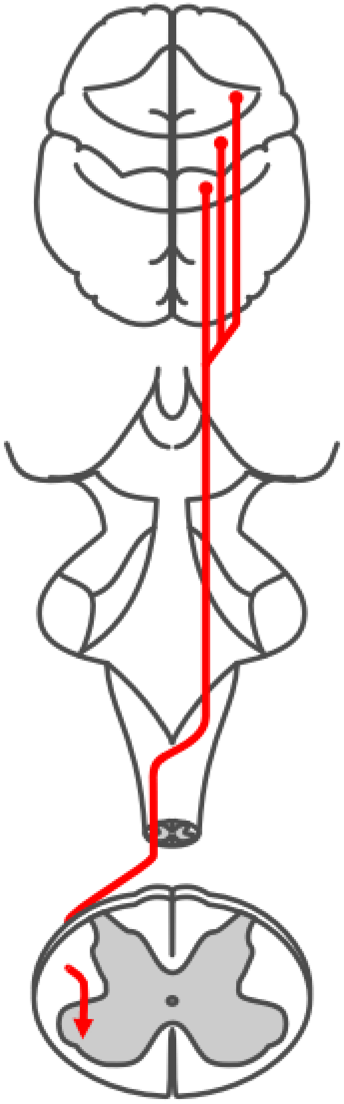
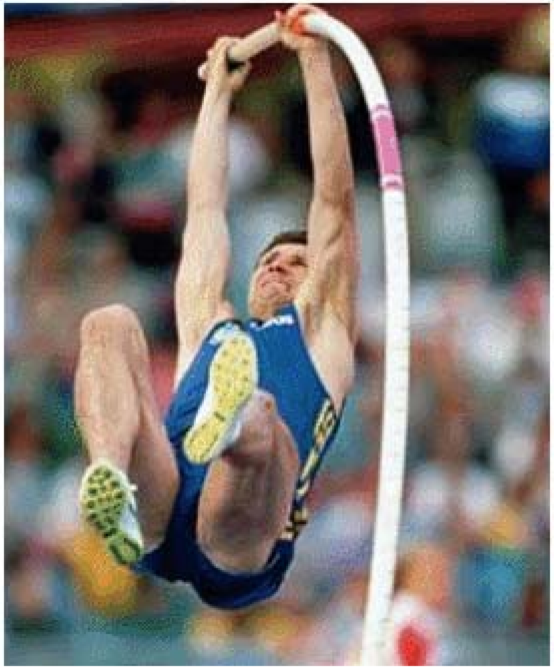


Biological motor control

Andrew Richardson
McGovern Institute for Brain Research

March 14, 2006

Why bother with biology?



- Both plant (musculoskeletal system) and controller (nervous system) optimized by evolution for versatility and efficiency.

Motor neuroscience: levels and themes

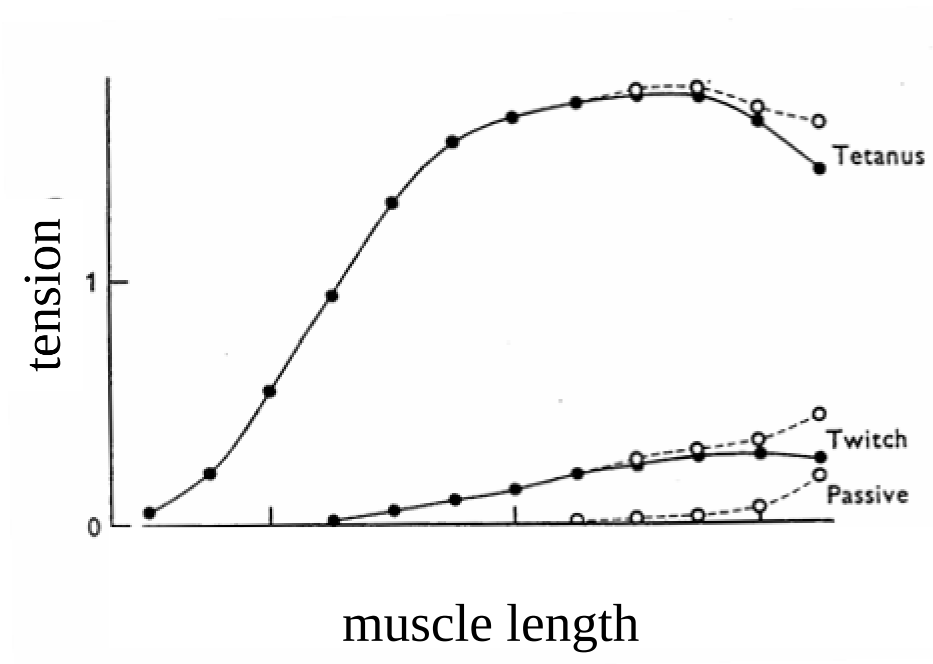
- Mechanics of the neuromusculoskeletal system
  - Simplification of control by neural modulation of the mechanics

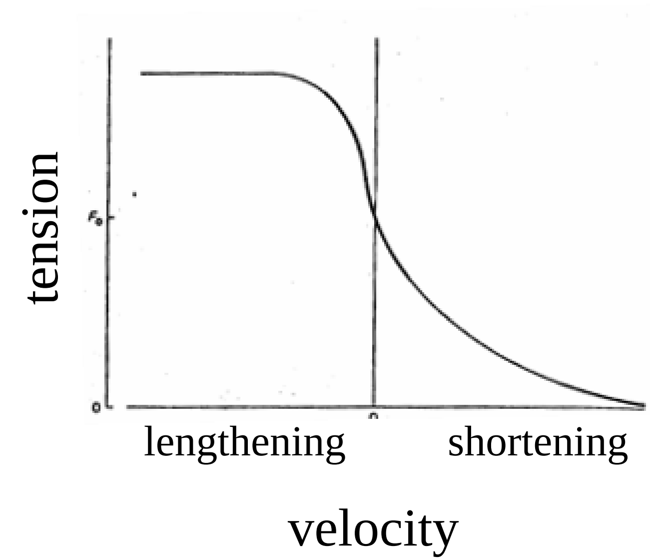
- Motor behavior
  - Model-based adaptive control in changing environments
  - Coordinate frames and methods for movement planning

- Motor neurophysiology
  - Neural representations in motor cortex
  - Cortically-controlled neural prosthetics

Mechanics of the neuromusculoskeletal system

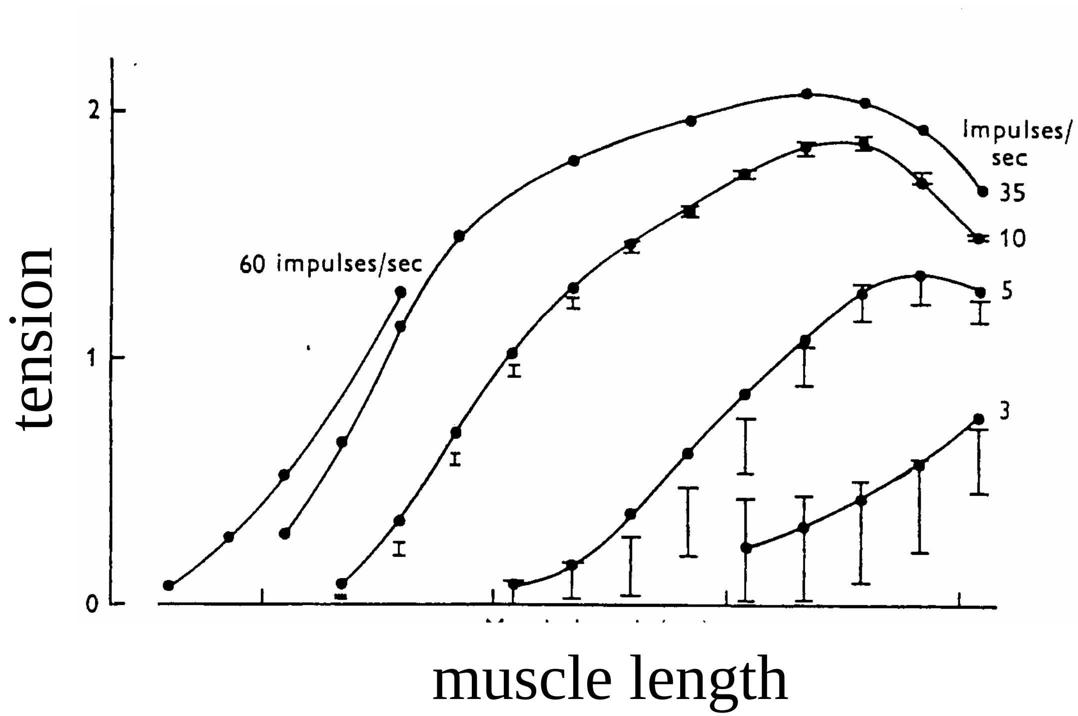
- Force production by a muscle is dependent on its length and velocity.





