ES 656**: Human-Robot Interaction**

Spring 2025
Class Project I

Topic: Biomechanical movement analysis of a Bicep Curl using OpenSim software
Task: Data collection, analysis, interpretation, and presentation

Author: Shashank Ghosh, Department of Mechanical Engineering
Vishal Ubnare, Department of Cognitive Science
Instructor: Prof. Vineet Vashista

Introduction

Biomechanics is the study of mechanical principles applied to biological systems, particularly the human body. It integrates physics, engineering, and physiology to analyze movement, forces, and their effects on muscles, bones, and joints. Understanding biomechanics is essential in fields such as sports science, rehabilitation, robotics, and ergonomics.

It demonstrates how the central nervous system regulates muscle recruitment, coordinates activation patterns, and fine-tunes joint movements. This analysis plays a crucial role in advancing robotic technologies, including prosthetics, exoskeletons, and rehabilitation robots, enabling them to replicate or support natural human motion more effectively

OpenSim is an open-source software used for musculoskeletal modeling and simulation. It allows researchers to analyze joint kinematics, muscle activation, and forces during movements like a bicep curl.

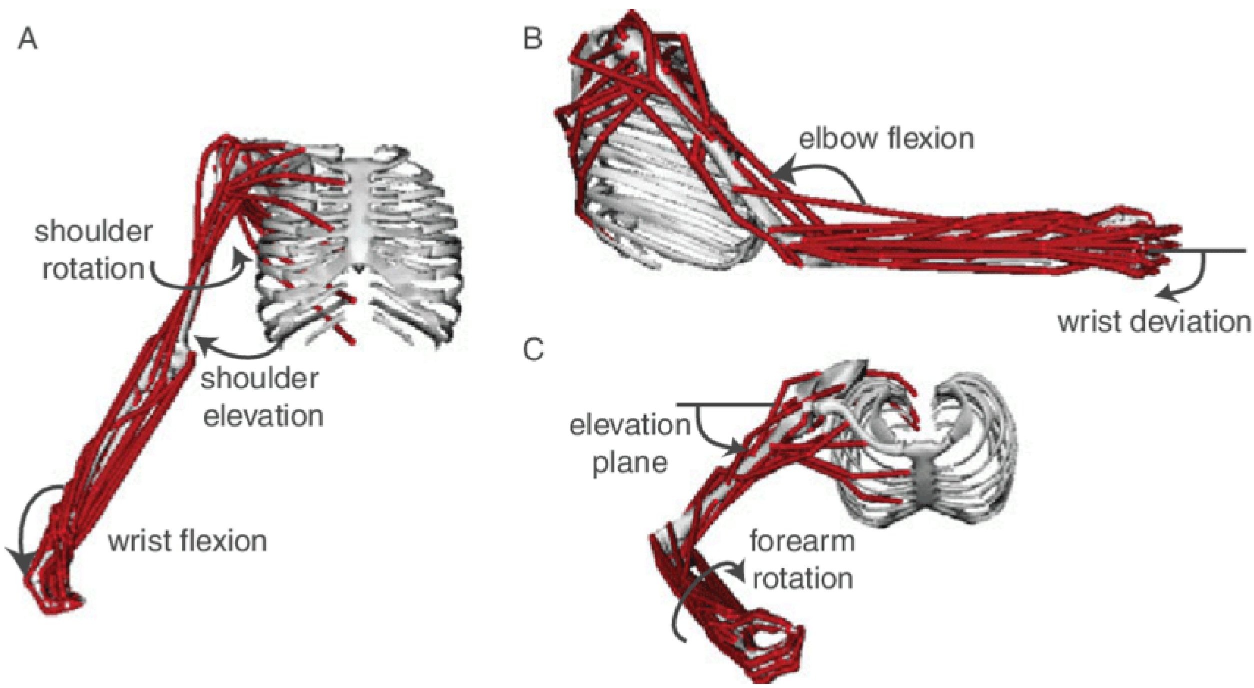
For this class project, our team investigates biomechanical movement analysis using OpenSim, focusing on the bicep curl. We systematically examine this movement by utilizing an open-source musculoskeletal model and relevant data. Our analysis involves applying inverse kinematics and dynamics to assess joint motion and forces, followed by estimating muscle activations required for the exercise. Through this study, we aim to gain deeper insights into human movement mechanics, contributing to a better understanding of human-robot interaction and optimizing performance in rehabilitation and training

Background

The CNS, comprising the brain and spinal cord, plays a crucial role in controlling movement. It processes sensory inputs, plans motor actions, and sends signals to muscles via neural pathways. Neural control regulates muscle activation, ensuring precise and coordinated movement. Muscle recruitment refers to the sequential activation of motor units to generate force, while actuation involves the conversion of neural commands into mechanical motion through muscle contractions.

