Parameter Identification for Multimodal Human Motion Measurement

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The Problem

Problem

Muscle forces/activation are hard to observe directly

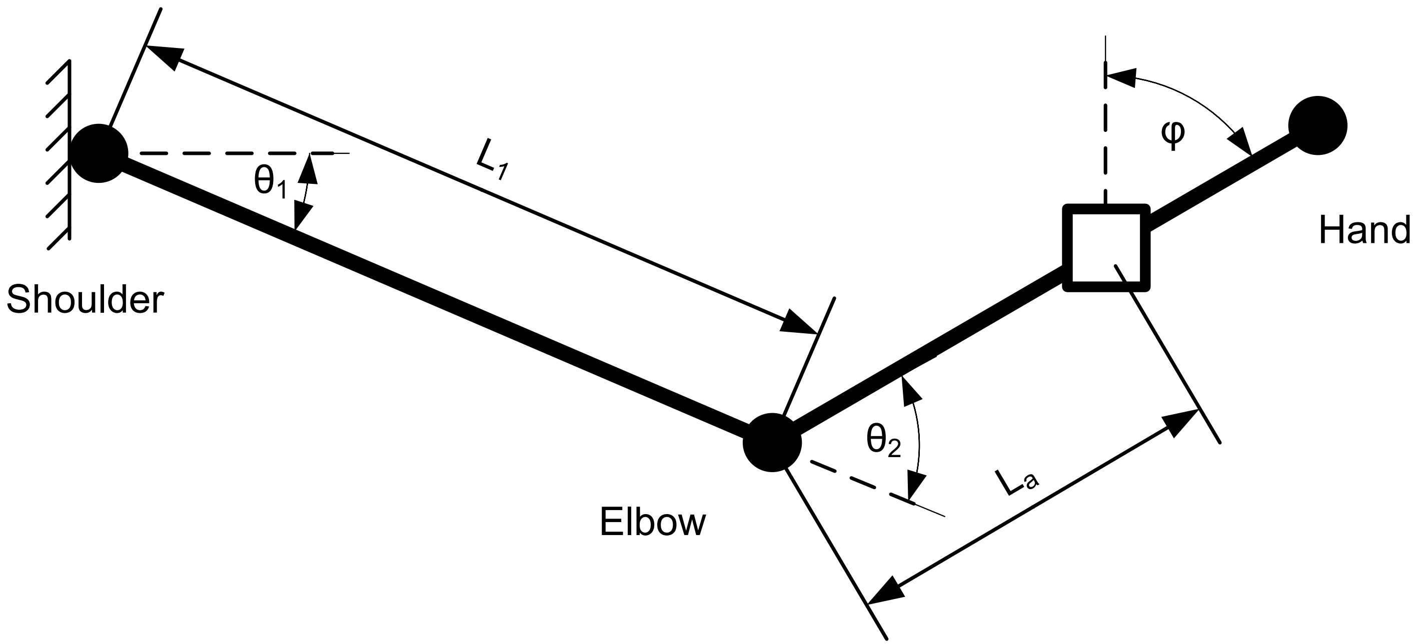
Goal

Infer muscle forces based on easily observed data (motion capture, IMU)

In this project

- Focus on one arm
- Create simplified model of arm
- Extract accurate state information from motion capture + accelerometers
- Combine arm model with state information to infer muscle forces

Mechanical Model



Observed

- θ_1 (mocap)
- θ_2 (mocap)
- Acceleration in sensor coordinates

Want to estimate

- $\dot{\theta}_1$
- $\dot{\theta}_2$ (joint angular rate/accel)
- $\ddot{\theta}_1$
- $\ddot{\theta}_2$

Parameters to learn

- l (accelerometer position)
- φ (accelerometer orientation)

Mathematical Model

Process Model

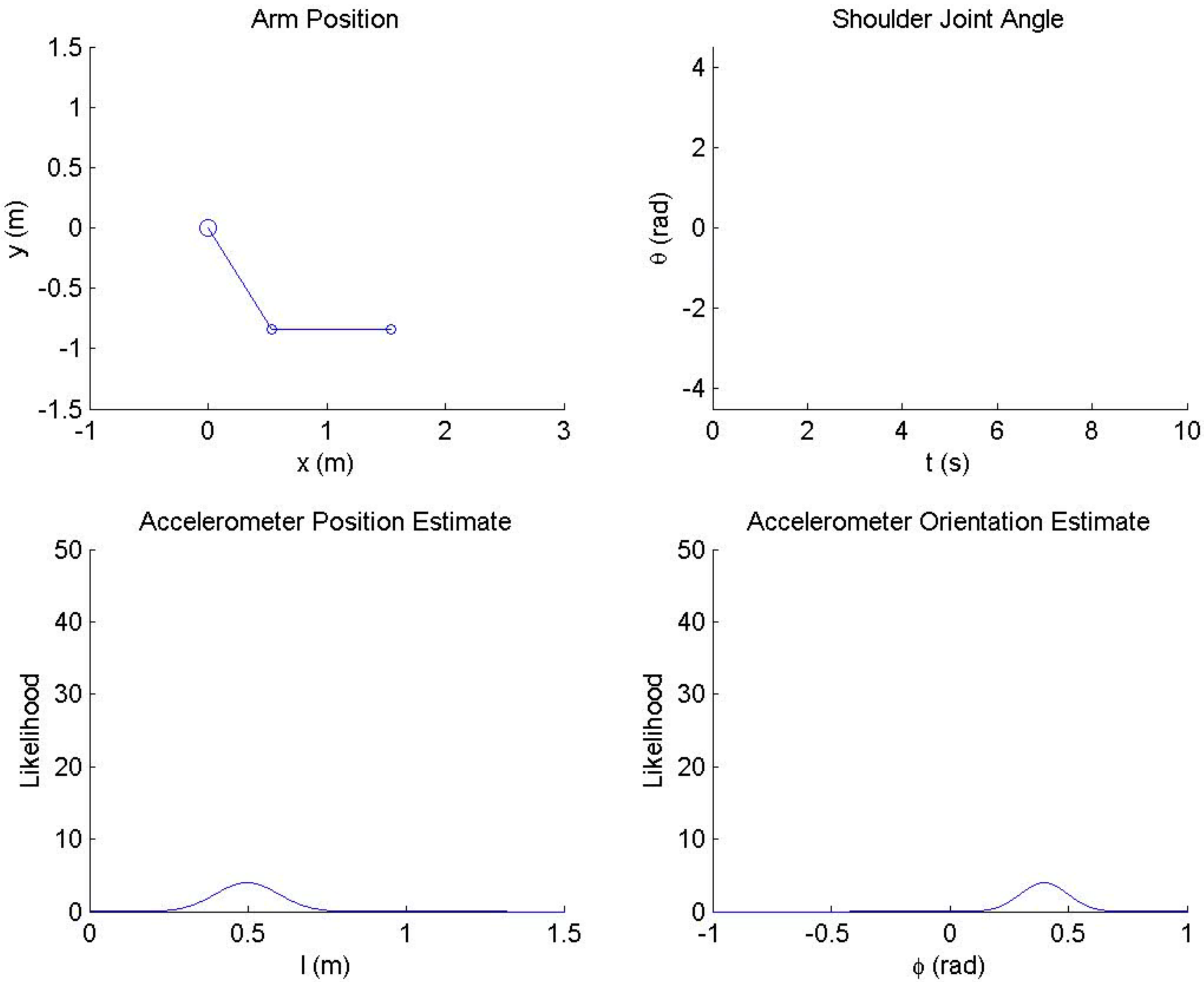
$$\begin{bmatrix} \theta_1 \\ \dot{\theta}_1 \\ \ddot{\theta}_1 \\ \vdots \\ l \\ \varphi \end{bmatrix}_{t+1} = \begin{bmatrix} \theta_1 + T\dot{\theta}_1 + 1/2T^2\ddot{\theta}_1 \\ \dot{\theta}_1 + T\ddot{\theta}_1 \\ \ddot{\theta}_1 + w_{\theta_1} \\ \vdots \\ l + w_l \\ \varphi + w_\varphi \end{bmatrix}_t$$

