Mass & COM distance, Link 1
m_2, r_2	Mass & COM distance, Link 2
m_m2	Mass of Motor 2 (at link junction)
m_p	Human arm mass (anthropometric avg. male)

L_1, L_2	Lengths of Link 1 and Link 2
α_1	Angular acceleration of the system
g	Gravitational acceleration (9.81 m/s²)

Concept Generation & Selection

Functional Decomposition   Concept Generation   Selection Criteria   Concept Selection

Functional Decomposition



Concept Generation

Three sub-system components were independently generated and evaluated against the engineering requirements.

1 Motor

3 candidates evaluated

Three brushless DC motors provided by Dr. Lerner were evaluated against the calculated peak torque requirement of 10–11.5 N·m to determine which could meet operational demands.

2 Joint Type

3 geometries considered

Ring (2 DOF), Ball (3 DOF), and Revolute (1 DOF) joints were assessed for degrees of freedom, transmission complexity, and ability to maintain a low-profile form factor.

3 Link Geometry

2 cross-sections compared

Hollow rectangular and hollow circular cross-sections were evaluated for directional stiffness, torsional resistance, and weight per unit length.

Concept Generation: Motor

Three motors provided by Dr. Lerner were evaluated. The AK45-36 KV80 was selected based on its peak torque exceeding the 11.5 N·m requirement.

Model	Rated Voltage (V)	Rated Power (W)	Rated Torque (Nm)	Peak Torque (Nm)	Speed (RPM)	Weight (g)	Size (mm)	Reduction	Encoder
AK45-36 KV80	24	33	8	**24 ✓**	40	340	φ55×54	36:1	Single
AK45-10 KV75	24	39	2.5	7	150	260	Φ53×43	10:1	Single
AK40-10 KV170	24	59	1.3	4.1	370	200	φ53×37	10:1	Single

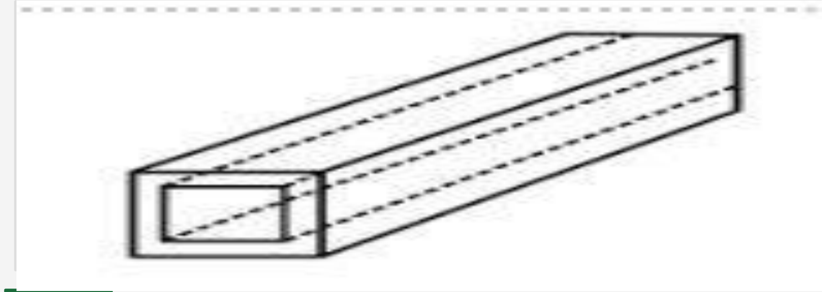
Info from CubeMars website [29]

✓ AK45-36 KV80 selected — peak torque of 24 N·m exceeds the 11.5 N·m requirement with a built-in factor of safety.

Concept Generation: Link Geometry

Two different cross-sectional geometries were evaluated for structural performance.

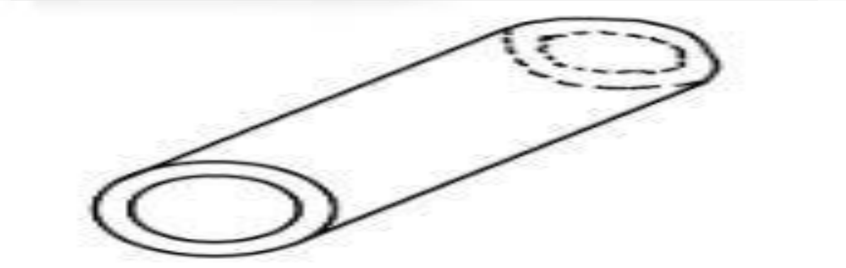
Hollow Rectangular



PRO Strong directional stiffness while keeping weight low.

CON Weak in torsion and off-axis bending.

Hollow Circular



PRO Resists twisting far better than rectangular cross-section.

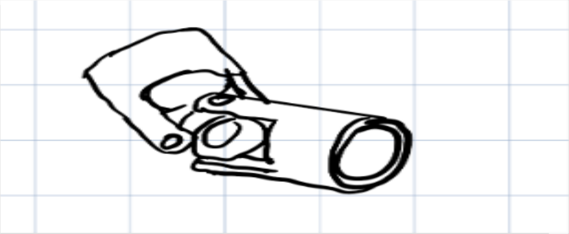
CON Less stiffness per unit weight in one direction compared to rectangular.

Concept Generation: Joint Types

Mechanical joint designs with varying DOF and geometries were researched and evaluated.

Ring Joint

2 DOF

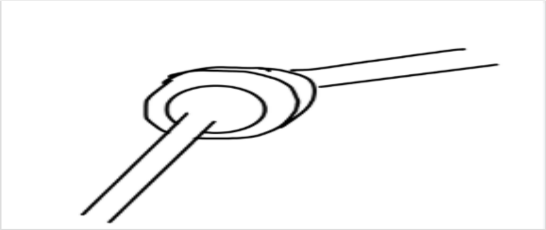


PRO Allows finer movements of the hand/arm.

CON Transmitting power to two axes increases cost and complexity.

