

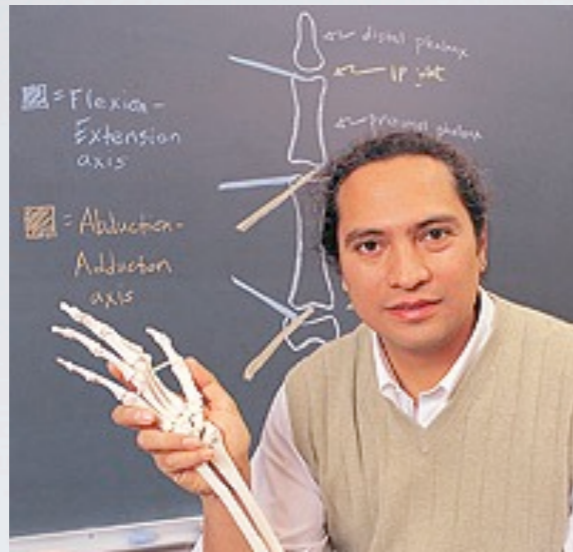
Impedance control doesn't matter

Contact transitions with the finger

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Acknowledgements



Francisco J. Valero-Cuevas
Biomedical Engineering, Univ Southern California



John Guckenheimer
Mathematics, Cornell University

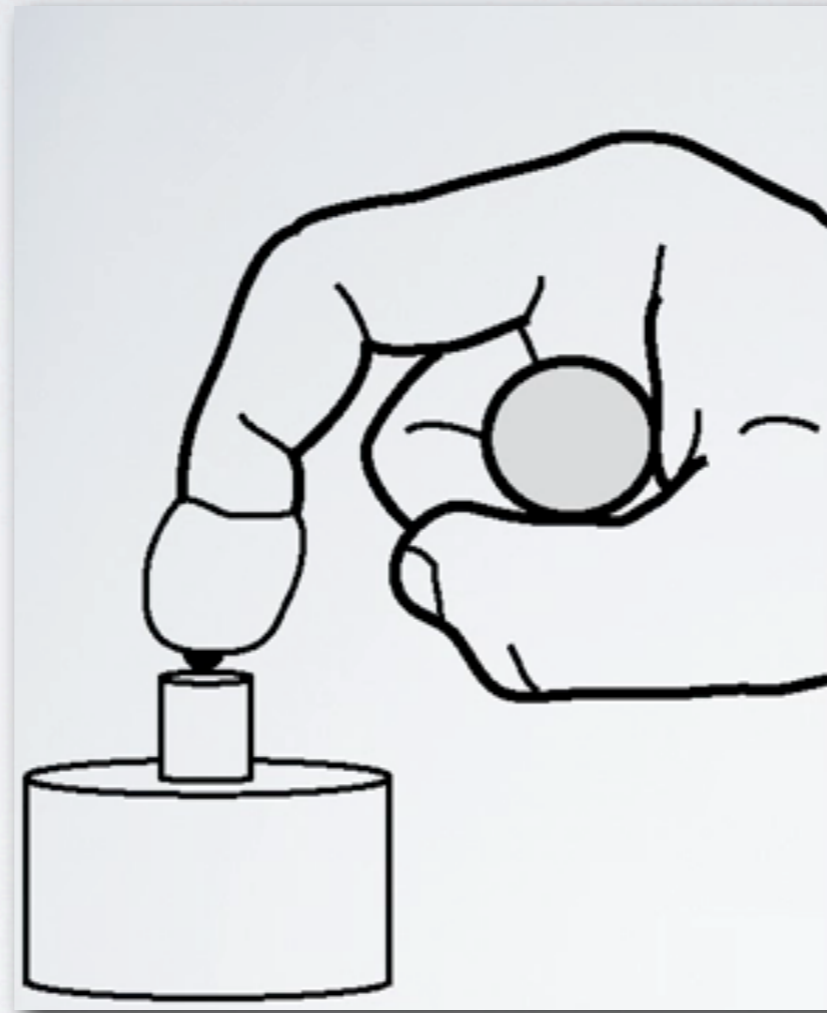


L. Mahadevan
Applied Mathematics, Harvard



Daniel E. Lieberman
Human Evolutionary Biology, Harvard

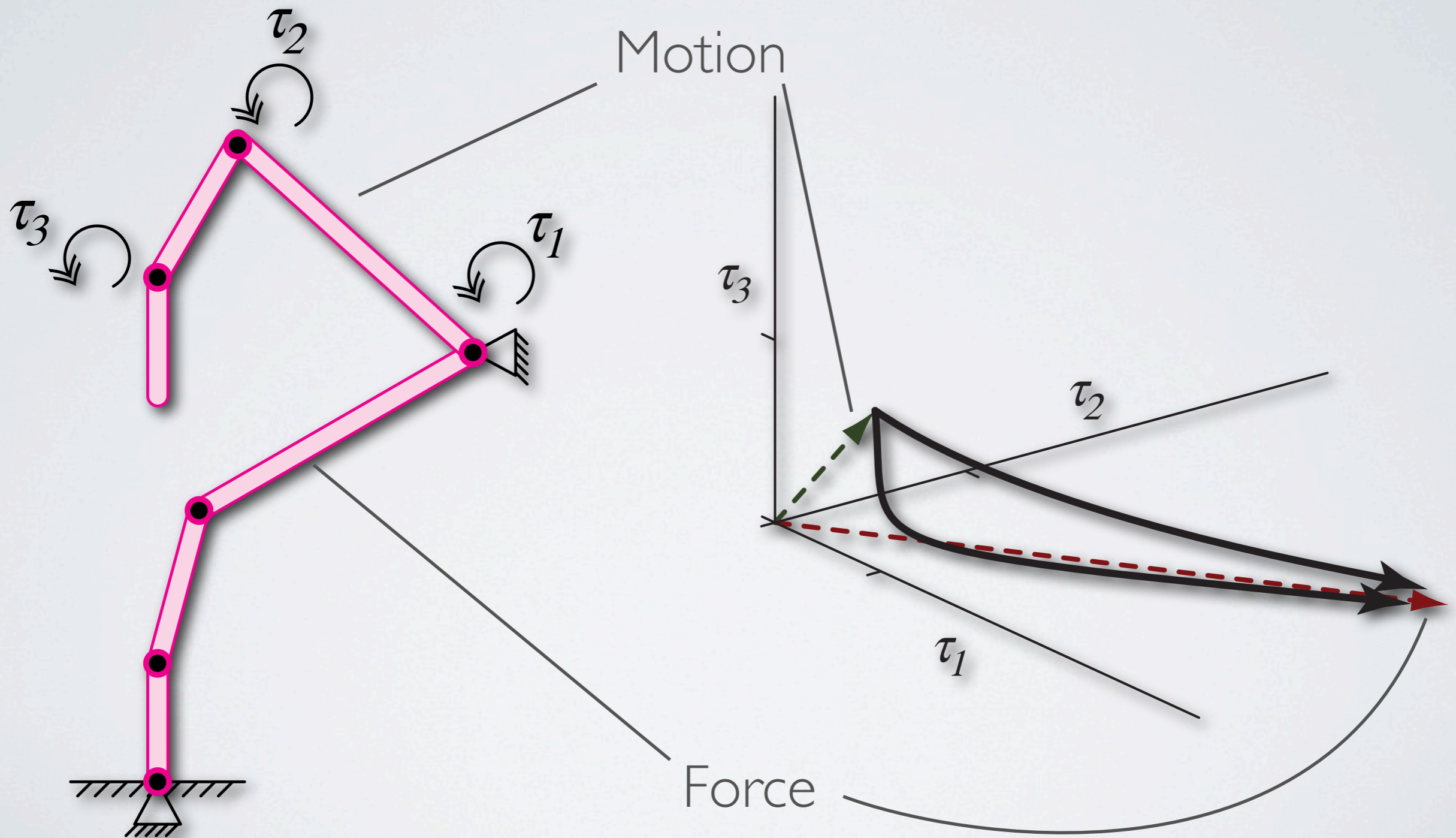
Contact transitions



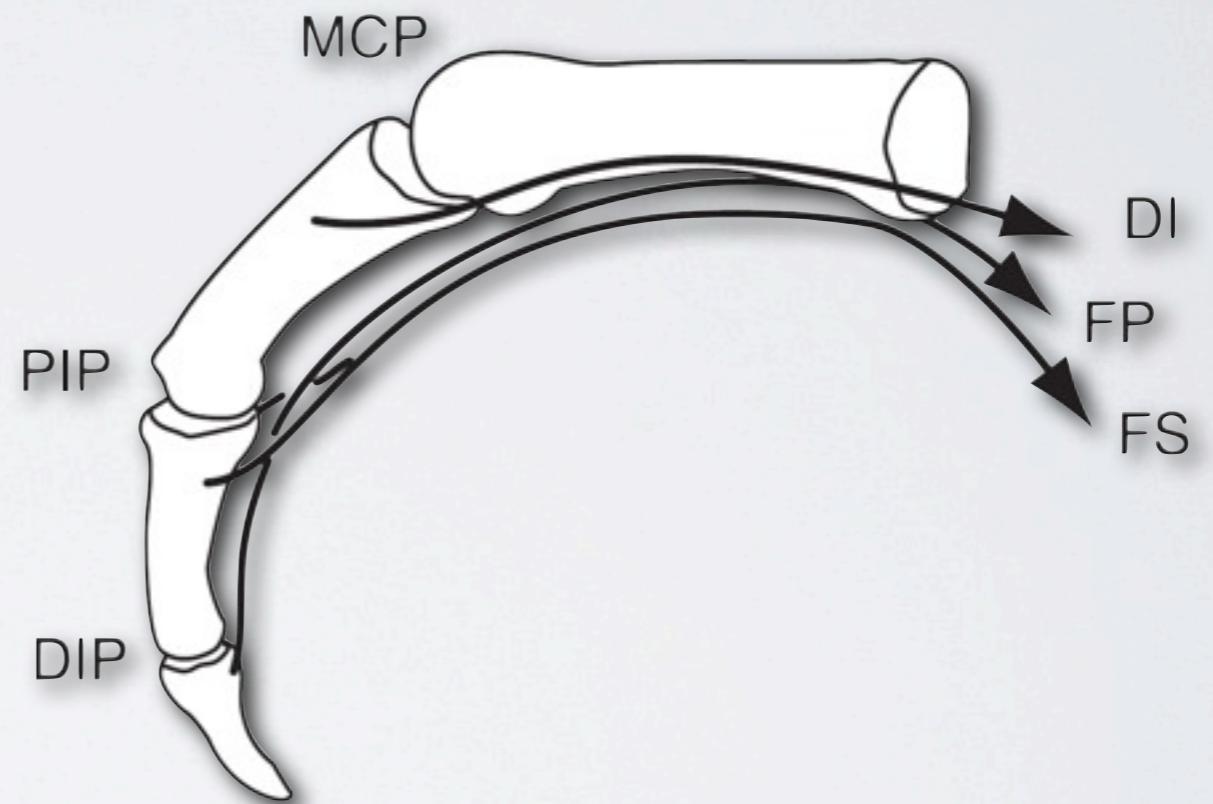
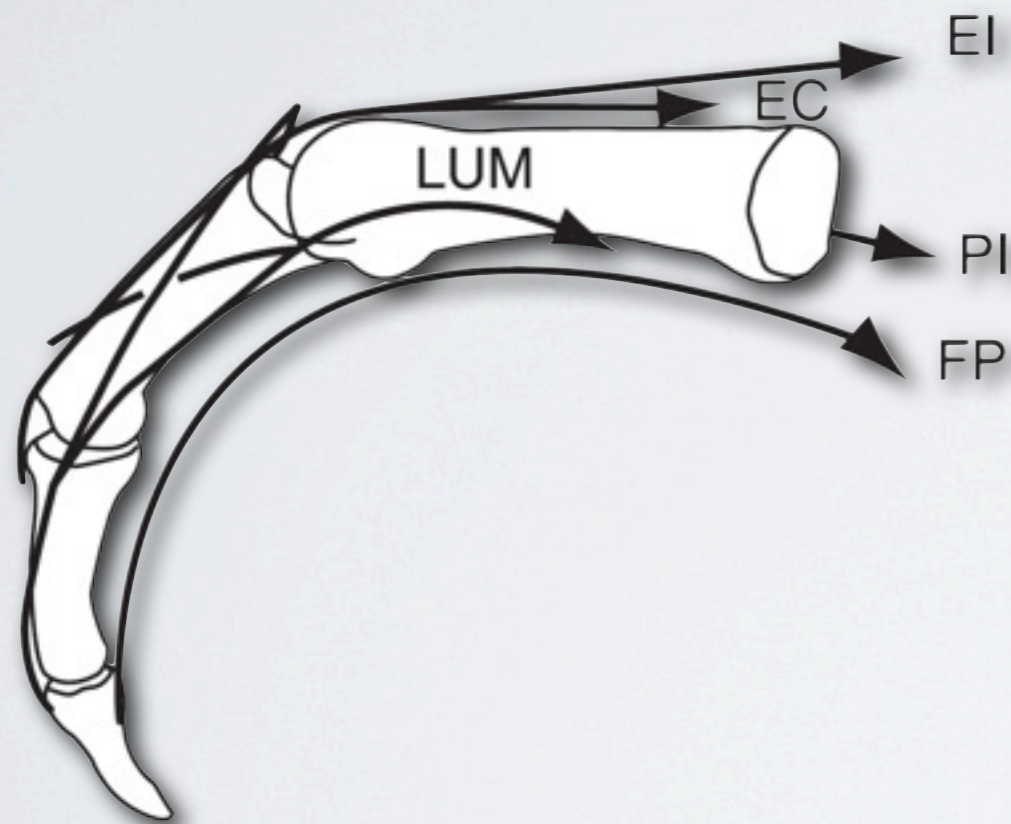
Venkadesan M, Valero-Cuevas FJ. *J Neurosci* 2008;28(6):1366-1373

