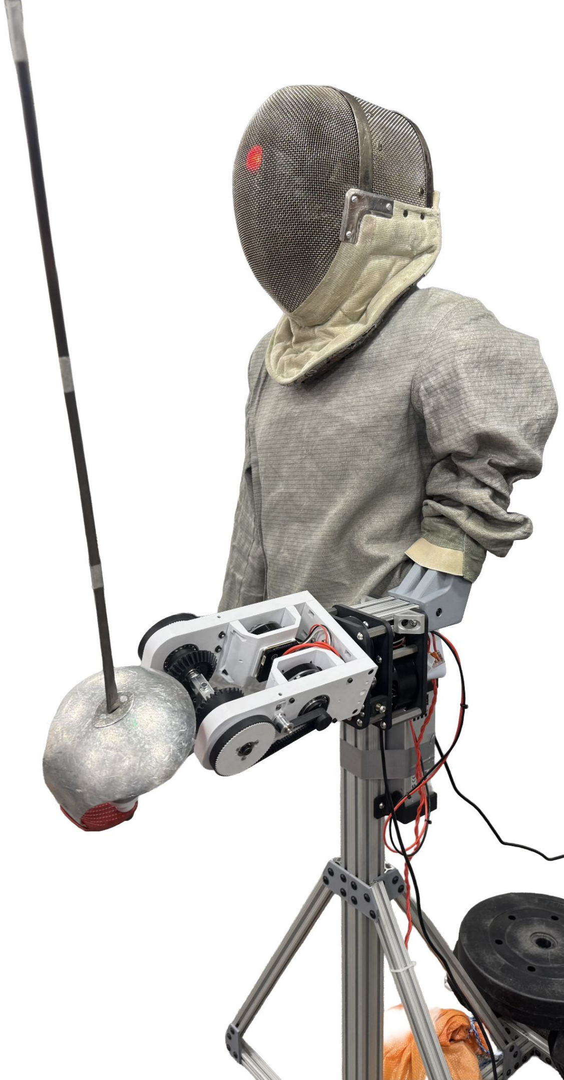
# Robotic Fencing Partner




**Team 23**
**Advisor**: Ms. Aparna Rector
**Team Members**: Josh Dillon, Peter Di Natale, Ethan Fisk, Shivansh Kumar, Zaki Loldj, Anson Mole

12.4.2025

# Background

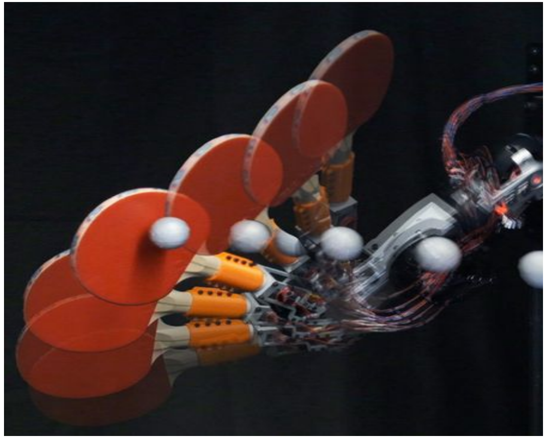
***Fencing is a niche sport***

## Challenges

- Finding a place to practice/compete
- Fencing centers generally operate in metropolitan areas
- In the US, the Fencing population is spread out and is comprised of mostly amateurs
- **One-on-one coaching can be inaccessible or too expensive to many potential Fencers.**

**Current Robotic Partners in Other Sports**


RoboGolfPro



MIT

# Robotics in Fencing

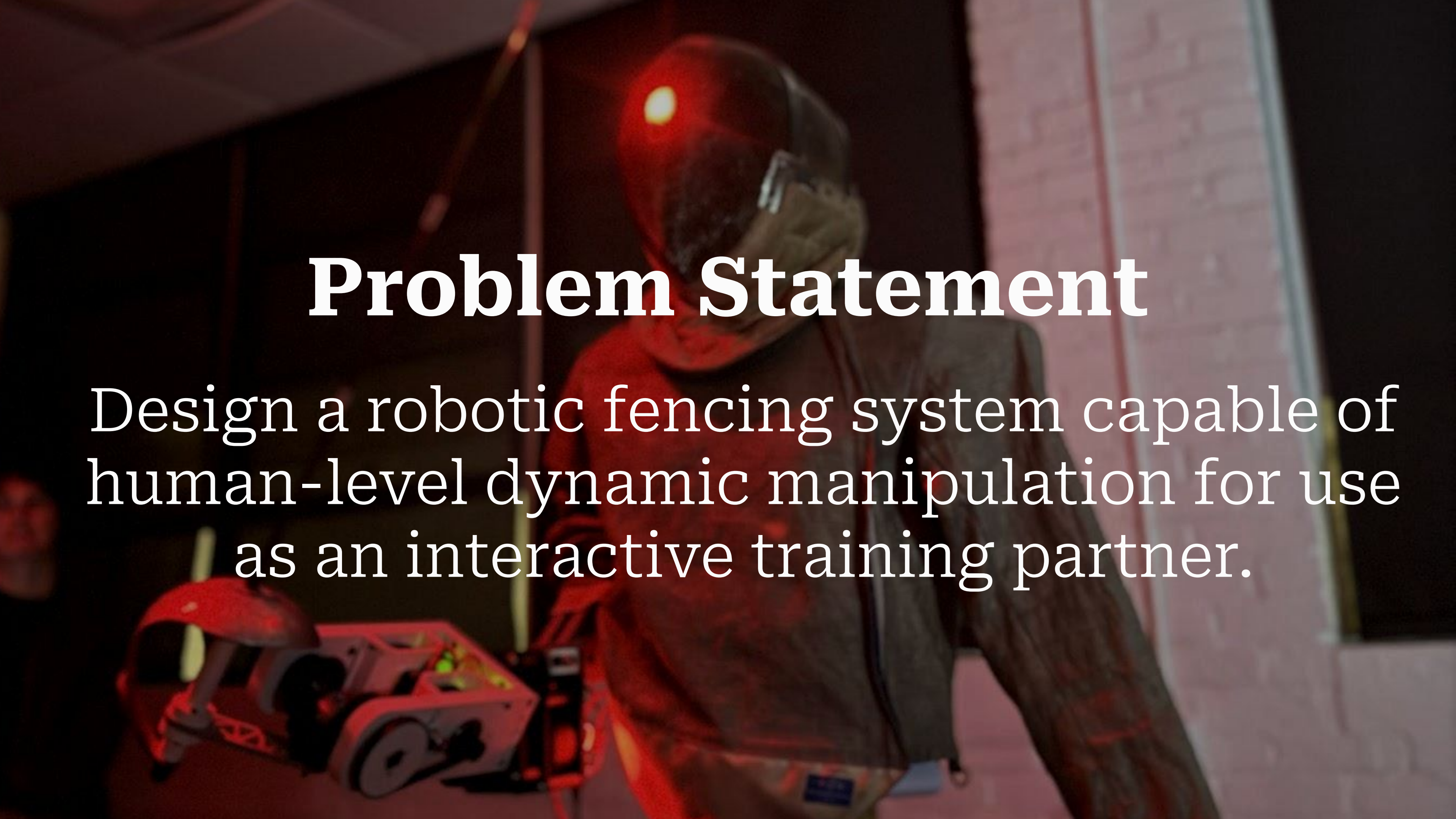
## Current Limitations

- Very few robotic trainers exist in Fencing today
- The most well funded research into Fencing robotics was performed with the German Fencing Federation
  - **Pro:** This robot can advance and retreat
  - **Con:** The wrist mechanism is limited to 1 DoF


**We aimed to improve the wrist mechanism with extra DoF and human-like velocities**

# Problem Statement

Design a robotic fencing system capable of human-level dynamic manipulation for use as an interactive training partner.