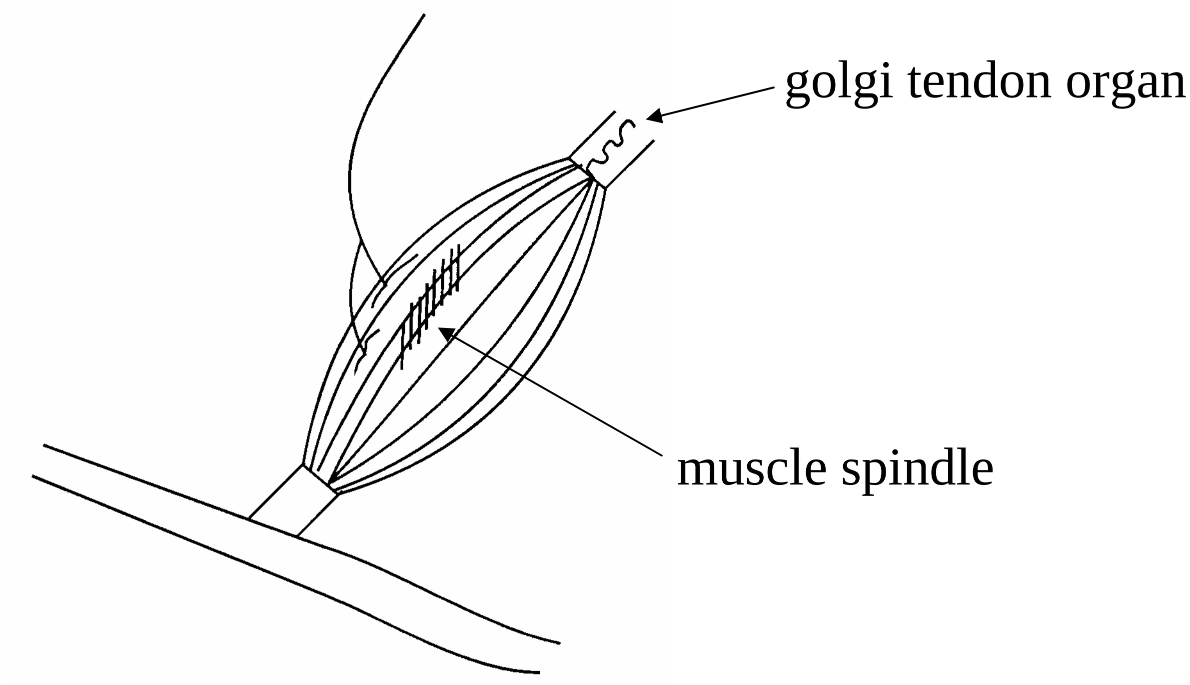
Mechanics of the neuromusculoskeletal system

- Changes in muscle activation cause changes in the viscoelastic properties of the muscle.



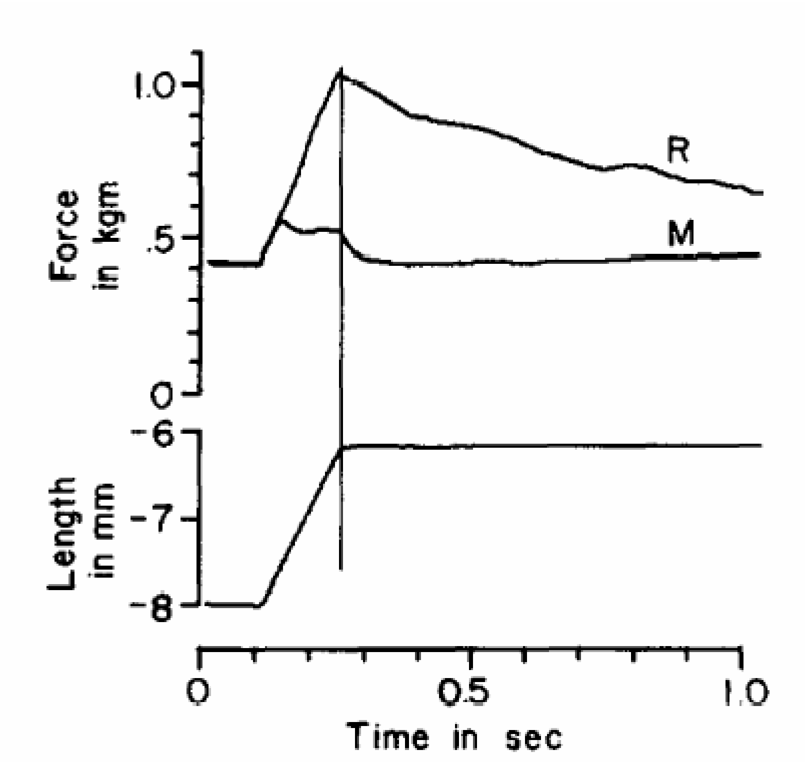
Mechanics of the neuromusculoskeletal system

- The nervous system receives information on muscle length, velocity, and force.



Mechanics of the neuromusculoskeletal system

- Reflexes are local feedback loops that can modify the viscoelastic behavior of the motor periphery.



Nichols and Houk, 1976

- Reflex gains can be modulated by higher levels of the neural controller (e.g. cerebellum, motor cortex).

Mechanics of the neuromusculoskeletal system

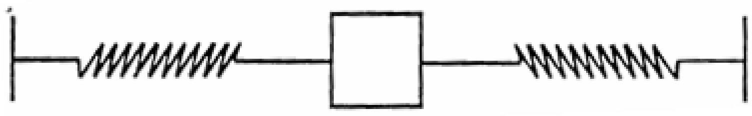
- Thus, total neuromuscular viscoelasticity has both intrinsic (i.e. muscle) and reflexive contributions. The gain of each of these contributions can be modulated by central commands.

- At least for some behaviors, the neural controller likely takes advantage of these mechanical properties …

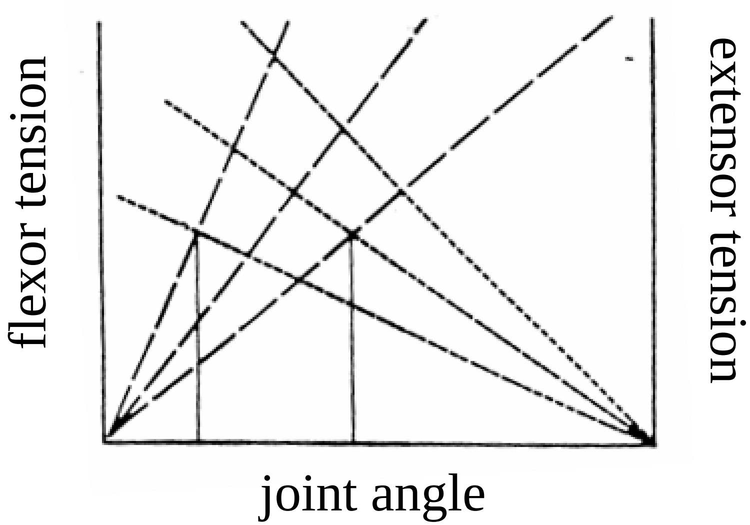
  1. Equilibrium-point (servo) control
  2. Impedance control

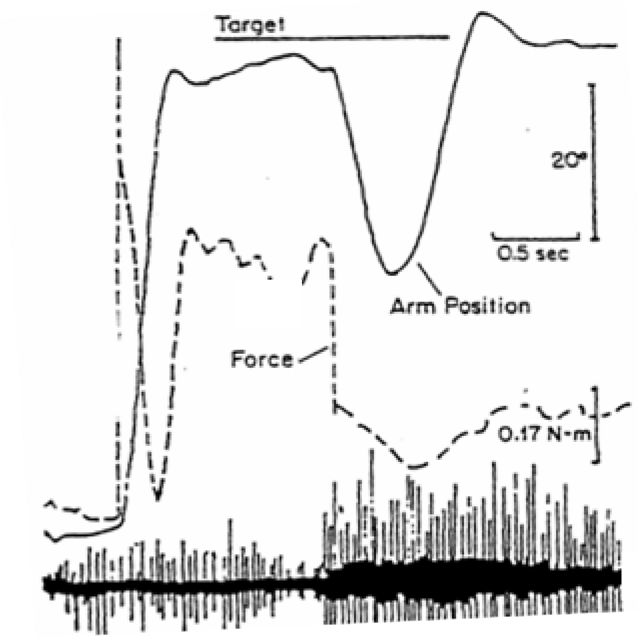
Mechanics of the neuromusculoskeletal system

- Equilibrium-point control



  - Equilibrium points dependent on neuromuscular elasticity & loads.
  - Changing the stiffness ratio for antagonistic muscles shifts the equilibrium point (producing a “virtual trajectory”).
  - Precludes need to compute inverse dynamics, thus simplifying neural computations.



