Human Robot Interaction Project 1

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1. INTRODUCTION

Understanding the biomechanics of human movement is essential in fields such as rehabilitation, sports science, ergonomics, and human-robot interaction. Musculoskeletal modeling, supported by tools like OpenSim, provides a powerful framework to simulate, analyze, and visualize internal dynamics such as joint kinematics, muscle forces, and joint torques—elements that are otherwise difficult to measure non-invasively.

This project focuses on the simulation and analysis of an overhead press, a fundamental upper-limb exercise that involves coordinated activation of multiple joints and muscle groups. Using a subject-specific upper limb musculoskeletal model, the motion was captured, processed, and analyzed through a comprehensive pipeline involving scaling, inverse kinematics (IK), inverse dynamics (ID), static optimization (SO), and muscle force estimation.

The aim of this study is to investigate how muscles such as the deltoids, triceps, and latissimus dorsi contribute to the motion, and how joint-level moments and reaction forces evolve throughout the exercise. Additionally, the project explores the effects of varying model parameters through a sensitivity analysis, and evaluates the optimization framework used for muscle recruitment estimation.

2. Model Selection and its Properties

In this project, we have selected an upper limb musculoskeletal model to study human arm dynamics and neuromuscular coordination using OpenSim. Specifically, the `MobL_ARMS_OpenSim41_unimanual_model` , a well-documented and publicly available model from the OpenSim library, has been used.

This model has been designed to capture detailed anatomical and functional properties of the human upper extremity, making it suitable for simulations involving human-robot interaction tasks such as reaching, manipulation, and load handling.

2.1. Joint Space Degreee of Freedom

The `MobL_ARMS_OpenSim3_unimanual_model` offers a total of seven degrees of freedom (7-DoF), enabling the representation of independent joint motion across the shoulder, elbow, forearm, and wrist. These degrees of freedom are categorized as follows:

Shoulder Joint (3-DoF)

The glenohumeral (shoulder) joint is modeled as a ball-and-socket joint, allowing three rotational degrees of freedom:

- Flexion/Extension
- Abduction/Adduction
- Internal/External Rotation

2.2. Elbow Joint (1-DoF)

The elbow joint is modeled with a single rotational degree of freedom, representing:

- Flexion/Extension

2.3. Forearm (1-DoF)

The forearm allows:

- Pronation/Supination of the radius relative to the ulna

2.4. Wrist Joint (2-DoF)

The wrist joint consists of:

- Flexion/Extension
- Radial/Ulnar Deviation

This kinematic structure enables realistic simulations of upper limb movements in three-dimensional space, essential for evaluating motion planning, control, and physical interaction in robotic systems.

2.5. Range of Motion

Typical ranges of motion incorporated in the model include:

Shoulder

- Flexion: up to ∼180°
- Extension: up to ∼60°
- Abduction: up to ∼180°
- Internal Rotation: ∼70–90°
- External Rotation: ∼90°

Elbow

- Flexion: up to ∼145°
- Extension: 0° (full extension)

Forearm

- Pronation/Supination: approximately ±90°

Wrist

- Flexion: ∼80°
- Extension: ∼70°
- Radial Deviation: ∼20°
- Ulnar Deviation: ∼30° **[1]**

These values ensure that the model can accurately capture a wide variety of functional movements of the upper limb.

2.6. Muscles Types

The model includes a comprehensive set of muscle-tendon actuators representing the major muscle groups responsible for upper limb movement. In total, the muscle set includes both superficial and deep muscles that span across the shoulder, upper arm, forearm, wrist, and hand. The muscles are implemented using Hill-type muscle models, which simulate active and passive force generation.