Venkadesan M, Valero-Cuevas FJ. *Phil Tran Roy Soc Lon A*, 2009;367(1891): 1163-1179

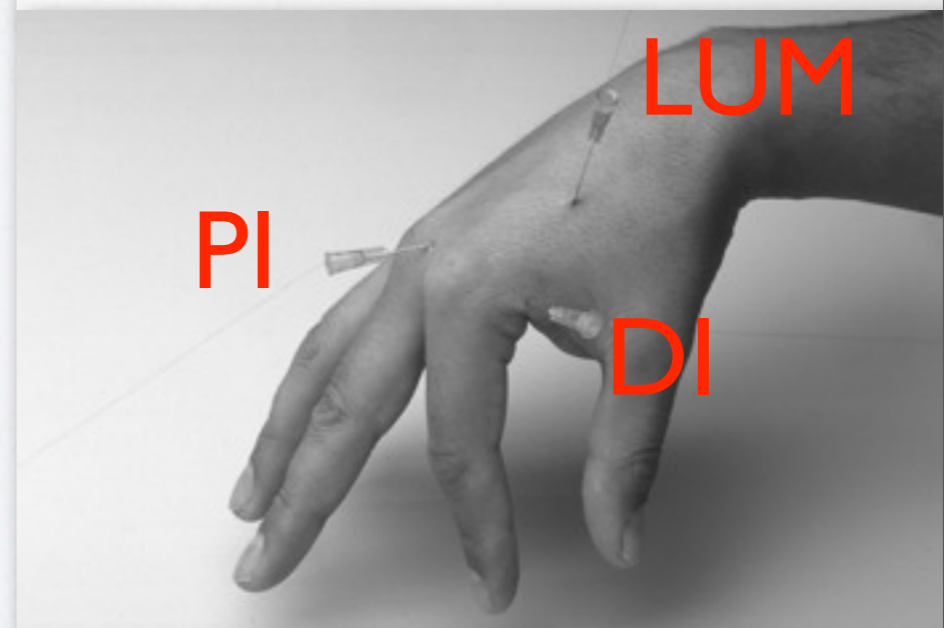
Joint torques are different for motion and force



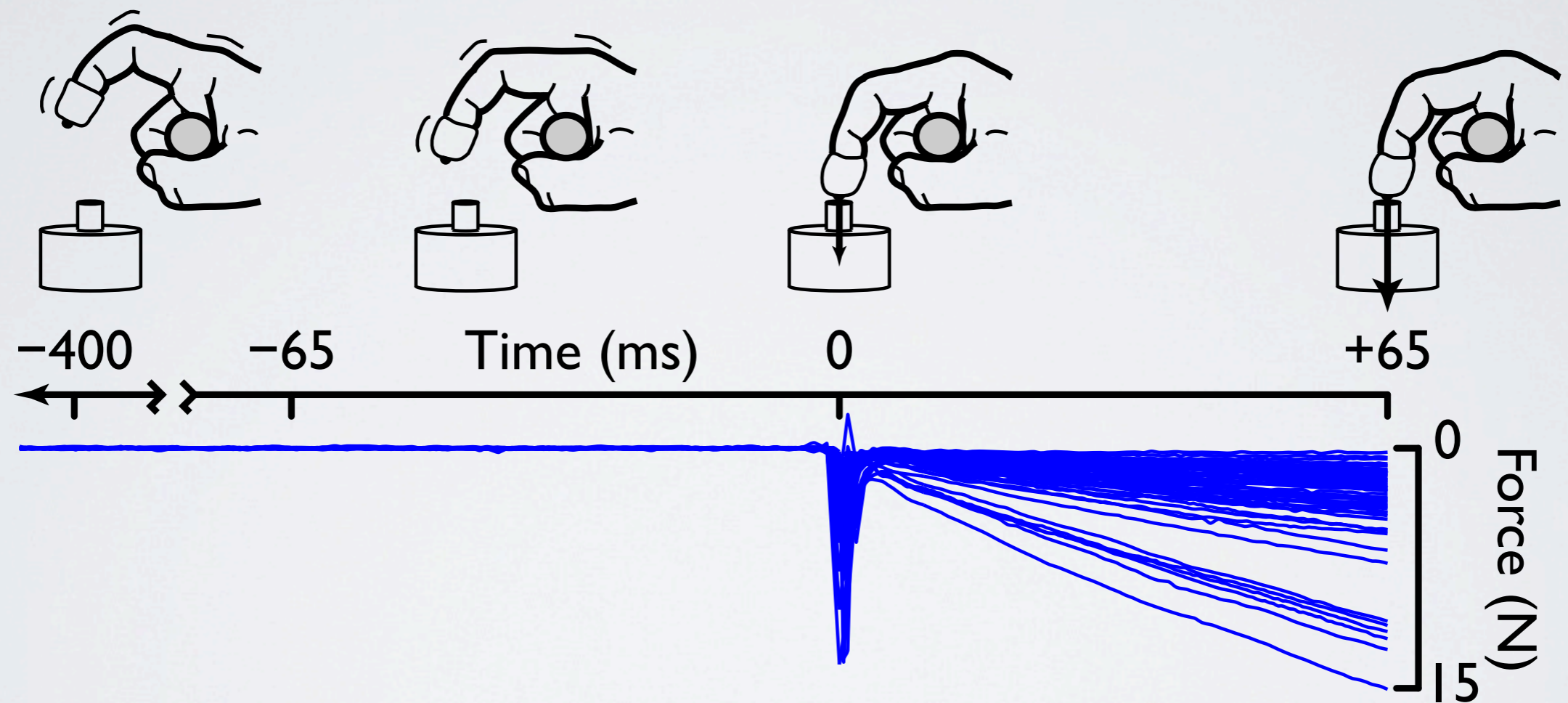
How do humans control contact transitions?



