Lecture Outline

How does the human nervous system generate a movement of the hand?

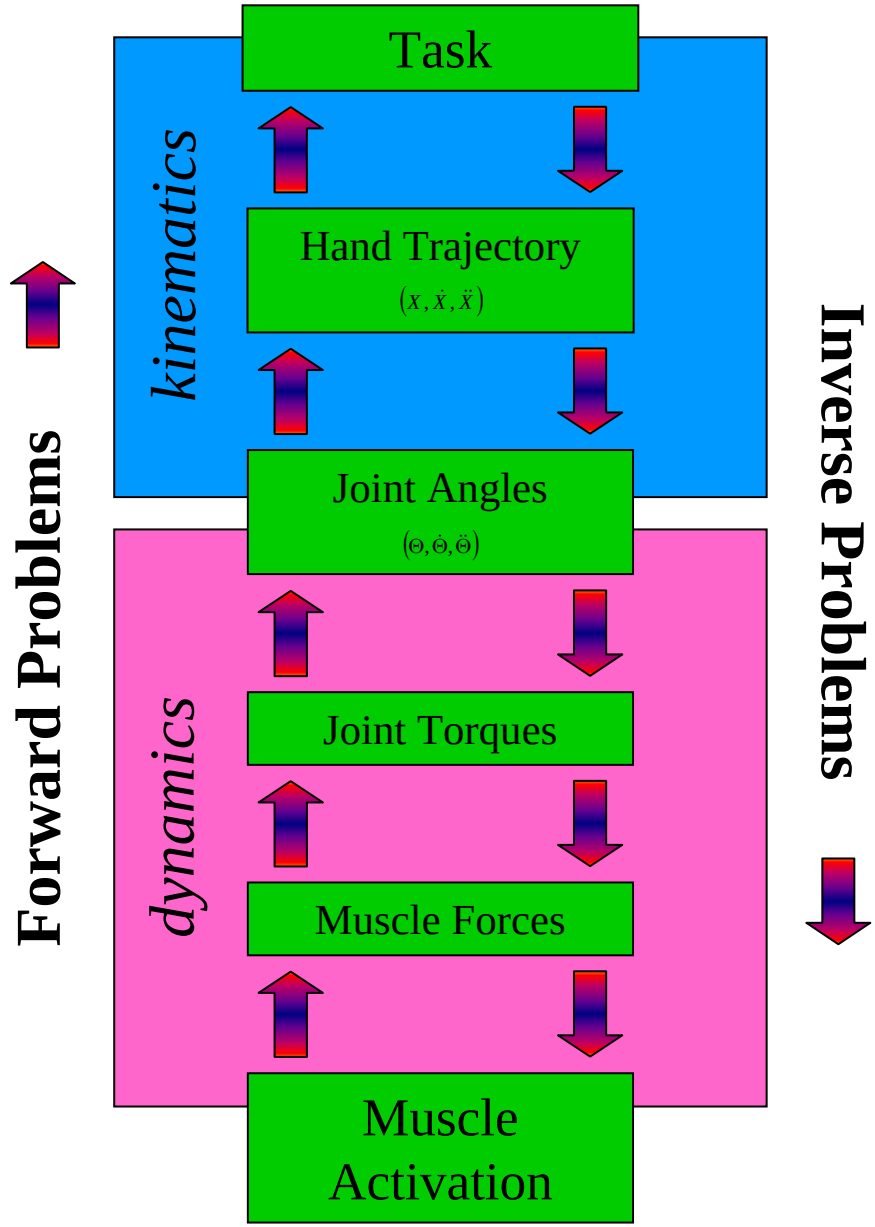
- Basic Control Theory

  Engineering for Neuroscientists

  – ***Feedforward and Feedback Control***
- Elements of the human motor system

  Neurophysiology for Engineers

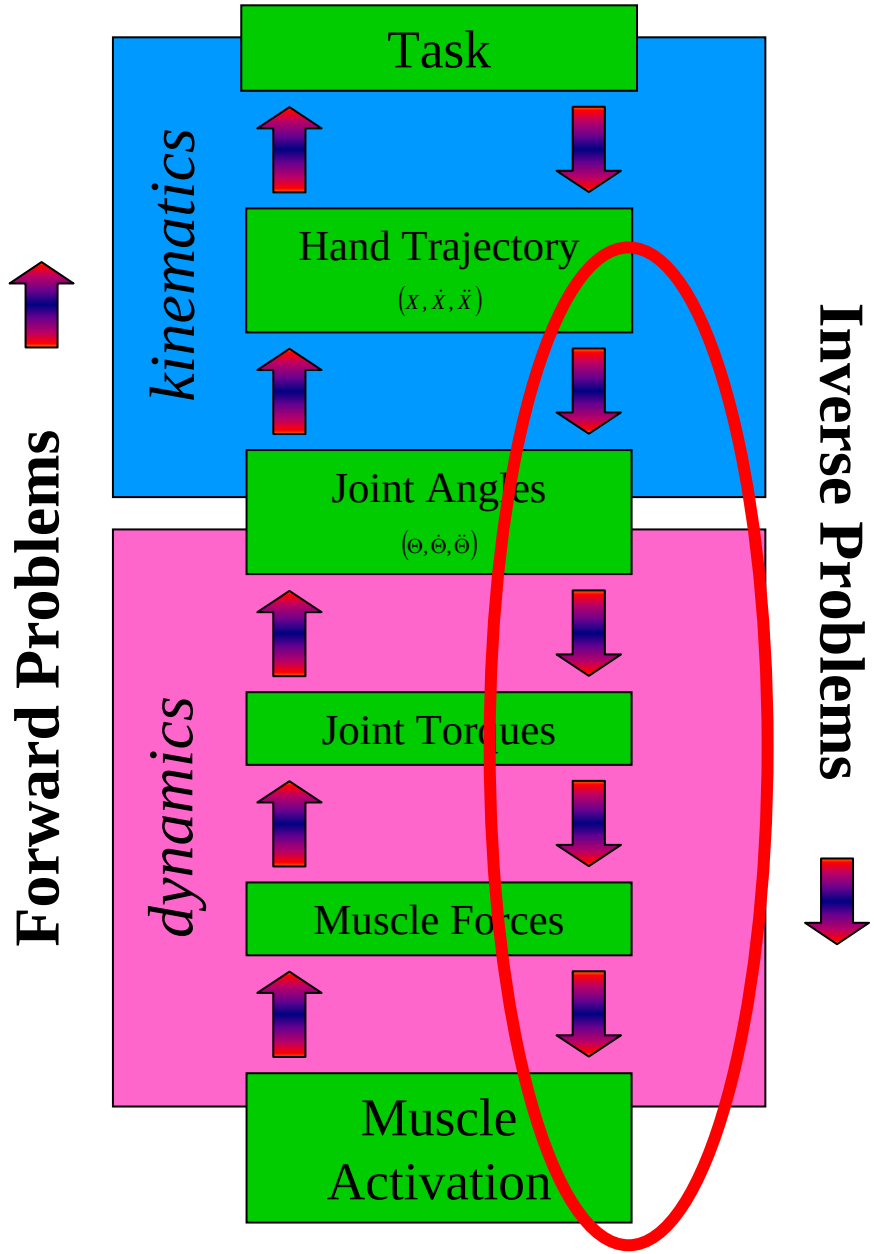
  – ***Actuators, Sensors, Circuits***
- Models of Human Motor Control
  – ***Theories, History, Experimental Evidence***
- Consequences for Neuro-Robotics
  – Brain-machine interfaces



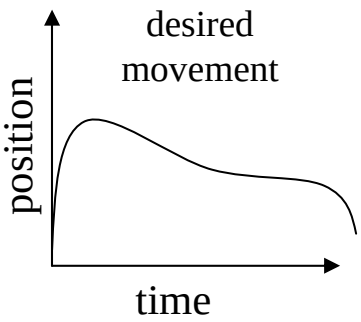
Source: J. McIntyre

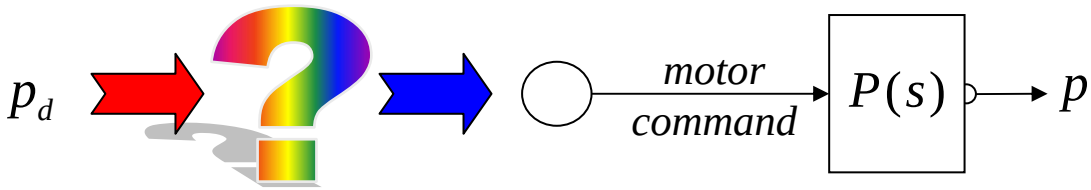
Computational Issues in Motor Control

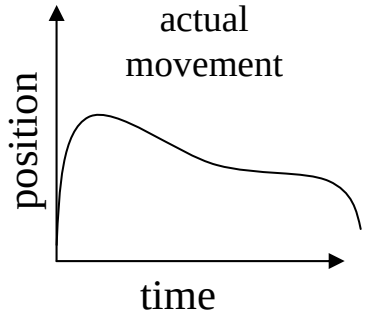
- The problem of controlling movement can be conceptually divided into discrete components.
  - Forward Computations
    What are the consequences of a given motor command?
  - Inverse Computations
    How to produce muscle activations necessary for a desired task?
- ***Question*** – How does the nervous system solve these conceptual problems?