Ball Joint

3 DOF

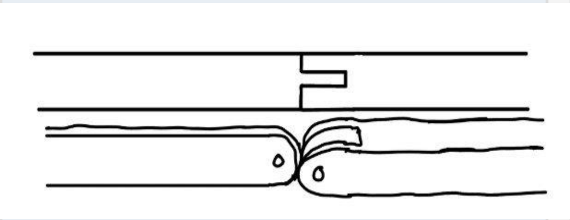


PRO Allows for smoother, more natural arm movement.

CON Requires three motors — one per DOF.

Revolute Joint

1 DOF



PRO Simplifies transmission; only requires one motor.

CON Limited DOF leads to less smooth motion.

Selection Criteria

Three quantifiable criteria were established, each rooted directly in the engineering requirements. Calculations and known specifications were used to evaluate each concept.

1 Factor of Safety

ER2 — Weight of Arm | **Link Geometry**

Link cross-sections must withstand the bending moments and torsional forces during operation. FoS calculations were performed on both hollow rectangular and circular sections to confirm structural adequacy.

2 Torque Capacity

ER3 — Speed of Arm | **Motor Selection**

Each candidate motor was evaluated against the calculated peak torque of 11.5 N·m. The selected motor must meet or exceed this value at the required speed to provide reliable gravitational compensation.

3 Low Profile

CR3 — Low Profile | **Joint Type**

The selected joint must achieve the required range of motion while folding compactly. Protrusion was minimized by prioritizing single-axis revolute joints that align inline with the link geometry.

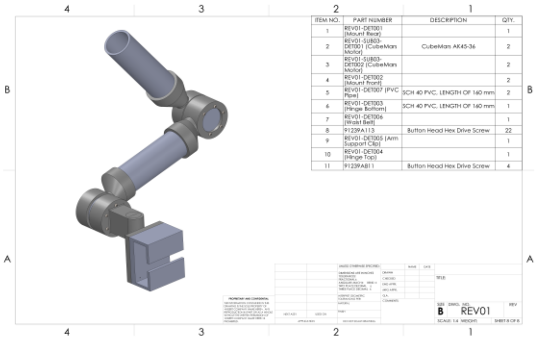
Concept Selection

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

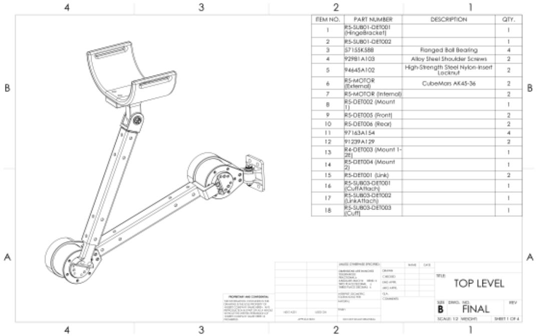
Decision matrix comparing Semester 1 and Semester 2 prototypes. Prototype 2 selected.

CAD Models

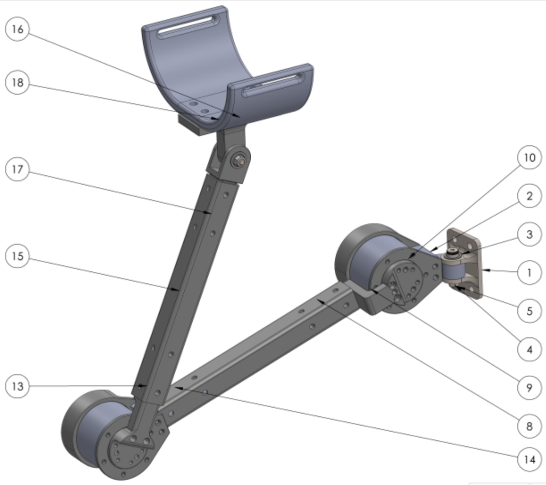
Prototype 1



Prototype 2 ✓



Concept Selection



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	R5-SUB01-DET001 (HingeBracket)		1
2	R5-SUB01-DET002		1
3	57155K588	Flanged Ball Bearing	4
4	92981A103	Alloy Steel Shoulder Screws	2
5	94645A102	High-Strength Steel Nylon-Insert Locknut	2
6	R5-MOTOR (External)	CubeMars AK45-36	2
7	R5-MOTOR (Internal)		2
8	R5-DET002 (Mount 1)		1
9	R5-DET005 (Front)		2
10	R5-DET006 (Rear)		2
11	97163A154		4
12	91239A129		2
13	R4-DET003 (Mount 1-2E)		1
14	R5-DET004 (Mount 2)		1
15	R5-DET001 (Link)		2
16	R5-SUB03-DET001 (CuffAttach)		1
17	R5-SUB03-DET002 (LinkAttach)		1
18	R5-SUB03-DET003 (Cuff)		1

TITLE: TOP LEVEL

SIZE B DWG. NO. FINAL REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 4

Selected Concepts

Motor
CubeMars AK45-36

Joint Type
Revolute (1 DOF)

Link Geometry
Hollow Rectangular

Motor Mounts
Partially Encapsulated

Final concept selected. This concept includes as many aspects of the customer and engineering requirements as possible.

Project Management

Schedule   Budget   Bill of Materials

Schedule: Semester 1

Key Milestones

1 Conceptual Design
Wks 4 – 6 | ✓ Complete

First design approach defined; team aligns on mechanical concept for the wearable arm.

2 Fundraising
Wks 4 – 16 | ✓ Complete

Secure at least 10% of project budget from W.L. Gore and other sources.

