HUMAN ROBOTICS

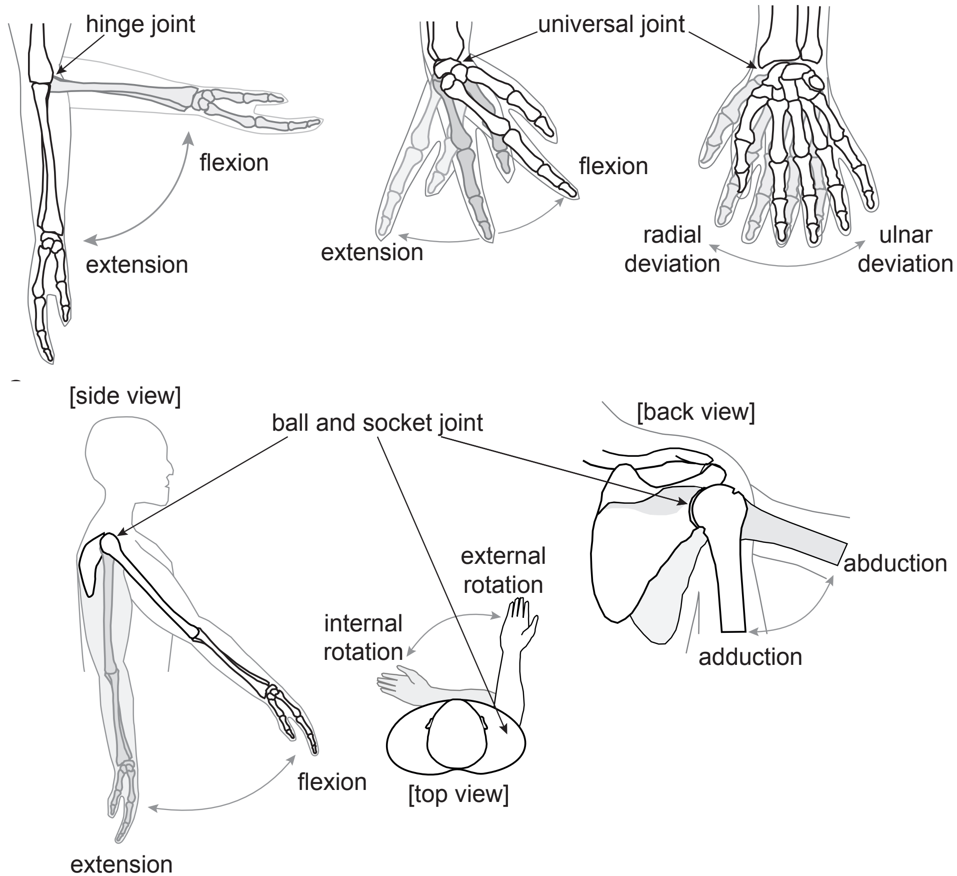
- muscle mechanics and control
- single-joint neuromechanics
- multi-joint multi-muscle kinematics
- multi-joint dynamics and control
- motor learning and memory
- interaction control
- motion planning and online control
- integration and control of sensory feedback
- applications in neurorehabilitation

ONE-JOINT SYSTEM

wrist

elbow

shoulder

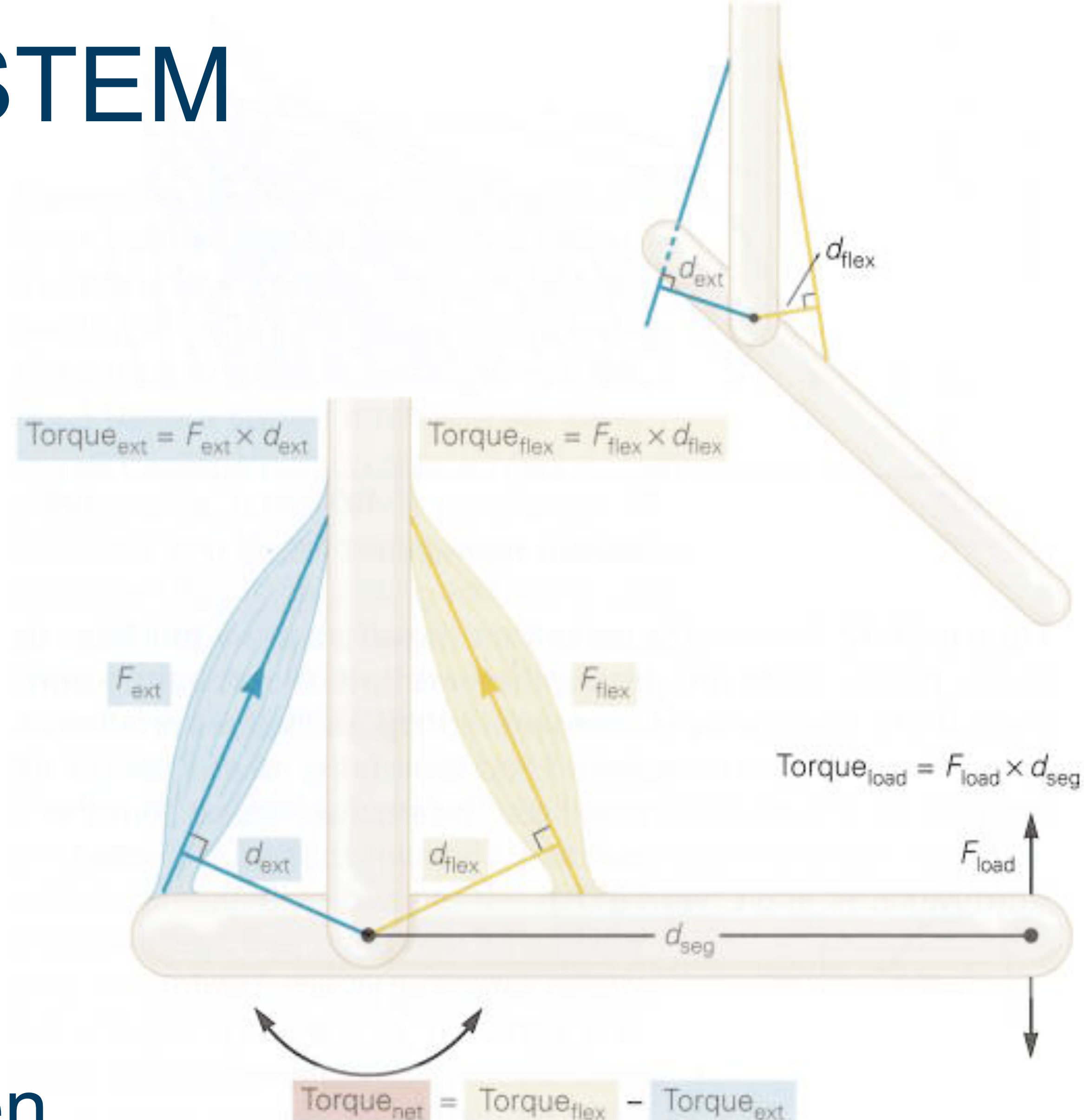


also knee.

- typical onejoint systems are the knee or the elbow, which can move in only one direction
- it is sometimes useful to analyze functions of more complex joints as a onejoint system
- example: wrist flexion/extension

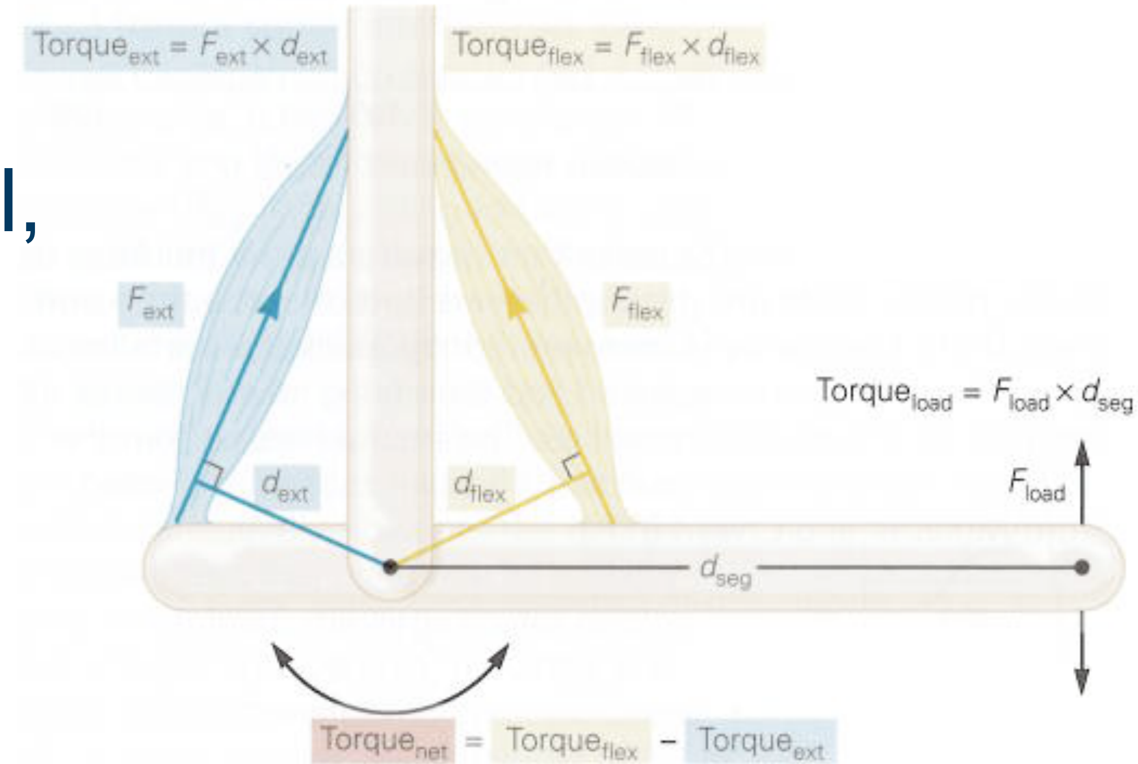
ONE-JOINT SYSTEM

- joint with muscles fixed to the two body segments
- the torque applied at a joint depends on the moment arm
- the moment arm often varies with joint angle



