When and how do humans modulate impedance?

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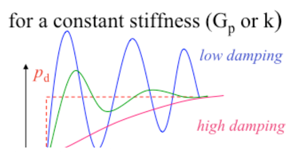
Joe McIntyre

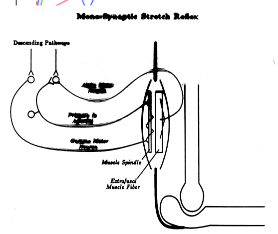
- Part I: Introduction to Impedance

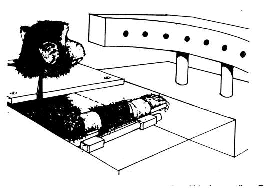
  Humans and otherwise (a refresher course)

  – Fundamental Concepts
    - bandwidth, damping ratio
    - feedforward / feedback
    - biological systems
      – muscle properties, co-contraction, reflex loops

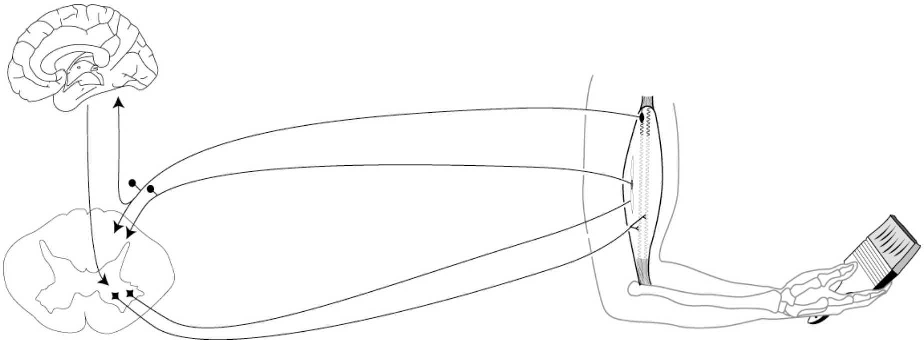
  – Historical Perspectives
    - early studies of human stiffness
      - trajectory control
      - internal models
      - stiffness modulation





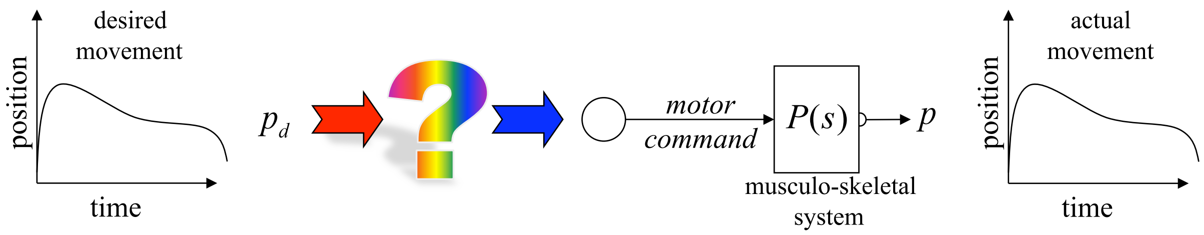


Human Motor Control

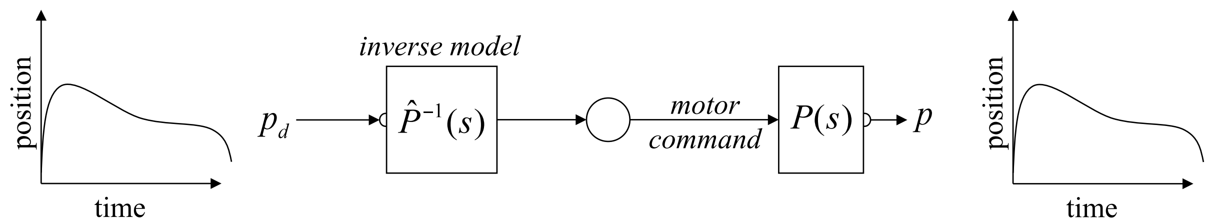


How does the brain activate muscles in order to generate a desired movement?

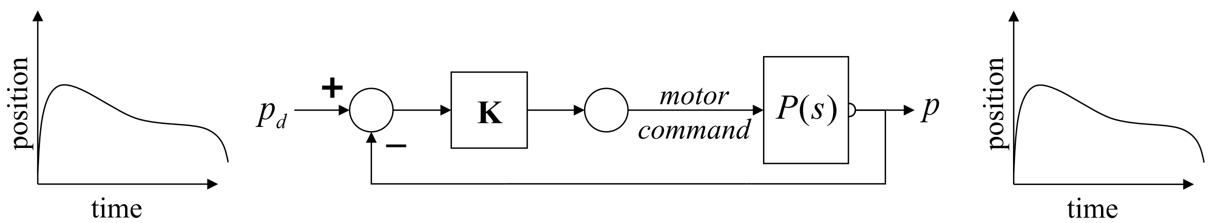
Feedforward versus Feedback Control



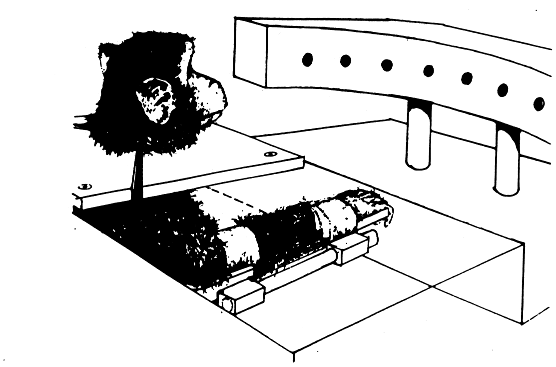
Feedforward Control: compute control based on knowledge of physics



Feedback Control: generate commands based on error signals



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

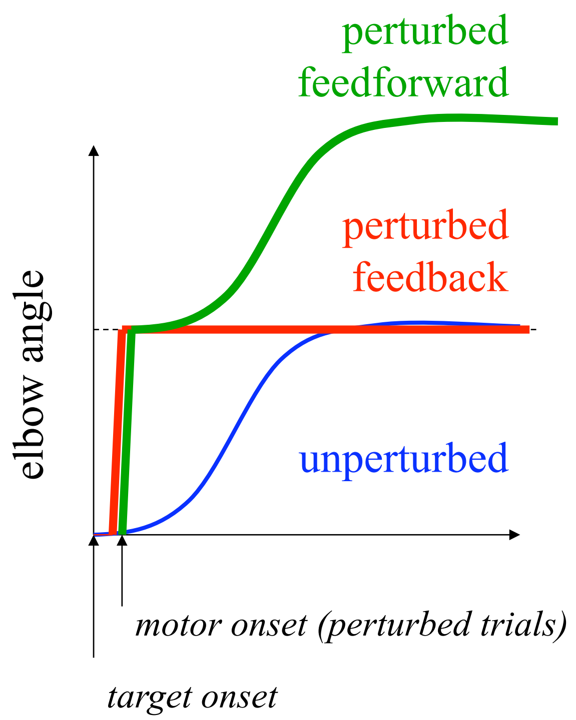


A. Polit and E. Bizzi *J Neurophysiol.* 1979 42 :183-194.

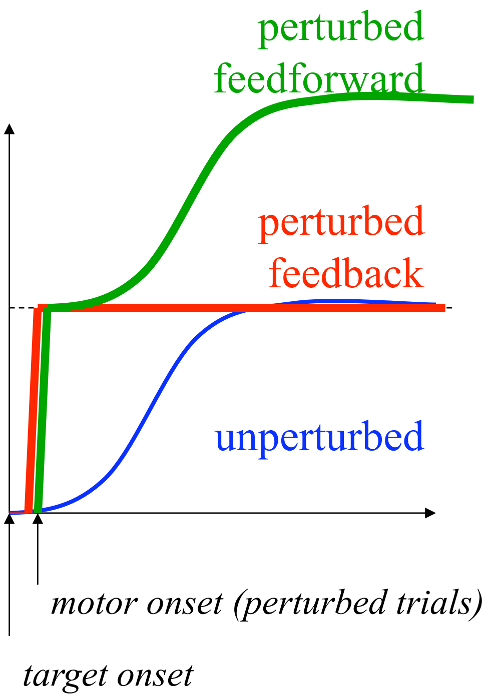
- Train a monkey to point to an illuminate target, without vision of the arm.
- On random trials, suddenly move the monkeys arm to the target position, just before the monkey starts to move the arm itself.

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

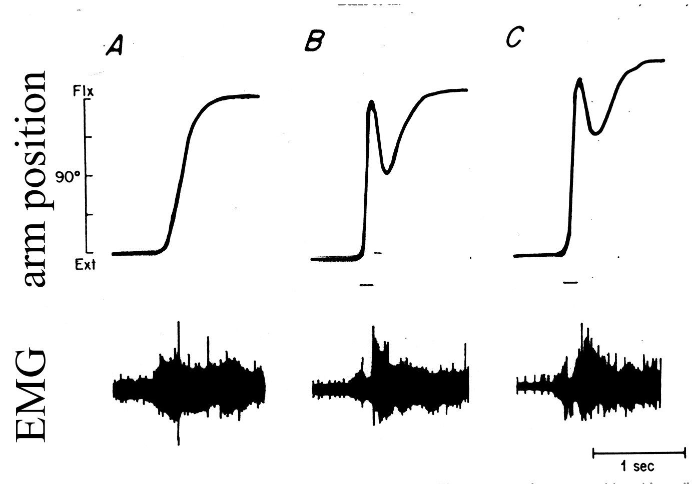
Predictions



Predictions



Experimental Results

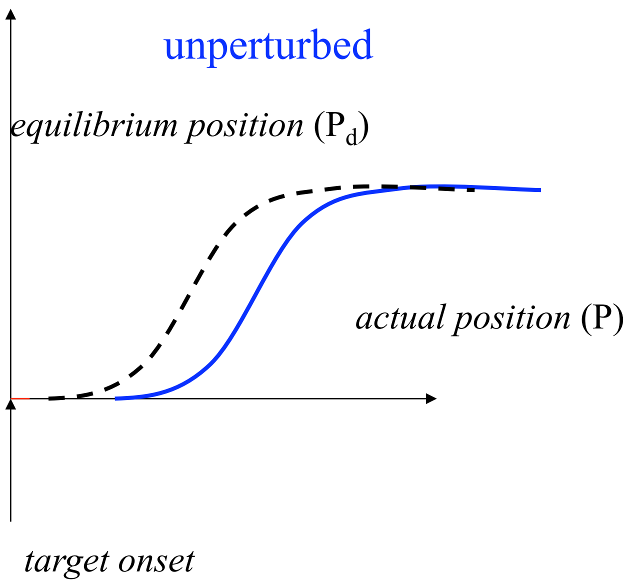


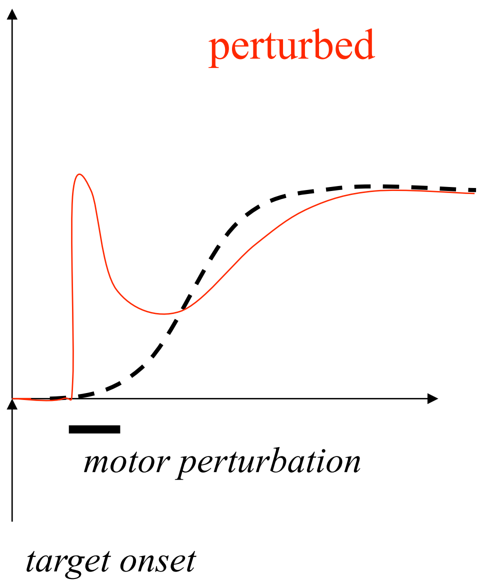
control
no perturbation

test
arm moved to target position at start of trial

Bizzi et al. 1984.