- Constant acceleration process model
- Parameters modeled as a random walk – allows for sensor movement over time
- Noisy measurements of joint angles and acceleration in accelerometer frame

Measurement Model

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} \theta_1 + \nu_1 \\ \theta_2 + \nu_2 \\ \cos(\theta_1 + \theta_2 + \varphi)(\ddot{x}_a) - \sin(\theta_1 + \theta_2 + \varphi)(\ddot{y}_a) + \nu_3 \\ \sin(\theta_1 + \theta_2 + \varphi)(\ddot{x}_a) + \cos(\theta_1 + \theta_2 + \varphi)(\ddot{y}_a) + \nu_4 \end{bmatrix}$$

Simulation Results: UKF



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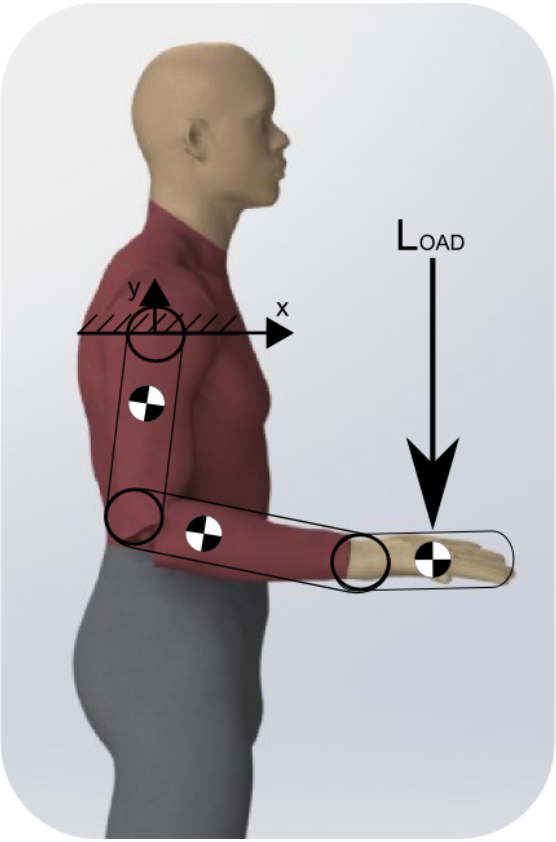
Experimental Data