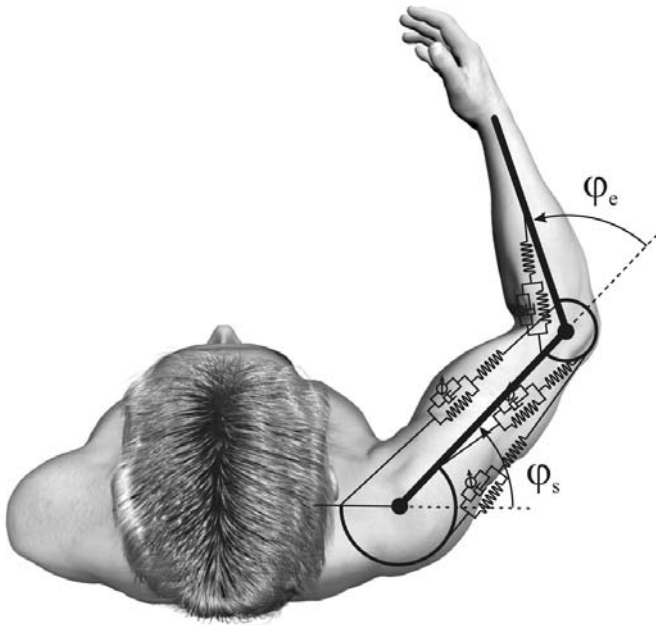


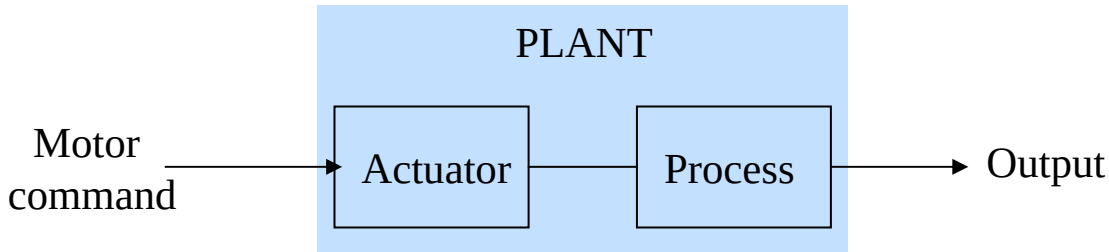
Feedforward versus Feedback Control



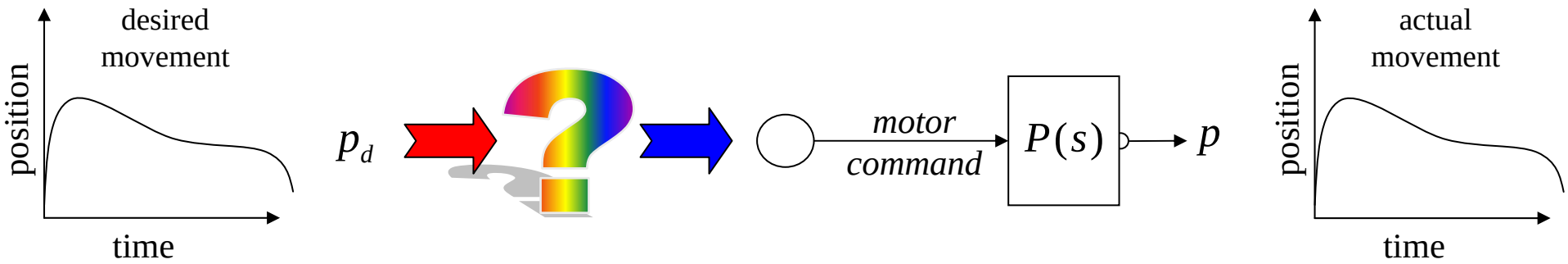




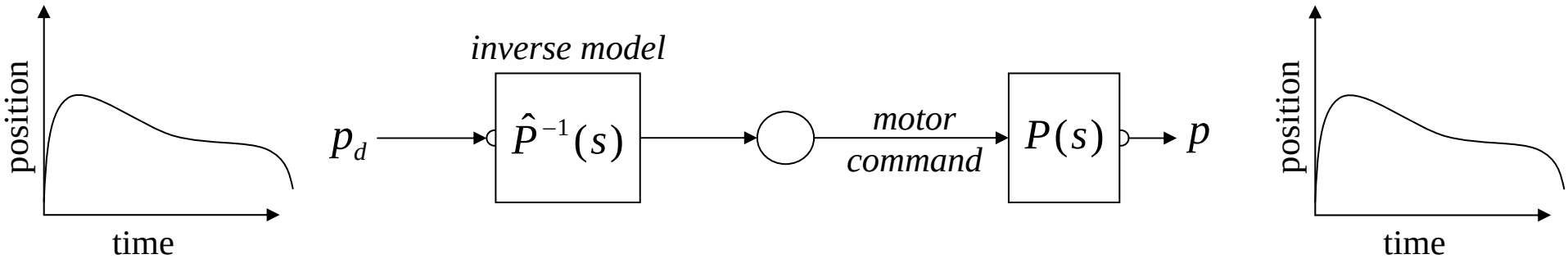




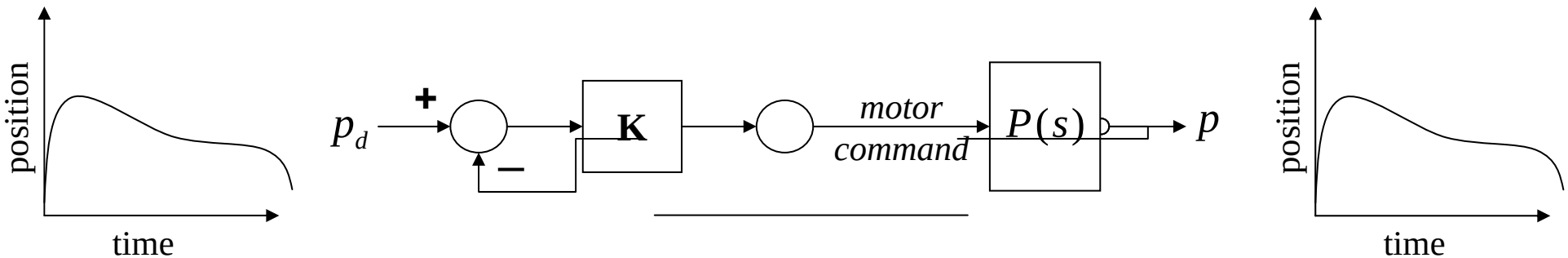
Feedforward versus Feedback Control



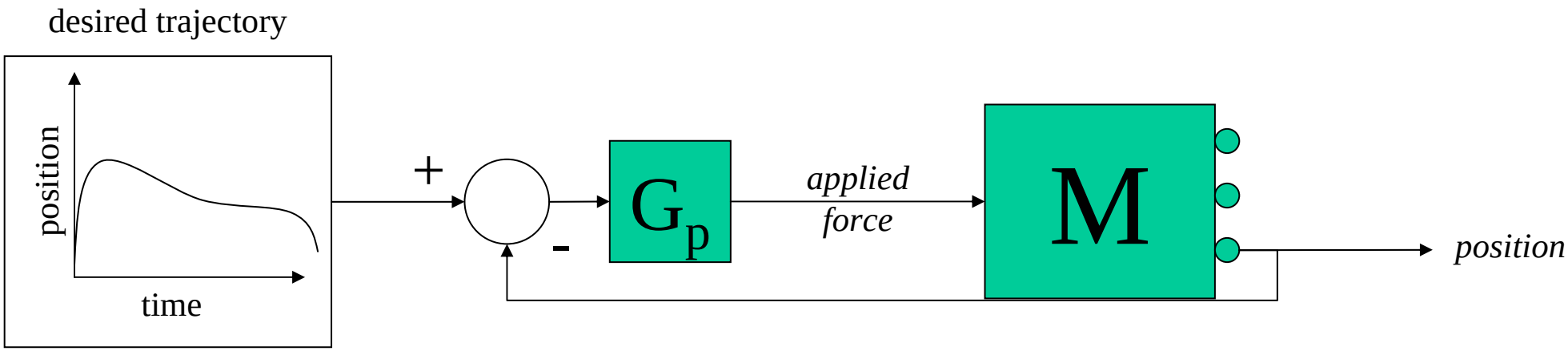
Feedforward Control: compute control based on knowledge of physics



Feedback Control: generate commands based on error signals

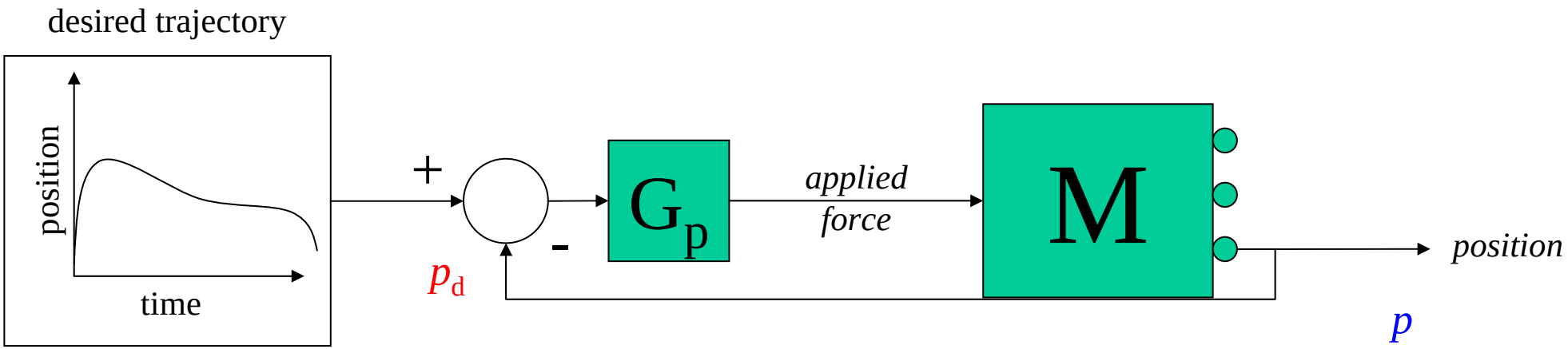


Simple feedback control of position.

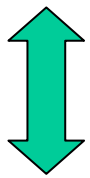


$$f = G_p\left(p_d - p\right)$$

What's missing?

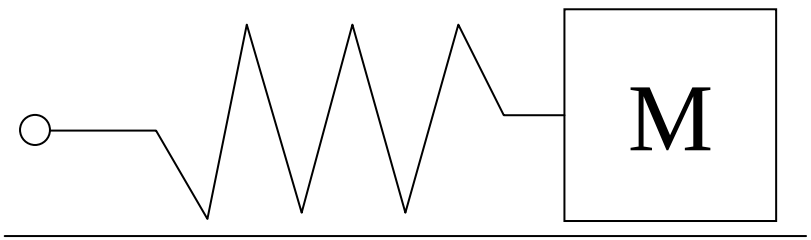


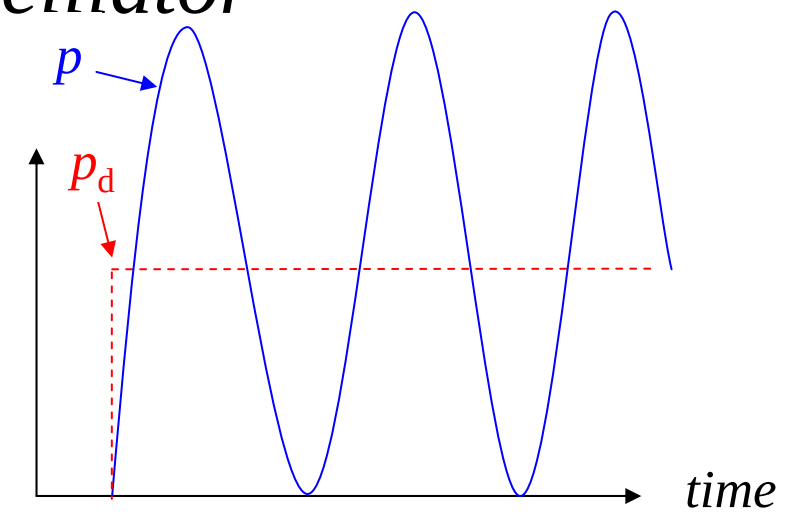
$$f = G_p\left(p_d - p\right)$$



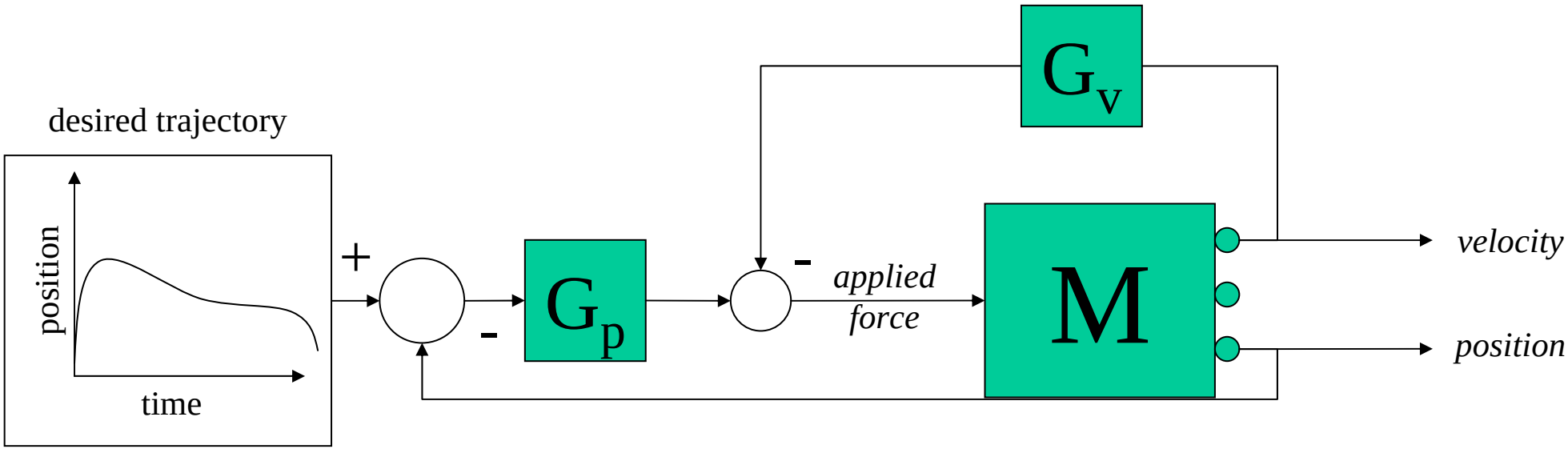
undamped oscillator

$$f = k\left(l - l_0\right)$$



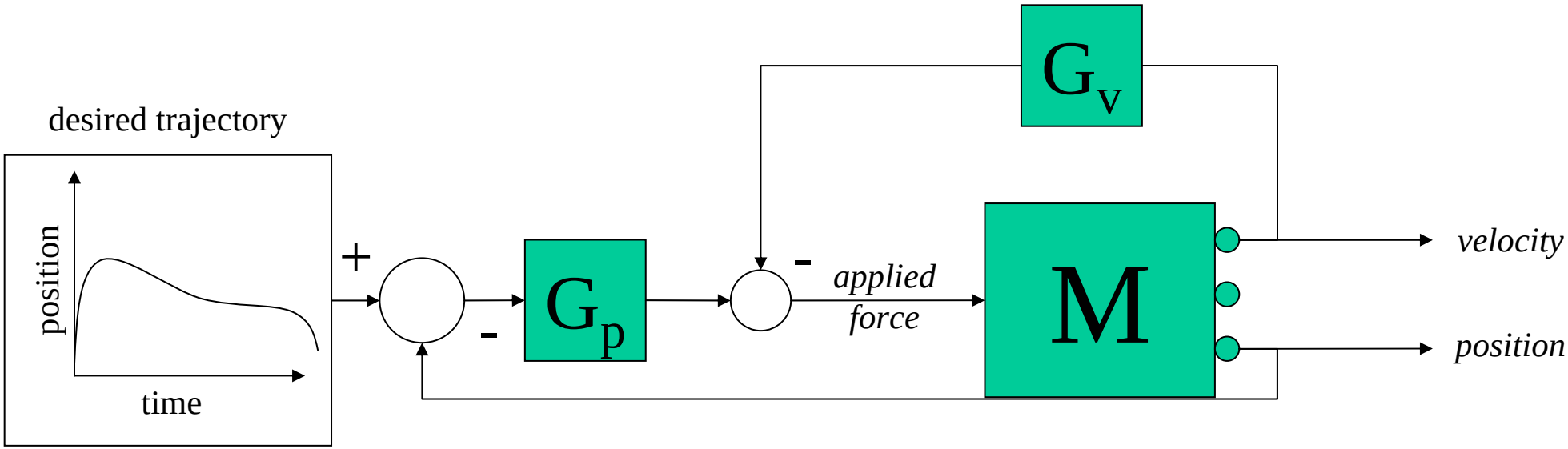


Position feedback requires velocity feedback to dissipate energy.

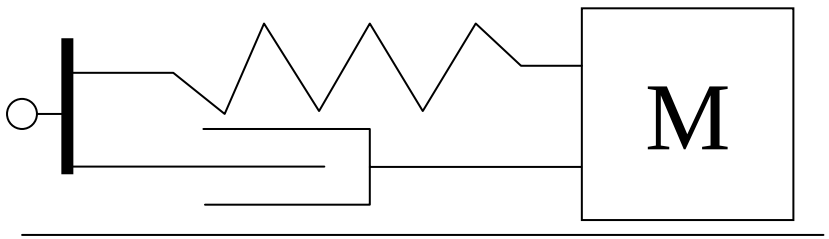


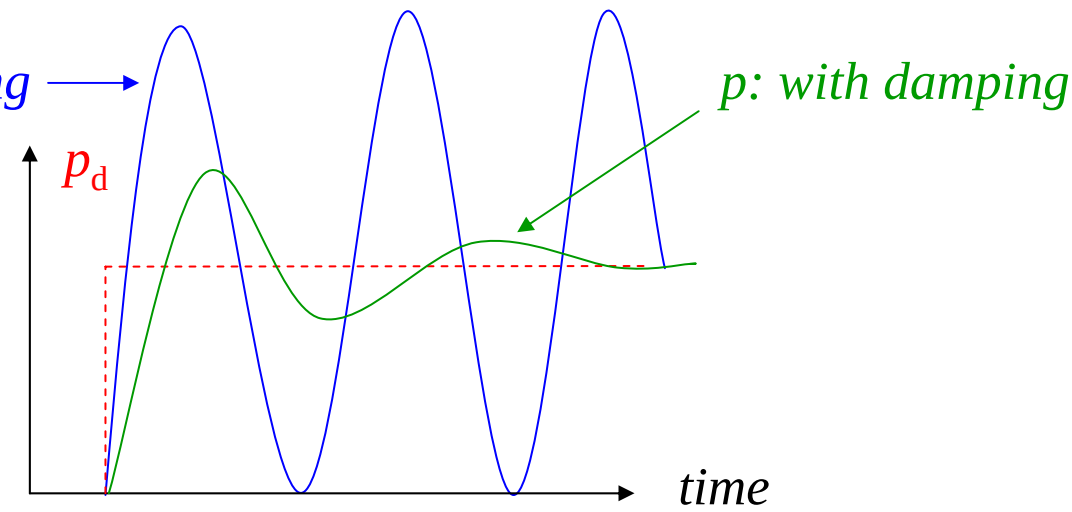
$$f = G_p\left(p_d - p\right) - G_v\left(\dot{p}\right)$$