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





Did Mother Nature study control engineering?

- Basic Control Theory

  Engineering for Neuroscientists

  - ***feedforward and feedback control***
  - ***effects of impedance modulation***
- Elements of the human motor system

  Neurophysiology for Engineers

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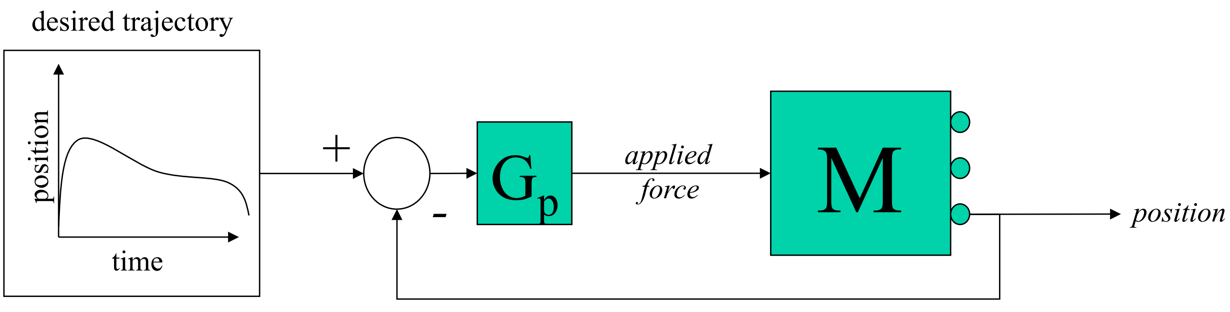
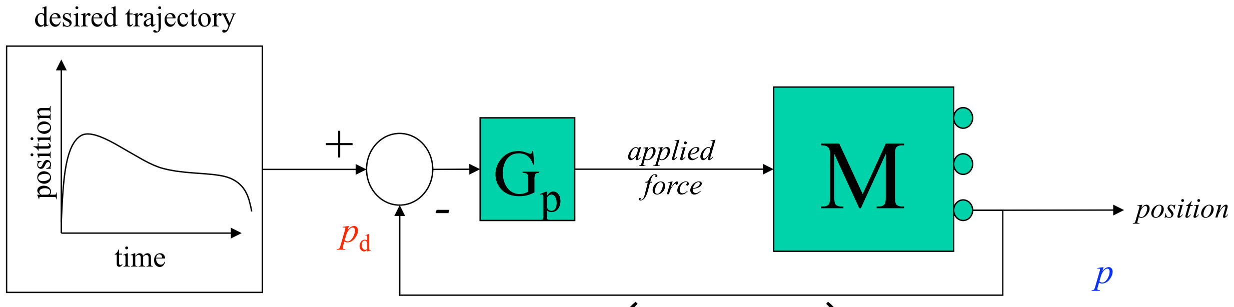
Simple feedback control of position.



$$f = G_p(p_d - p)$$

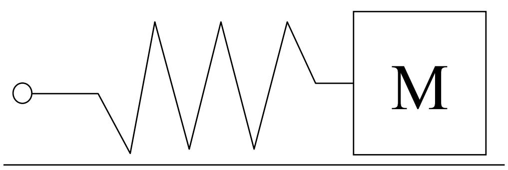
What's missing?

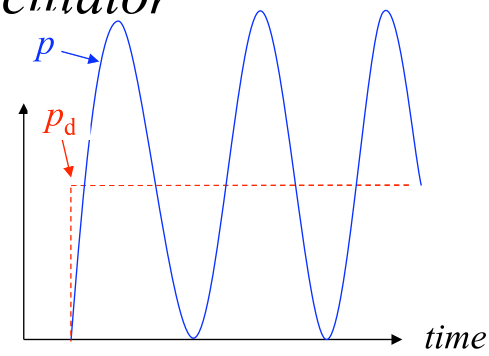


$$f = G_p(p_d - p)$$

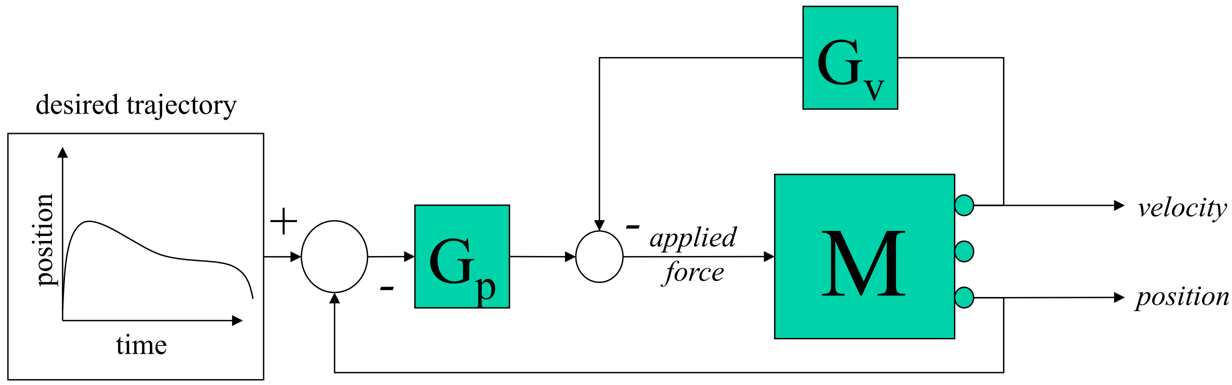
undamped oscillator

$$f = k(l - l_0)$$



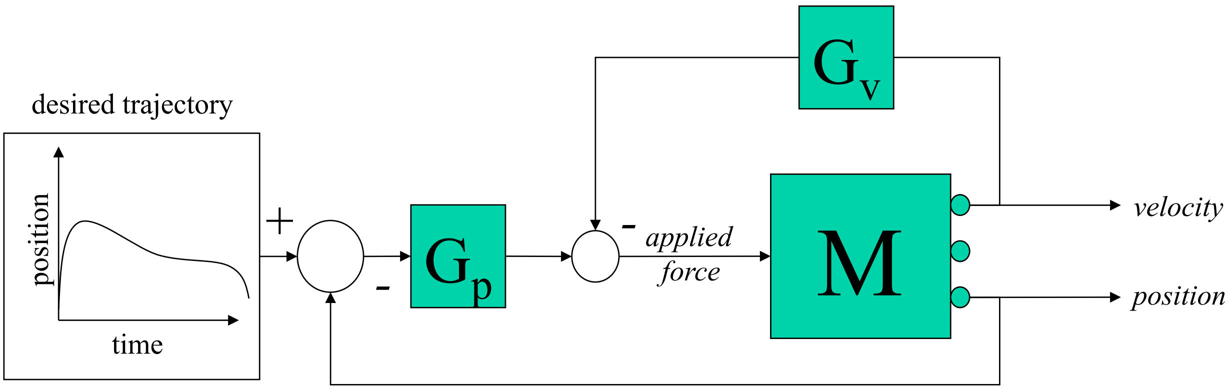


Position feedback requires velocity feedback to dissipate energy.

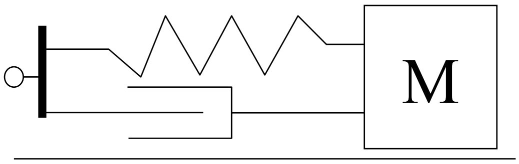


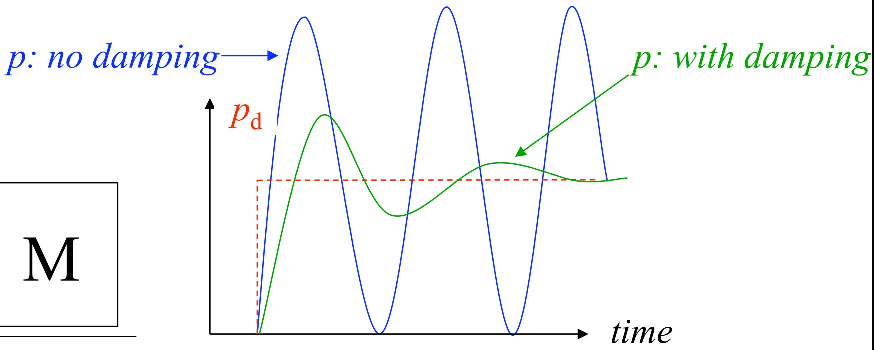
$$f = G_p(p_d - p) - G_v(\dot{p})$$

Position feedback requires velocity feedback to dissipate energy.



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

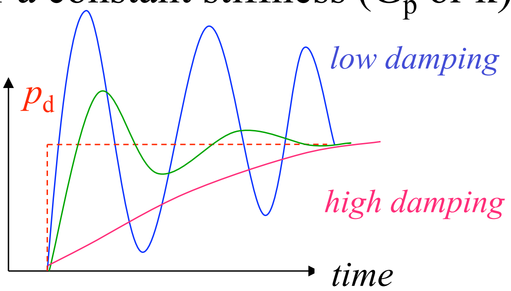




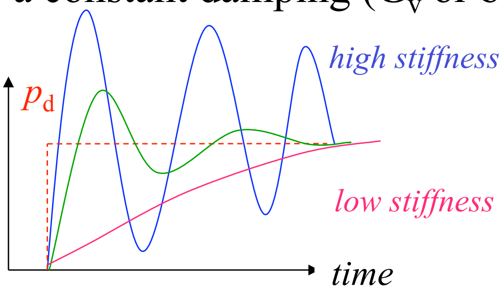
What are the effects of G_p and G_v?

