Lecture Outline

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

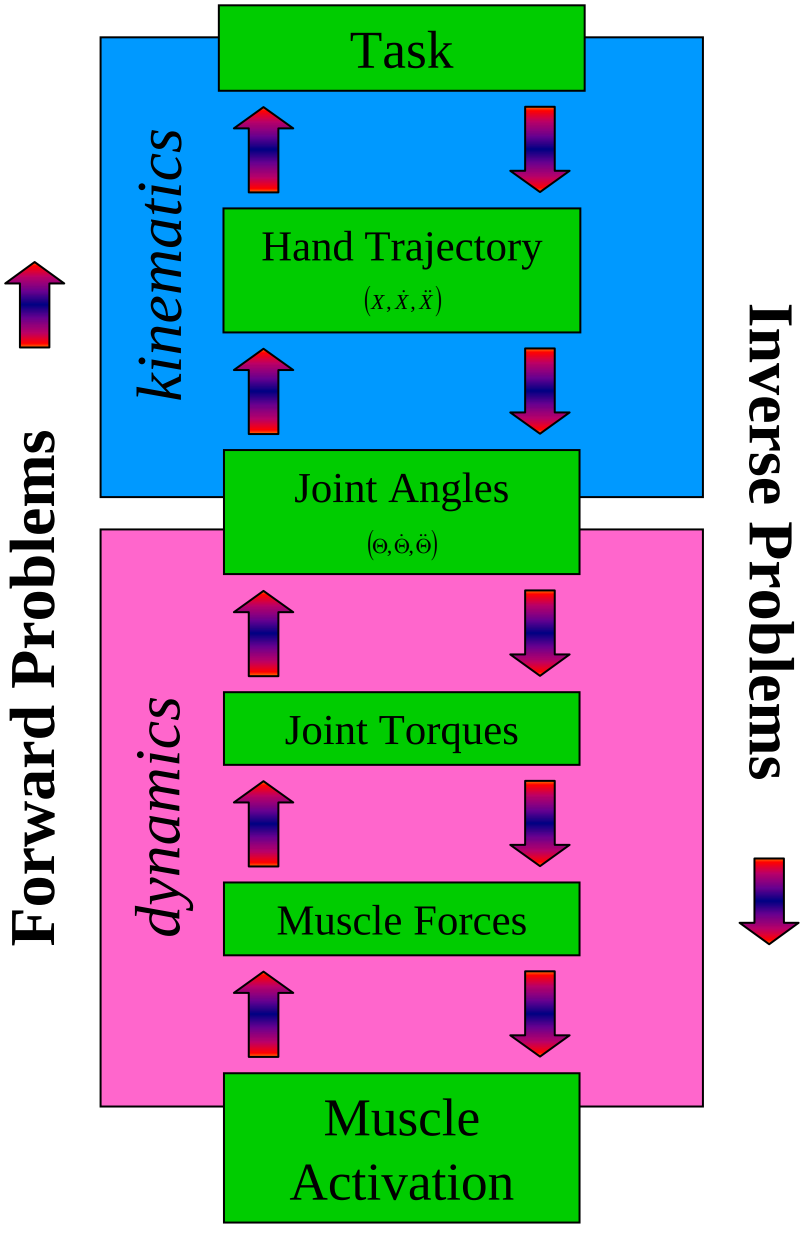
- Basic Control Theory

  Engineering for Neuroscientists

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

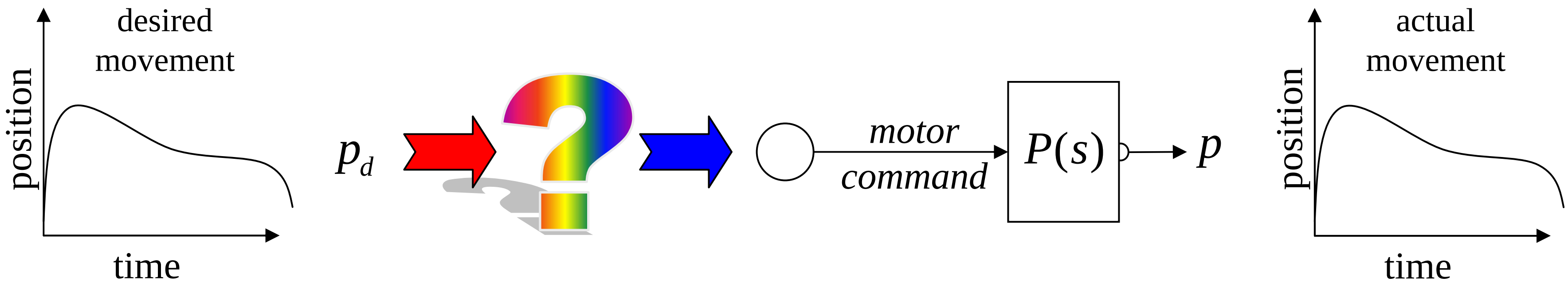
  Neurophysiology for Engineers

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

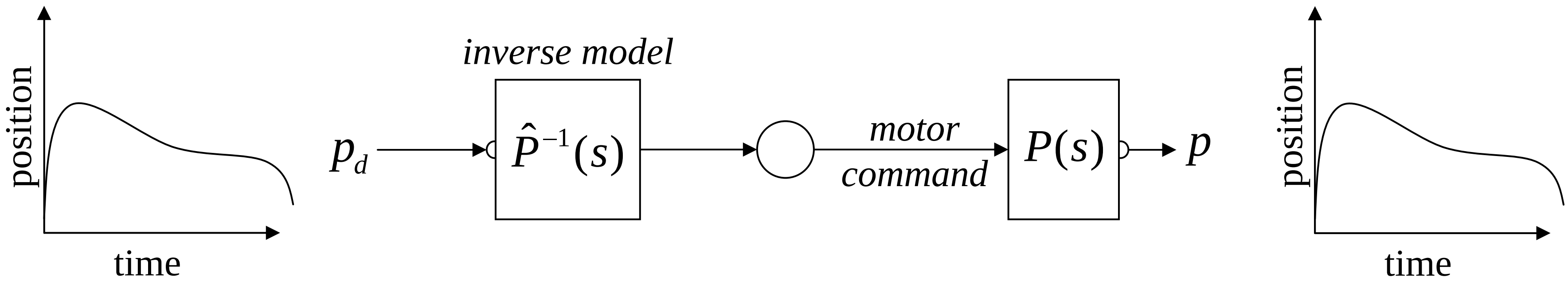


Source: J. McIntyre

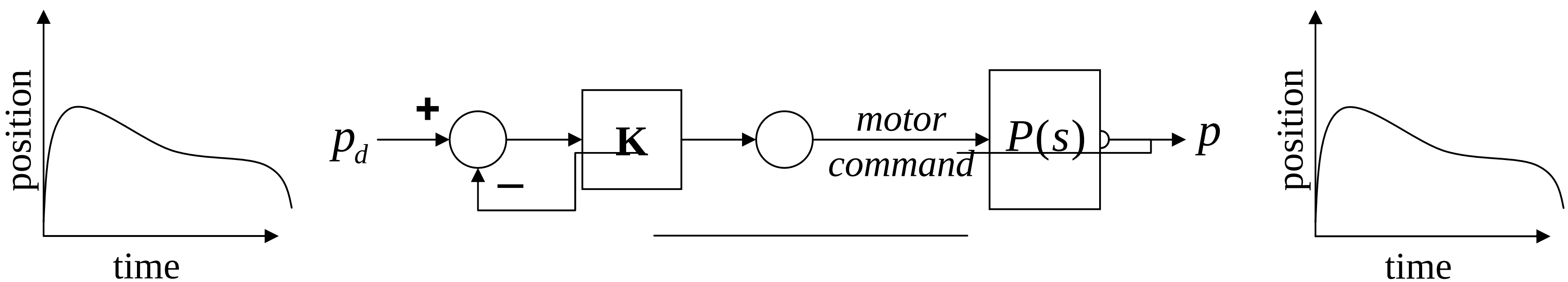
Feedforward versus Feedback Control



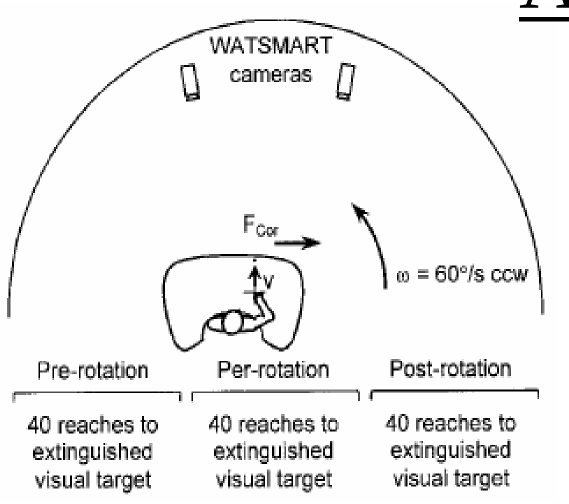
Feedforward Control: compute control based on knowledge of physics