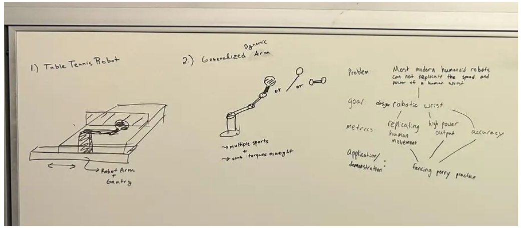
# Self Defined Scope

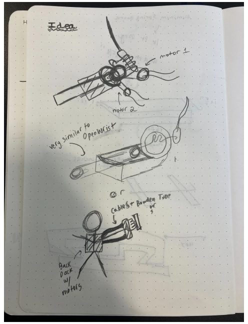
## Development of Scope

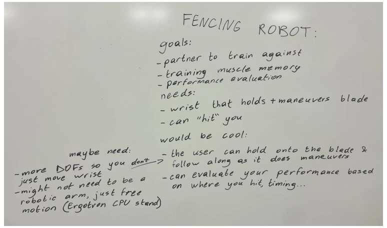
- **Self developed** project started with ambitious goals
- Meetings with **10+ professors and industry experts** helped define realistic objectives

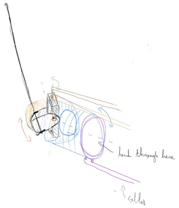
## Project Scope

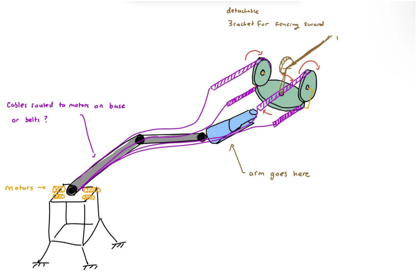
- Actuation of **3 DoF wrist** only
- Ability to **match trajectories and velocities** of a human fencer
- Functional as a **robotic saber fencing partner**
- Dimensionally similar to a human fencer



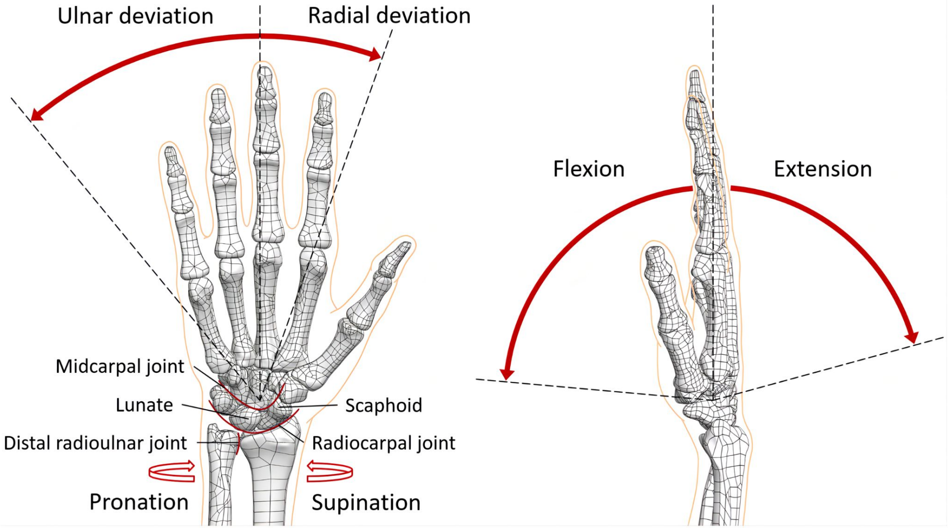






# Dynamics of A Human Wrist/Terminology

***We want our design to mimic the dynamics of a human wrist***

- Approximated as a 3 DoF spherical joint
- **Degrees of Freedom**
    - Pronation/Supination
    - Radial/Ulnar
    - Flexion/Extension
- Important values:
    - Range of motion (deg)
    - Speed Output (rad/s)
    - Torque Output (N·m)



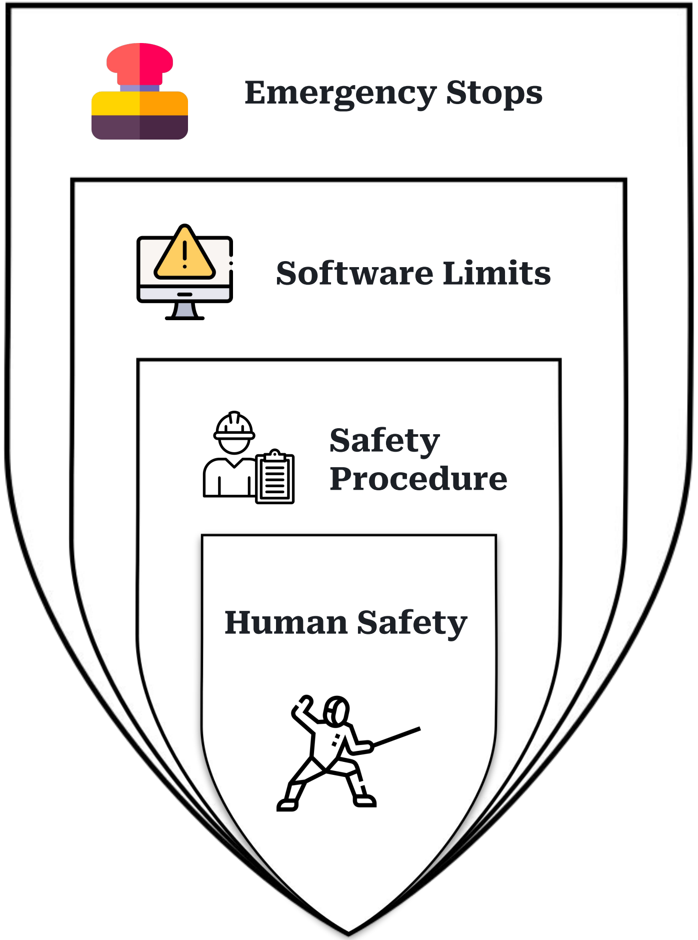
# Safety

**This project came with several safety considerations**

- The robot would be swinging a Fencing sabre at human-like speeds and torques

***While isolating the wrist limits the robot's danger considerably,***

- Some of our safety precautions include:
  - Emergency-Stops (Button/Software Stop)
  - Software Torque Limits
  - 6-ft radius safety zone used for any testing with User-interaction
  - Protective Gear requirements (Fencing Uniform)




**Redundant systems ensure safety at every level**

# Safety Cont.

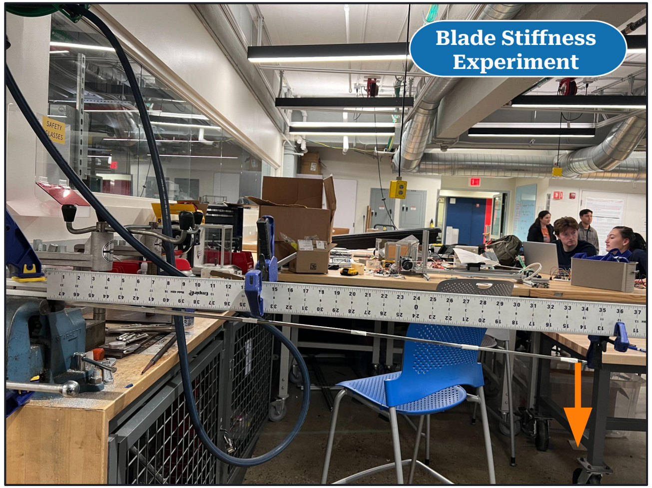
## Conducted hand calculations to verify robot safety

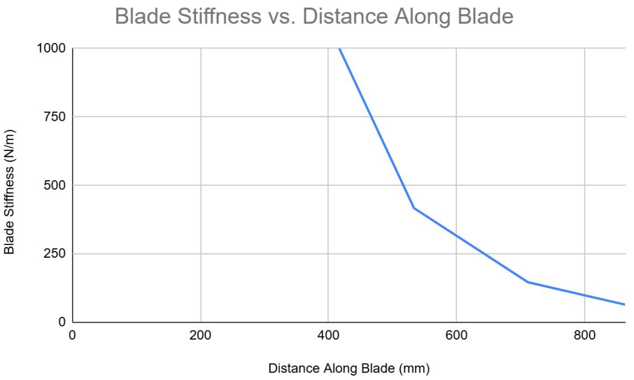
- Estimated the force/pressure a user would feel if the blade struck their arm moving at its fastest velocity.