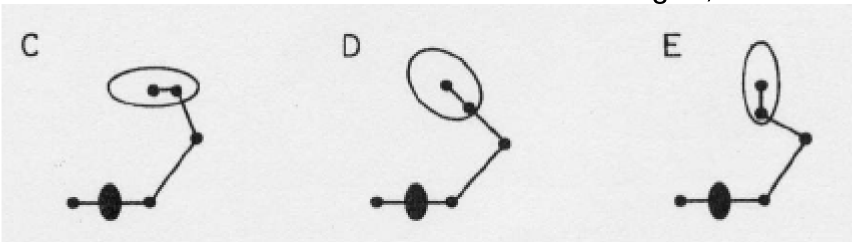


Bizzi et al, 1984

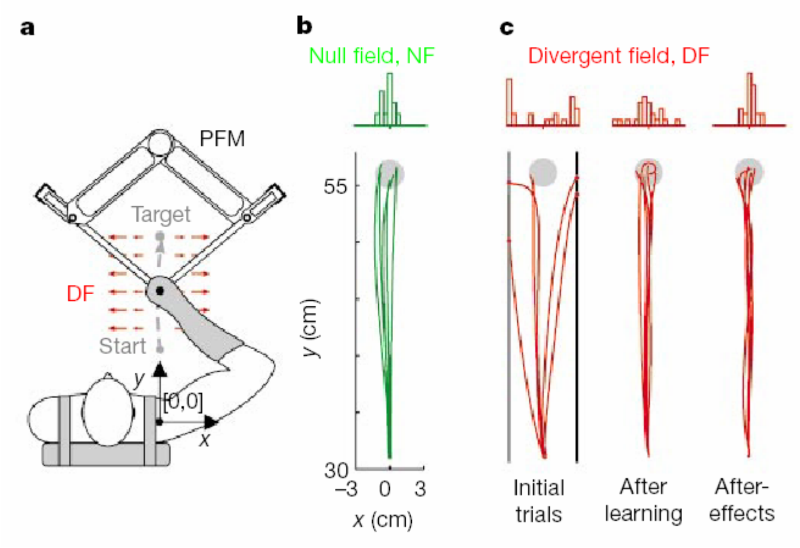
Mechanics of the neuromusculoskeletal system

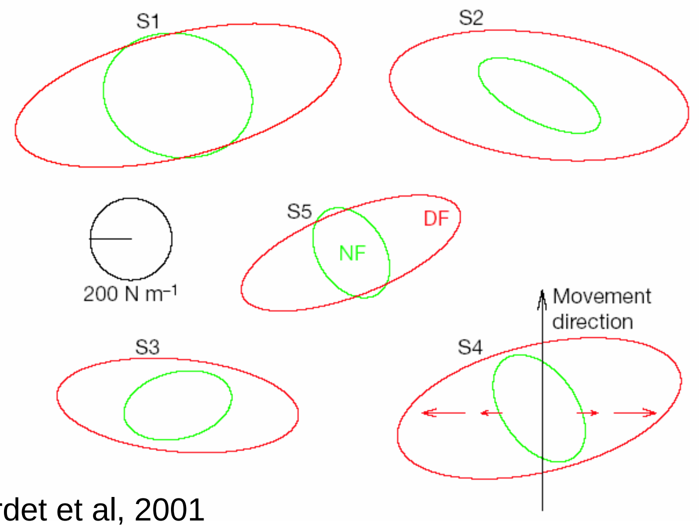
- Impedance control

Hogan, 1985



  - In addition to viscoelastic behavior, inertial behavior can be modulated due to the kinematically redundant skeleton.
  - Modulate full mechanical impedance (force-length, force-velocity, and force-acceleration relationships) of the limb for improved stability or performance.





Burdet et al, 2001

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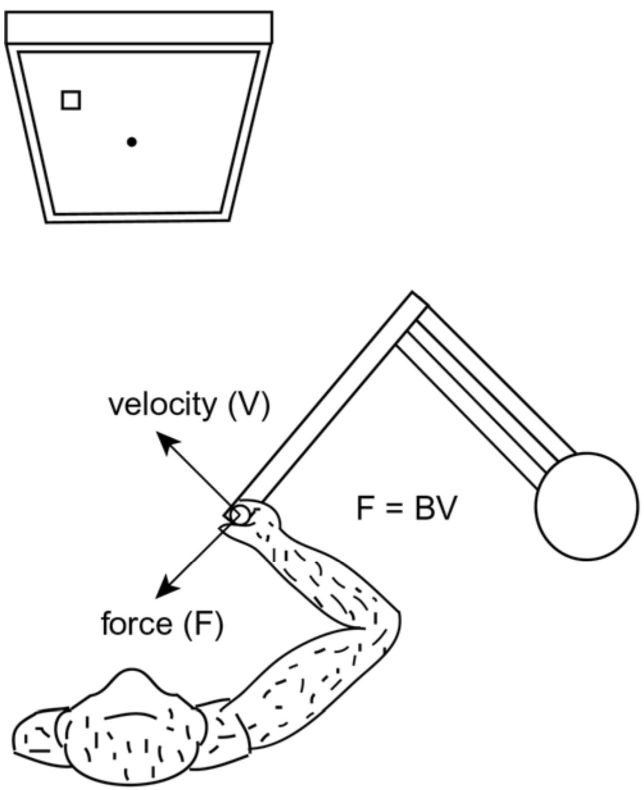
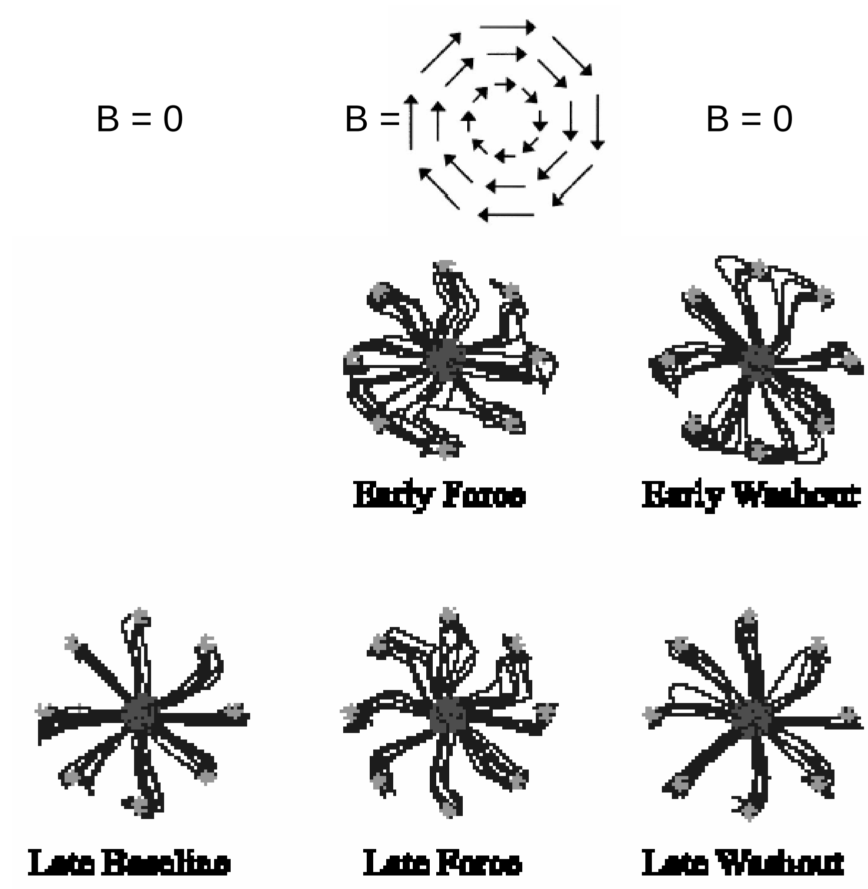
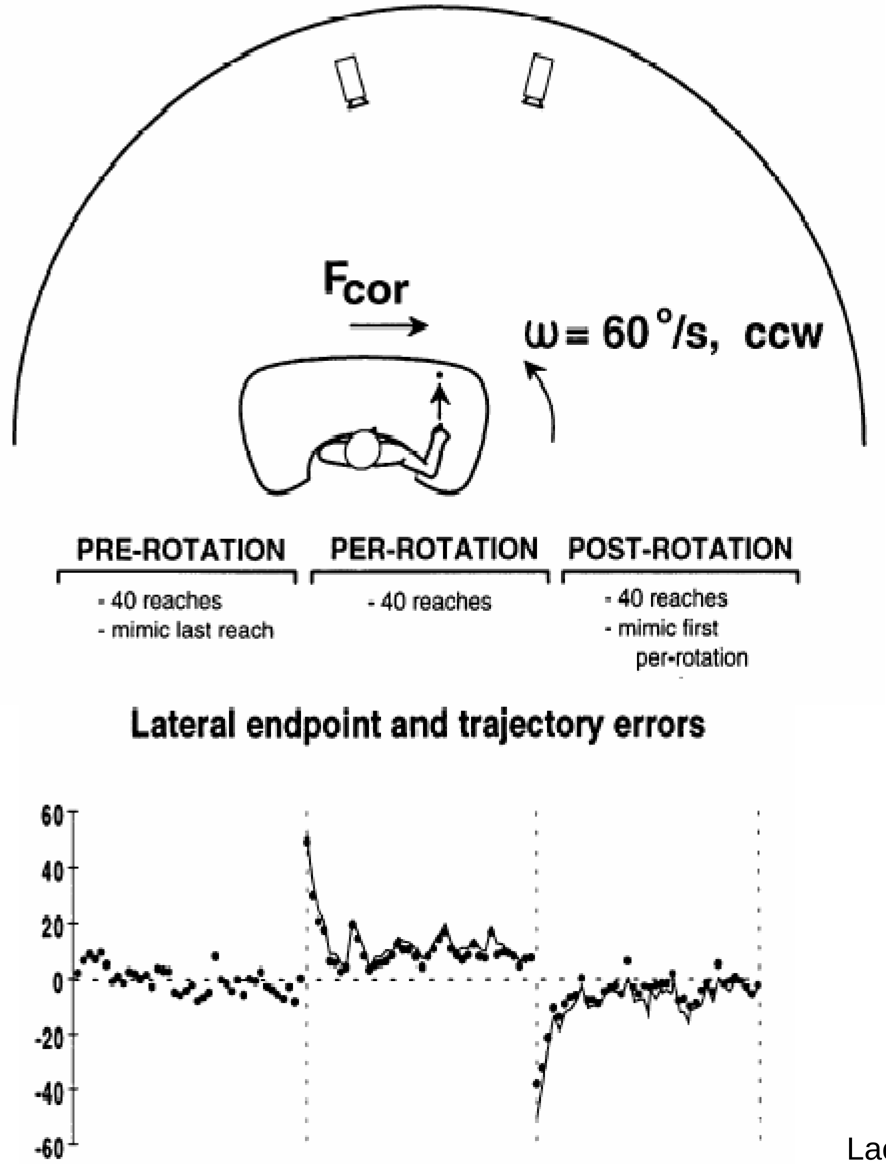
Motor behavior