Biomechanical analysis helps decode the complex interactions between muscles, joints, and external forces. It aids in improving athletic performance, preventing injuries, and designing prosthetics, exoskeletons, and rehabilitation devices that closely mimic human motion.

Inverse kinematics (IK) determines joint angles needed to achieve a desired limb position, while inverse dynamics (ID) calculates joint forces and torques based on motion data. These methods are essential for understanding human movement mechanics, we analyse IK and ID results with time using OpenSim. We also do static optimization of the movements to see what muscles are activated the most during the movement.



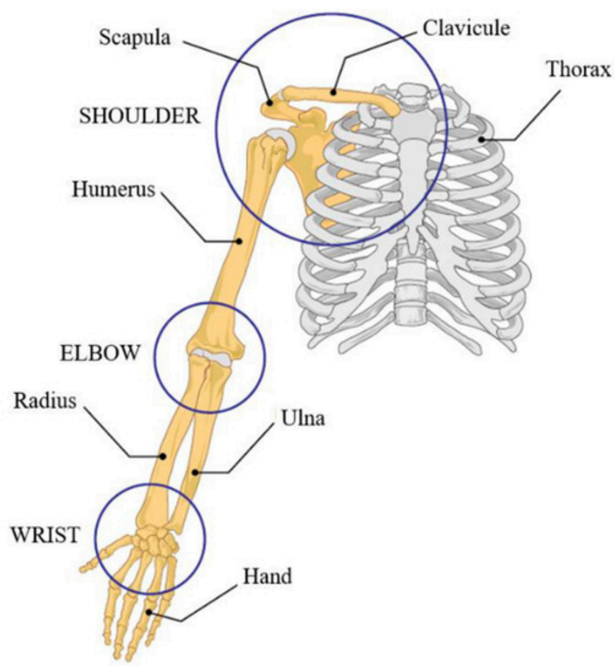
Methods

Model

For this project, our team chose an upper-limb unimanual musculoskeletal model based on the work of Saul et al. (2015). This model was selected for its detailed representation of upper-limb dynamics, incorporating accurate anatomical structures, joint mechanics, and muscle functions. Its comprehensive design makes it ideal for biomechanical simulations, Open-Sourced, particularly in studying human-robot interaction tasks involving arm and hand movements.

Data collection

We use the Vicon Motion Capture system from HRI lab to place 10 markers on the upper limb at different locations of joints and bones to see their movement in space while a Bicep curl is performed. We then use this data to scale the model in OpenSim and perform IK, ID and Static Optimizations to analyze the results.



Description of Model

Joint Space Degrees of the Unimanual Freedom

The selected upper-limb model features a total of seven degrees of freedom (DOF), distributed across key joints:

- ➢ **Shoulder (3 DOF):**

- Elevation (thoracohumeral angle)
- Rotation
- Plane of elevation

➢ **Elbow (1 DOF):**

- Flexion and extension

➢ **Forearm (1 DOF):**

- Pronation and supination (rotational movement of the forearm)

➢ **Wrist (2 DOF):**

- Flexion and extension
- Radial and ulnar deviation (side-to-side wrist movement)

This model accurately represents upper-limb motion, enabling biomechanical analysis of complex arm movements.

Markers Placement on Body

The dataset contains three-dimensional motion capture data obtained using a standard set of 10 reflective markers positioned at key anatomical landmarks of the upper limb. These markers were strategically placed to ensure accurate tracking of joint movements and interactions throughout the motion. The specific marker locations include:

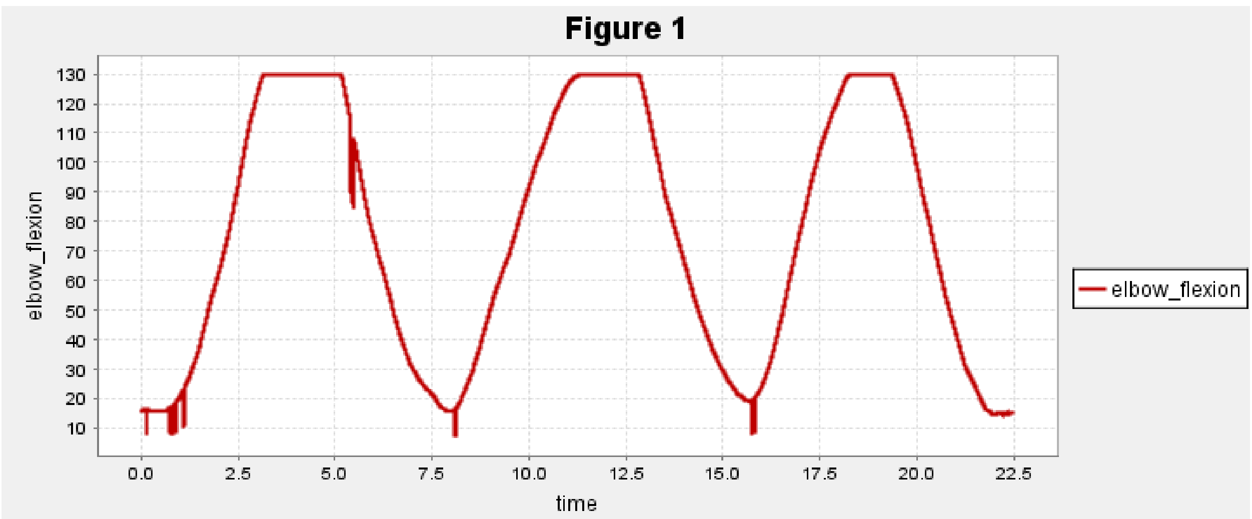
★ Clavicle
★ C7 vertebra
★ Shoulder
★ Bicep
★ Lateral elbow
★ Medial elbow
★ Forearm
★ Handle
★ Radius
★ Ulna

This marker setup enables precise measurement of upper-limb kinematics, facilitating detailed biomechanical analysis.

Analysis and interpretation

Inverse Kinematics -

Inverse kinematics (IK) is a computational technique used to determine joint angles required to achieve a specific limb position. It is essential in biomechanical analysis for tracking motion, understanding joint coordination, and optimizing movement efficiency. IK helps reconstruct human motion from motion capture data, aiding in injury prevention and rehabilitation research.



Elbow flexion joint angles with time

Observations:

1. **Cyclic Pattern:**
   - The curve shows a repeating motion, indicating multiple repetitions of the bicep curl.
   - Each cycle consists of **a rise (flexion) followed by a fall (extension)**.

2. **Range of Motion:**
   - The flexion angle starts near **0°** (fully extended elbow).
   - Peaks at around **130°**, which is typical for a full contraction in a bicep curl.

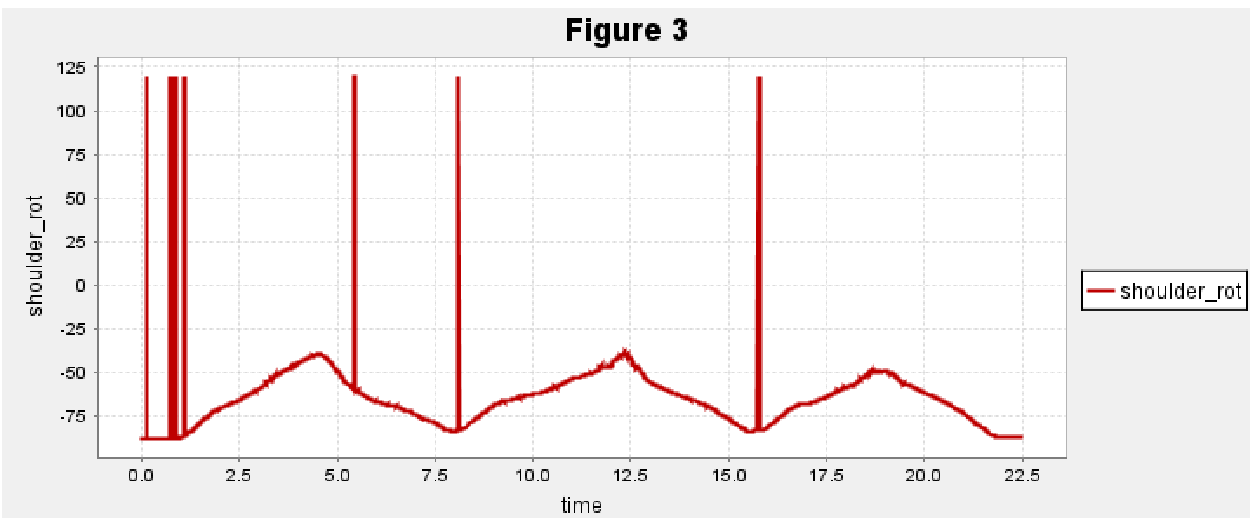
3. **Smoothness of Motion:**

- The motion is mostly smooth, except for some fluctuations at the **start of each flexion phase** and at the **lowest flexion angle**.