3 Build & Test Prototype 1
Wks 7 – 10 | ✓ Complete

Build first physical prototype; test whether design meets functional requirements.

4 Testing & Iteration
Wks 11 – 14 | ✓ Complete

Validate prototype 1 against client specs; identify failure modes and update design.

5 2nd Prototype Demo
Wks 14 – 16 | ✓ Complete

Demonstrate improved prototype to client; confirm design direction for Semester 2.

Schedule: Semester 2

Key Milestones

1 Begin New Prototype

Wks 1 – 4 | ✓ Complete

Review Semester 1 design; source filament, motors, and remaining parts; start construction.

2 Hardware Status Gates

Wks 3 – 8 | ✓ Complete

Three build checkpoints at 33%, 67%, and 100% completion to track hardware progress.

3 Final Prototype

Wks 9 – 11 | ✓ Complete

Arm fully assembled; client and customer sign-off on 100% build.

4 Final Test Plan & CAD

Wks 11 – 13 | ✓ Complete

Complete final arm testing, finish CAD model, and produce final UGRADS poster.

5 UGRADS Presentation

Wks 13 | ⟳ In Progress

Present completed wearable robotic arm at the UGRADS symposium.

Budget

INCOME

Source	Amount
W.L. Gore	**$4,000.00**
NAU 5% Processing Fee	($200.00)
Total Income	**$3,800.00**

PROJECTED BALANCE

Projected Income − Expenses	Amount
$3,800.00 − $3,379.85	**$420.15**

EXPENSES

Category	Item(s)	Cost
Tools & Materials	3D Printer Parts	$0.00
	3D Printer Filament	$1,197.34
Manufacturing	PCB & Assembly	$308.00
Parts	Motors	$598.35
	Battery	$67.12
	Miscellaneous Parts	$353.98
Prototyping	1st Prototype	$647.84
	2nd Prototype	$144.22
	3rd Prototype	$63.00
TOTAL		**$3,379.85**

Bill of Materials

COMPONENTS

Category	Description	Qty	Cost	Status	Make/Buy
Motors	CubeMars AK45-36	2	$598.35	Purchased	Buy
3D Filament	Sunlu PLA 3KG, MarkForged Onyx & Carbon Fiber CFF	1+2 CF	$1,197.70	Purchased	Buy
Battery	Amazon LiPo Battery XT60 Plug	1	$67.12	Purchased	Buy
Hip Belt	Atlas Hiking Grade Belt (Black/LRG-XL), Foam Padding	1	$160.64	Purchased	Buy
Provided by Lab	AK Board, Hinges, JLCPCB	1+2 CF	$308.00	Donated	Make/Buy
Capstone	Brackets, Arm Links, Motor Mounts, Elbow Attachment	Various	$0.00	Donated	Make
Fasteners	McMaster-Carr Screws, Nuts, Bolts (all prototypes)	1+2 CF	$313.67	Purchased	Buy
Electrical	LiPo Bag, Charger, Arduino Nano 33 BLE, Teensy 4.1, OAK-D Pro	Various	$694.24	Purchased	Buy
Other	Belt Supports, PVC Piping, misc. small items	1 Ea.	$40.31	Purchased	Buy
TOTAL			**$3,379.85**		

Design Validation & Prototyping

6.1 FMEA 6.2 Initial Prototyping

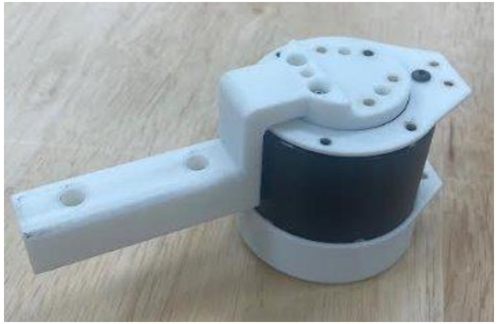
FMEA

⚠ RISK	✓ MITIGATION
Thin pieces could be easy to break	Print parts with carbon infill to reinforce structure
Cracks around mounting hole on belt	Add larger washers to reduce stress concentration
Parts slipping during operation	Fasten all parts at all mounting positions for maximum contact
Hinge fatigue over time	Use stainless steel parts to ensure higher durability
Battery movement / instability	Encase batteries and microcontroller in dedicated housing

**For more detailed FMEA please review website*

Initial Prototyping

Motor 1 Assembly



Q Can the motor mount fit over the motor?

A Confirmed — the design fits over the motor as intended.

↻ Extended width and thickness of the top motor mount to better protect the motor from bumps.

Initial Prototyping

Motor 2 Assembly

Q Can the arm fold up to its desired range of motion?

A Failure — The arm does not fully fold over itself in the initial design.

↻ Extended the arm gap to allow full fold-over and maintain a low-profile form factor.

Initial Prototyping

Hinge Sub Assembly

Q Can the desired motion be achieved? Does the hinge fit in the motor mount subassembly?

A Motion confirmed, but the hinge does not fit in the existing motor mounts.