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

for a constant stiffness (G_p or k)

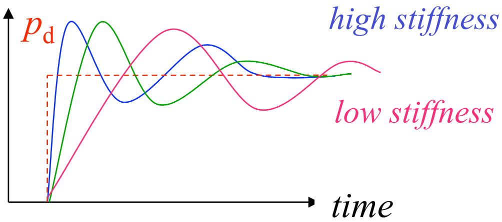


for a constant damping (G_v or b)

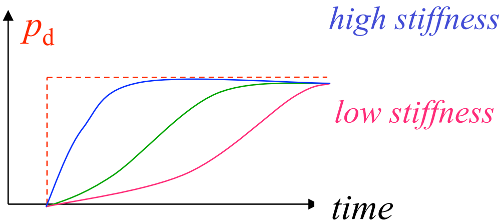


for a constant *damping ratio*: $\zeta = \frac{b}{2\sqrt{km}}$

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

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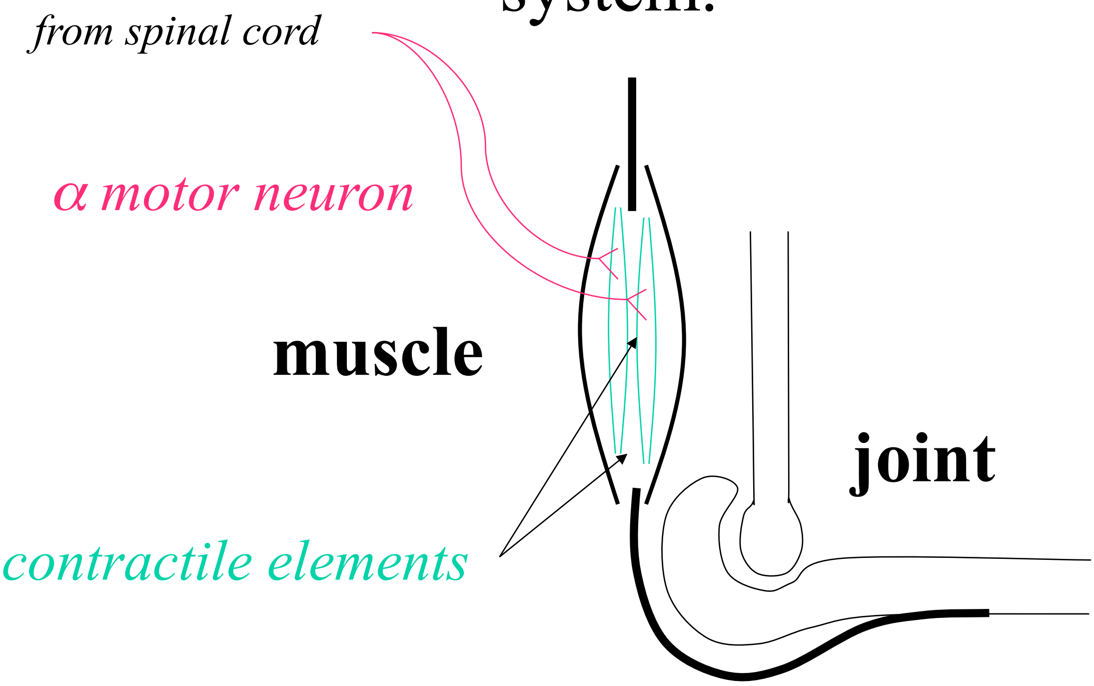
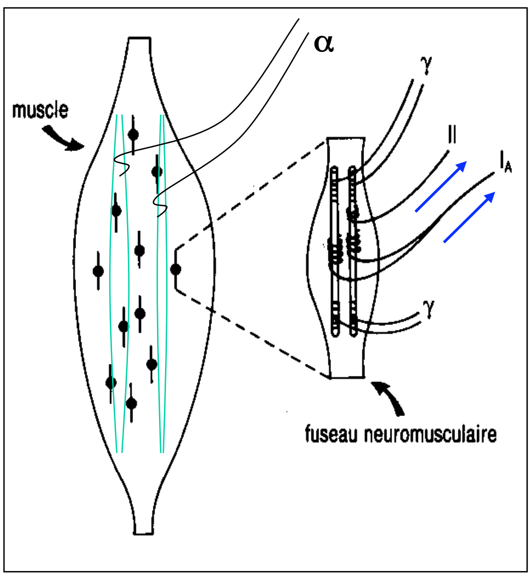
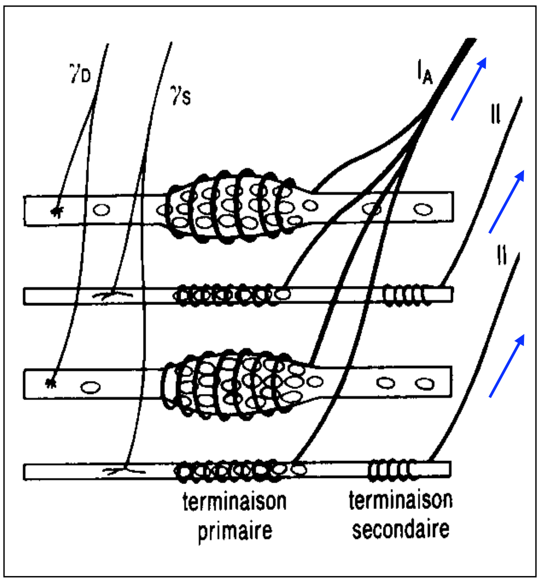
Elements of the human motor system.



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

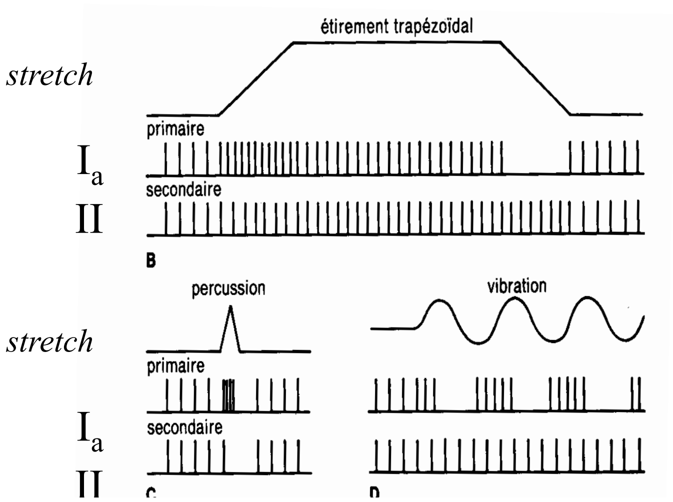




afferents: $\mathbf{I_a}$ and **II** fibres

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

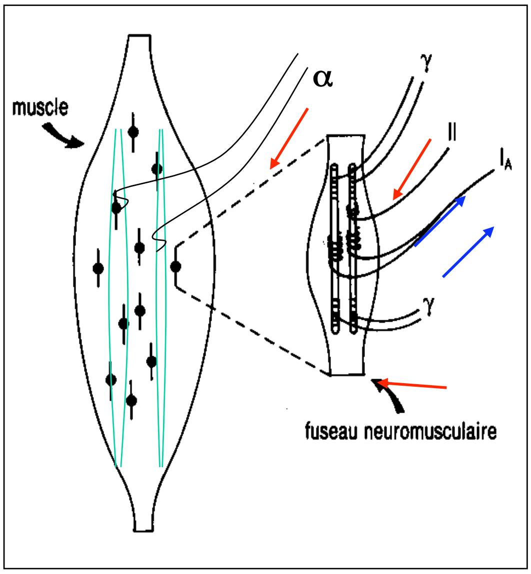
I_a = dynamic response

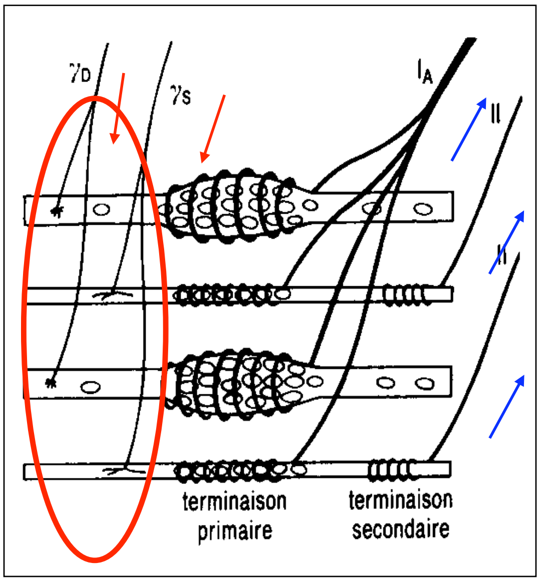
II = static response

more or less!!!

Spindle fibers carry information about muscle length and lengthening velocity.

Spindle organs are also equipped with contractile elements of their own.





afferents: **I_a** and **II** fibres

efferents: **α** *and* **γ** motor neurons

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

Motor System Physiology (just the minimal basics!)

- Muscles are made up of active contractile elements (extrafusal fibers) and sensory organs (intrafusal fibres).
- Efferent α motor neurons innervate the extrafusal fibers.
- Afferent type I_a and type II never 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.

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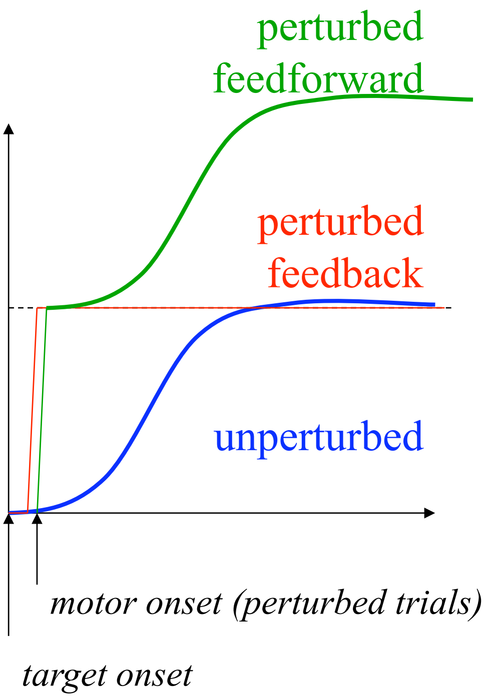
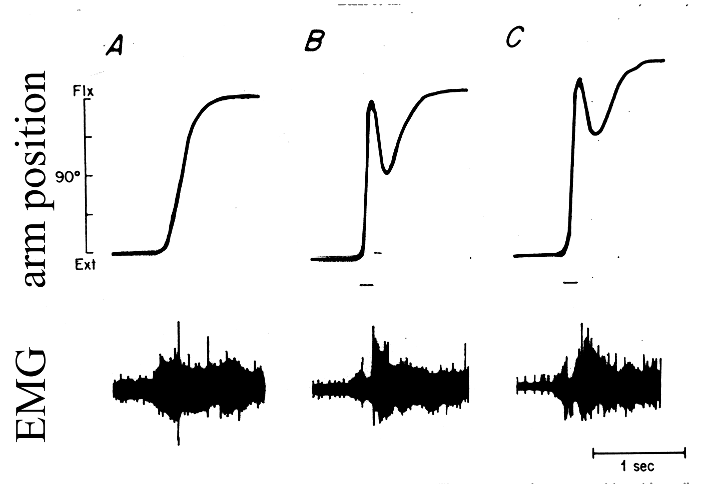
If movement of the arm is feedback driven …