Below is a classification of the muscles included in the model:

a. Shoulder Muscles

Deltoid Group: DELT1, DELT2, DELT3

Rotator Cuff Muscles:

- Supraspinatus (SUPSP)
- Infraspinatus (INFSP)
- Subscapularis (SUBSC)
- Teres Minor (TMIN)

Other Shoulder Stabilizers:

- Teres Major (TMAJ)
- Pectoralis Major (PECM1, PECM2, PECM3)
- Latissimus Dorsi (LAT1, LAT2, LAT3)
- Coracobrachialis (CORB)

b. Elbow Muscles

Flexors:

- Biceps Brachii (BIClong, BICshort)
- Brachialis (BRA)
- Brachioradialis (BRD)

Extensors:

- Triceps Brachii (TRIlong, TRIlat, TRImed)
- Anconeus (ANC)

c. Forearm Muscles

Pronators and Supinators:

- Pronator Teres (PT)
- Pronator Quadratus (PQ)
- Supinator (SUP)

d. Wrist Muscles

Flexors:

- Flexor Carpi Radialis (FCR)
- Flexor Carpi Ulnaris (FCU)
- Palmaris Longus (PL)

Extensors:

- Extensor Carpi Radialis Longus (ECRL)
- Extensor Carpi Radialis Brevis (ECRB)
- Extensor Carpi Ulnaris (ECU)

e. Finger Muscles

Flexors:

- Flexor Digitorum Superficialis (FDSL, FDSR, FDSM, FDSI)
- Flexor Digitorum Profundus (FDPL, FDPR, FDPM, FDPI)
- Flexor Pollicis Longus (FPL)

Extensors:

- Extensor Digitorum (EDCL, EDCR, EDCM, EDCI)
- Extensor Digiti Minimi (EDM)
- Extensor Indicis Proprius (EIP)

f. Thumb Muscles

Extensors and Abductors:

- Extensor Pollicis Longus (EPL)
- Extensor Pollicis Brevis (EPB)
- Abductor Pollicis Longus (APL)

This diverse set of muscles provides the capability to model a wide range of functional tasks with biomechanical accuracy. The redundancy in muscle paths also enables realistic force distribution during optimization-based simulations such as inverse dynamics and static optimization.

3. DATA COLLECTION

The overhead press activity was performed by a human subject as part of this project aimed at analyzing upper limb kinematics. A total of ten reflective markers were strategically placed on the subject's right upper limb and associated anatomical landmarks to accurately capture the movement trajectory during the task. These markers were positioned according to established biomechanical conventions to ensure precise joint and segment tracking. The placement included locations such as the C7 vertebra, shoulder, clavicle, bicep, medial and lateral elbow, forearm, ulna, radius, and the handle, facilitating comprehensive motion reconstruction.

The experiment was recorded using a Vicon Nexus motion capture system, equipped with multiple high-speed infrared cameras. The subject was positioned within the calibrated capture volume, and the overhead press movement was performed under controlled laboratory conditions. The camera system tracked the 3D position of each reflective marker at a high frame rate to ensure temporal accuracy.

Following the recording session, the captured data were processed using Vicon Nexus software, where the raw marker positions labelled as shown in the figure. Marker labeling was performed manually with reference to the physical marker setup on the subject to maintain anatomical consistency throughout the dataset. This post-processing step was critical in preparing the data for downstream kinematic analysis and visualization.