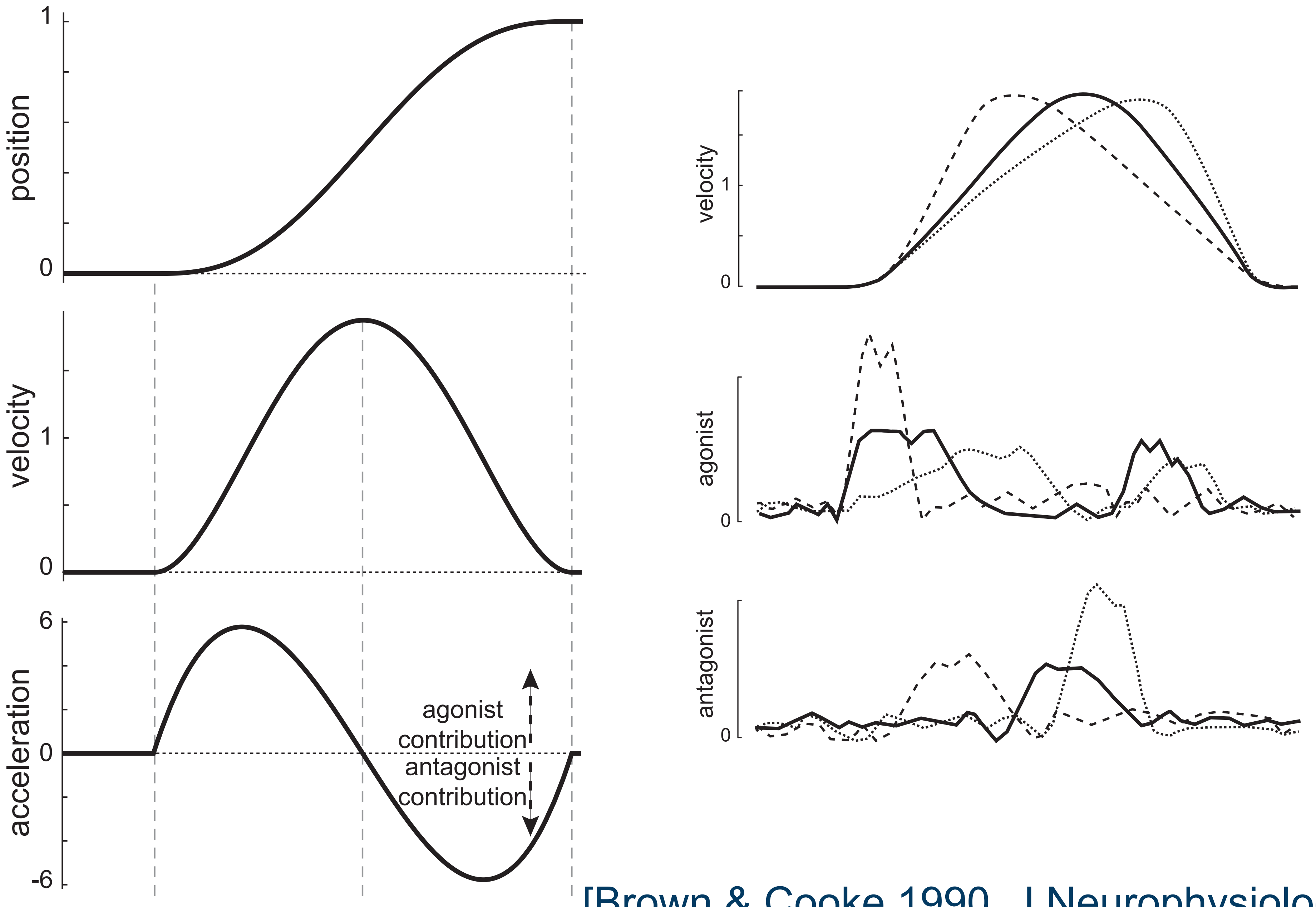
ONE-JOINT SYSTEM

- since individual muscles can only pull, there must be separate sets of muscles at opposite sides of a joint to actuate it



- agonist: prime movers, accelerating the limb
- antagonist: muscles counteracting the agonists and braking movement

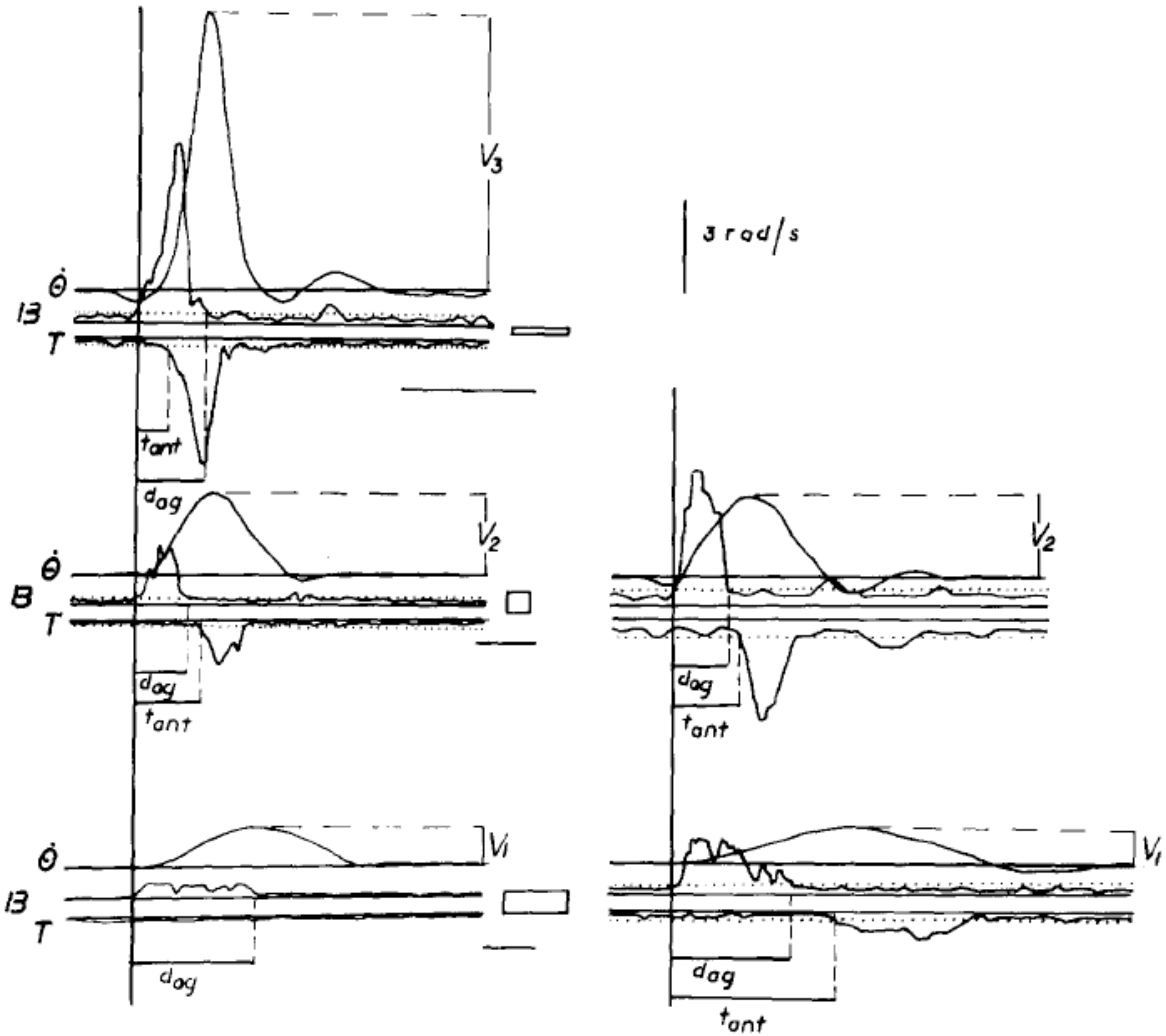
SINGLE JOINT MOTION (1)