Experimental Setup

- Upper body motion capture
- 3-axis accelerometer on forearm
- EMG Sensors

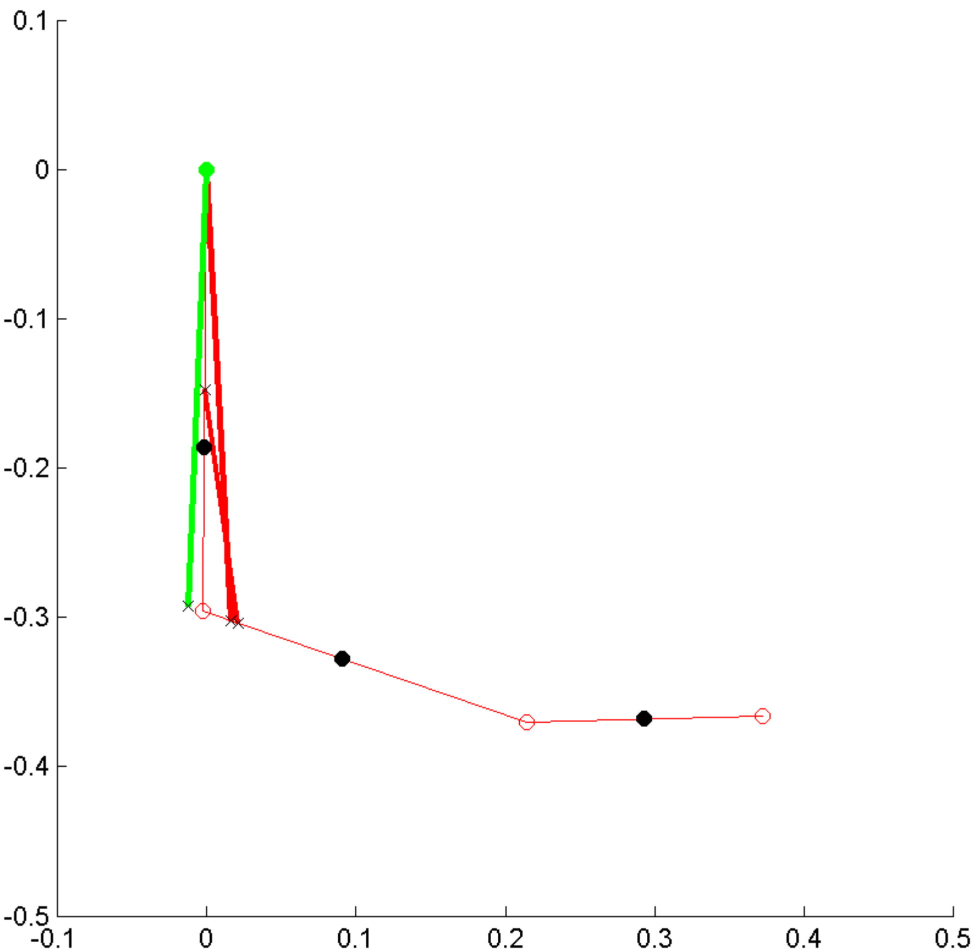
Experiments

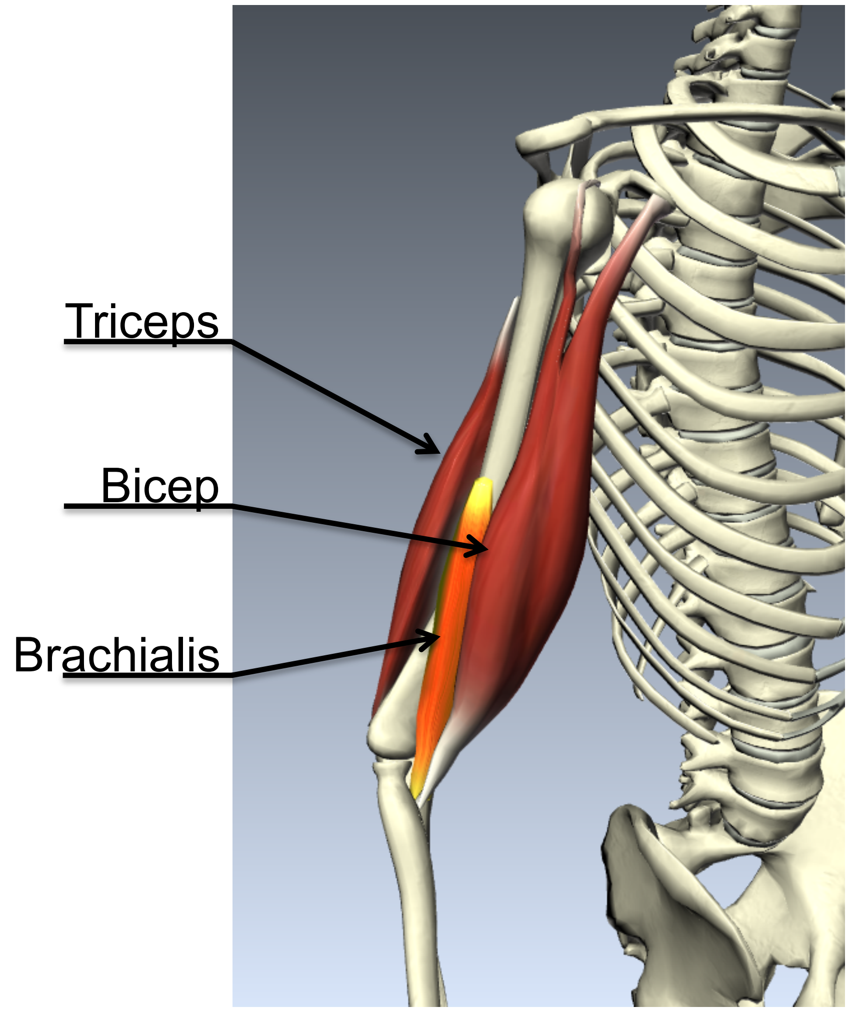
1. Planar arm movements
2. 3D arm movements
3. Weight drop tests