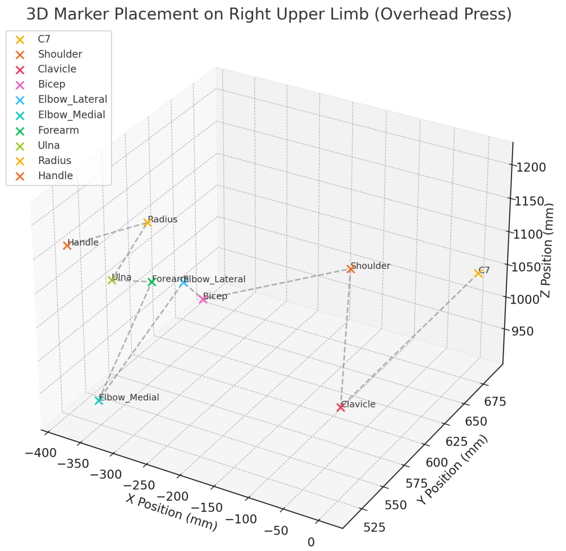

Figure 1. *Markers Setup*

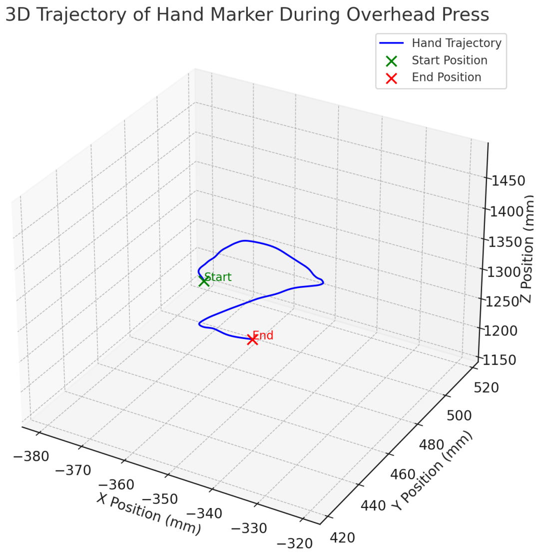

Figure 2. *Movement of the hand during Overhead Press Activity*

This figure illustrates the three-dimensional trajectory of the hand marker Handle throughout the overhead press activity.

The plot begins with a green-labeled point, representing the **initial position of the hand** at the start of the movement. At this point:

- The subject is in the *ready position*, with the hand positioned at approximately **shoulder height**.
- Handle is being held securely before initiating the press.
- This marks the beginning of the **concentric phase** of the overhead press, i.e., the *lifting phase*.

The blue line represents the **continuous path** traced by the hand marker across time. It captures:

- The **upward movement** of the hand as the subject presses the bar overhead.
- A short **pause or stabilization point** at the top, visible as a subtle curve or flattening in the trajectory.
- The **downward return** of the hand to the starting position, completing the *eccentric phase* of the movement.

The red marker indicates the **final recorded position** of the hand:

- The hand has returned close to its initial position, suggesting that a **full repetition** was completed.
- The change in **Z-position** from start to peak and back again confirms that both the *lifting* and *lowering* phases of the overhead press were performed.

This XZ plane plot shows how the shoulder, elbow, and hand move in a forward-backward (X) and vertical (Z) direction during an overhead press. The hand's red curve rises and falls, indicating the bar is pushed upward and then lowered. The dashed shoulder and elbow paths show smooth, coordinated motion, with the elbow extending and the shoulder elevating as the hand moves overhead. This confirms proper vertical pressing mechanics, with only slight forward displacement as expected for a natural overhead press.

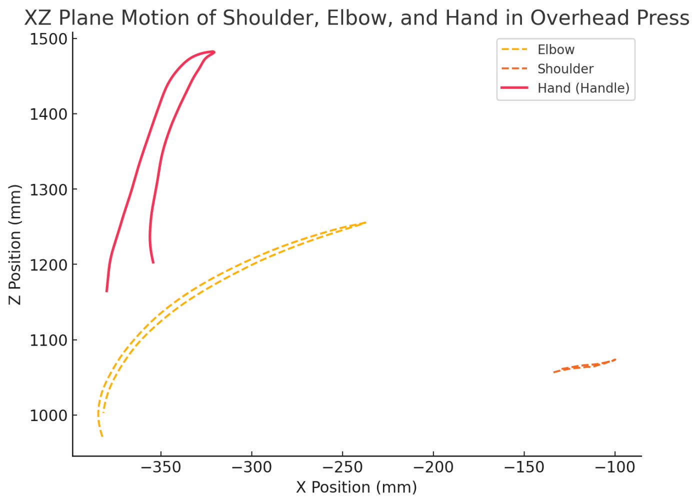

Figure 3. *2D plot of the movement of the various markers*

4. INVERSE KINEMATICS AND DYNAMICS

The overhead press activity that was performed and recorded earlier, resulted in a motion capture data file in the .trc (trajectory) format. This file contains the time-varying positions of markers placed on the subject's body during the movement.