**Energy Balance:** $\frac{1}{2}Iw^2 + \frac{1}{2}mv^2 \rightarrow \frac{1}{2}kx^2$

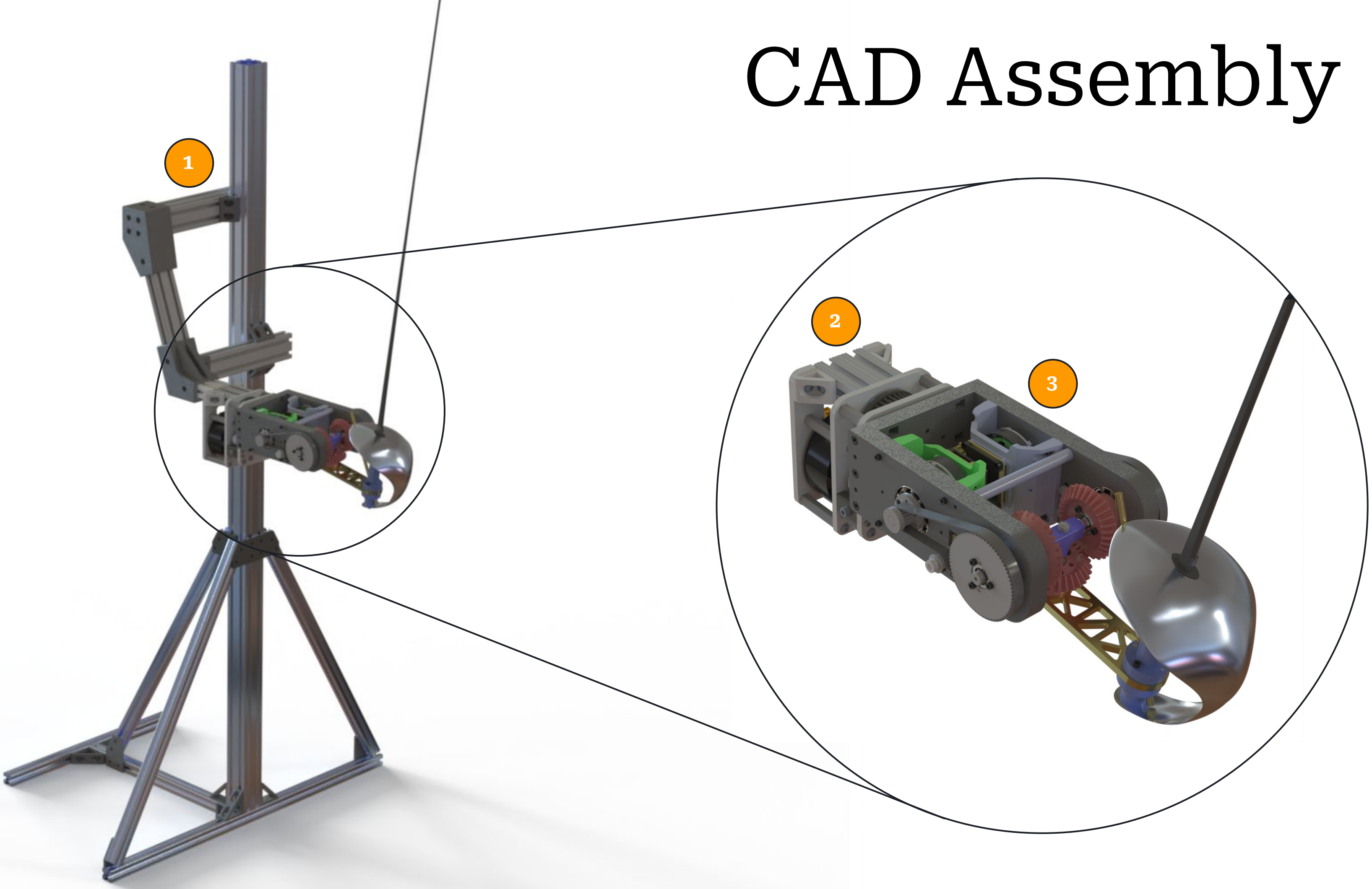
**Force Calculation:** $F = kx$

- Found that the maximum pressure a user will feel is ~37 psi → below the 100 psi threshold that can penetrate unbroken skin.
- **Note:** this number would be even *lower* since the user is wearing protective gear.