Goals

- Test parameter identification on 1-2
- Infer muscle forces in 3

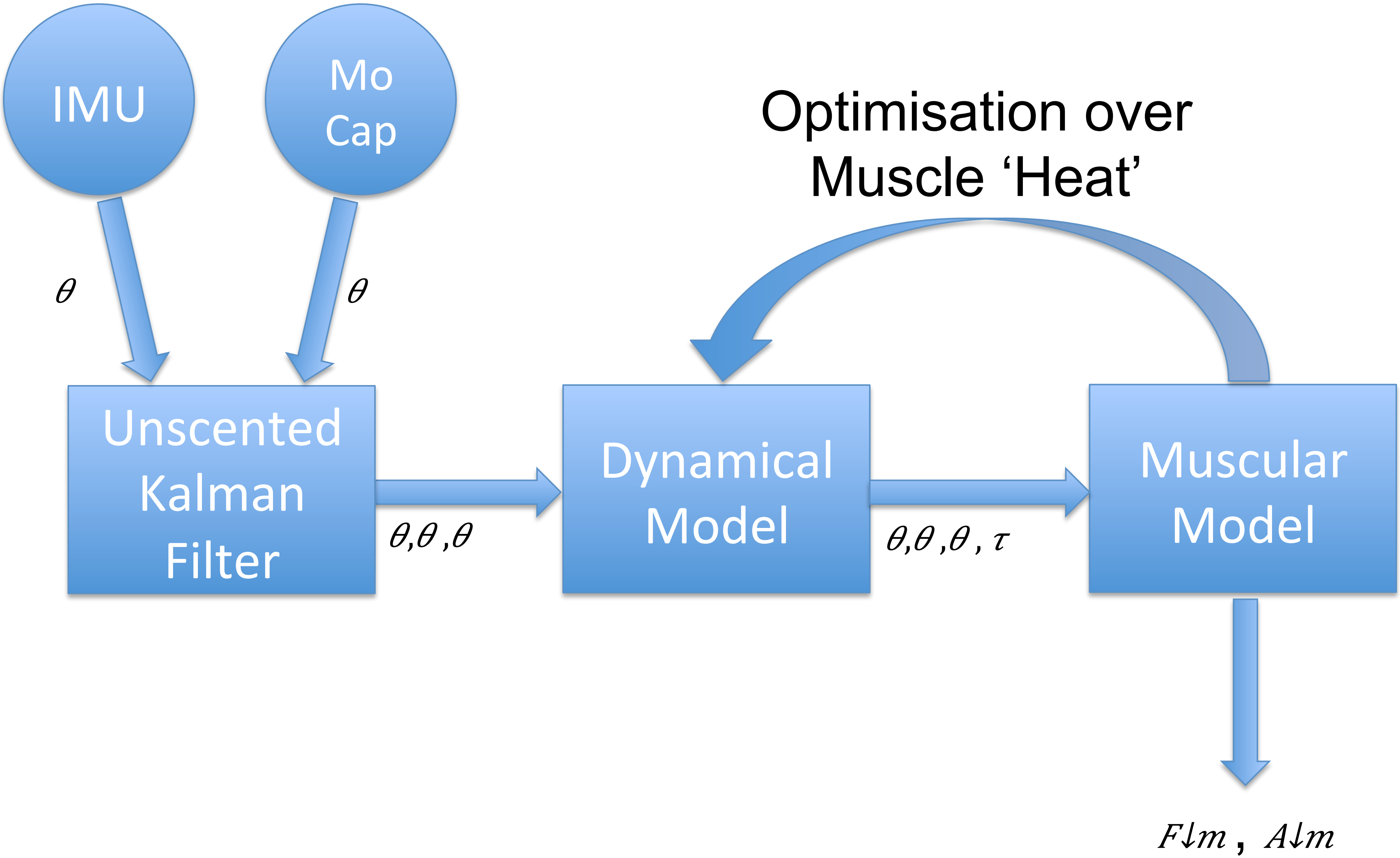
Model: Rigged Skeleton



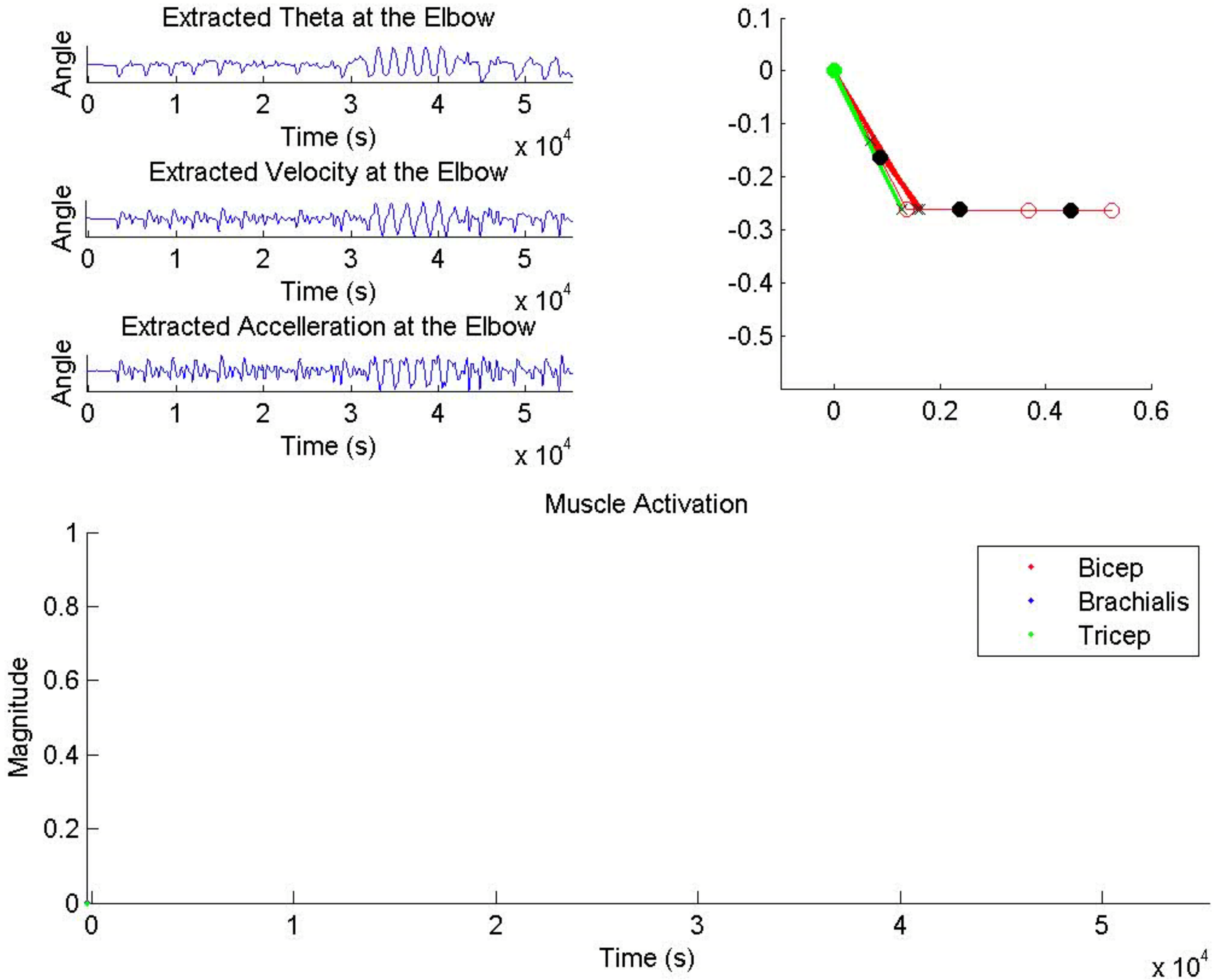


The head of shortening and the dynamic constants of muscle, A Hill, 1938
Muscle and Tendon: properties, models, scaling, and application to biomechanics and motor control. F. Zajac, 1989
Biodigital Human. Biodigital Systems 2013. Online: https://www.biodigitalhuman.com/ Retrieved 2013-04-20.
Regularity Aspects in Inverse Musculoskeletal Biomechanics, Marie Lund 2008
Dynamic simulation of human motion: numerically efficient inclusion of muscle physiology by convex optimization, Goele Pipeleers 2008

Entire Process



Arm Motion Video



Remaining Work

Mechanical Modeling

- Extend mechanical model to 3D
- Perform accelerometer localization on a real world dataset
- *Question:* What are the optimal actions for estimating a given parameter?

