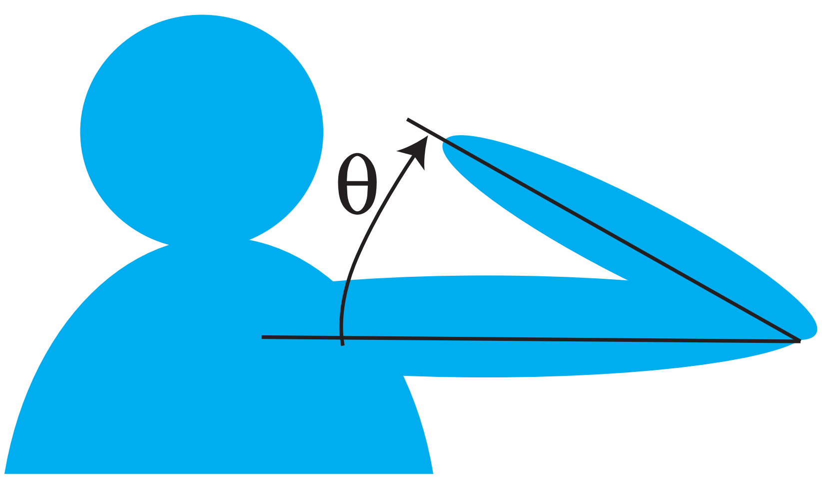
Human motor control

Gregor Schöner

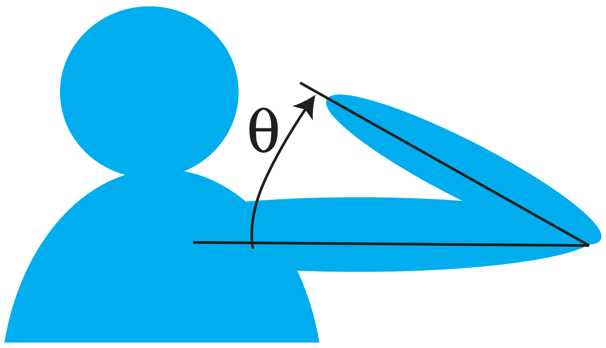
Human motor control

- human movement is highly compliant…



Is posture “controlled”?

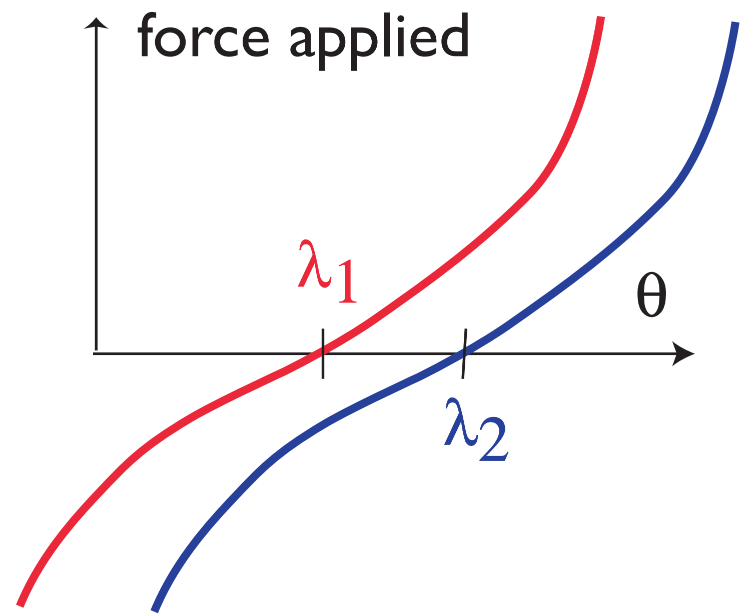
- the elbow does not behave like a passive mechanical system with a free joint at the elbow: $J\ddot{\theta} = 0$
  - where J is inertial moment of forearm (if upper arm is held fixed)
- Instead, the elbow resists, when pushed => there is active control= stabilization of the joint



=>experiment

the mass spring model

- Anatol Feldman has figured out, what the macroscopic description of this stabilization is
- the invariant characteristic



the mass-spring model

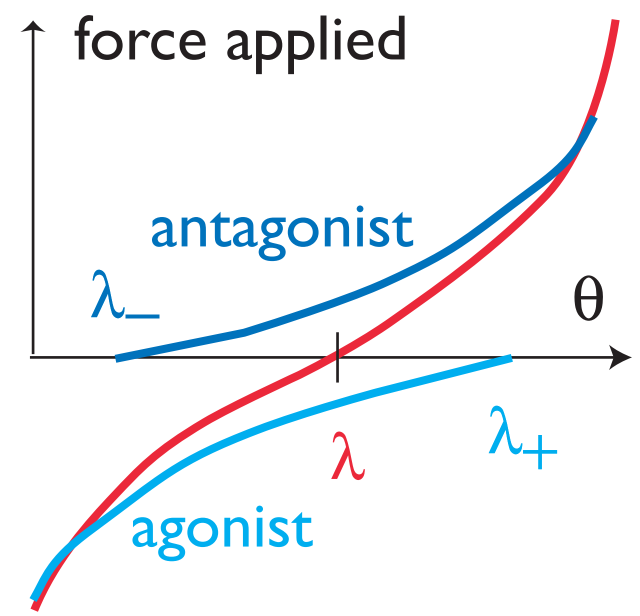
- this is an elastic force (because it is proportional to position)
- there is also a viscous component (resistance depends on joint velocity)

$$J\ddot{\theta} = \boxed{-k(\theta-\lambda)-\mu\dot{\theta}}$$

active torques generated by the muscle

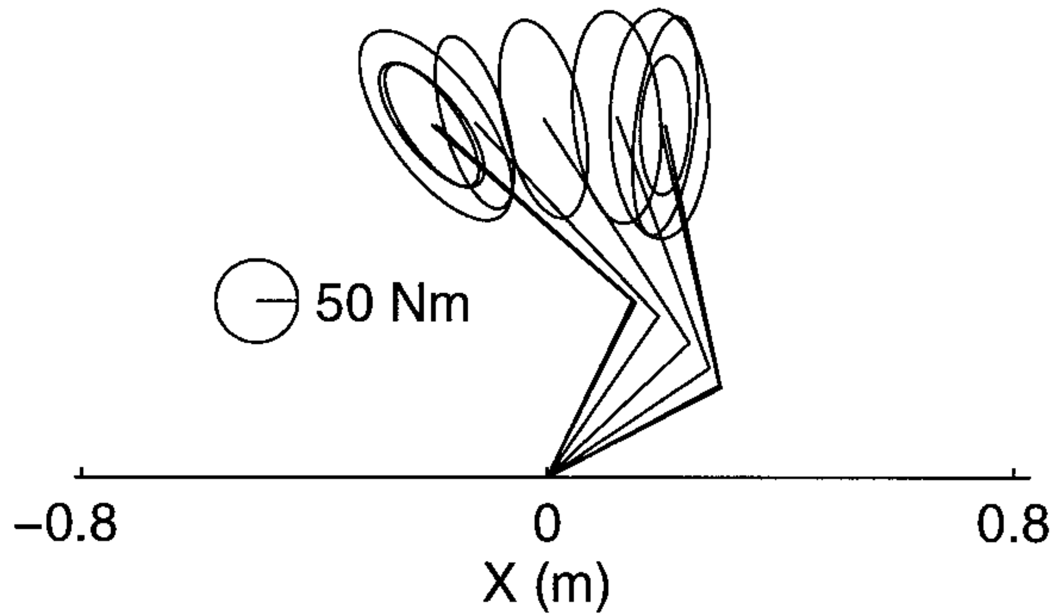
agonist-antagonist action

- one lambda per muscle
- tested on muscles detached at one end
- co-contraction controls stiffness



stiffness

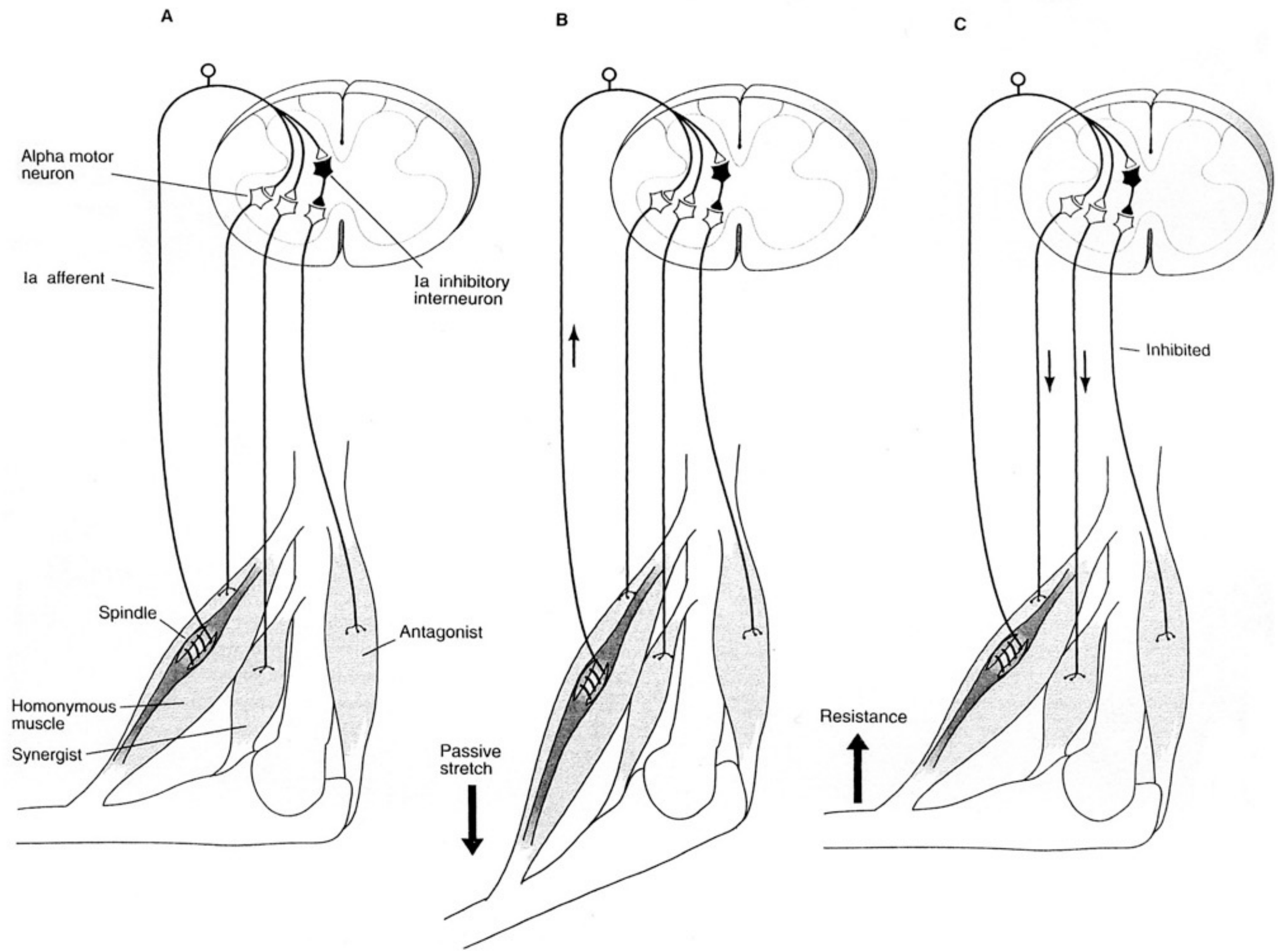
- the stiffness, k, can be measured from perturbations
- the viscosity "mu" is more difficult to determine