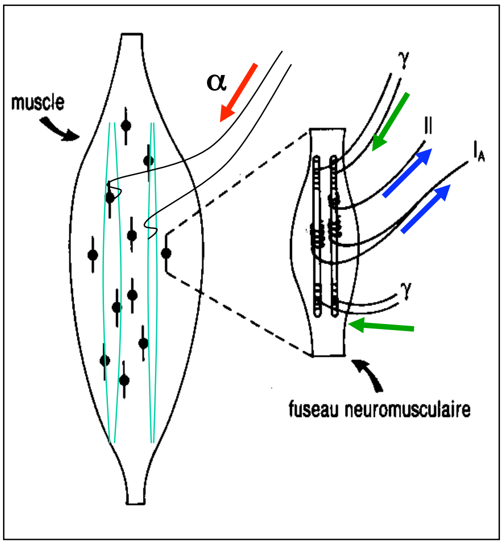
control
no perturbation

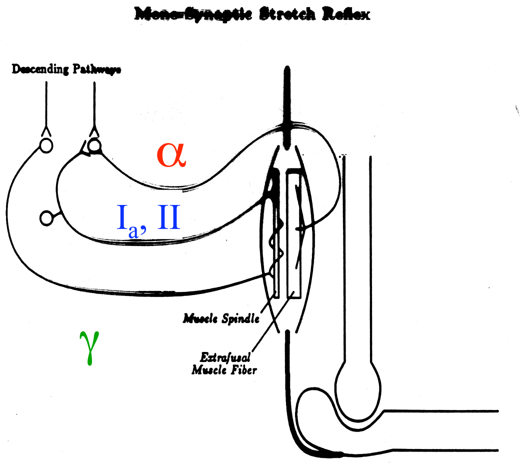
test
arm moved to target position at start of trial

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

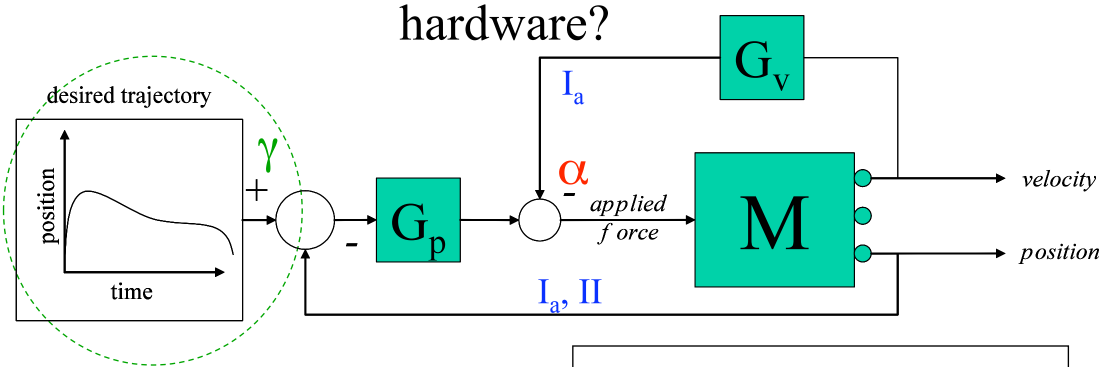
… how to implement a feedback servo with biological hardware?

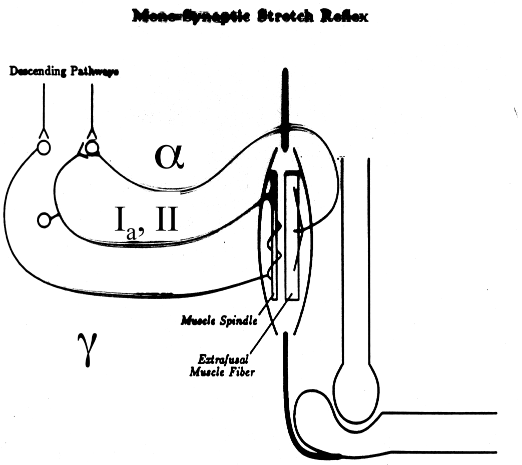
How to implement a feedback servo with this?

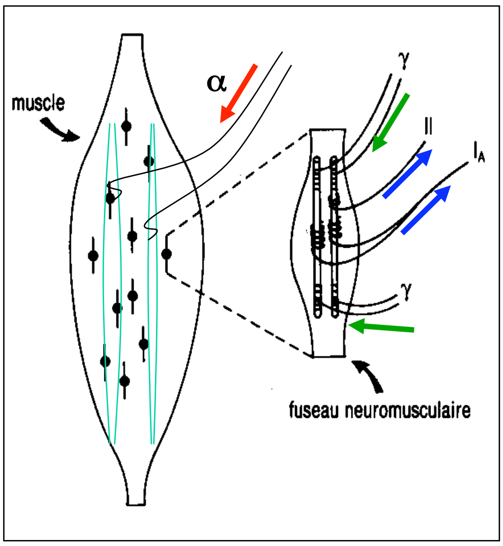




How to implement a feedback servo with the biological hardware?

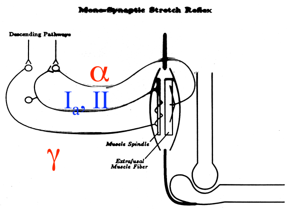


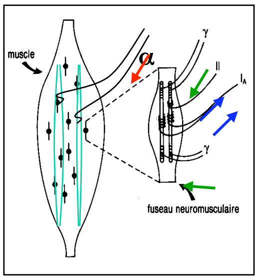




Merton's (1953) reflex servo control hypothesis

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





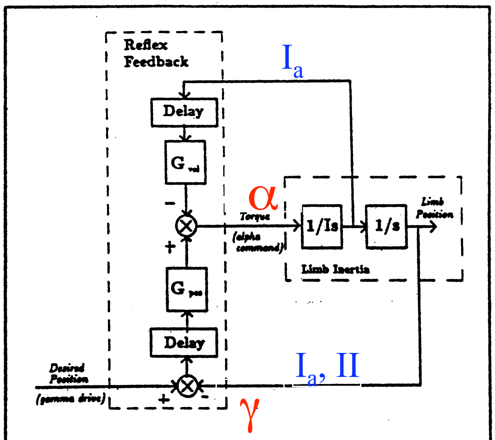
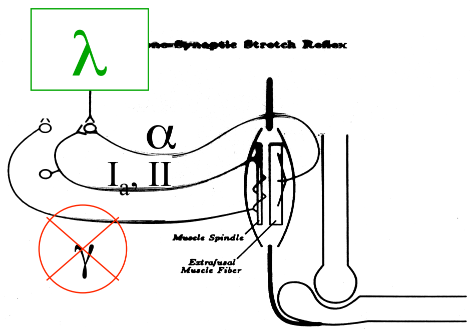


FIGURE 2. Merton's (1953) reflex servo control model.

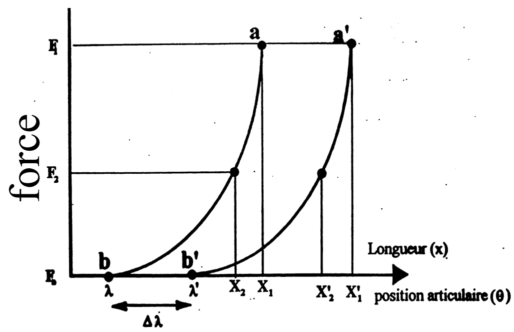
From: J. McIntyre and E. Bizzi *J. Motor Behav.* 1993.

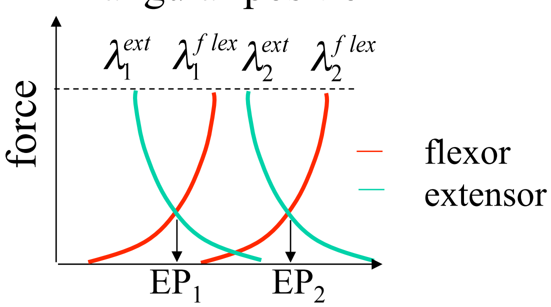
Not covered during the lecture just because of time constraints.

Feldman's Equilibrium Point Hypothesis



stretch reflex

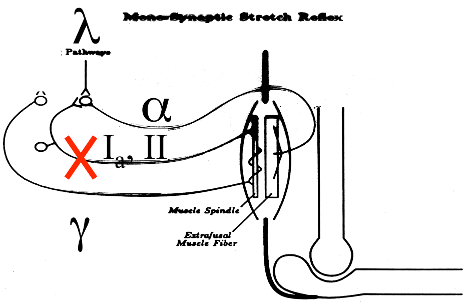


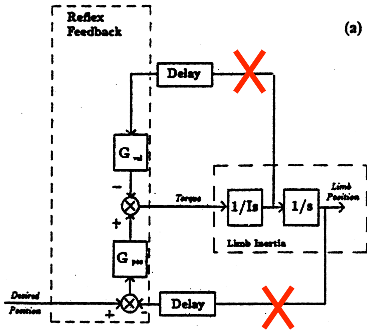


- Central command λ sets the threshold of the stretch reflex
- The desired position (equilibrium position) is determined by setting λ's for agonist/antagonist pairs.

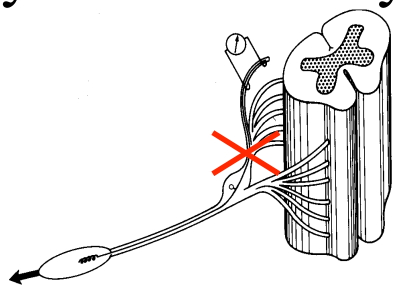
See Feldman, A. *J. Mot. Behav.* 1986.

What happens if feedback is interrupted?

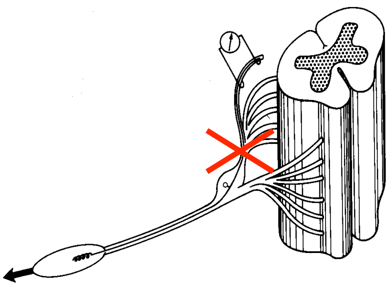


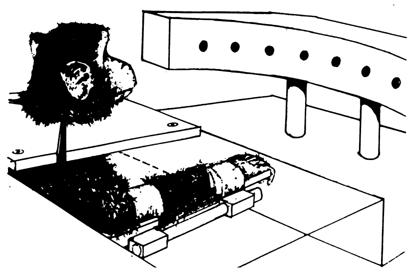


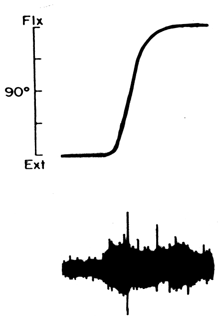
How can you cut sensory feedback?

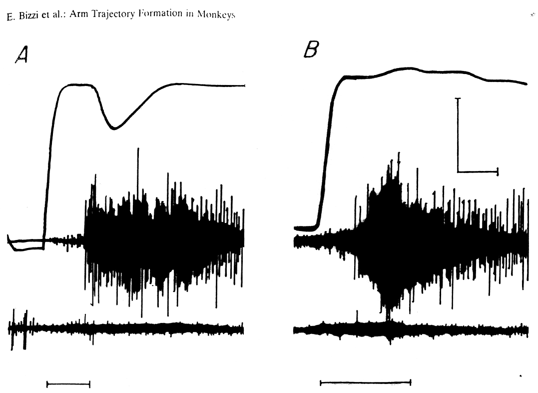


What happens if feedback is interrupted?