Muscle Modeling

- Compare estimated muscle activations to measured EMG data

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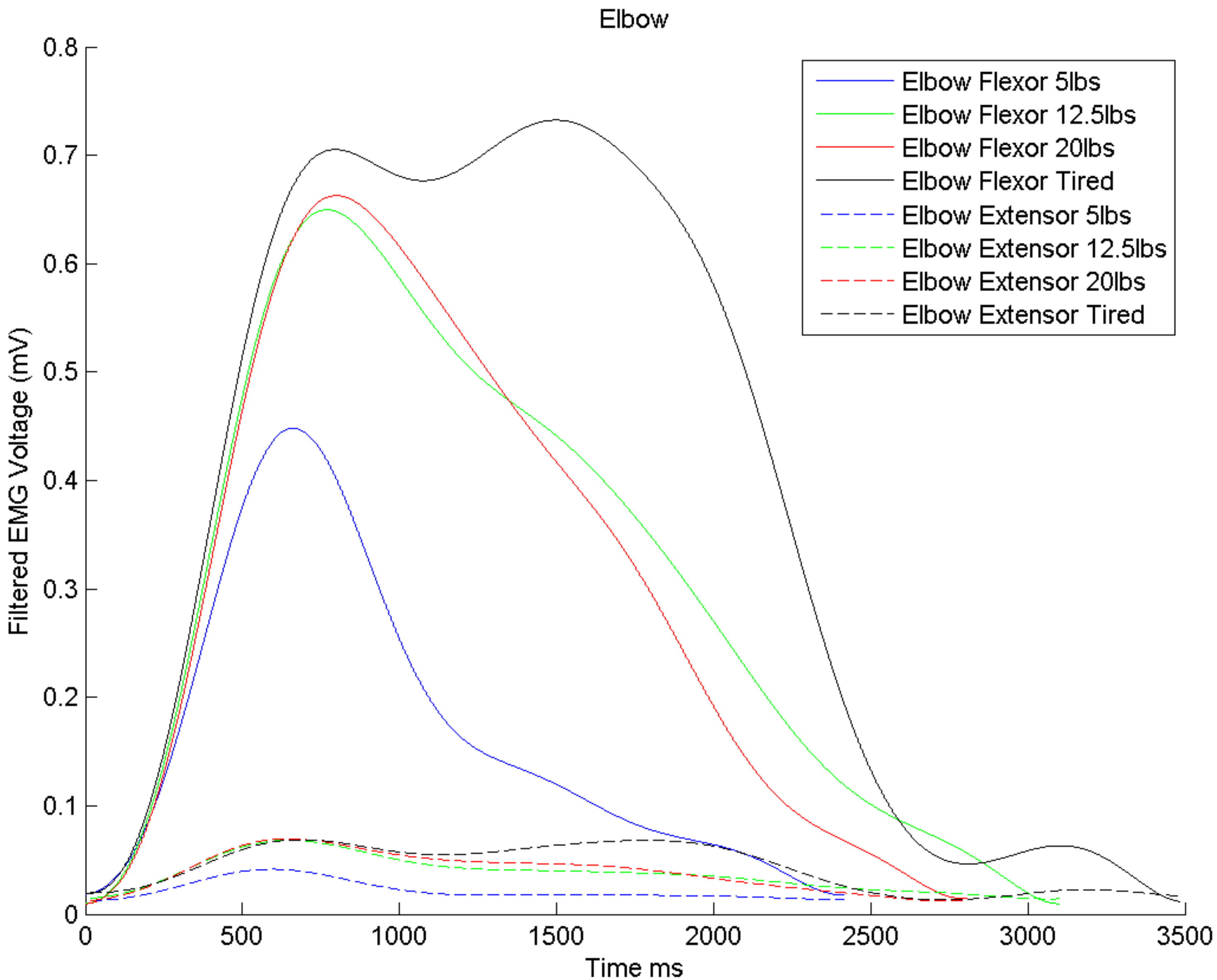
