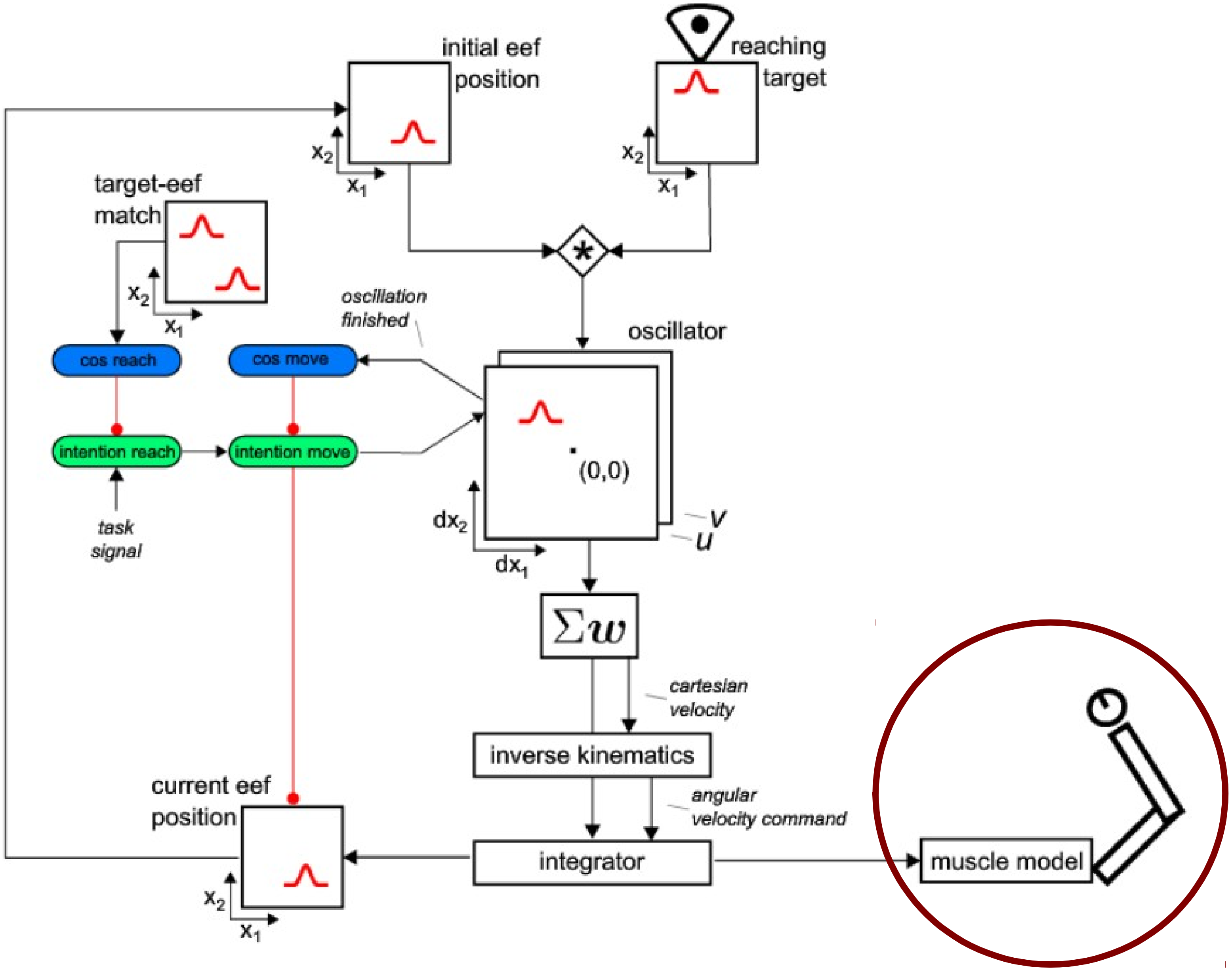
Motor control and muscles

Cora Hummert

Jan's Architecture



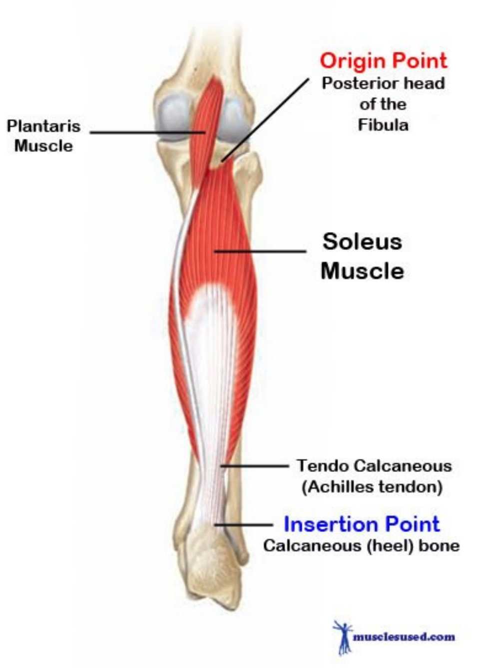
Motivation

- Conventional robotic control:

  - No posture problem
  - High stiffness

↮

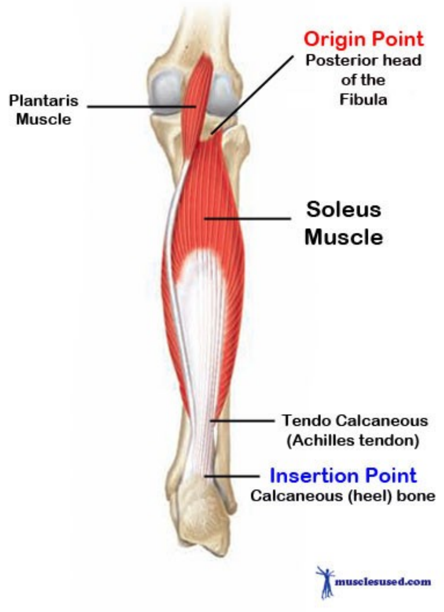
- Human motor control:



  - Force generated by muscles with low stiffness

motor control with muscles

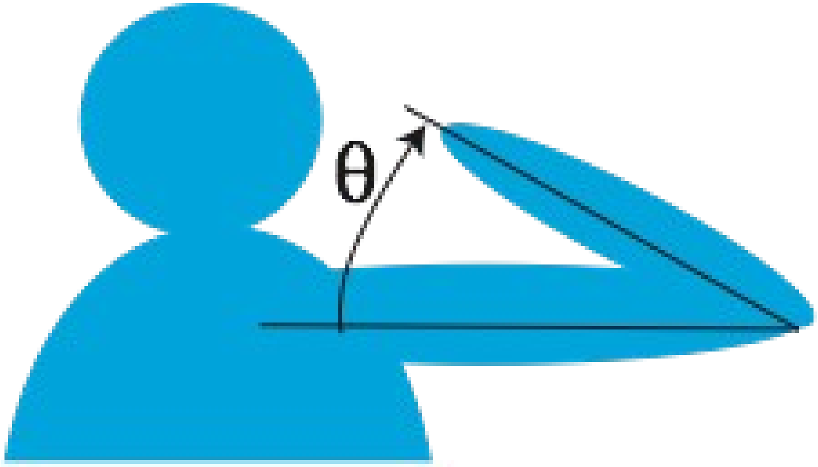
- Force generated by muscles with low stiffness
  - Muscles consist of tendons, muscle fibers, ligaments, ..
  - Spring-like properties



- Forces from Gravity, inertia, interaction torques

Posture

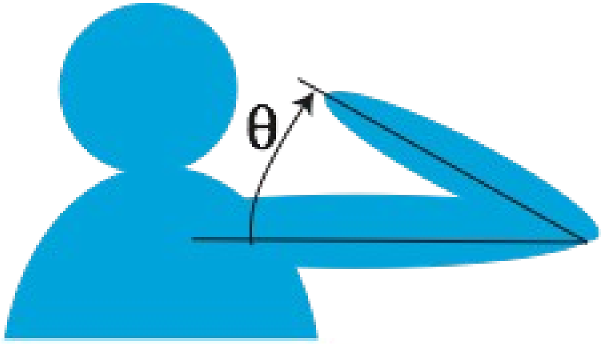
Posture of the elbow joint with the arm in horizontal position



what about the elbow is “controlled”?

- the elbow does not behave like a passive mechanical system with a free joint at the elbow:

$$J\ddot{\theta} = 0$$



- Instead, the elbow resists, when pushed

=> there is active control = stabilization of the joint

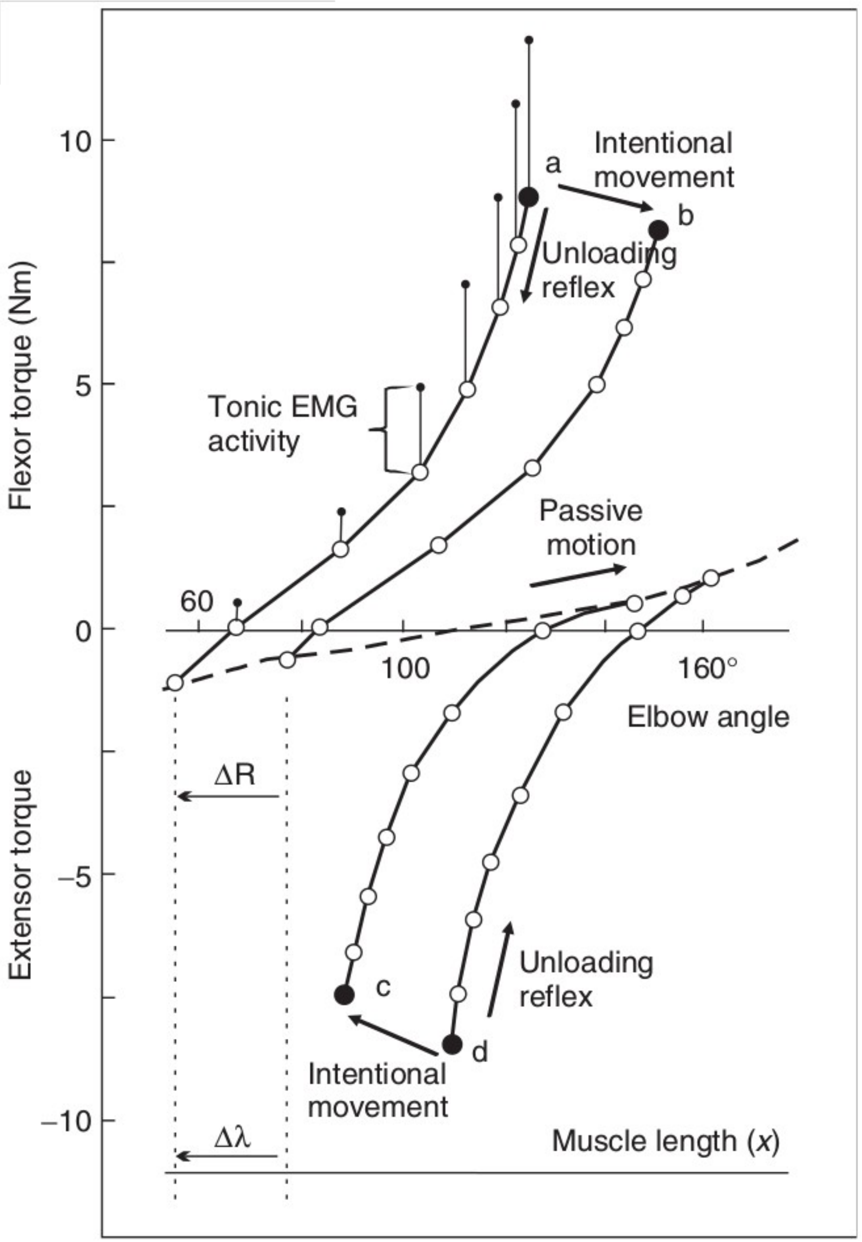
→ Volunteer?