- Adaptive control of reaching movements generally leads to proactive, not reactive (i.e. impedance control), compensation.





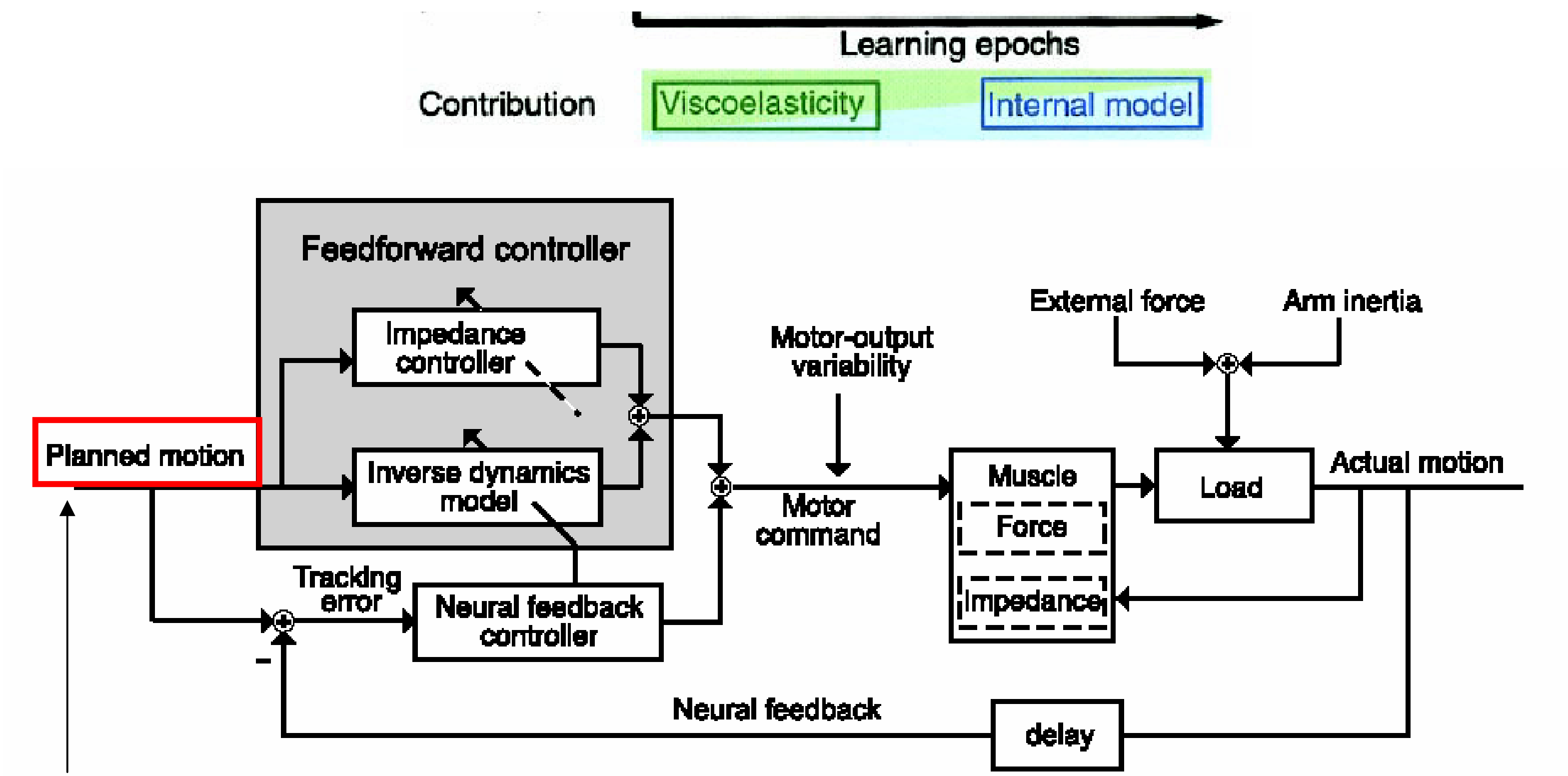
Motor behavior



Lackner and DiZio, 1994

Motor behavior

- Control of reaching movements may depend on the type of task (e.g. nominally stable or unstable) and familiarity with the task.



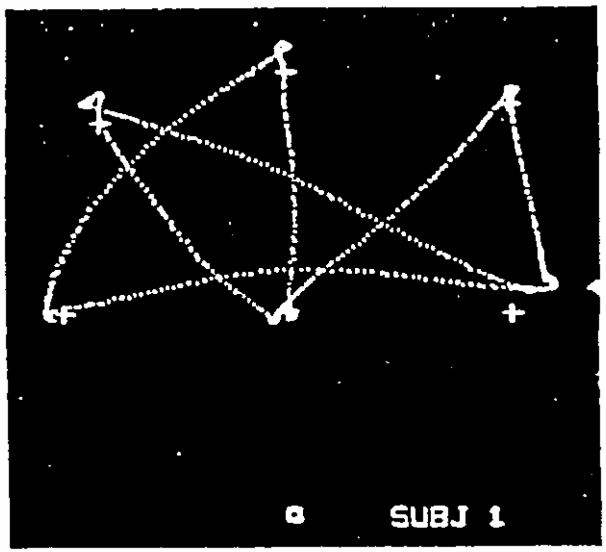
But how do we plan motions?