$$J\ddot{\theta} = -k(\theta - \lambda) - \mu\dot{\theta}$$

neural basis of EP model: spinal reflex loops

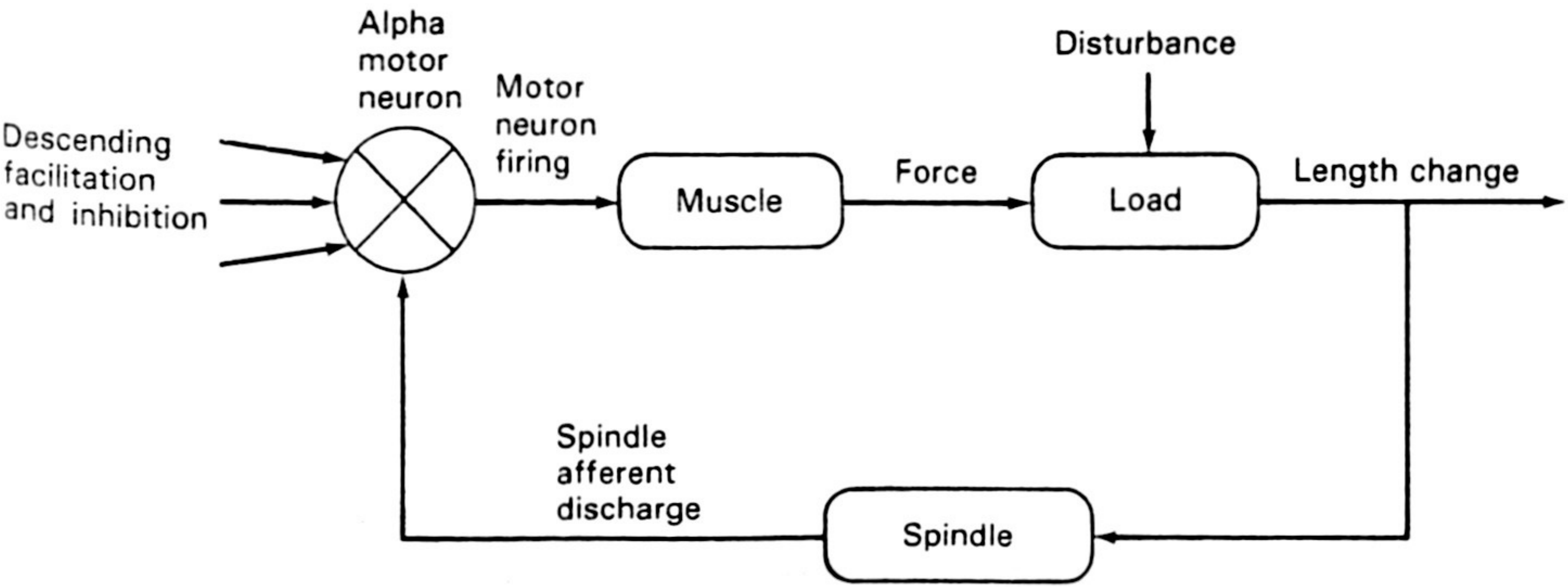
- alpha-gamma reflex loop generates the stretch reflex



[Kandel, Schartz, Jessell, Fig. 37-11]

spinal cord: reflex loops

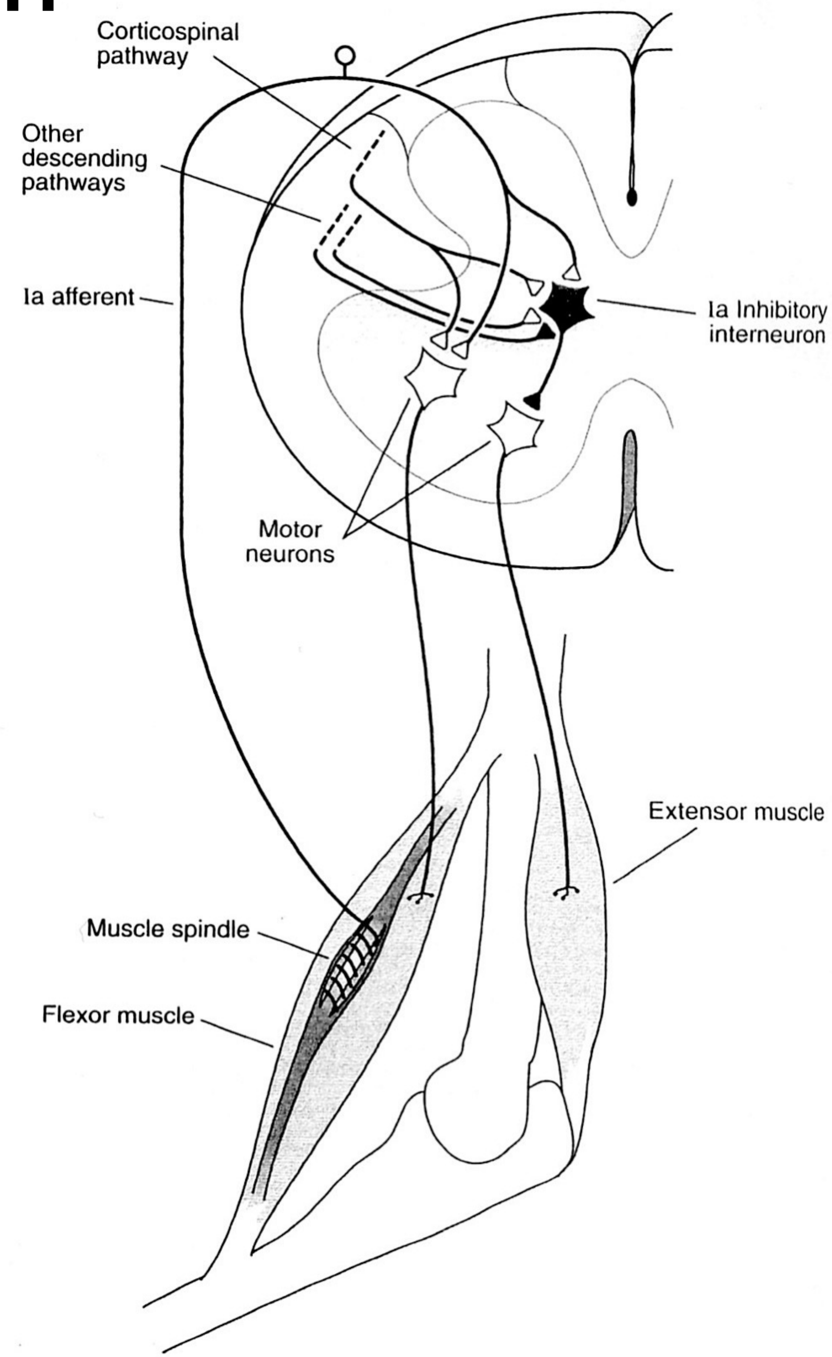
- the stretch reflex acts as a negative feedback loop