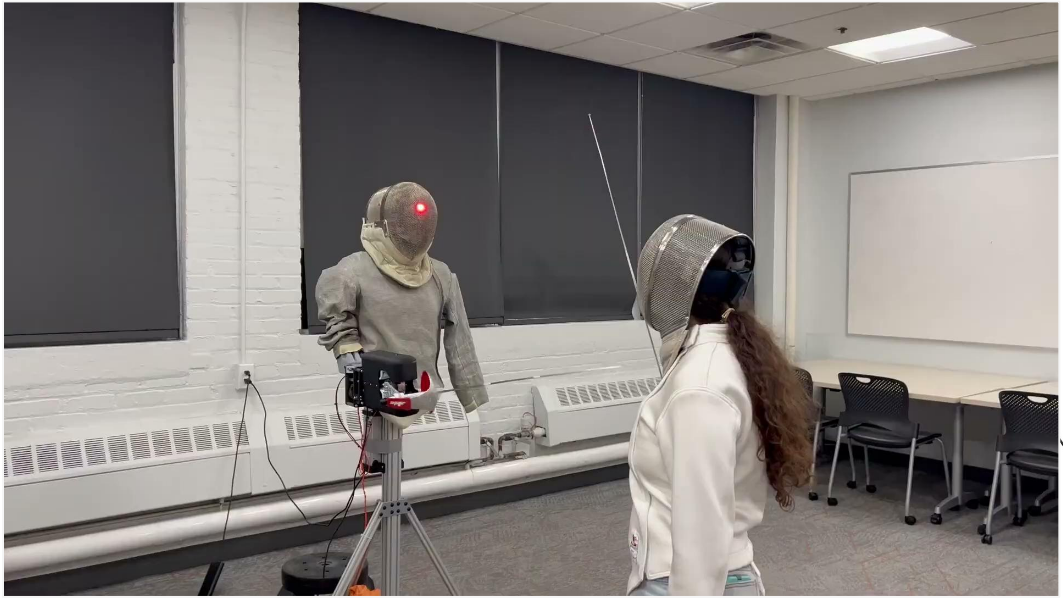



# CAD Assembly

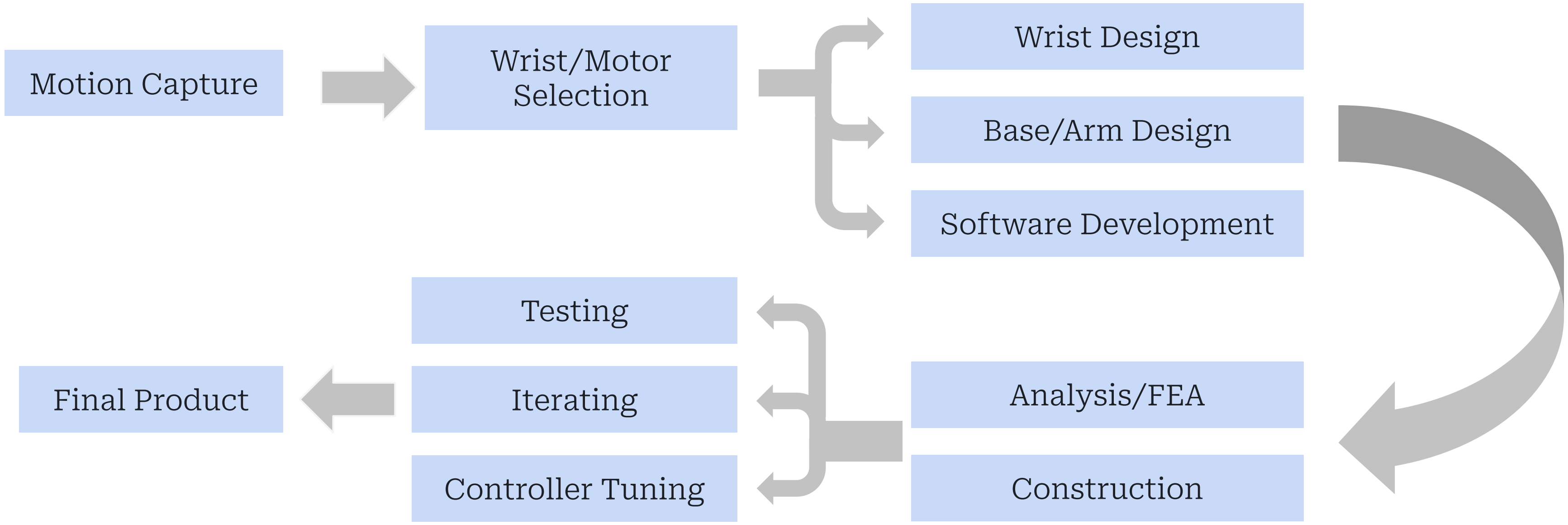


# Final Assembly

**Meet FR3D - *F*encing *R*obot *3 D*oF**



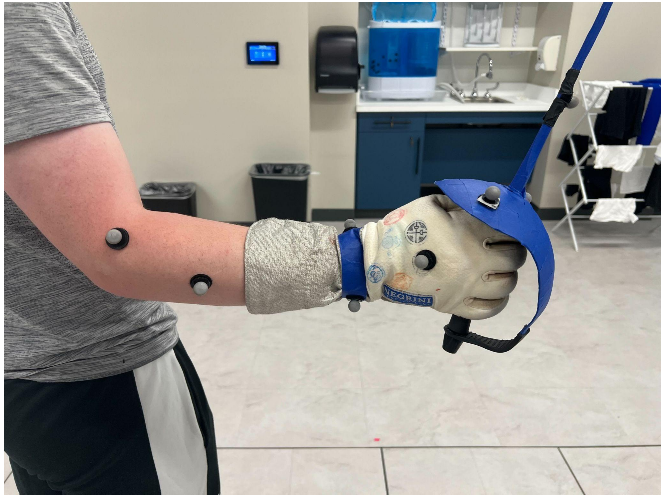
# Design Process



# Motion Capture Analysis

## 1. Data Collection

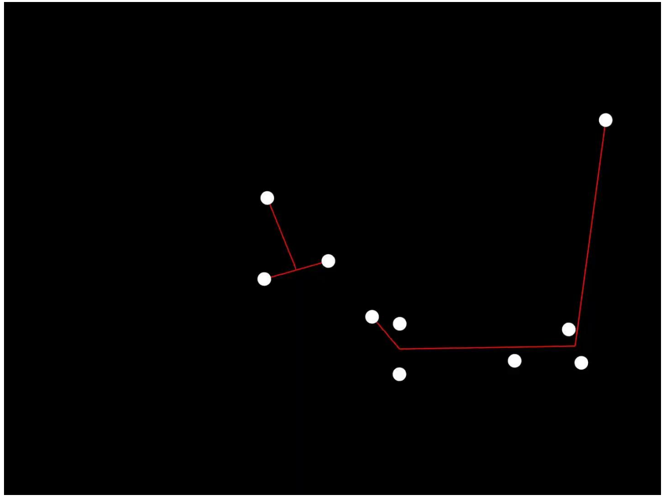
- Motion capture studio on the 4th floor of Richards Hall
- Access provided by the Shepherd Lab




Marker Placement

## 2. Post-Processing

- Post-processing was performed partially with the Mo-Cap toolbox in MATLAB
- Additional software was created to automatically remove duplicate markers and create visuals

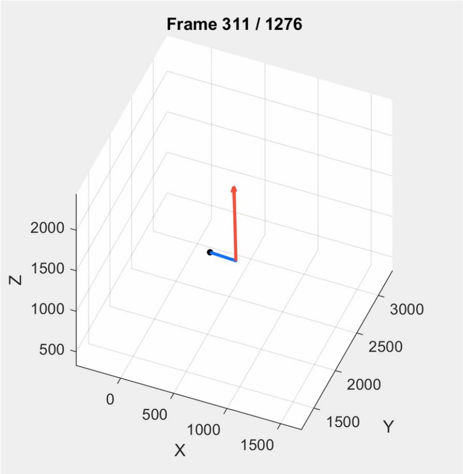


Processed Animation

# Motion Capture Analysis Cont.

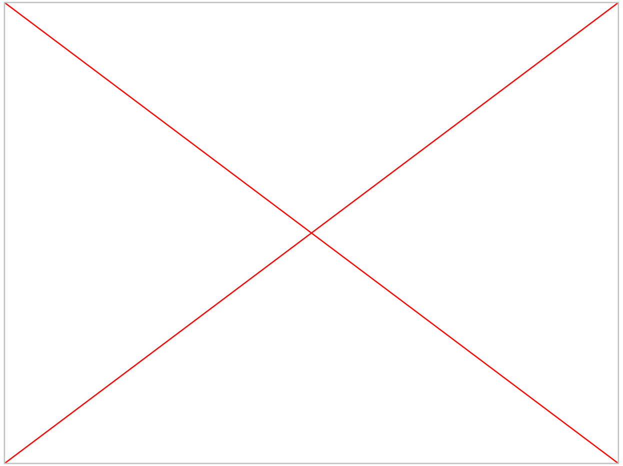
## 3. **Wrist Motion Isolation**

- Removed non wrist and blade markers
- Used the blade vector to drive the orientation
  - This captures any in-hand manipulation




## 4. **Convert to Robot Trajectories**

- Used *Onshape-to-Robot* to export URDFs of simple wrist geometries
- Animated with Robotic System Toolbox for MATALB
- Repeated for a variety of designs

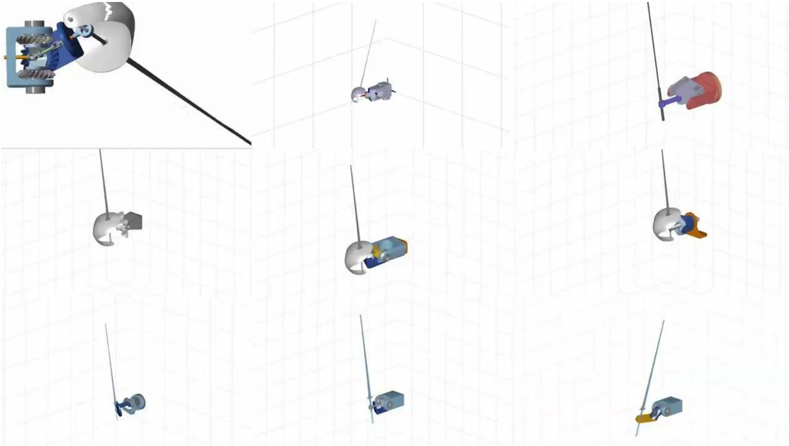


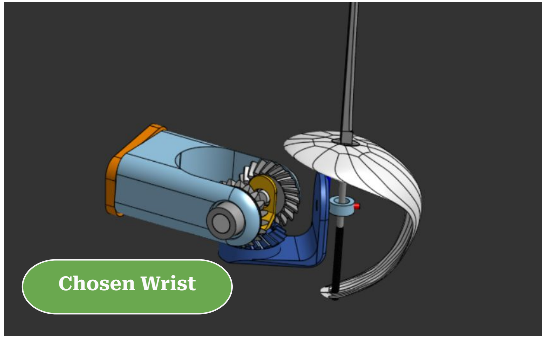
# Wrist Mechanism Selection

**We developed a list of viable wrist candidates and formed a decision matrix**

- 12 criteria were identified, with weights defined anonymously
- Team underwent a 1-5 rating system and calculated a total score for each mechanism

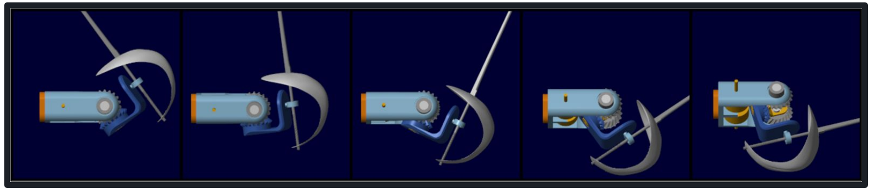
| Mechanism Option | Total (1-5) |
|---|---|
| joystick | 2.75 |
| gimbal mechanism | 3.15 |
| differential with U-joint X | 3.29 |
| cable differential wrist | 2.64 |
| XYZ differential base roll | 3.86 |
| Completely serial mechanism | 3.27 |





# Simscape Dynamic Analysis

## <u>Methodology</u>



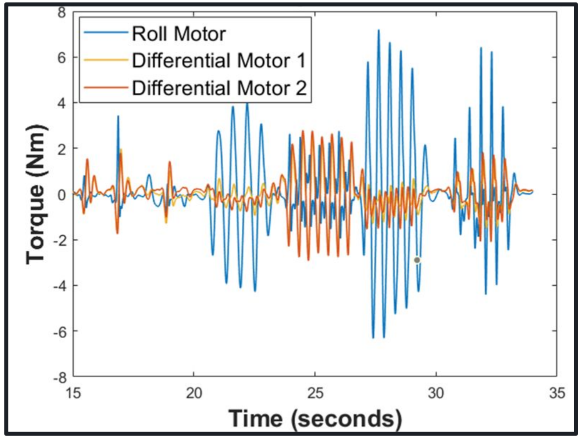
- Using Simulink/Simscape, we determined the actuation torque required to achieve the motion capture trajectories → Motor Selection

- To obtain accurate motor torque trajectories  results from our simulation...

$$I\alpha = T$$

Good Data In | Good Data Out

- Also experimented with which components were most sensitive to increasing inertia

