Musculoskeletal Modeling for Physical HRI

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Motivation

- Understanding contact forces and joint torques is imperative to the **creation of safe and effective assistive devices** and **HRI control schemes**
- **Non-physiological models cannot predict dynamics at sufficient resolution** or **accomodate pathologies common to assistive device users** (SCI, muscular dystrophy, etc.)

Challenges

- **Existing systems rely on population-based models** [1] that minimally account for variation/pathology
- **Musculoskeletal system complexities** exist at every level of abstraction

Objectives

- Accurately **predict subject-specific kinematics/dynamics of the human arm** during manipulation tasks from non-invasive sensor data (**P1**)
- **Quantify variation across individuals** and changes in error **across model resolutions** to **establish model quality** and generalizability (**P2**)

P1: Building a Predictive Dynamics Model

Project Objective

Predict human arm dynamics using a wide range of non-invasive sensing modalities to **generate subject-specific models**

Simplified Initial Model (Static)

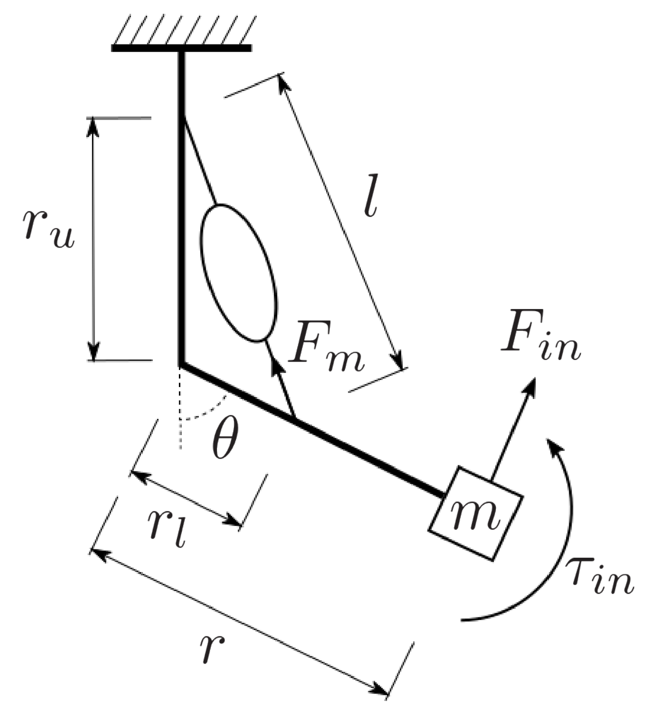
Assuming muscle force-length relation

$$F_m(\bar{l}) = F_0(\beta_1 \bar{l}^2 + \beta_2 \bar{l} + \beta_3)$$

and normalized muscle activation/length

$$\bar{a} = \frac{a}{a_{max}} \qquad \bar{l} = \frac{l}{l_{opt}}$$

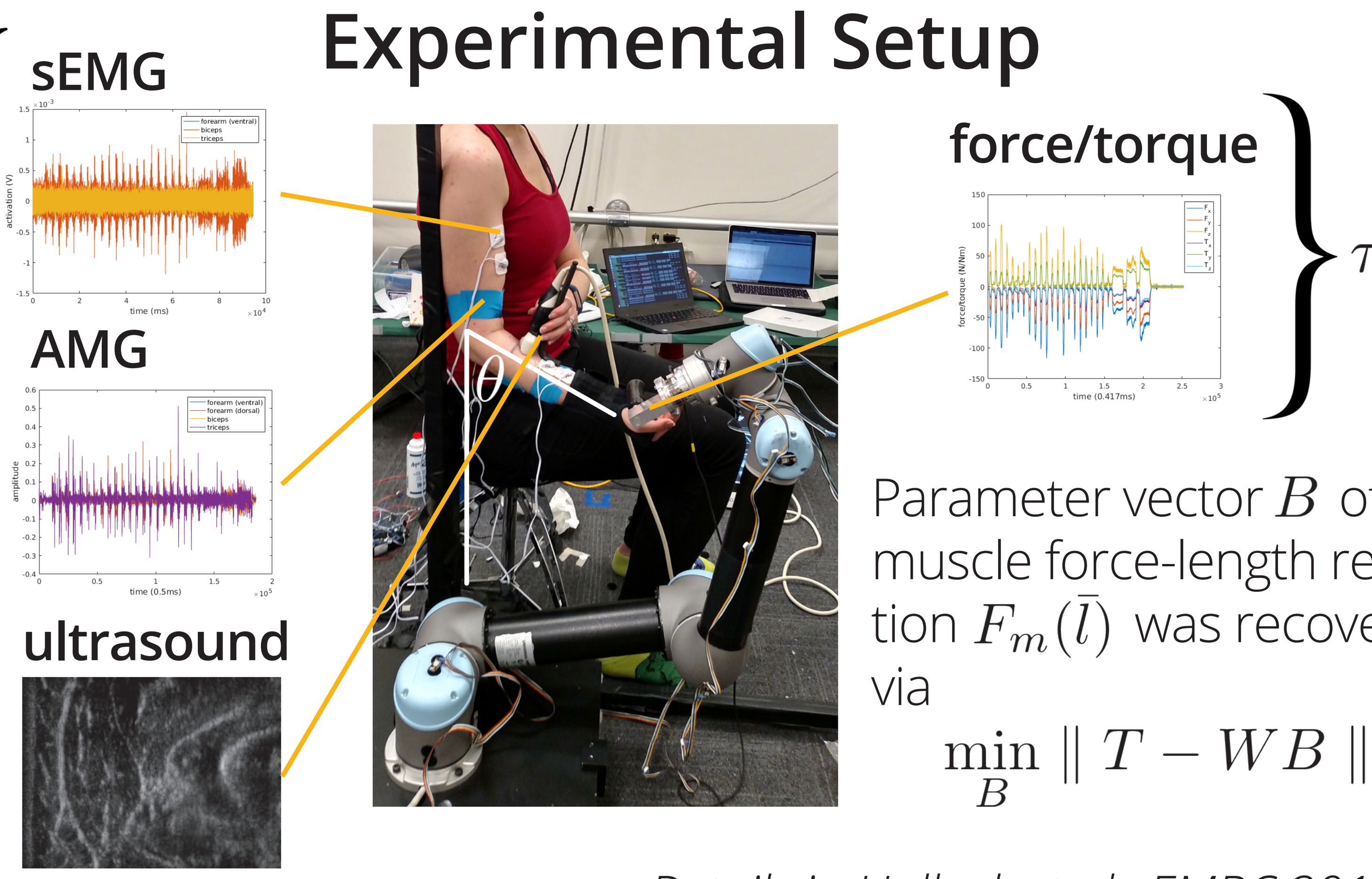
the dynamics relation of each $(\bar{a}, \tau, \theta)$ pair is described by



$$\begin{bmatrix} \tau_1 \\ \vdots \\ \tau_n \end{bmatrix} = F_0 r_l r_u \begin{bmatrix} \frac{l_1}{l_{opt}^2} \sin\theta_1 \bar{a}_1 & \frac{1}{l_{opt}} \sin\theta_1 \bar{a}_1 & \frac{1}{l_1} \sin\theta_1 \bar{a}_1 \\ \vdots & \vdots & \vdots \\ \frac{l_n}{l_{opt}^2} \sin\theta_n \bar{a}_n & \frac{1}{l_{opt}} \sin\theta_n \bar{a}_n & \frac{1}{l_n} \sin\theta \bar{a}_n \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix}$$

i.e., $T = WB$.