The .trc motion capture data was uploaded to the Opensim software. **[2]**

An inverse kinematics (IK) analysis was performed. IK uses the marker position data to estimate the joint angles of the scaled model over time. The scaling of the model is done to personalize the genric model to the specific subject, providing more accurate representation of their body. This process solves for the joint angles that would produce the observed marker trajectories.The output of the IK analysis was saved as an inverse kinematics.mot file.

The IK results graph displays the joint angles of the right upper limb over time during the overhead press task.

The blue curve indicates shoulder elevation, rising from approximately 55° to a peak near 130°, reflecting the upward motion of the arm during the press. A brief plateau marks the top of the movement, followed by a smooth decline as the arm lowers, representing the eccentric phase of the overhead press.

The red curve indicates motion in the plane of elevation. It starts near 5°, peaks around 50°, and returns to baseline. This suggests that the motion was performed primarily in the scapular plane, which is biomechanically preferred for overhead pressing due to enhanced shoulder stability and reduced risk.

The green curve, representing shoulder rotation, starts at approximately -35° (external rotation) and transitions toward a more neutral or slightly internally rotated position (close to 0°) as the motion progresses. This trend reflects the natural external-to-neutral shoulder rotation that occurs as the arm is elevated overhead, which helps maintain joint alignment and optimal scapulohumeral rhythm.

The pink and cyan curves remain relatively constant throughout the movement, indicating minimal deviation or flexion at the elbow and wrist. This suggests that the subject maintained a stable elbow and wrist posture throughout the overhead press.

The blue curve shows shoulder elevation torque, rising steadily during the lifting phase and peaking near mid-press as the arm nears full elevation. It then gradually decreases during the lowering phase, indicating reduced muscular effort. This pattern confirms the shoulder as the primary torque-generating joint in the overhead press.

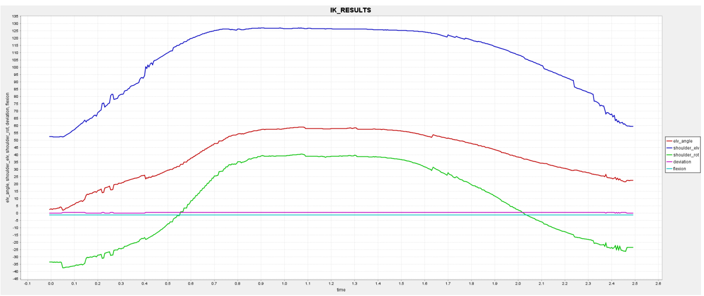

Figure 4. *Inverse Kinematics Results*

To reduce noise and improve the smoothness of the kinematic data, a MATLAB script was employed. The inverse kinematics.mot file was loaded into MATLAB.The filtering script was executed, processing the joint angle data.The filtered joint angle data was saved as a new file (referred to as "filtered IK results"). This filtered data represents a cleaner, more reliable representation of the joint kinematics.

The filtered IK results (the smoothed joint angle data) were used as input for an inverse dynamics (ID) analysis, also performed in the Opensim software.

Inverse dynamics uses the joint kinematics along with the model's inertial properties and external forces to estimate the net joint forces and moments required to produce the observed motion. It essentially works "backward" from the motion to determine the underlying forces and torques.

The ID analysis generated results representing the time-varying joint forces and moments during the overhead press.