Position feedback requires velocity feedback to dissipate energy.



$$f = k(l - l_0) - b\dot{l}$$

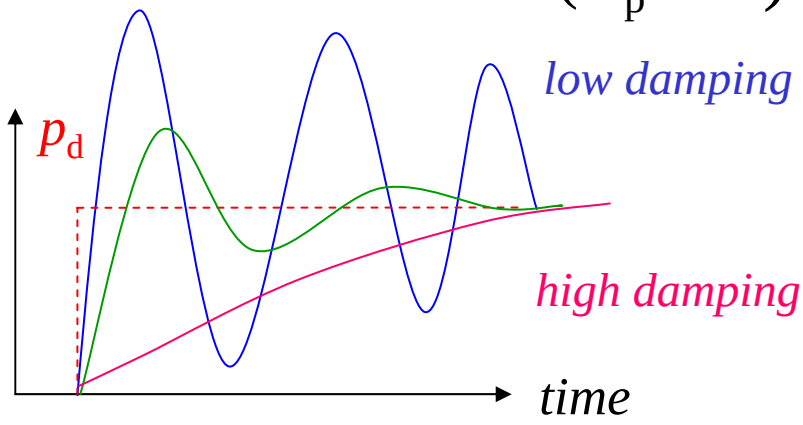




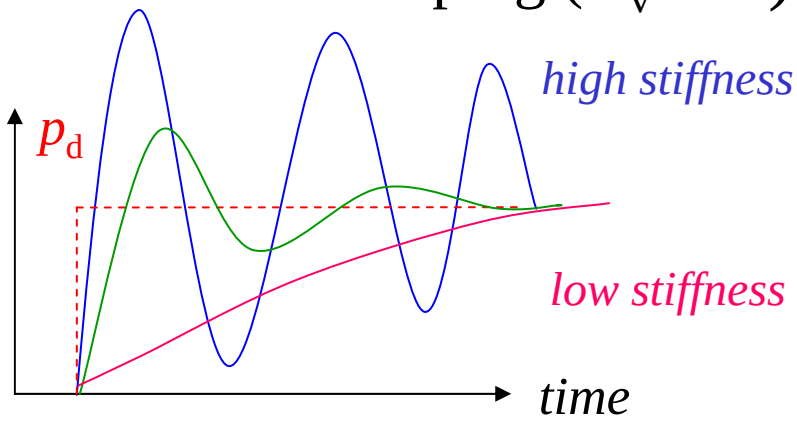
What are the effects of G_p and G_v?

(i.e. What are the effects of ***k*** and ***b***?)

for a constant stiffness (G_p or k)

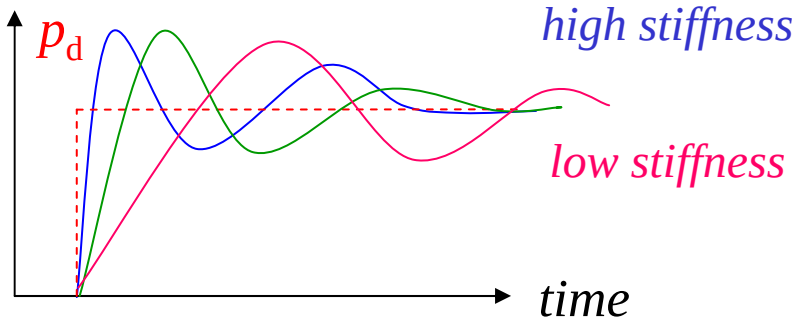


for a constant damping (G_v or b)

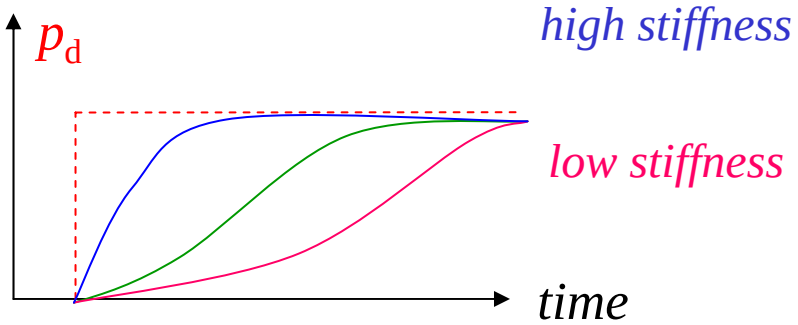


for a constant *damping ratio*: $\zeta = \frac{b}{2\sqrt{km}}$

underdamped ($\zeta < 1$)



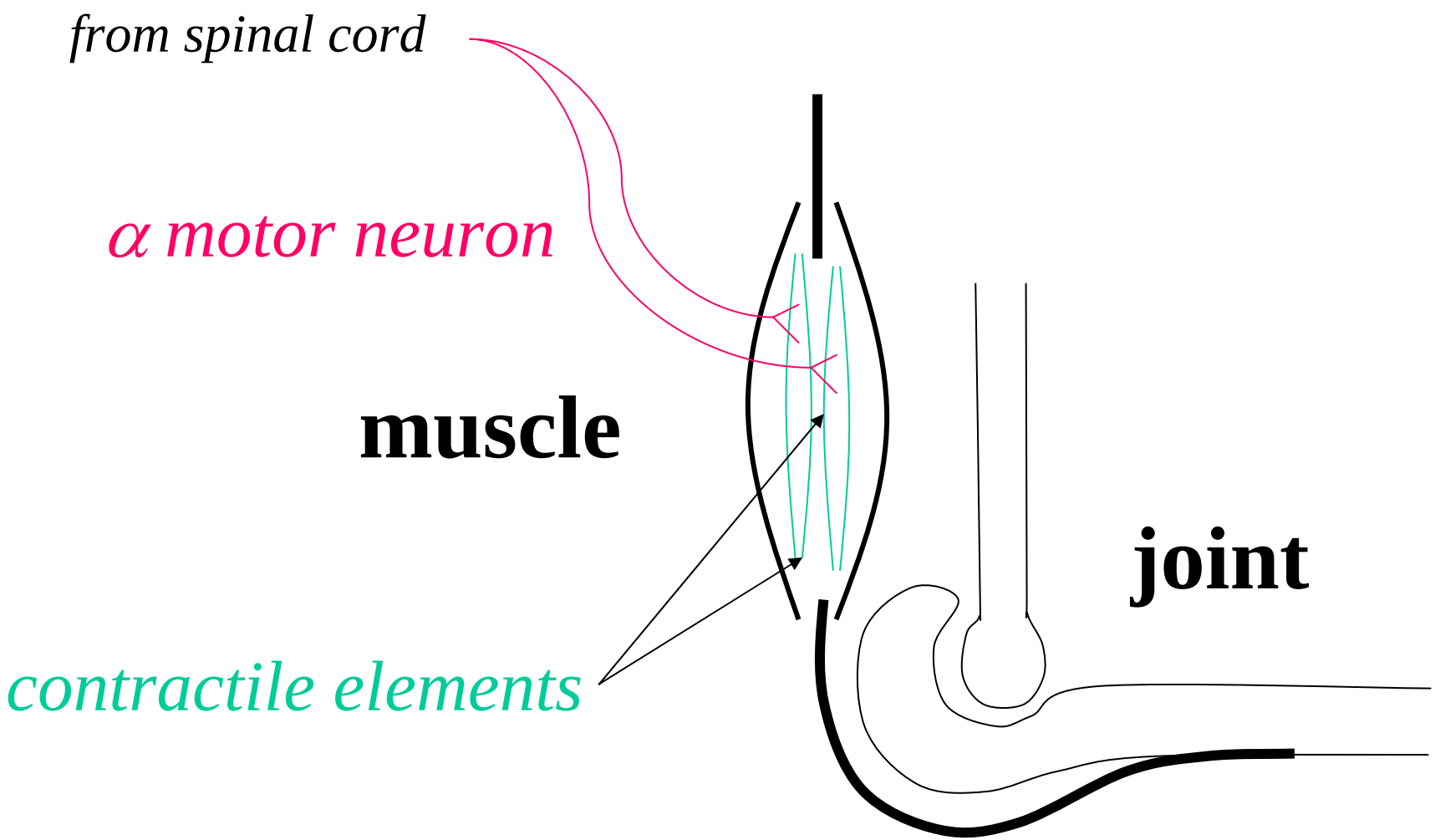
overdamped ($\zeta > 1$)



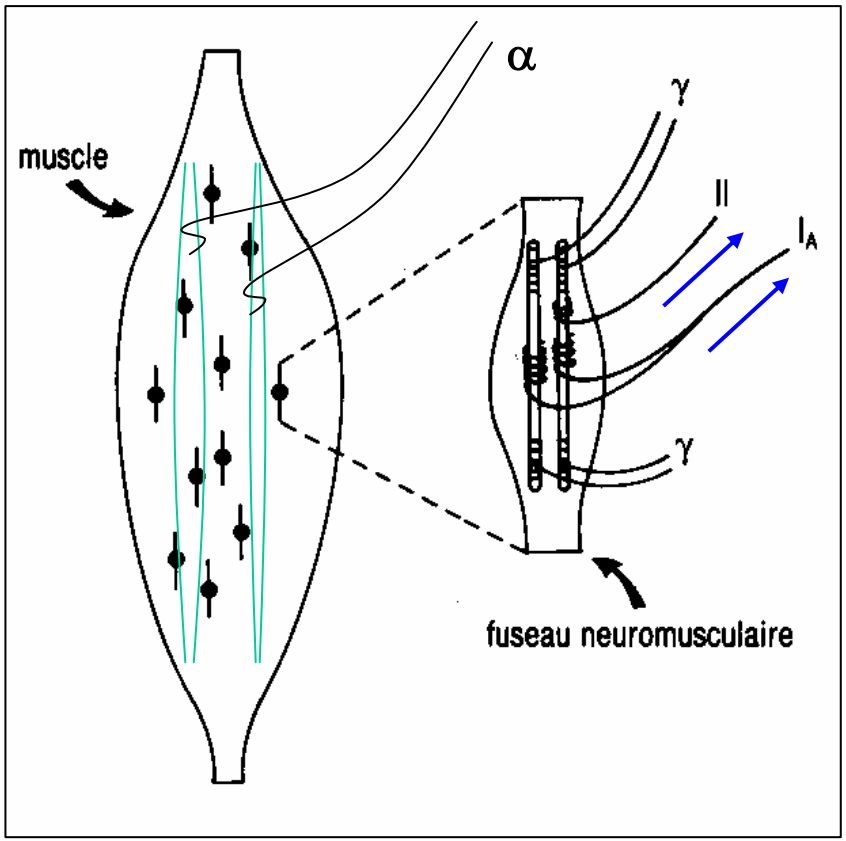
Feedback Control

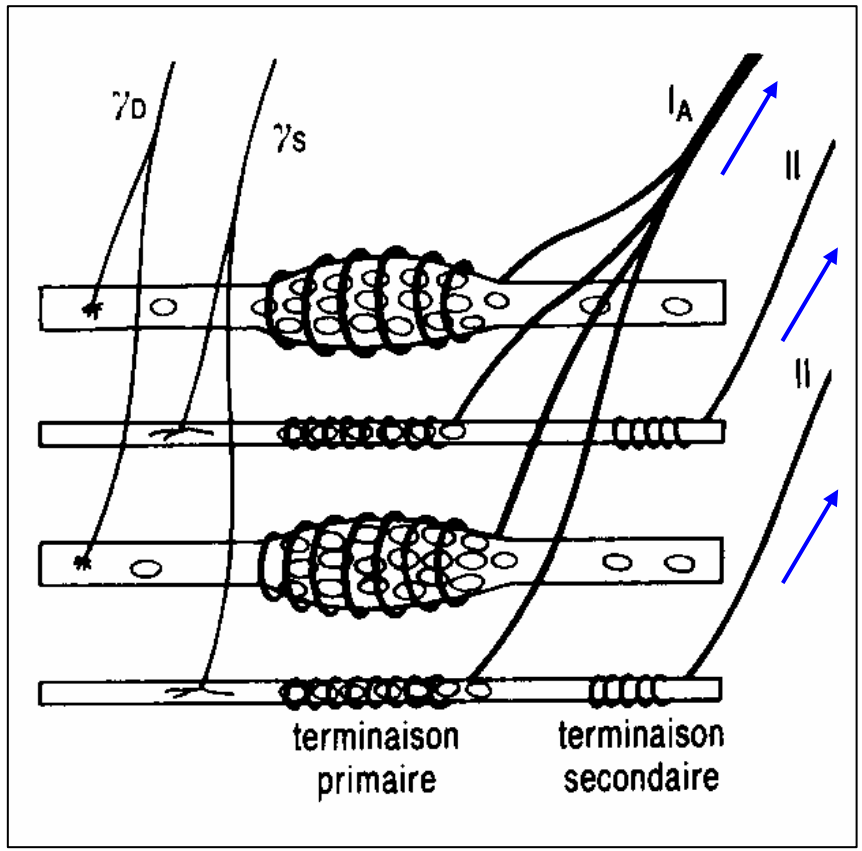
- Based on error signals between the desired trajectory and the measured position.
- No need to compute the inverse dynamics of the system you want to control.
- Performance depends on the feedback gains:
  - high stiffness $\Rightarrow$ fast performance
  - high damping $\Rightarrow$ low oscillations

Elements of the human motor system.