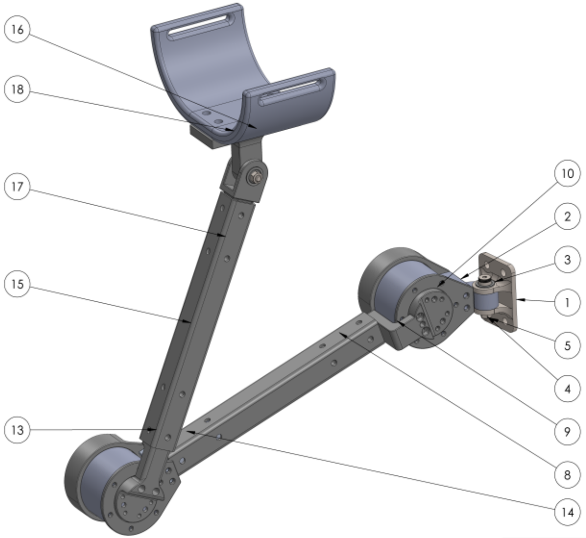
↻ Made slight dimensional changes to improve fit, accounting for earlier design modifications.

Final Hardware

Top-Level Assembly · Sub-assemblies · Individual Part Highlights

Final Hardware

Top-Level Assembly



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7	R5-MOTOR (Internal)		2
8	R5-DET002 (Mount 1)		1
9	R5-DET005 (Front)		2
10	R5-DET006 (Rear)		2
11	97163A154		4
12	91239A129		2
13	R4-DET003 (Mount 1-2E)		1
14	R5-DET004 (Mount 2)		1
15	R5-DET001 (Link)		2
16	R5-SUB03-DET001 (CuffAttach)		1
17	R5-SUB03-DET002 (LinkAttach)		1
18	R5-SUB03-DET003 (Cuff)		1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

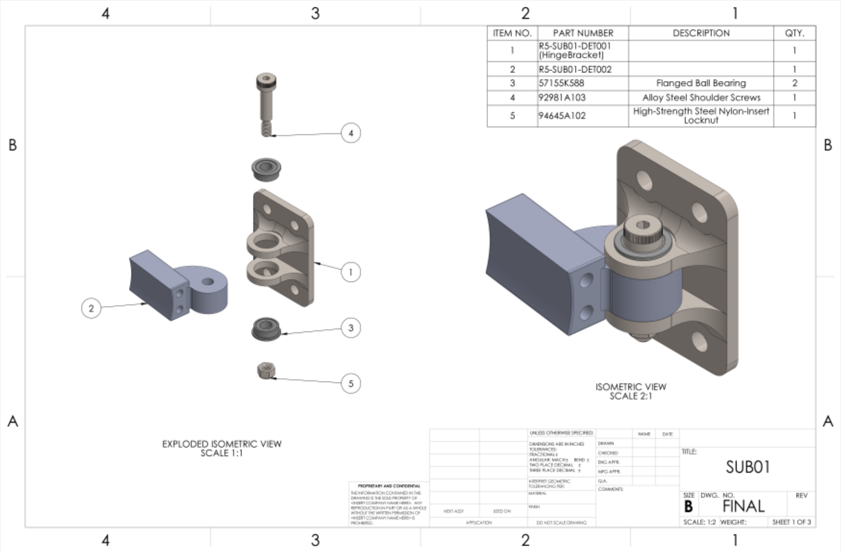
TITLE: TOP LEVEL

SIZE B | DWG. NO. FINAL | REV

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 4

SUB01 – Hip Mounted Hinge Subassembly

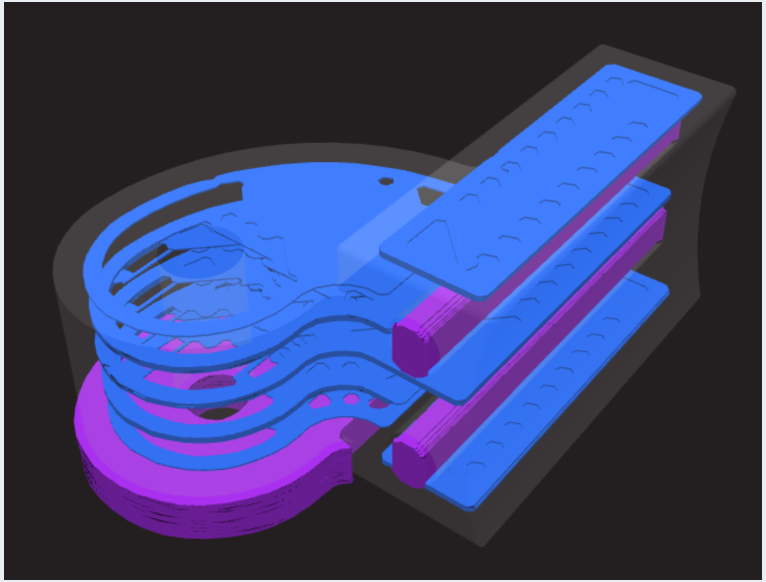
Subassembly 1



Hinge subassembly (left), top view of the hinge (right). The hinge provides a passive degree of freedom to the device.