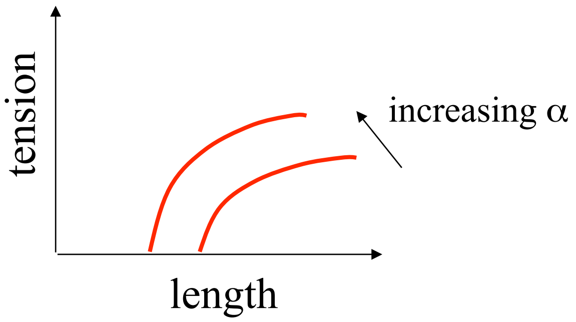


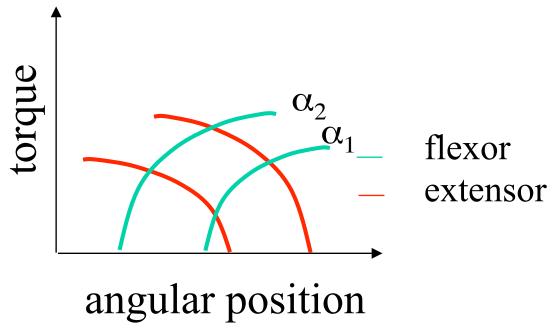


A. Polit and E. Bizzi *J Neurophysiol.* 1979 42 :183-194.

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.

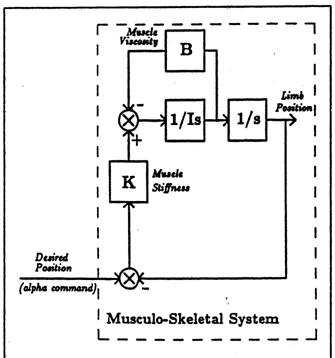
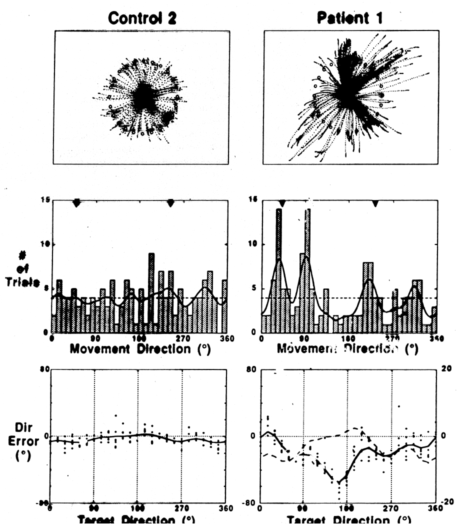


FIGURE 3. Block diagram of the α equilibrium-point model of motor control.

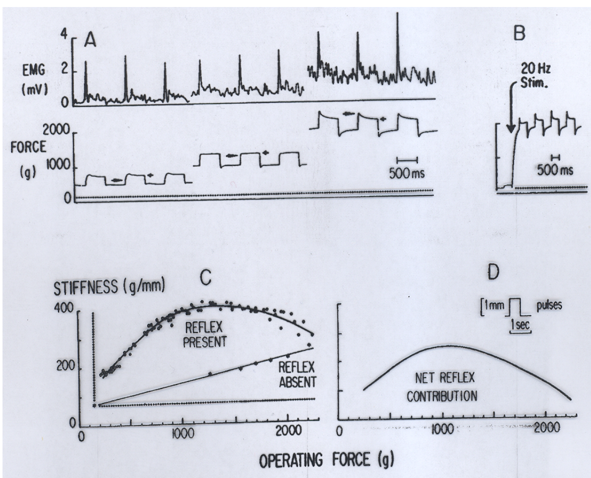
From: J. McIntyre and E. Bizzi *J. Motor Behav.* 1993.

Do reflexes serve a purpose? Of course!



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

Reflexes are essential to the accurate control of movement.



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

Reflexes modulate effective muscle stiffness.

A more accurate model includes both muscle properties and reflexes to provide feedback

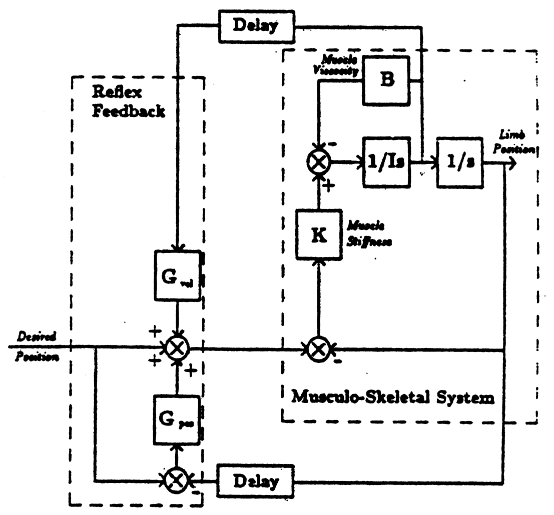
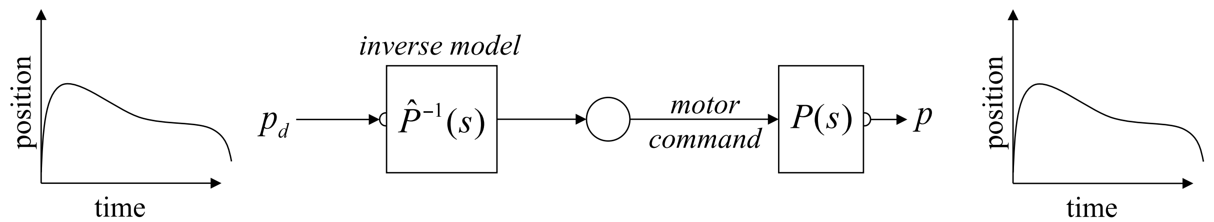
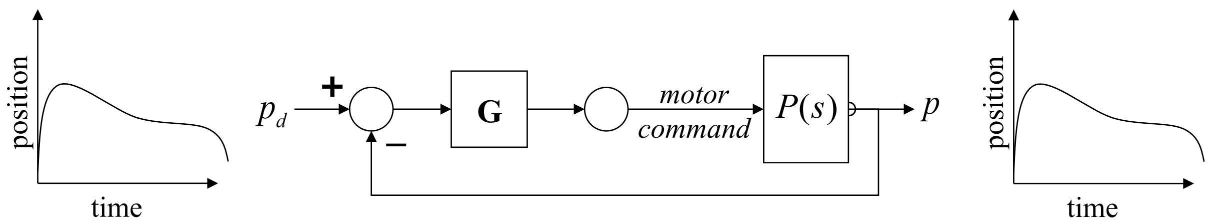


FIGURE 5. Consistent formulation of the equilibrium-point model. The model is consistent with alpha-gamma coactivation, deafferented monkey experiments, and reflex function.

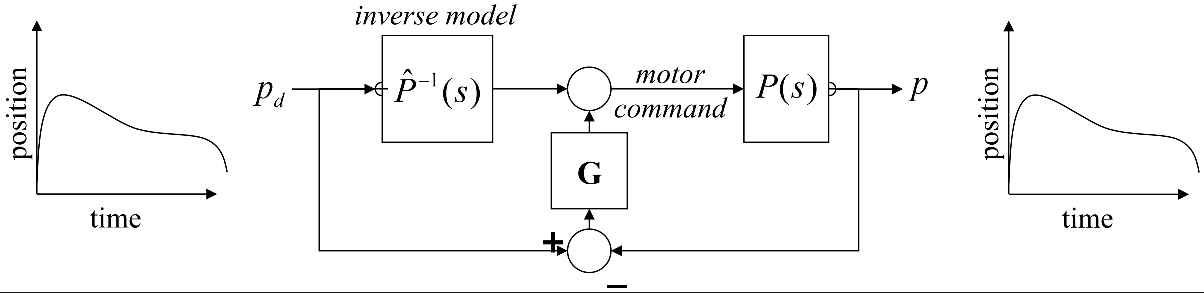
Feedforward Control: compute control based on knowledge of physics



Feedback Control: generate commands based on error signals



Combined: compute feedforward, correct with feedback

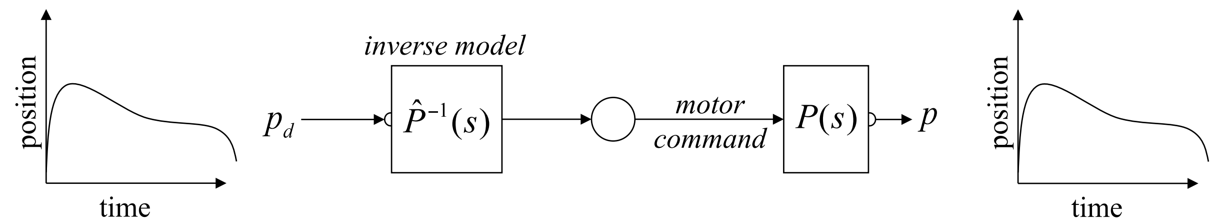


Summary

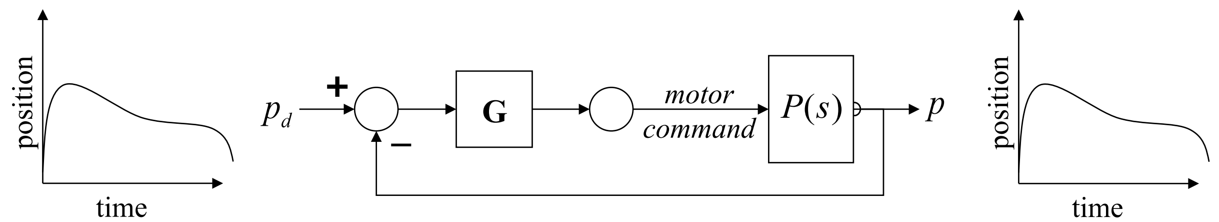
- A fundamental question:

  Feedforward or feedback control?
- Evidence for feedback control of biological movement
- Plausible biological mechanisms for implementing feedback-based motor control.
  - Merton's servo control hypothesis
  - Feldman's λ equilibrium point hypothesis
  - Bizzi's α equilibrium point hypothesis
- Passive mechanical properties of muscles are important!