[Brown & Cooke 1990, J Neurophysiology]

SINGLE JOINT MOTION (2)

- point-to-point (elbow)movements require activation of agonist (biceps) muscle for acceleration followed by activation of antagonist muscle (triceps) to decelerate and stop motion
- agonist activation increases with torque, i.e. with faster movement and larger load



[Lestienne, Experimental Brain Research 1979]

ELASTICITY OF AN ANTAGONIST MUSCLE PAIR

- stiffness $K \equiv \frac{dF}{dx}$

- elastic elements in parallel

$$F = F_1 + F_2 \qquad x = x_1 = x_2$$

$$\rightarrow K = \frac{dF}{dx} = \frac{dF_1}{dx} + \frac{dF_2}{dx} = \frac{dF_1}{dx_1} + \frac{dF_2}{dx_2} = K_1 + K_2$$

- example: agonist-antagonist muscle pair

JOINT MECHANICS MODELLING

joint mechanics are frequently assumed to be a simple linear transformation of muscle mechanics:

$$\tau = \rho\, m\,, \qquad d\lambda = \rho\, dq$$

m: muscle tension

λ: muscle length

ρ: moment arm

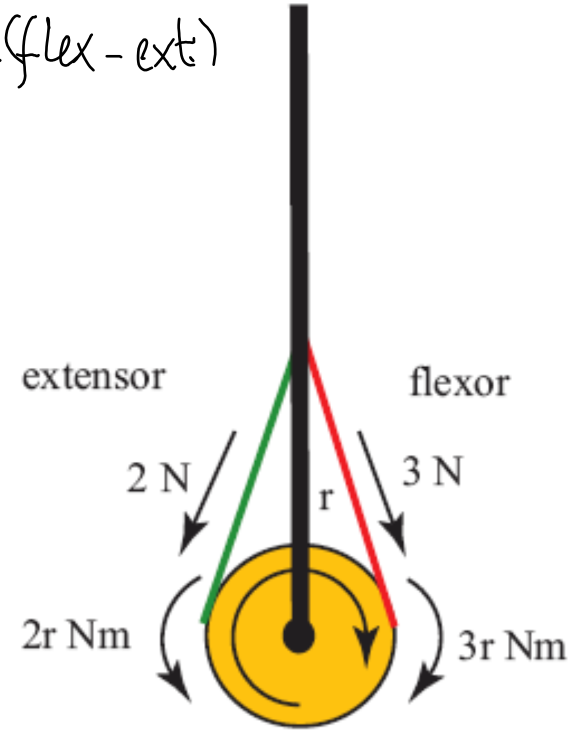
q: joint angle

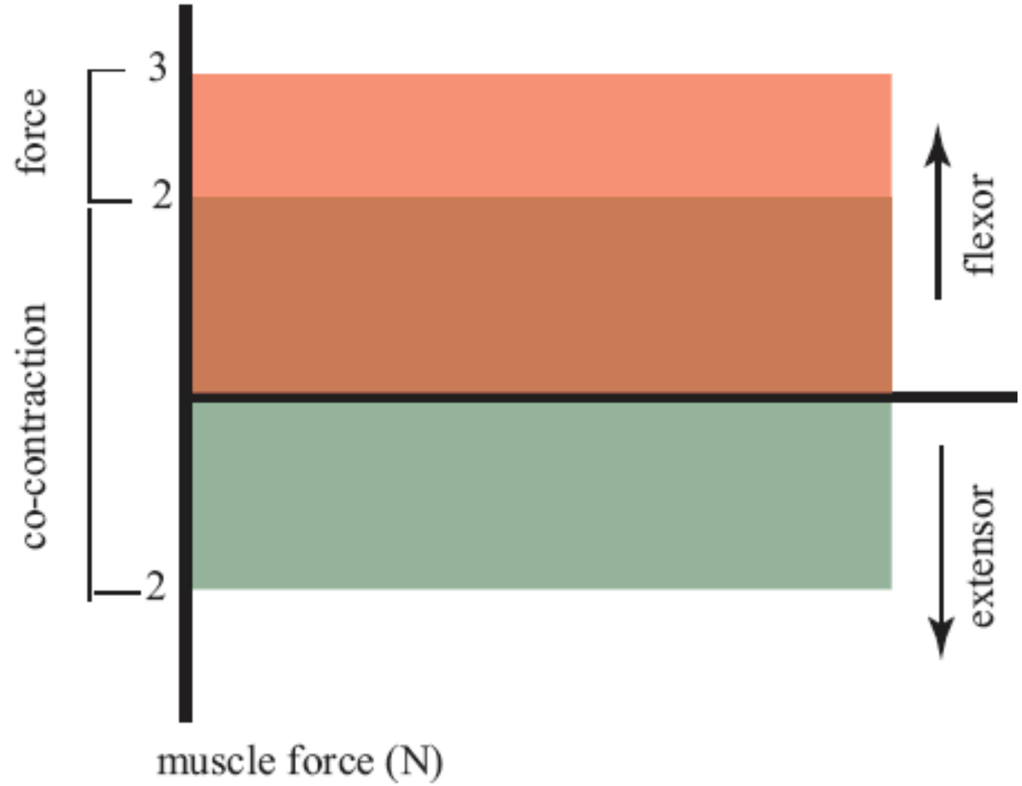
$$\rightarrow K_q \equiv \frac{d\tau}{dq} = \rho\,\frac{dm}{dq} = \rho^2\,\frac{d\cancel{F}m}{d\lambda} \equiv \rho^2\, K_m$$

$$\rightarrow D_q \equiv \frac{d\tau}{d\dot{q}} = \rho\,\frac{dm}{d\dot{q}} = \rho^2\,\frac{d\cancel{F}m}{d\dot{\lambda}} \equiv \rho^2\, D_m$$

JOINT MECHANICS MODELLING

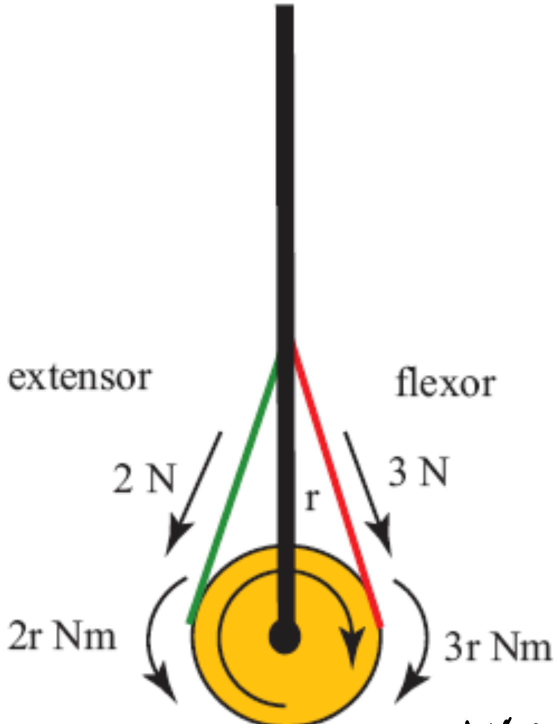
$\tau = \Delta(\text{flex} - \text{ext})$