4. **Consistency Between Repetitions:**
    - If one cycle deviates significantly, it could suggest **fatigue, external interference, or improper execution**.

Inverse Dynamics

Inverse Dynamics is a computational approach used in biomechanics and robotics to determine the forces and torques required to produce a given motion. It is useful for analyzing human movement, designing prosthetics, optimizing athletic performance, and controlling robotic systems by estimating joint forces based on observed kinematics and external forces.



Shoulder Rotation angle with time

Multiple Joint Contributions:

- The plot includes various joint angles and movements, such as **elbow flexion, shoulder elevation, pronation/supination, and wrist angles**.

Variability in Motion:

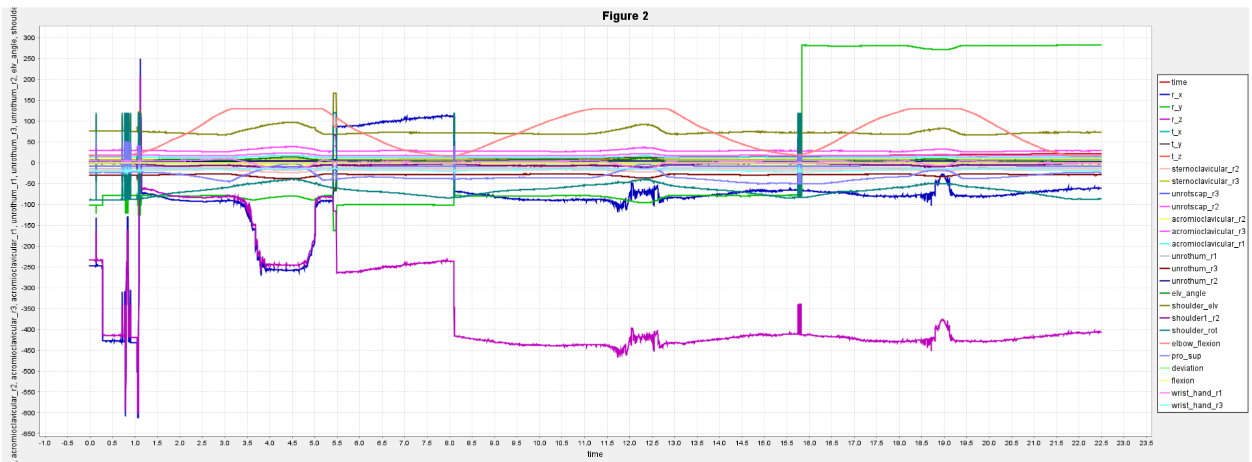
- **Elbow flexion and shoulder elevation** follow smooth, periodic cycles, indicating a consistent movement pattern.
- **Sternoclavicular and acromioclavicular movements** exhibit more fluctuations, possibly due to minor compensatory motions in the shoulder and upper arm.

Sharp Spikes and Sudden Changes:

- These could be caused by **measurement noise, abrupt movement changes, or instabilities in motion tracking**.

Range of Motion for Different Joints:

- The **elbow flexion** follows a smooth sinusoidal pattern, showing flexion-extension cycles during the curls.
- **Shoulder movements (shoulder_elv, shoulder_rot)** remain relatively stable but show minor variations, indicating **secondary involvement** in stabilizing the movement.
- **Pronation/Supination (pro_sup)** fluctuates, possibly due to slight wrist rotation during the curl.



Inverse Dynamics (Joint Moment/Torque) with time

Fluctuations at Certain Points (Potential Noise or Instability):

- Some joints, particularly **acromioclavicular_r2, unrot_humeral_r1, and wrist moments (wrist_hand_r1, r3)**, show **sudden spikes** early in the movement (0-2s) and around 15-16s.

Cyclic Patterns for Major Joint Moments:

- **Elbow flexion (elbow_flexion)** appears to follow a **smooth sinusoidal wave**, which aligns with the expected torque pattern for a bicep curl.