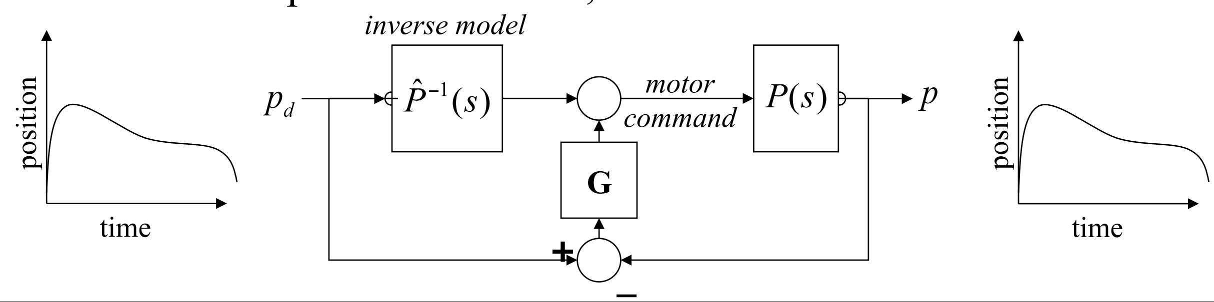
Feedforward Control: compute control based on knowledge of physics



Feedback Control: generate commands based on error signals

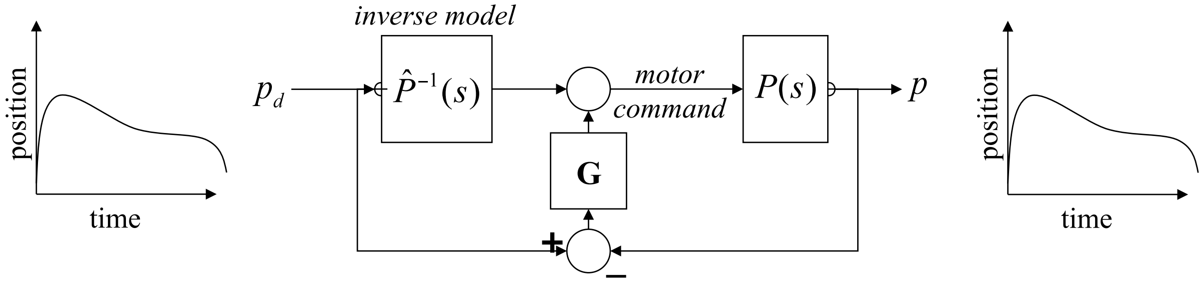


Combined: compute feedforward, correct with feedback

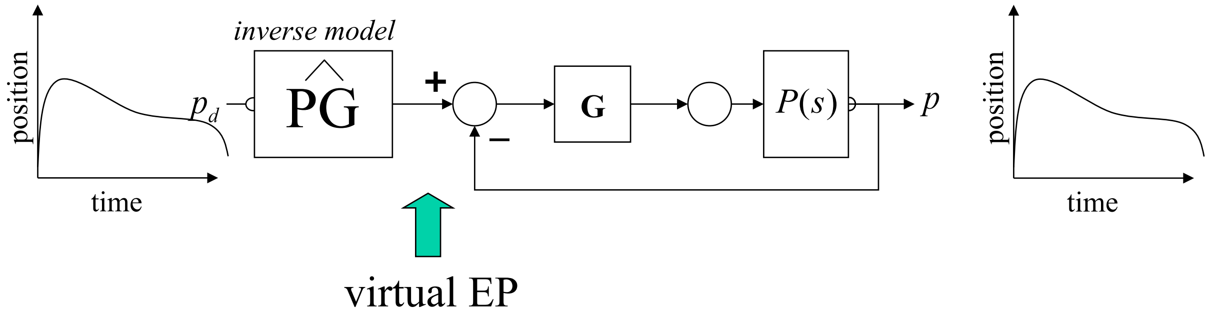


Two mathematically equivalent formulations.

Combined: compute feedforward, correct with feedback

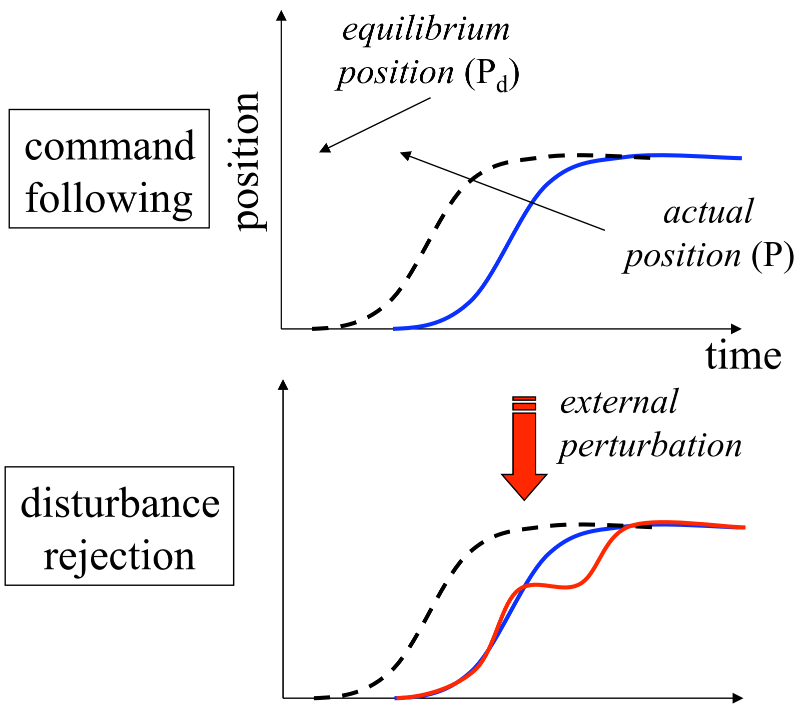


Virtual EP Control: inverse model of motor system + feedback



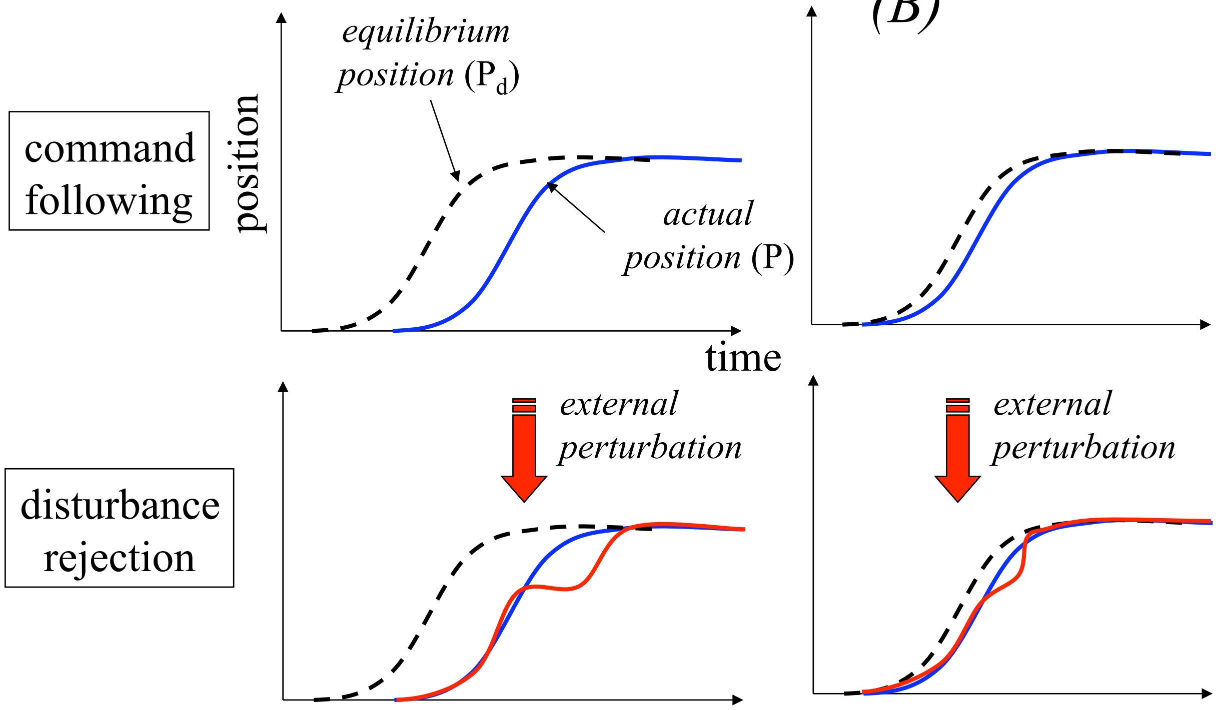
Disturbance Rejection

How does one reduce the effects of an external disturbance?

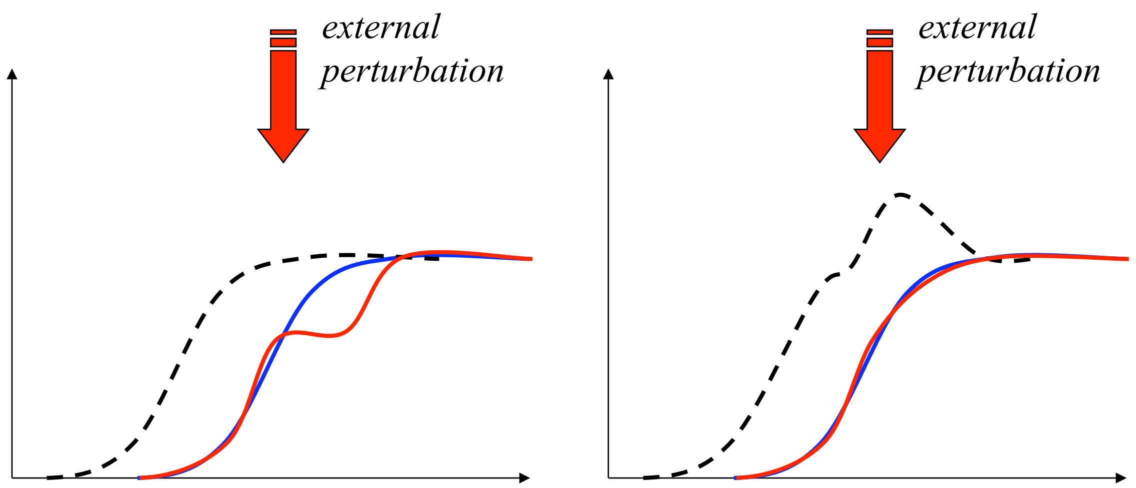


Disturbance Rejection via Impedance

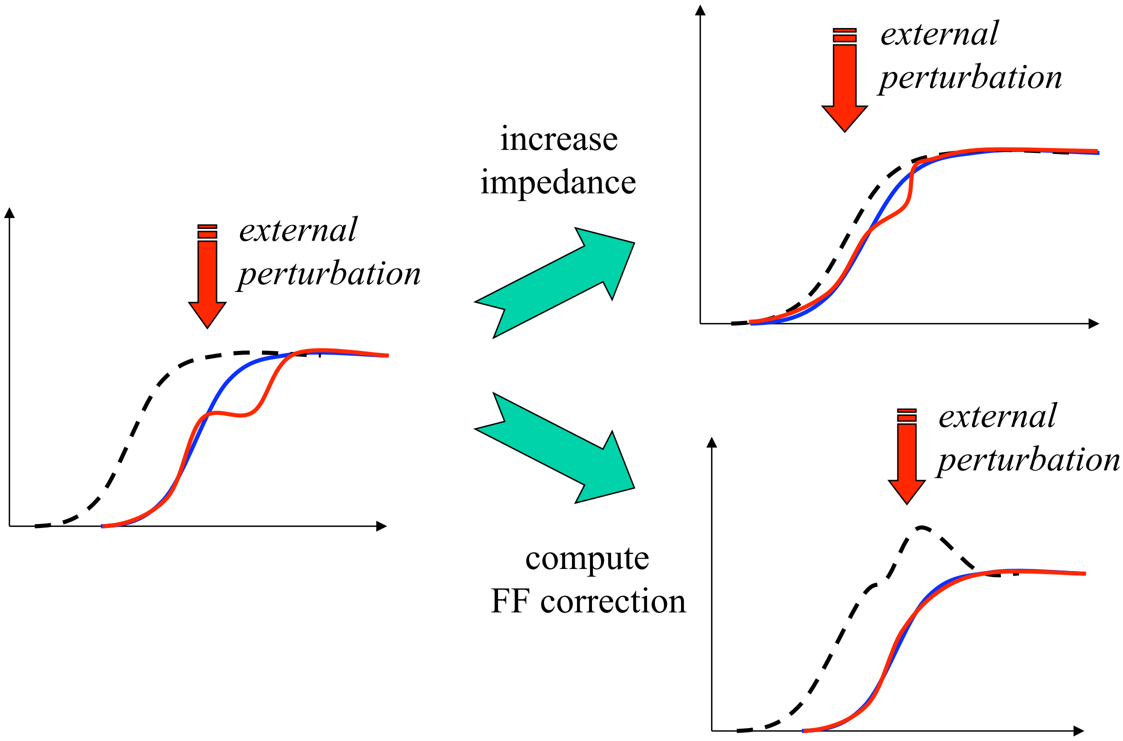
increase stiffness (K) and damping (B)



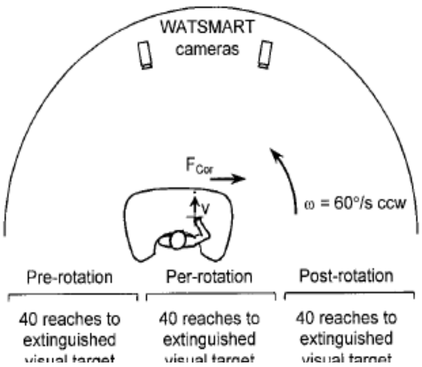
Feedforward Compensation of Perturbations



Which mechanism for disturbance compensation?