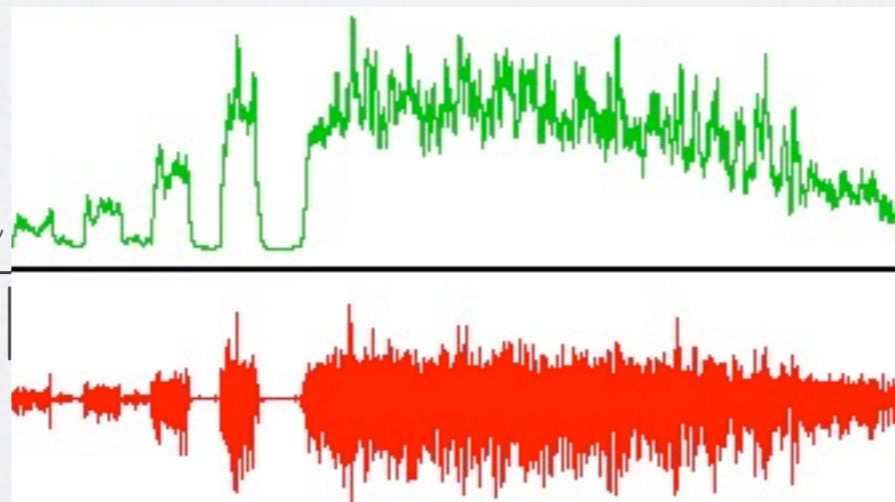
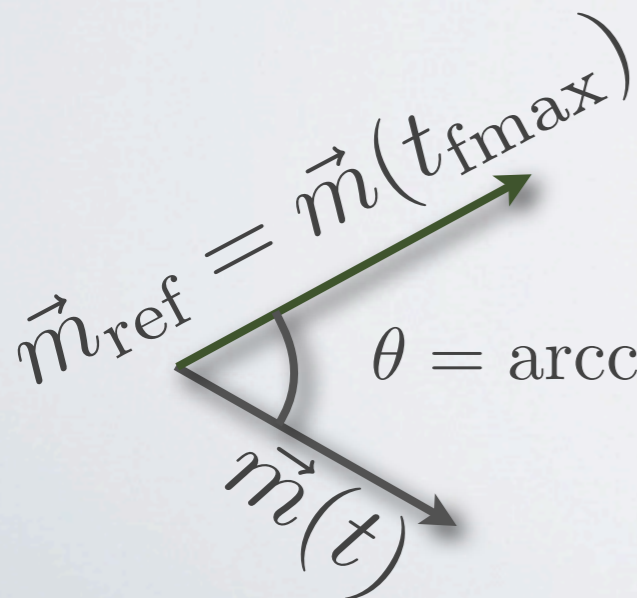
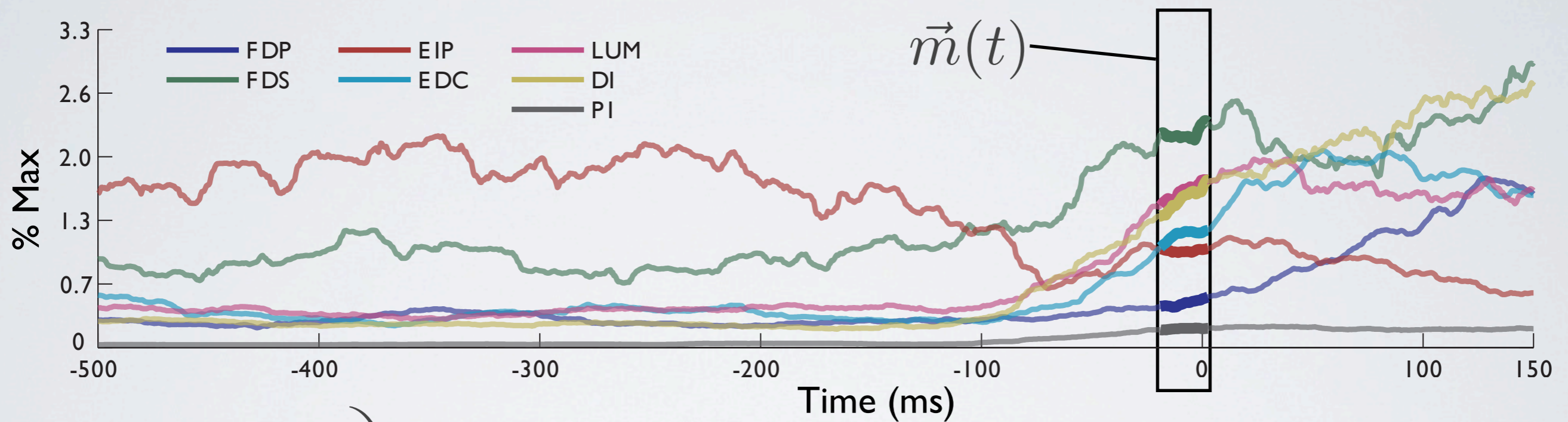
How do humans control contact transitions?