Experimental Setup



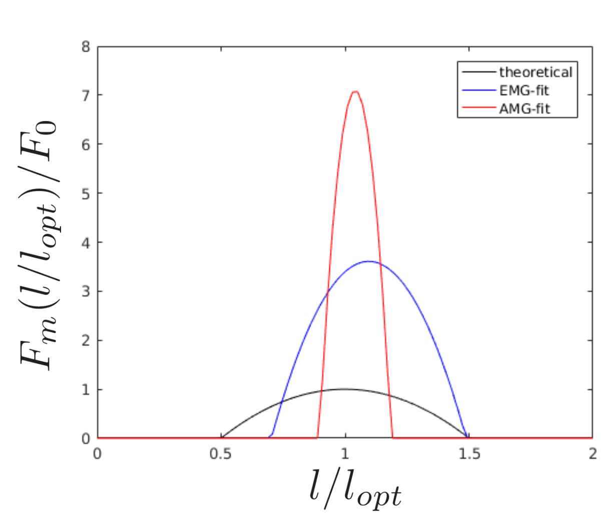
Parameter vector B of muscle force-length relation $F_m(\bar{l})$ was recovered via

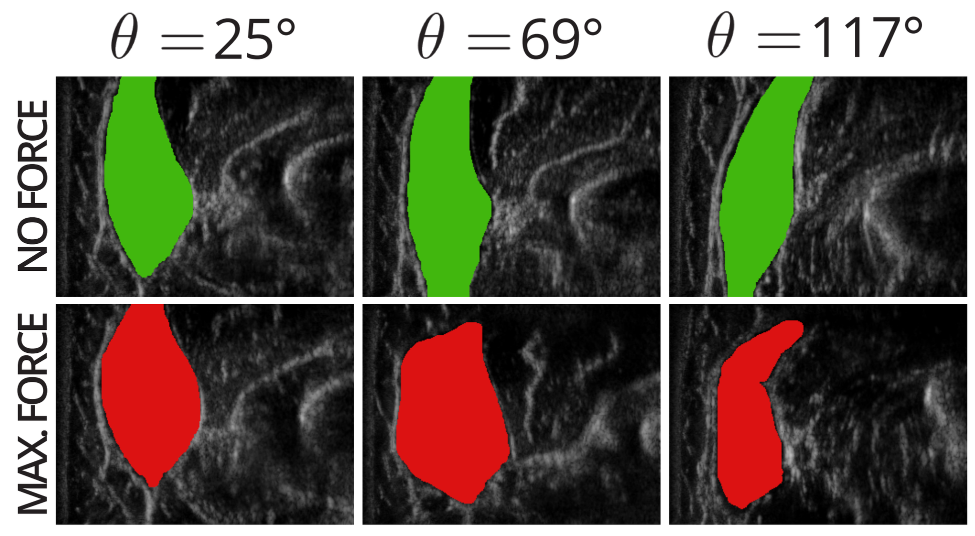
$$\min_B \| T - WB \|_2^2$$

Details in Hallock et al., EMBC 2016 [6].

Preliminary Results

The **predicted force-length relation** is **biologically reasonable** but differs across sensors.





Muscle deformation during exertion is **obvious** but **highly nonlinear** and poorly characterized thus far.

P2: Characterizing Model Quality

Project Objective

Examine, via ~10 subjects' **upper-limb MRI scans**,

- **morphological variation** across subjects
- **impact of this variation** on model **prediction accuracy**