Feedback Control: generate commands based on error signals

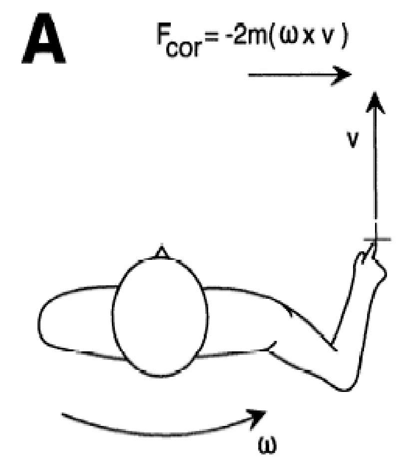


A Key Experiment



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

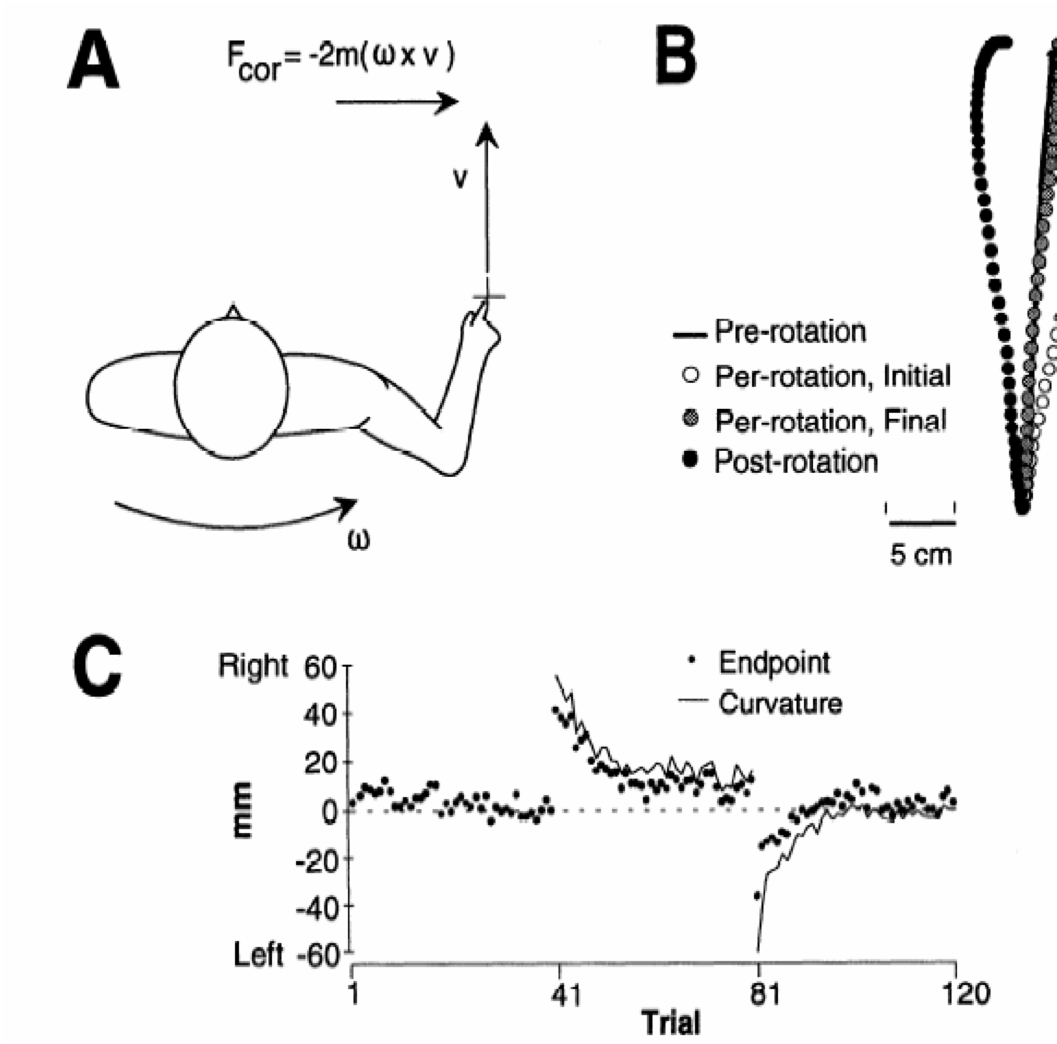
- Subjects seated at the center of circular room.
- The entire room spins continuously at 60°/s.
- The vestibular system is sensitive to changes in angular velocity.
- After a few seconds, the subject has **no perception that the room is turning**.



- 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

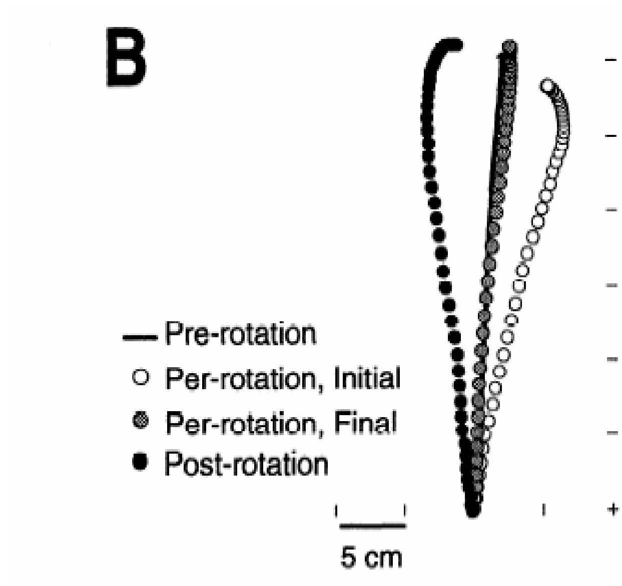


P Dizio and J Lackner *J. Neurophysiol.* 1994.

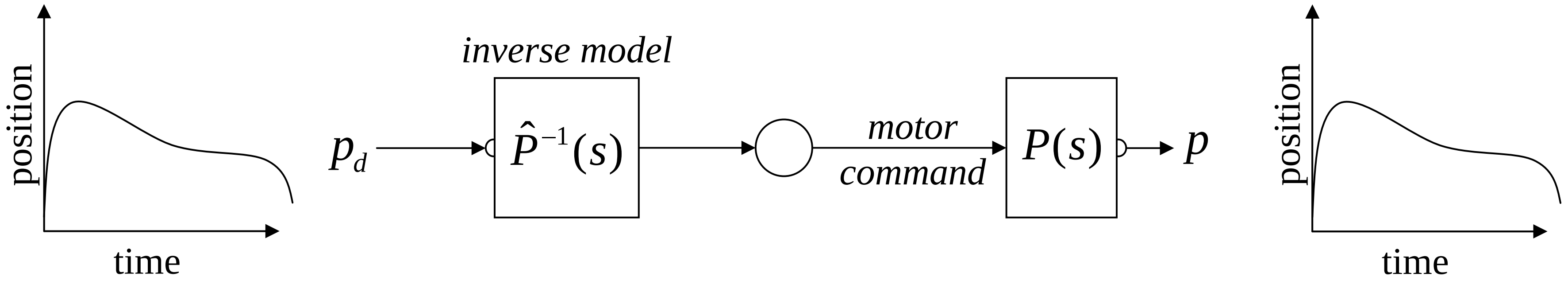
Question: Is this evidence for feedforward or feedback control of movement?

Answer: YES!

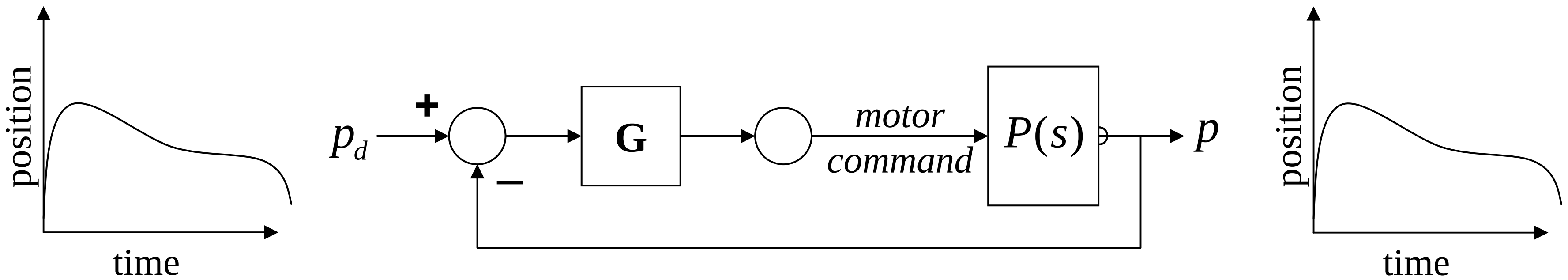
- Feedback
  - Correction of hand trajectory toward the target.
- Feedforward
  - Learning
  - After-effect