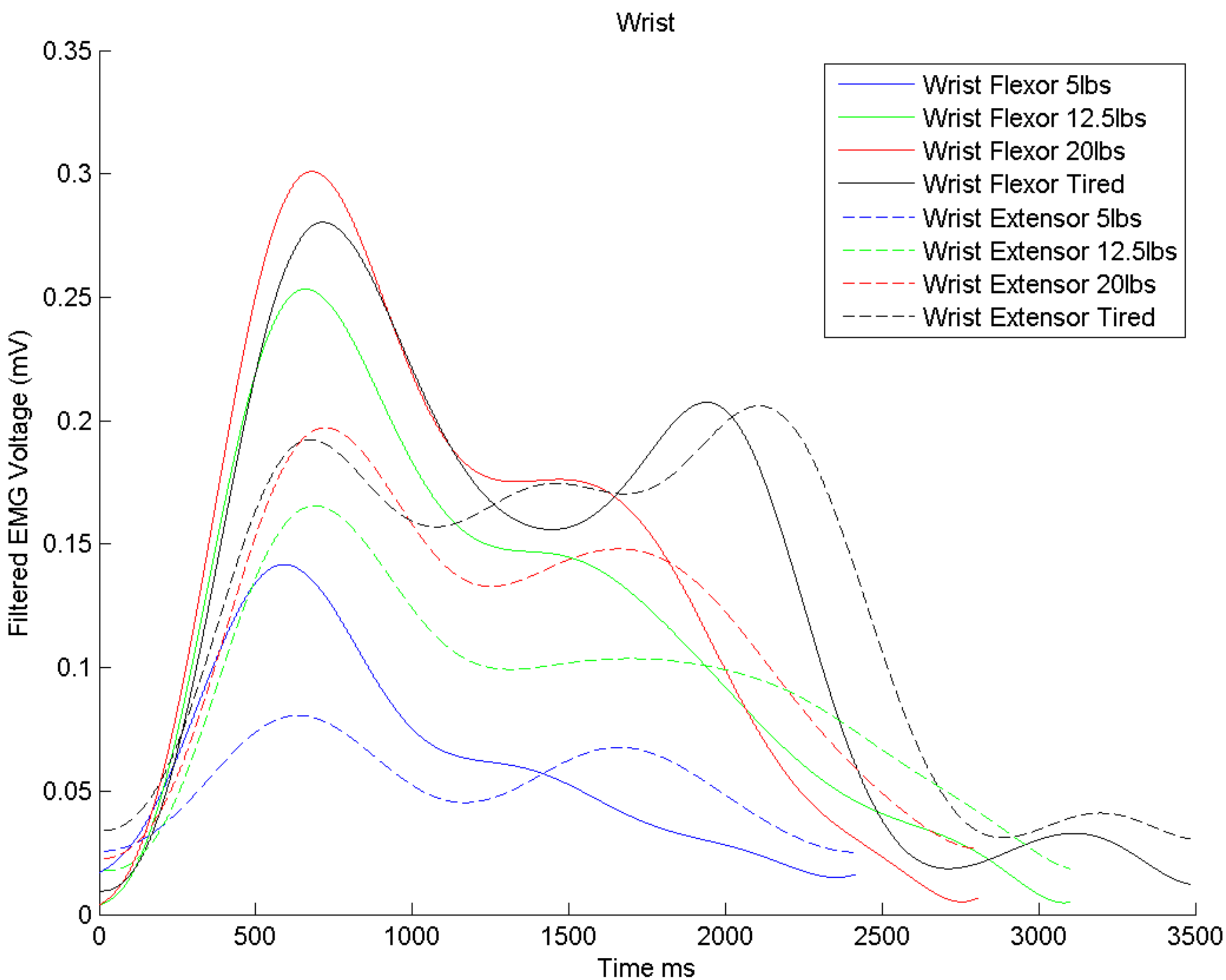
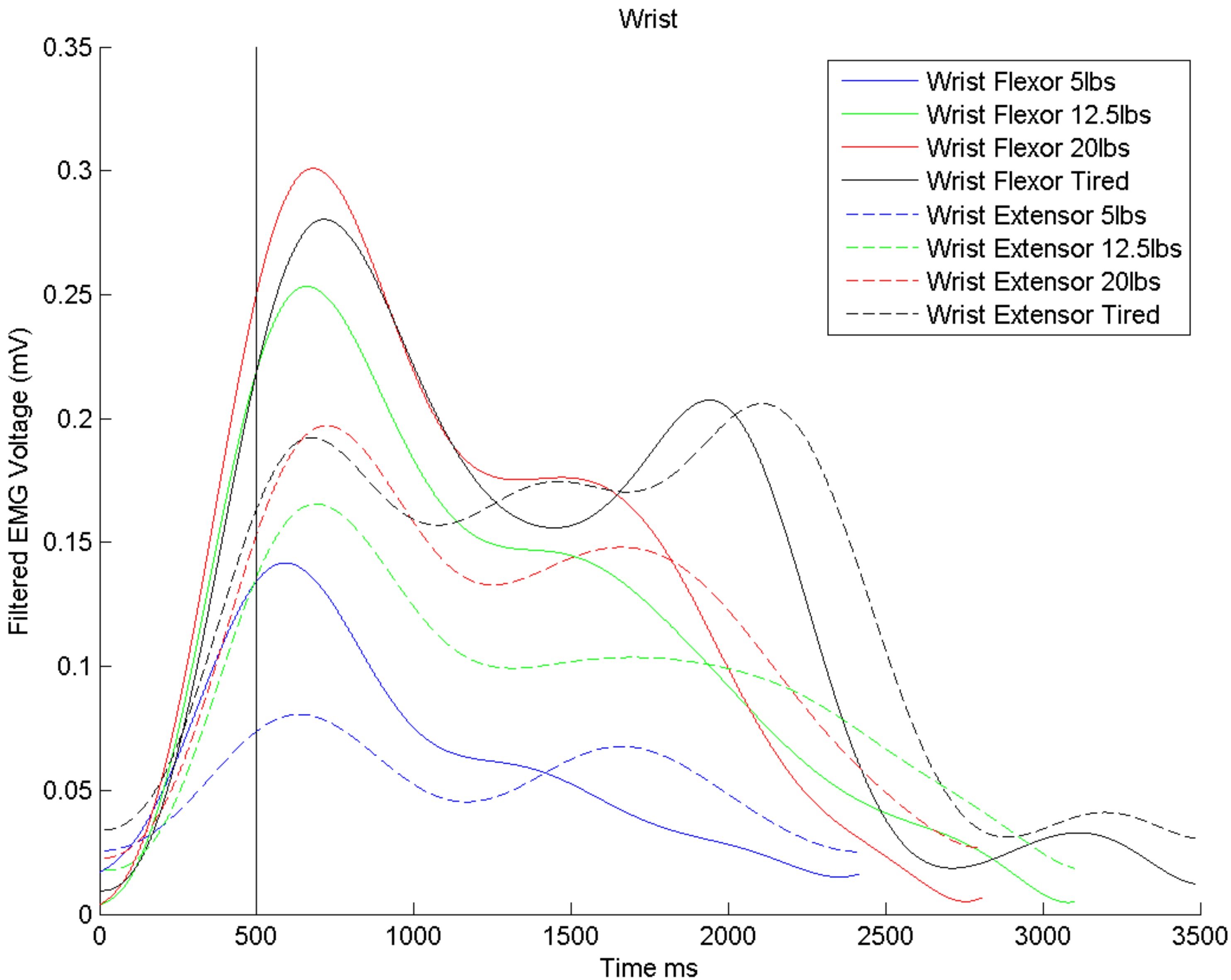
Experimental Results- Elbow- Single Muscle Action