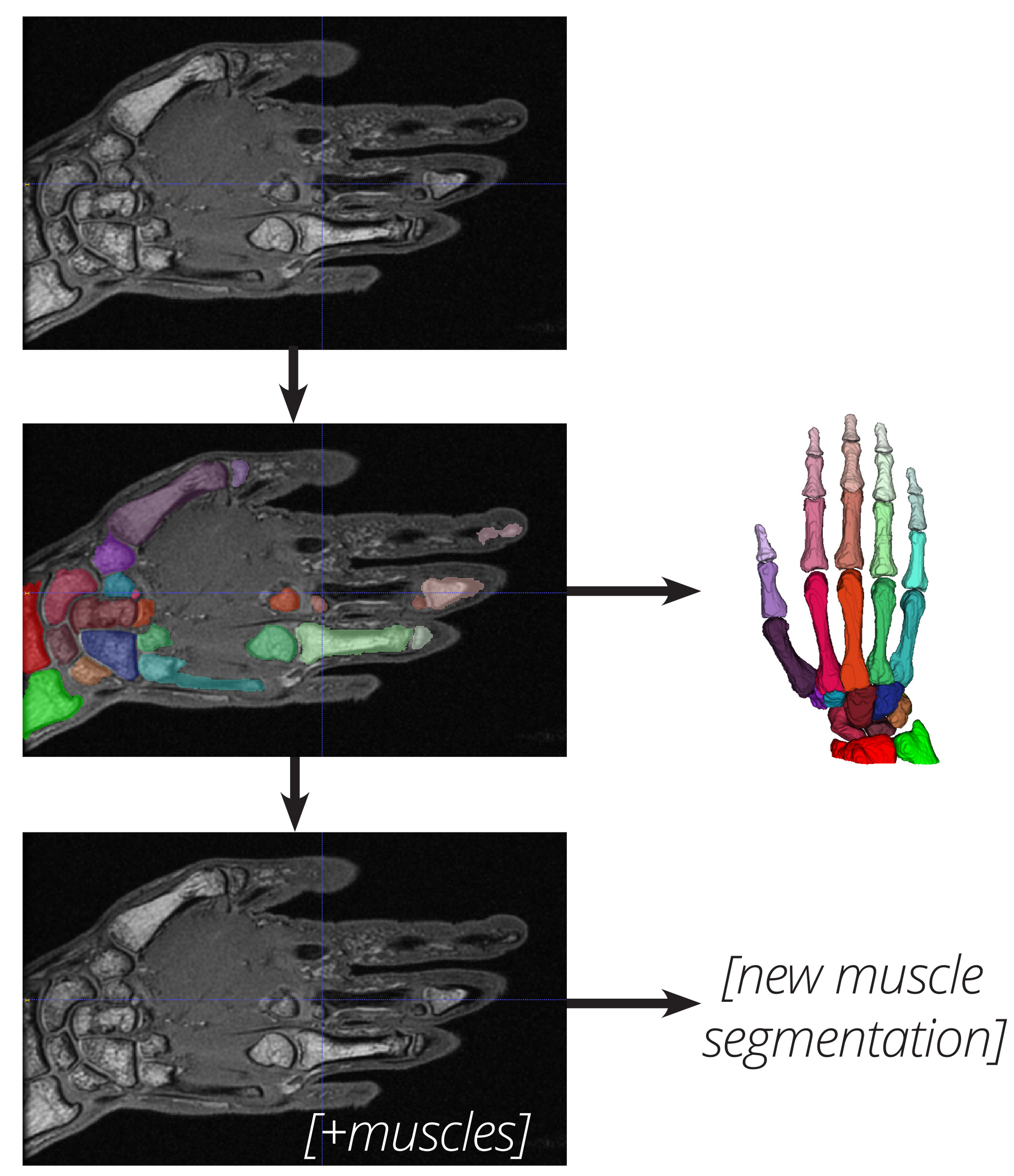
Tissue Segmentation

Bone Segmentation:

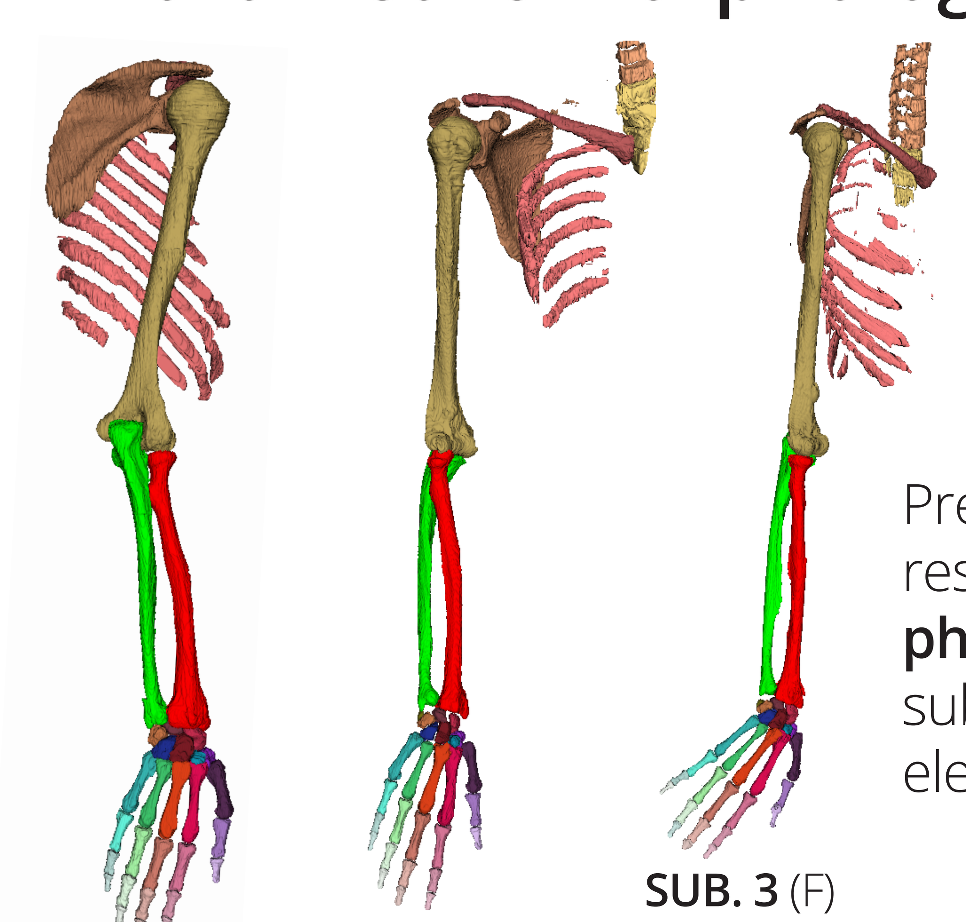
- **active contouring** [2]
- **MSER** blob detection [3]
- manual cleanup

Muscle Segmentation:

- **registration** (via SimpleElastix [4]) with **manually-segmented atlas** [5]
- manual cleanup



Parametric Morphology Comparison



Preliminary bone segmentation results show **significant morphological variation** across subjects that cannot be modeled in existing frameworks.

Parametric Dynamics Comparison
(Current / Future Work)

- Convert existing cohort of segmentations to dynamical models
- Establish **biologically-motivated control scheme** of muscle actuators
- Quantify inter-subject/resolution **variation in predicted dynamics**

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References

[1] Delp, Scott L., et al. "OpenSim: open-source software to create and analyze dynamic simulations of movement." *IEEE transactions on biomedical engineering* 54.11 (2007): 1940-1950. **[2]** Yushkevich, Paul A., et al. "User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability." *Neuroimage* 31.3 (2006): 1116-1128. **[3]** Matas, Jiri, et al. "Robust wide-baseline stereo from maximally stable extremal regions." *Image and vision computing* 22.10 (2004): 761-767. **[4]** Marstal, Kasper, et al. "SimpleElastix: A user-friendly, multi-lingual library for medical image registration." *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops*. 2016. **[5]** Menon, Samir, Toki Migimatsu, and Oussama Khatib. "A parameterized family of anatomically accurate human upper-body musculoskeletal models for dynamic simulation & control." *Humanoid Robots (Humanoids), 2016 IEEE-RAS 16th International Conference on*. IEEE, 2016. **[6]** Hallock, Laura et al. "Sensor-Driven Musculoskeletal Dynamic Modeling." *International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2016.