Osu et al, 2003

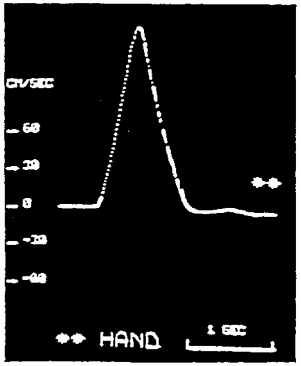
Motor behavior

- Motions are planned in endpoint coordinates.

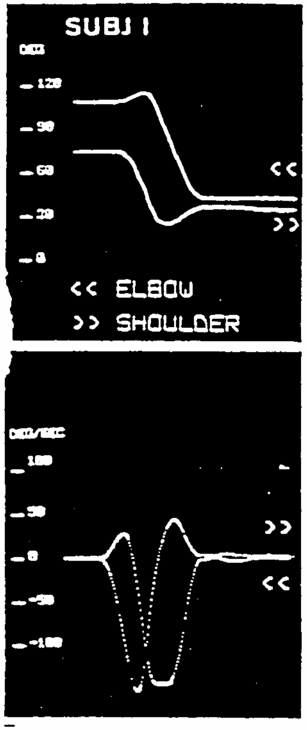
Endpoint hand paths are straight



Endpoint velocity is “bell-shaped”



Joint trajectories are complex



Morasso, 1981

Motor behavior

- Optimization criteria have been proposed to explain the observed behavior, given the seemingly ill-posed problem of getting from point A to point B.

  - Minimum jerk (Hogan, 1984)

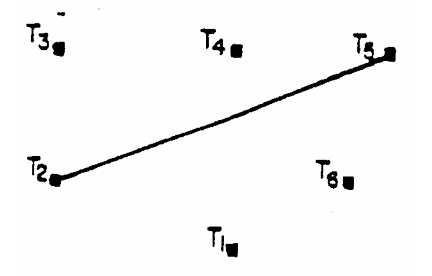
$$\int_{t_0}^{t_f} \left(\left(\frac{d^3 x}{dt^3} \right)^2 + \left(\frac{d^3 y}{dt^3} \right)^2 \right) dt$$

  - Minimum torque change (Uno et al, 1987)

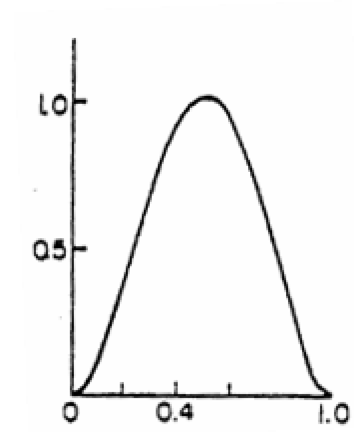
$$\frac{1}{2} \int_{t_f}^{t_f} \sum_{i=1}^{n} \left(\frac{dz_i}{dt} \right)^2 dt$$

  - Minimum endpoint variance (Harris and Wolpert, 1998)

Endpoint hand paths are straight



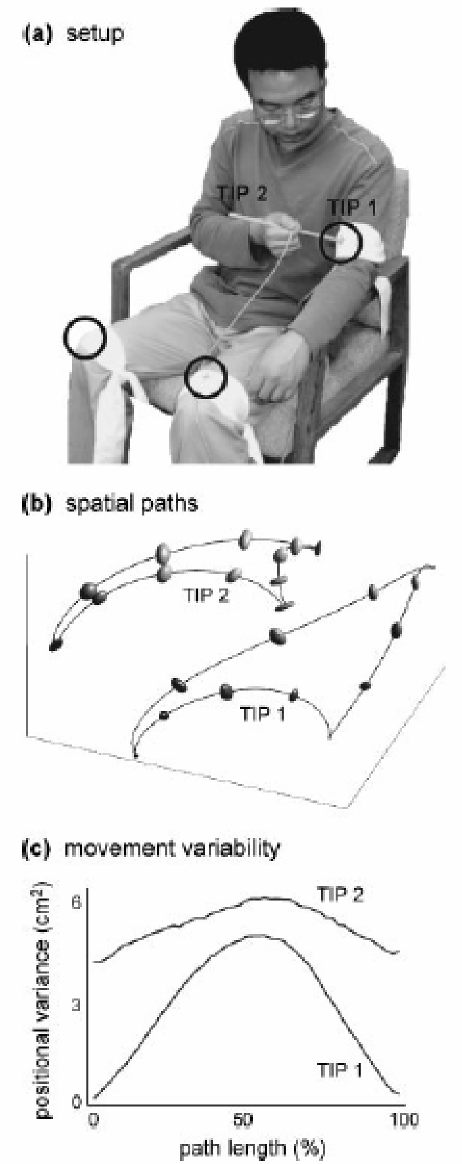
Endpoint velocity is “bell-shaped”



Motor behavior

- But production of a fixed “desired trajectory”, whether through optimization or not, does no account for some features of motor behavior.

- For example, it doesn’t predict increased variability in dimensions of state-space that are not relevant to the task.

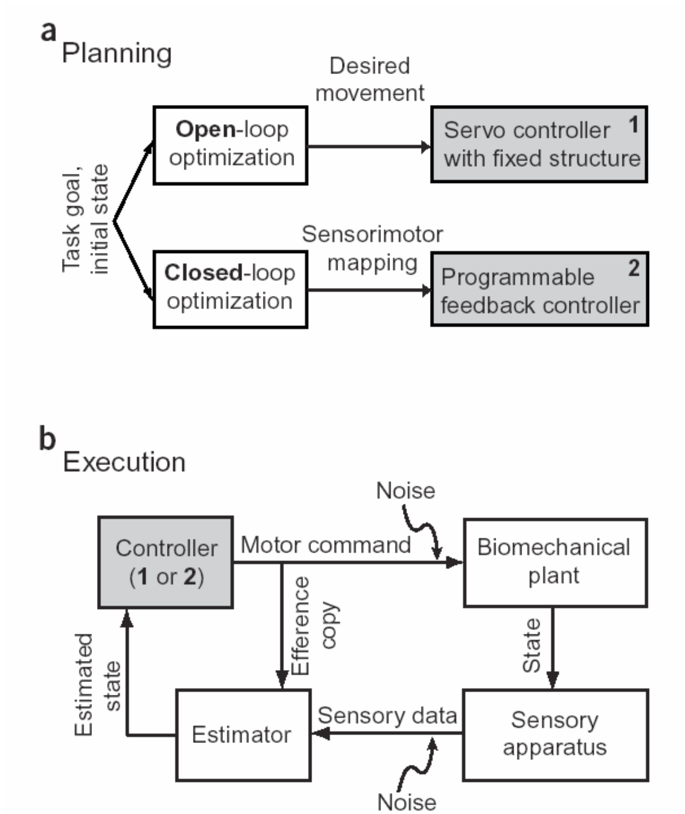


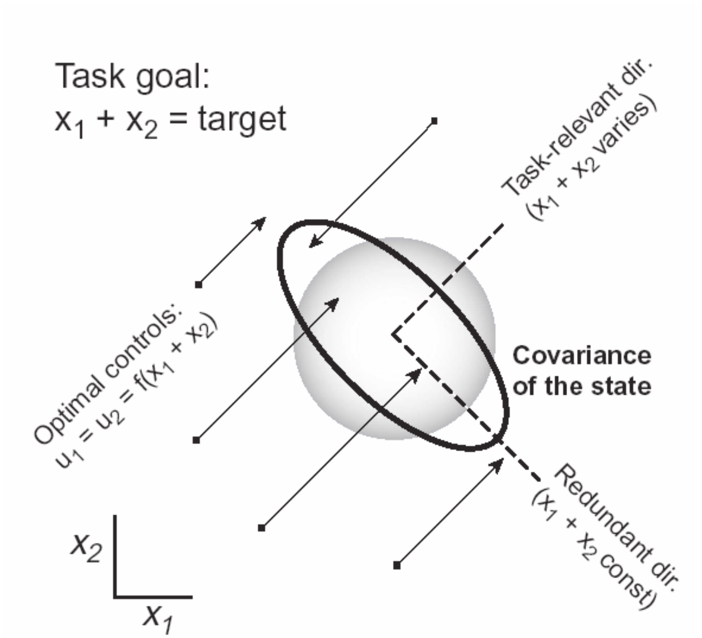
Todorov et al, 2005

Motor behavior

- Optimal feedback control may provide a better description of motor planning, as well as motor execution.

- But what is the cost function?