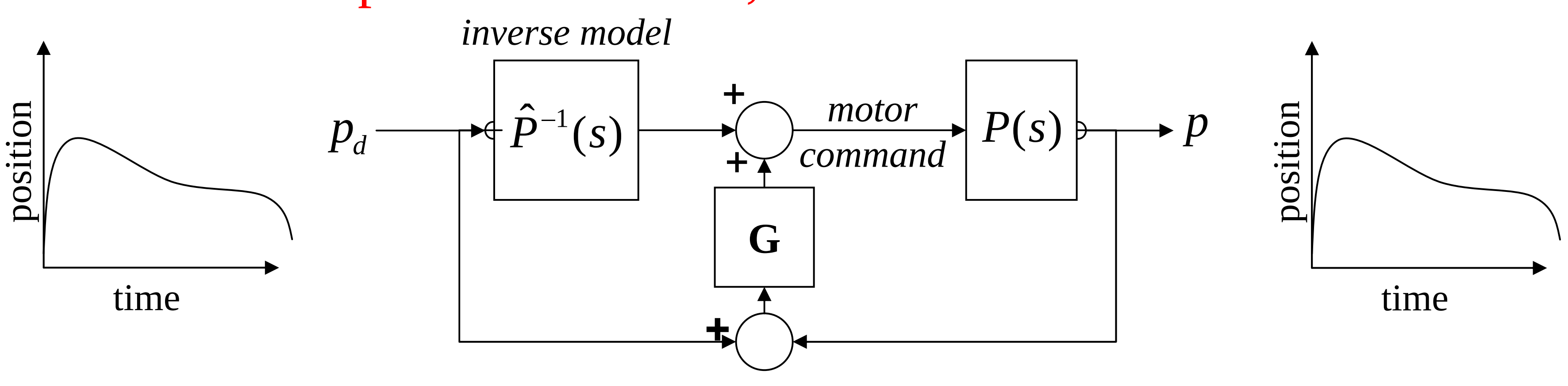
Feedforward Control: compute control based on knowledge of physics



Feedback Control: generate commands based on error signals



Combined: compute feedforward, correct with feedback



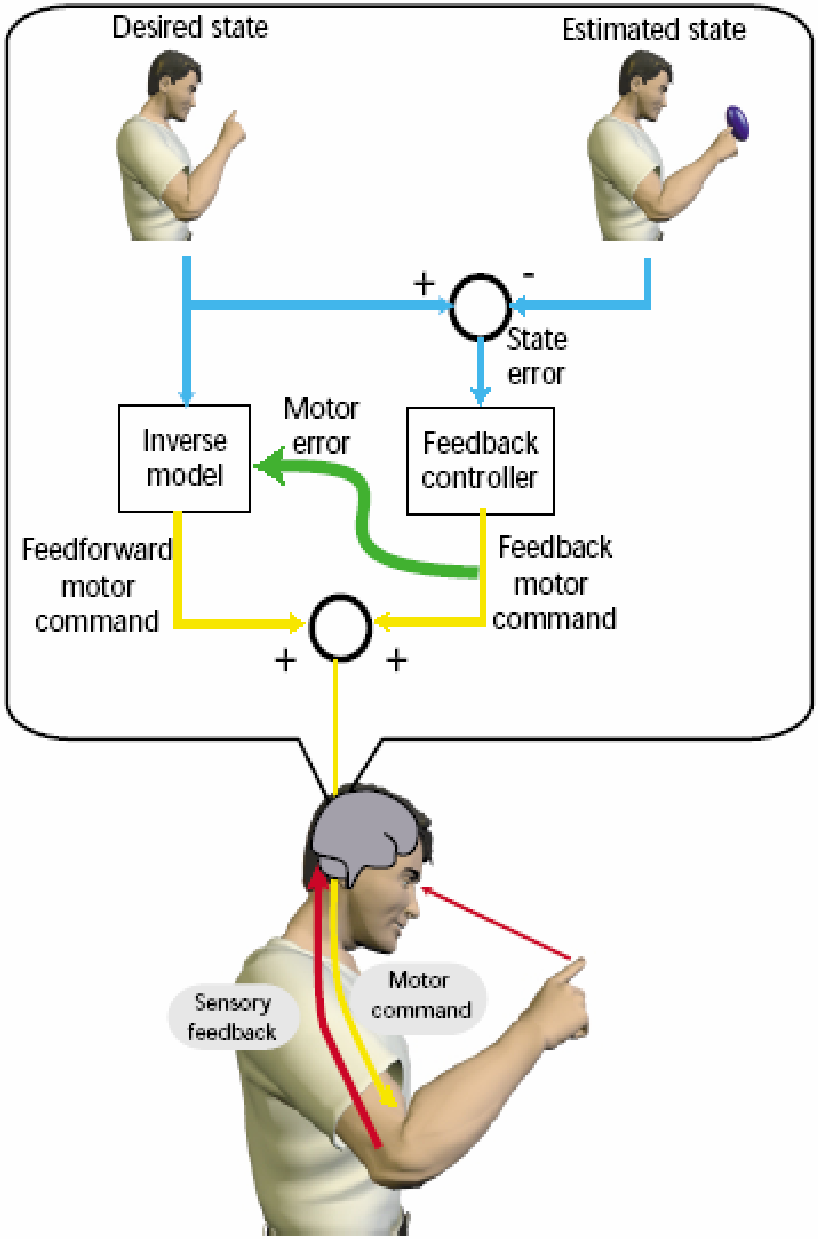
Where do **Inverse Models** come from?

Hypothesis:
Feedback
tunes
Inverse Model

Kawato, M., Furawaka, K. & Suzuki, R. A. *Biol. Cybern.* **56**, 1–17 (1987).

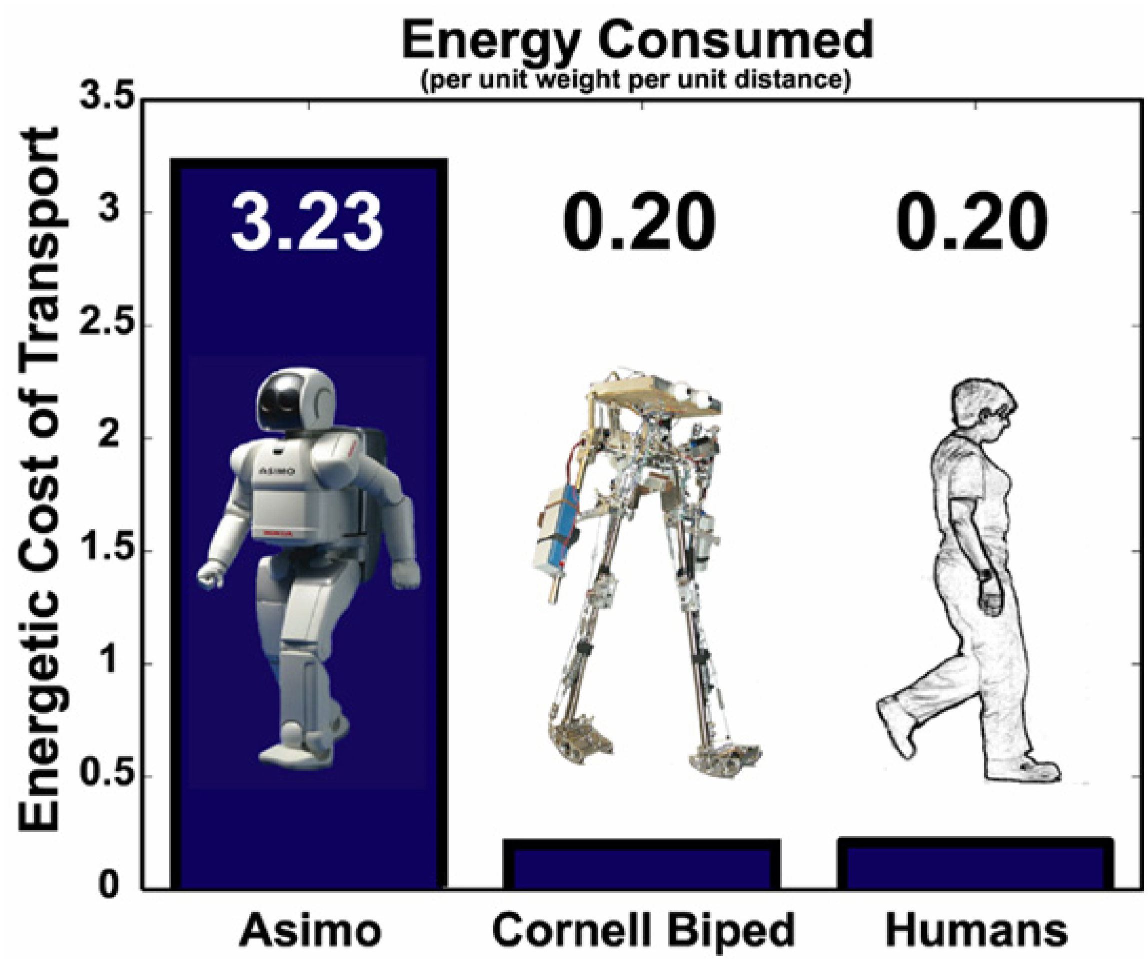
Kawato, M. & Gomi, H. *Trends Neurosci.* **15**, 445–453 (1992).

see: Wolpert, D and Ghahramani, Z. *Nat. Neurosci. Suppl.* 3, 1212–1217 (2000).