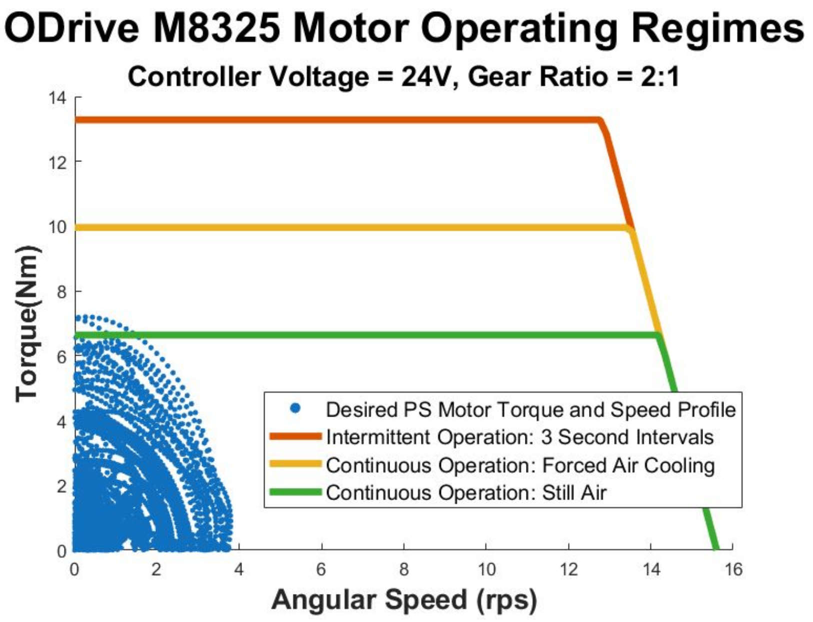


# Motor/Transmission Ratio Selection

## Methodology

- We used a BLDC motor model where we could input a motor’s design parameters and find all the combinations of torque and speed a motor can achieve
- We overlaid our desired torque and speed requirements onto these operating regions for different motors + gear ratios

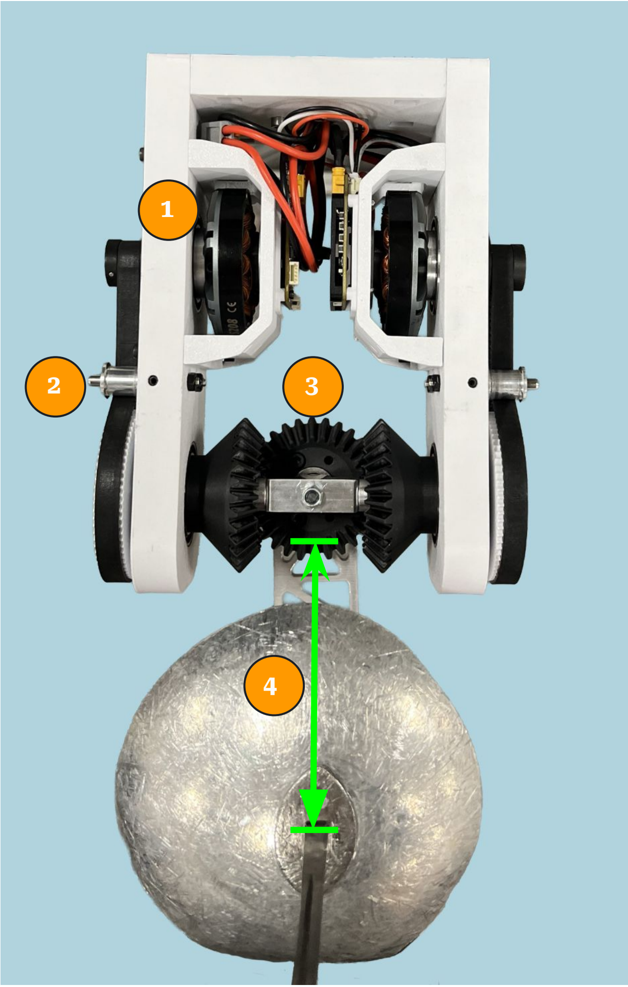
- Result:
    - We selected…
        - ODrive M8325 for the Roll Joint (2:1 GR)
        - MJ5208 for the Differential Joint (4:1 GR)



# Differential for R/U & F/E

## Subassembly Features

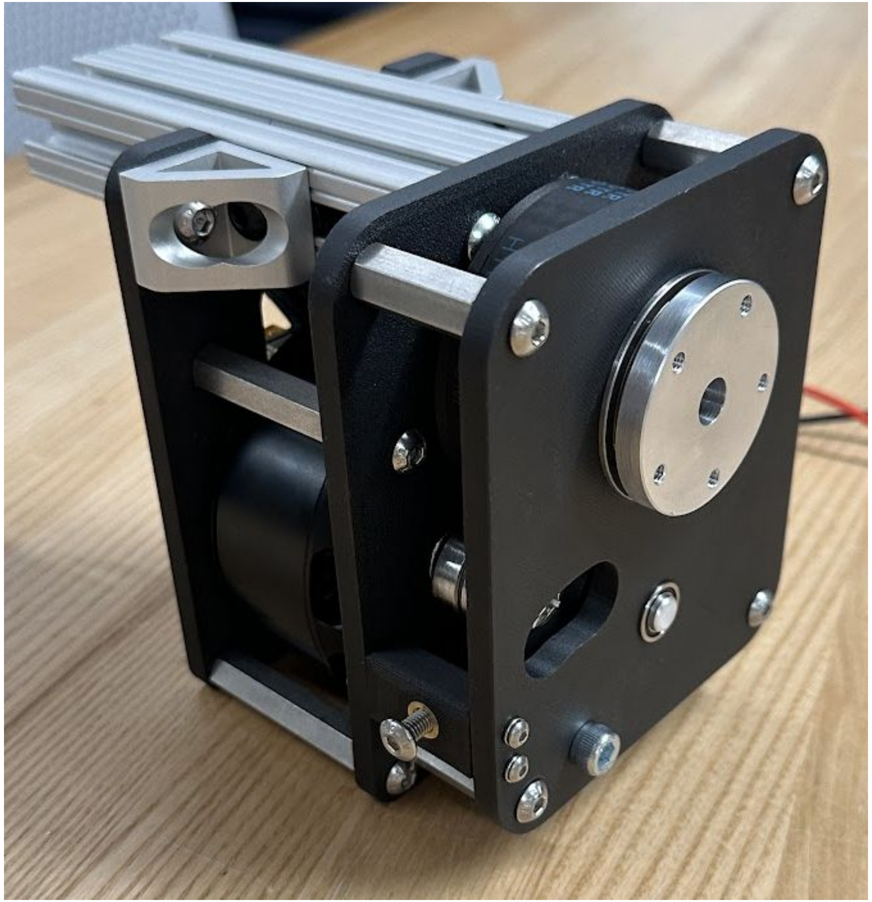
1. Powered by two MJbots motors each with a **4:1** gear reduction
2. The belts were preloaded with **~50 N** of tension
3. Three 3D-printed **CF-PLA** bevel gears create the dynamics for the first two DoF
4. A **100 mm** offset inspired by average human wrist geometry



# P/S Joint

## Design Features & Considerations

- The blade and the two downstream motors create a large moment of inertia, so this joint requires the largest motor
    - Powered by an ODrive M8325s with a 2:1 gear ratio
- Features 3D-printed pulleys and custom aluminum hubs
- Hollow output shaft for wiring



# Stationary Base

## Goals

- Hold the arm **fixed** while motors are actuated
- Provide **mounting surfaces** for hardware or wiring
- **Minimize weight** for ease of transportation

## Features

- Made of 80/20 10-Series Aluminum extrusions
  - The main post is  2” x 2” to resist torsion
  - Remaining posts are 1” x 1”
- Utilizes counterweight to maintain stability
- **Weight**
  - **Base** ~ 15 Pounds
  - Added **Counterweight**: ~100 Pounds

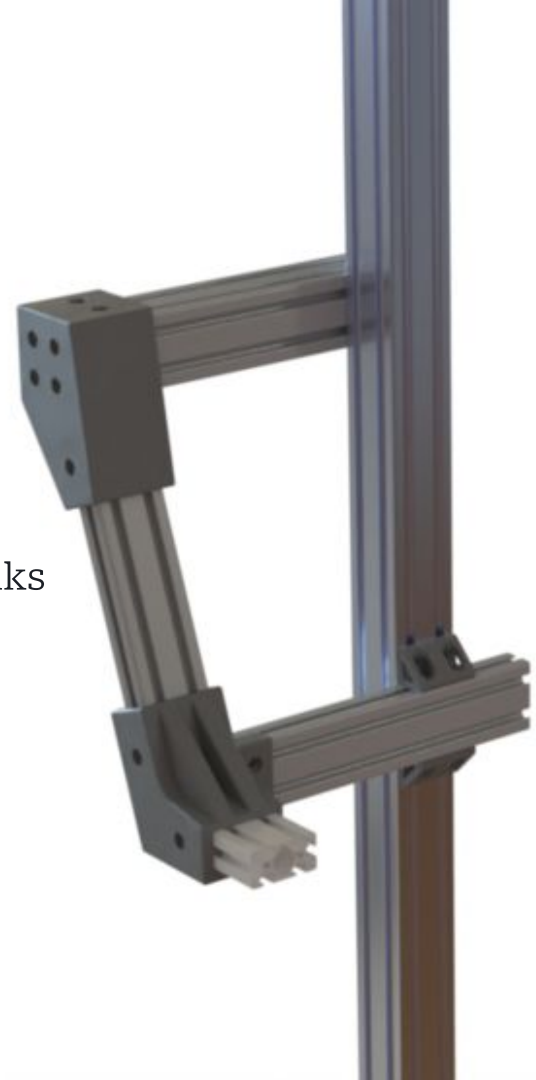
# Passive Arm

**Goals**

- Carry an **~11 lb** payload
- Hold the wrist mechanism in **fixed** position
- Maintain **human-like** upper body proportions