Todorov, 2004

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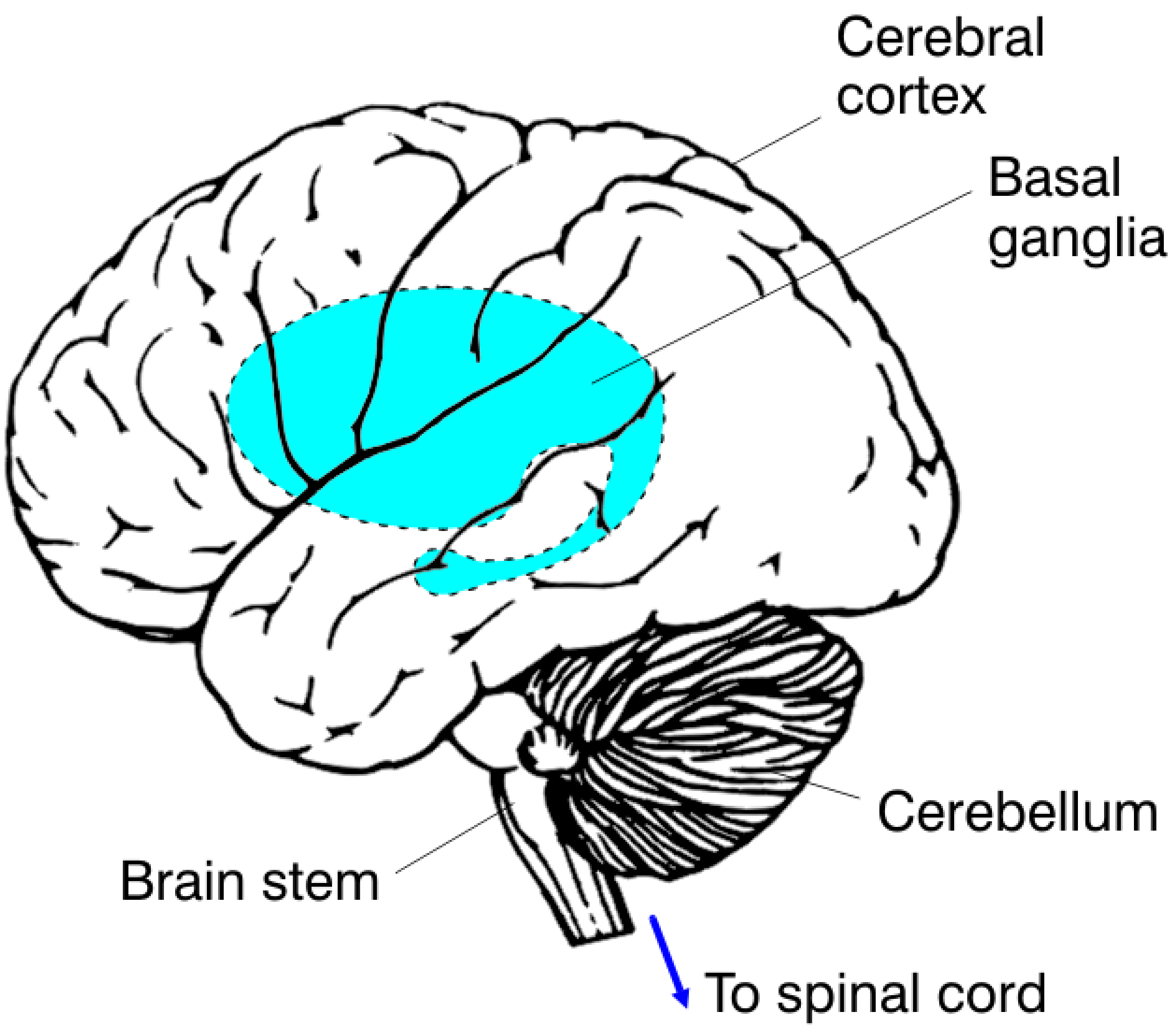
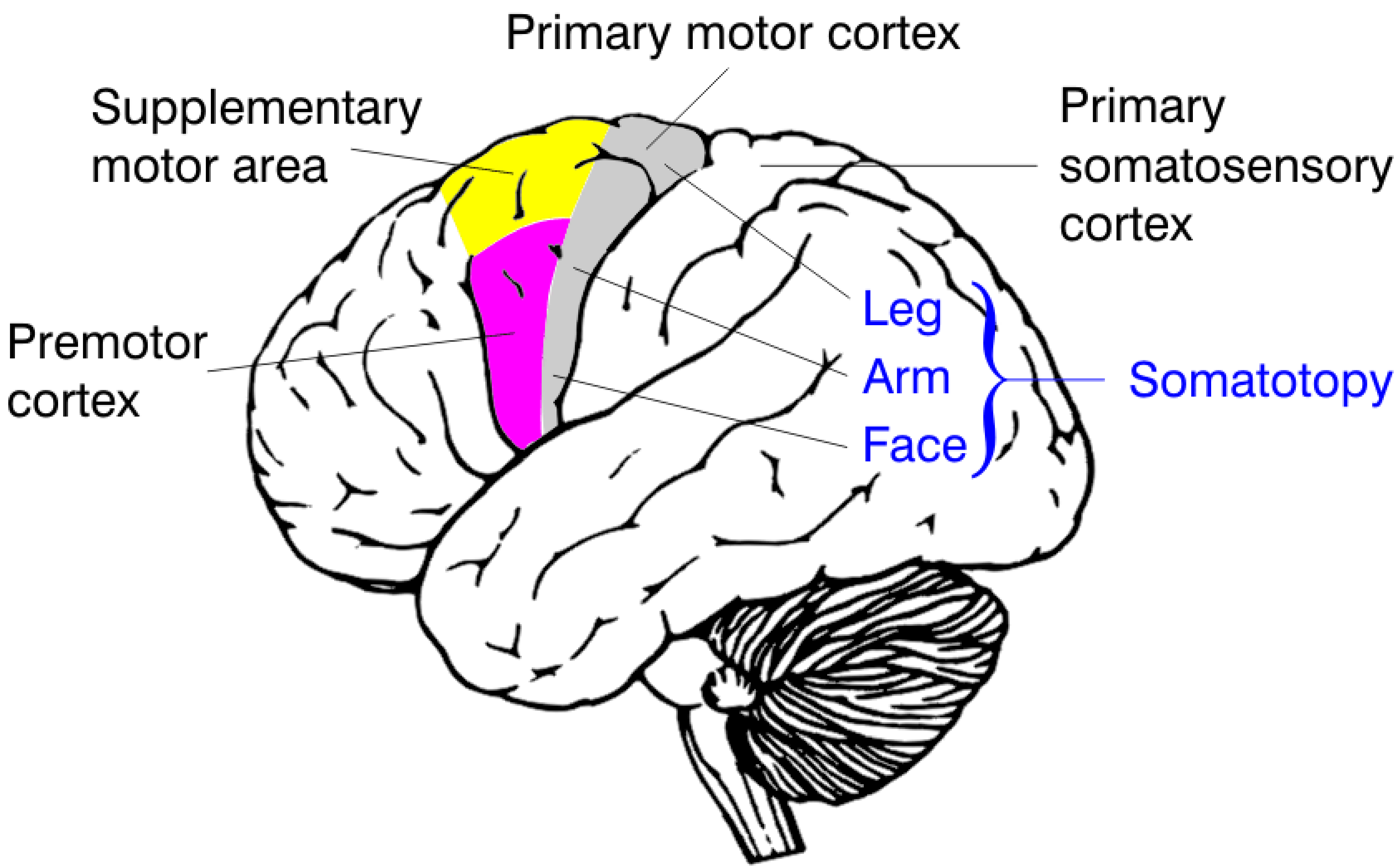
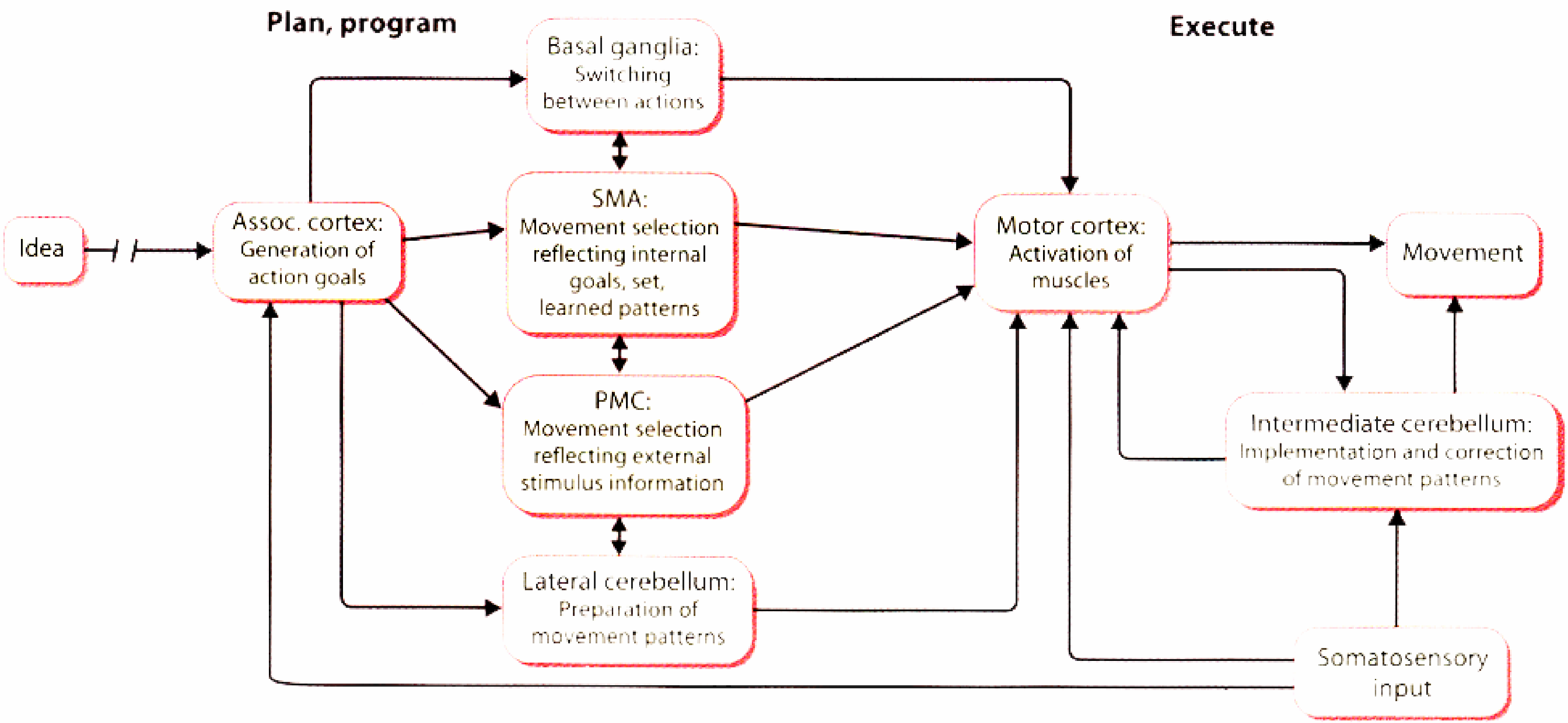
Motor neurophysiology