Experimental protocol



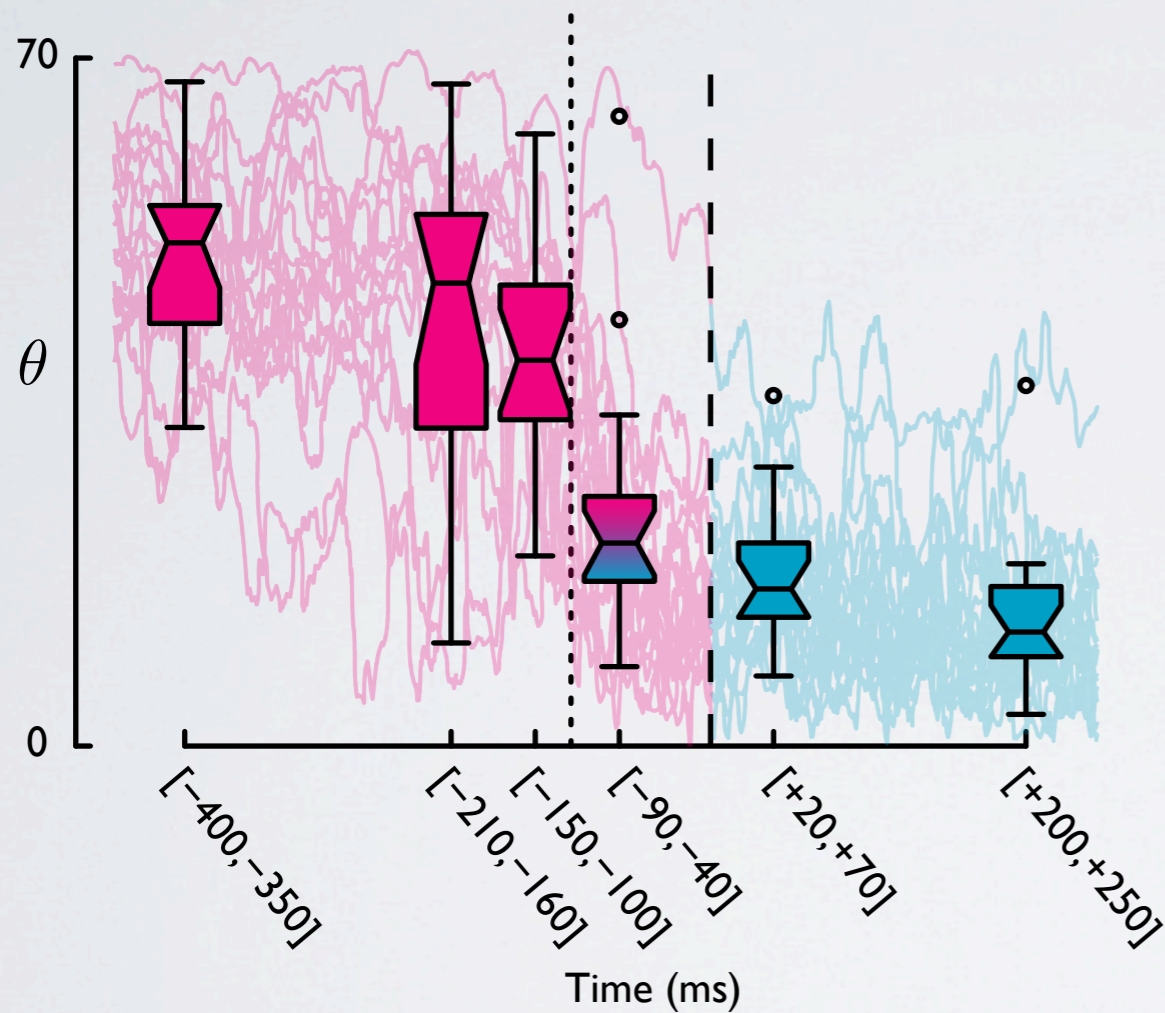
“Coordination pattern” of seven electromyograms



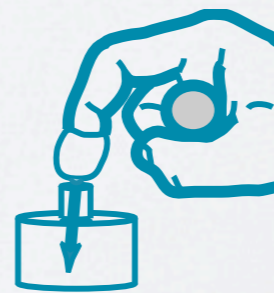
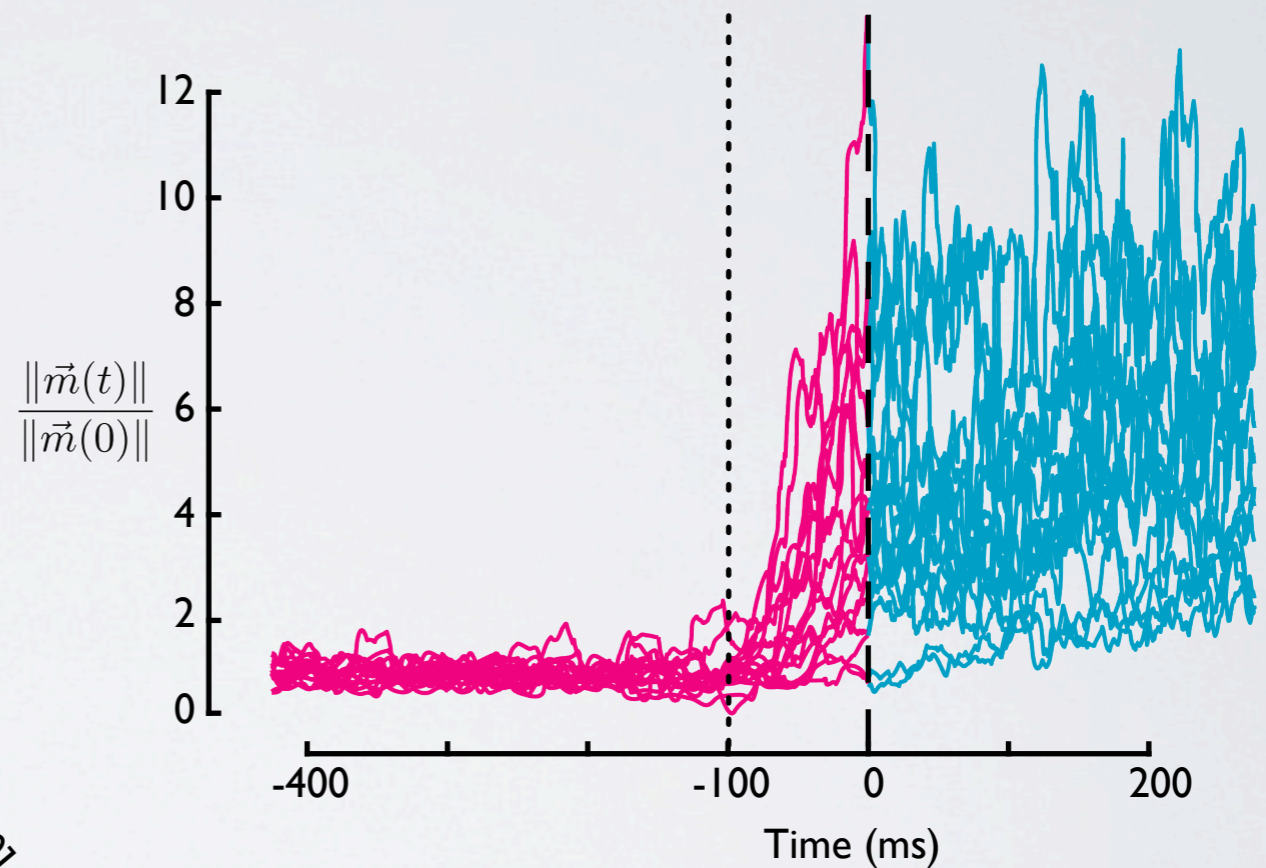
Warning
in high dimensions!