Sensory organs are embedded in muscles, in parallel with the contractile elements

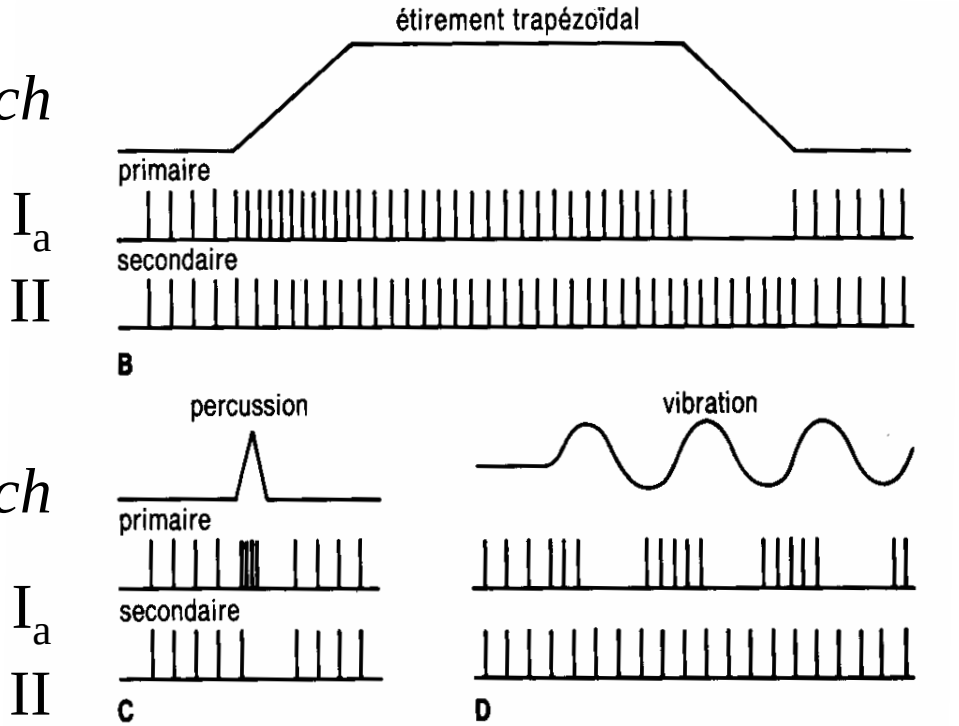




afferents: **I_a** and **II** fibers

E. Godaux et G. Cheron *Le Mouvement* (Medsi-McGraw-Hill, France).

Spindle organ afferents are sensitive to muscle stretch.



From: E. Godaux et G. Cheron *Le Mouvement* (Medsi-McGraw-Hill, France).

$I_a \propto$ static length

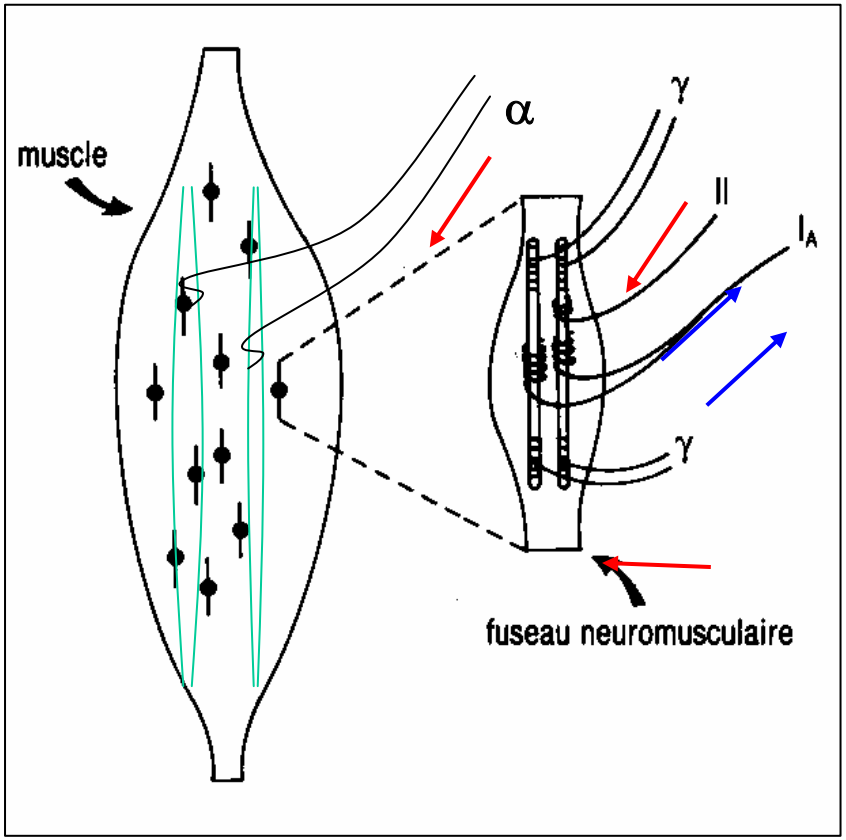
$I_a \propto$ lengthening velocity

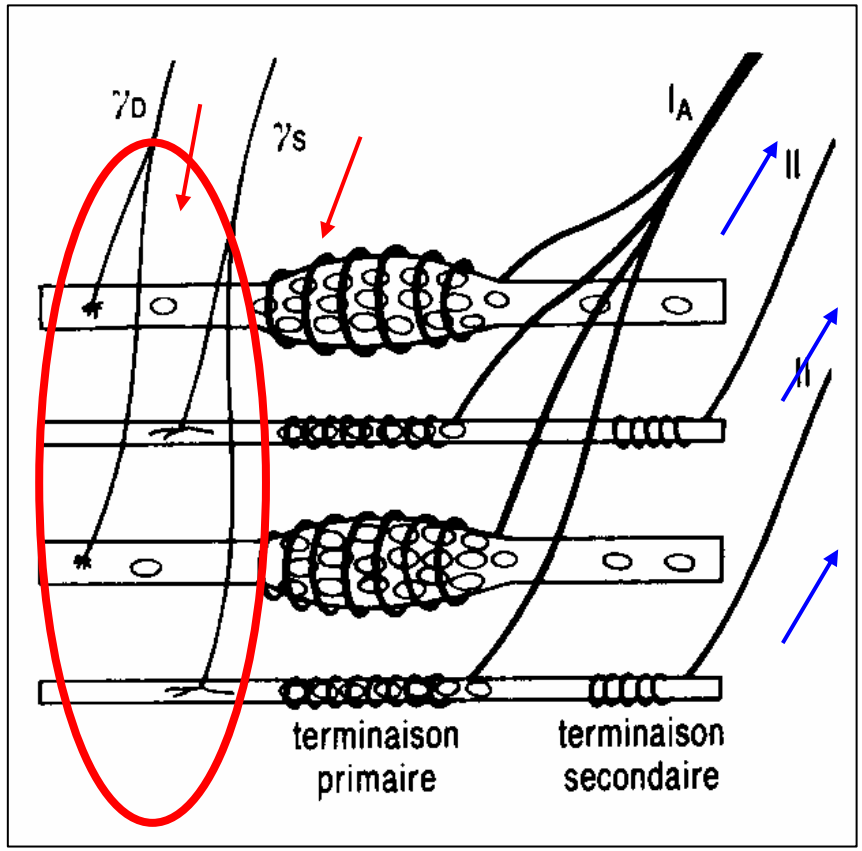
II $\propto$ static length

more or less!!!

Spindle fibers carry information about muscle length and lengthening velocity.

Spindle organs are equipped with contractile elements of their own.





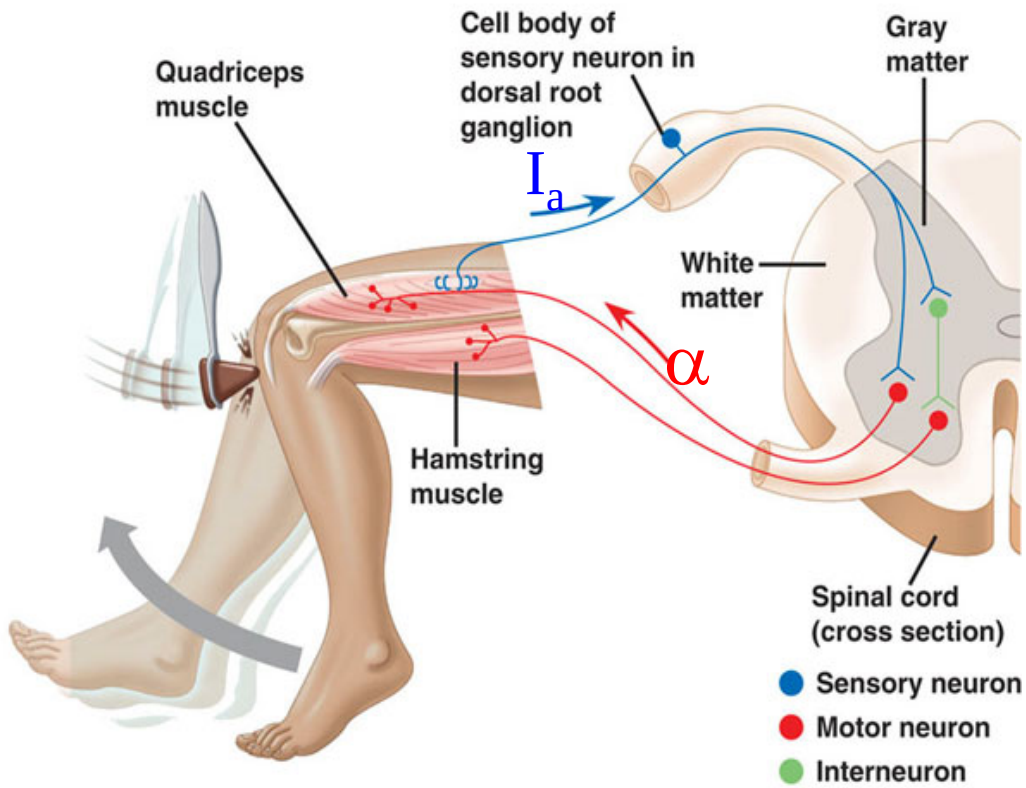
afferents: **I_a** and **II** fibers

efferents: α *and* γ motor neurons

Activating γ will evoke activity in I_a and II afferent fibers if there is no concomitant shortening of the muscle.

Example

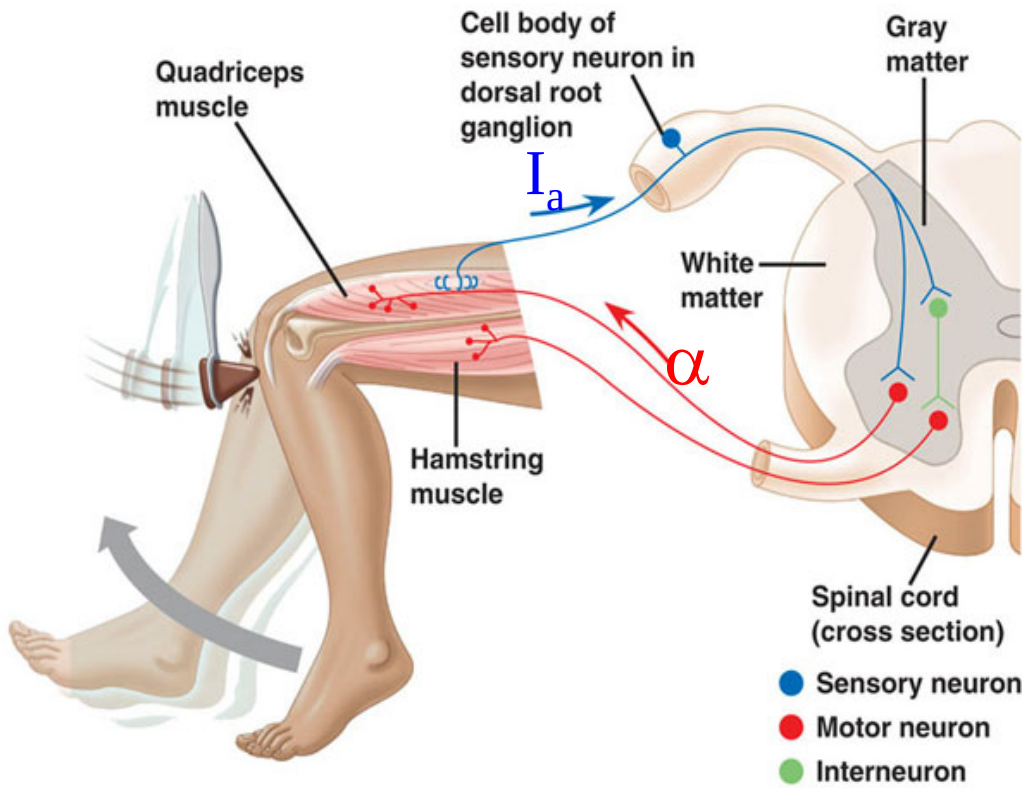
The ubiquitous **knee jerk stretch reflex**…



Example

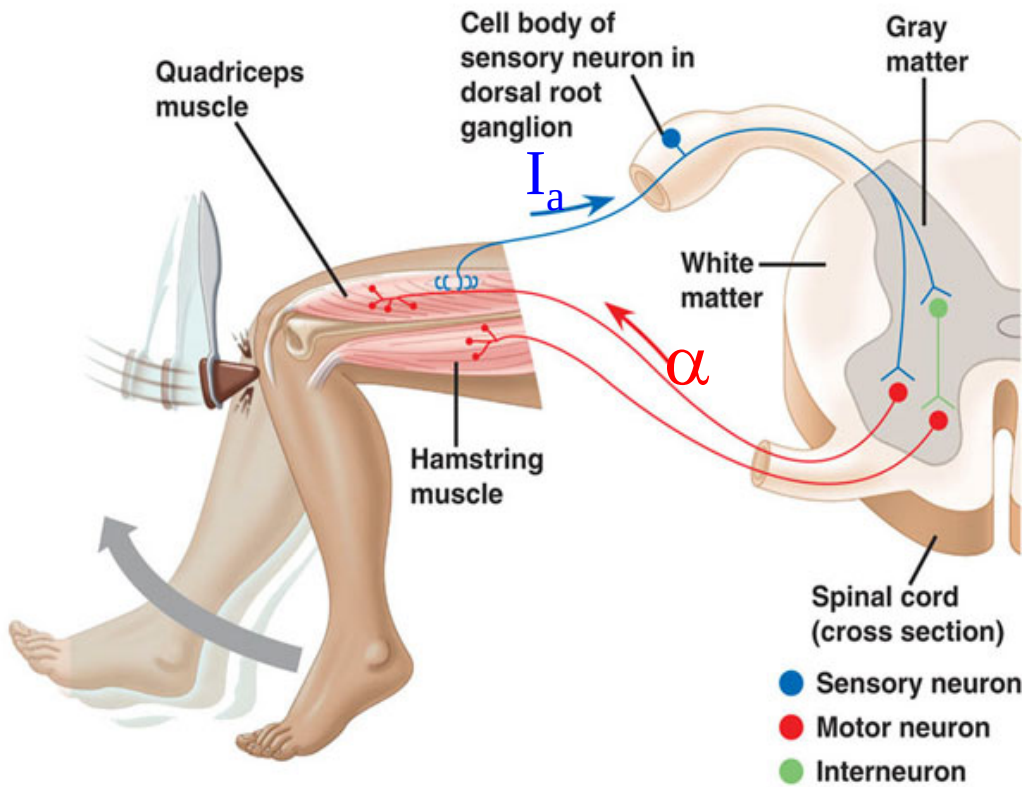
The ubiquitous **knee jerk stretch reflex**…