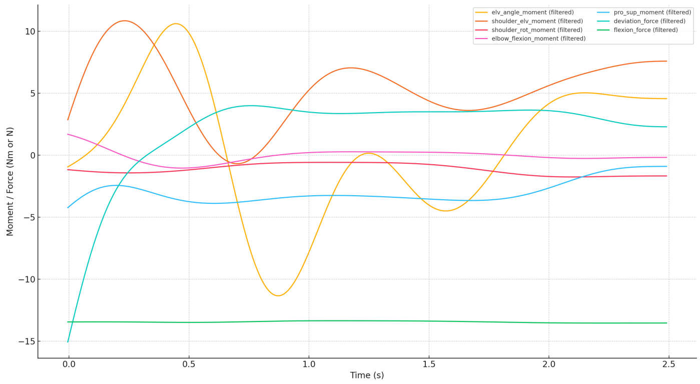

Figure 5. *Inverse Dynamics Results*

The above graph presents an inverse dynamics analysis of a movement, likely an overhead press, spanning approximately 2.5 seconds. The graph displays joint angles and deviation over time.

Starting Position (0 – ~0.3 seconds):

- **elv_angle_moment**: Starts at a small positive value.
- **shoulder_elv_moment**: Begins near zero.
- **elbow_flexion_moment**: Begins with a small positive value.
- **pro_sup_moment**: Starts with a small negative value.
- **flexion_force**: Remains constant and negative.

Lifting Phase (~0.3 – ~1.0 seconds):

- **elv_angle_moment**: Increases significantly, peaking around 11 Nm. This represents the main shoulder elevation torque produced by the deltoids to lift the weight.
- **shoulder_elv_moment**: Also increases, peaking near 7 Nm, reinforcing the effort in shoulder elevation.
- **elbow_flexion_moment**: Decreases, crosses zero, and becomes negative—indicating a shift from stabilization to active elbow extension by the triceps.
- **pro_sup_moment**: Exhibits a rising trend.

Midpoint/Lockout (~1.0 – ~1.8 seconds):

- **elv_angle_moment**: Decreases slightly but remains positive—shoulder elevators remain active to maintain arm elevation.
- **shoulder_elv_moment**: Declines from its peak, staying positive.
- **elbow_flexion_moment**: Remains negative and relatively constant, reflecting sustained effort in elbow extension.
- **pro_sup_moment**: Begins to decrease.

Lowering Phase (~1.8 – 2.5 seconds):

- **elv_angle_moment**: Continues to drop and becomes negative, indicating eccentric control by the deltoids as they resist the weight's descent.
- **shoulder_elv_moment**: Follows a similar trend and turns negative, confirming the shift to eccentric contraction.
- **elbow_flexion_moment**: Gradually increases toward zero and may become slightly positive—signaling reduced triceps effort and controlled elbow flexion.
- **pro_sup_moment**: Stabilizes and becomes nearly constant.
- **deviation_force**: Initially decreases, then stabilizes, suggesting wrist control during descent.

5. Muscle Force Estimation During Overhead Press

Following the inverse kinematics and inverse dynamics analyses, muscle forces during the overhead press were estimated using the Static Optimization (SO) algorithm implemented within the Opensim software. SO provides a computationally efficient method for determining muscle forces, although it does not account for muscle contraction velocity.

The graphs show the estimated muscle forces (in Newtons) over time (in seconds) for three major muscle groups: **Deltoids**, **Triceps**, and **Latissimus Dorsi**. Each group includes three components (likely corresponding to different anatomical heads or functional segments of each muscle). To ensure clarity and reduce noise, the force data have been smoothed using a low-pass filter.

Deltoid Muscles (DELT1, DELT2, DELT3)