Exploiting the physics (revisited)

- Exploiting the physics (revisited)
  - Example: **Passive walkers**
    - Strong coupling between body architecture and control
    - http://www.sciencemag.org/feature/misc/hp_jumps/robots/cornell.html



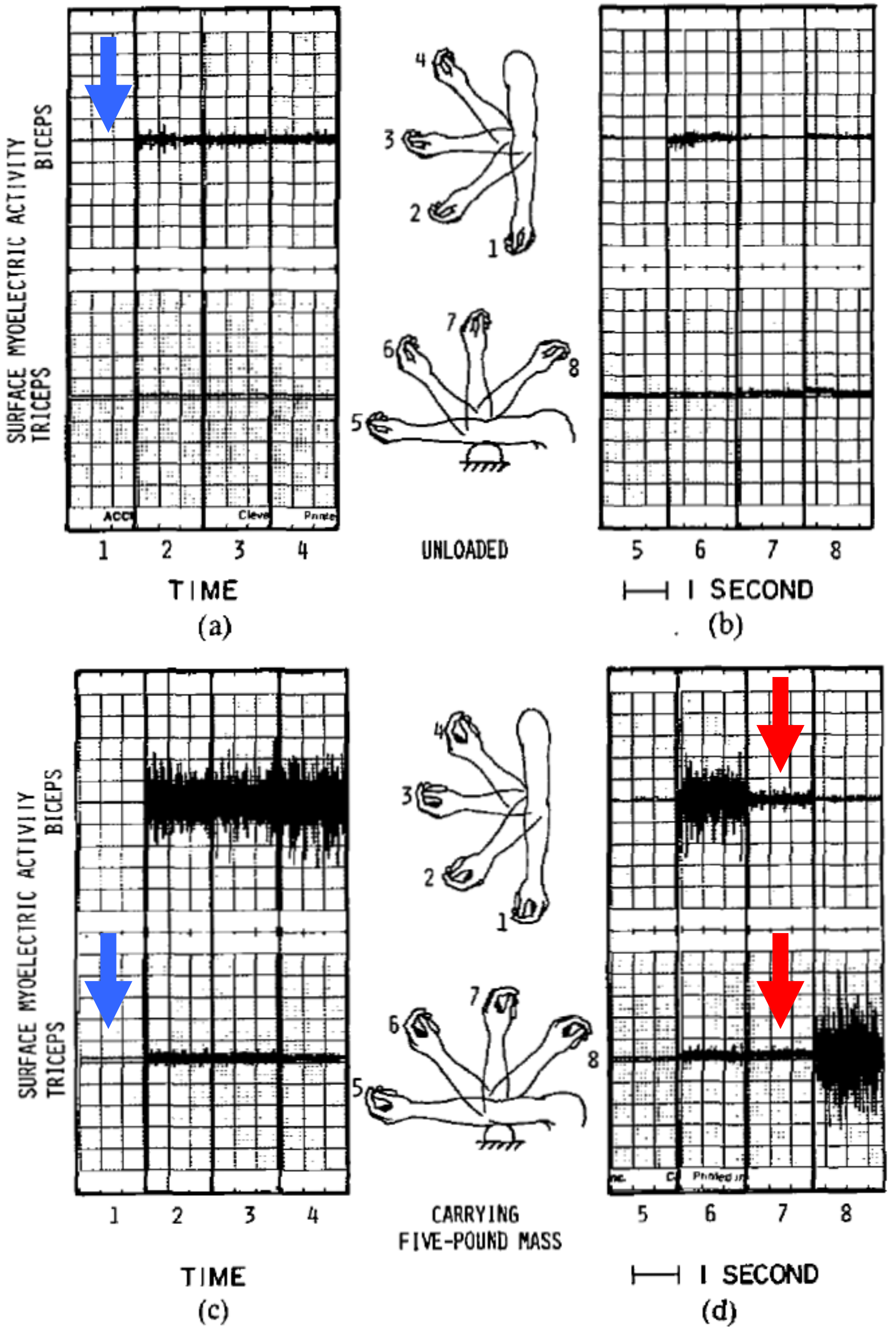
*Collins et al. Science **307**, 1082 (2005)*

Impedance control

- The **mechanical impedance** of the neuromuscular system determines the **reaction forces on the hand in response to perturbations from the manipulated object**
- Q. **Does the CNS modulate impedance?**
  - Fact: CNS is capable of varying the total stiffness and viscosity about a joint…

Impedance control

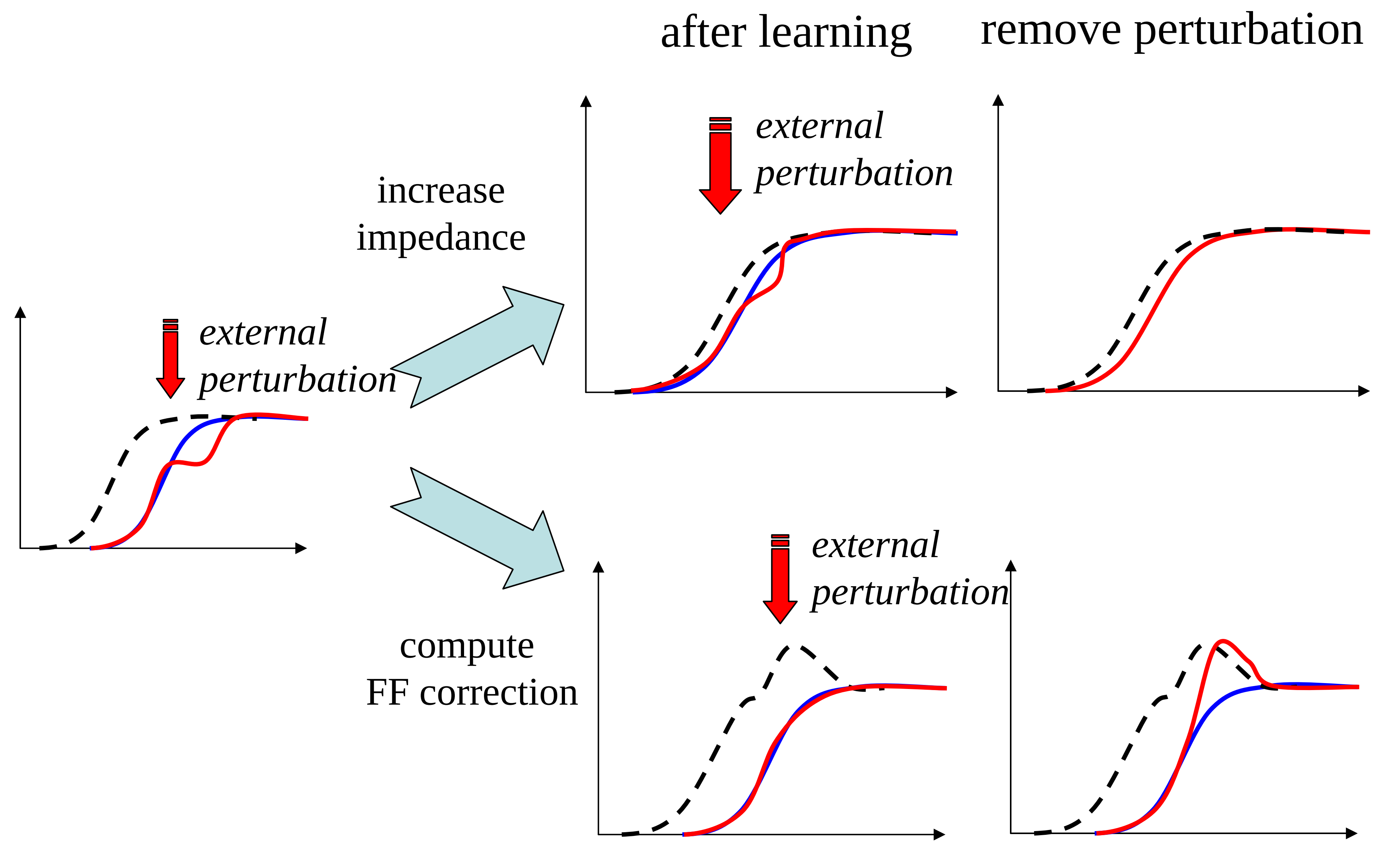
- Coactivation of antagonist muscles is frequently observed under normal physiological conditions
- Simultaneous activation of antagonists does not contribute to the useful work output of muscles (work = energy transferred by a force)
- Yet it costs input metabolic energy!
  - Question: What is the purpose?



- Hogan's postulate: CNS adaptively tunes the parameters of controlled system by **antagonist coactivation**
- Z control strategies
  - **Feedback**
    - + computationally cheap
    - - limited bandwidth and delay problems
  - **Feedforward**
    - + no bandwidth and delay limits
    - - metabolically expensive

N. Hogan, IEEE Trans Automatic Control, 1984

Which mechanism for disturbance compensation?