[Kandel, Schartz, Jessell, Fig. 31-12]

spinal cord: coordination

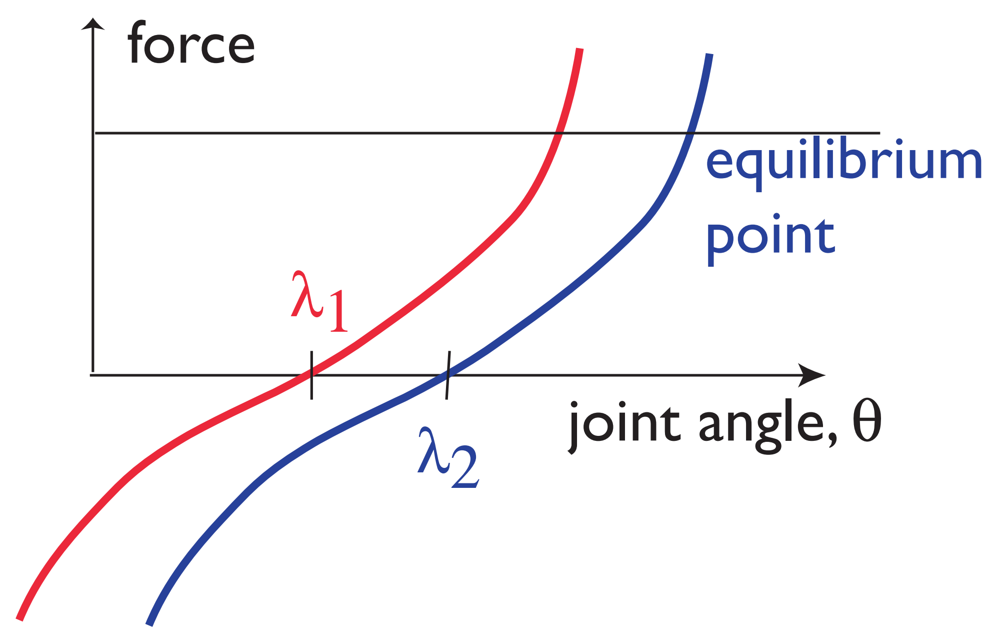
- Ia inhibitory interneuron mediates reciprocal innervation in stretch reflex, leading to automatic relaxation of antagonist on activation of agonist



[Kandel, Schartz, Jessell, Fig. 38-2]

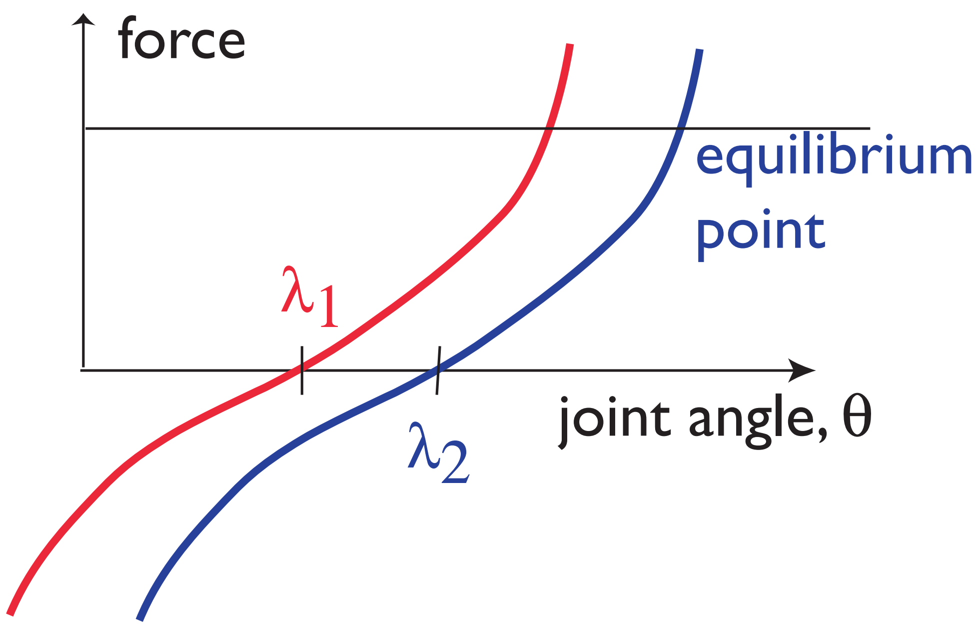
Movement entails change of posture

- that equilibrium point is shifted during movement so that after the movement, the postural state exists around a new combination of muscle lengths/joint configurations



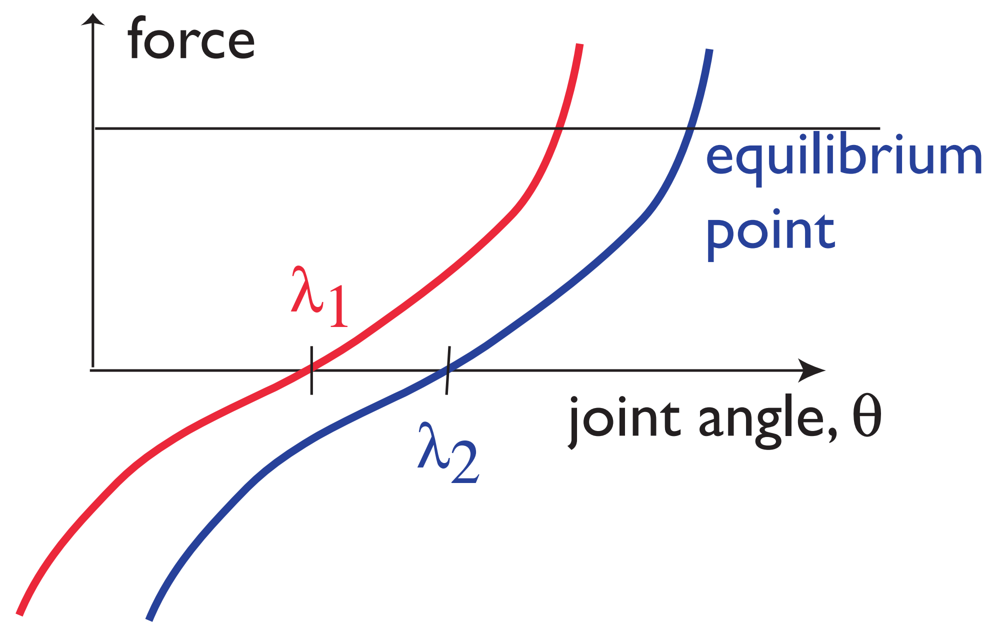
Movement entails change of posture

- most models account for movement in terms of generation of joint torques….
- => the shift of the EP is the single most overlooked fact in control models of movement generation



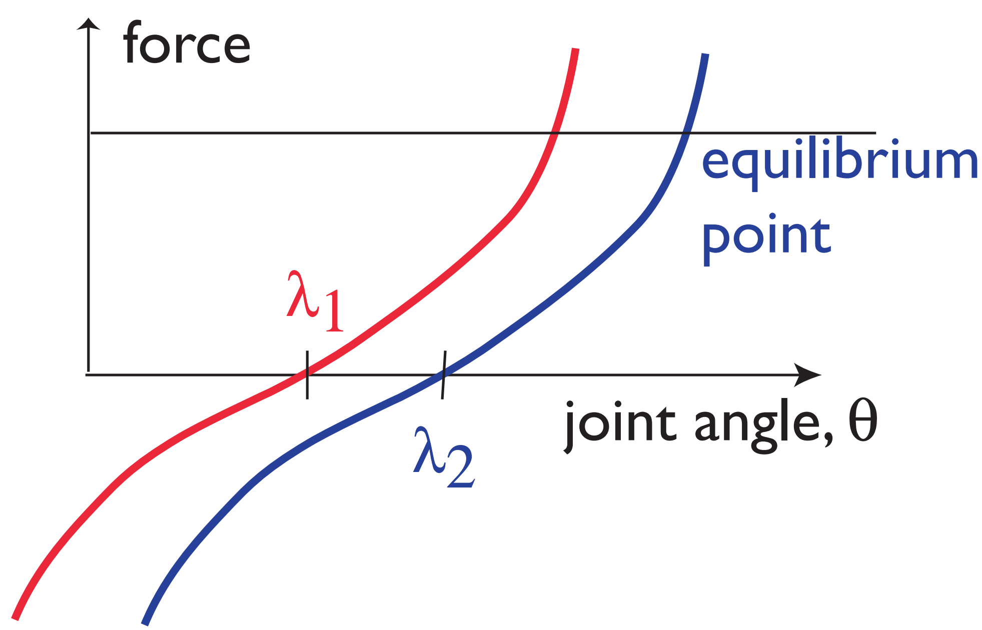
Does the "motor command" specify force/torque?

- no! Because the same descendent neural command generates different levels of force depending on the initial length of the muscle