The mass spring model

The invariant characteristic

- macroscopic description of this stabilization found by A. Feldman

- Torque-angle characteristic from each EP merges with passive joint characteristic

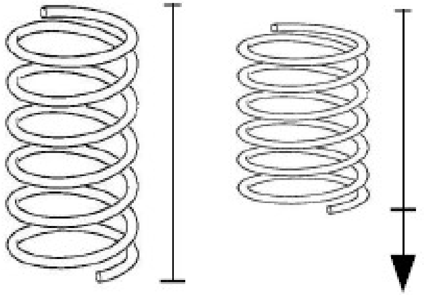


the mass-spring model

Muscle as a spring

- elastic force (because it is proportional to position)
- viscous component (resistance depends on joint velocity → Golgi cells in tendon)

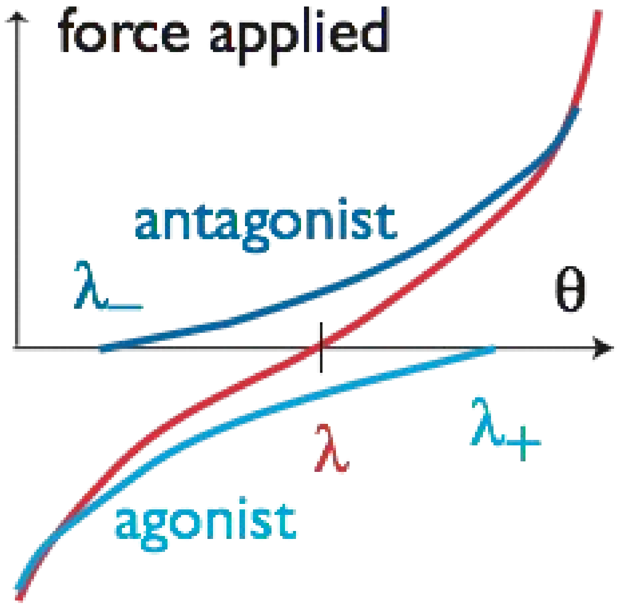
$$J\ddot{\theta} =$$ [redacted]



active torques generated by the muscle

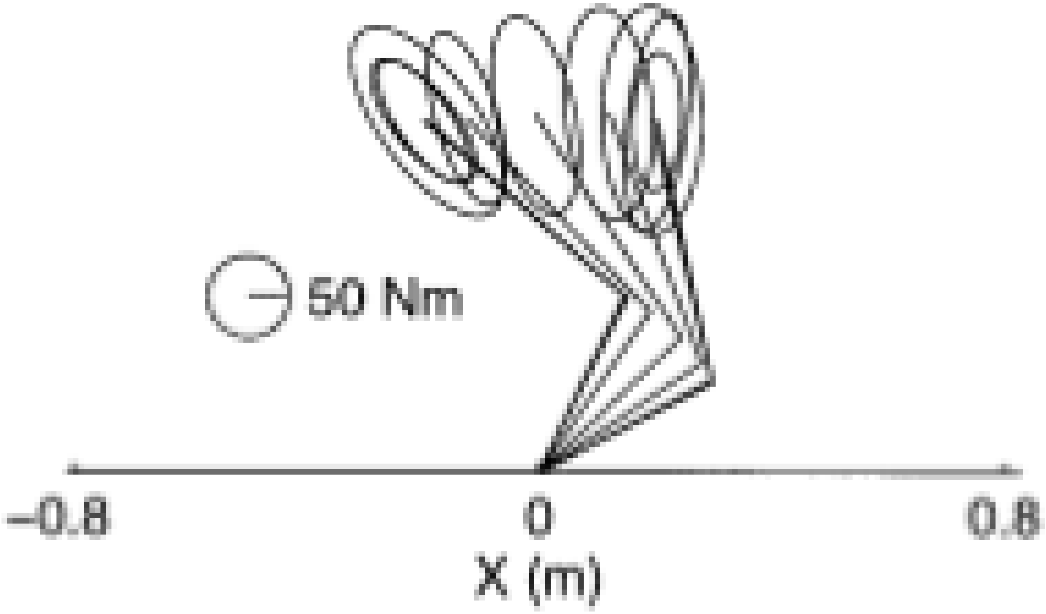
agonist-antagonist action

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



stiffness

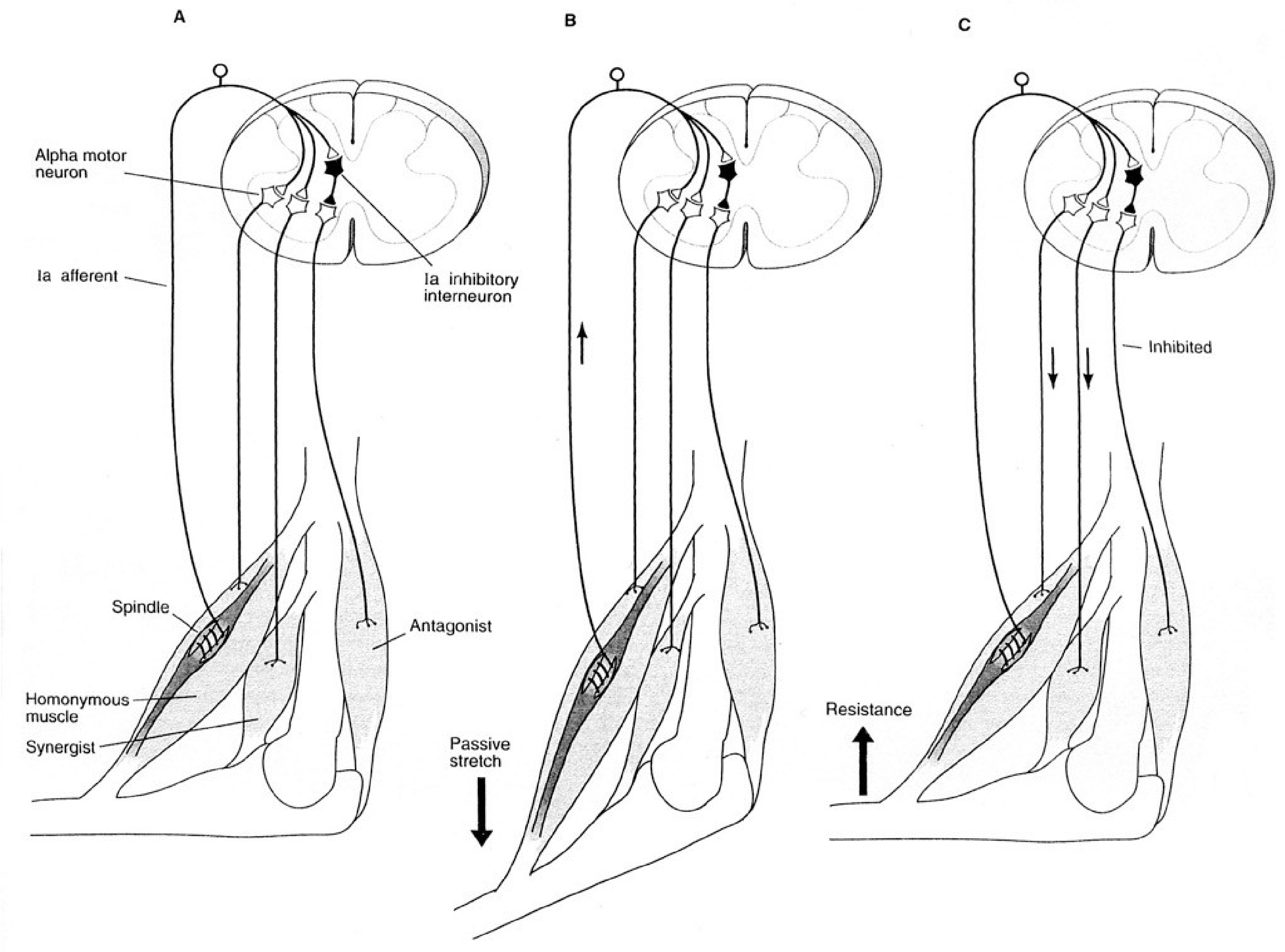
- the stiffness, k, can be measured from perturbations
- the viscosity “mu” is more difficult to determine



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

neural basis of EP model: spinal reflex loops

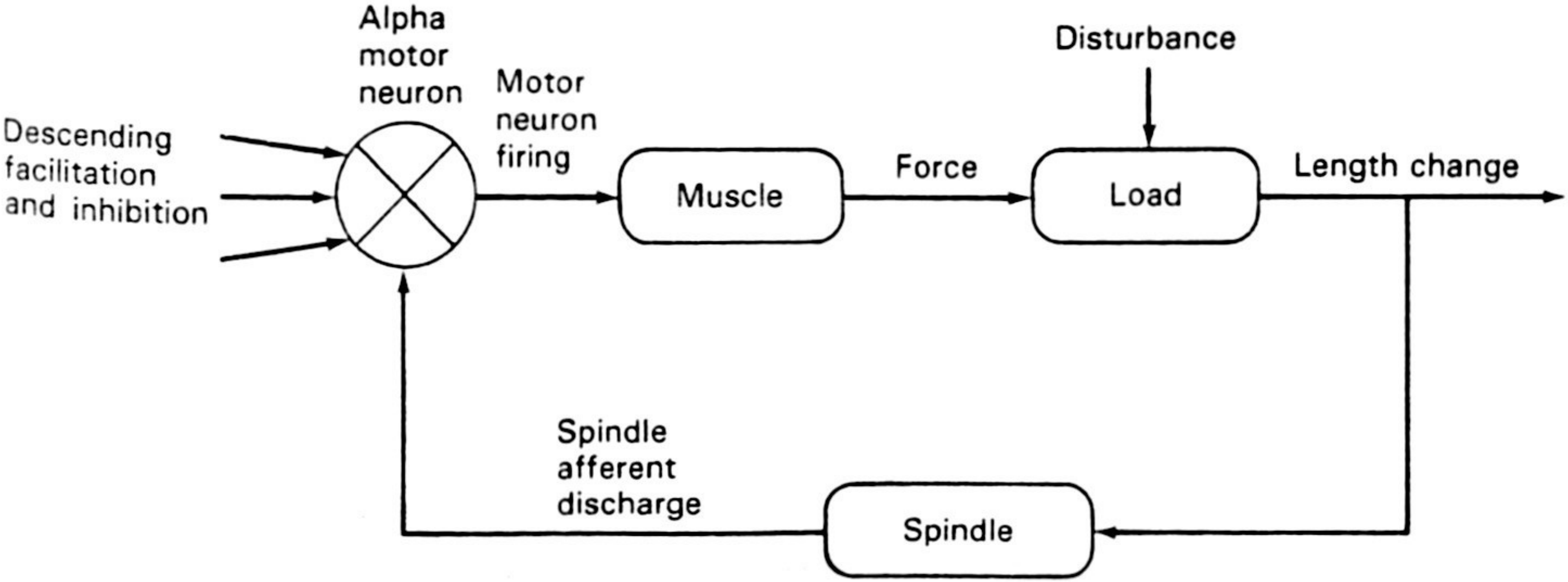
alpha-gamma reflex loop generates the stretch reflex



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

spinal cord: reflex loops

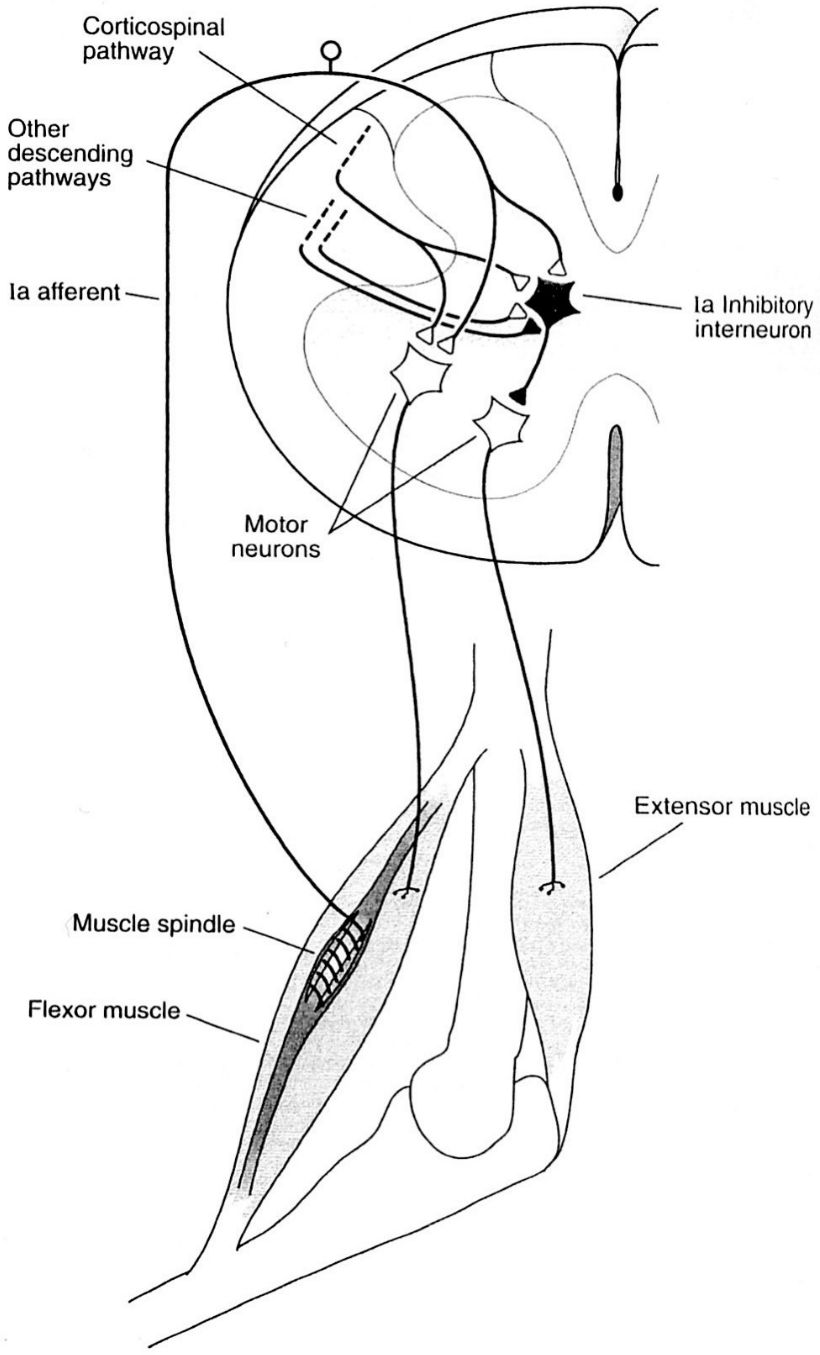
The stretch reflex acts as a negative feedback loop