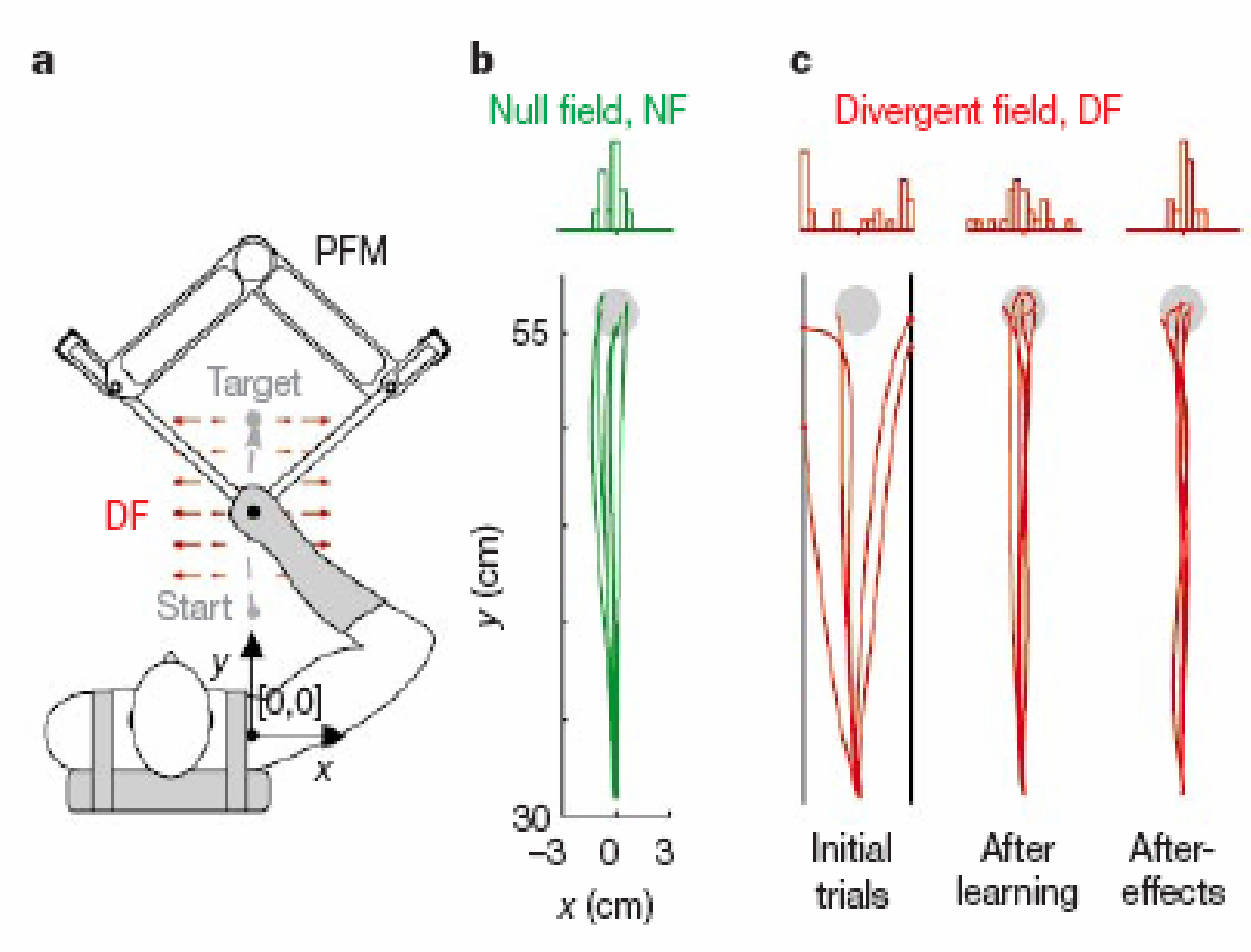


How do we succeed in performing mechanically unstable tasks?

H. Impedance can be voluntarily modified independently of the force applied by the hand

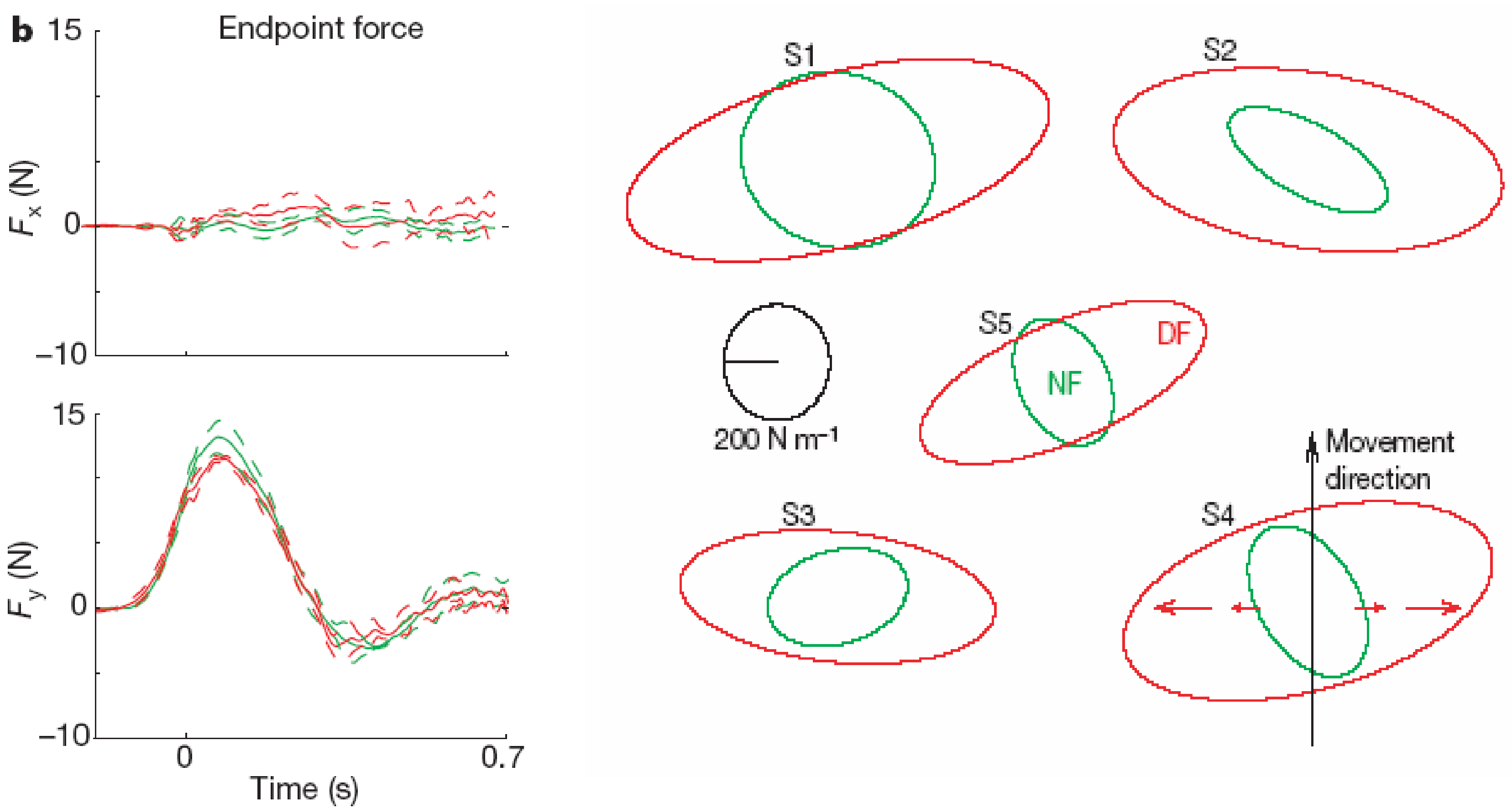
E Burdet et al. *Nature* 2001.