SUB01-DET002 – Hinge Cam

Individual Part Highlight



Carbon Fiber

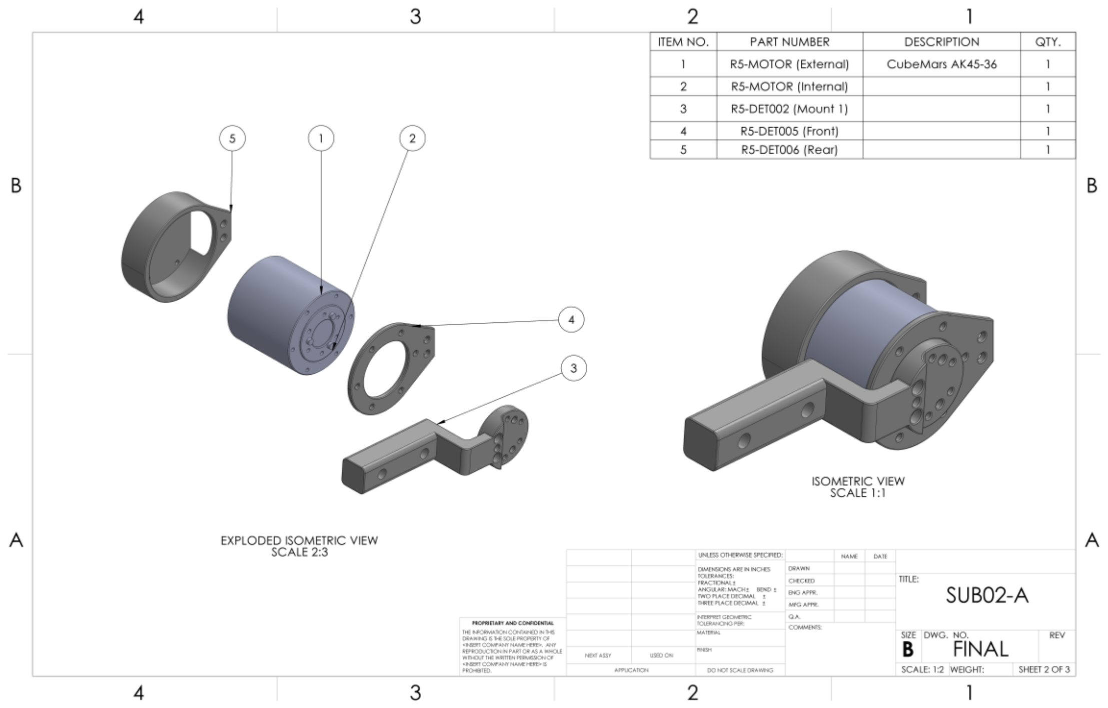
Support

Part

Hinge cam attached to bracket (left), Eiger software photo showing carbon fiber inlay (right)

SUB02-A – First Motor Subassembly

Subassembly 2A



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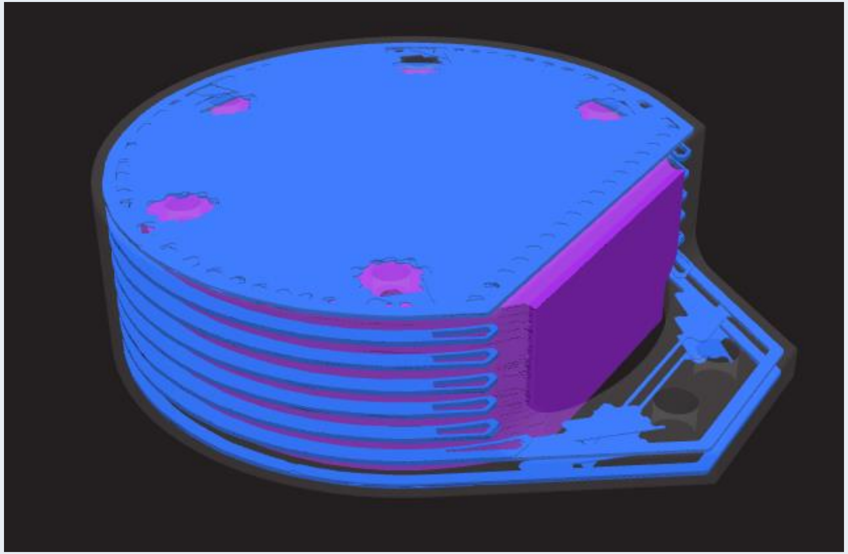
3	R5-DET002 (Mount 1)		1
4	R5-DET005 (Front)		1
5	R5-DET006 (Rear)		1

DET006 – Motor Mount Rear

Individual Part Highlight



Real photo of the printed mount with opening for electronic connections (left), Eiger software showing carbon fiber inlay (right)