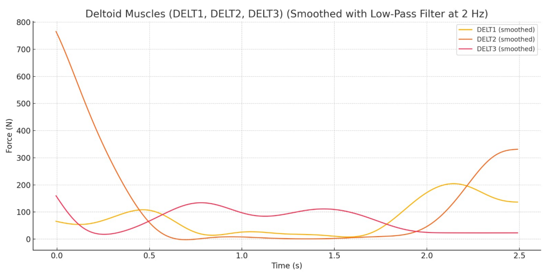

Figure 6. *Deltoids Muscles Forces*

- **DELT1 (anterior deltoid)**: Exhibits a significant initial peak of approximately **750 N** at time 0, which rapidly drops to around **100 N** by 0.5 seconds. This reflects its primary role in initiating shoulder flexion and abduction. Toward the end of the movement (around 2.5 seconds), the force rises again to about **350 N**, likely for shoulder stabilization and control during the lowering phase.
- **DELT2 (middle deltoid)**: Demonstrates sustained activation, beginning near **100 N**, peaking around **220 N** at 1.8 seconds, and tapering off afterwards. This aligns with its consistent role in arm abduction throughout the movement.
- **DELT3 (posterior deltoid)**: Shows low force values, mostly under **50 N**, with a modest peak of about **120 N** near 1.0 second. Its role appears to be primarily in shoulder stabilization.

Triceps Muscles (TRIlong, TRImed, TRIlat)

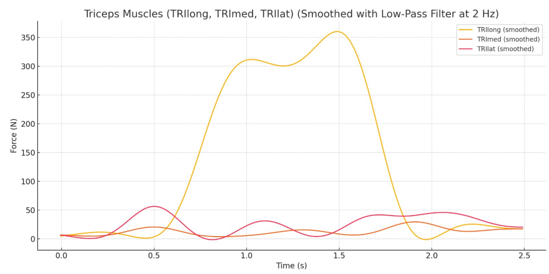

Figure 7. *Triceps Muscle Forces*

- **TRIlong (long head)**: Shows the highest force among the triceps heads, peaking at approximately **360 N** near 1.5 seconds, corresponding to the elbow extension phase required to push the weight overhead.
- **TRImed (medial head)**: Displays much lower activation, peaking around **30 N**.
- **TRIlat (lateral head)**: Also shows low force, with a peak of approximately **40 N**. Both heads support the long head but are not primary contributors.

Latissimus Dorsi (LAT1, LAT2, LAT3)

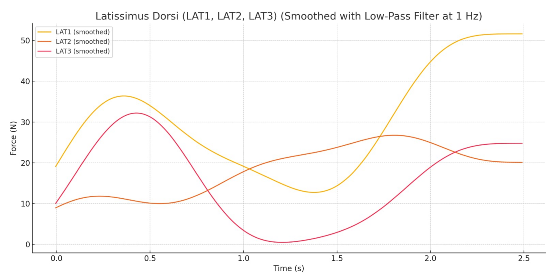

Figure 8. *Latissimus Dorsi muscle forces*

- **LAT1**: Begins around **35 N**, dips briefly, and rises to **50 N** by 2.0 seconds.
- **LAT2**: Starts near **12 N**, reaches a small peak of **23 N**, and displays another minor peak later in the movement.
- **LAT3**: Initiates with a force of about **20 N**, drops to zero at 1.0 second, and then increases again to roughly **26 N**.

Phase-wise Interpretation and Justification

- **Early Phase (0–0.5 seconds):** The anterior deltoid (DELT1) dominates with a peak force of **750 N**, initiating shoulder flexion and abduction to overcome the load's inertia. The high activation is consistent with its biomechanical function in beginning the upward press.
- **Mid-Phase (0.5–1.5 seconds):** The middle deltoid (DELT2) maintains abduction and peaks around **220 N**.

Meanwhile, the triceps, especially TRIlong, begin to activate significantly, reaching a peak of **360 N** at 1.5 seconds, corresponding to the critical elbow extension required to drive the bar overhead.

- **Late Phase (1.5–2.5 seconds):** The triceps (primarily TRIlong) continue to extend the elbow and support the locked-out position. DELT1 rises again to **350 N**, stabilizing the shoulder in the overhead position and likely preparing to eccentrically control the descent.

- **Lowering Phase:** While peak forces are not prominent, the continued activation of DELT1 and DELT2 implies *eccentric contractions*, where the muscles lengthen under tension to control the downward return. The increase in LAT1 and LAT3 force also suggests their role in decelerating and guiding the return to the initial position.