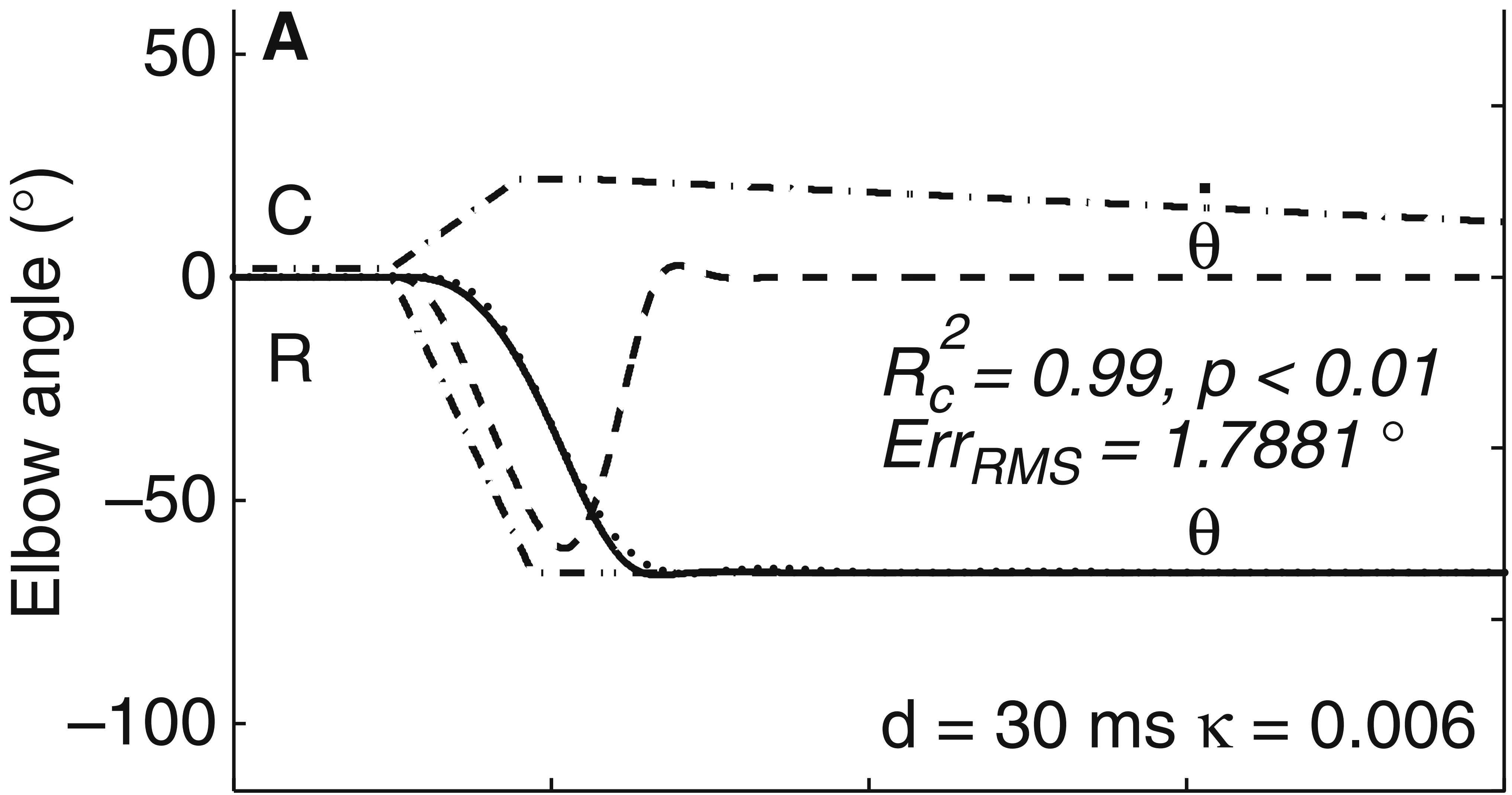


Virtual trajectory

- shifting the equilibrium point is necessary, but is it also sufficient?
- first answer: yes… simple ramp-like trajectories of the “r” command (“virtual trajectories”) shift the equilibrium point smoothly in time…



Pilon, Feldman, 2006



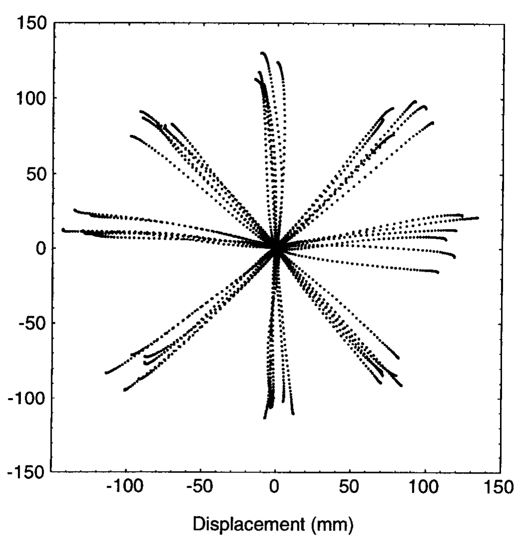
Shifting the equilibrium point is necessary, but is it also sufficient?

- such simple ramp-like trajectories of the "r" command ("virtual trajectories") may be sufficient when movements
  - are sufficiently slow
  - interaction torques/mechanical conditions unchallenging
- but is this generally true?

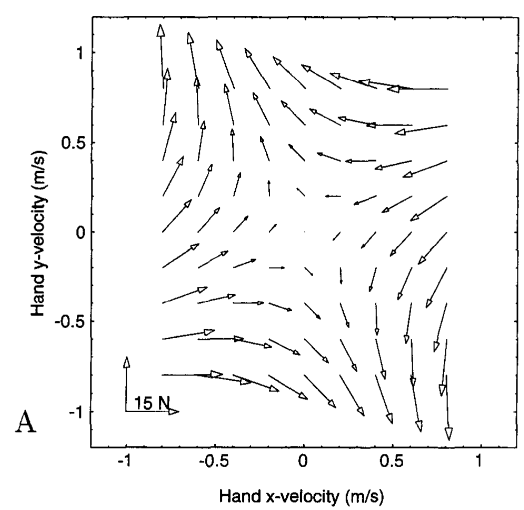
Limit case: velocity dependent force field

- after adapting to a velocity dependent force field the hand reproduces the "natural" path, but must generate compensatory forces on the way

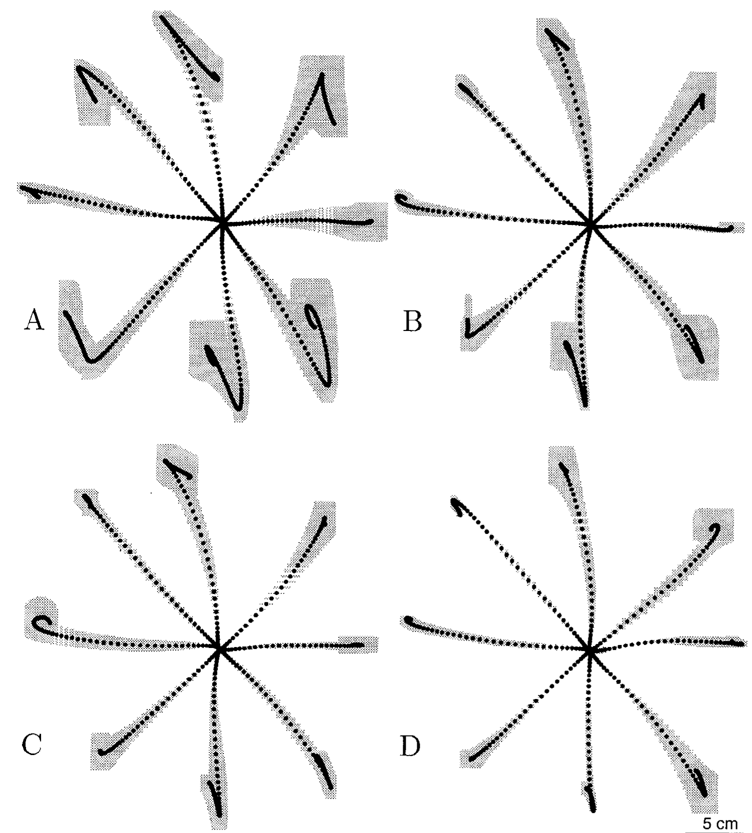
[Shadmehr, Mussa-Ivaldi, 1994]



center-out movements before force-field adaptation



velocity dependent force-field = zero at rest



center-out movements at four stages during force-field adaptation

Shifting the equilibrium point is necessary, but is it also sufficient?

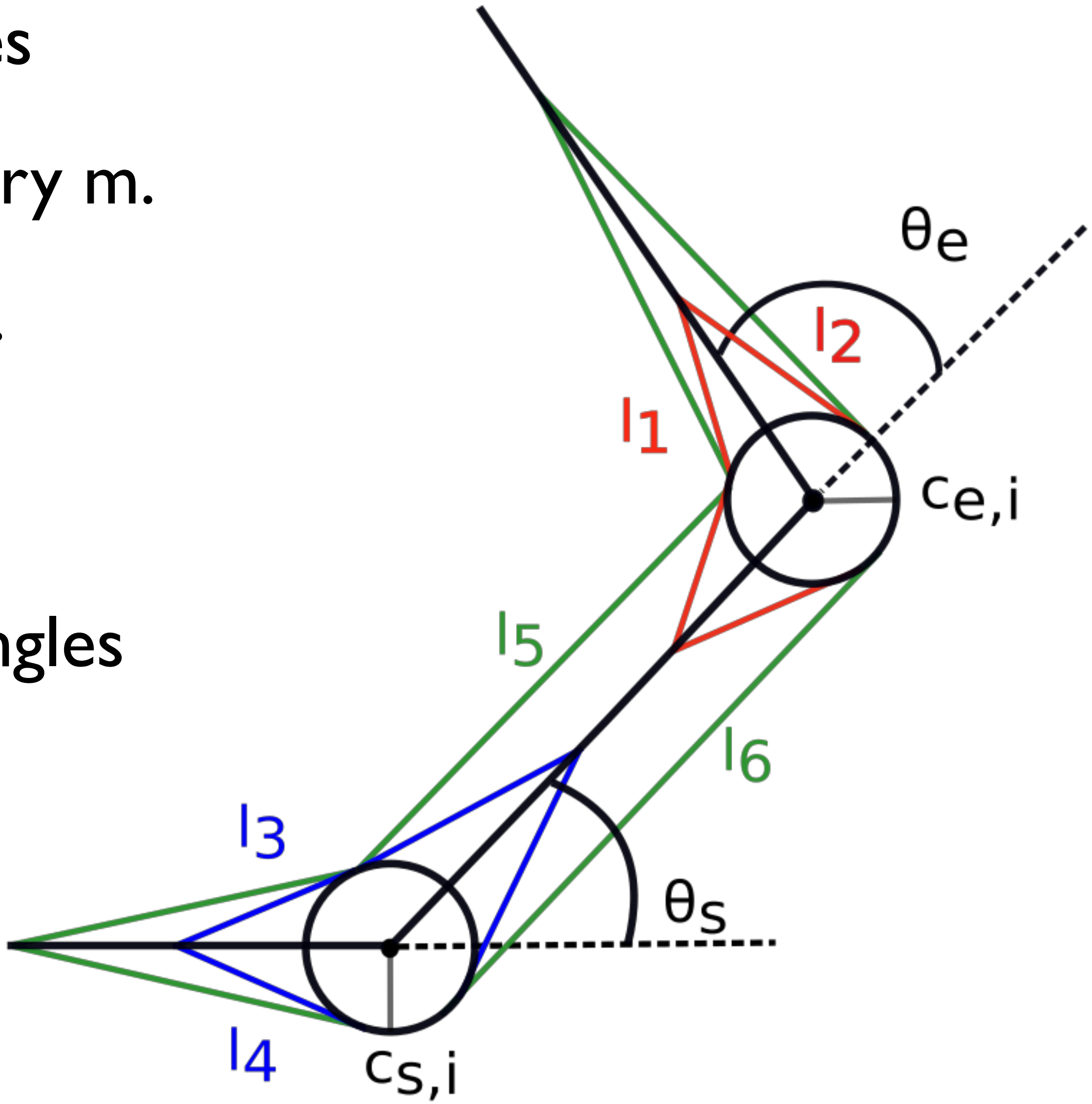
- => r-command must still shift from initial to final posture, but must also generate the forces to compensate for the force field during the movement
- that probably takes the form of non-monotonic, “complex” time courses…
- are such temporally complex (e.g,. non-monotonic) r-commands necessary during unperturbed movement

The minimal reference command

- two joint limb with 6 muscles
- = 2 pairs of mono-articulatory m.
- + 1 pair of bi-articulatory m.