Lab version: Divergent Force Field



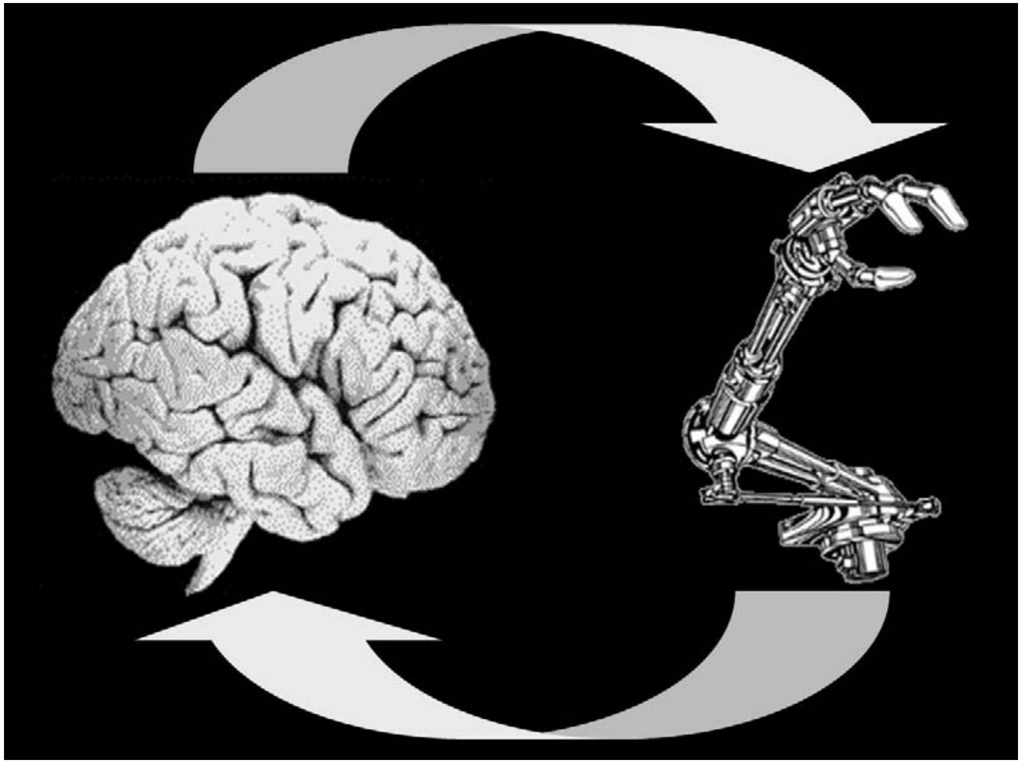
E Burdet et al. *Nature* 2001.

Adaptation of Hand Impedance



E Burdet et al. *Nature* 2001.

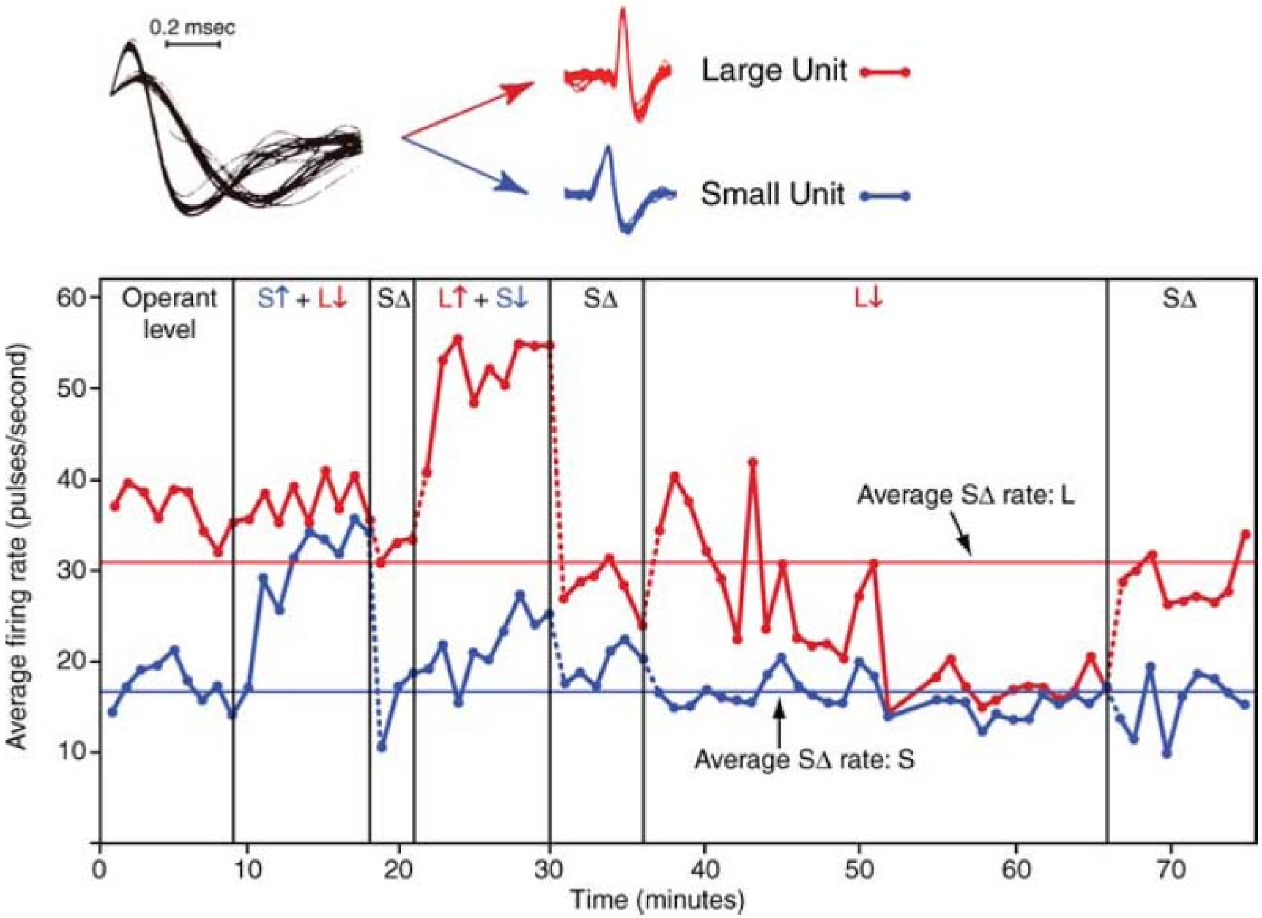
Brain Machine Interfaces

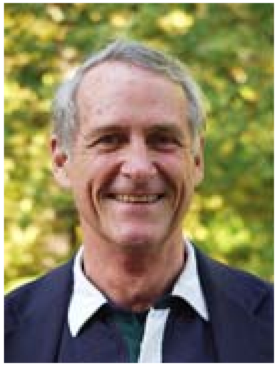


Key facts in BMI history

- Studies from Fetz and colleagues in the 70s demonstrated the concept of **biofeedback.**

Volitional control of neural activity





Eb Fetz (U. Washington)

Fetz and Baker, ***1973***

Key facts in BMI history

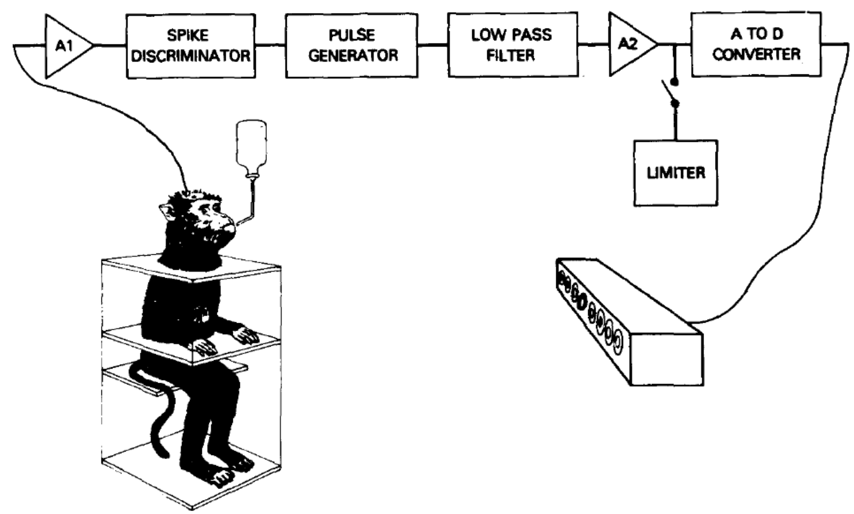
Annals of Biomedical Engineering, Vol. 8, pp. 339-349, 1980
Printed in the USA.

0090-6964/80/040339-11 $02.00/0
1981 Pergamon Press Ltd.