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

spinal cord: coordination

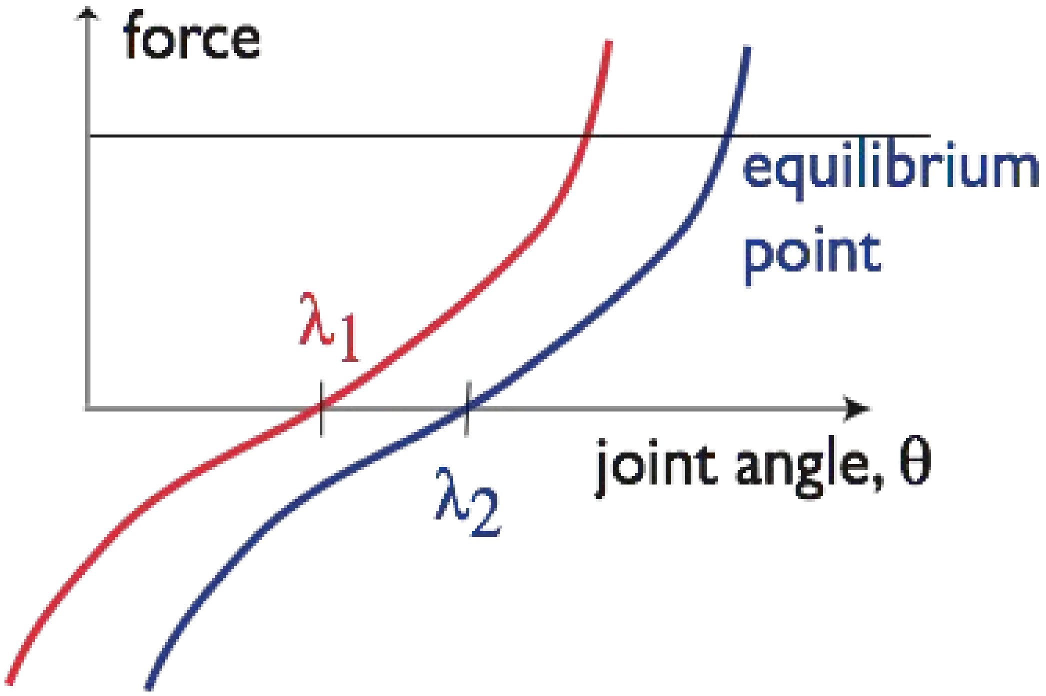
Ia inhibitory interneuron mediates reciprocal innervation in stretch reflex, leading to automatic relaxation of antagonist on activation of agonist



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

Conclusion on Posture

Muscle-joint systems have an equilibrium point during posture that is stable against transient perturbation



Movement entails change of posture

➡ equilibrium point is shifted during movement

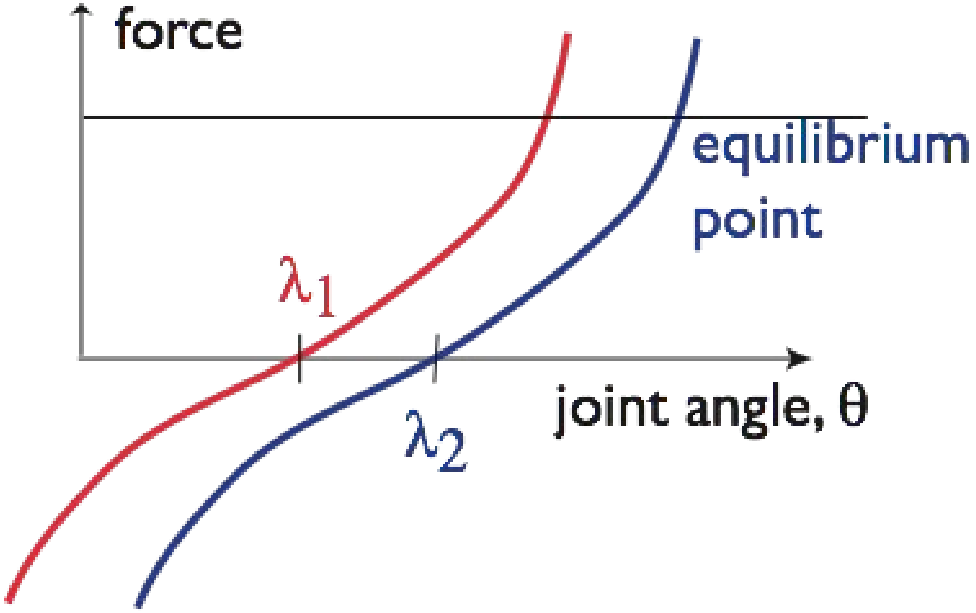
- after the movement, the postural state exists around a new combination of muscle lengths/joint configurations
- Models that account for movement in terms of generation of joint torques overlook the necessary shift of the EP

Feldmans EP-hypothesis explains voluntary movements as a shift of the EP

Voluntary movement

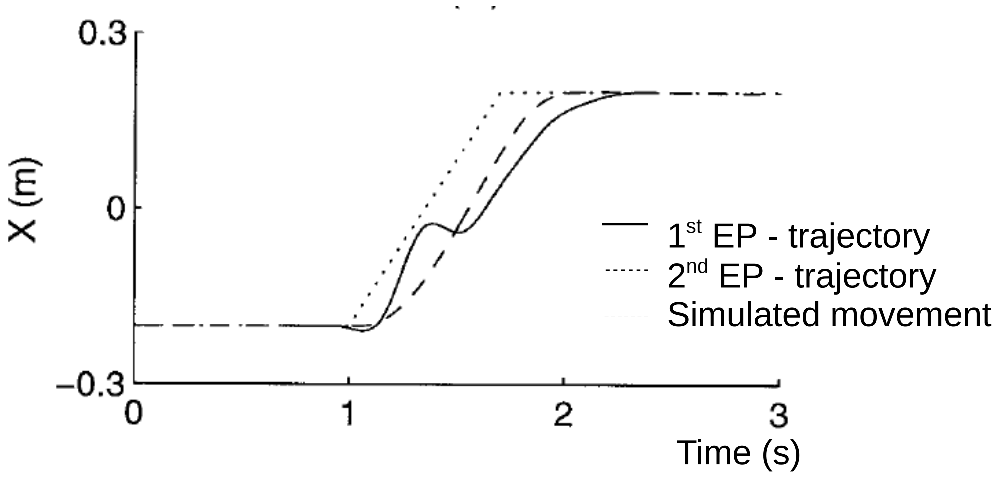
The “motor command” does not specify force/torque

- the same descendent neural command may generate different levels of force depending on the initial length of the muscle



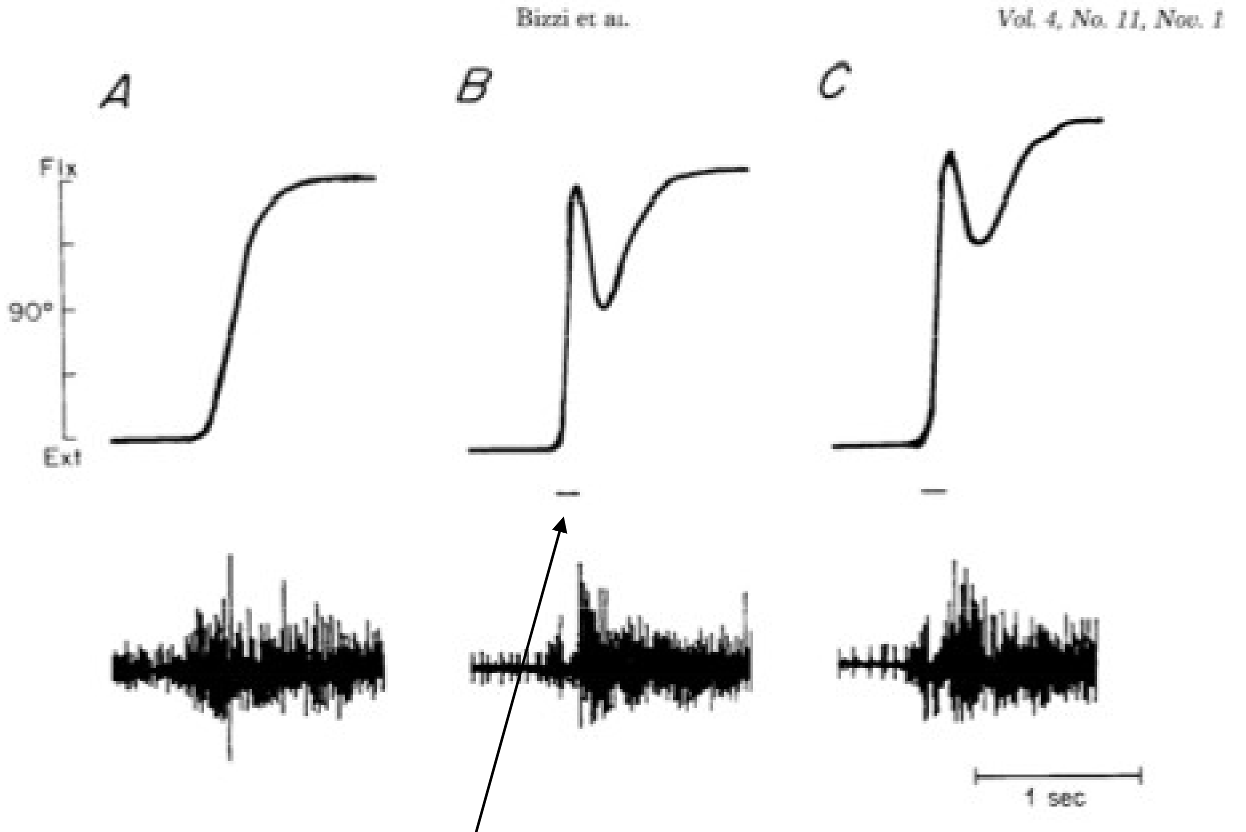
Virtual trajectory

- Virtual trajectory = a set of EPs defining a movement
- 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…



time continuous shift of the equilibrium point

- during movement an external torque moves a joint to the target position
- in the deafferented animal, the joint returns to the "virtual trajectory"



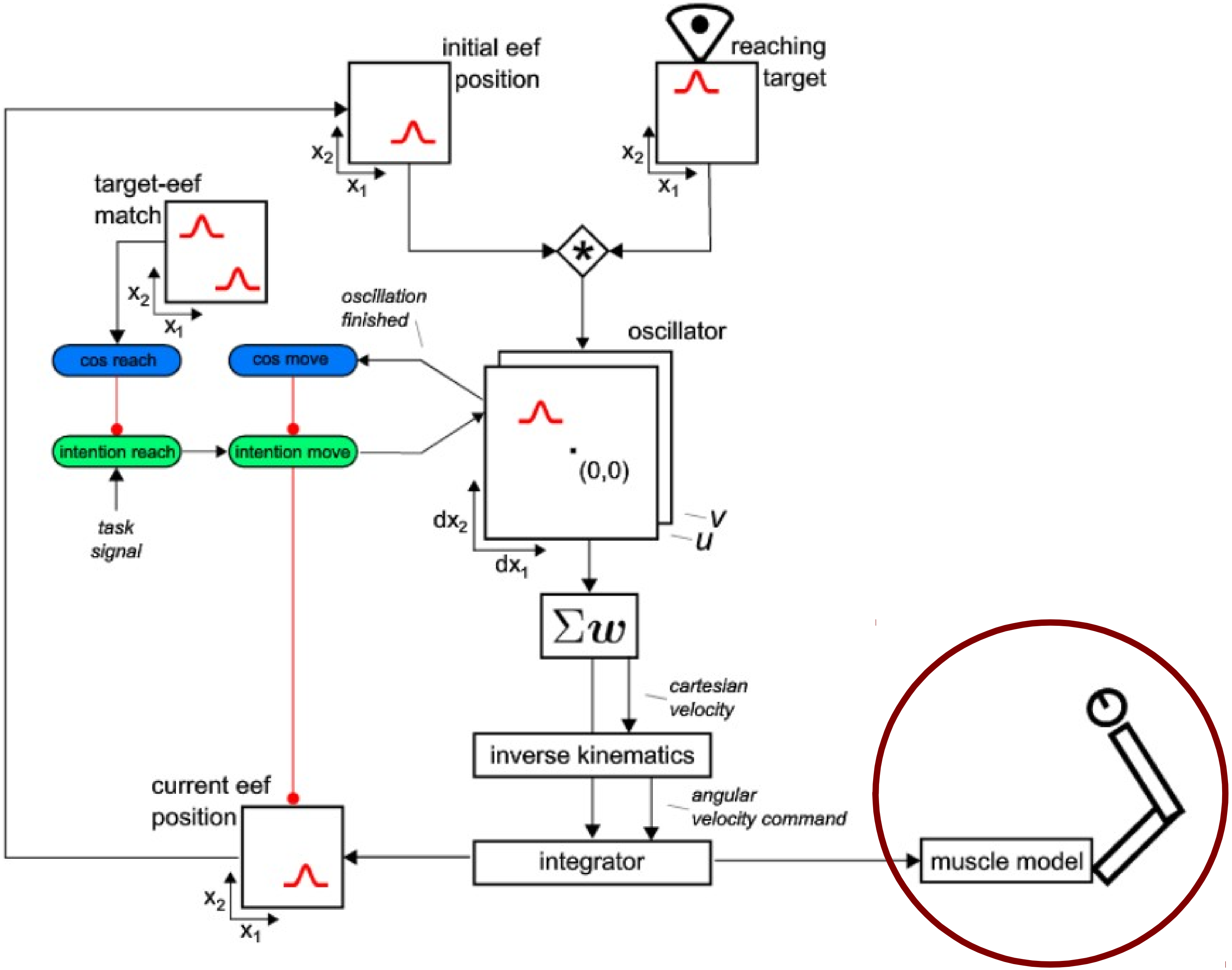
torque

[from Bizzi et al., J. Neurophys. 1984]