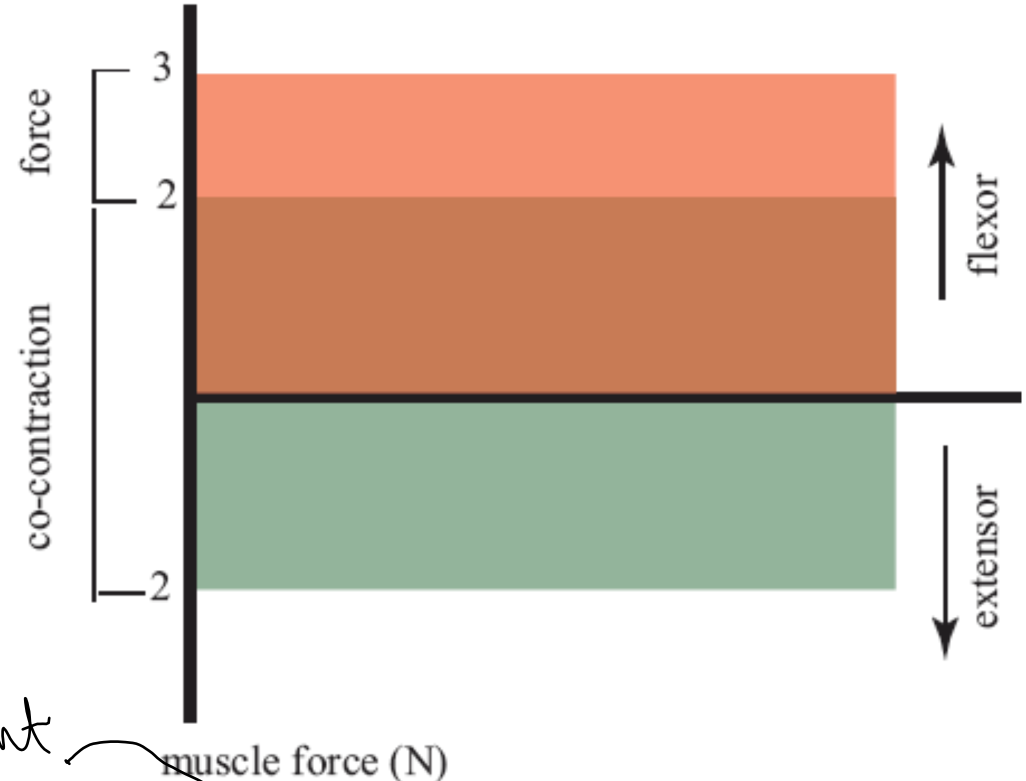




- for simplicity we consider an antagonist pair with one flexor and one extensor
- in each muscle, stiffness increases with muscle tension, e.g. $K = \kappa_o + \kappa_1 m$

JOINT MECHANICS MODELLING





moment arm

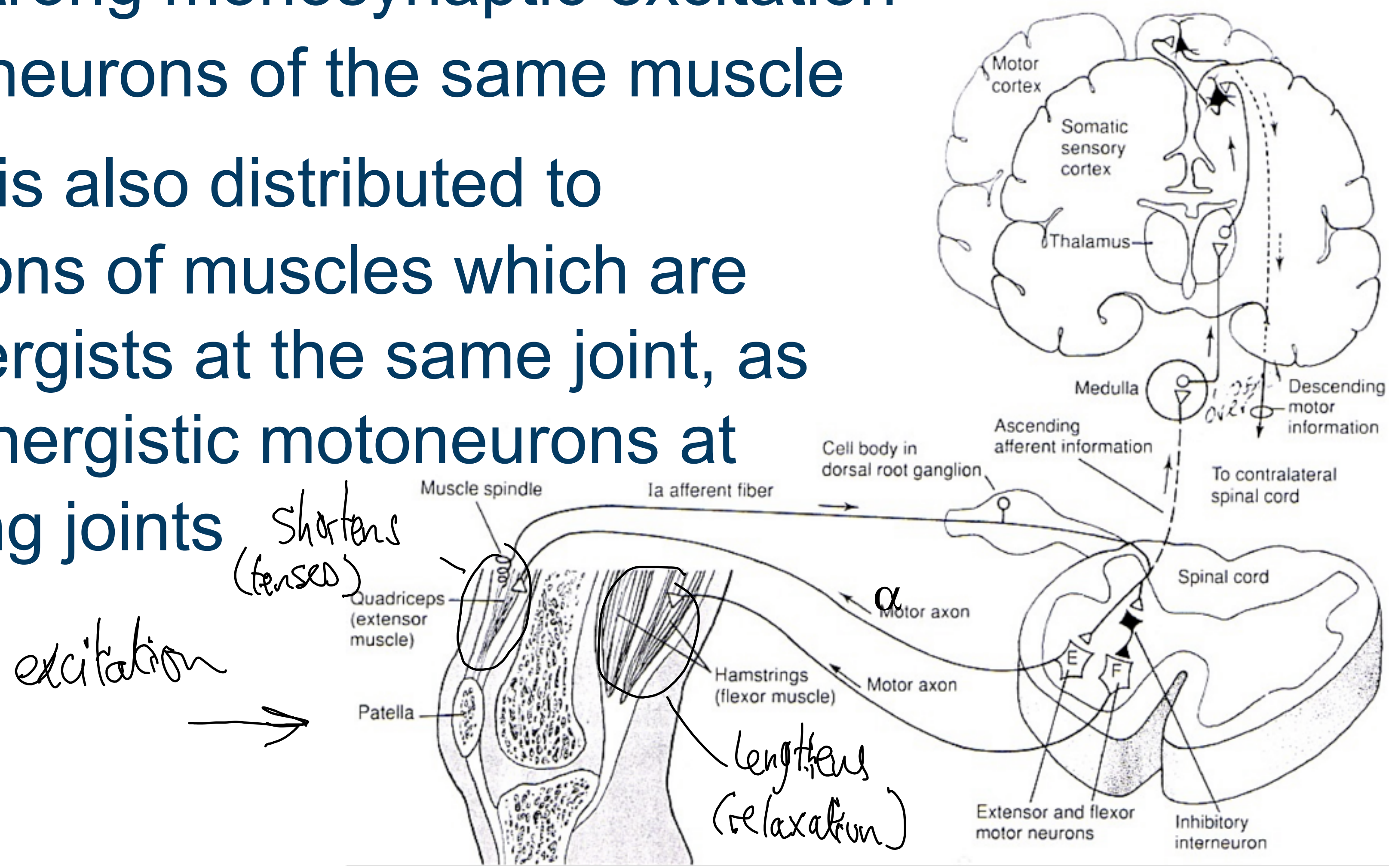
- stiffness $K_q = \rho_e^2 K_e + \rho_f^2 K_f$ increases with muscle tensions m_e and m_f, while torque depends on their difference: $\tau = \rho_e m_e - \rho_f m_f$
- joint stiffness can be modulated independently of torque by co-contraction of antagonistic muscles

REFLEX

- reflex: involuntary and relatively stereotyped response to a specific sensory stimulus
- spinal reflex: sensory signals originating from receptors in muscles, joints, and skin, activate the neural circuitry entirely within the spinal cord responsible for muscle activation
- the same spinal circuits involved in reflexes may be used by higher brain centres to generate complex behaviour: decentralised control

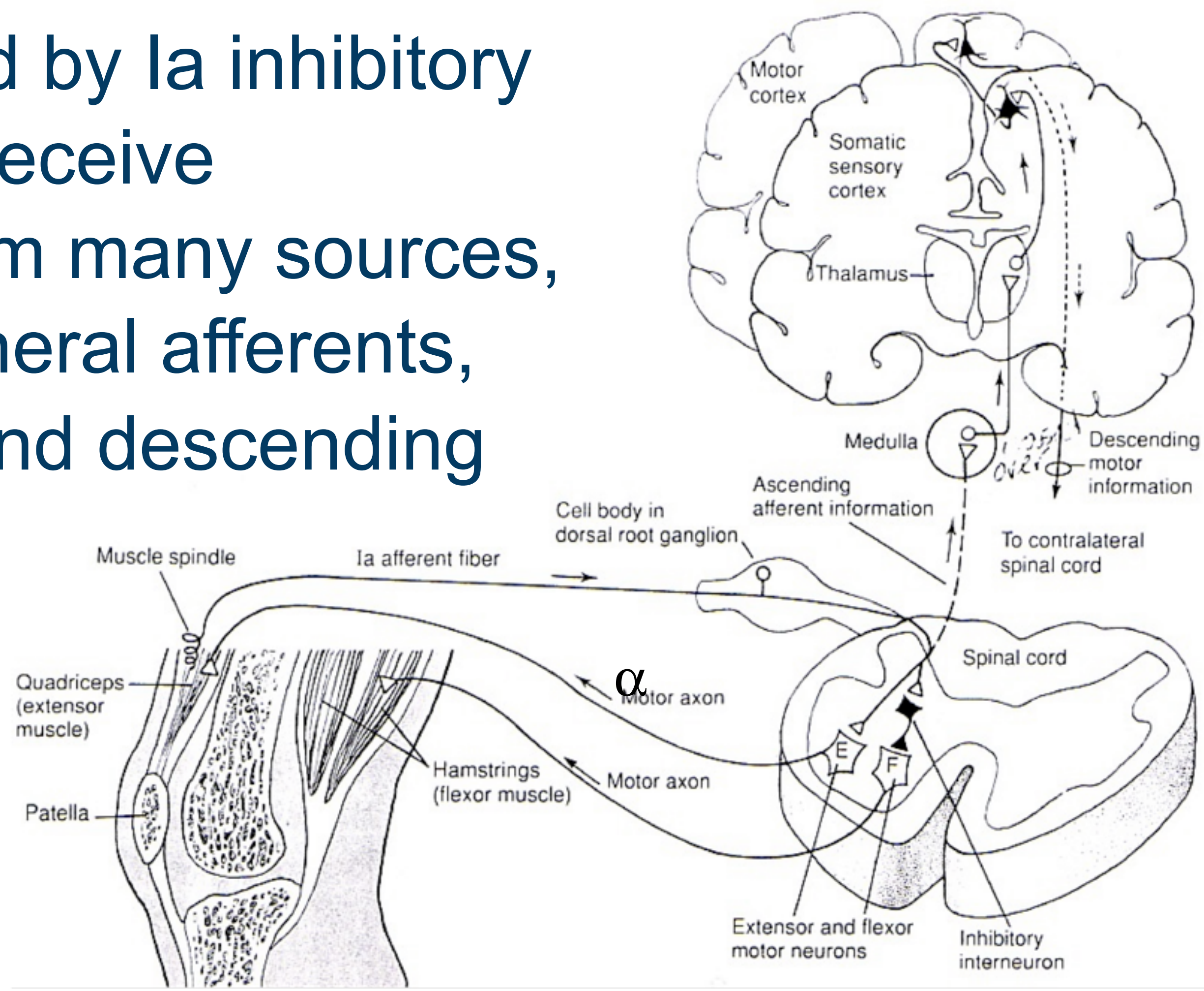
MONOSYNAPTIC STRETCH REFLEX

- fastest and generally most powerful feedback loop (tendon-tap reflex)
- primary muscle spindle afferents (Ia) produce strong monosynaptic excitation of α-motoneurons of the same muscle
- excitation is also distributed to motoneurons of muscles which are close synergists at the same joint, as well as synergistic motoneurons at neighboring joints

