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
- $\theta_1$ (mocap)
- $\theta_2$ (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)
- $\varphi$ (accelerometer orientation)

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Mathematical Model

**Process Model**

\[
\begin{bmatrix}
\theta_1 \\
\dot{\theta}_1 \\
\ddot{\theta}_1 \\
\vdots \\
\theta_l \\
\dddot{\varphi}
\end{bmatrix}_{t+1} =
\begin{bmatrix}
\theta_1 + T\dot{\theta}_1 + \frac{1}{2}T^2\ddot{\theta}_1 \\
\dot{\theta}_1 + T\ddot{\theta}_1 \\
\ddot{\theta}_1 + w_{\theta_1} \\
\vdots \\
l + w_l \\
\varphi + w_\varphi
\end{bmatrix}_t
\]

- 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**

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

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Simulation Results: UKF

Arm Position

Shoulder Joint Angle

Accelerometer Position Estimate

Accelerometer Orientation Estimate

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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

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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
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

IMU

Mo Cap

Unscented Kalman Filter

Dynamical Model

Muscular Model

Optimisation over Muscle ‘Heat’

\[ F_{\downarrow m}, A_{\downarrow m} \]

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Arm Motion Video

Extracted Theta at the Elbow

Extracted Velocity at the Elbow

Extracted Acceleration at the Elbow

Muscle Activation

- Bicep
- Brachialis
- Tricep
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
[9]- Gray’s Anatomy (Anatomy: Descriptive and Surgical), Henry Gray, 1858, Public works.
Experimental Results - Elbow - Single Muscle Action
Experimental Results - Wrist- Co-contraction

The graph shows the filtered EMG voltage (mV) over time (ms) for different conditions:
- Wrist Flexor 5lbs
- Wrist Flexor 12.5lbs
- Wrist Flexor 20lbs
- Wrist Flexor Tired
- Wrist Extensor 5lbs
- Wrist Extensor 12.5lbs
- Wrist Extensor 20lbs
- Wrist Extensor Tired

The y-axis represents the filtered EMG voltage in millivolts, while the x-axis represents time in milliseconds. The curves illustrate the muscle activity and response under various conditions.
Experimental Results - Wrist Prediction

The graph shows the filtered EMG voltage (mV) over time (ms) for different conditions of wrist flexor and extensor muscles under various loads (5lbs, 12.5lbs, 20lbs) and when tired. The lines are distinguished by color and style, indicating different conditions and loads.
Experimental Results: Elbow

![Graph showing filtered EMG voltage over time for different conditions involving the elbow.](image-url)
Model: Triple Planar Pendulum

• **Dynamical Model**

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

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

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

• **Where:**

\[
\begin{align*}
\alpha &= I_{3Z} + m_3 r_3^2 \\
\beta &= I_{2Z} + L_2^2 m_3 + m_2 r_2^2 + L_2 m_3 r_3 c_3 \\
\gamma &= I_{1Z} + L_1^2 m_2 + L_1^2 m_3 + m_1 r_1^2 + L_1 (L_2 m_3 + m_2 r_2) c_2 + L_1 m_3 r_3 c_{23} \\
\delta &= L_2 m_3 r_3 \\
\epsilon &= L_1 m_3 r_3 \\
\zeta &= L_2 m_3 + m_2 r_2 \\
\eta &= L_2 m_3 r_3 \\
\kappa &= \delta s_3 + \epsilon s_{23}
\end{align*}
\]
Muscle Model

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

Muscle Passive force:
\[ f_p(l_m) = \frac{2.5}{1 + e^{-12(l_m - 1.425)}} f_o \]

Muscular Active force:
\[ f_a(a, l_m, \dot{l_m}) = a f_t(l_m) f_v(\dot{l}_m) f_o \]

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

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

where:
\[ \dot{l}_{min} = -1 \]
\[ f_{v_{min}} = \frac{2}{1 + e^6} \]
\[ \dot{l}_{max} = -\frac{1}{6} \ln \left( \frac{2}{1.8} - 1 \right) \]
\[ f_{v_{max}} = 1.8 \]