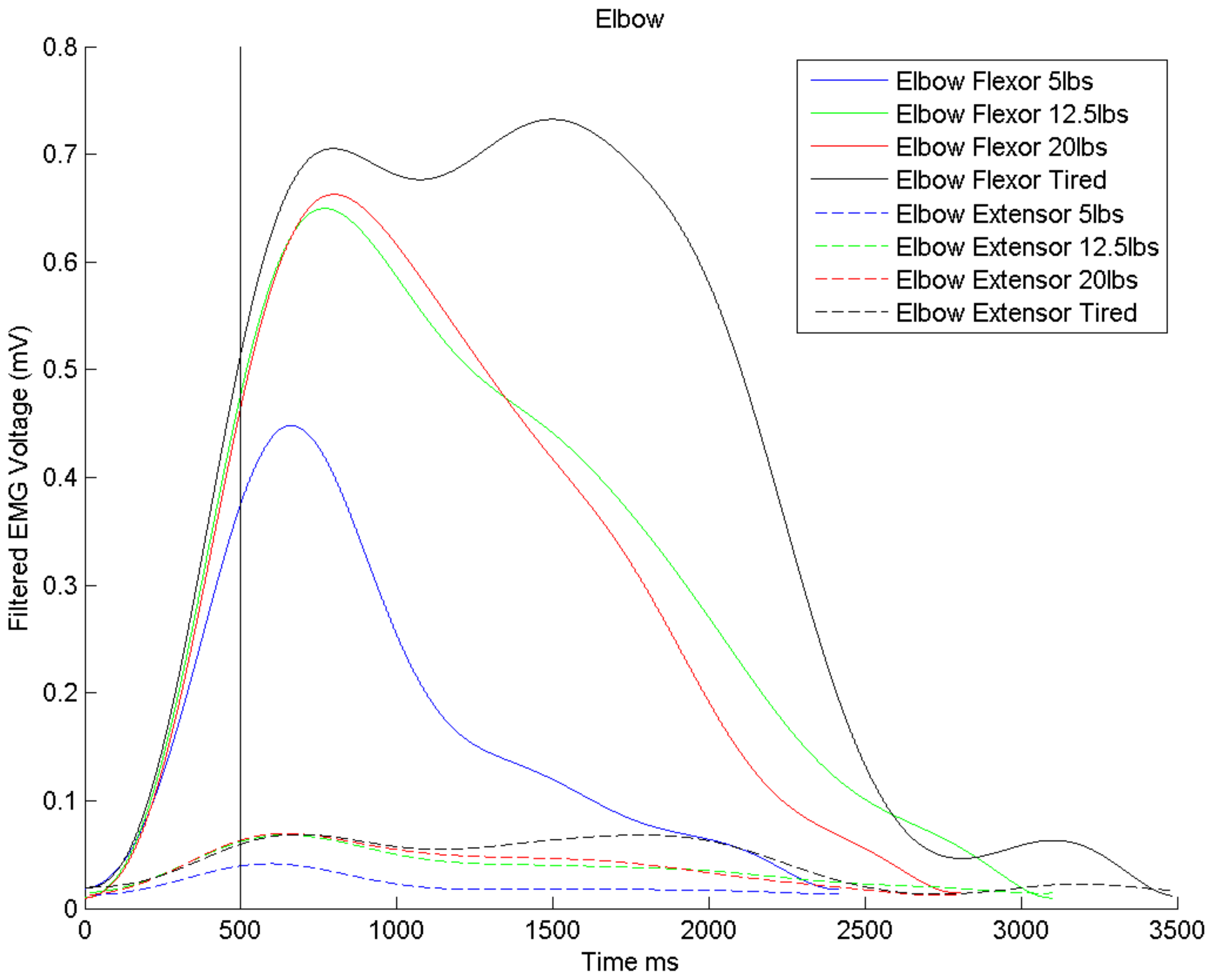
Experimental Results- Wrist- Co-contraction