**Features**

- Created using 10-Series 80/20 extrusions and 3D printed links
    - **3** - 2” x 1” extrusions
    - **1** - 2” by 2” extrusion
- **3D Prints**
    - Upper arm is angled at 20° from the vertical
    - Both Prints
        - 50% Infill Density
        - 5 Wall Loops
        - Gyroid Infill pattern

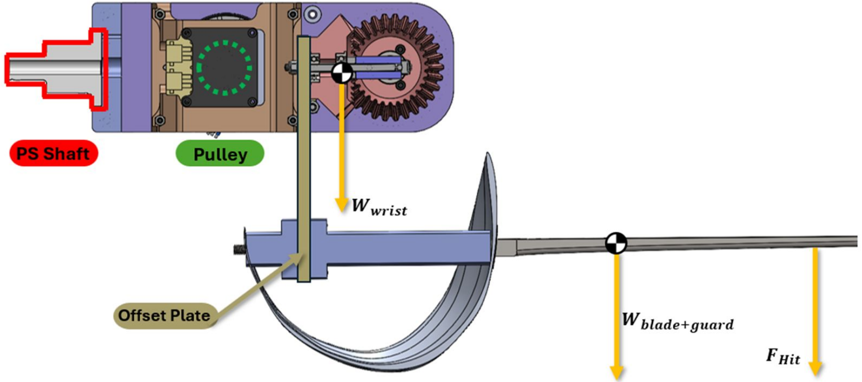


# Failure Analysis

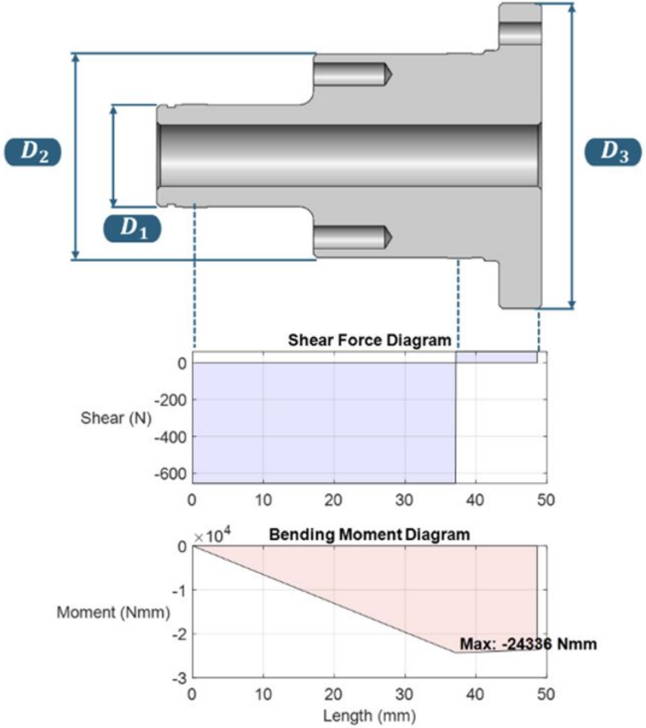
**Analyzed:** PS shaft, pulley, and offset plate

**Steps:**

1. Made loading condition **assumptions** (Force on blade corresponds to max torque the motors can handle before being backdriven.)
2. **Static equilibrium** calculations to derive reaction moments and loads
3. Input results into **FEA** and verify with hand calculations



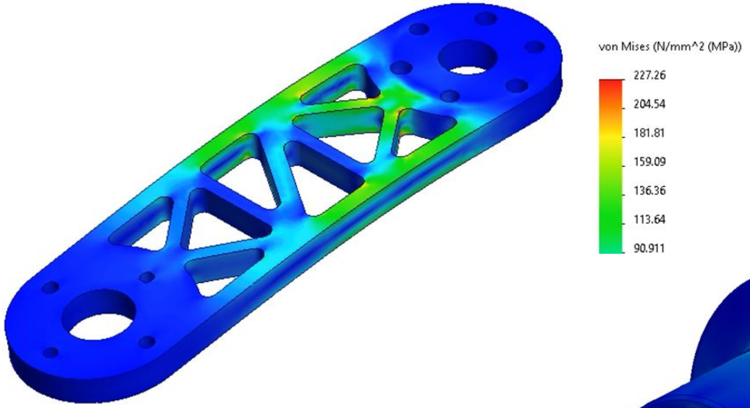
Free-Body Diagram



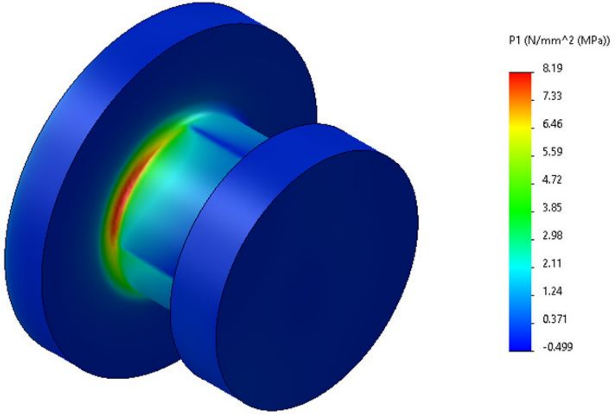
Component Stress Hand Calculations

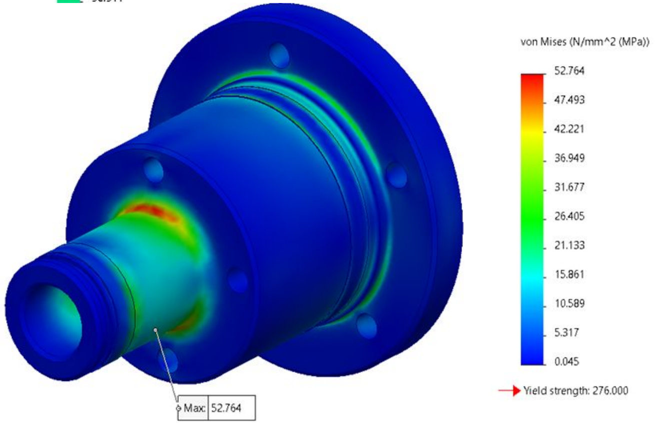
# Finite Element Analysis

**Wrist Offset FOS (Von Mises): 1.7**




**Differential Driving Pulley FOS (BCM): 1.8**




**PS Shaft FOS (Von Mises): 5.3**

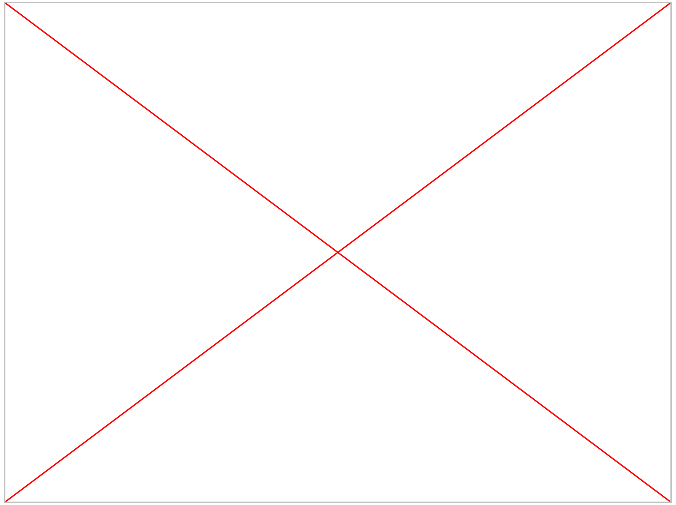
# Software

## Features

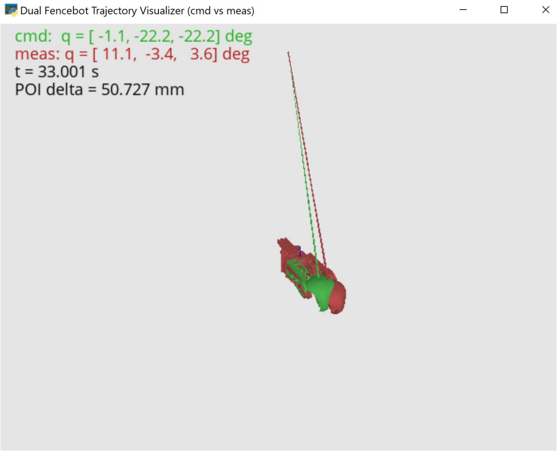
- Control Software: Python using Moteus library
- Visualizer created using Pyrender and CAD geometry
- Custom input device: Raspberry Pi Pico w/ BNO055 Orientation sensor