- muscle length link to joint angles

$$l_i = c_i + c'_{\mathrm{i,s}}\theta_{\mathrm{s}} + c'_{\mathrm{i,e}}\theta_{\mathrm{e}}$$



[Ramadan, Hummert, Jokeit, Schöner, under revision]

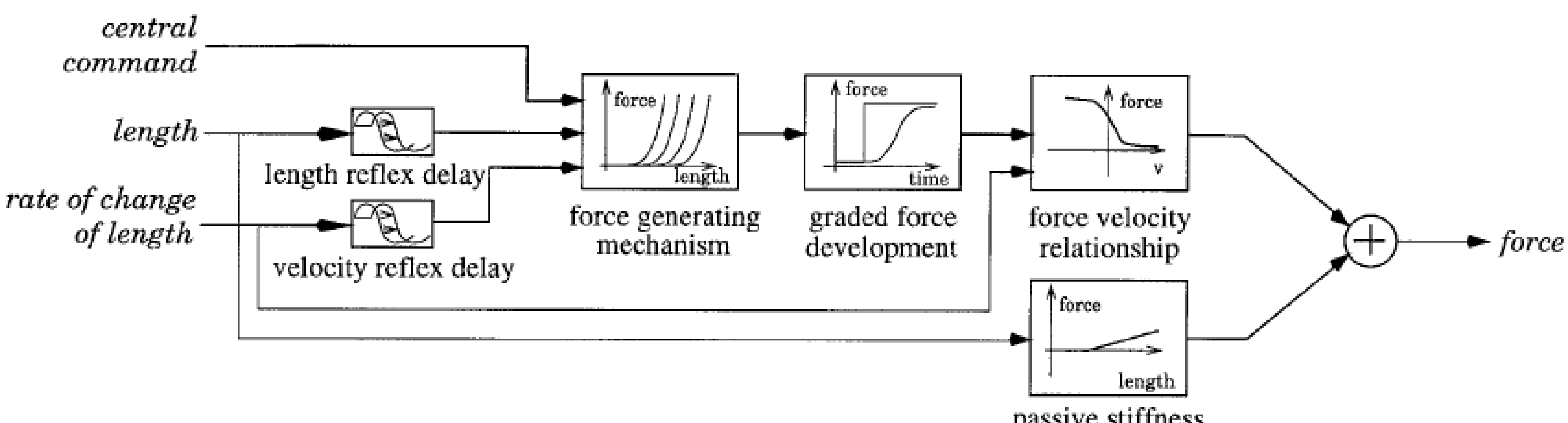
- Neuro-muscular model based on Gribble, Ostry et al., 98…
consistent with EP hypothesis

$$A_{\mathrm{i}} = [l_{\mathrm{i}} - \lambda_{\mathrm{i}} + \mu \cdot \dot{l}_{\mathrm{i}}]^+ \qquad [x]^+ = \begin{cases} x, & \text{if } x > 0 \\ 0, & \text{if } x \le 0 \end{cases}$$

$$\tilde{M}_{\mathrm{i}} = \rho_{\mathrm{i}} \cdot (e^{sA_{\mathrm{i}}} - 1).$$

$$\tau^2 \ddot{M} + 2\tau\dot{M} + M = \tilde{M}$$

$$F_i = M_i[(f_1 + f_2 \cdot \arctan(f_3 + f_4 \cdot \dot{l}_i)] + k(l_i - c_i).$$



- Biomechanical dynamics… standard…

$$T = -H \cdot F$$

with H defined as

$$H = \frac{\partial l}{\partial \theta} = \begin{pmatrix} \frac{\partial l}{\partial \theta_1} & \frac{\partial l}{\partial \theta_2} \end{pmatrix}$$

$$\ddot{\theta} = I^{-1}(T - T_{ext} - C\dot{\theta})$$

$$x = \cos(\theta_1) \cdot l_1 + \cos(\theta_1 + \theta_2) \cdot l_2$$
$$y = \sin(\theta_1) \cdot l_1 + \sin(\theta_1 + \theta_2) \cdot l_2$$

back to muscle:

$$l_i = c_i + c'_{\mathrm{i,s}}\theta_{\mathrm{s}} + c'_{\mathrm{i,e}}\theta_{\mathrm{e}}$$

- determine the "minimal" motor command that changes all lamda's the least possible:

$$\min_{\vec{\lambda}} \Psi(\vec{\lambda}) = \int_0^{t_f} \dot{\vec{\lambda}}(t)^2 \; \mathrm{d}t.$$

- given that the EP shifts: with boundary conditions

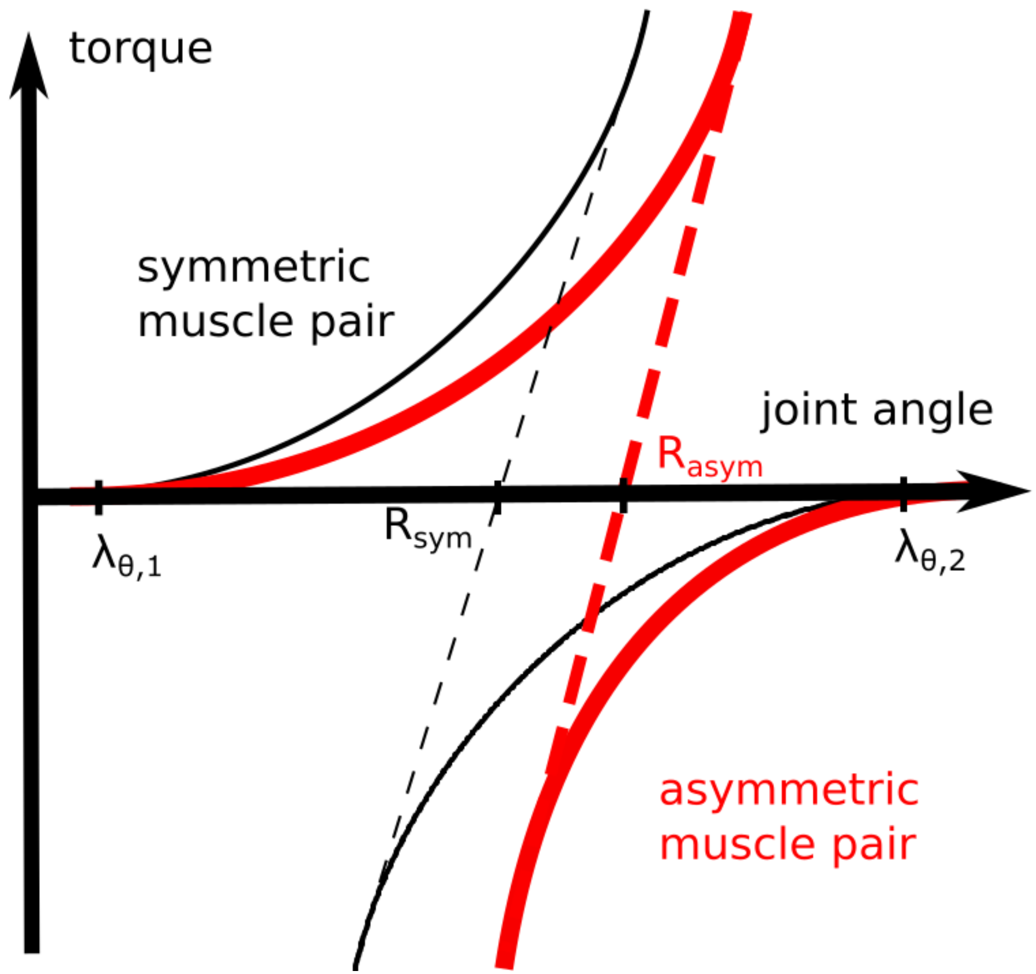
$$\vec{\theta}(t_0) - \vec{\theta}_{\text{start}} = 0, \qquad \dot{\vec{\theta}}(t_0) = 0, \qquad \ddot{\vec{\theta}}(t_0) = 0,$$

$$\vec{\theta}(t_f) - \vec{\theta}_{\text{final}} = 0. \qquad \dot{\vec{\theta}}(t_f) = 0. \qquad \ddot{\vec{\theta}}(t_f) = 0.$$