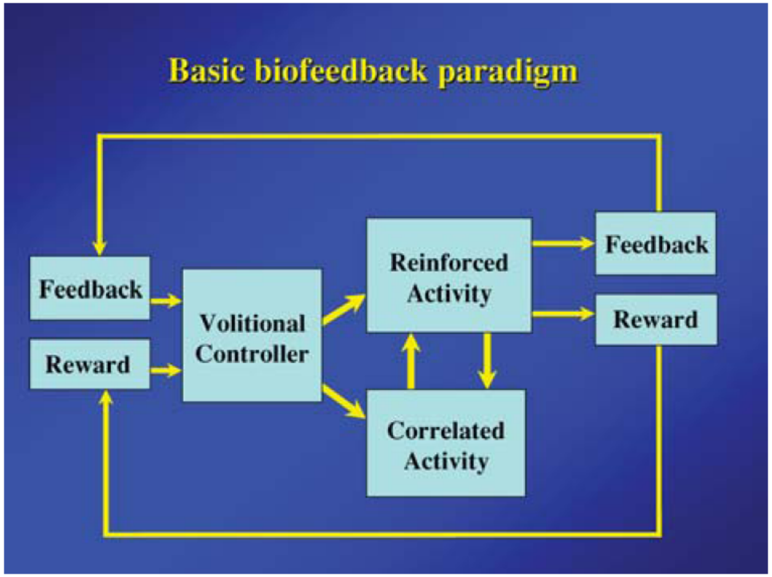
SINGLE NEURON RECORDING FROM MOTOR CORTEX AS A POSSIBLE SOURCE OF SIGNALS FOR CONTROL OF EXTERNAL DEVICES

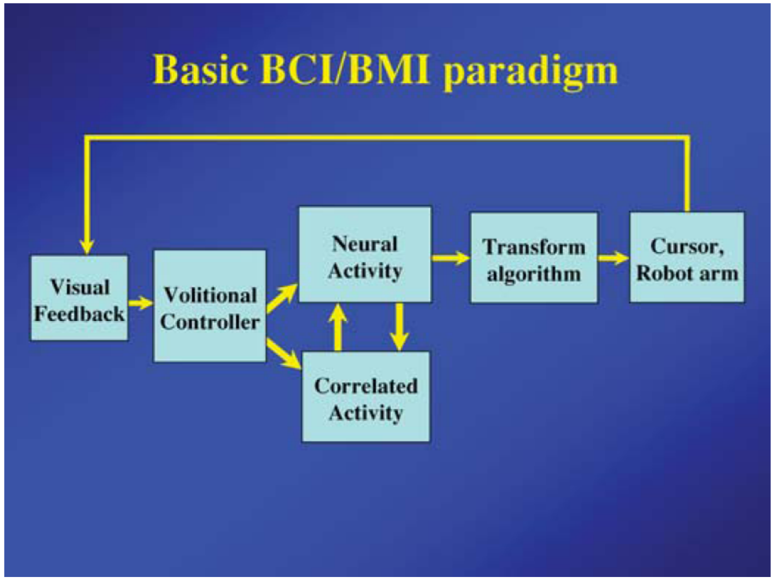
Edward M. Schmidt

Laboratory of Neural Control
National Institute of Neurological and Communicative Disorders and Stroke
National Institutes of Health
Bethesda, Maryland



Volitional control of neural activity





E. Fetz, J Physiology, 2007

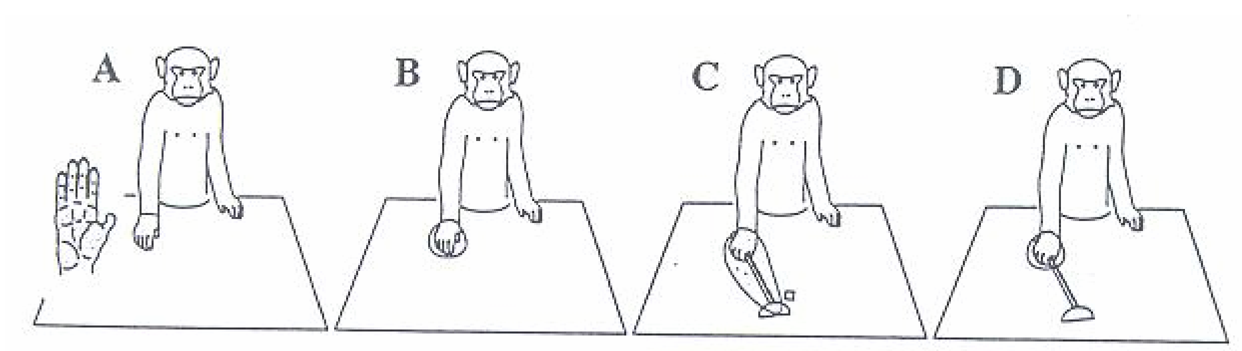
Evidence of volitional activation associated with behavior

- **During control of movement**
  - Movement preparation (Wise *et al.* 1983; Kurata & Wise, 1988; Alexander & Crutcher, 1990; Riehle & Requin, 1995; Crutcher *et al.* 2004).
  - Execution of voluntary movements (Evarts, Mountcastle, Georgopoulos and many others)
  - Imagined movements (Jeannerod, 1995; Roth *et al.* 1996; Jeannerod & Frak,1999; Niyazov *et al.* 2005)

Key facts in BMI history

- Studies from Fetz and colleagues in the 70s demonstrated the concept of **biofeedback.**

- More recently, Iriki and others showed how **body schema extends** along a reaching **tool** after long term **usage**.



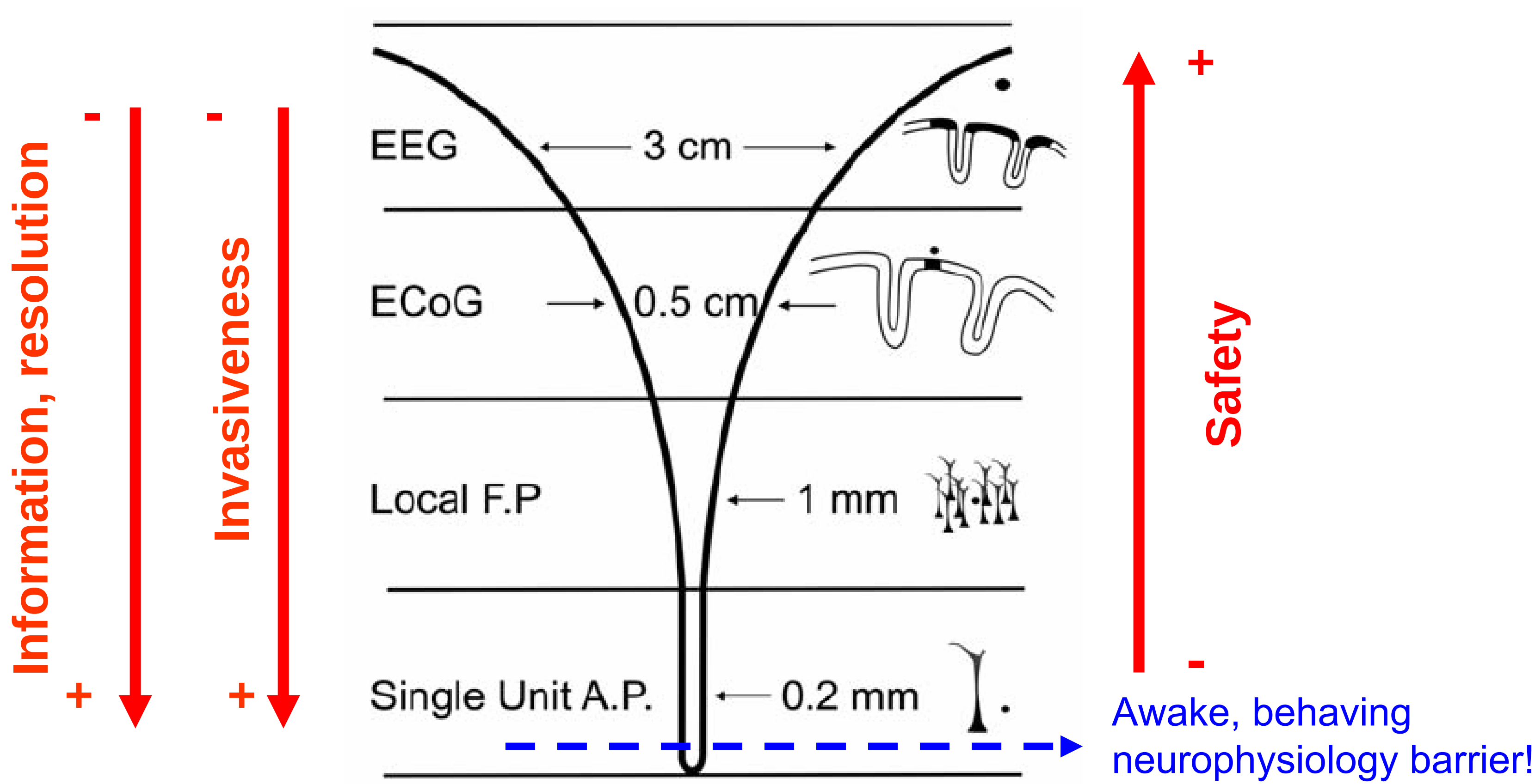
Key facts in BMI history

- Studies from Fetz and colleagues in the 70s demonstrated the concept of **biofeedback.**
- More recently, Iriki and others showed how **body schema extends** along a reaching **tool** after long term **usage**.
- Recent fMRI studies indicate that **cortical areas** involved in motor planning and execution **remain active in paralyzed patients** years after spinal cord injuries.