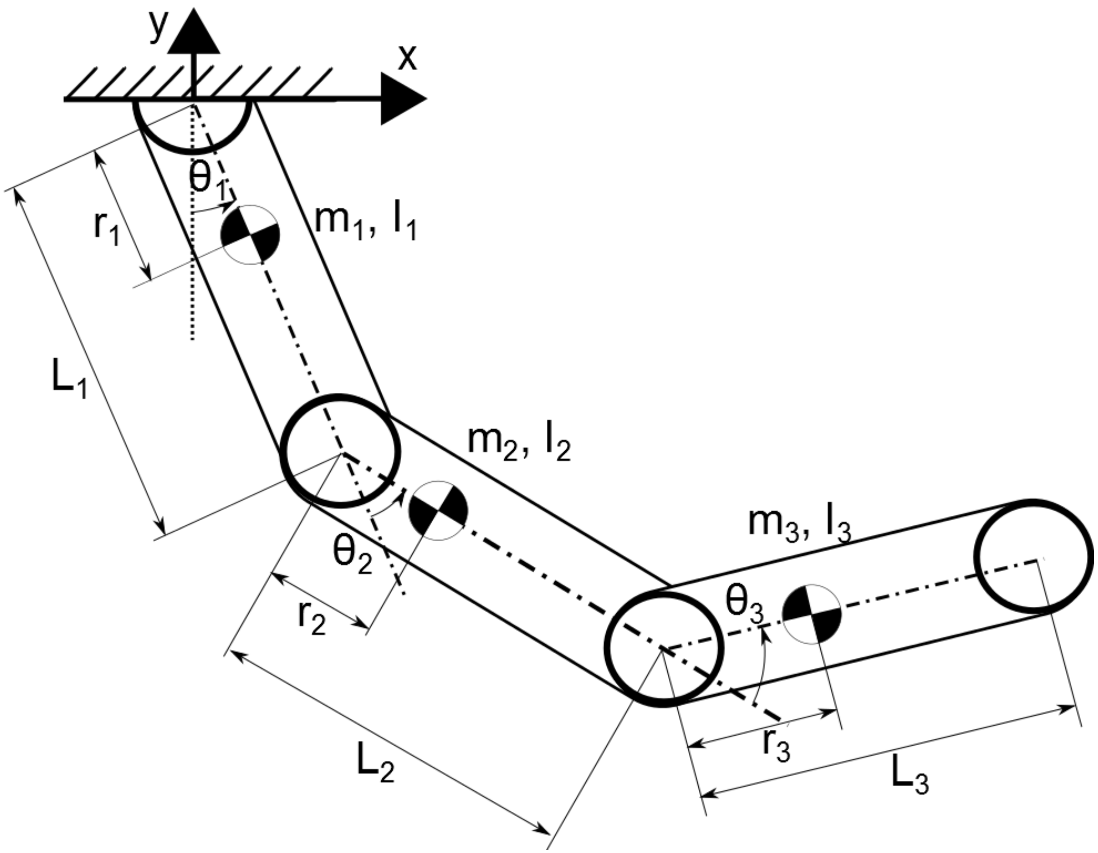
Experimental Results- Wrist- Prediction

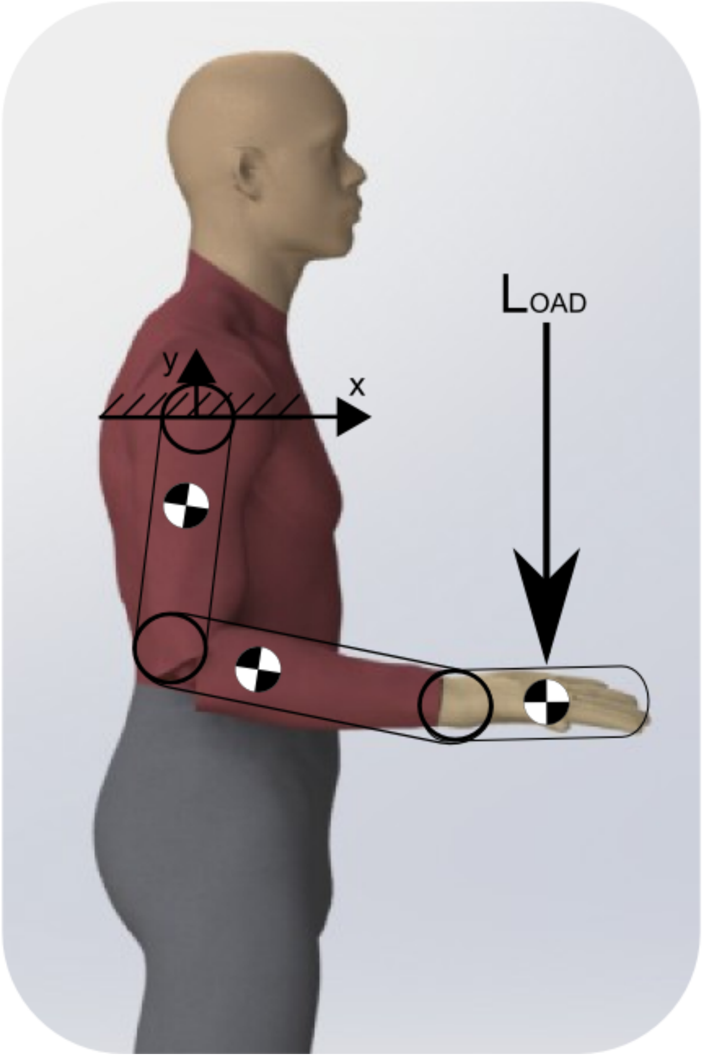


Experimental Results: Elbow



Model: Triple Planar Pendulum





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Dynamical Model

- Dynamical Model

$$\begin{bmatrix} \alpha+\beta+\gamma+\delta c_3+\epsilon c_{23}+\zeta L_1 c_2 & \alpha+\beta+\delta c_3+\epsilon c_{23}+\zeta L_1 c_2 & \alpha+\delta c_3+\epsilon c_{23} \\ \alpha+\beta+\delta c_3+\epsilon c_{23}+\zeta L_1 c_2 & \alpha+\beta+\eta c_3 & \alpha+\eta c_3 \\ \alpha+\delta c_3+\epsilon c_{23} & \alpha+\eta c_3 & \alpha \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix}$$

$$+ \begin{bmatrix} -2\left(\left(\zeta L_1 s_2+\epsilon s_{23}\right)\dot{\theta}_2+\kappa\dot{\theta}_3\right) & -\left(\zeta L_1 s_2\dot{\theta}_2+2\eta s_3\dot{\theta}_3+\epsilon s_{23}\left(\dot{\theta}_2+\dot{\theta}_3\right)\right) & -\left(\kappa\dot{\theta}_3+\epsilon s_{23}\dot{\theta}_2\right) \\ \left(\zeta L_1 s_2+\epsilon s_{23}\right)\dot{\theta}_1-2\delta s_3\dot{\theta}_3 & -2\delta s_3\dot{\theta}_3 & -\delta s_3 \\ \kappa\dot{\theta}_1+2\delta s_3\dot{\theta}_2 & \delta s_3\dot{\theta}_2 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix}$$

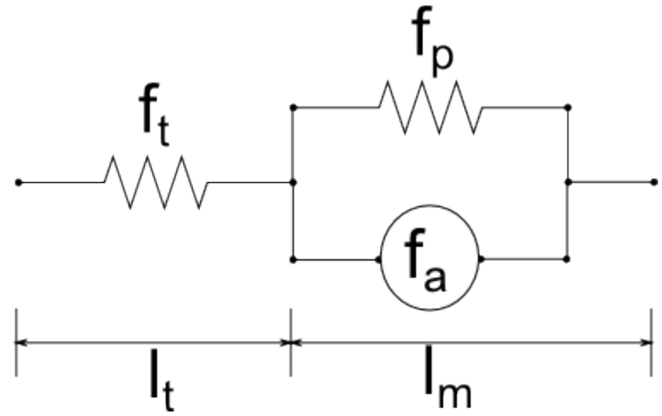
$$-g \begin{bmatrix} \left(L_1\left(m_2+m_3\right)+m_1 r_1\right)+\zeta c_{12}+m_3 r_3 c_{123} \\ \zeta c_{12}+m_3 r_3 c_{123} \\ m_3 r_3 c_{123} \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix}$$

- Where:

$$\begin{aligned} \alpha &= I_{3Z}+m_3 r_3^2 \\ \beta &= I_{2Z}+L_2^2 m_3+m_2 r_2^2+L_2 m_3 r_3 c_3 \\ \gamma &= I_{1Z}+L_1^2 m_2+L_1^2 m_3+m_1 r_1^2+L_1\left(L_2 m_3+m_2 r_2\right)c_2+L_1 m_3 r_3 c_{23} \\ \delta &= L_2 m_3 r_3 \end{aligned}$$

$$\begin{aligned} \epsilon &= L_1 m_3 r_3 \\ \zeta &= L_2 m_3+m_2 r_2 \\ \eta &= L_2 m_3 r_3 \\ \kappa &= \delta s_3+\epsilon s_{23} \end{aligned}$$

Muscle Model



Tendon model: $$f_t\left(l_t\right) = K_t\left[\frac{l_t - l_s}{l_s}\right] f_o$$

Muscle Passive force: $$f_p\left(\bar{l}_m\right) = \frac{2.5}{1 + e^{-12\left(\bar{l}_m - 1.425\right)}} f_o$$

Muscular Active force: $$f_a\left(a, \bar{l}_m, \dot{\bar{l}}_m\right) = a f_l\left(\bar{l}_m\right) f_v\left(\dot{\bar{l}}_m\right) f_o$$

Length-Force relation: $$f_l\left(\bar{l}_m\right) = \left[\frac{1}{1 + e^{-12\left(\bar{l}_m - 0.6\right)}} + \frac{1}{1 + e^{12\left(\bar{l}_m - 1.4\right)}} - 1\right]$$

Velocity-Force relation: $$f_l\left(\dot{\bar{l}}_m\right) = \begin{cases} f_{v_{min}} & \dot{\bar{l}}_m < \dot{\bar{l}}_{min} \\ \frac{2}{1+e^{-6\dot{\bar{l}}_m}} & \dot{\bar{l}}_{min} \le \dot{\bar{l}}_m \le \dot{\bar{l}}_{max} \\ f_{v_{max}} & \dot{\bar{l}}_m > \dot{\bar{l}}_{max} \end{cases}$$

where:

$$\dot{\bar{l}}_{min} = -1 \qquad f_{v_{min}} = \frac{2}{1 + e^6}$$

$$\dot{\bar{l}}_{max} = -\frac{1}{6} ln\left(\frac{2}{1.8} - 1\right) \qquad f_{v_{max}} = 1.8$$