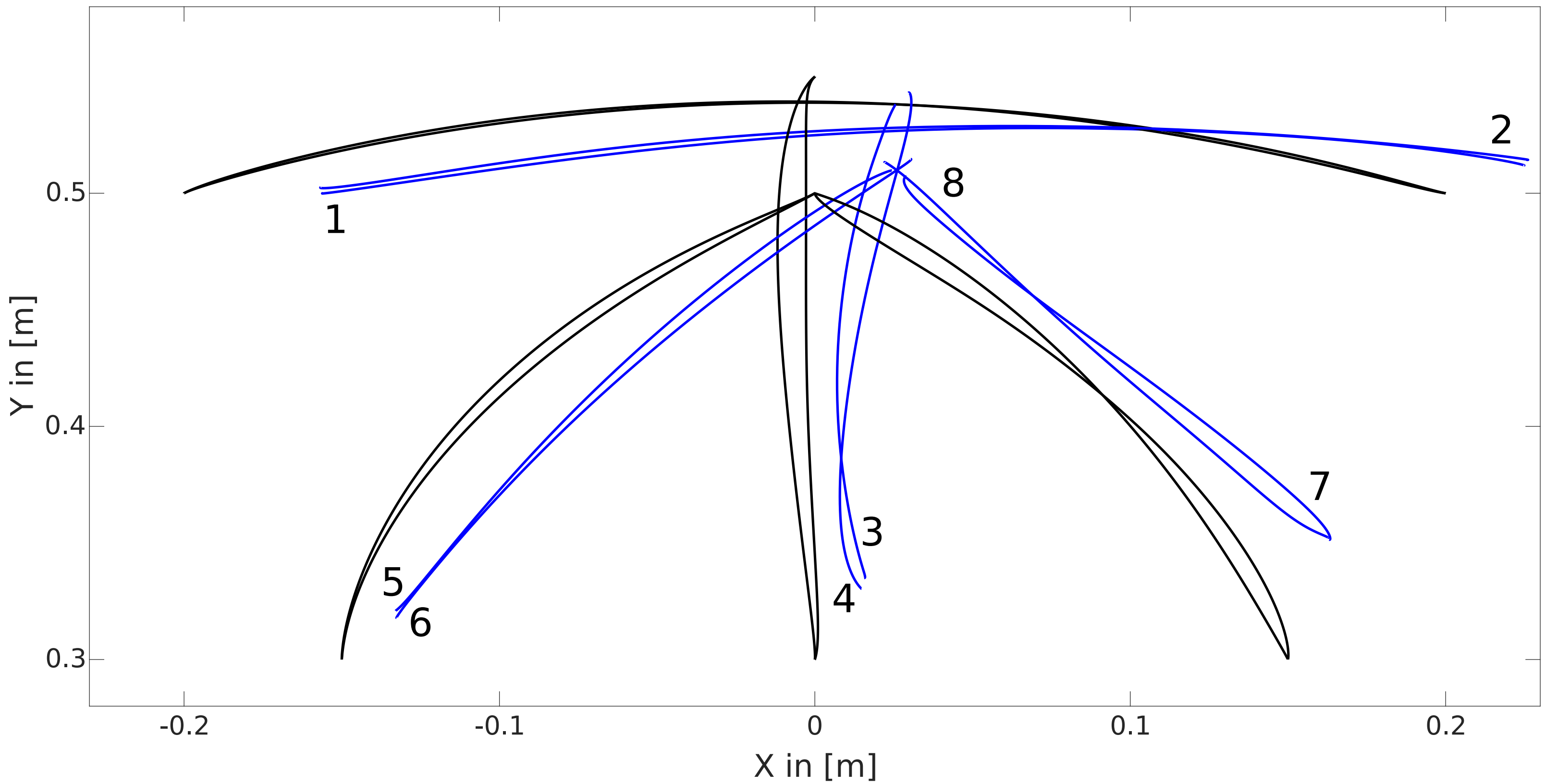
$$\vec{\theta}(t) < \vec{\theta}_{\max}, \qquad \lambda_{\min} \leq \vec{\lambda}(t) \leq \lambda_{\max} \qquad t \in [t_0, t_f].$$

$$\dot{\vec{\theta}}(t) < \dot{\vec{\theta}}_{\max}.$$

Why "lambda" rather than R?