Motor neurophysiology

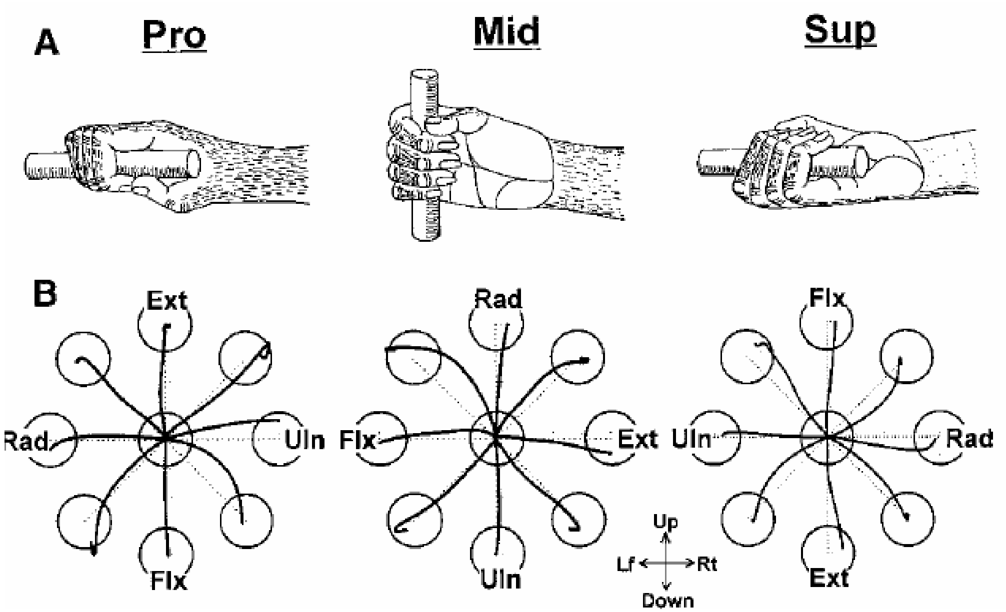


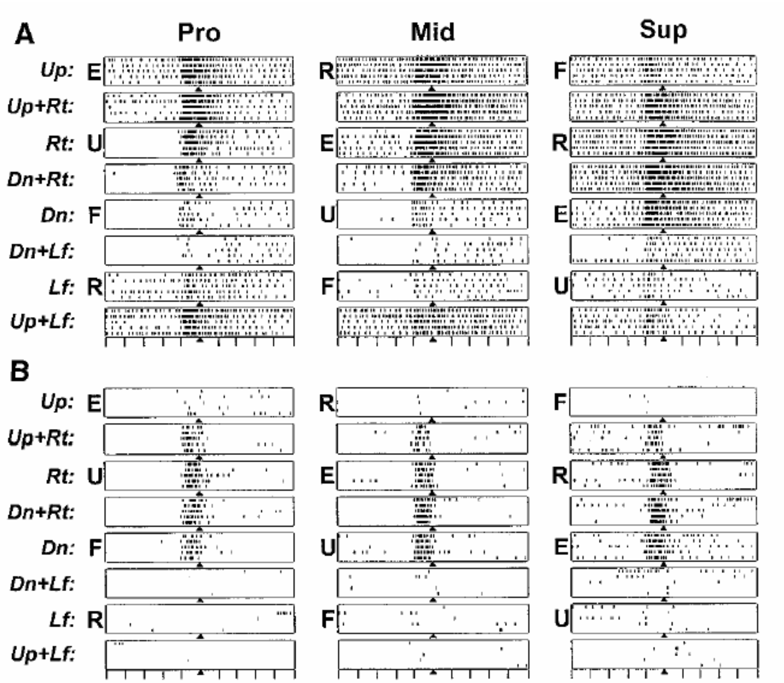
Motor neurophysiology



Motor neurophysiology

- What is encoded in motor cortex – kinematics or dynamics?
  - Neural recording experiments