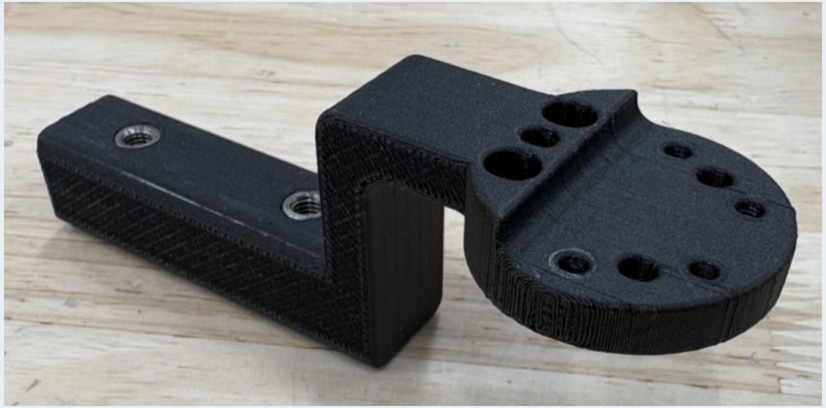
Carbon Fiber

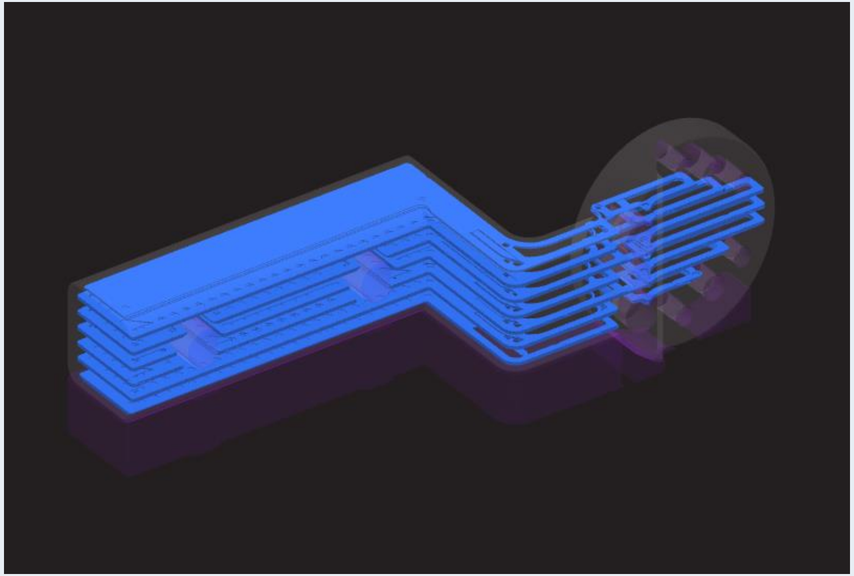
Support

Part

DET002 – Link Mount 1

Individual Part Highlight





Mount 1 printed in ONYX with carbon fiber inlay (left), Eiger software photo showing carbon fiber inlay striping (right)