Anticipatory switch before contact

Direction



Magnitude

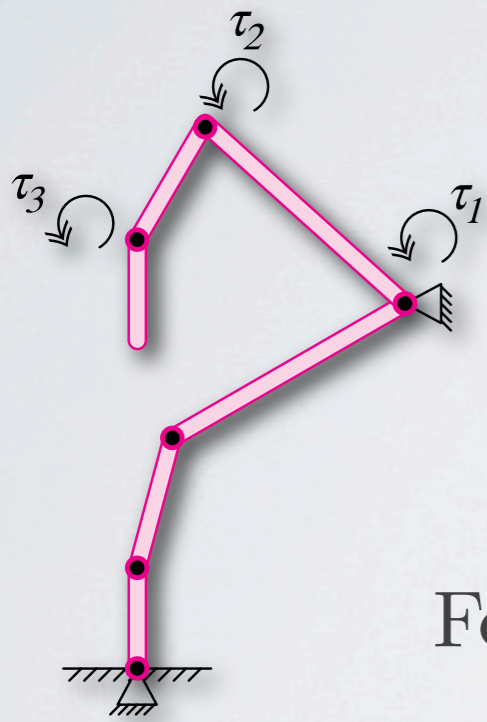


Why and how to transition?

- Transition happens ~60 ms before contact
 - Does uncertainty lead to anticipation?
- Rotation followed by magnitude increase
 - Desire to avoid high speed collisions?
- Deterministic, mechanical explanation

Two-phase model

Motion: $M(\varphi(t))\ddot{\varphi}(t) + C(\varphi(t), \dot{\varphi}(t))\dot{\varphi}(t) + \mathbf{N}(\varphi(t)) = \boldsymbol{\tau}(t)$



$$\begin{pmatrix} \dot{r}_x \\ \dot{r}_y \\ \dot{r}_\alpha \end{pmatrix}^+ = \begin{pmatrix} 0 \\ 0 \\ \dot{r}_\alpha^- \end{pmatrix} \quad \begin{pmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \end{pmatrix}^\pm = \mathbf{A}(\varphi)^{-1} \begin{pmatrix} \dot{r}_x \\ \dot{r}_y \\ \dot{r}_\alpha \end{pmatrix}^\pm$$

Force: $M(\varphi)\ddot{\varphi} + C(\varphi, \dot{\varphi})\dot{\varphi} + \mathbf{N}(\varphi) + \mathbf{A}(\varphi)^T \mathbf{f} = \boldsymbol{\tau}(t)$

where, $\mathbf{f} = (\mathbf{A}\mathbf{M}^{-1}\mathbf{A}^T)^{-1} (\mathbf{A}\mathbf{M}^{-1}(\boldsymbol{\tau} - \mathbf{C}\dot{\varphi} - \mathbf{N}) + \dot{\mathbf{A}}\dot{\varphi})$

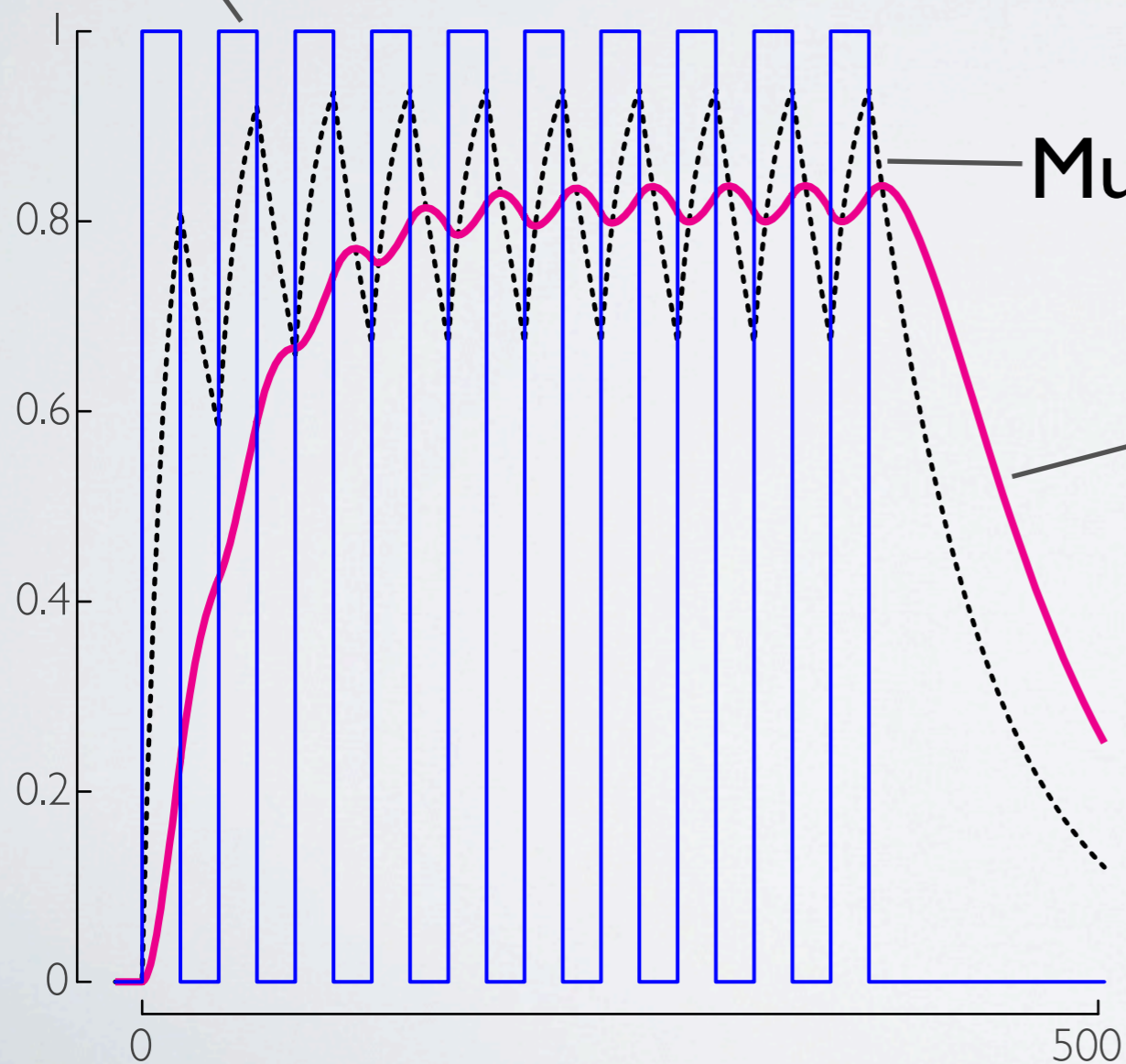
- Measured / estimated inertia and lengths
- Specified fingertip trajectory (from experiments)