Paths exp-model



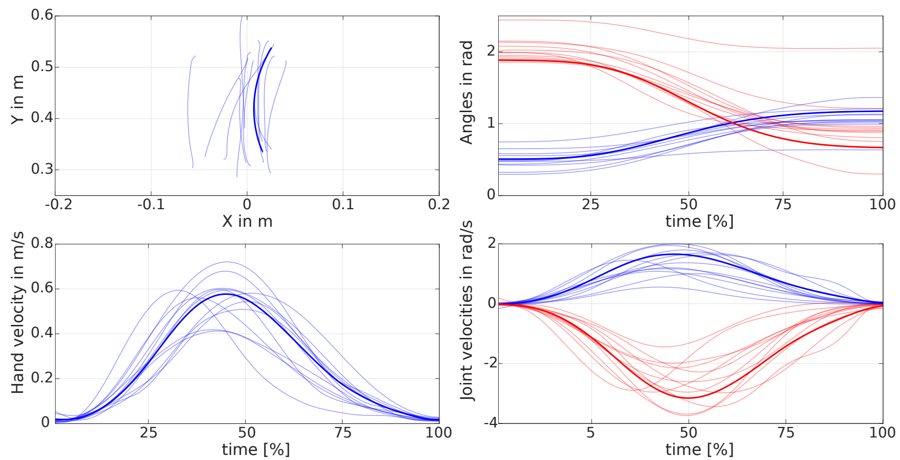
blue: experiment
black: model

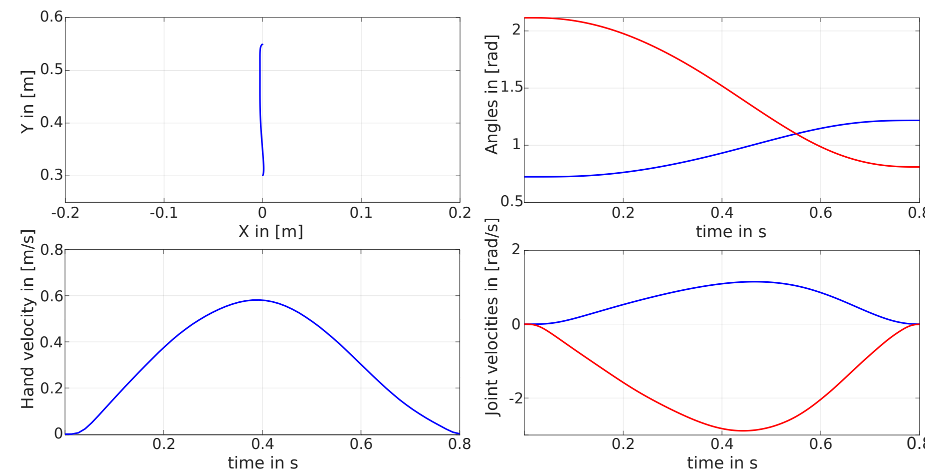
Trajectories exp-data

slow

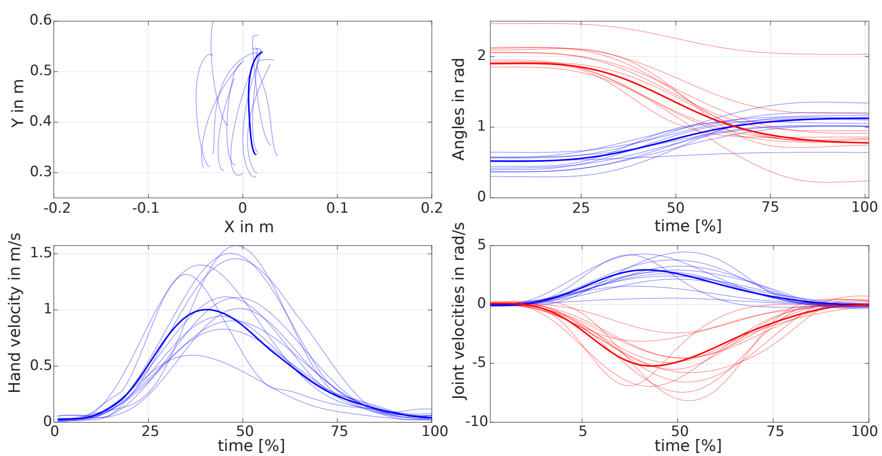
experiment

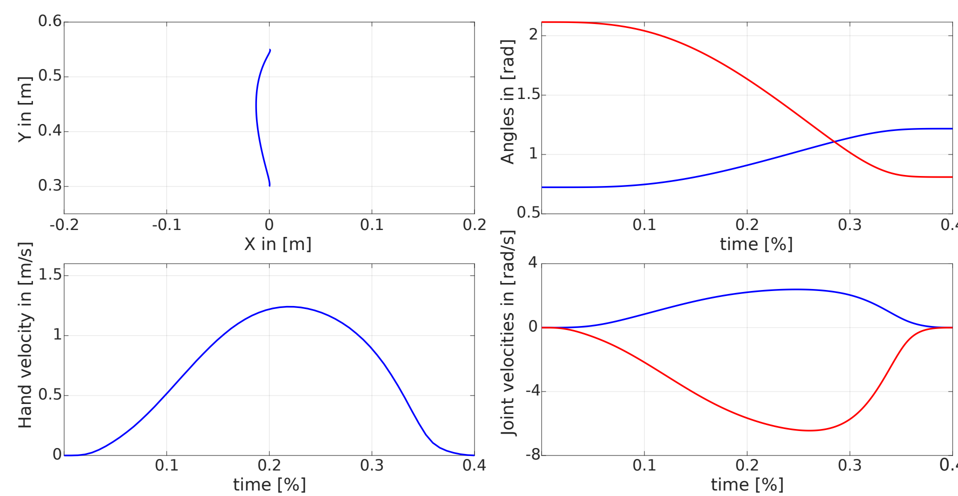
model



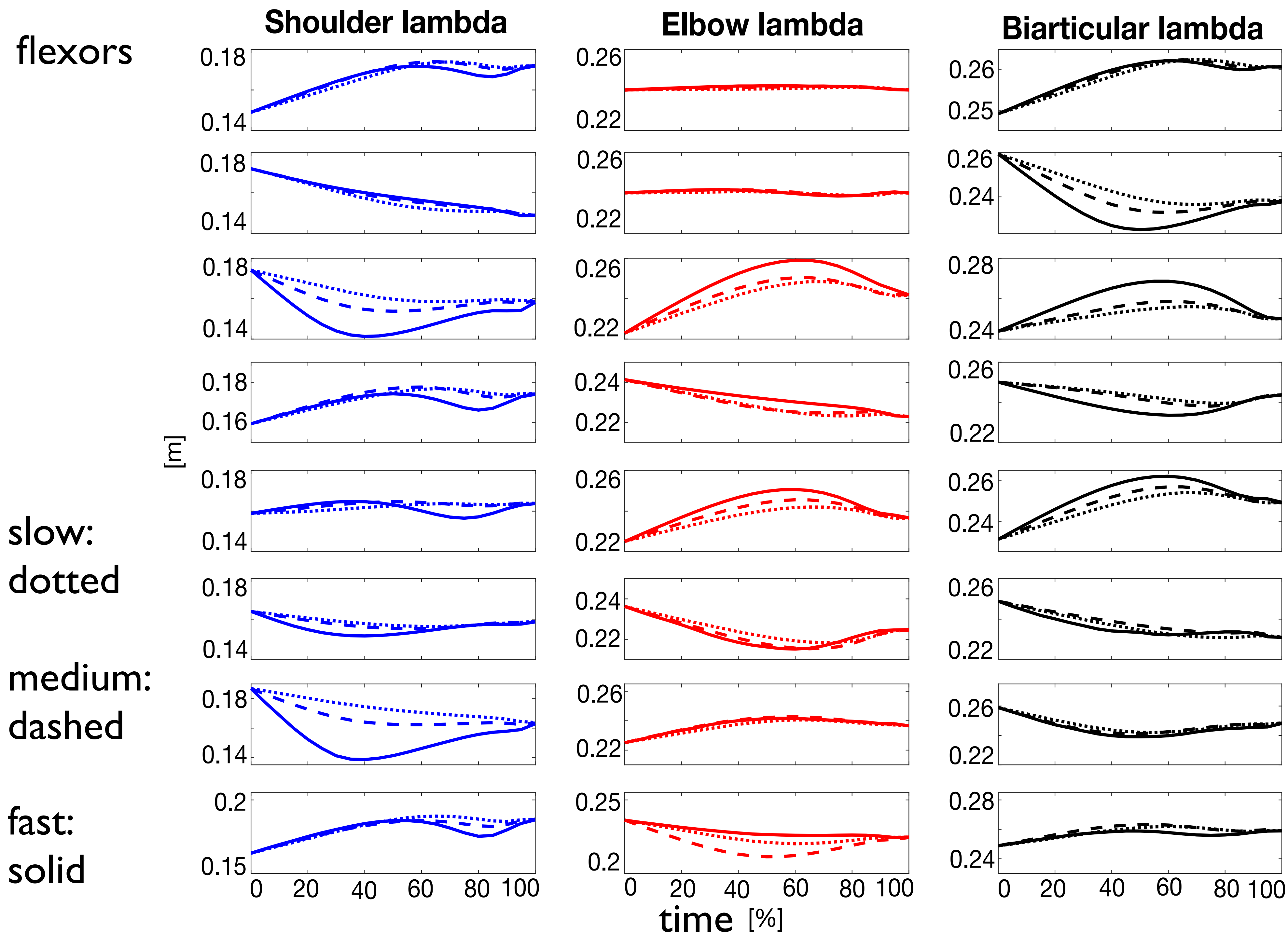


fast

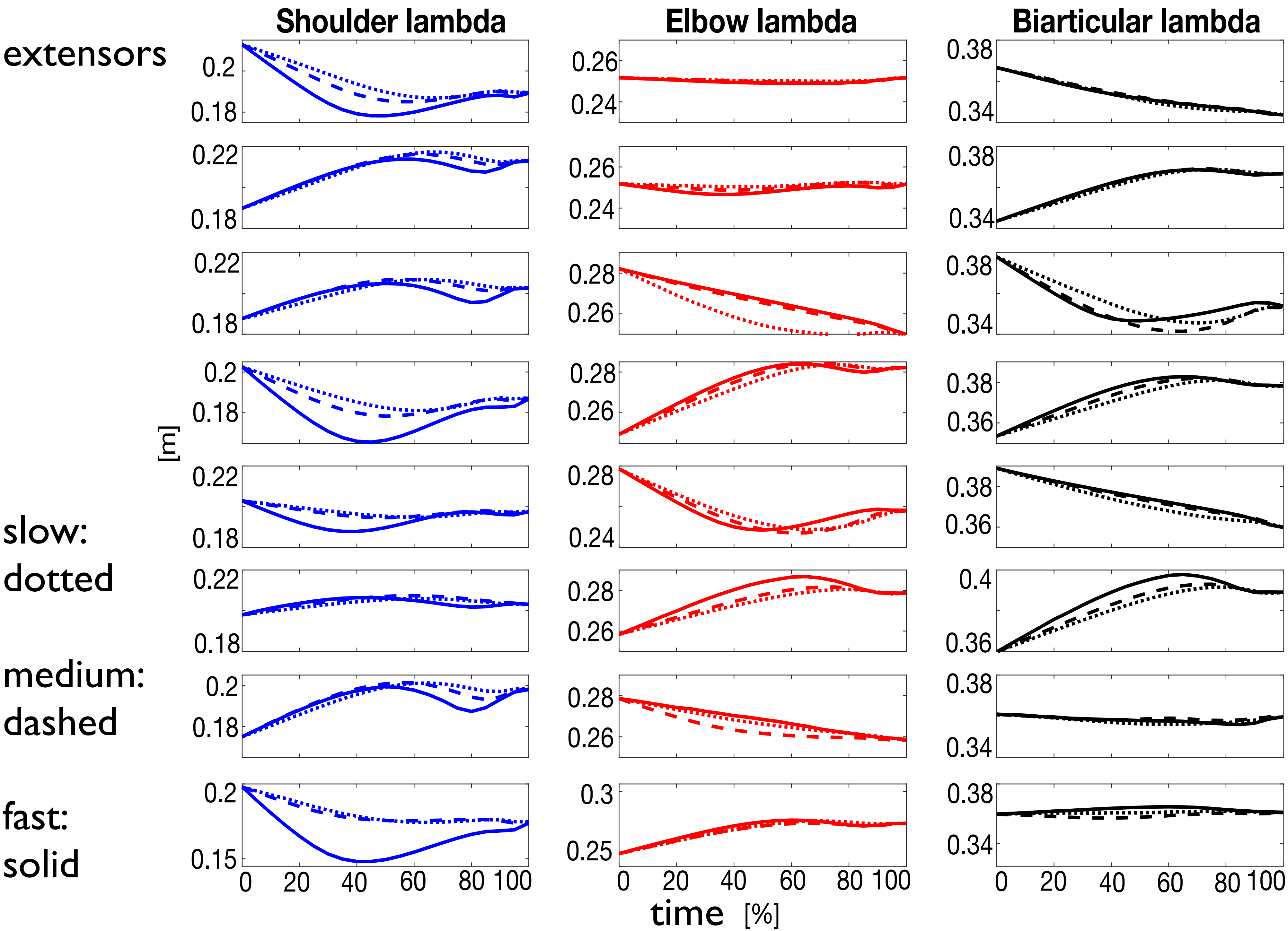




Minimal lambda trajectories

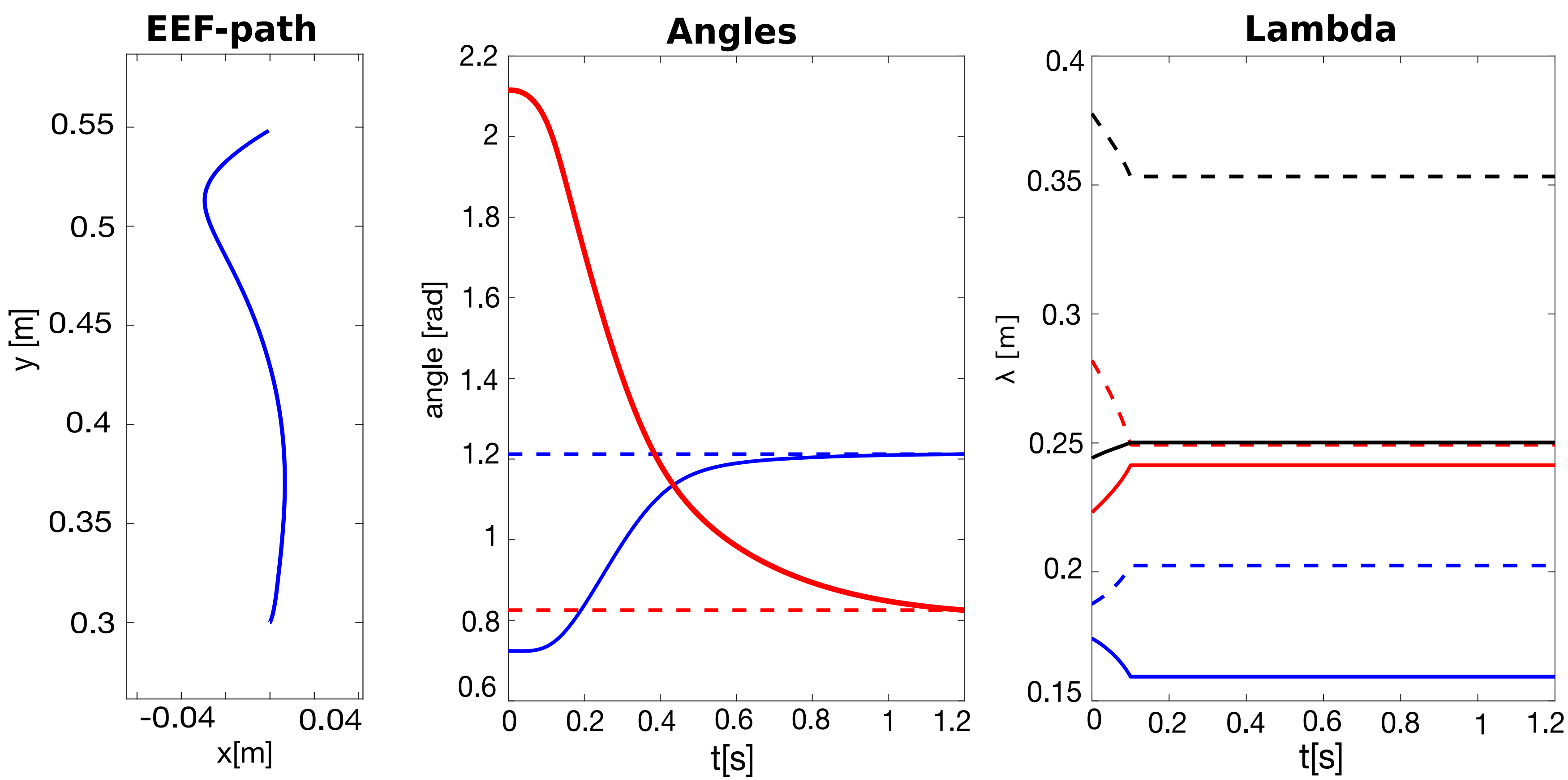


Minimal lambda trajectories



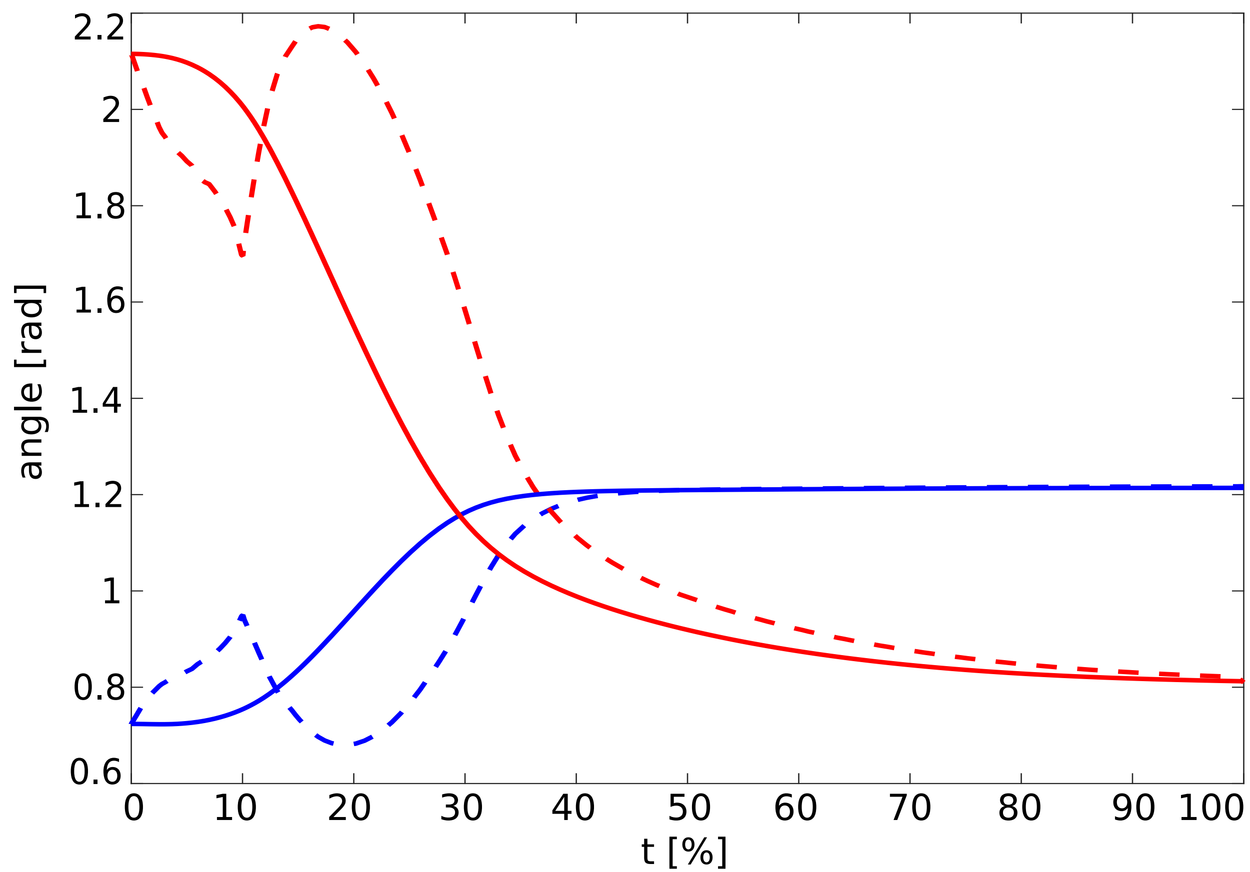
Do the time courses of lambda matter?