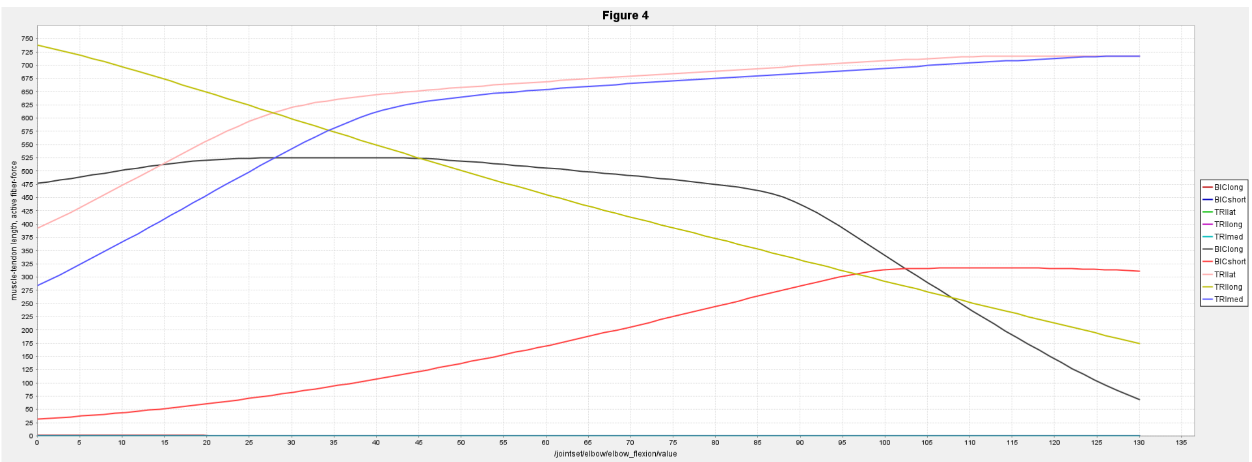
- Shoulder elevation **(shoulder_elv) and** pronation/supination **(pro_sup)** also show **periodic** trends, indicating coordinated movement of the upper limb.

Negative & Positive Torque Variations:

- Some joints exhibit high **negative** torque values **(e.g., acromioclavicular and humeral components)** at certain timestamps, which indicates **muscle co-contraction** or an external force acting against movement.

Static Optimization

Static Optimization is a numerical method used in biomechanics to estimate muscle forces during motion. It is applied after Inverse Dynamics to distribute the computed joint moments among multiple muscles based on an optimization criterion (e.g., minimizing total muscle activation or effort). It identifies which muscles contribute to movement without requiring direct EMG data.



Active Fiber force (Triceps and Biceps) with Elbow Flexion

Analysis:-

The x-axis represents elbow flexion angle **(degrees)**.
The y-axis represents **muscle-tendon length or active fiber force**.

- BIClong - (Biceps Long Head)
- BICshort - (Biceps Short Head)
- TRIlat - (Triceps Lateral Head)
- TRIlong - (Triceps Long Head)
- TRImed - (Triceps Medial Head)

Biceps (BIC) Behavior:

- The BIClong and BICshort increase in force as elbow flexion increases.
- The BIClong force rises initially, peaks, and then drops at higher flexion angles (~100°).
- The BICshort force increases steadily, reaching its highest values at higher flexion angles.

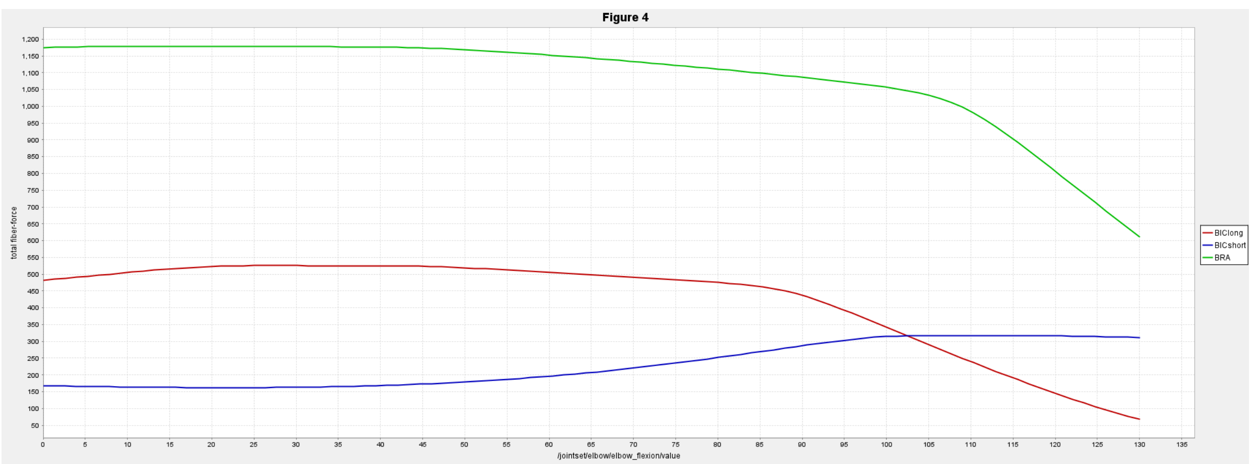
➢ This suggests that the biceps are **most active** at mid-to-high flexion angles before losing mechanical advantage.