Muscle-like actuator dynamics

$$T_{\text{act}} \dot{a}^{(i)} + \left(\beta + (1 - \beta) \left| \tau_D^{(i)} \right| \right) a^{(i)} = \tau_D^{(i)}$$

$$T_{\text{con}} \dot{\tau}^{(i)} + \tau^{(i)} = a^{(i)}$$

Neural impulse: τ_D



Muscle activation: a

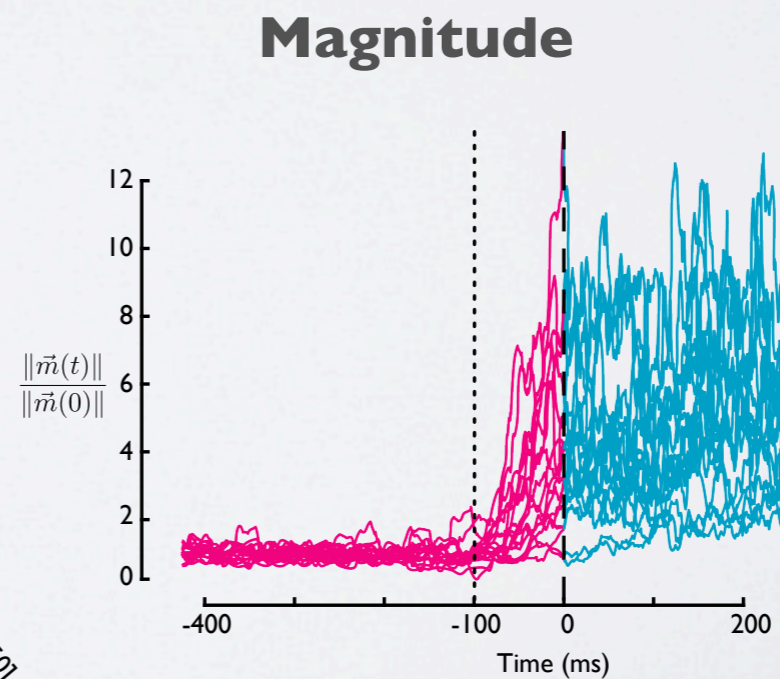
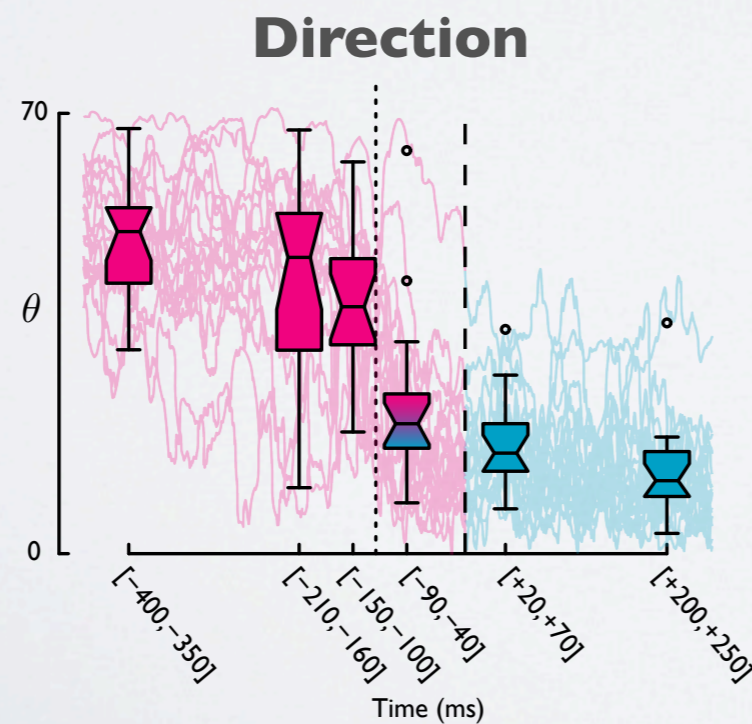
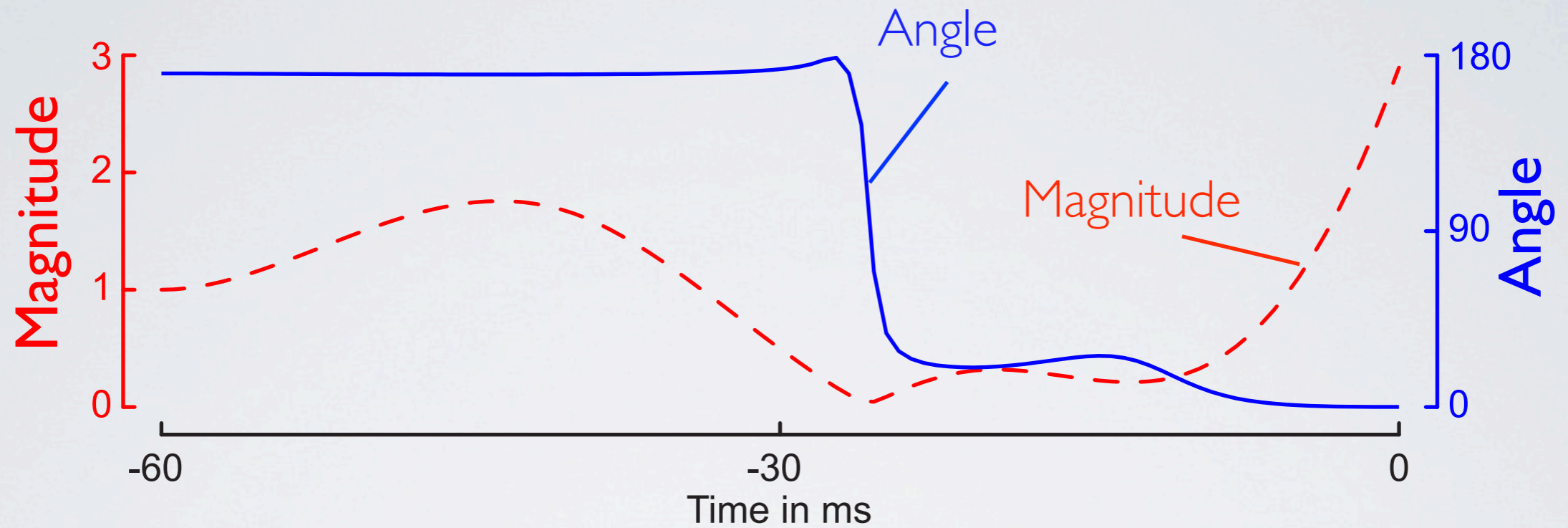
Actual torque output: τ