Summary so far

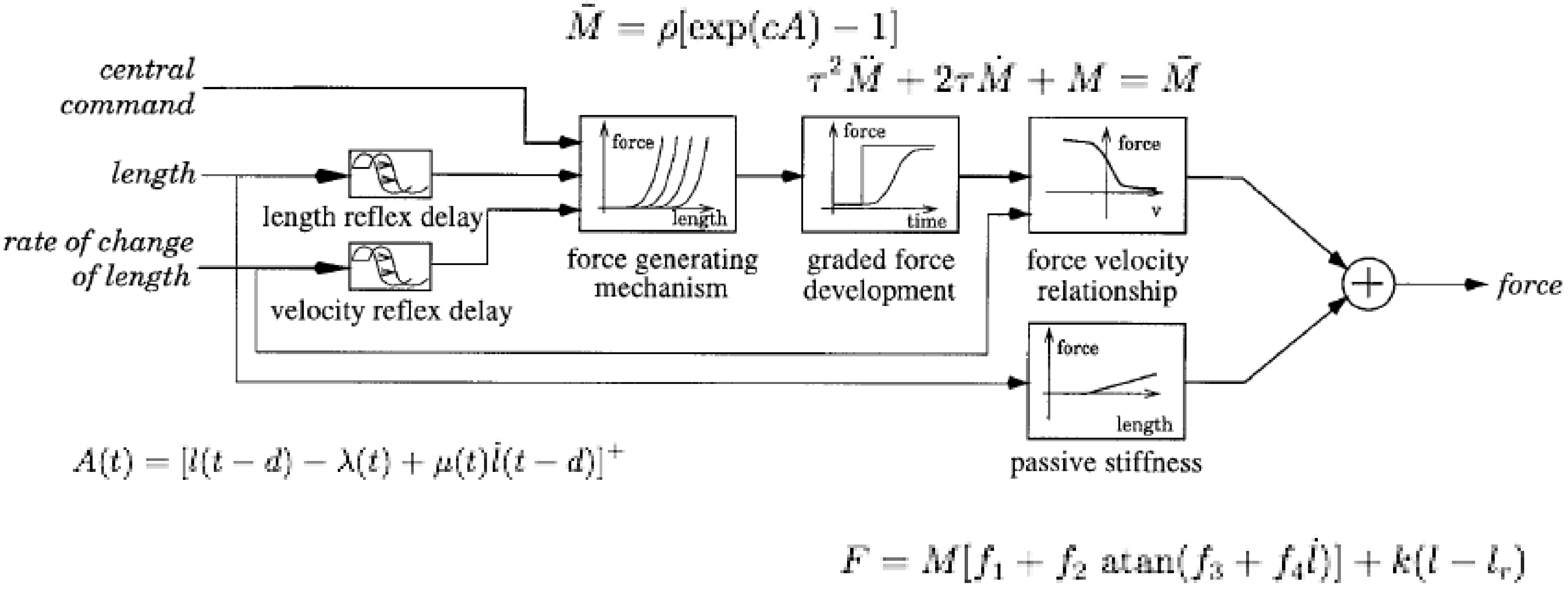
- Posture has an active control mechanism
- The stretch reflex maintains muscles at a certain length
- Voluntary movement can be induced through a continuous shift of the EP

Jan's Architecture



Muscle model

By Gribbel and Ostry



$$\bar{M} = \rho[\exp(cA) - 1]$$

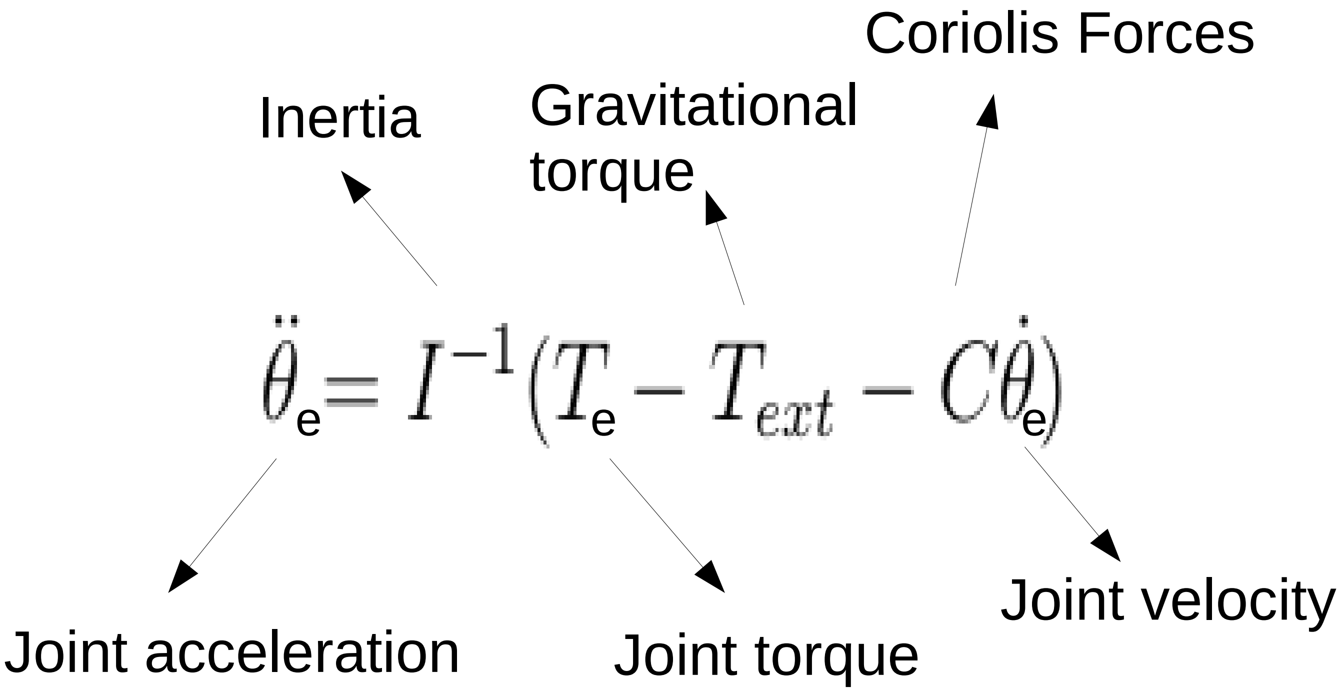
$$\tau^2 \ddot{M} + 2\tau\dot{M} + M = \bar{M}$$

$$A(t) = [l(t-d) - \lambda(t) + \mu(t)\dot{l}(t-d)]^+$$

$$F = M[f_1 + f_2 \,\mathrm{atan}(f_3 + f_4\dot{l})] + k(l - l_r)$$

Equation of motion

For the elbow



Coriolis Forces

Inertia

Gravitational torque

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

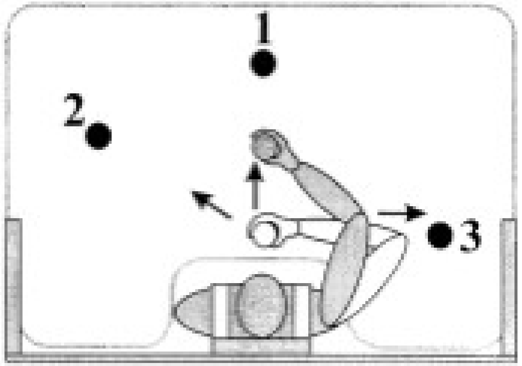
Joint velocity

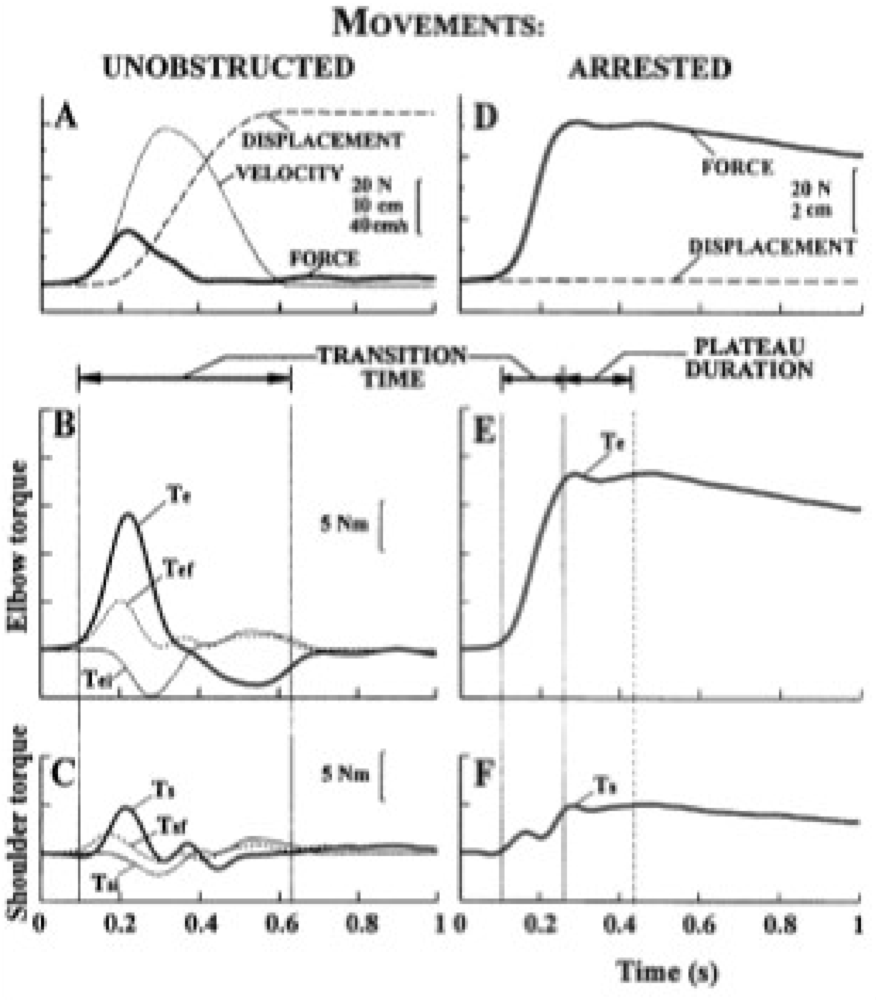
Joint acceleration

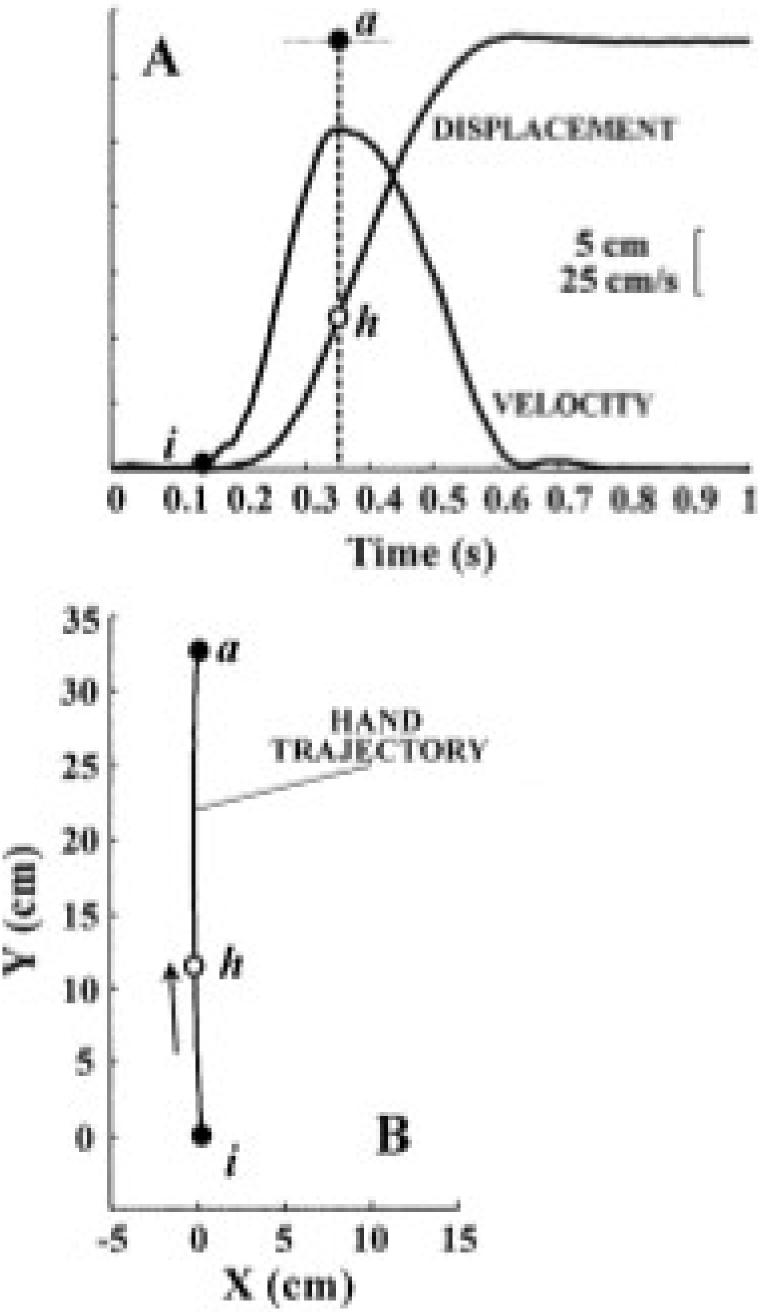
Joint torque

Experimental data

[Ghafouri Feldman, 2001]