A Key Experiment



P Dizio and J Lackner *J. Neurophysiol.* 1994.

Subjects are seated at the center of a circular room.

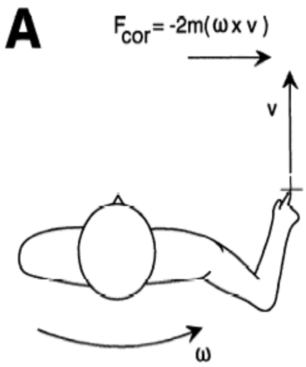
The entire room spins continuously at 60°/s.

The vestibular system is sensitive to changes in angular velocity. After a few seconds, the subject has no perception that the room is turning.

Subjects perform a reaching movement toward a target located straight ahead.

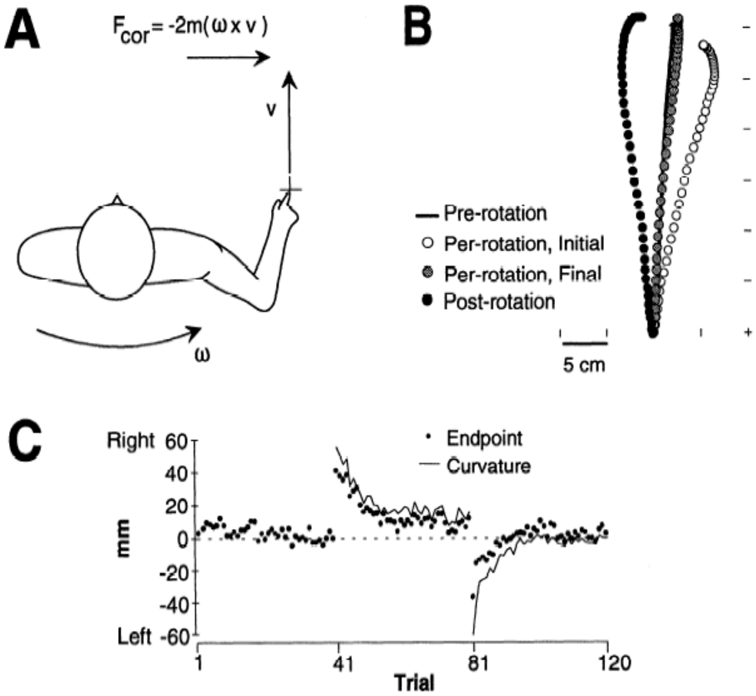
The interaction of the hand linear velocity and the rotation of the room results in a Coriolis force.

The Coriolis force is perpendicular to the hand velocity and proportional in amplitude.



no velocity = no Coriolis Force

Results

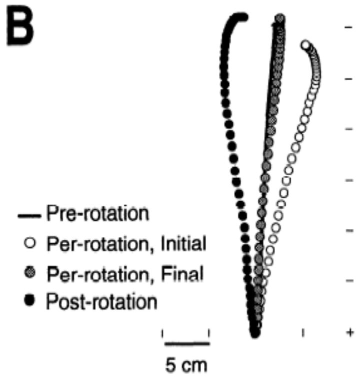


P Dizio and J Lackner *J. Neurophysiol.* 1994.

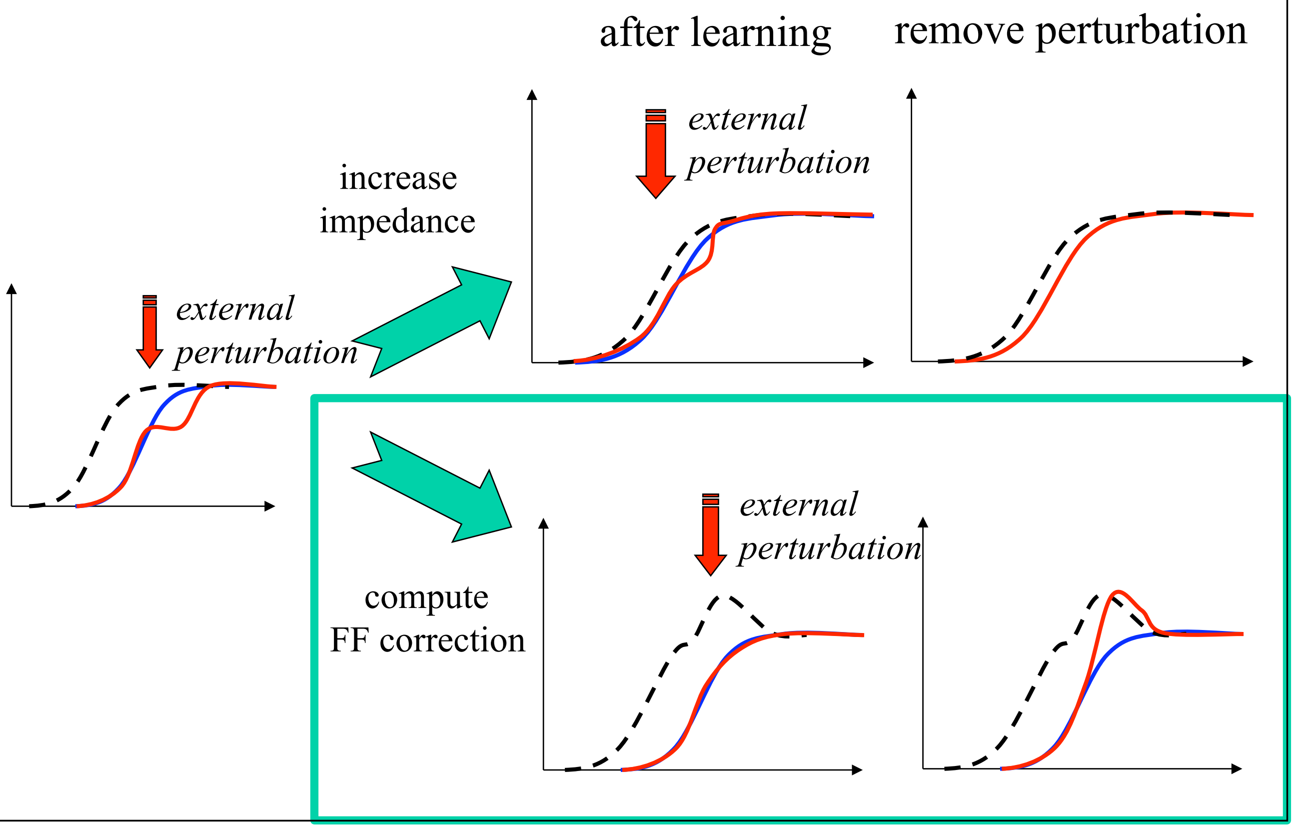
Question: Is this evidence for feedforward or feedback control of movement?

Answer: YES!

- Feedback
  - Correction of hand trajectory toward the target.
- Feedforward
  - No equifinality
  - Learning
  - After-effect



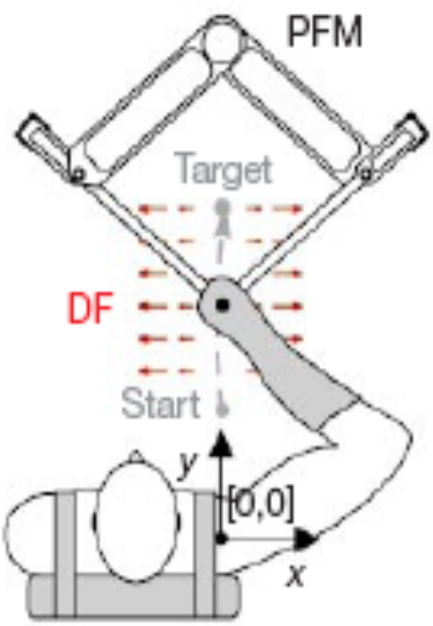
After Effects



Another Key Experiment

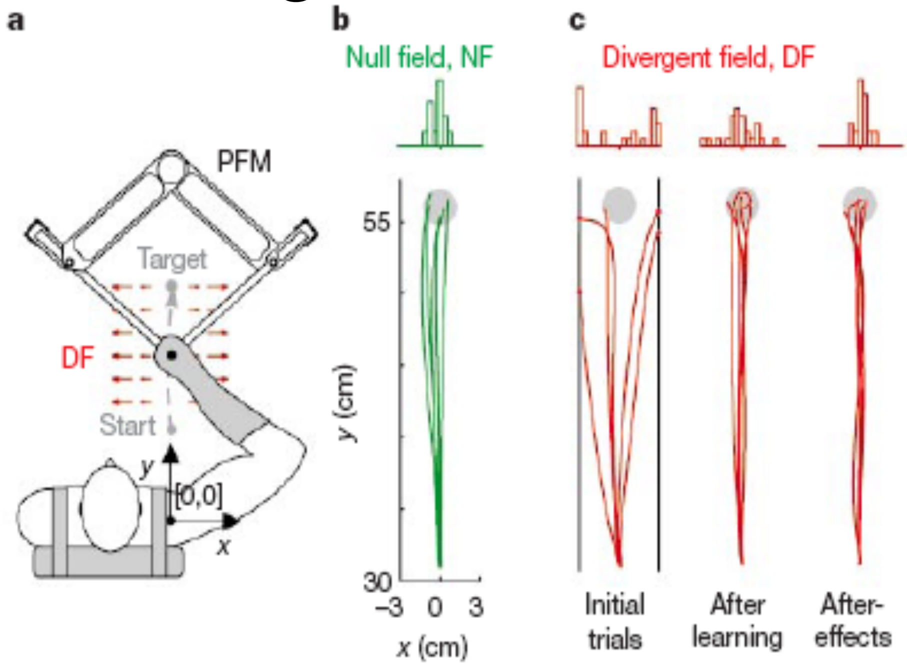
Divergent Force Field

E Burdet et al. *Nature* 2001.