Triceps (TRI):

➢ TRIlong decreases as elbow flexion increases.
➢ TRImed increases significantly with elbow flexion.
➢ TRIlat remains close to zero, indicating minimal contribution.
➢ This suggests that **the long head of the triceps is more active during elbow extension** and loses its ability to generate force as flexion increases.
➢ The **medial head of the triceps compensates** at higher flexion angles.

Force Distribution Between Muscle Groups:

➢ At low elbow flexion angles (~0-40°), the triceps contribute more to joint stabilization and force.
➢ At higher elbow flexion angles (~80-120°), the biceps dominate.
➢ The transition point (~60°-80°) is where force contributions shift significantly from triceps to biceps.



Active Fiber force (Brachialis and Biceps) with Elbow Flexion

X-axis: Elbow flexion angle (degrees).
Y-axis: Total fiber force (N).

Muscles Analyzed:

- BIClong (Biceps Long Head) - Red
- BICshort (Biceps Short Head) - Blue
- BRA (Brachialis) - Green

Brachialis (BRA):

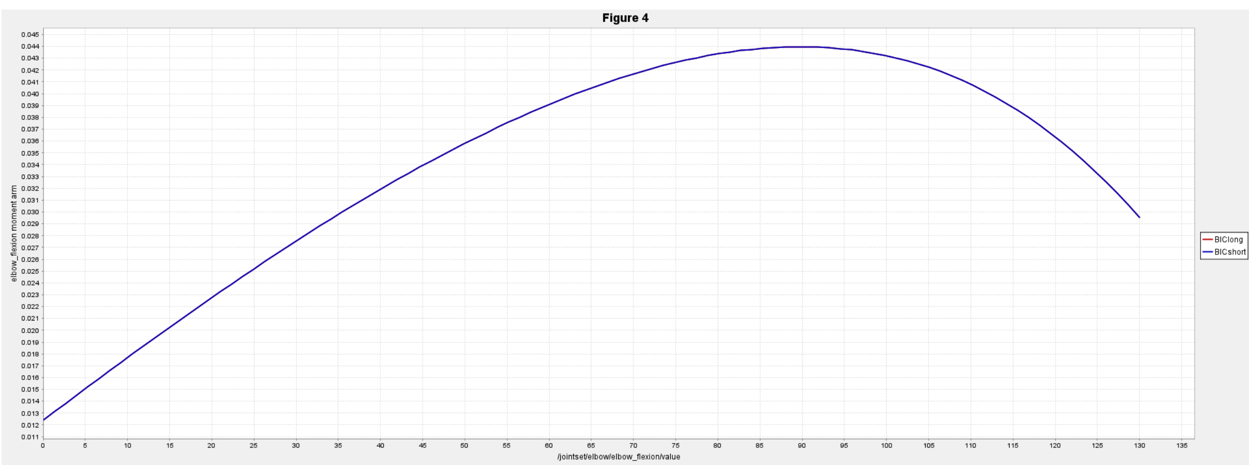
- The brachialis muscle generates the **highest force** among the three.
- It maintains a nearly constant force from **0° to ~90°**, with a slight decline afterward.
- This suggests that the **brachialis is active throughout elbow flexion**, contributing significantly to flexion stability.

Biceps Long Head (BIClong):

- The force **slightly increases** up to ~30°-40°, then plateaus before **decreasing rapidly after ~90°**.
- This suggests that the biceps long head is more **effective at lower flexion angles** and loses mechanical advantage at higher flexion.