6. Muscle Recruitment Solution

6.1. Deltoid Group

The **anterior deltoid (DELT1)** was identified as a primary initiator of the movement, exhibiting a substantial peak force of approximately **750 N** at the onset of the lift (0–0.5 seconds), followed by a decrease, and a second increase (around **350 N**) later in the movement. This pattern suggests its role in both the initial elevation and the stabilization/control during the lowering phase.

The **middle deltoid (DELT2)** demonstrated sustained activation throughout the overhead press, with a peak force of approximately **220 N** around 1.8 seconds, highlighting its crucial role in shoulder abduction.

The **posterior deltoid (DELT3)** was activated at lower levels, peaking around **120 N**, indicating a likely contribution to shoulder stability and control, rather than acting as a primary mover.

6.2. Triceps Group

The **long head of the triceps (TRIlong)** was the dominant elbow extensor, exhibiting a pronounced peak force of approximately **360 N** around 1.5 seconds, coinciding with the period of maximal elbow extension.

The **medial (TRImed)** and **lateral (TRIlat)** heads of the triceps contributed at significantly lower force levels (generally below **50 N**), assisting the long head in elbow extension.

6.3. Latissimus Dorsi Group

- **LAT1:** Activated initially and again at the end of the motion, with a peak force of approximately **50 N**.

- **LAT2:** Activated during the initial and mid phases of the press, reaching a peak force of approximately **23 N**.

- **LAT3:** Activated at the start, then decreased before rising again, with a peak force of approximately **26 N**.

7. Model Sensitivity Analysis

Deltoid Group (DELT1, DELT2, DELT3)

The deltoid muscles—particularly the middle deltoid (DELT2)—are primary contributors to shoulder abduction and elevation in an overhead press. If **DELT2** is removed or excluded from the model:

- The model may produce *non-physiological compensation* by overloading secondary muscles such as the supraspinatus or pectoralis major.

- Joint torque at the shoulder may appear underestimated, or the motion might fail in muscle-driven simulations (e.g., CMC).

Removing **DELT1** or **DELT3** would impact joint stability, especially during the transition phases of the lift. On the other hand, adding or refining deltoid muscle subdivisions (e.g., incorporating multiple fiber lines or dynamic wrapping surfaces) improves the model's ability to distribute forces and replicate shoulder stabilization mechanisms realistically.

Additionally, altering the mass of the *upper arm segment* (to which the deltoid contributes torque) would affect the moment of inertia, directly influencing the required deltoid force output to initiate or control elevation.

Triceps Group (TRIlong, TRImed, TRIlat)

The **long head of the triceps (TRIlong)** plays a dominant role in elbow extension during the overhead press. If this muscle is removed from the model:

- The joint moment at the elbow would have to be compensated by **TRImed** and **TRIlat**, which are significantly smaller.

- This might result in *implausible muscle activations* or underestimation of elbow torque.

If the mass of the *forearm or hand segments* is increased, it amplifies the demand on TRIlong, requiring greater force to extend and stabilize the elbow, especially when the arm is fully overhead. Removing either TRImed or TRIlat would not drastically affect gross joint torque but may lead to unrealistic asymmetry or lack of stabilization in the elbow, especially during deceleration (eccentric) phases.

Latissimus Dorsi Group (LAT1, LAT2, LAT3)

The latissimus dorsi group provides *postural control*, *scapular stabilization*, and subtle contributions to shoulder extension and internal rotation during an overhead press. If any of the LAT subdivisions (e.g., LAT1) are removed:

- The model may show increased *compensatory effort* from synergistic muscles like the teres major or posterior deltoid.

- Scapulothoracic rhythm and trunk stabilization may be inaccurately represented, especially during the lowering phase.

Moreover, since the lats originate from the trunk and insert into the humerus, changes to *trunk mass or segment inertias* (e.g., scapula, thorax) can significantly impact their function. Increasing trunk mass may cause latissimus force requirements to rise, especially in tasks involving *anti-gravity stabilization*.