<u>Fundamental question</u>: What happens when multiple knee jerk reflexes occur **simultaneously?**

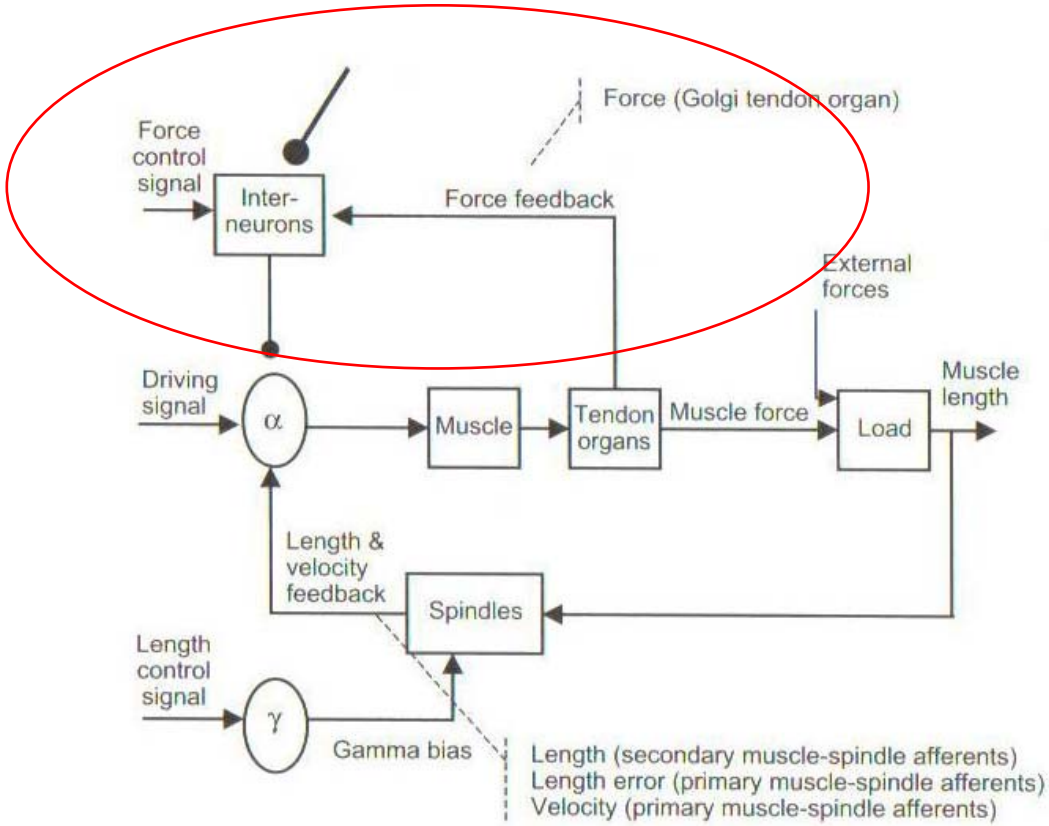


Example

The ubiquitous **knee jerk stretch reflex**…



What about Golgi tendon organs?



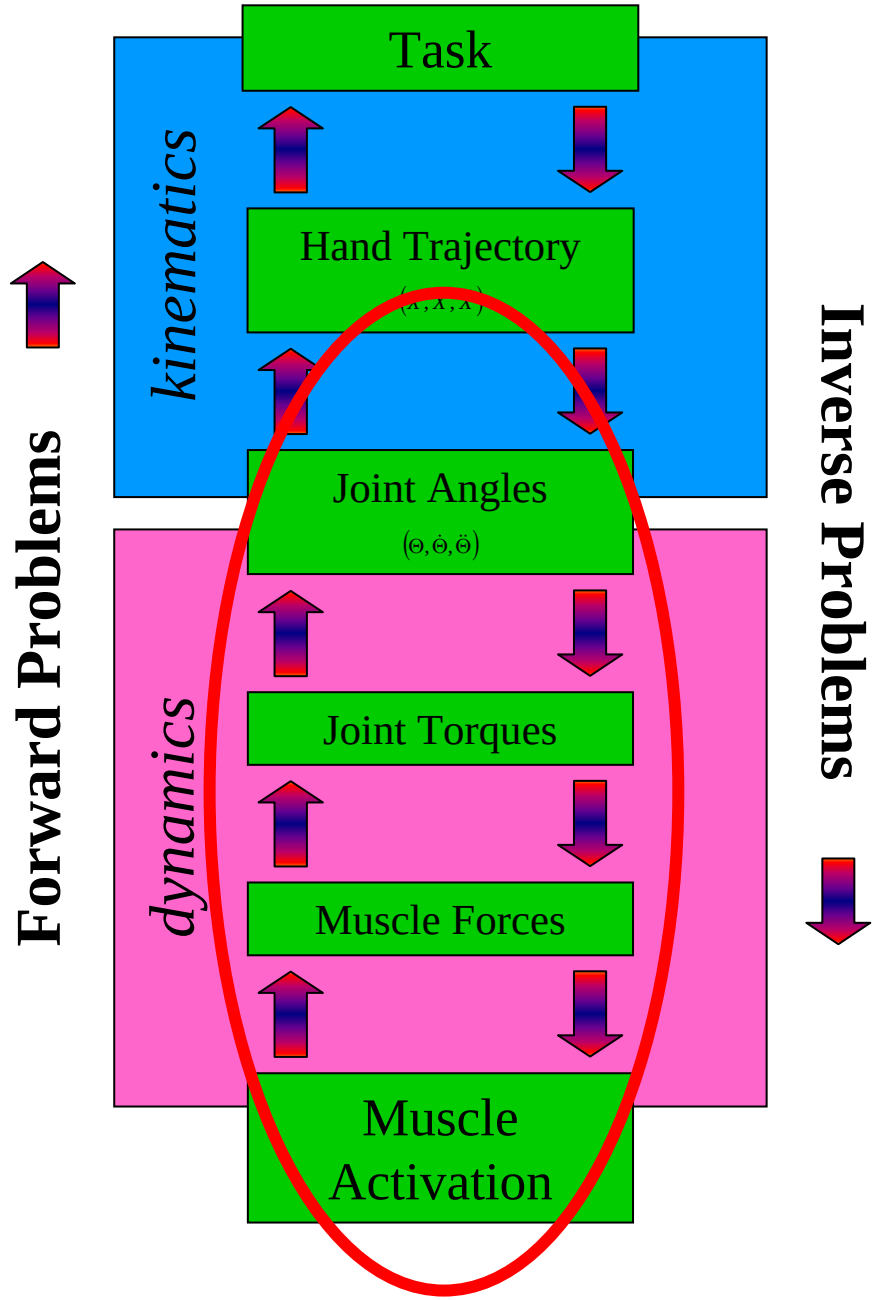
Motor System Physiology (just the minimal basics!)

- Muscles are made up of active contractile elements (extrafusal fibers) and sensory organs (intrafusal fibers).
- Efferent α motor neurons innervate the extrafusal fibers.
- Afferent type $\mathbf{I_a}$ and type **II** nerve fibers emanating from the intrafusal fibers (muscle spindles) **respond to muscle stretch** (**static length and velocity**)
- Efferent γ **motor neurons** innervate the contractile elements of the muscle spindles, allowing central **modulation of the spindle output.**
- Golgi tendon organs ($\mathbf{I_b}$ afferents) act as **force transducers**

Lecture Outline

How does the human nervous system generate a movement of the hand?

- Basic Control Theory
  Engineering for Neuroscientists
  - ***Feedforward and Feedback Control***
- Elements of the human motor system
  Neurophysiology for Engineers
  - ***Actuators, Sensors, Circuits***
- Models of Human Motor Control
  - ***Theories, History, Experimental Evidence***
- Consequences for Neuro-Robotics
  - Brain-machine interfaces

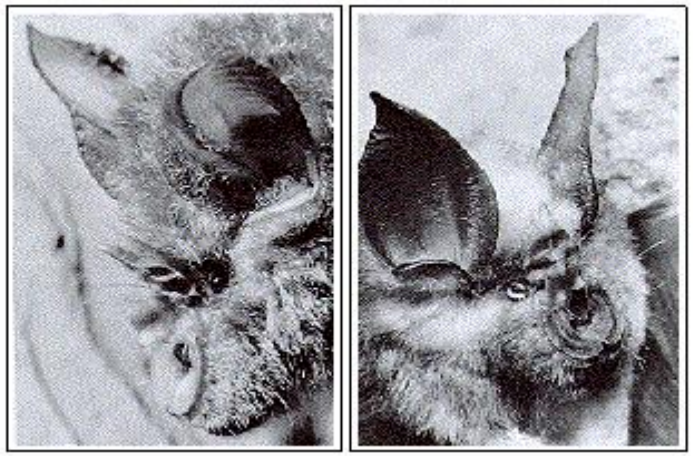


Intermission

The physics matter!

Q. How do bats survive in the world?

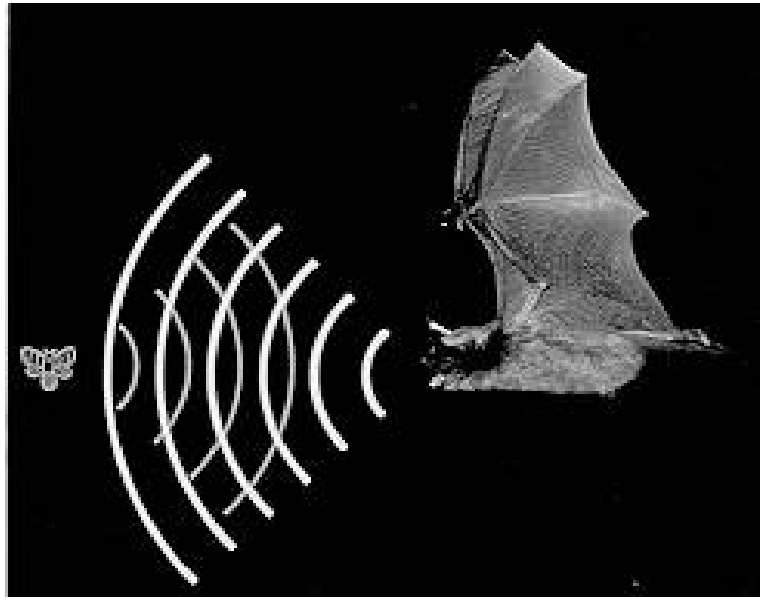
- CF (constant frequency) bat



CF-bat *Rhinolophus Ferrumequinum*

- FM (frequency modulation) bat

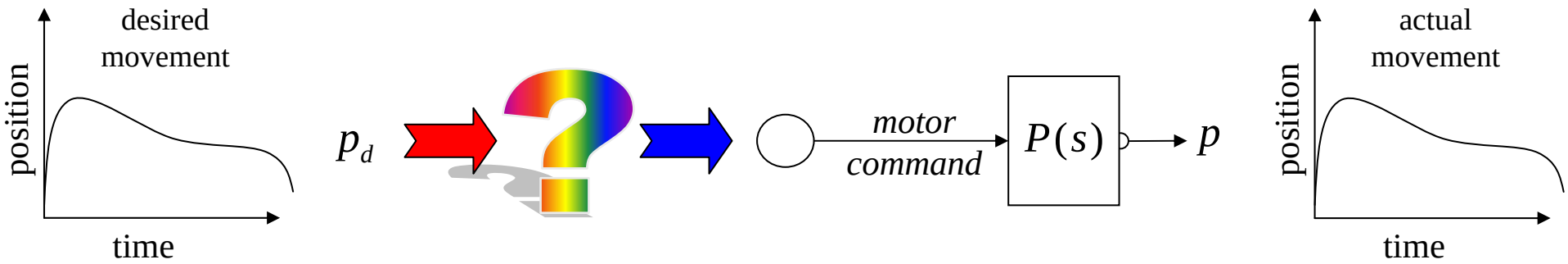
A. Exploiting the physics!



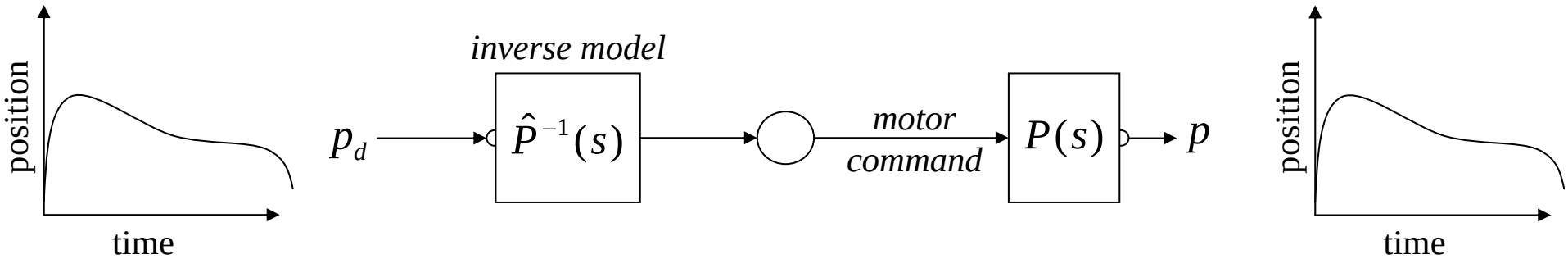
Doppler-shift $\delta f = 2f\frac{v}{c}\cos\alpha.$

where ***v*** and ***α are*** the relative velocity and angle between bat and prey, ***c*** the speed of sound (~345 m/s), and ***f*** the emitted frequency.