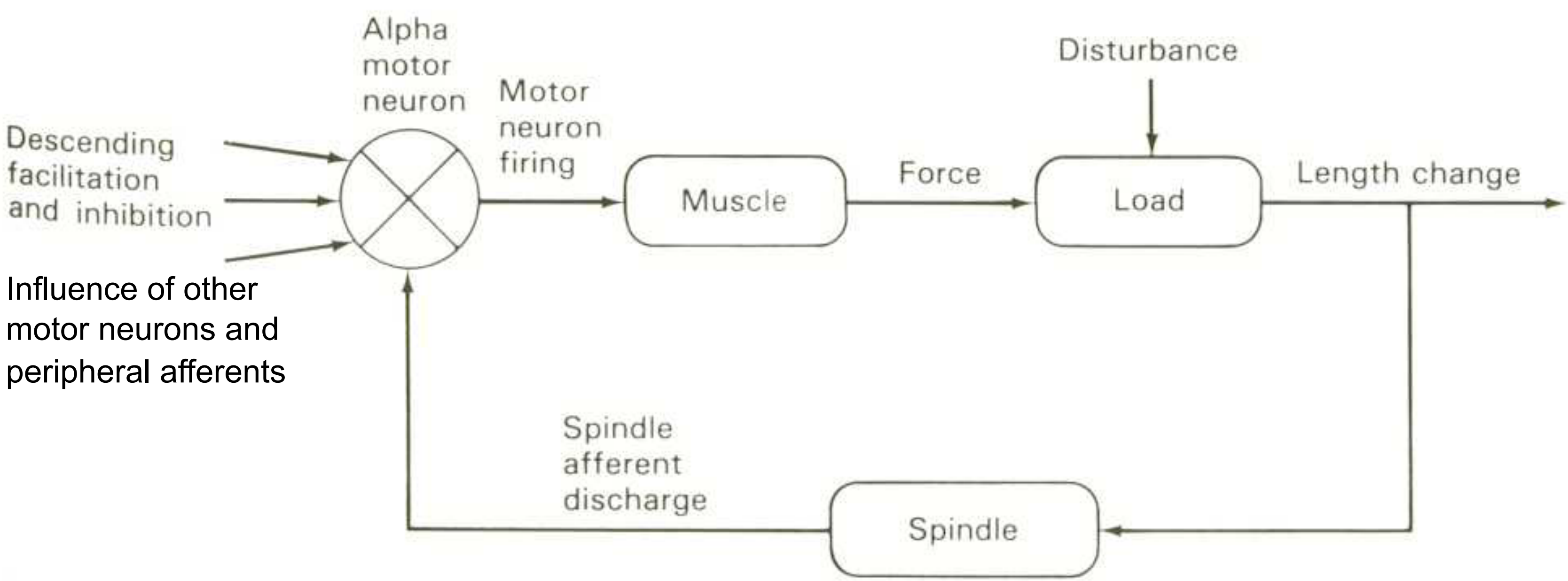


MONOSYNAPTIC STRETCH REFLEX

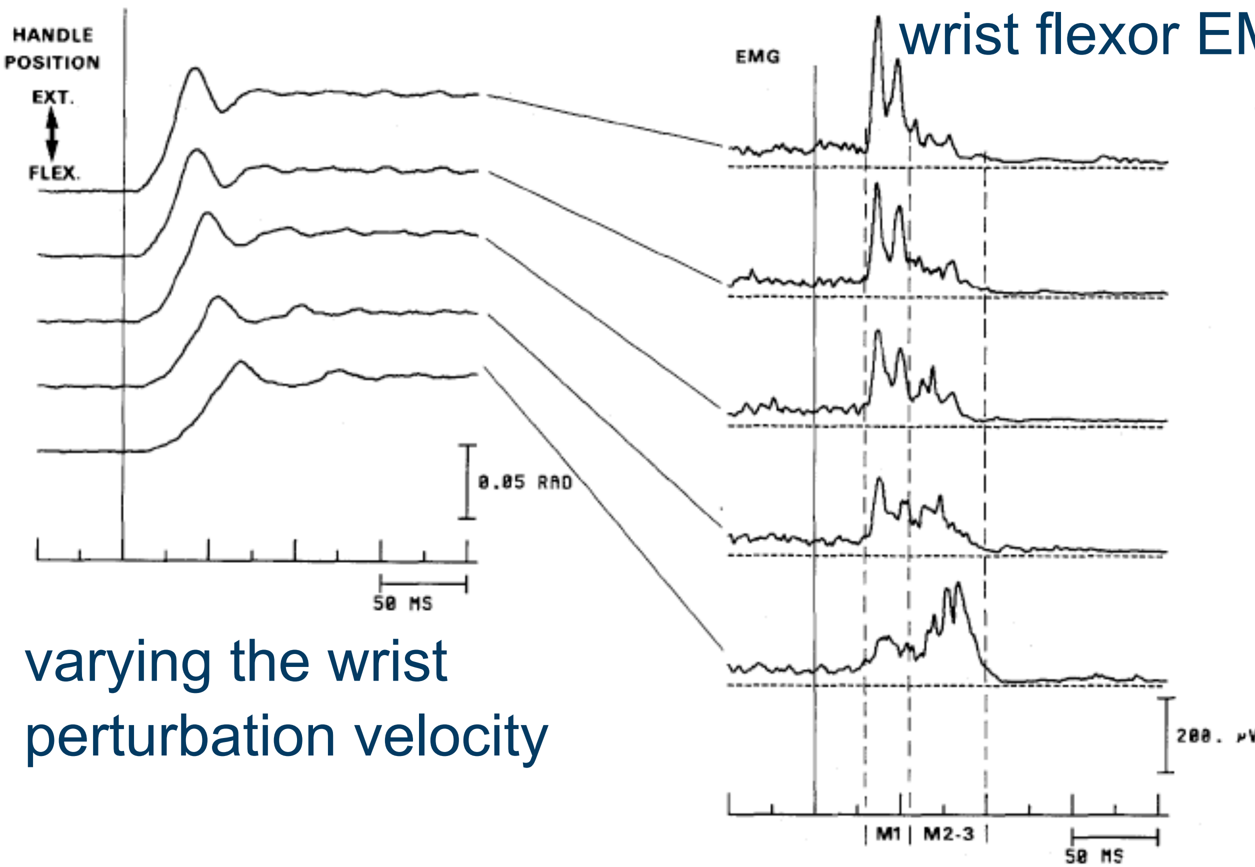
- activity of Ia afferents also causes reciprocal inhibition of α-motoneurons of antagonist muscles
- inhibition is mediated by Ia inhibitory interneurons which receive convergent input from many sources, including both peripheral afferents, other interneurons and descending pathways