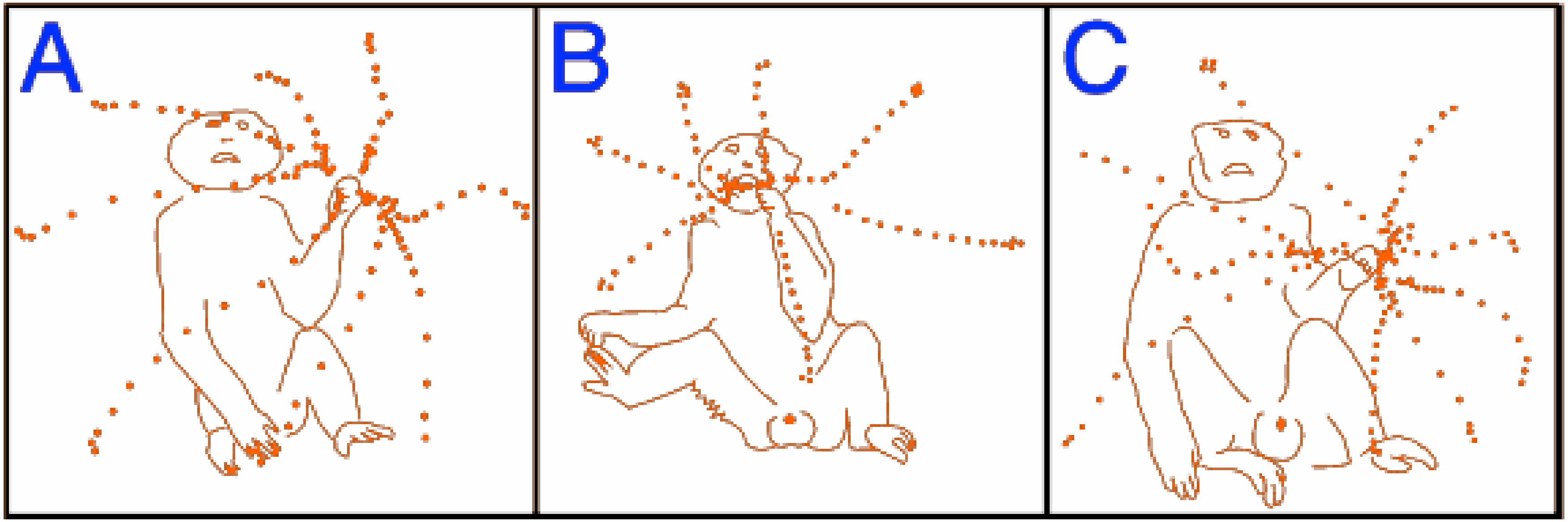




Kakei et al, 1999

Motor neurophysiology

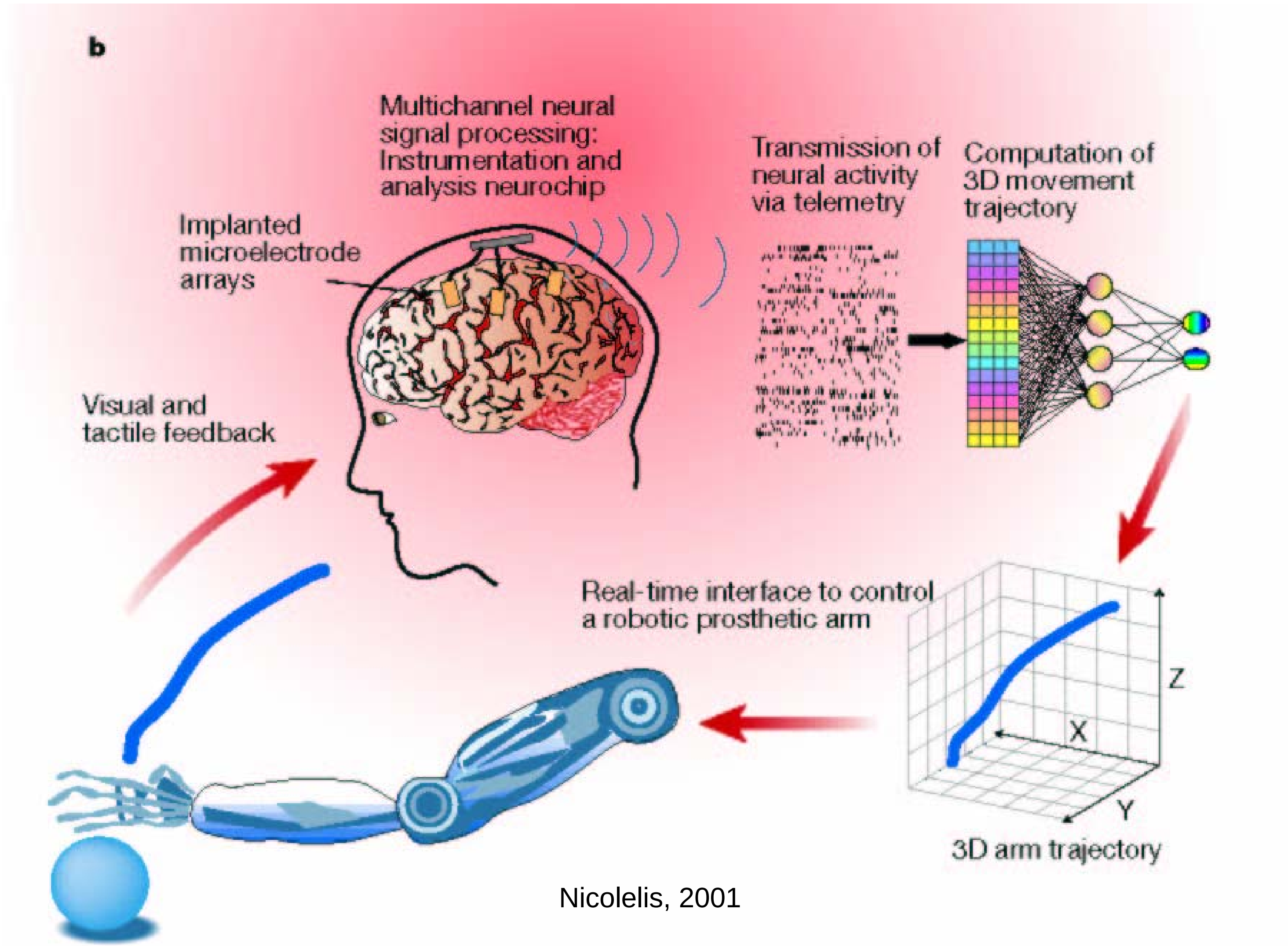
- What is encoded in motor cortex – kinematics or dynamics?
  - Neural stimulation experiments



Graziano, 2002

Motor neurophysiology

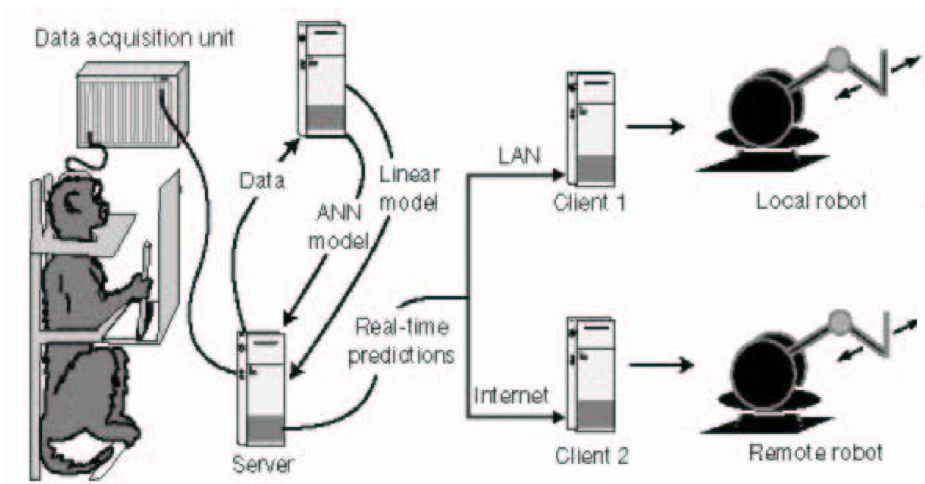
- Engineering application: cortically-controlled neural prosthetics

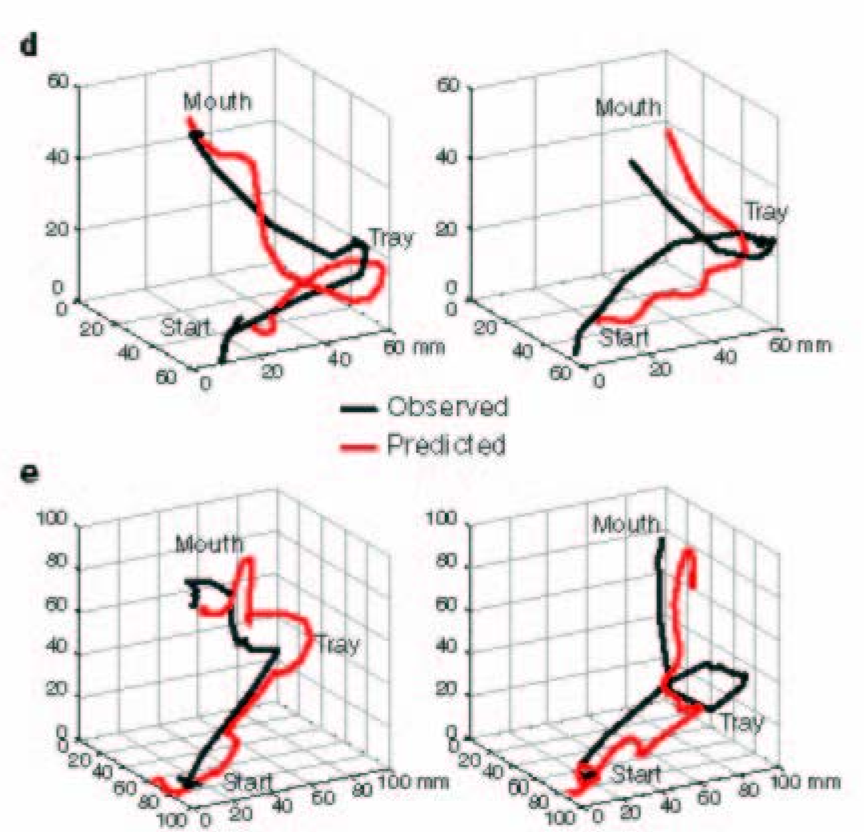


Nicolelis, 2001

Motor neurophysiology

- Neural control of a robot





Wessberg et al, 2000