- T_{act} Activation (12 ms)
- T_{con} Contraction (36 ms)
- β Act/Deact time, 0.2

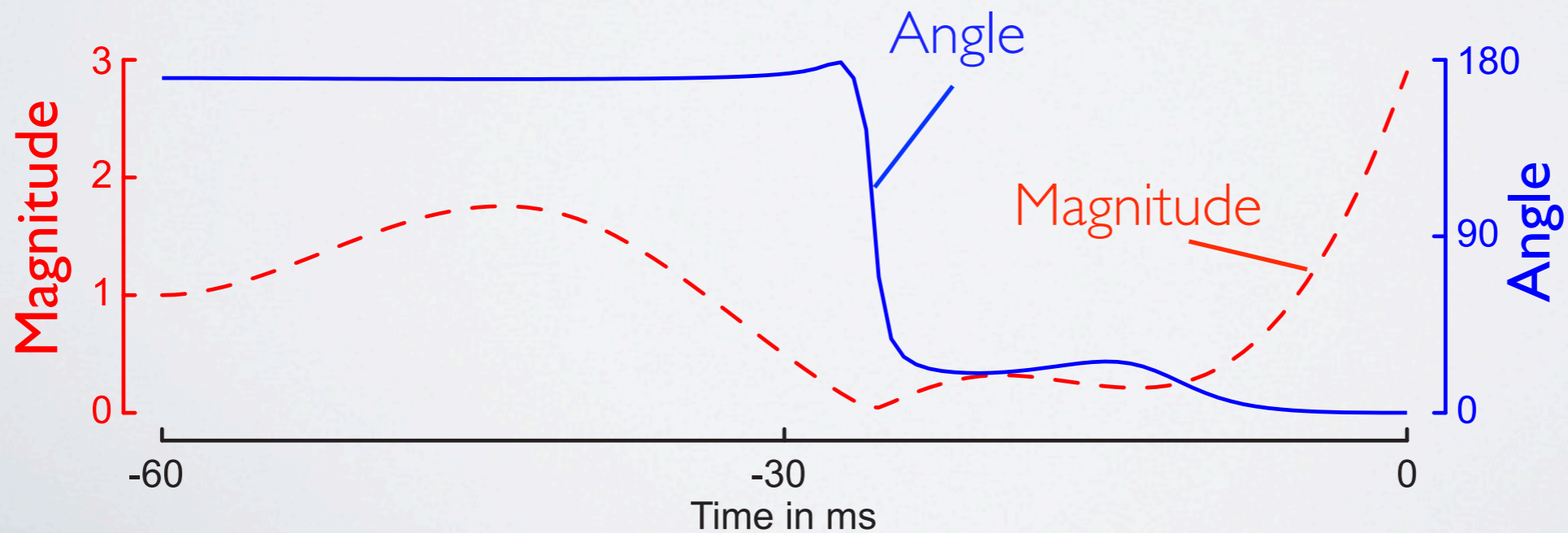
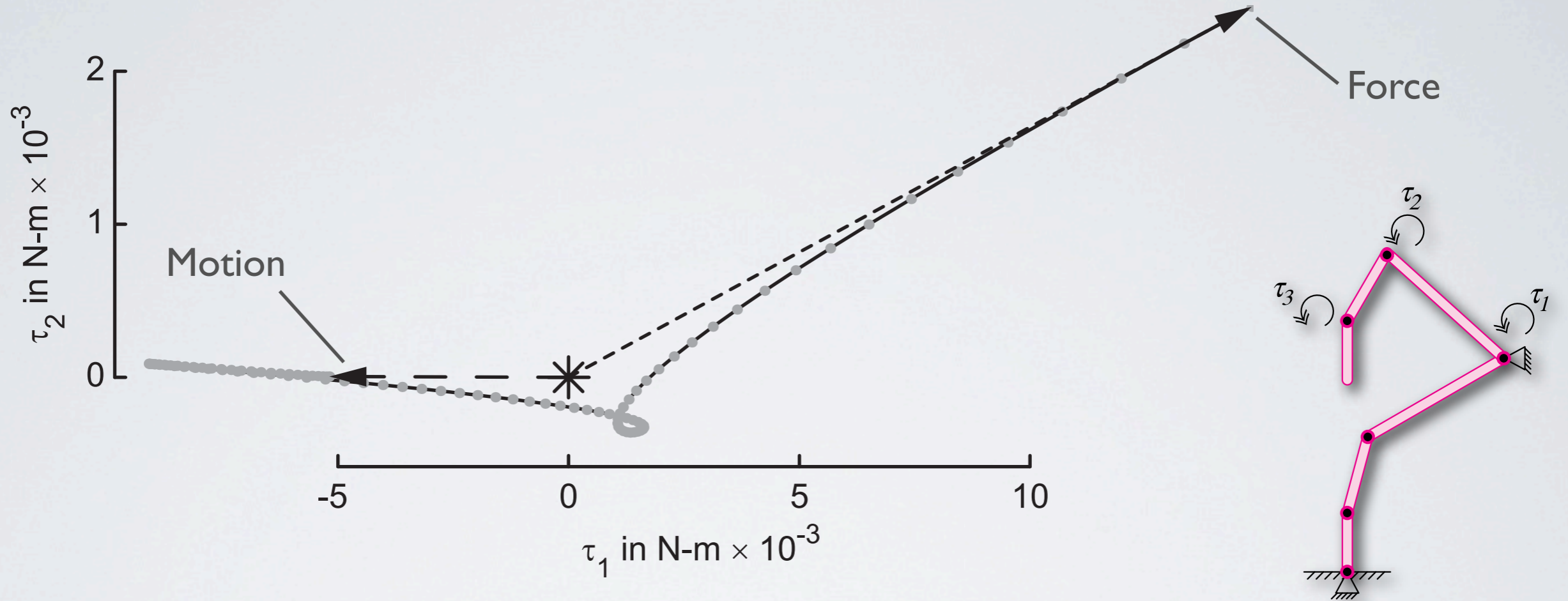
Optimal control solution method

- Only terminal cost: force direction
- Piecewise linear control, specified every 20 ms
- Specified initial conditions at -60 ms
- Nelder-Mead and sequential quadratic programming
 - Multiple starts to verify local uniqueness
 - Found a global optimum (may be non-unique)

Anticipation in the face of certainty



Trajectory in joint-torque space



Controlling contact transitions

- Humans anticipate and switch strategies
- The timing of strategy switching governed by tendon elasticity
- How does impedance control figure here?

Thank you!