STRETCH REFLEX DIAGRAM



STRETCH REFLEX EMG



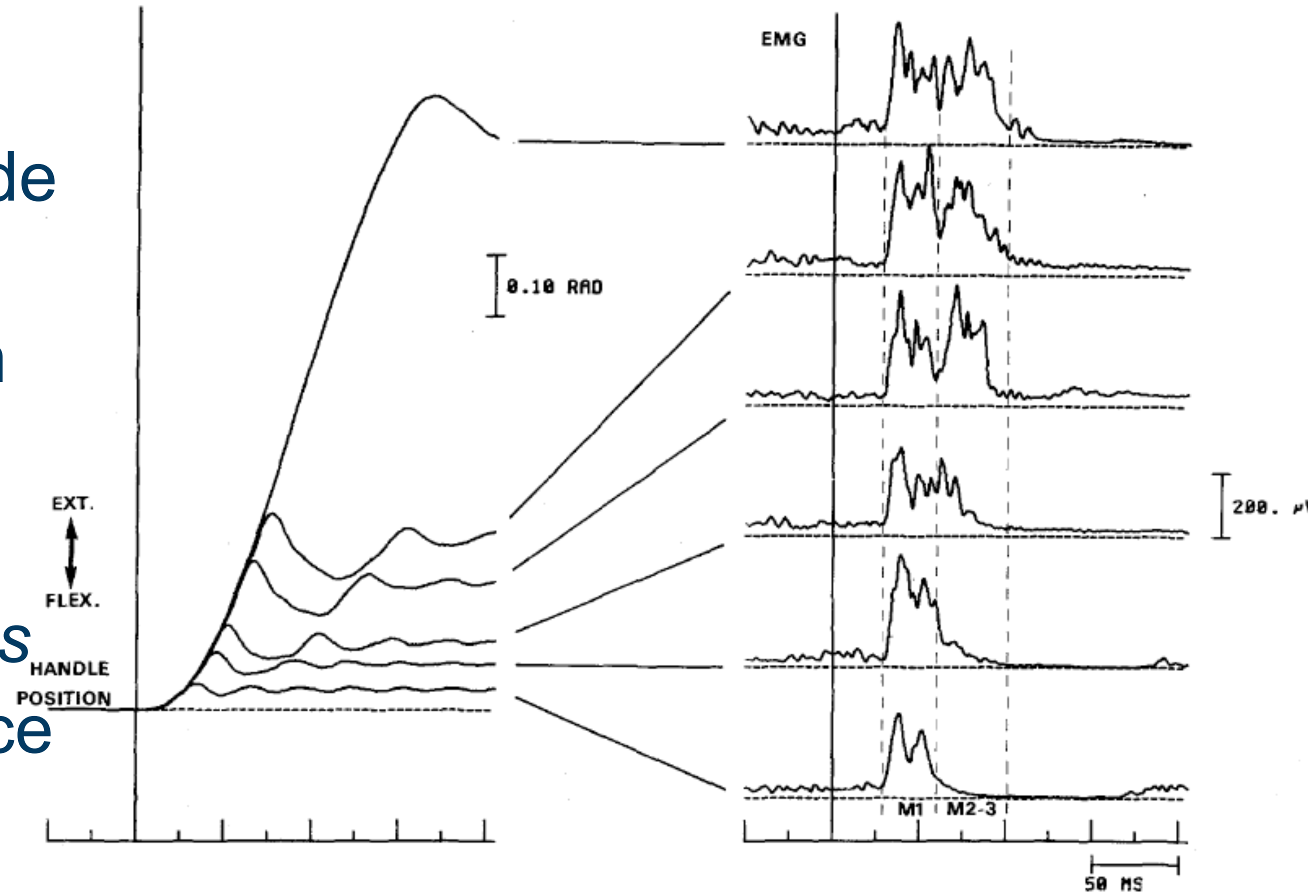
earliest component of stretch reflex (monosynaptic reflex) is brief increase in electrical activity of muscle, typically after 20-30*ms* for arm

- duration of the electrical activity is generally less than 50*ms*, but force will last at least 200*ms*
- size of response depends mainly on velocity of stretch and state of motoneuron excitability

[Lee and Tatton Experimental Brain Research 1982]

STRETCH REFLEX EMG

- effect of increasing duration and amplitude of displacement on EMG responses from the wrist flexor
- responses at longer delays of up to 150*ms* can extend reflex force production to several hundred milliseconds

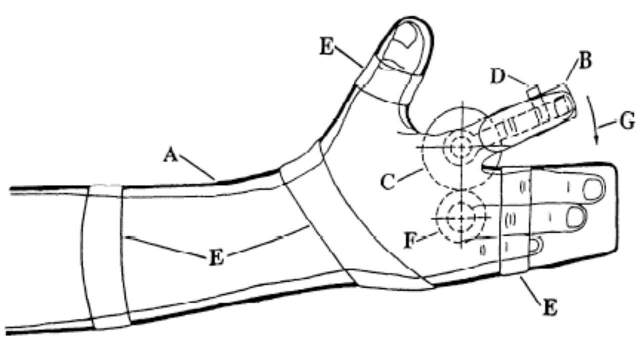


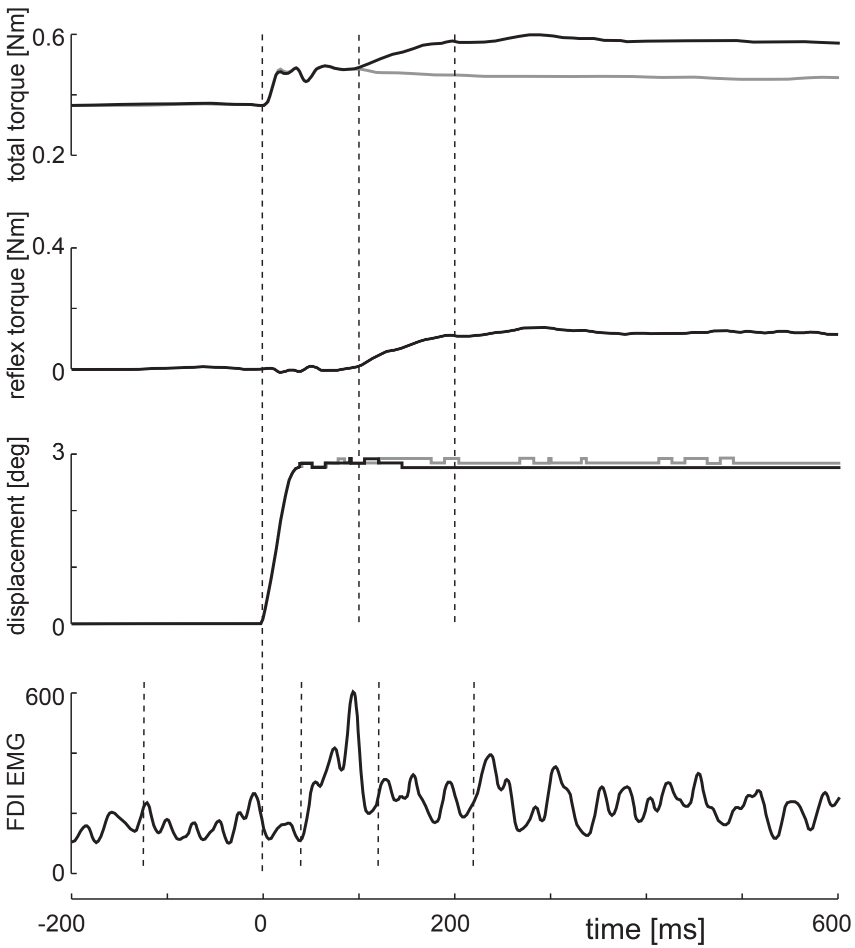
- size of longer latency responses depend on the amplitude and duration of the stretch, as well as mechanical factors such as stability and environmental dynamics or psychological factors such as intention (resist, ignore, etc.)

[Lee and Tatton Experimental Brain Research 1982]

SINGLE JOINT POSTURE

- subjects produce constant torque
- total torque due to displacement
- intrinsic: movement due to electrical stimulation if relaxed
- reflex= total - intrinsic
- torque due to stretch reflexes occurs at some delay after perturbation





[Leger & Milner 2000, Clinical Biomechanics]

REFLEX MUSCLE ACTIVATION

- reflex pathways will be activated during voluntary movement due to output of muscle sensory receptors sensitive to movement variables
- central nervous system controllers must compensate for changes in motoneuron activation due to input from reflex pathways during movement