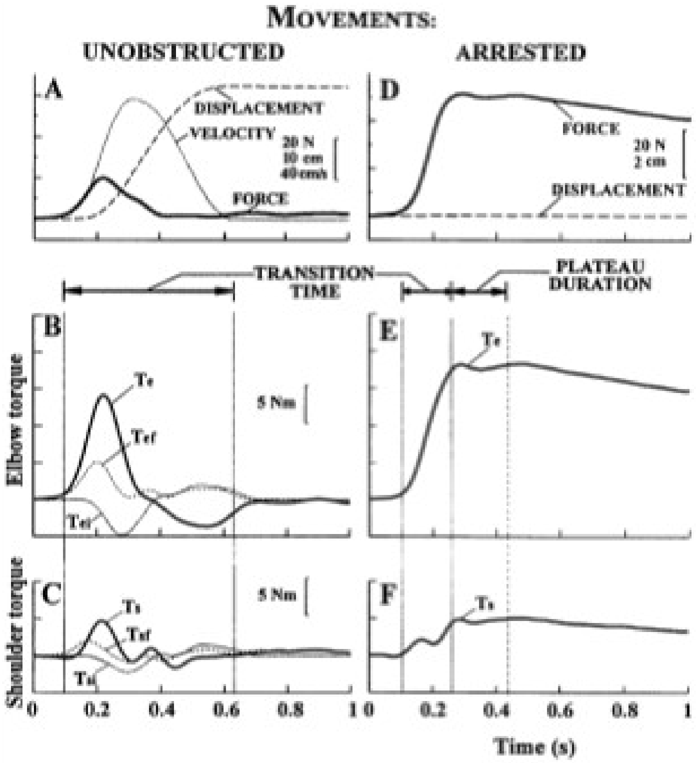


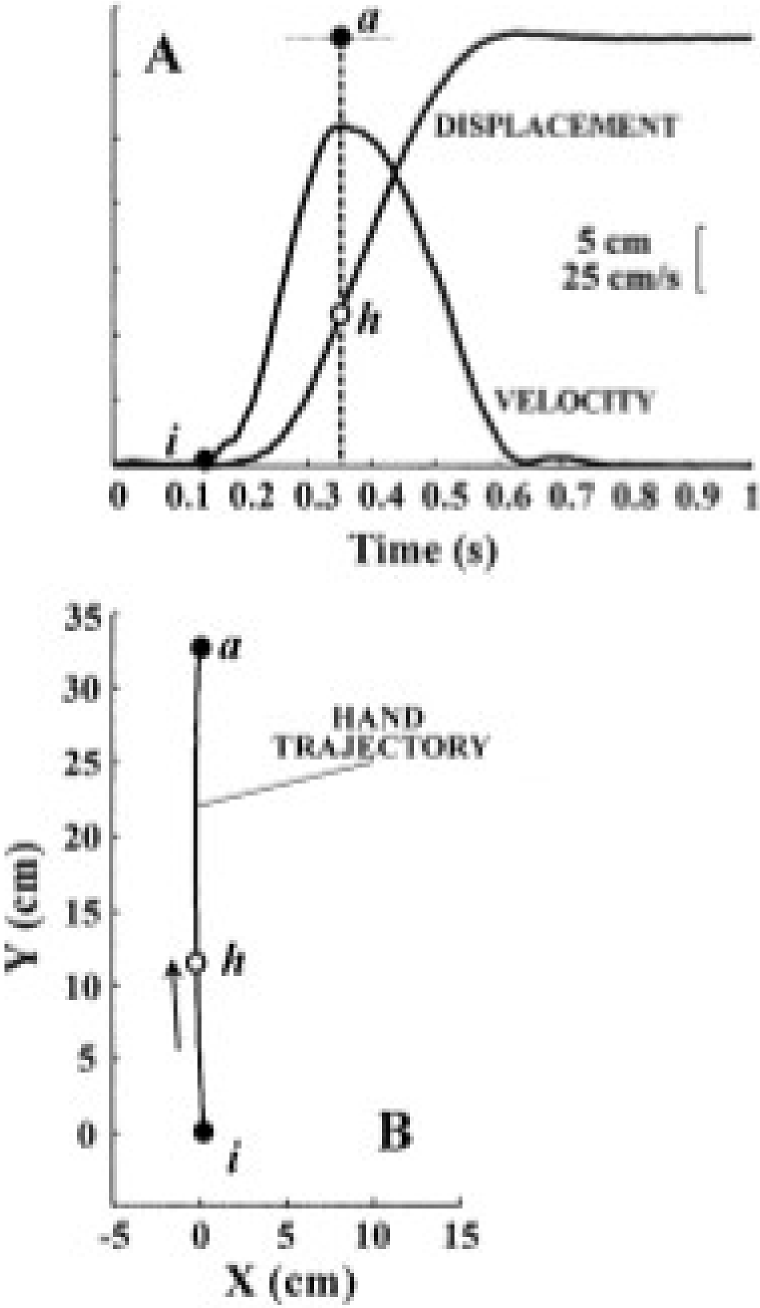




Experimental data

[Ghafouri Feldman, 2001]





- Fast movements completed without continuous guidance
- Timing of control signals different from resulting motor output

Virtual trajectory

- This view of movement generation is “quasi-static”: the effector “tracks” the attractor that is shifted by the virtual trajectory
- This seems to trivialize 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).

But

- is this simplification of movement generation as a “quasi-postural” system feasible for fast movements given the relatively soft muscles, the time delays involved in generating torque from muscles, etc. ?
- the strong time delay between the command and the movement is a hint that this needs investigation

Types of Virtual trajectories

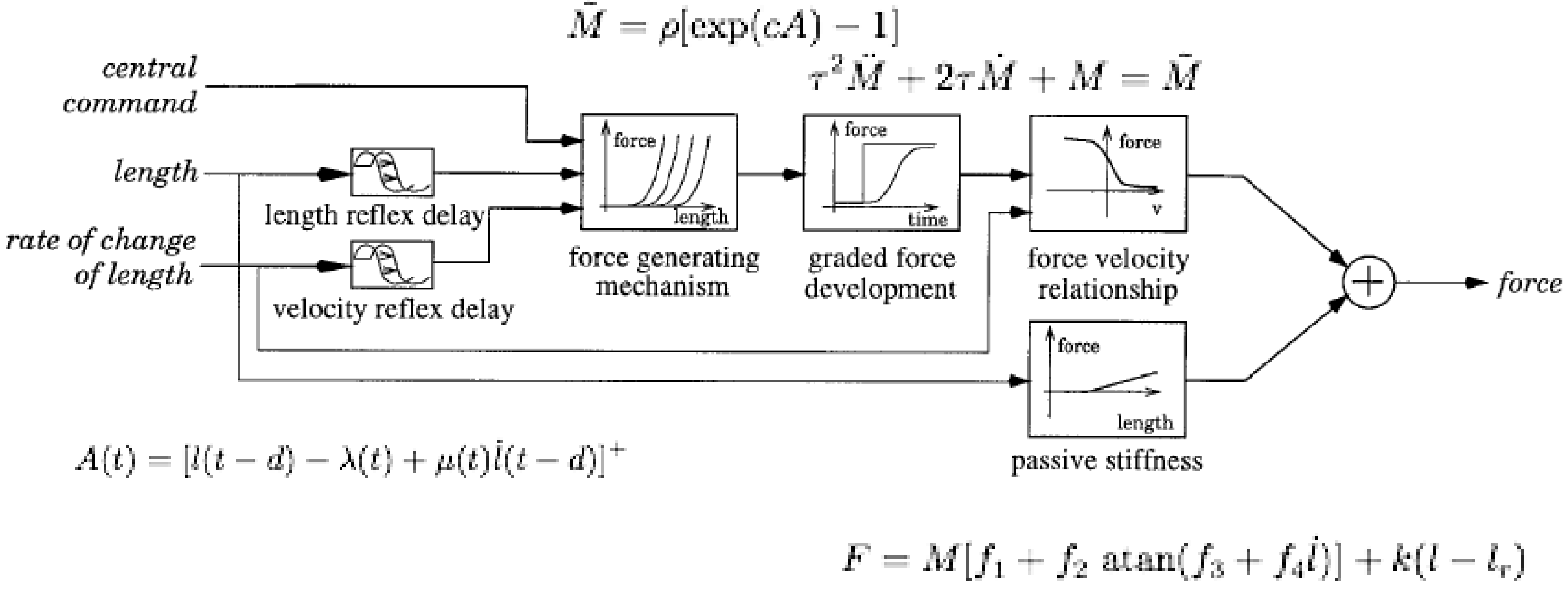
Project to simulate fast movements

- uses a simplified version of the Gribble Ostry muscle model
- and examines the demands on virtual trajectories (r and c commands) to achieve realistic movement trajectories

Muscle model

to enable analytical treatment, simplify

Gribble Ostry: symmetry, neglect passive elastic force



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$$F = M[f_1 + f_2\,\mathrm{atan}(f_3 + f_4\dot{l})] + k(l - l_r)$$

Biomechanical dynamics

- … standard…
- bi-articulatory muscles make a proportional contribution

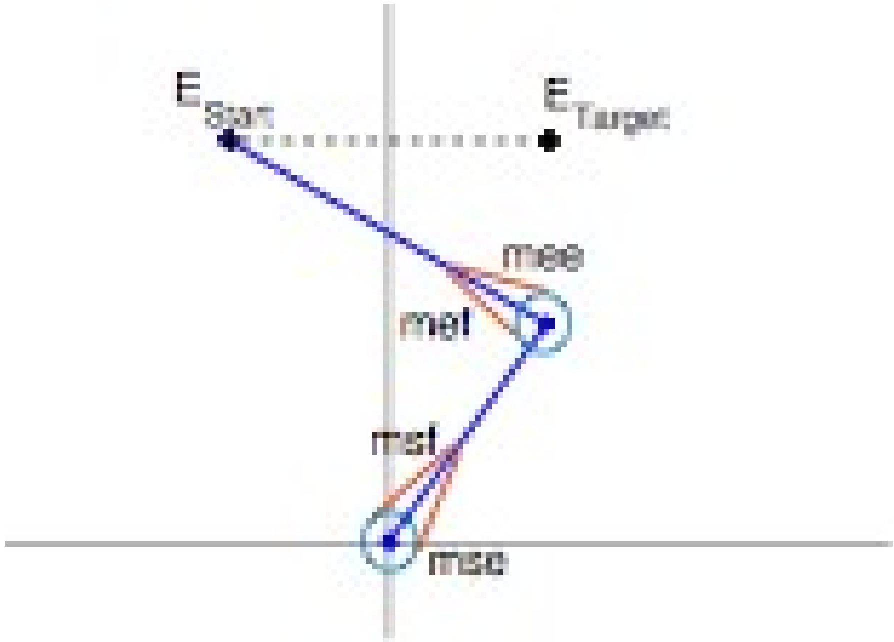
$$T = -H \cdot F$$

with H defined as

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

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

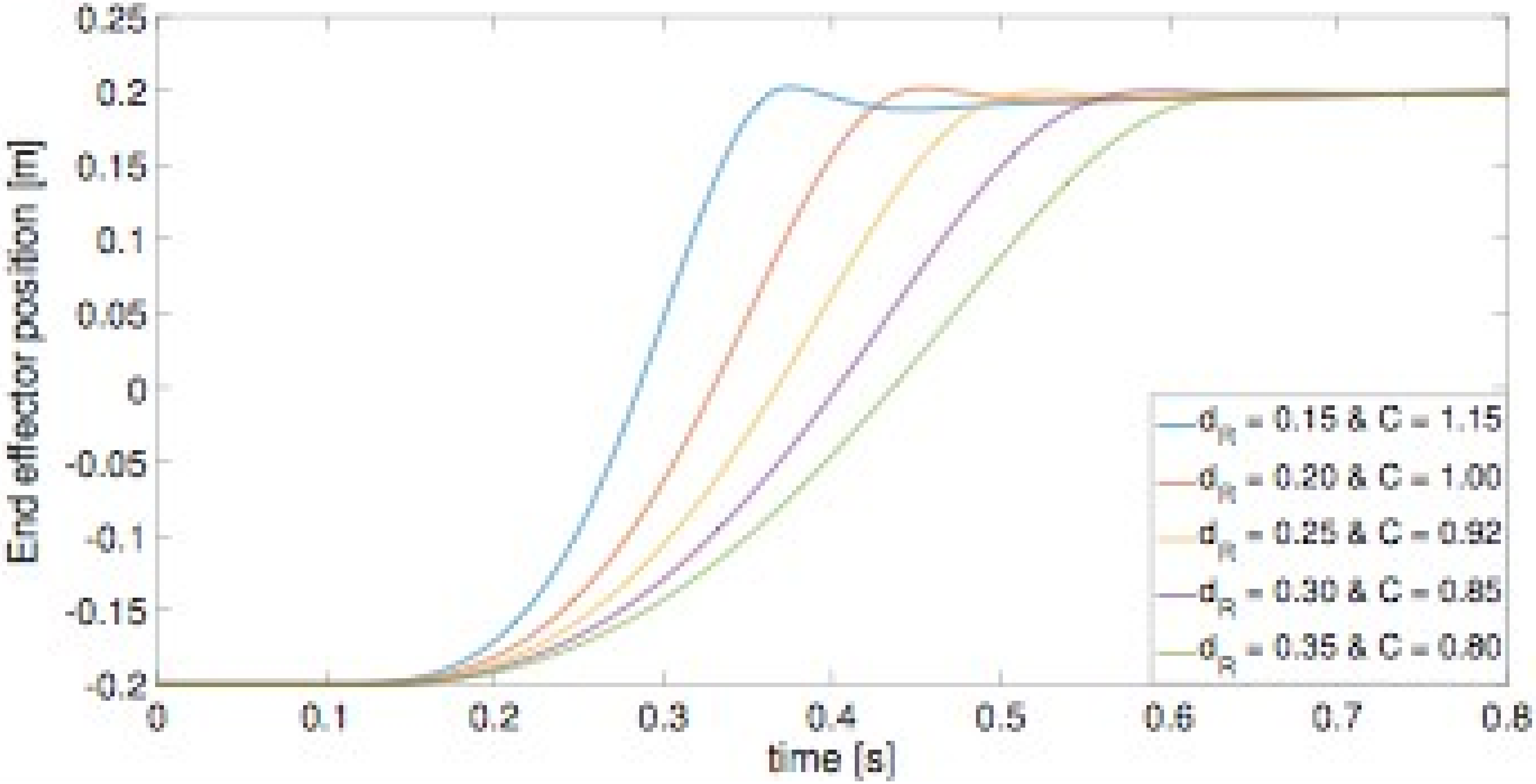
$$x = \cos(\theta_1) \cdot l_1 + \cos(\theta_1 + \theta_2) \cdot l_2$$
$$y = \sin(\theta_1) \cdot l_1 + \sin(\theta_1 + \theta_2) \cdot l_2$$



back to muscle:

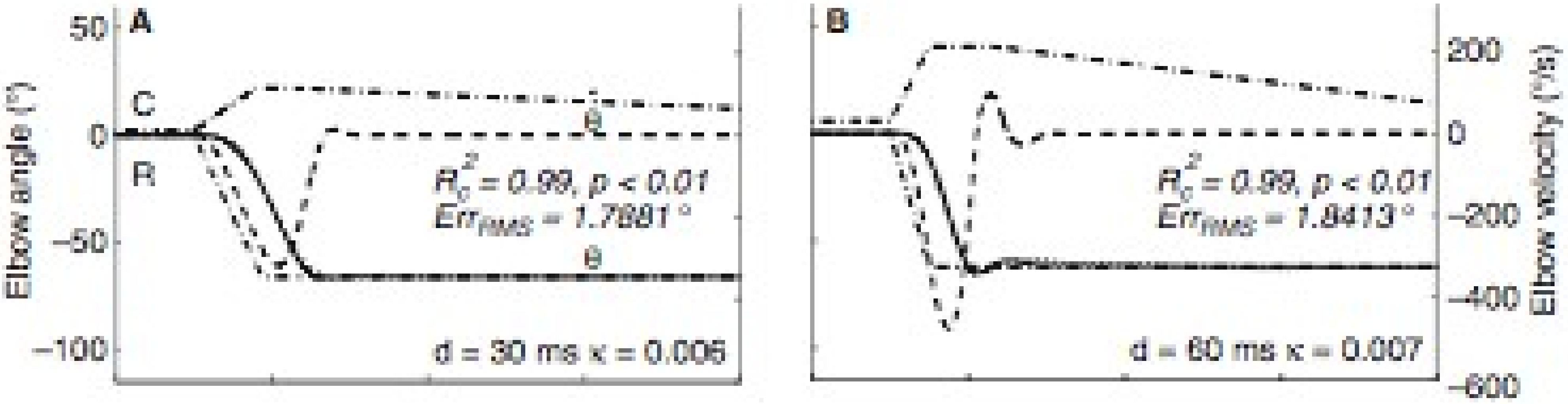
$$l = c + c'\theta + c''\theta^2$$

virtual trajectories: ramps



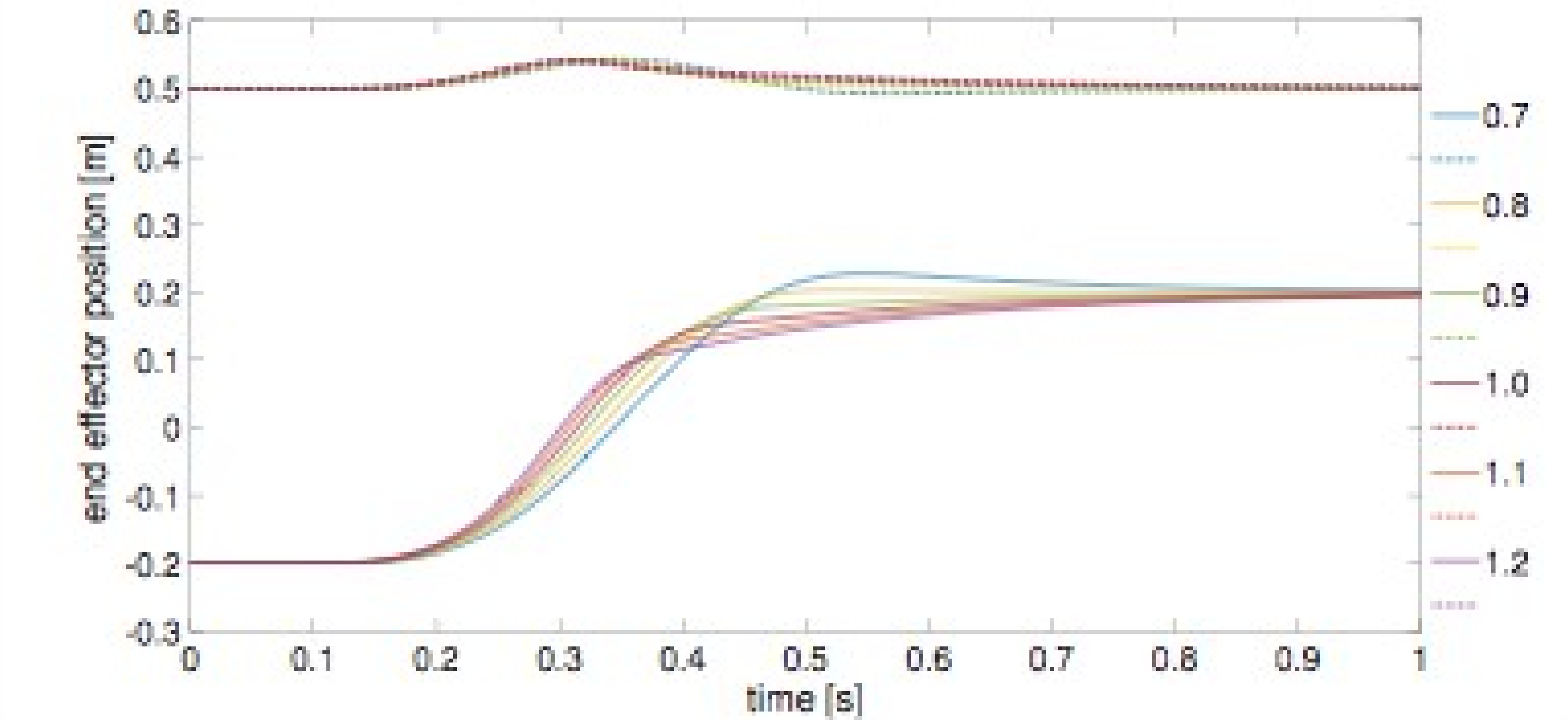
virtual trajectories: ramps

reproduces Pilon, Feldmann 2006



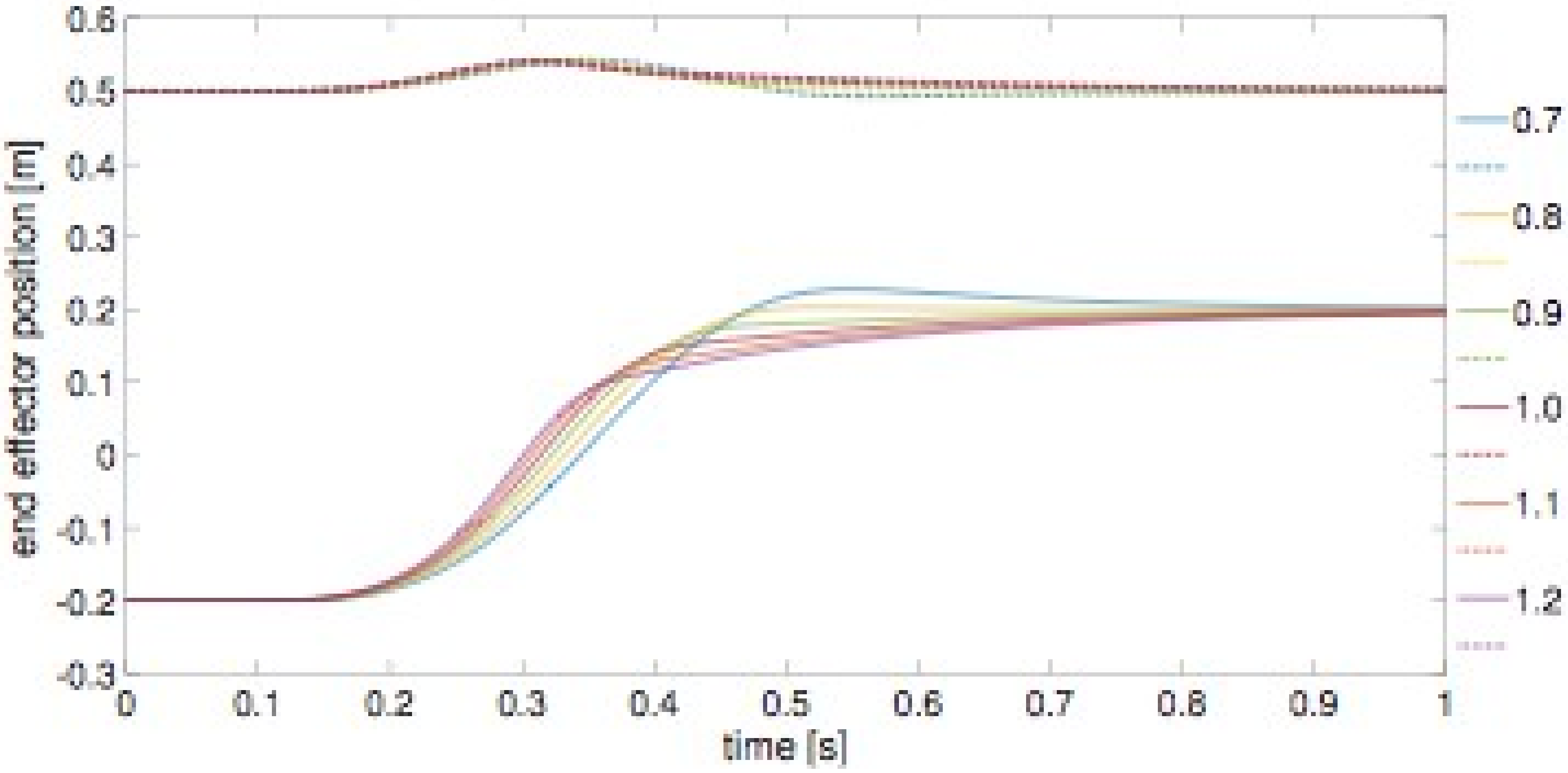
virtual trajectories: ramps

ramps of “r” command produce realistic movement trajectories only if the co-contraction “c” command is just right