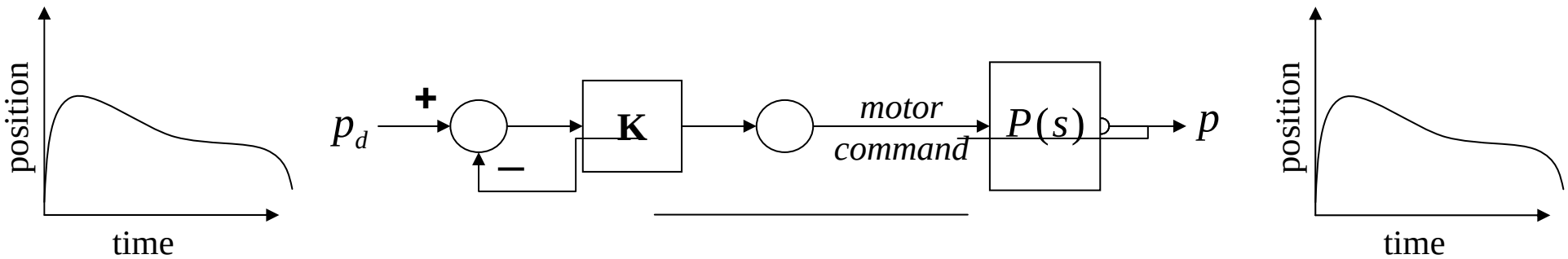
Feedforward versus Feedback Control



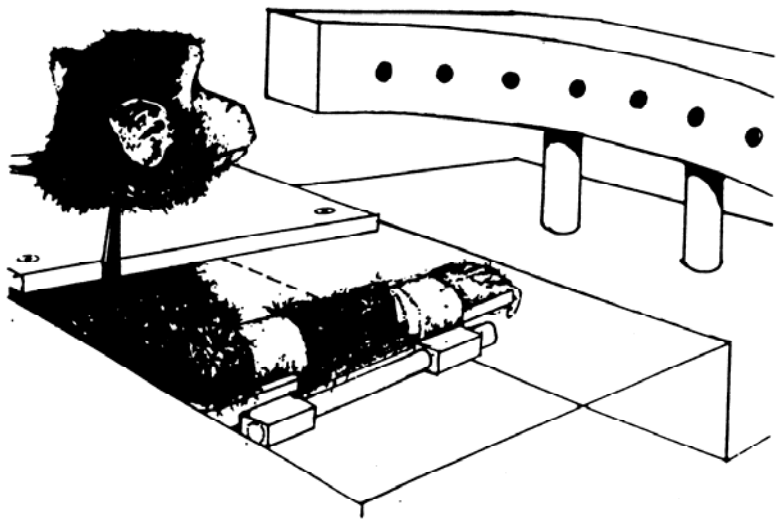
Feedforward Control: compute control based on knowledge of physics



Feedback Control: generate commands based on error signals



Are targeted arm movements controlled in a *feedfoward* or *feedback* manner?

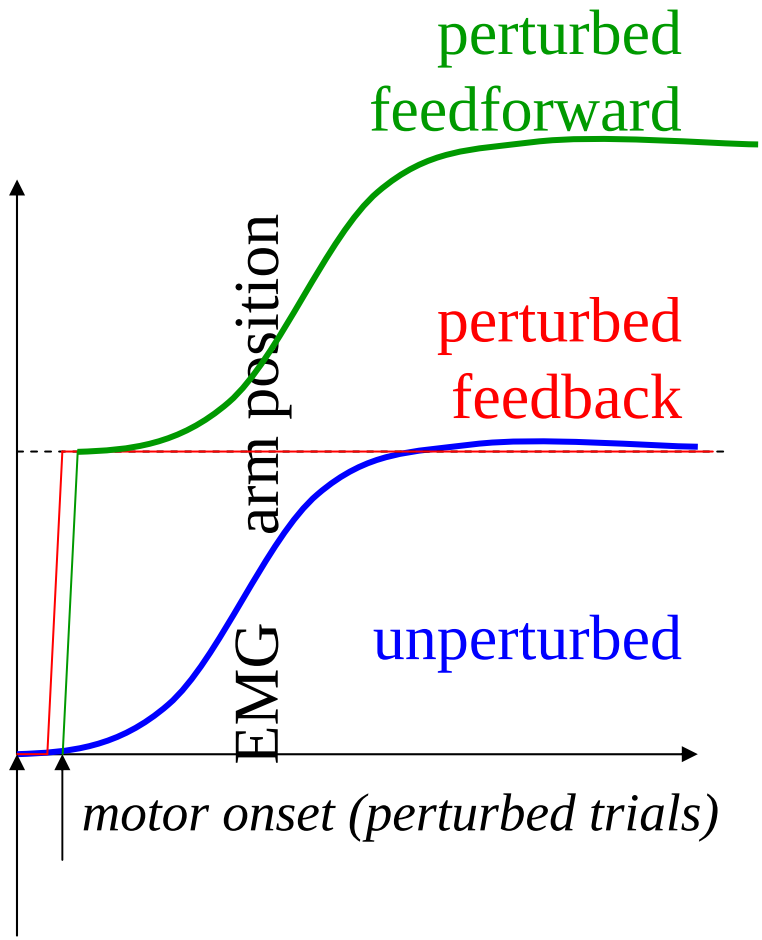


A. Polit and E. Bizzi *J Neurophysiol.* 1979 42 :183-194.

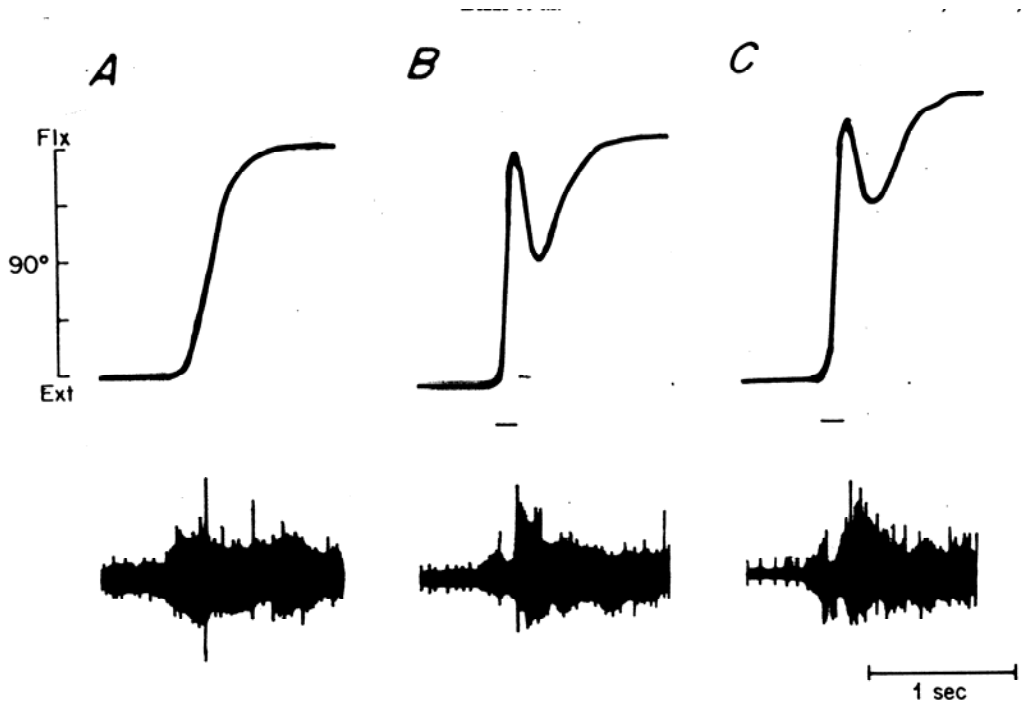
- Train a monkey to point to an illuminate target, without vision of the arm.
- On random trials, suddenly move the monkeys arm to the target position, just before the monkey starts to move the arm itself.

Assuming that the monkey is unaware that the arm has already been moved to the target, what will be the movement if feedforward or feedback control is used?

Predictions



Experimental Results

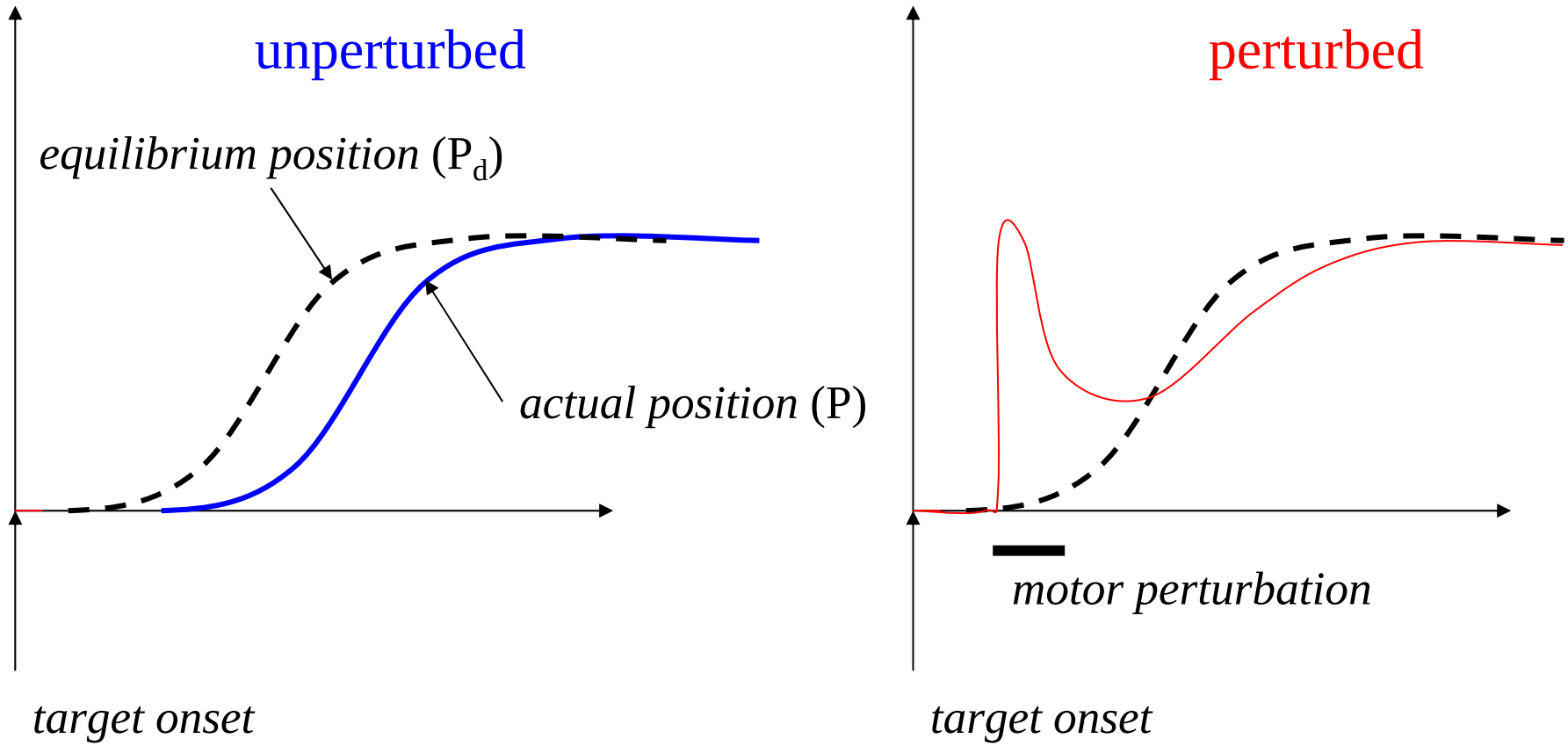


control
no perturbation

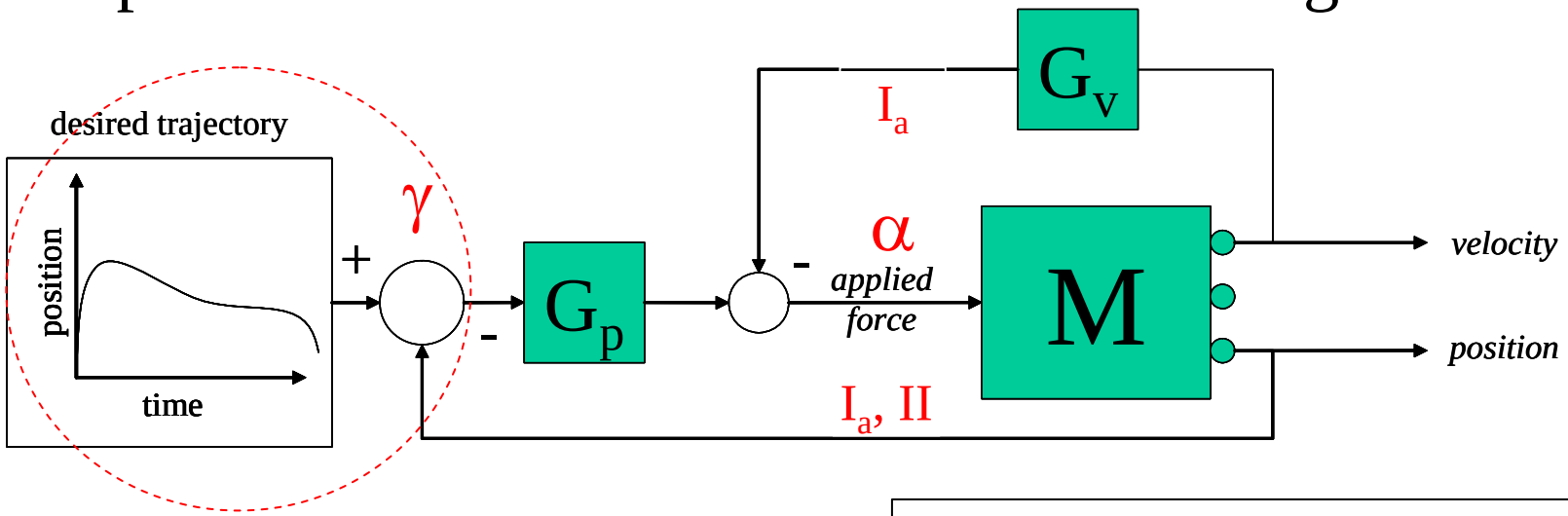
test
arm moved to target position at start of trial

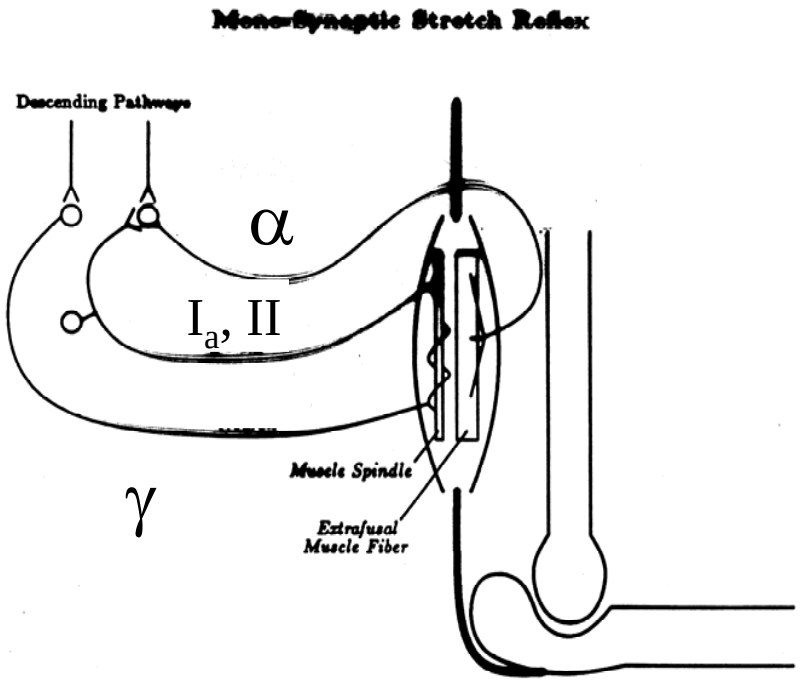
A. Polit and E. Bizzi *J Neurophysiol.* 1979 42 :183-194.