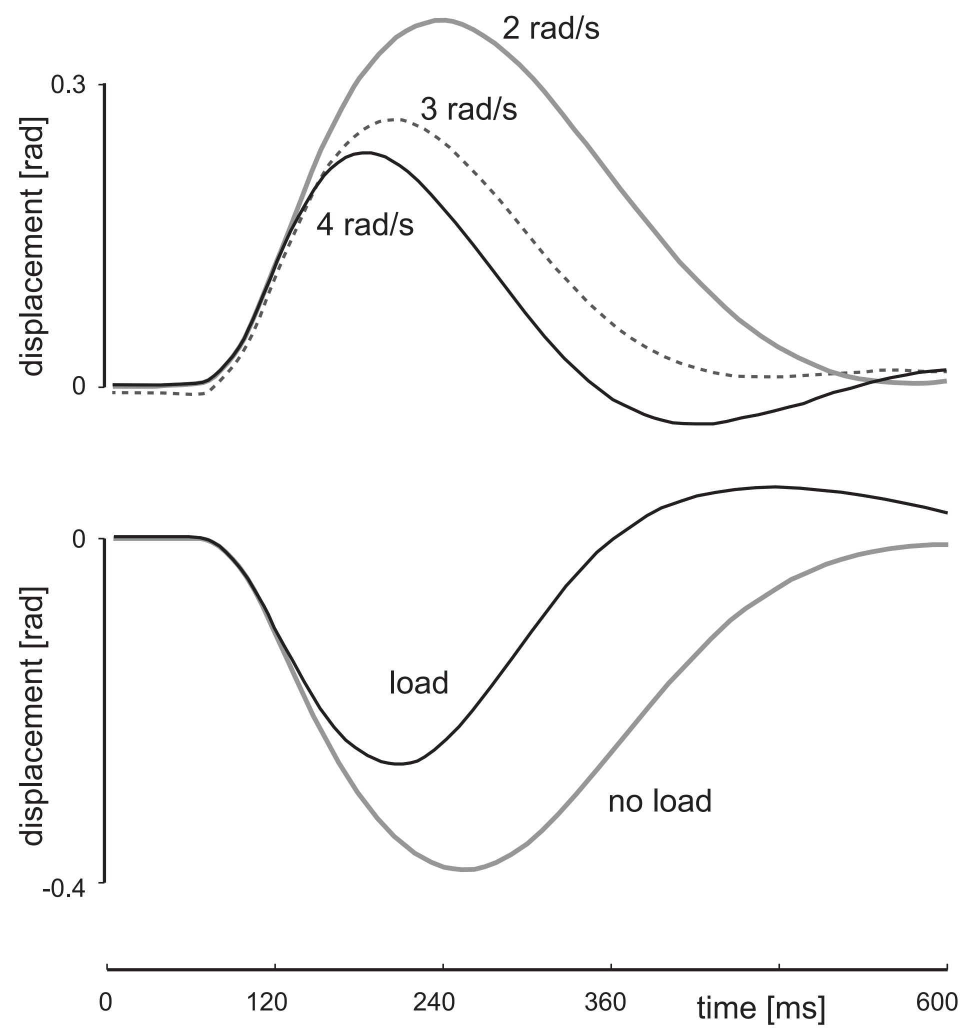
REFLEX MUSCLE ACTIVATION

- reflex feedback to muscles on both sides of a joint contributes to “apparent” stiffness and damping by means of a delayed change in muscle torque
- reflex impedance can be negative depending on the natural frequency, which increases with muscle activation
- currently there is no consensus on the most appropriate model structure for reflex feedback, which poses a problem for theoretical analysis of system stability
- this problem is partly resolved if torque due to muscle impedance can be assumed to be sufficiently greater than torque due to reflex feedback

JOINT ELASTICITY (1)

Linear Control.

- elbow point-to-point movement
- (+-5*Nm*, 50*ms*) torque pulse at peak velocity
- loads: interface inertia, and added damping
- faster motion is stiffer
- load or larger speed produces a larger restoring force



[Milner Experimental Brain Research 1993]

LINEAR CONTROL OF ROBOTS

- for tasks such as welding or milling, robots have to follow a trajectory

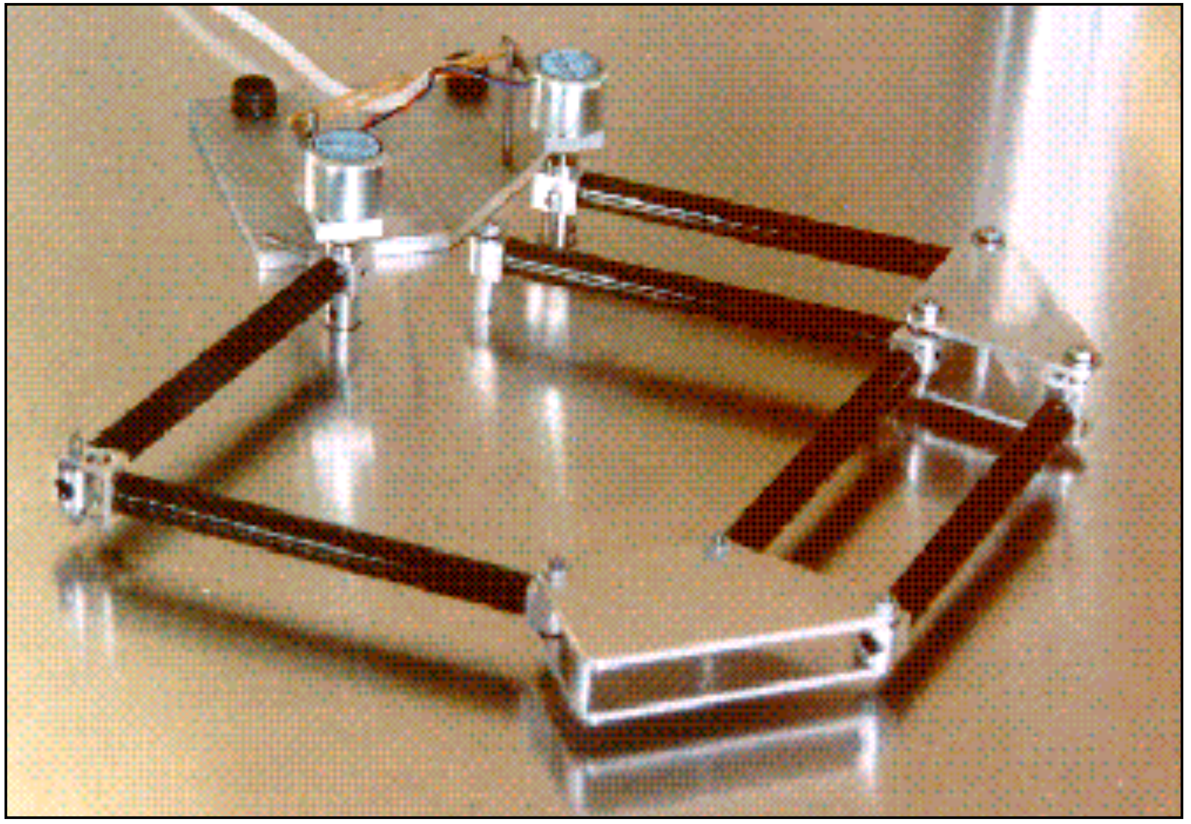
- linear PD control is typically used: motor torque to minimize the tracking error along movement

$$\boldsymbol{\tau}(t) = \mathbf{P}\,\mathbf{e}(t) + \mathbf{D}\,\dot{\mathbf{e}}(t)$$

$\mathbf{e}(t) = \mathbf{q}_p(t) - \mathbf{q}(t)$ tracking error between the planned and realised trajectories

$\mathbf{P}=\mathbf{P}^T$, $\mathbf{D}=\mathbf{D}^T$ positive definite matrices, e.g. diagonal matrices with positive gains

LINEAR CONTROL OF ROBOTS



$$\boldsymbol{\tau}(t) = \mathbf{P}\,\mathbf{e}(t) + \mathbf{D}\,\dot{\mathbf{e}}(t)$$
$$\mathbf{e}(t) = \mathbf{q}_p(t) - \mathbf{q}(t)$$

- PD controller to provide the motion dynamics...
- and stabilise the plant against perturbations