Biceps Short Head (BICshort):

- The force remains relatively **low at small angles (0°-40°)**.
- This indicates that the biceps **short head** plays a greater role at **higher** flexion angles.



Moment arm with Elbow Flexion

X-axis: Elbow flexion angle (degrees).

Y-axis: Elbow flexion moment arm (meters).

- Muscles Analyzed:
    - BIClong (Biceps Long Head)
    - BICshort (Biceps Short Head)

Observations:

1. General Trend:

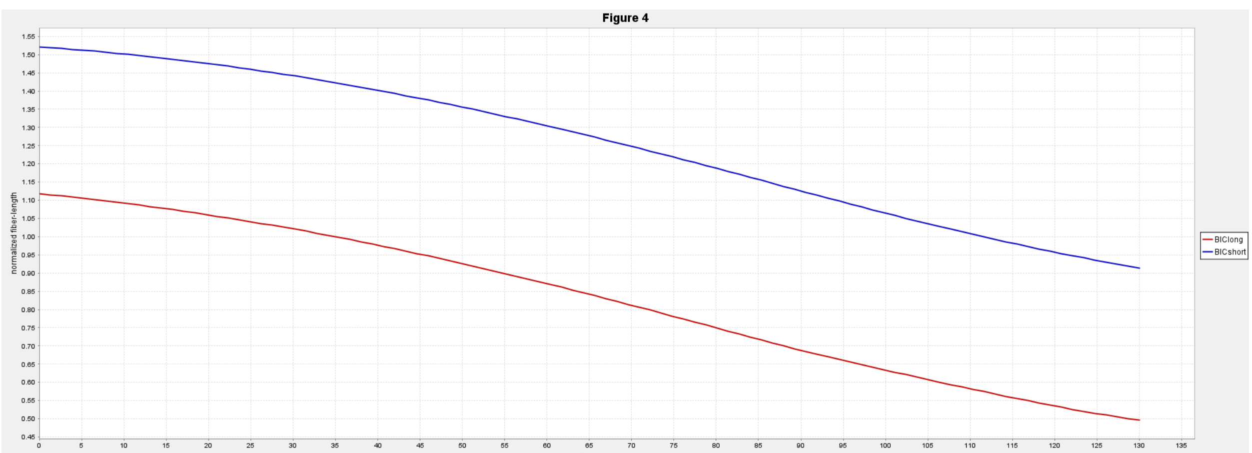
    - Both the biceps long head and short head moment arms increase initially as elbow flexion increases.
    - The **moment arm peaks** around 85°-90° flexion.
    - After 90°, the moment arm **gradually decreases**.

2. Peak Moment Arm (~85°-90°):

    - The **biceps is most mechanically efficient at this range**, meaning it generates maximum torque at mid-range elbow flexion.
    - This explains why exercises like bicep curls **feel strongest** around **90°** flexion.

3. **Post-90° Decline:**

    - As elbow flexion increases beyond 90°, the moment arm **decreases**, reducing the mechanical advantage of the biceps.
    - This suggests that at high flexion angles (>100°), other muscles (like the brachialis) contribute more to elbow flexion.



Fiber length (Biceps) vs Elbow Flexion

X-axis: Elbow flexion angle (degrees).
Y-axis: Normalized fiber length (dimensionless)

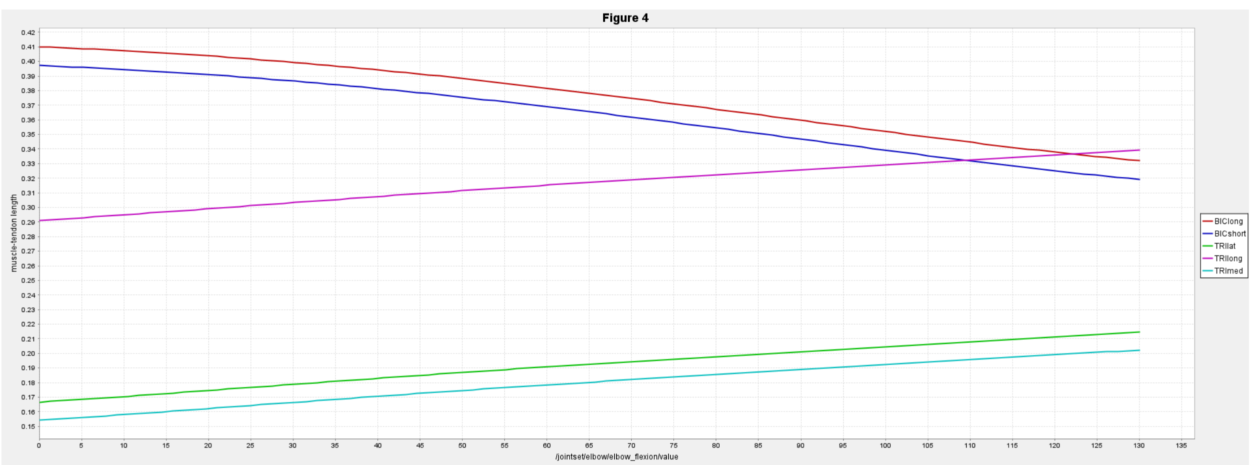
Observations:

1. General Trend:
    - Both the biceps long head and short head fiber **lengths decrease** as elbow flexion increases.

    - The fiber length starts highest at full extension (~0°) and progressively shortens as the elbow flexes to ~130°.

2. Biceps Long Head vs. Short Head Fiber Length**:**
    - Biceps Short Head (Blue) remains longer than the Biceps Long Head (Red) at all angles.
    - This suggests that the short head maintains a greater contractile length, which could influence force generation at different angles.

3. Rate of Fiber Shortening:
    - Both **muscles shorten consistently**, with the long head shortening slightly faster than the short head.
    - The **long head reaches a more contracted state earlier**, possibly due to its attachment at the supraglenoid tubercle of the scapula, giving it a larger resting length.



X-axis: Elbow flexion angle (degrees)
Y-axis: Muscle-tendon length (normalized)

Muscles Represented:

- Biceps Long Head (BIClong)
- Biceps Short Head (BICshort)
- Triceps Lateral Head (TRIlat)
- Triceps Long Head (TRIlong)
- Triceps Medial Head (TRImed)

Biceps Muscle-Tendon Lengths:

- BIClong & BICshort
    - Both **decrease in length as elbow flexion increases**, indicating active contraction.
    - The **long head (BIClong) starts longer but shortens more steeply** than the short head (BICshort)..

2. Triceps Muscle-Tendon Length:

- TRIlat, TRIlong, TRImed
    - All three **increase in length as elbow flexion increases**, showing passive stretch.
    - The long head of the triceps (TRIlong) starts the longest and increases more steeply, indicating it plays a major role in elbow extension.

The figures show how muscle-tendon lengths change with elbow flexion, indicating muscle activation patterns. As elbow flexion increases, **biceps brachii (long and short heads)** shorten, suggesting increased activation to generate flexion torque. In contrast, **triceps brachii (long, lateral, and medial heads)** lengthen, indicating they act eccentrically to control flexion. Around 100-110° flexion, biceps and triceps tendon lengths converge, implying a transition in muscle dominance or co-contraction for stability. The **biceps long head** maintains a slightly greater length than the short head, showing its role in multi-joint coordination. These trends reflect dynamic muscle coordination required for controlled elbow motion.

OpenSim determines muscle recruitment by solving an optimization problem that minimizes activation while ensuring sufficient force for movement. Based on the results, **biceps brachii (long and short heads) are primarily actuated** during elbow flexion, with activation increasing as flexion progresses. In contrast, **triceps brachii (long, lateral, and medial heads) are recruited eccentrically** to control the motion. The recruitment follows a **coordination strategy** where muscles actuate at optimal moments to balance joint torques. The peak activation of biceps occurs around mid-range flexion, while triceps activation increases during extension. This solution efficiently distributes force among muscles, preventing overuse and improving stability

Model Sensitivity Analysis

Modifying model properties can significantly impact muscle recruitment results. **Removing muscles** would force greater compensation from remaining muscles, potentially leading to unrealistic activations or excessive joint stress. **Adding muscles** may distribute forces more evenly but could alter natural movement patterns. **Changing limb segment masses** affects inertia and moment arms, requiring muscles to generate different forces to maintain movement stability. For instance, **increasing forearm mass** would demand higher biceps activation during flexion to counteract greater torque. These changes highlight the importance of accurate model properties for biomechanical realism and optimal muscle coordination prediction.

References -

[1] K. R. Saul, X. Hu, C. M. Goehler, M. E. Vidt, M. Daly, A. Velisar, and W. M. Murray, "Benchmarking of dynamic simulation predictions in two software platforms using an upper limb musculoskeletal model," Comput. Methods Biomech. Biomed. Eng., vol. 18, no. 13, pp. 1445–1458, 2015.