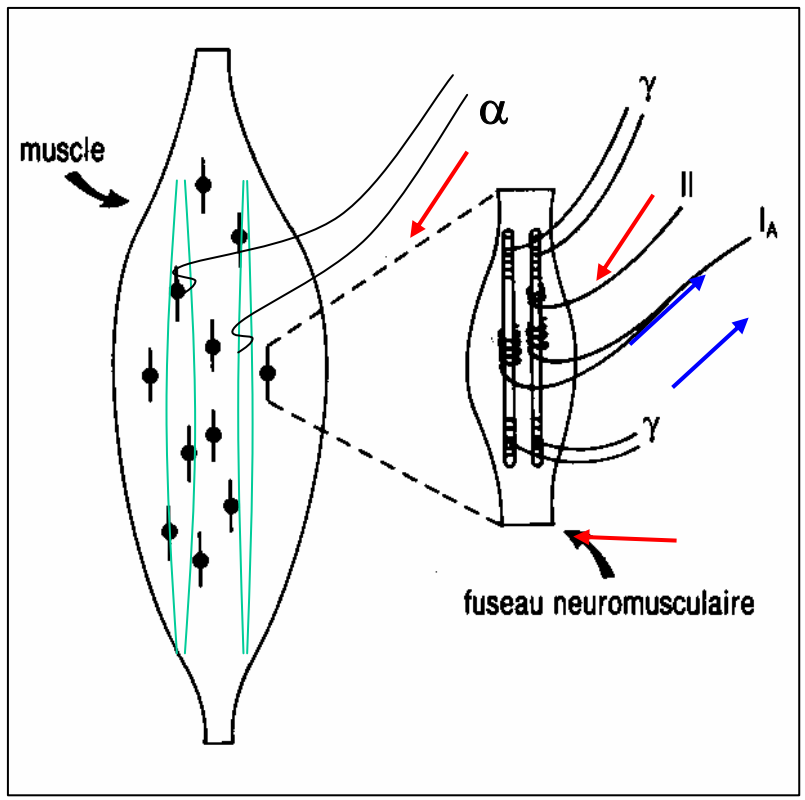
The motor command appears to be a smooth transition of desired positions.



How to implement a **feedback servo** with the biological hardware?

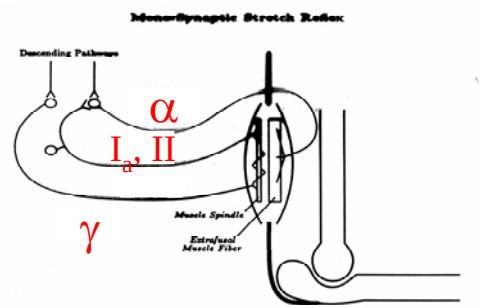


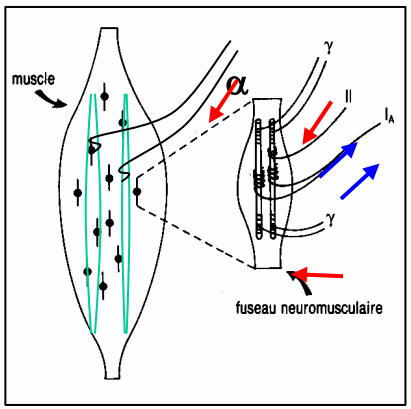




Merton's (1953) reflex servo control hypothesis

- γ specifies the desired trajectory
- muscle spindles compare desired and actual length
- I_a and II afferents activate α proportional to the difference





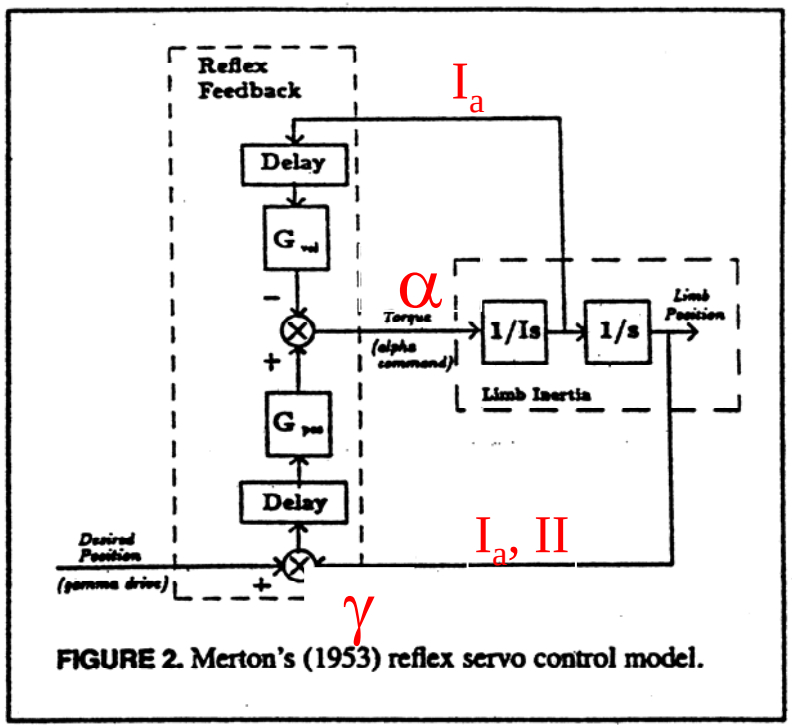


FIGURE 2. Merton's (1953) reflex servo control model.

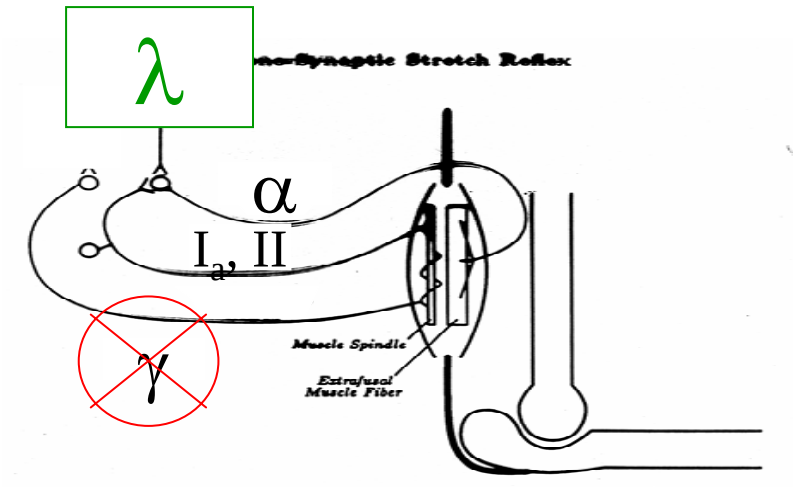
From: J. McIntyre and E. Bizzi *J. Motor Behav.* 1993.

Was Merton correct?

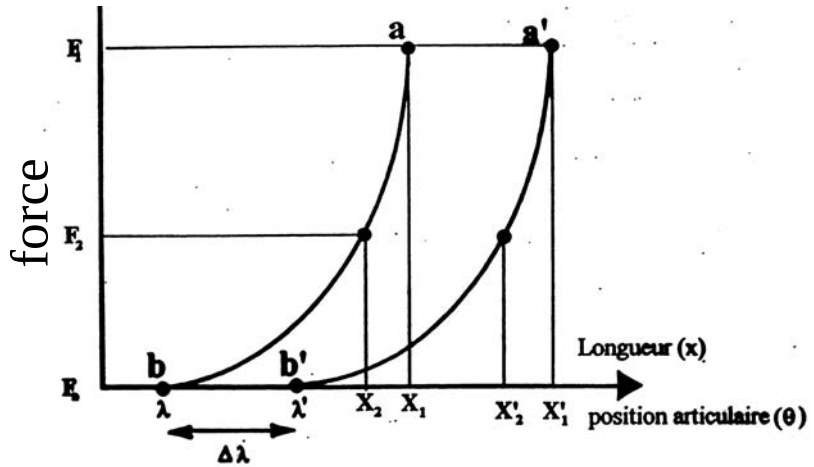
- No! α and γ are activated simultaneously, contrary to predictions

Feldman's Equilibrium Point Hypothesis

CNS controls movement by specifying the trajectory of a moving equilibrium point

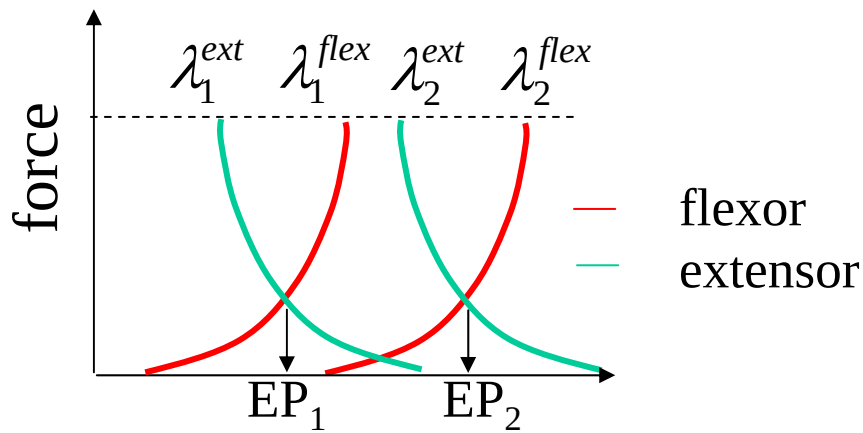


stretch reflex



angular position

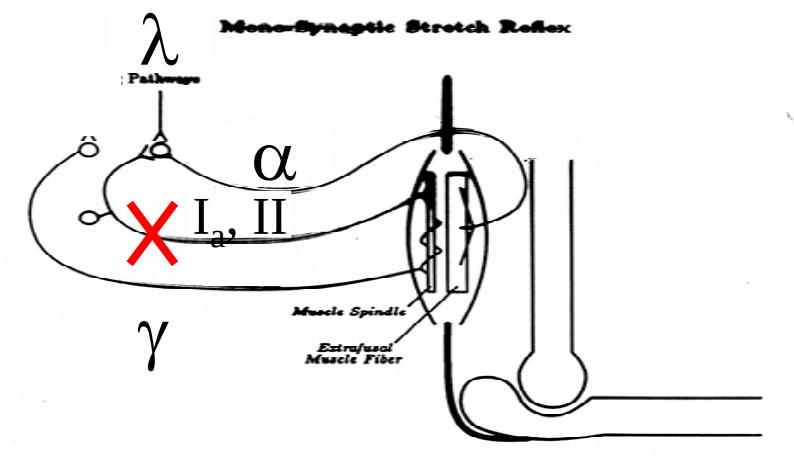
- Central command λ sets the threshold of the stretch reflex
- The desired position (equilibrium position) is determined by setting λ's for agonist/antagonist pairs.

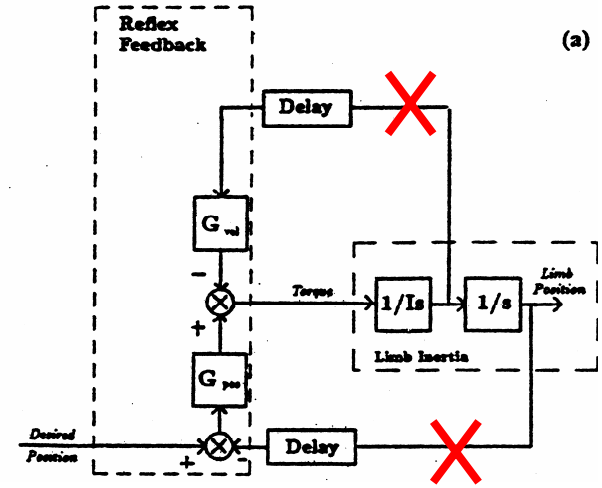


angular position

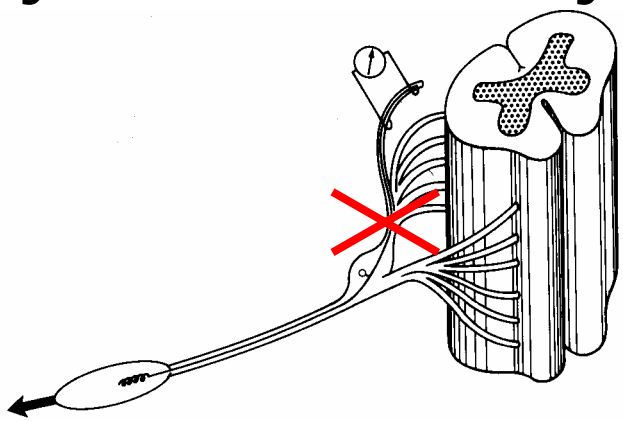
See Feldman, A. *J. Mot. Behav.* 1986.

What happens if feedback is interrupted?