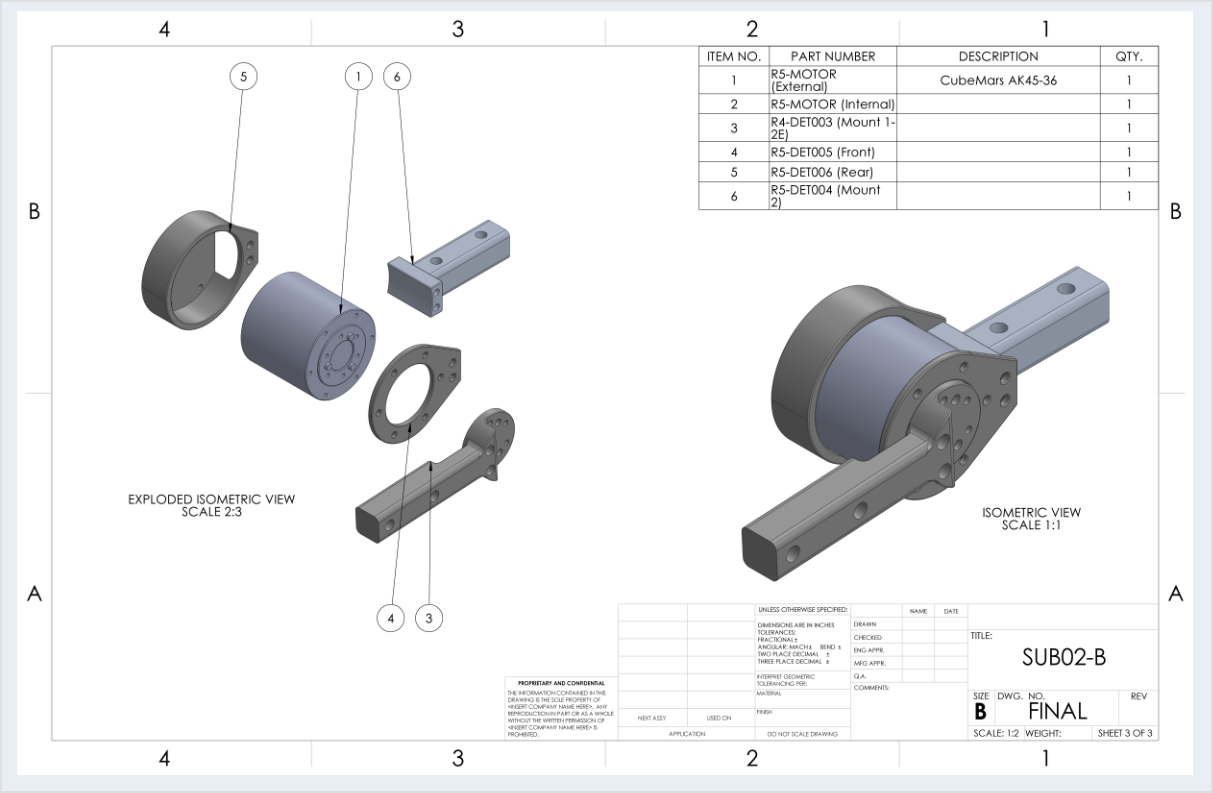
Carbon Fiber

Support

Part

SUB02-B – Second Motor Subassembly

Subassembly 2B



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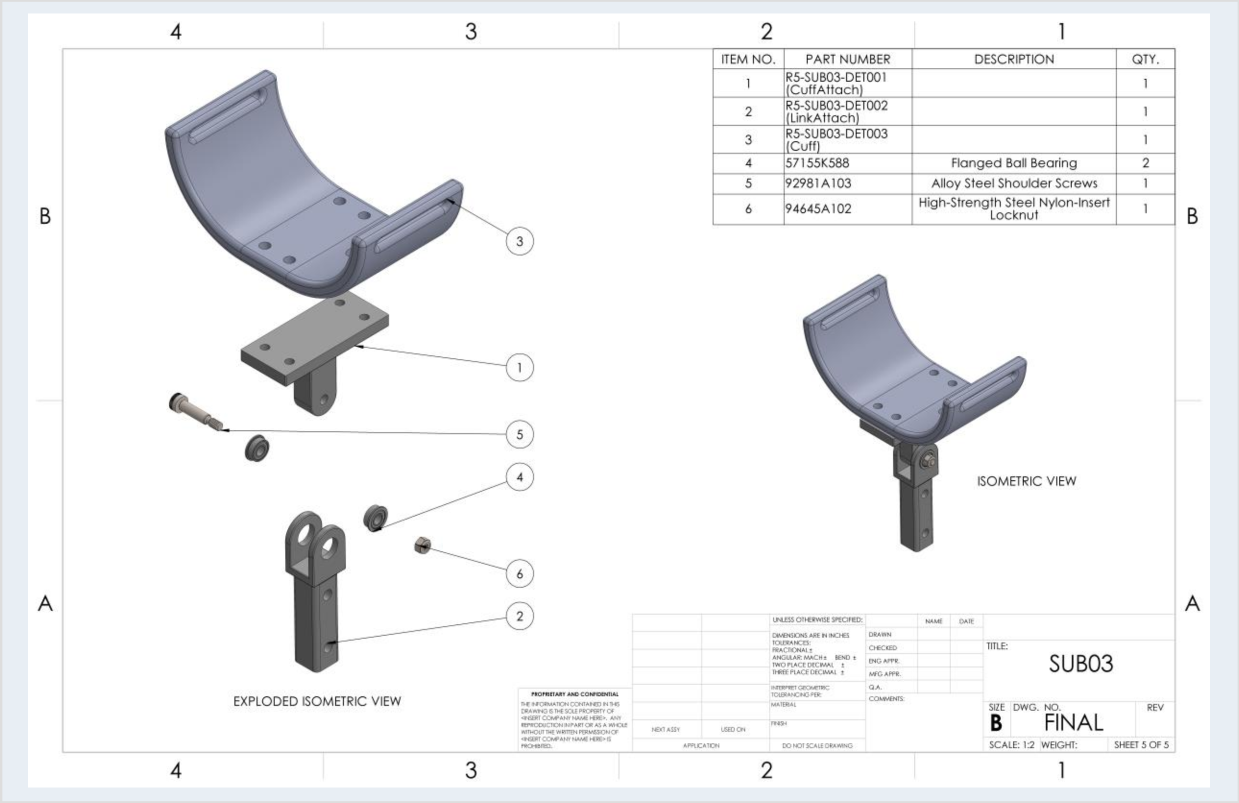
2	R5-MOTOR (Internal)		1
3	R4-DET003 (Mount 1-2E)		1
4	R5-DET005 (Front)		1
5	R5-DET006 (Rear)		1
6	R5-DET004 (Mount 2)		1

SUB03 – End Effector Subassembly

Subassembly 3



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2	R5-SUB03-DET002 (LinkAttach)		1
3	R5-SUB03-DET003 (Cuff)		1
4	57155K588	Flanged Ball Bearing	2
5	92981A103	Alloy Steel Shoulder Screws	1
6	94645A102	High-Strength Steel Nylon-Insert Locknut	1

Final Testing

Testing Summary Specification Sheet Demonstration Video

8 - Final Testing

Test	Relevant DRs	Equipment Needed	Other Requirements
Endurance Test	ER4 — Battery Life	Device, Timer, User, Camera, Battery	Battery fully charged
Range Test	ER1 — Degrees of Freedom	Device, Camera, User	N/A
Weight Test	ER2 — Weight of Arm	Scale, Camera, Device	Arm weighed disassembled
Comfortability Test	CR1, CR3 — Comfortability, Low Profile ER2 — Weight of Arm	Device, Multiple Users, Camera	N/A
Chair Test	CR1, CR2, CR3 — Comfortability, Ability to Sit, Low Profile	Multiple Chairs, Device, Multiple Users, Camera	N/A
Sensor Test	ER1 — Degrees of Freedom	Device, Camera, Computer	Ability to read sensors
Speed Test	ER3 — Speed of Arm	Device, Camera, User, Timer	Avg. time to lift arm
Bump Test	CR5, CR3 — Durability, Low Profile	Device, Camera	N/A