- making a slow ramp (in hand space) fast



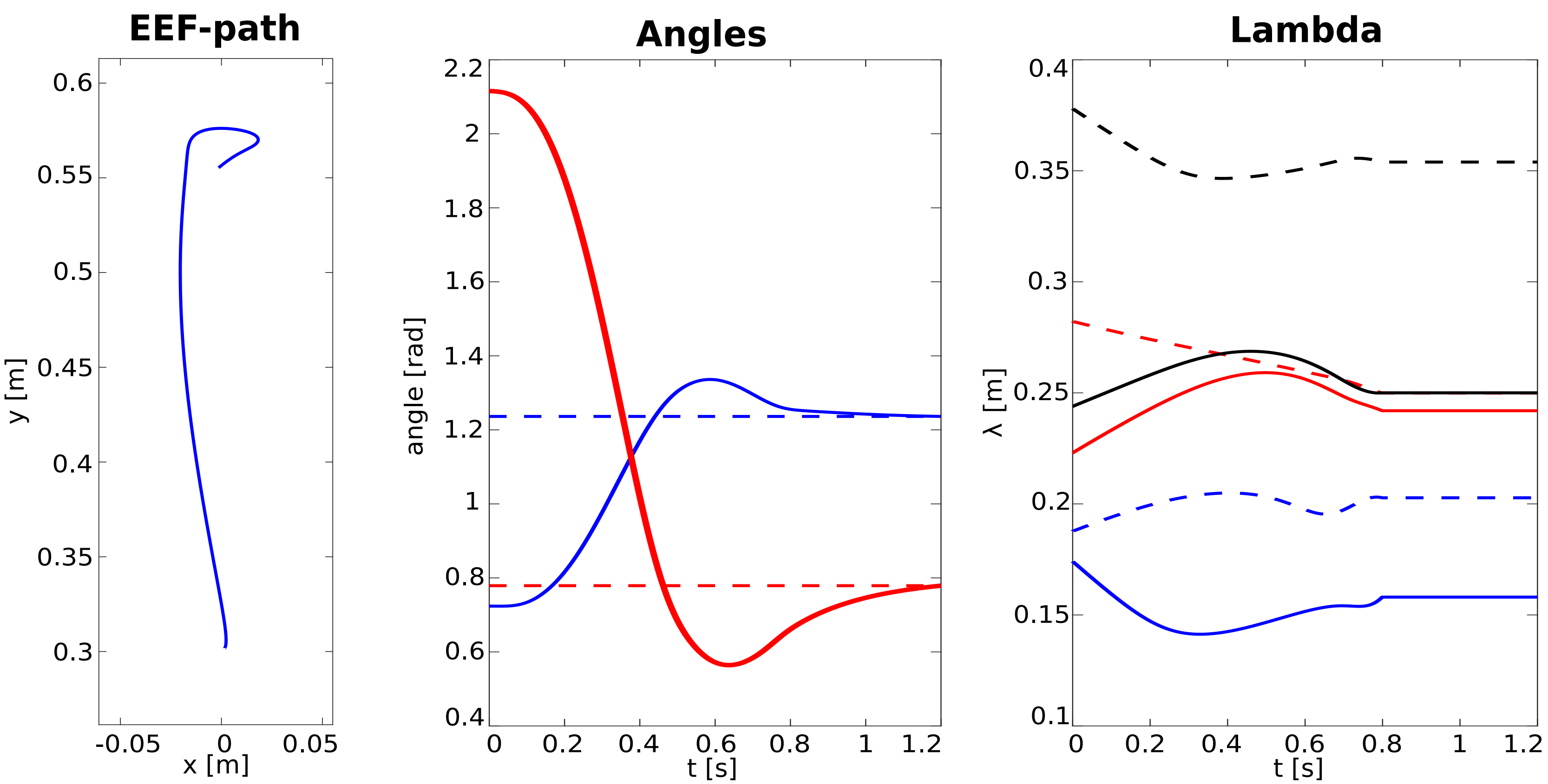
Do the time courses of lambda matter?

- attractor (dashed) and real (solid) trajectory from fast ramp



Do the time courses of lambda matter?

- slowing down lambda of a fast movement



Optimal control

- => CNS needs to solve the "optimal control" problem = generating the right time course of motor commands so that the effector arrives at the target in the desired time with zero velocity (and has some desired smooth temporal shape).