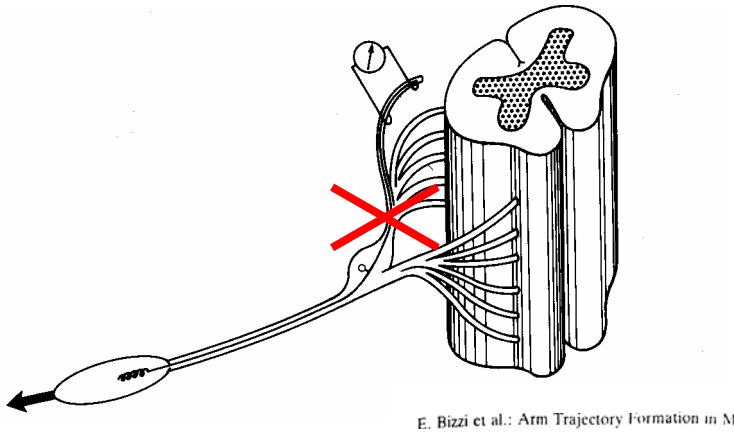




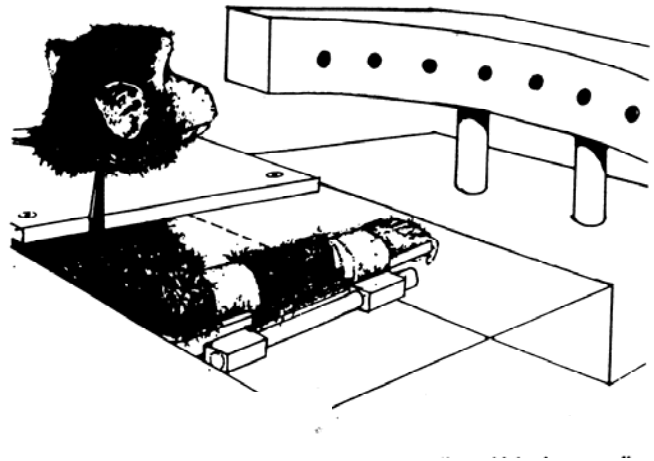
How can you cut sensory feedback?

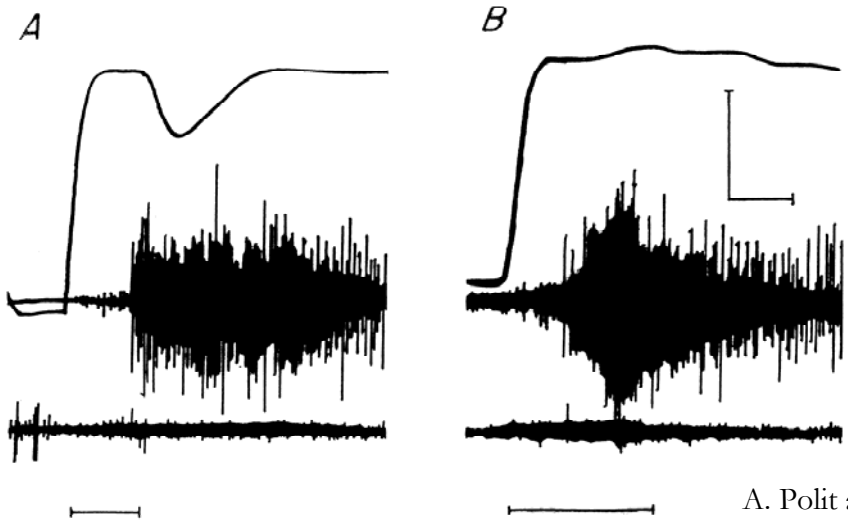


What happens if feedback is interrupted?



E. Bizzi et al.: Arm Trajectory Formation in Monkeys

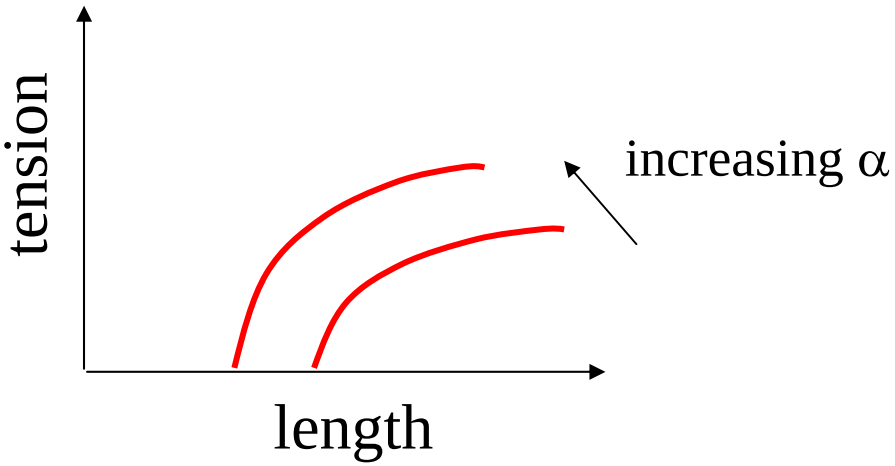


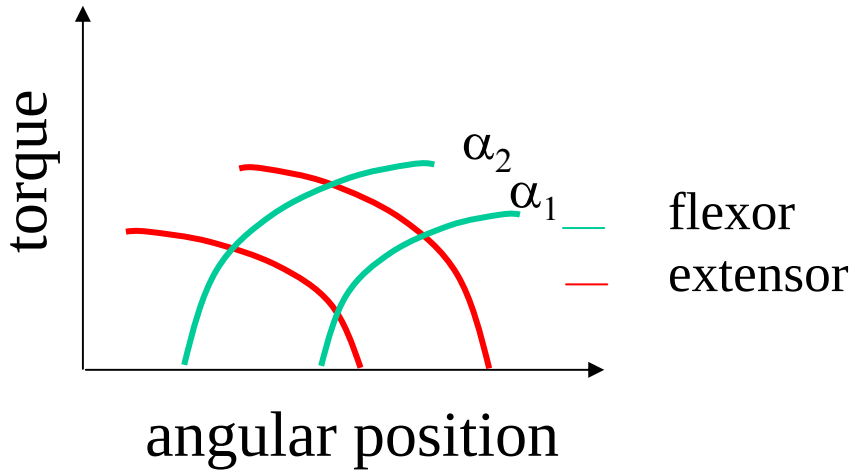


A. Polit and E. Bizzi *J Neurophysiol.* 1979 42 :183-194.

The monkeys were still able to achieve the target position!

Bizzi's Equilibrium Point Hypothesis





- Muscles present *spring-like* properties.
- Increasing α decreases the rest-length.
- Equilibrium positions can be specified by a activation in agonist/antagonist pairs.
- Servo control is achieved through muscle mechanical (spring-like) properties.

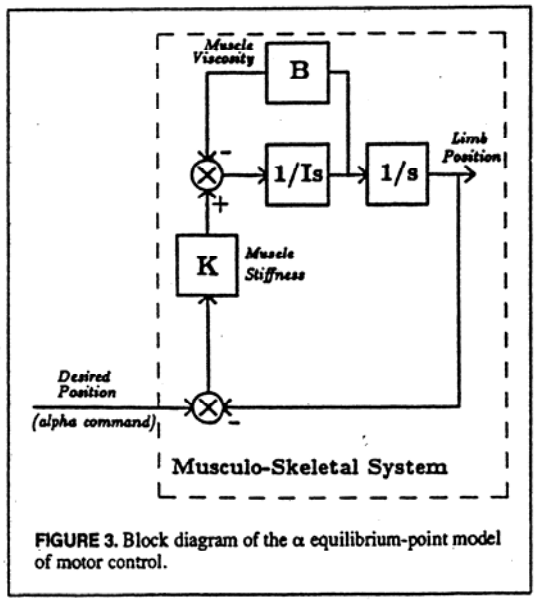
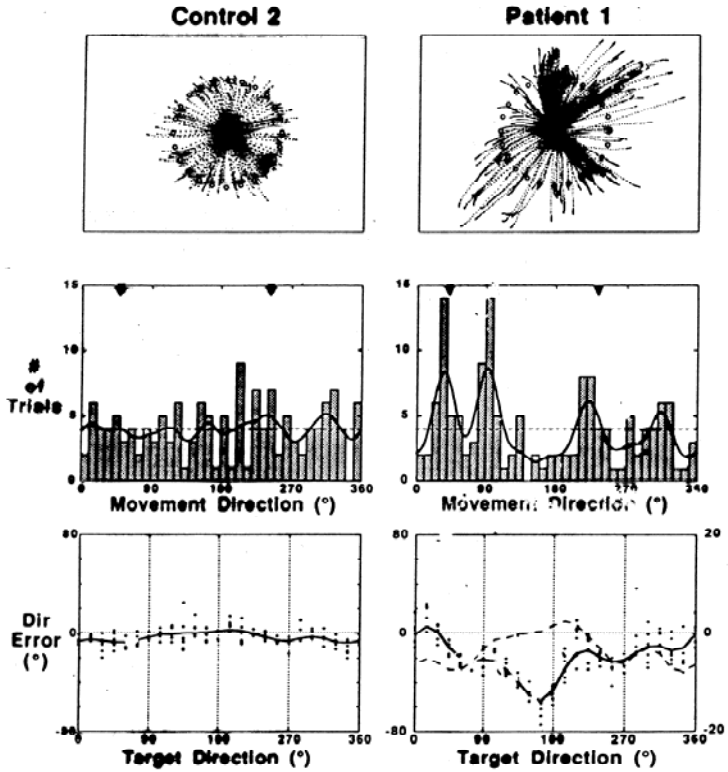


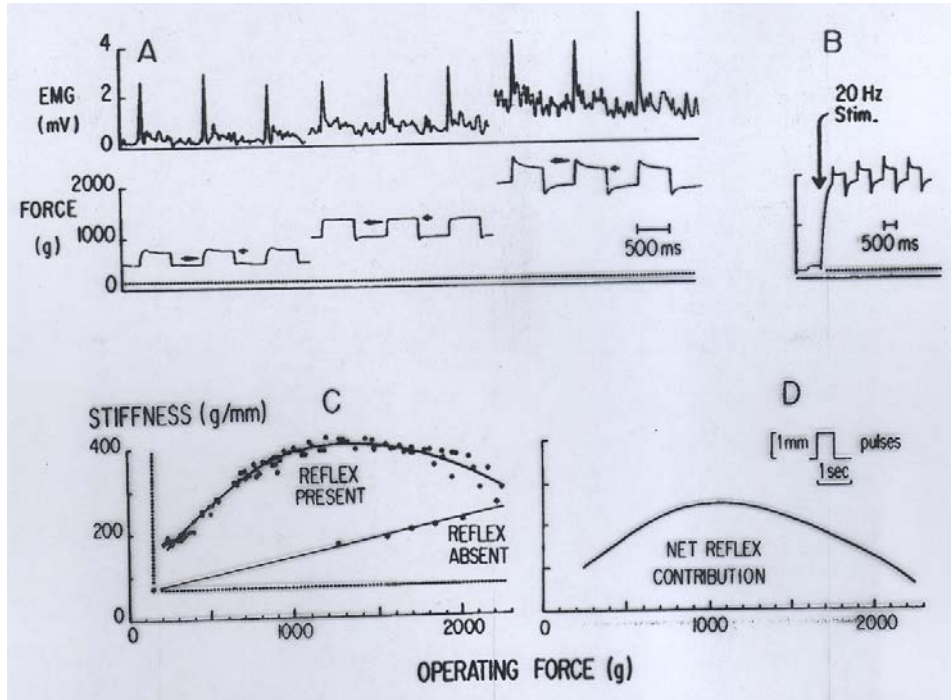
FIGURE 3. Block diagram of the α equilibrium-point model of motor control.

From: J. McIntyre and E. Bizzi *J. Motor Behav.* 1993.

Do reflexes serve a purpose?
Of course!



J. Gordon, MF Ghilardi and C Ghez *J. Neurophysiol.* 1995.



JA Hoffer and S Andreassen *J. Neurophysiol.* 1981.

Reflexes are essential to the accurate control of movement.

Reflexes modulate effective muscle stiffness.

A more accurate model includes both **muscle properties and reflexes** to provide feedback control of movement.

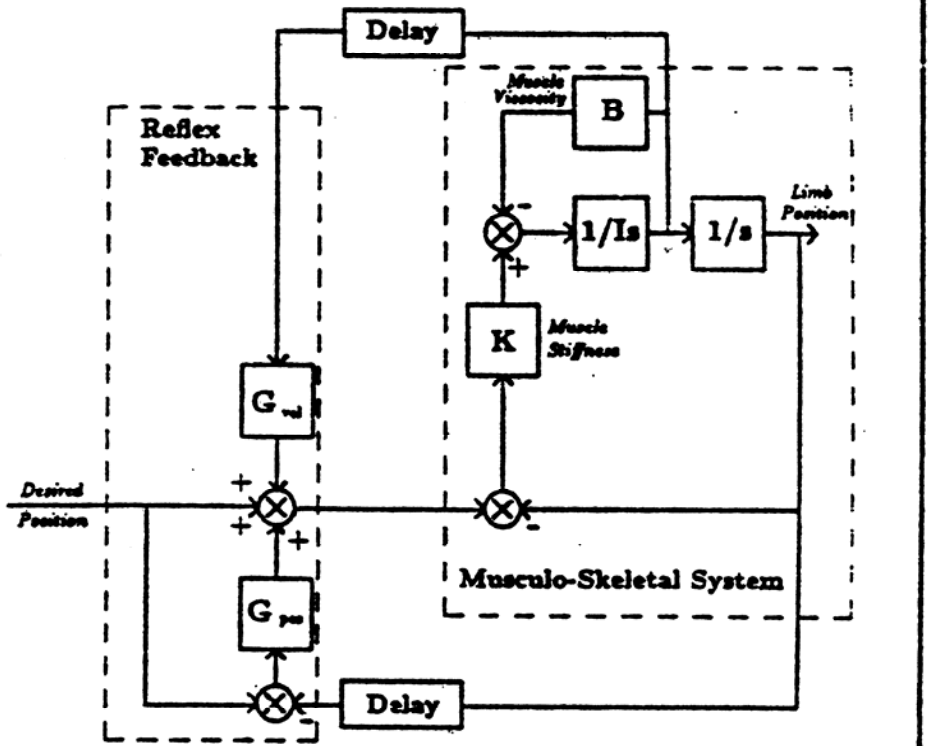


FIGURE 5. Consistent formulation of the equilibrium-point model. The model is consistent with alpha-gamma coactivation, deafferented monkey experiments, and reflex function.

From: J. McIntyre and E. Bizzi *J. Motor Behav.* 1993.

Summary

- Basic control theory
- Basic sensorimotor physiology
- A fundamental question:

Feedforward or feedback control?

- Evidence for feedback control of biological movement
- Plausible biological mechanisms for implementing feedback-based motor control.
- Passive mechanical properties of muscles are important!

Next week

- Is it all done by feedback?
  - What is the evidence for model-based, feedforward control?
- Impedance control
  - How and why are feedback gains modulated?
- Internal models
- Discussion
  - What are the consequences for neuro-robotic systems.