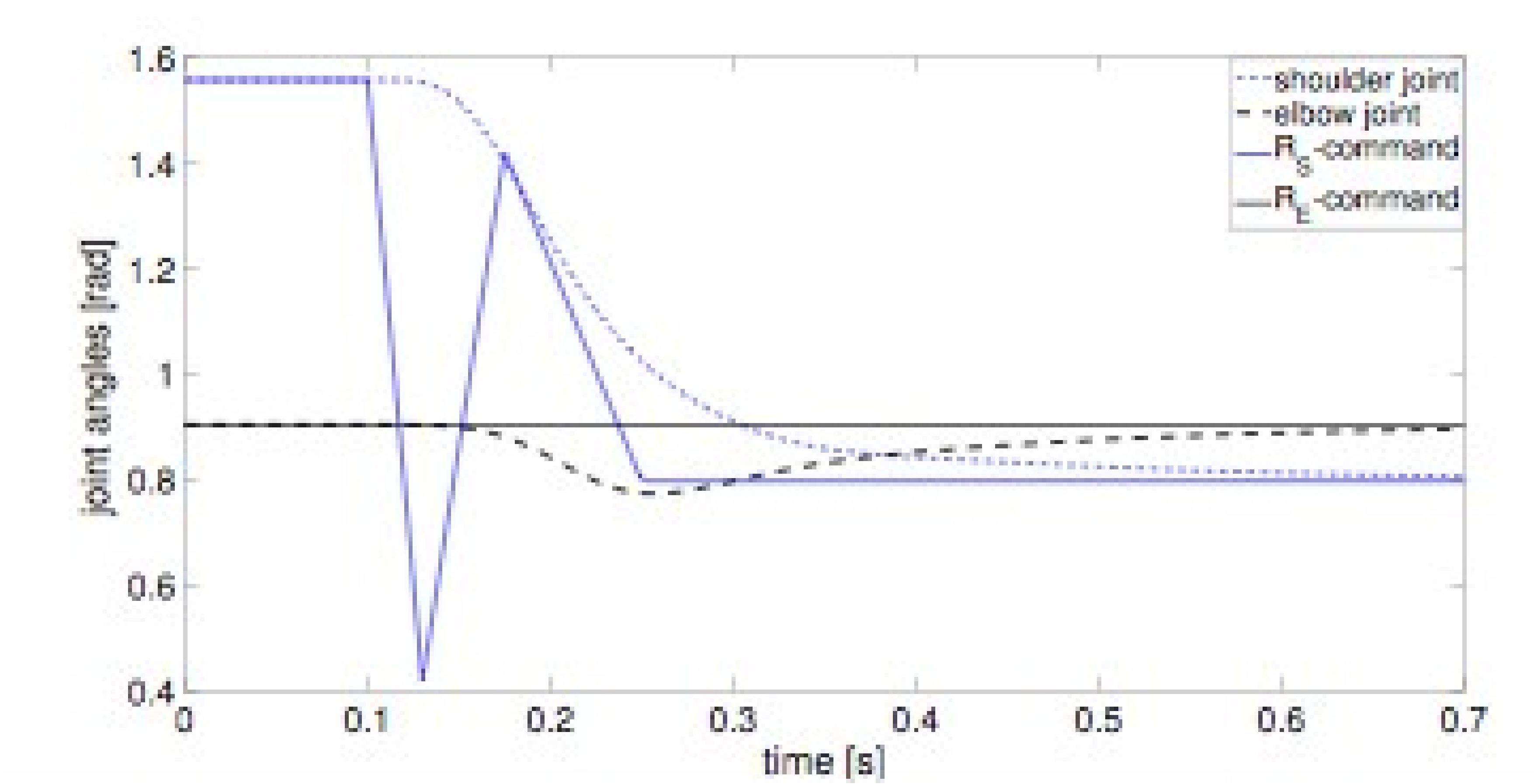
virtual trajectories: ramps

increasing the co-contraction command does not robustly speed up movement



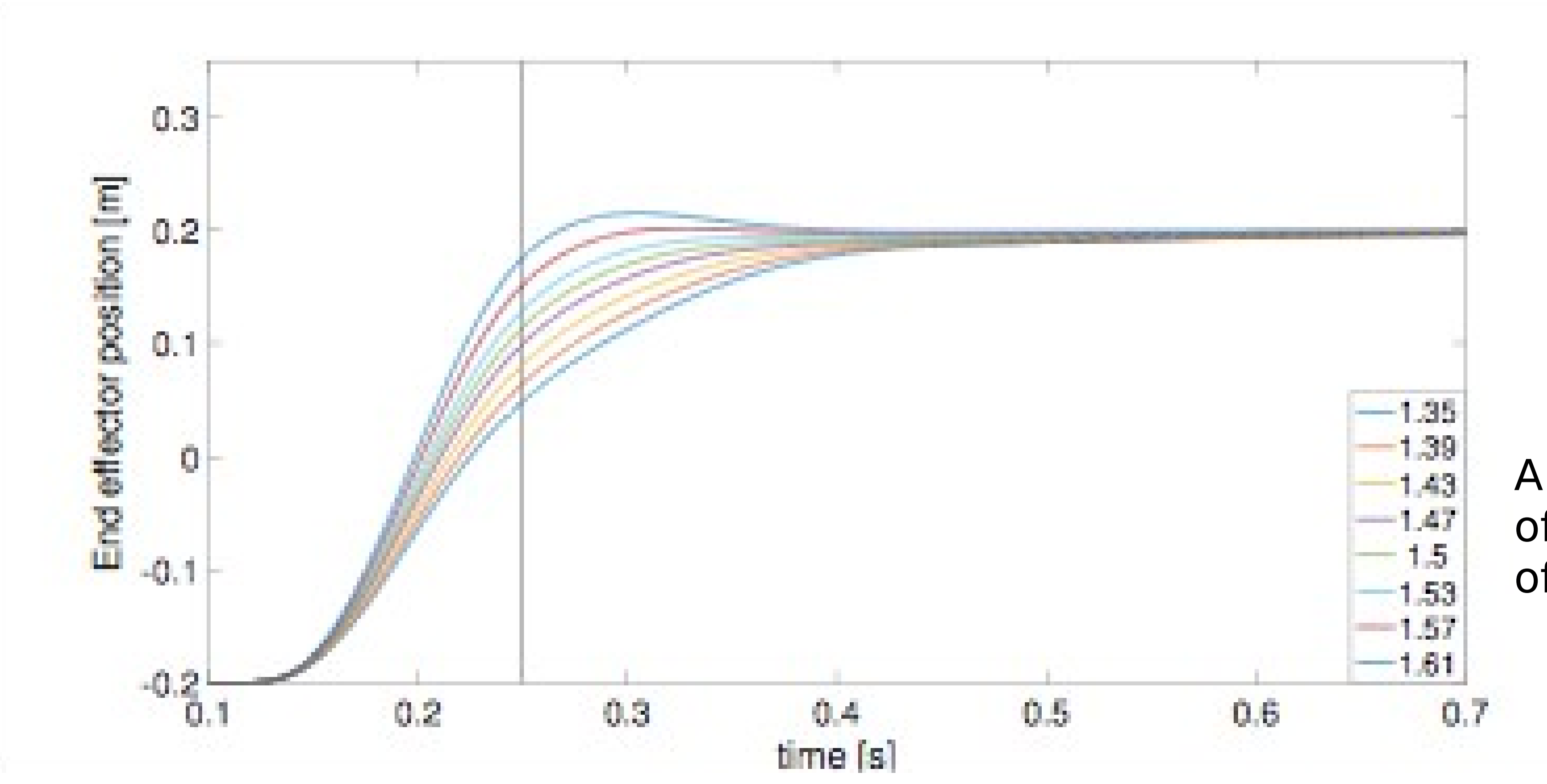
N-shape

the Latash “N-shape” of the r-command is capable of creating fast movements



N-shape

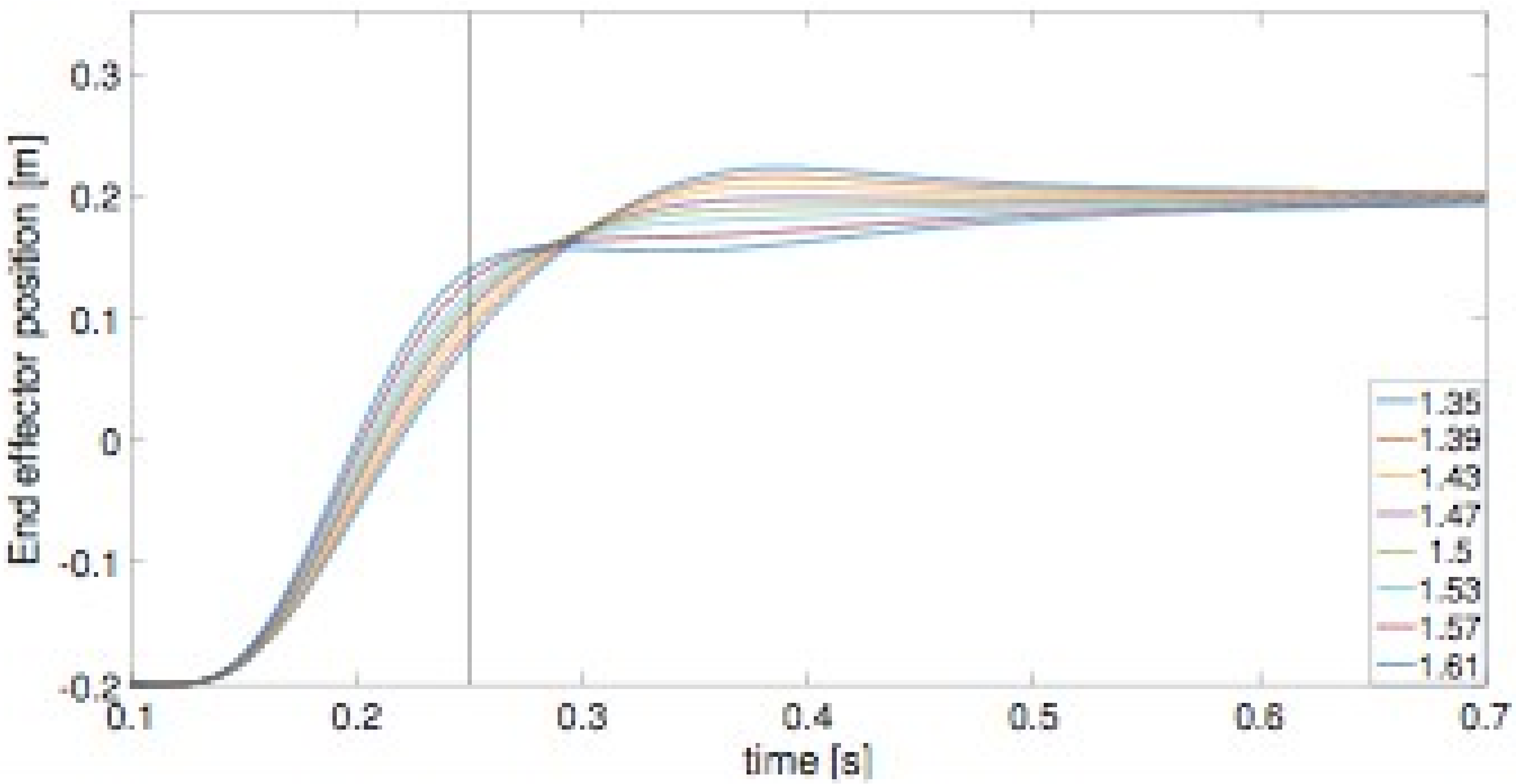
but the “N-shape” needs to be just “right” to obtain correct movement trajectories



Amplitude of 1st part of N varied

N-shape

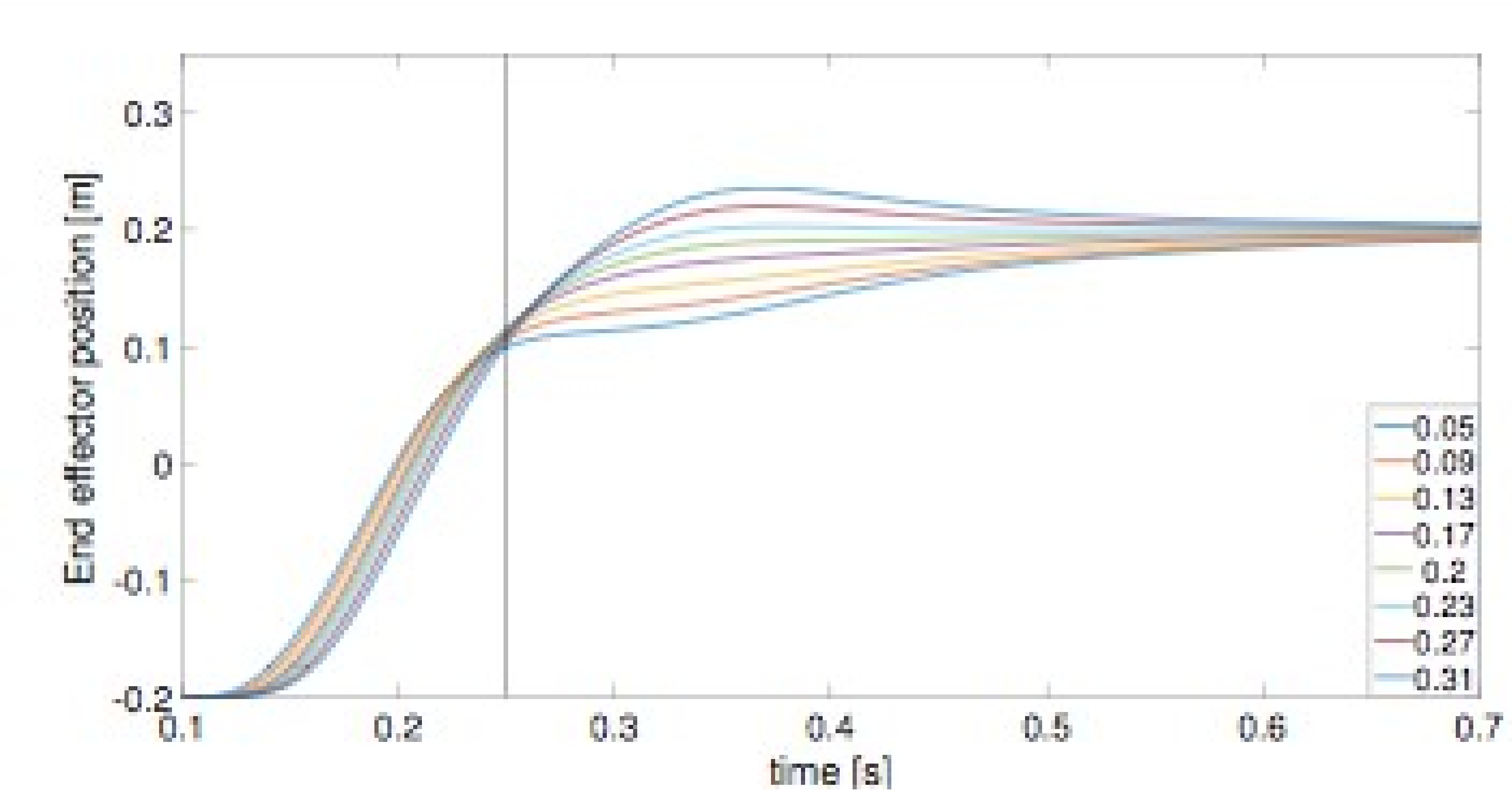
but the “N-shape” needs to be just “right” to obtain correct movement trajectories