## Functions

- Command the robot, log robot position, velocity, torque, etc.
- Visualize robot motion offline
- Show real time robot position
- Teleoperate the virtual copy or the real robot



Robot Control



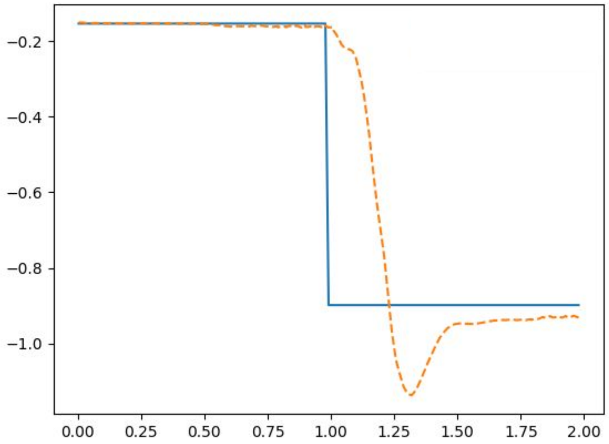

Past Trajectory Playback

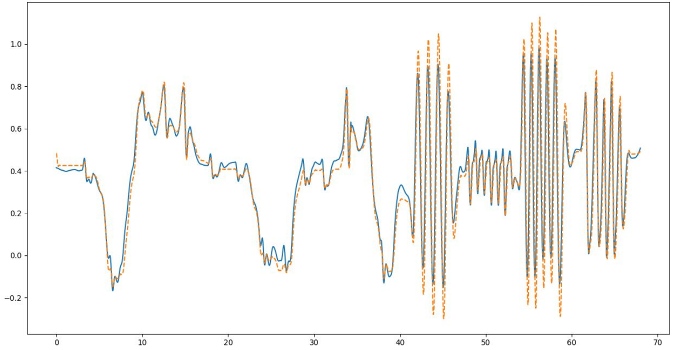
# Controller Tuning

## Methodology

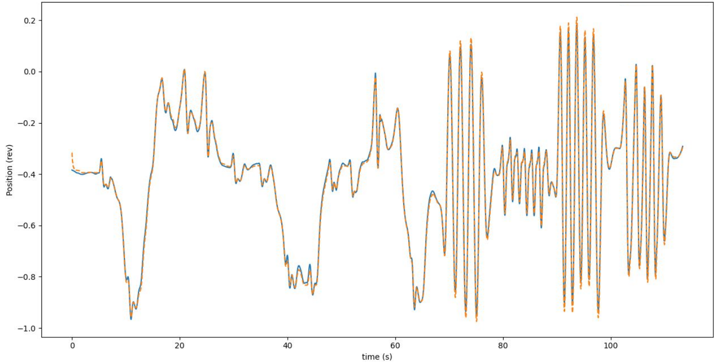
- PID gains tuned empirically based on executing step responses and through observations of trajectory tracking performance at lower speeds
- Motion capture trajectories were executed at increasing speeds as tracking performance improved (0.1x,0.3x,0.5x,0.7x,1x)

Base Motor Step Response (during tuning)




**Base Motor 0.5x trajectory tracking (during tuning)**

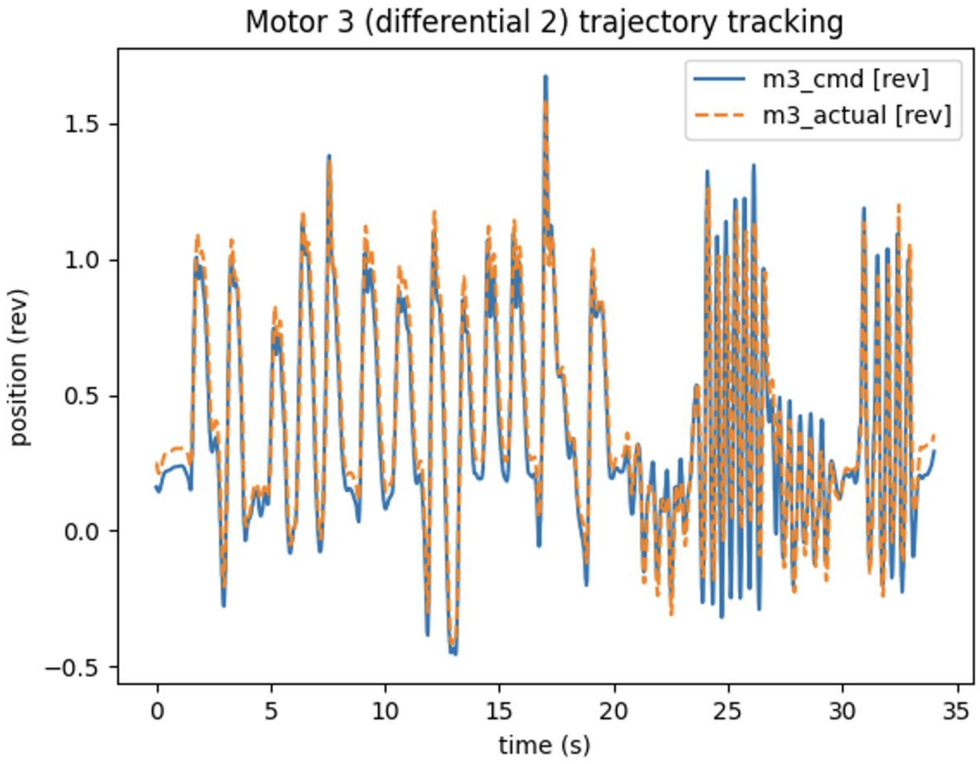



**Base Motor 0.5x trajectory tracking (post-tuning)**

# Trajectory Tracking Results

- Tested performance of the system by comparing the commanded trajectories (Blue) with the actual trajectories (Orange)

- **This motion capture trajectory varies between:**
    - Fencing movements (1st half)
    - Rapid Repeated motions to test maximum exertion (2nd half)




One Differential Motor Full-Speed Trajectory Tracking

# Key Successes

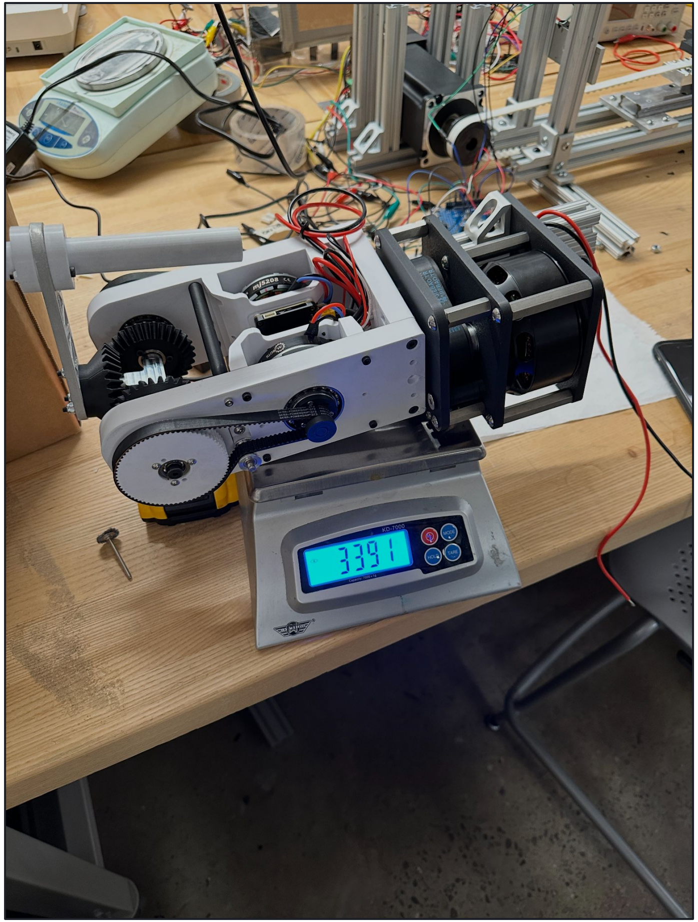
***Our performance metrics were based on the motion capture analysis performed in the summer**

| Degree of Freedom | Max ROM *Desired* | Max ROM *Actual* | Max Mo-Cap Speed Desired | Max Mo-Cap Speed *Actual* |
|---|---|---|---|---|
| **Pronation/Supination** | **~198°** | **360°** | **3.6 rev/s** | **3.6 rev/s** |
| **Radial/Ulnar** | **~126°** | **180°** | **2.2 rev/s** | **2.6 rev/s** |
| **Flexion/Extension** | **~83°** | **180°** | **1.6 rev/s** | **1.9 rev/s** |