LINEAR ONE JOINT MODEL

$$\tau = I\ddot{q} + D\,\dot{e} + K\,e$$

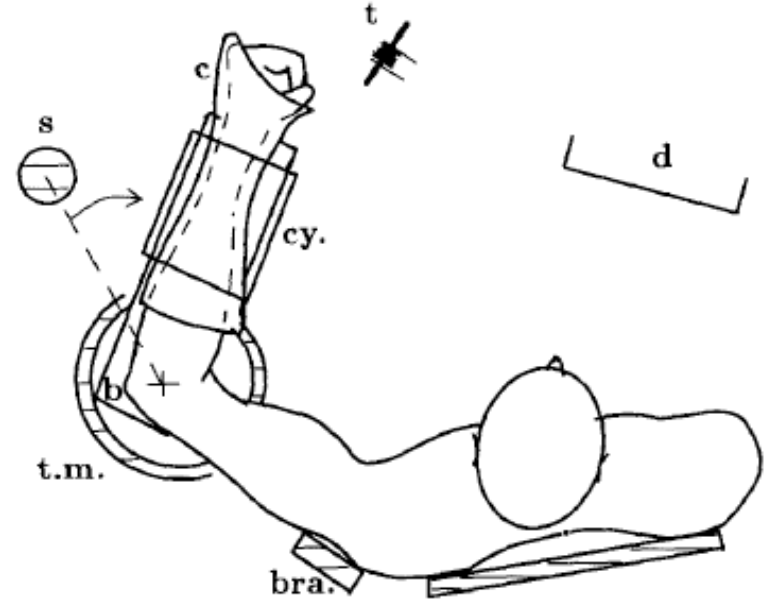
q_p : undisturbed trajectory

$e \equiv q_p - q$: kinematic error

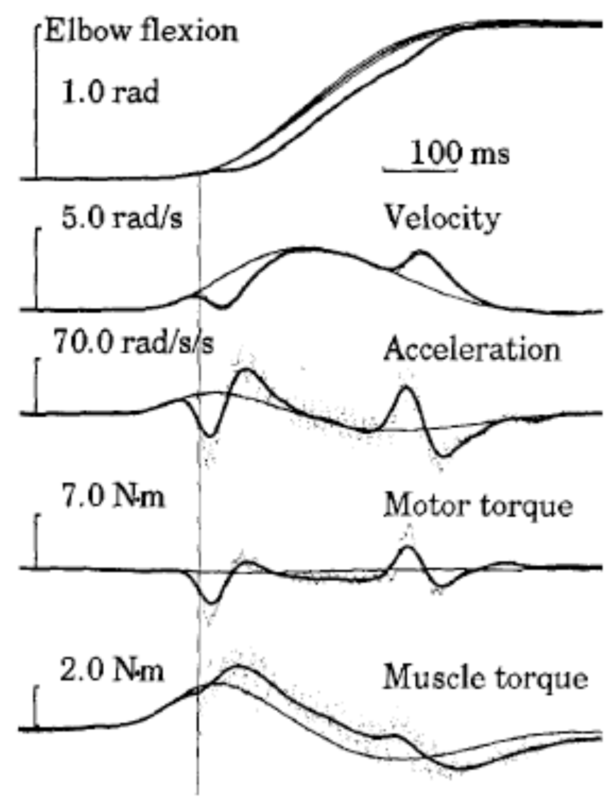
D : damping , K : stiffness

I : inertia , $\ddot{q}$: joint acceleration

JOINT ELASTICITY (2)



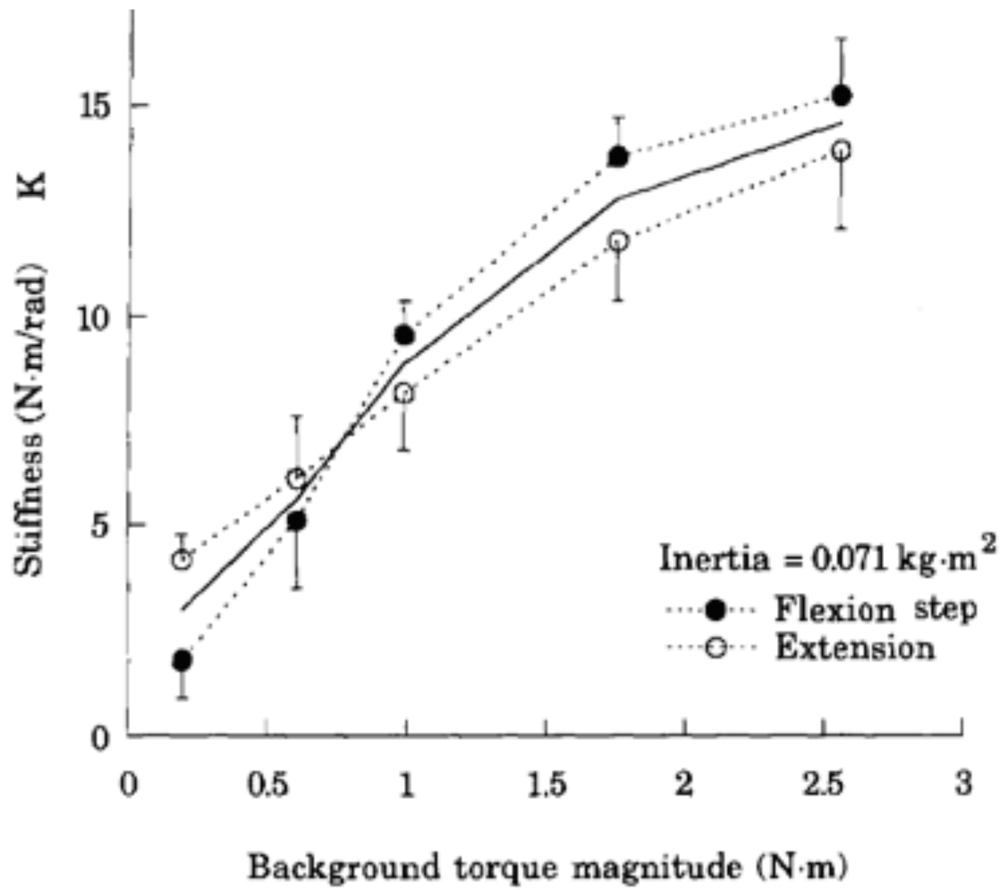
- 1.0*rad* elbow reaching
- 0.15*rad* angle displacement during movement
- joint stiffness: $\frac{\Delta\tau}{\Delta q}$



[Bennett Experimental Brain Research 1993]

JOINT ELASTICITY (3)

- 1.0*rad* elbow reaching
- 0.15*rad* angle displacement during movement
- joint stiffness: $\frac{\overline{\triangle \tau}}{\overline{\triangle q}}$
- stiffness increases linearly with torque!!

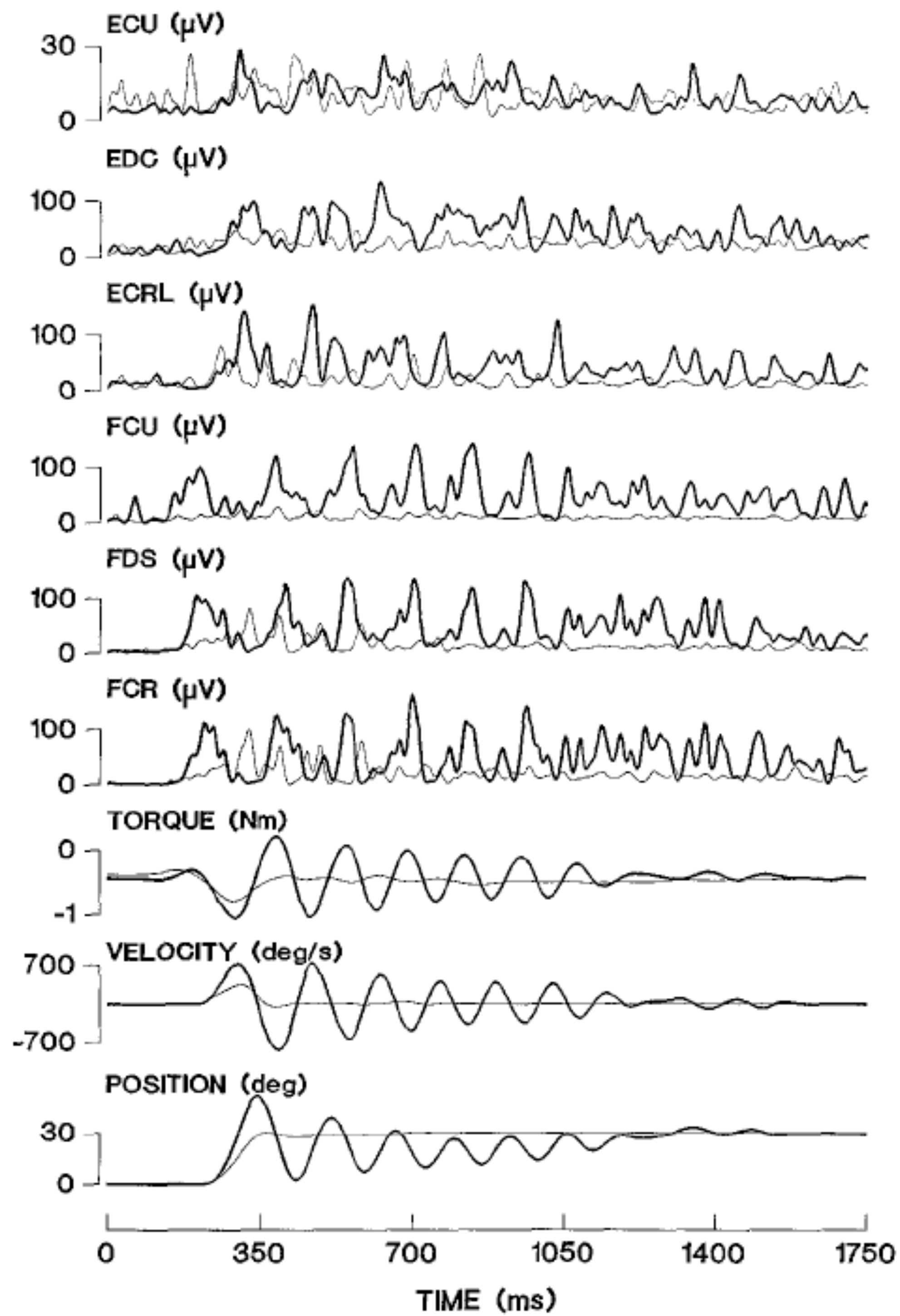


[Bennett Experimental Brain Research 1993]

JOINT ELASTICITY ADAPTATION

Do we have control of I, D & K independantly? Yes!!

- wrist 30° reaching mvt
- unstable viscous load assisting motion
- subjects learned to reduce the oscillations
- second order linear model -> increase of damping and stiffness



[Milner and Cloutier Exp Brain Res 1993]