Specification Sheet

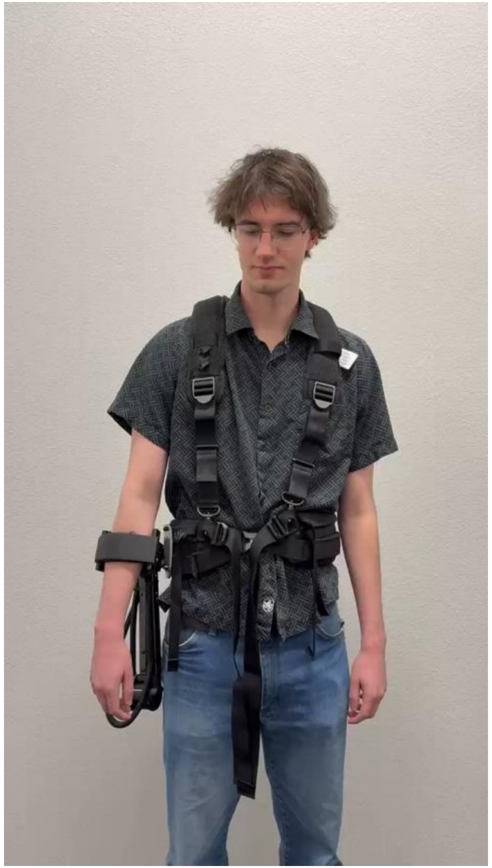
Customer Requirements

Requirement	CR Met?	Client OK?
CR1 — Comfortability	✓	✓
CR2 — Ability to Sit in Chairs	✓	✓
CR3 — Low Profile	✓	✓
CR4 — Accessibility of Design	✓	✓
CR5 — Durability	✓	✓

Engineering Requirements

Requirement	Target	Tolerance	Measured	Met?
ER1 — Degrees of Freedom	3 DOF	±0	**3**	✓
ER2 — Weight of Arm	<2 kg	+0.25 kg	**1.3 kg**	✓
ER3 — Speed of Arm	≥10 RPM	−2 RPM	**14.91 RPM**	✓
ER4 — Battery Life	30 min	±5 min	**34 min**	✓
ER5 — Mfg. Cost	<$2,000	+$250	**$1,038.34**	✓

Demonstration Video



Future Work

Future Work

The device will be handed off to Jackson Truitt in the NAU Biomechatronics Lab to continue development for patient rehabilitation. Three key areas of iteration have been identified:

1

Advanced Controller Design

Transition from the current control scheme to hybrid control and impedance control strategies, enabling more natural and compliant interaction with user arm motion.

2

Adjustable Link Lengths

Redesign the link system to be able to print adjustable lengths to accommodate users with different arm geometries — critical for expanding from this design to a usable clinical and home product.

3

Additional Degree of Freedom

Add a rotational DOF along the transverse plane to enable more human-like arm motion, allowing the device to support reaching across the body.

Thank You
Any Questions?

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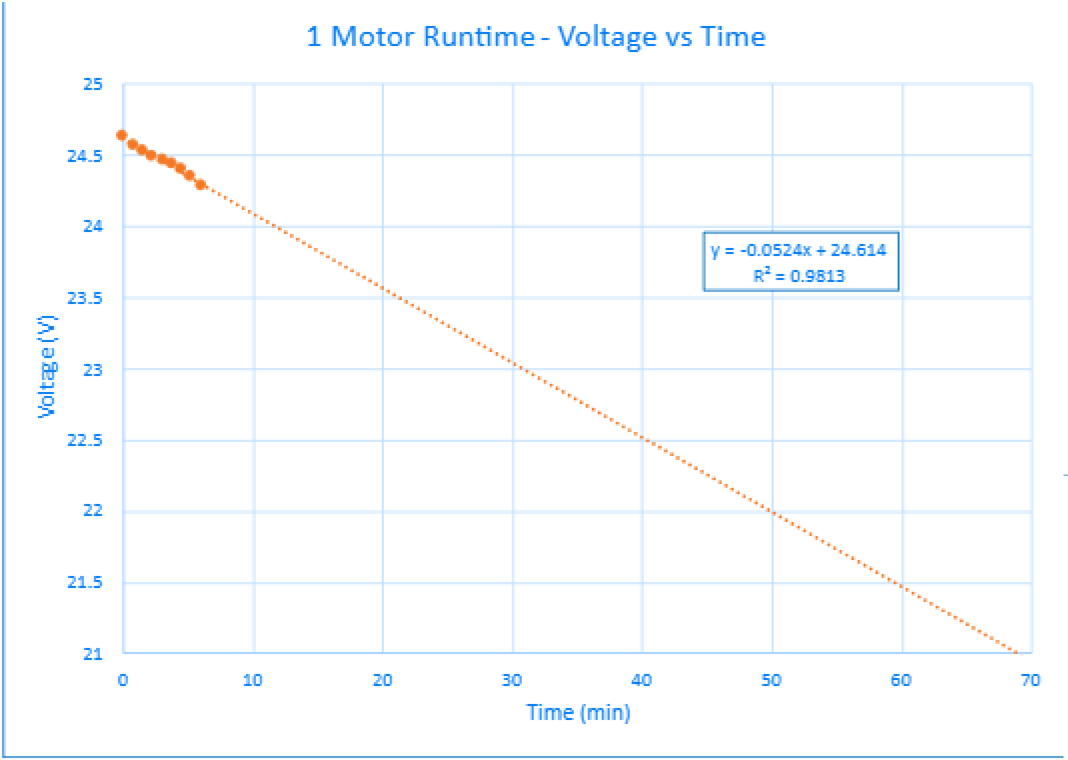
Appendix

Appendix



This graph is a projection of the battery life if only one motor was spinning. The minimum y value is 21 V and correlates to the minimum Voltage per Cell for the 6 cell battery.

1 motor = 68 minutes of runtime
2 motors = 34 minutes of runtime