1. Met and exceeded our **Range of Motion** and **Rotational Speed** goals
2. Created a base that **maintained rigidity** throughout actuation
3. The robot performed fencing drills using **teleoperation** and **pre-programmed** paths
4. The robot achieved **repeatable** motions
5. Nobody was harmed in the making of this robot

# Challenges

- Continuously refining the project scope
- Determining parameters to decide on a wrist mechanism
- Mechanical effects of motor vibration
- Reducing weight while maintaining strength of materials
- Tuning motor gains to properly follow input trajectories



# Reflection and Next Steps

## Improvements

- Developing a full system model to optimize gains for improved tracking
- Recording more interactive training demos
- Establishing a hit notification system in the vest for user feedback

## Exit strategy

- **If this project were to be continued, we believe the best next step would be to actuate the arm to allow wrist mechanism translation**
    - Since we achieved our weight goal of <5 kg, the wrist mechanism could be mounted on a range of shelf arms

# Questions?

(P.S. Come to our booth to see more cool demos!)

Recommended Sections (notes from the capstone class session on Tuesday Nov. 25):

- Problem statement (one slide, nothing but the statement)
- Background/context/motivation
- Prior work
- Your solution and general description (get to this as soon as you set the stage)
    - Show an image of CAD or visually show the user experience, then show the product
    - Should include team strategy, challenges, design process, analysis
    - Don't need to go deep into detail for analysis, they want methods and results, as well as how those results were used (specific aspects of the design motivated by the analysis
    - How did we approach iteration? One big build with analysis behind it or many cheap iterations?
    - Show images throughout the process, early models or mockups
    - Do NOT show a bunch of design iterations before showing your main design, use example images to explain the process but don't get into detail on previous iterations
    - Show key successes, show we have met our goals or say what we have contributed, be specific and quantitative, use feedback if we received any

- Reflection/improvements
    - Inclusivity?
    - What needs to be done to truly capitalize on our work?

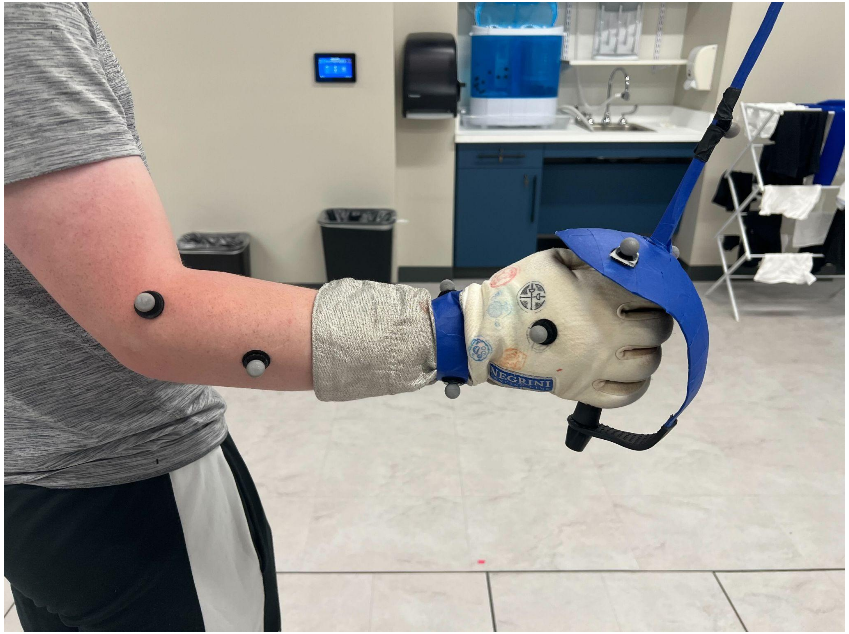
- Exit strategy
    - Where is it going to go? Be realistic, don't over promise if you have not already done work towards any of your claims
    - Don't force it, if you are going to dismantle it and move on it's ok to say that too unless you have a better plan

Dress code is formal, we are expected to be wearing suits

# Motion Capture Analysis

## 1. **Data Collection**

- Motion capture studio on the 4th floor of Richards hall
- Access provided by the Shepherd Lab
- Data was collected in late August

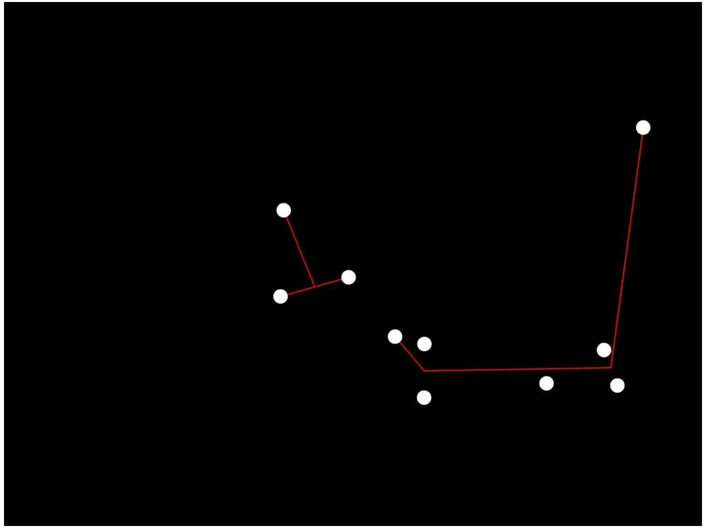


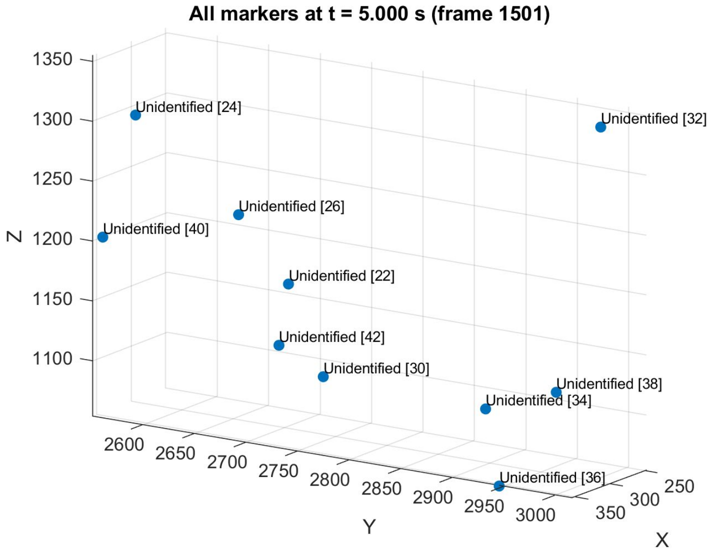
Marker Placement

# Motion Capture Analysis

## 2. **Post-Processing**

- Post-processing was performed partially with the Mo-Cap toolbox written for MATLAB [X]
- Additional software was created to visualize marker sets and automatically remove duplicates





# Motion Capture Analysis

## 4. **Convert to Robot Trajectories**

- Used *Onshape-to-Robot* [X] to export URDFs of simple wrist geometries
- Created animations and solved for joint angles using the Robotic System Toolbox for MATLAB with orientation input from the previous step
- Repeated this process for a variety of designs

- After we present our cad and final assembly, we need to emphasize how the information that follows led to decisions for our final robot
  - We can say that due to budget and time, we knew we would only get 1-2 iterations so alot of our work was analytical (motion capture, wrist mechanism selection)
  - We should explain how we split up the work
  - Maybe a good way to structure the wrist and base arm slides could be to think of 1 slide for design solution, one for design process and one for challenges/displaying results

Flowchart for Team Strategy, Challenges, Design Process and Analysis Section

- Everybody can comment and we can move stuff around for flow just putting a template

Motion Capture
(2-3 Slides?)

Wrist Selection
(2-3 Slides?)

Base and arm
(2-3 Slides?)

Results/Key Successes
(1-2 Slides?)

Analysis/FEA
(2-3 Slides?)

Challenges
(1-2 Slides?)

Reflection/ Improvements/ Exit Strategy
(2 Slides?)

**Total**
11-18 Slides

Think about phrases like…

*"Early on, we realized our biggest challenges would be… so we…."*

*"Because of xxx… a lot of our work was experimental/analytical/computational…."*

*"We split up our team/schedule in the following way…."*