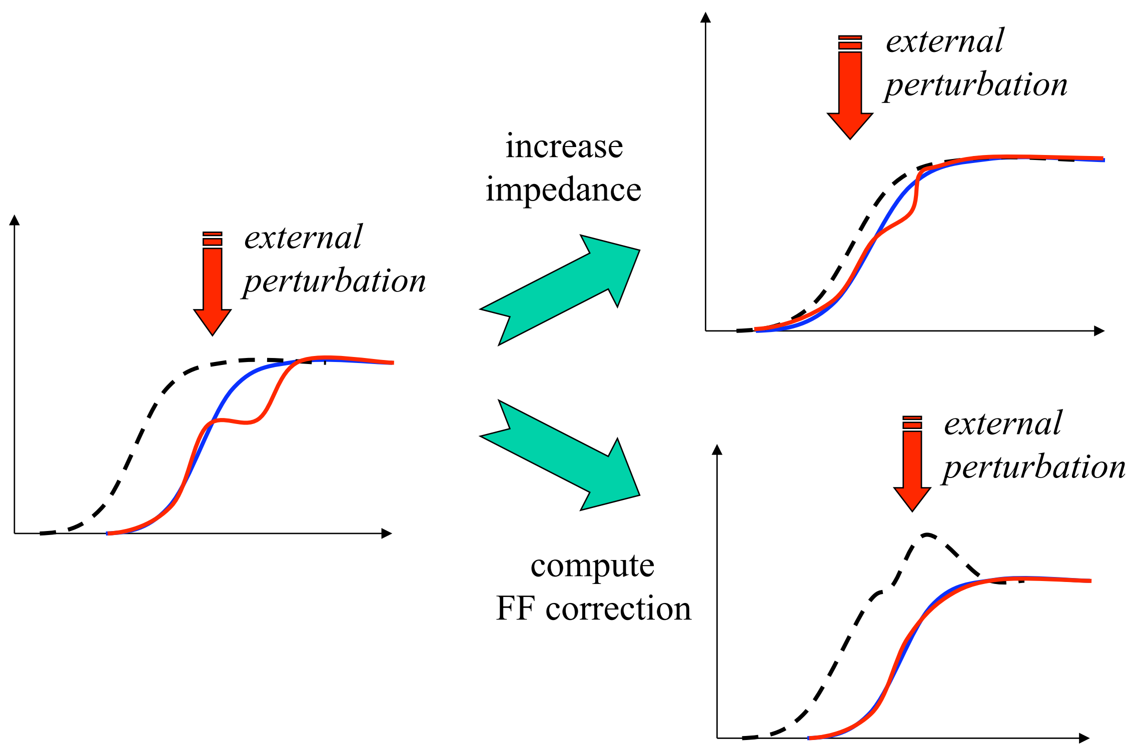
Another Key Experiment

Divergent Force Field



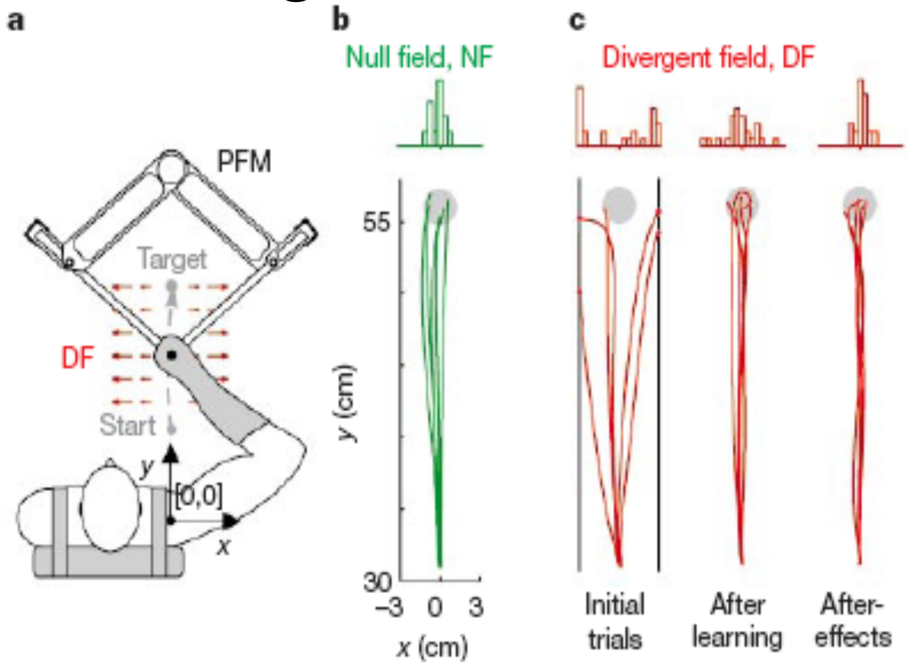
E Burdet et al. *Nature* 2001.

Which mechanism for disturbance compensation?



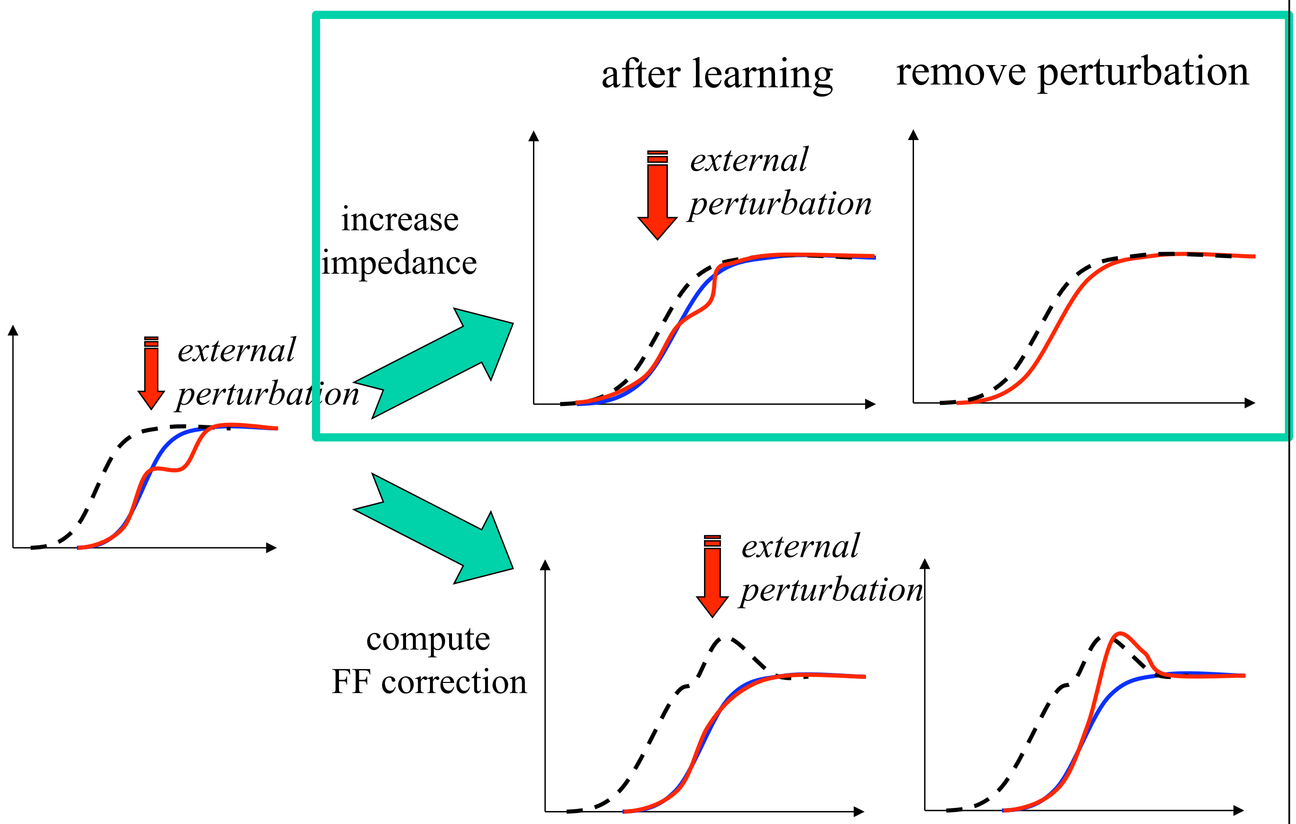
Another Key Experiment

Divergent Force Field

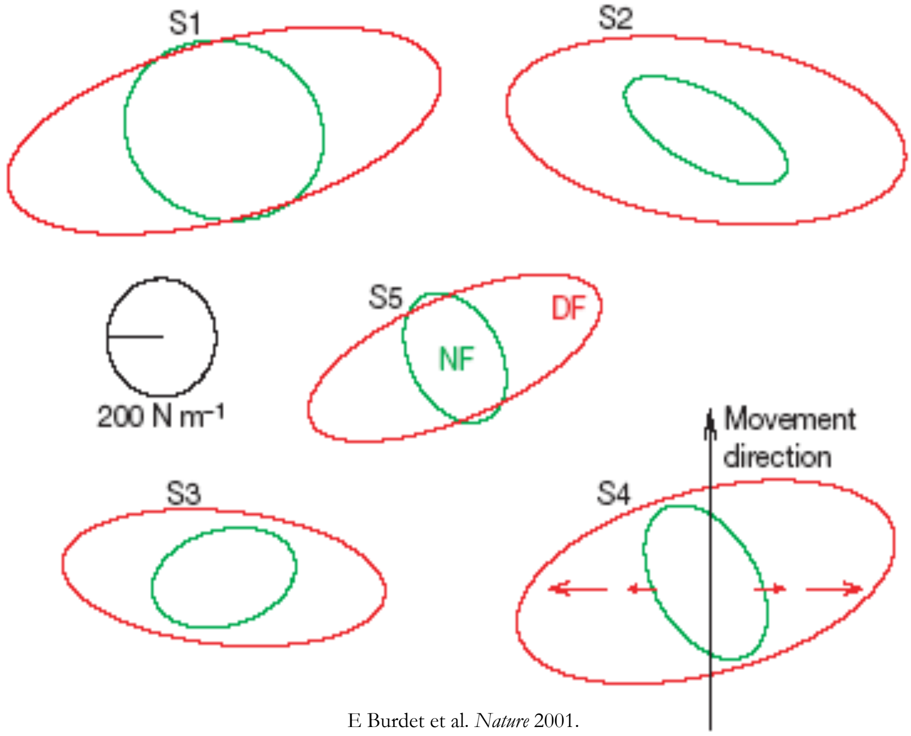


E Burdet et al. *Nature* 2001.

No After Effects



Adaptation of Hand Impedance



E Burdet et al. *Nature* 2001.

Conclusions / Discussion

- Combined feedforward/feedback control of force for the control of limb trajectories
- Feedforward correction of disturbances
  – must be predictable
- Feedback correction of disturbances
  – increase impedance to reject external forces
- The brain can use both mechanisms by specifying EPs and **impedance** as well as (instead of?) forces

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