Amplitude of 1st part and 2nd part of N varied

N-shape

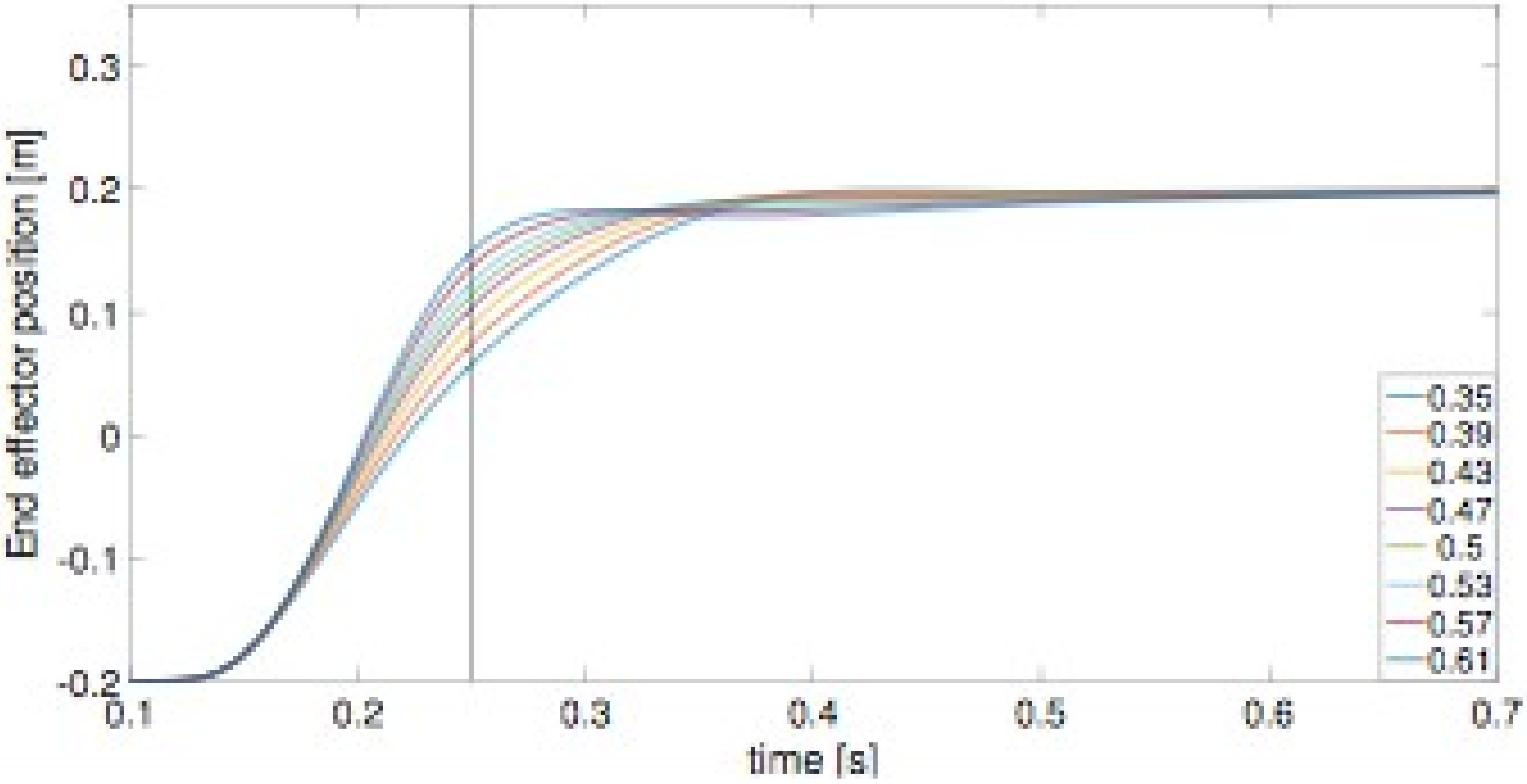
but the “N-shape” needs to be just “right” to obtain correct movement trajectories



Timing of
1st part
N varied

N-shape

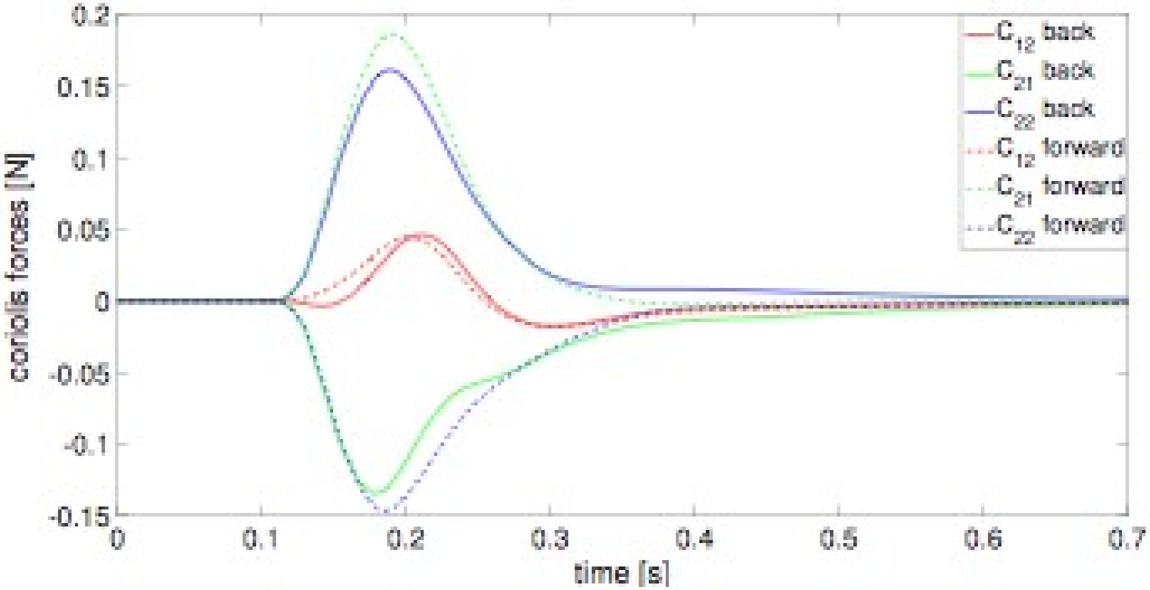
but the “N-shape” needs to be just “right” to obtain correct movement trajectories

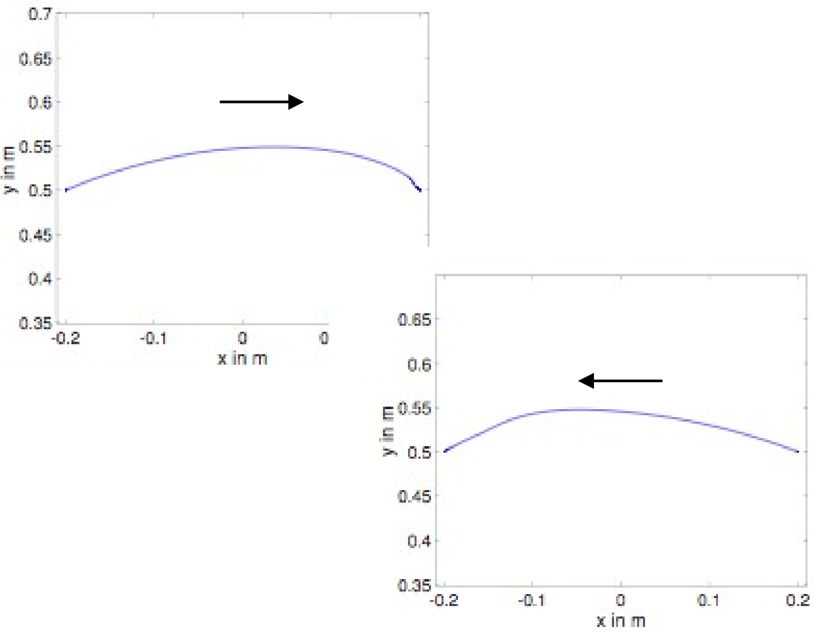


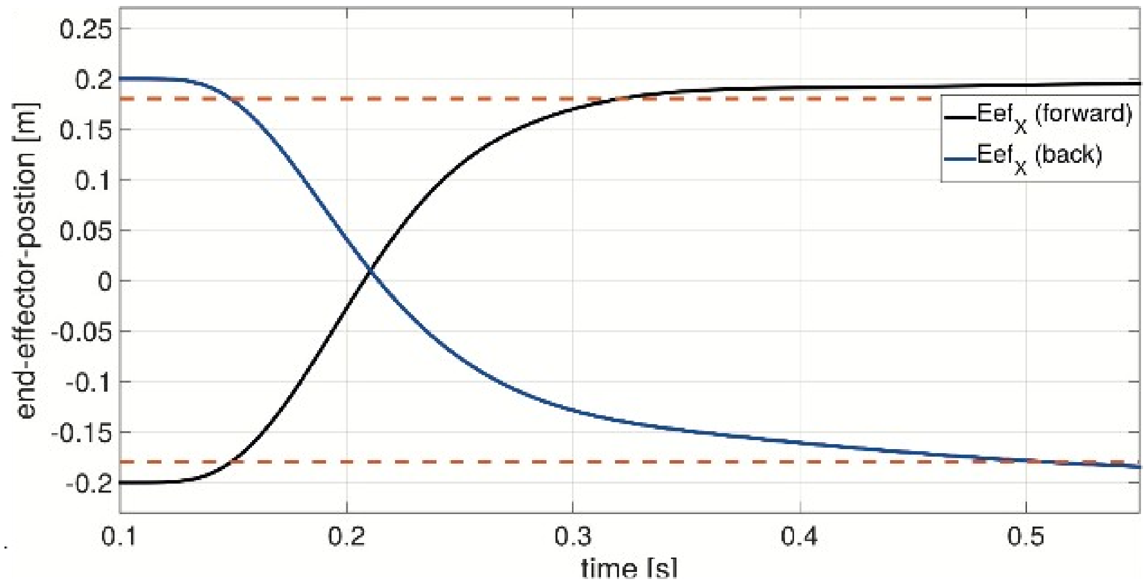
Timing of
2nd part
N varied

interaction torques

when the interaction torques vary, the same virtual trajectory generates significantly different movements







interaction torques

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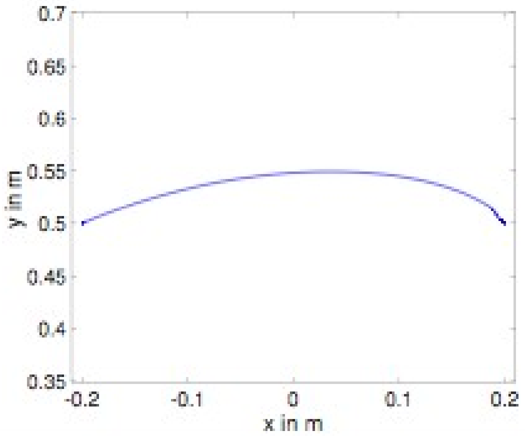

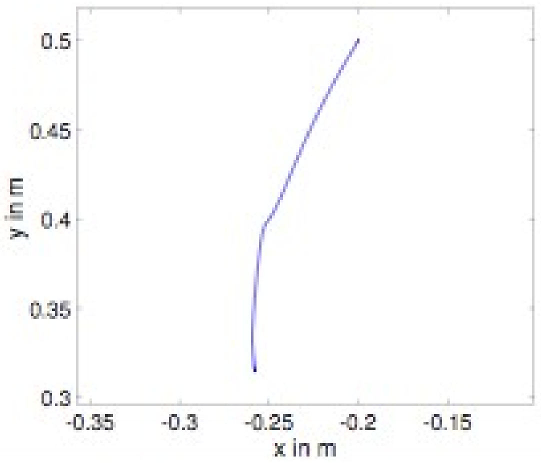

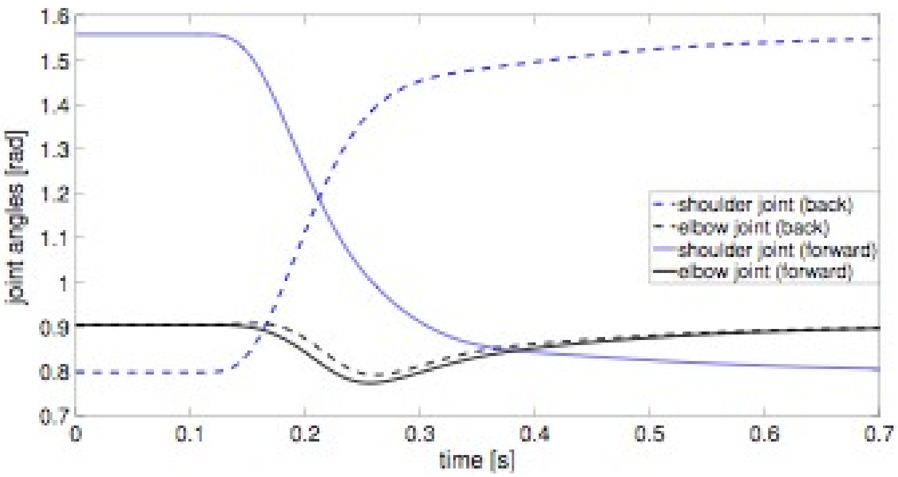

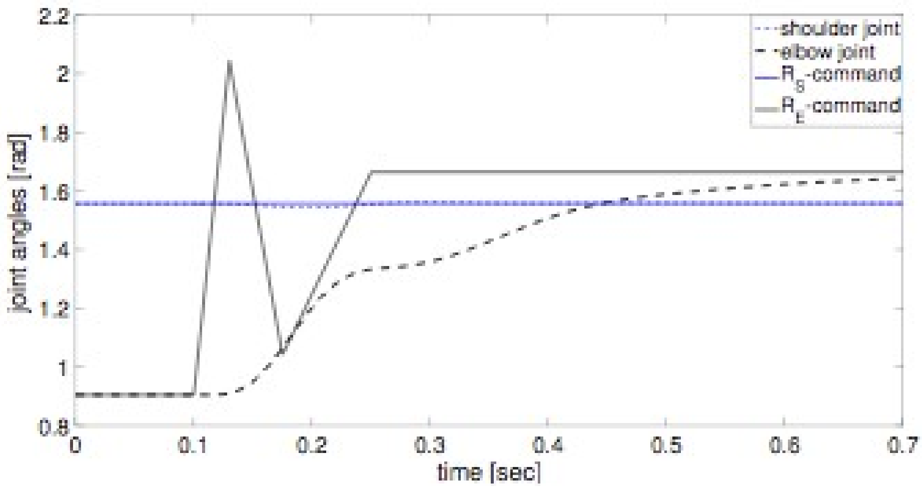

inverse models

in different places in work space where different inertial and interaction torques arise, the motor commands must be different to achieve realistic trajectories

=> kinetics must be taken into account

Conclusion

muscle dynamics and biomechanical dynamics make that the optimal control problem cannot be entirely trivialized: appropriate space-time virtual trajectories are needed to generate realistic movement behavior