8. Static Optimisation

OpenSim's Static Optimization (SO) addresses the muscle redundancy problem by formulating an optimization problem that determines the set of muscle activations necessary to reproduce the observed joint torques while satisfying biomechanical constraints. This is particularly useful in musculoskeletal simulations where the number of muscles exceeds the number of joint degrees of freedom.

Mathematical Formulation. The optimization problem is defined as:

$$\begin{aligned} \text{Minimize:} \quad & J(\mathbf{a}) \\ \text{Subject to:} \quad & \sum_{i \in M_j} f_i(a_i, l_i) \cdot r_{i,j} = M_j \quad \forall j \in J \\ & 0 \leq a_i \leq 1 \quad \forall i \in M \end{aligned}$$

where:

- $\mathbf{a} = [a_1, a_2, \ldots, a_n]^T$ is the vector of muscle activations, where each $a_i \in [0, 1]$ represents the activation of muscle i.
- $J(\mathbf{a})$ is the cost function to be minimized.
- $f_i(a_i, l_i)$ is the force generated by muscle i, which depends on its activation level a_i and length l_i.
- $r_{i,j}$ is the moment arm of muscle i about joint j.
- M_j is the net joint moment at joint j computed from inverse dynamics.
- M_j is the set of muscles spanning joint j.
- J is the set of all joints in the model.
- M is the set of all muscles in the model.

Cost Function Options. The most commonly used cost functions include:

- **Sum of Squared Activations:**

  $$J(\mathbf{a}) = \sum_{i \in M} (a_i)^2$$

  This promotes a distributed muscle recruitment strategy with lower overall effort.

- **Sum of Cubed Activations:**

  $$J(\mathbf{a}) = \sum_{i \in M} (a_i)^3$$

  This penalizes high activations more severely and tends to favor recruitment of multiple low-activation muscles over few high-activation ones.

Solver. OpenSim typically uses a gradient-based solver, such as Sequential Quadratic Programming (SQP), to solve this constrained nonlinear optimization problem. The solver iteratively adjusts the muscle activations to minimize the cost function while satisfying the equality and inequality constraints.

Applicability to the Overhead Press. Static Optimization is particularly suitable for modeling slow, controlled movements like the overhead press. Its strengths include:

- **Computational Efficiency:** Solves the problem frame-by-frame without simulating dynamic muscle activations.
- **Effective Load Sharing:** Distributes muscle forces realistically under the assumption of minimal activation.
- **Satisfies Biomechanical Constraints:** Ensures that muscle forces generate joint moments consistent with observed kinematics.

However, it also has notable limitations:

- **No Temporal Dynamics:** Muscle activation history and contraction velocity are not considered.
- **Neglects Force-Velocity Effects:** May overestimate force in rapid contractions.
- **Dependent on Cost Function:** Different cost functions yield different recruitment patterns.
- **Ignores Passive Forces:** Passive muscle-tendon contributions are not explicitly optimized.

OpenSim's Static Optimization provides a practical and computationally efficient method for estimating muscle forces during quasi-static movements such as the overhead press. While the method captures key aspects of muscle recruitment and load sharing, the simplifications introduced—particularly the omission of time-dependent behavior—must be considered when interpreting results. For dynamic or highly time-sensitive tasks, methods like Computed Muscle Control (CMC) or forward dynamic simulations may offer more physiologically accurate predictions at the cost of increased computational complexity.

References

[1] *Physiotutors. (2022, November 8). Wrist/Hand Active Range of Motion (AROM) | Basic assessment. https://www.physiotutors.com/wiki/wrist-hand-active-range-of-motion/.*

[2] *SIMTK: OpenSim: Downloads. (2024, January 10). https://simtk.org/frs/index.php?group*$_i$*d* $= 91$.

[3] *https://simtk.org/projects/upexdyn*