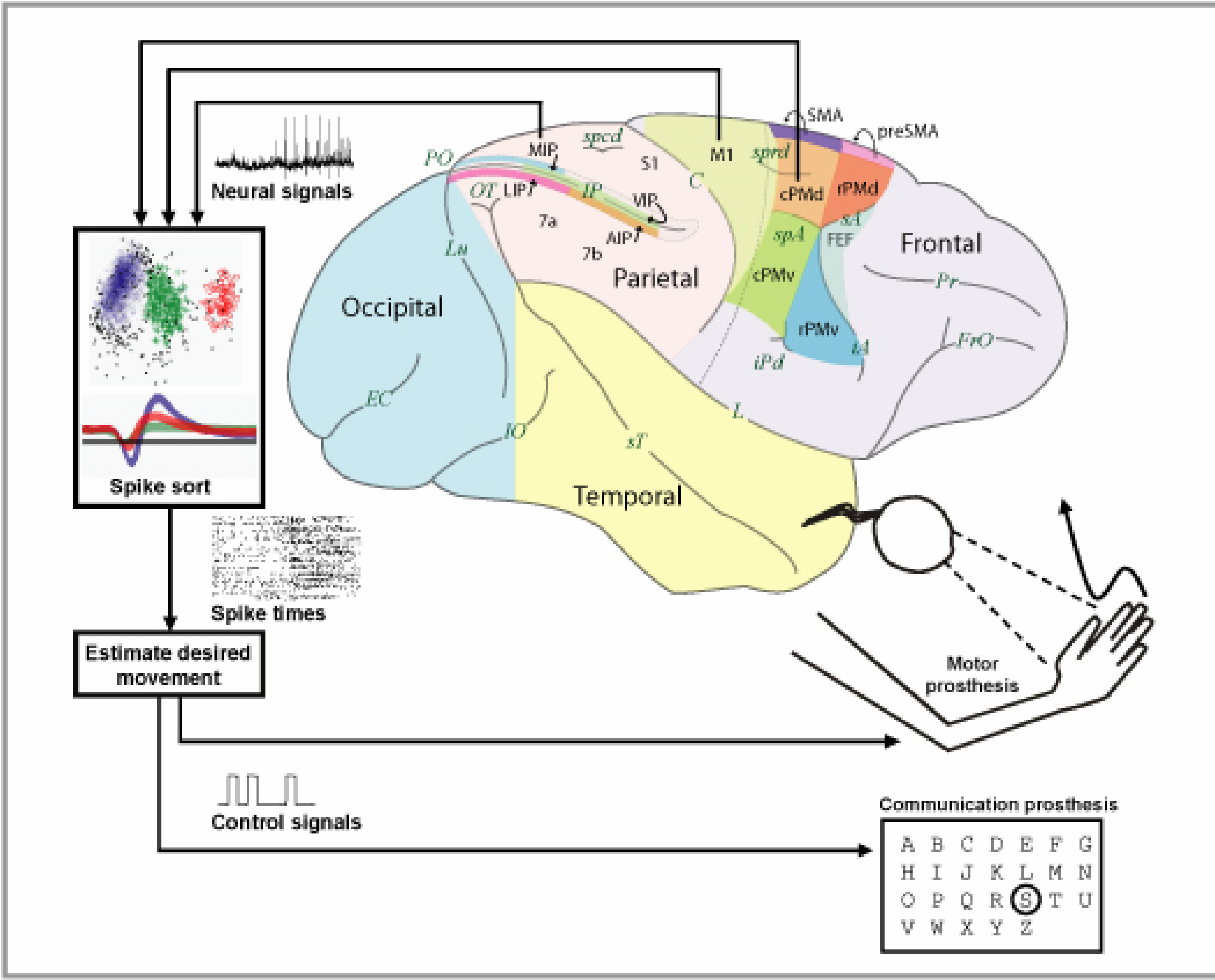
BMI classification

- Based on the approach used
  - Non-invasive
    - EEG, e.g. cursor and wheelchair control
    - PET/MRI/MEG are **not portable** and very expensive
  - Invasive
    - Chronic microelectrode arrays
- Based on the flow of information
  - Encoding (sensory prosthesis)
    - e.g. cochlear implant, artificial retina…
  - Decoding (motor prosthesis)
    - e.g. cursor control, robot reaching and grasping…

Recorded neural activity: spatial domains

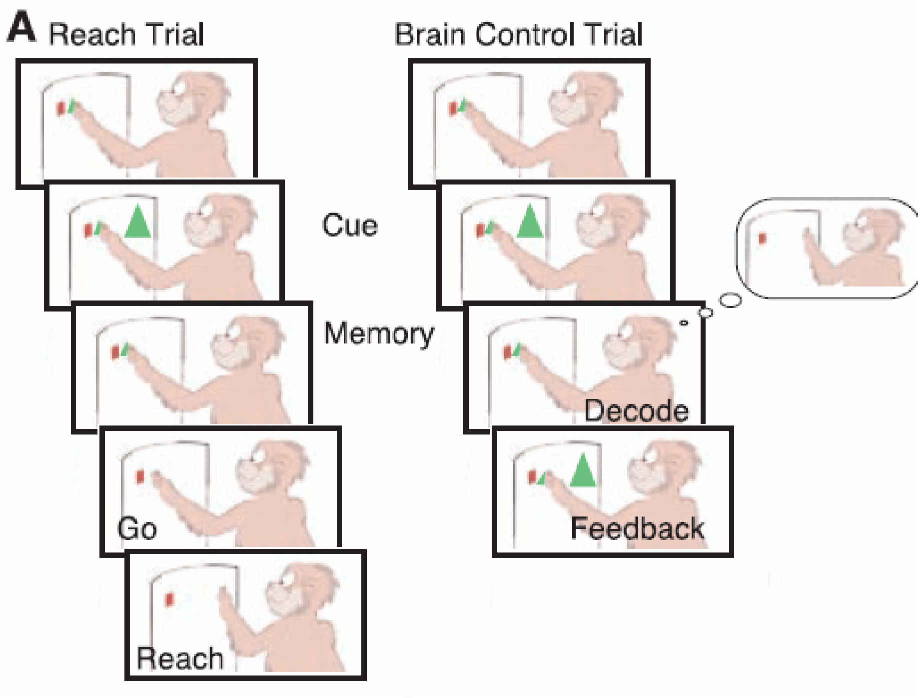


Schwartz et al. *Neuron*, 2006



Source: Shenoy's lab

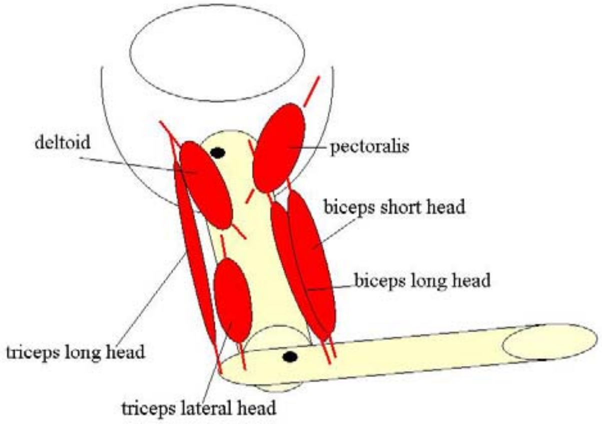
Cognitive prosthesis
Musallam et al., 2004



- Example of <u>discrete control</u> BMI
- Simultaneous decoding of goal of movement + **expected value** signals (e.g. juice reward)
- Subjects became proficient through training (BMI induced cortical plasticity)

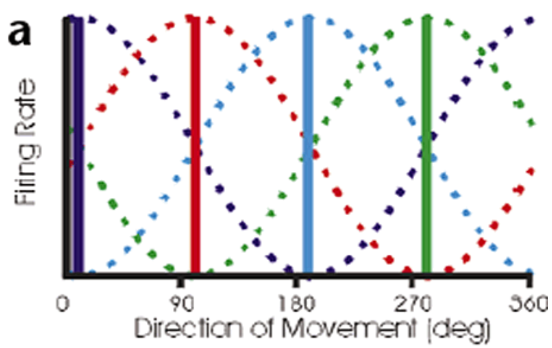
Motor prostheses

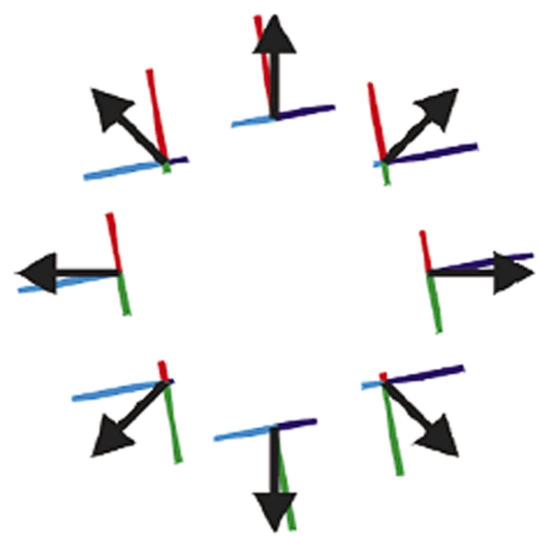
- Previous BMI work has relied on predictions of the end effector (hand) position and velocity.
- Is this because M1 encodes high-level parameters of hand movement ?
  - Big debate in neuroscience!



One motor cortex, two different views

1. **Georgopoulos**
   - Neuronal population vector
   - M1 correlates with <u>**high-level parameters**</u> of hand movement





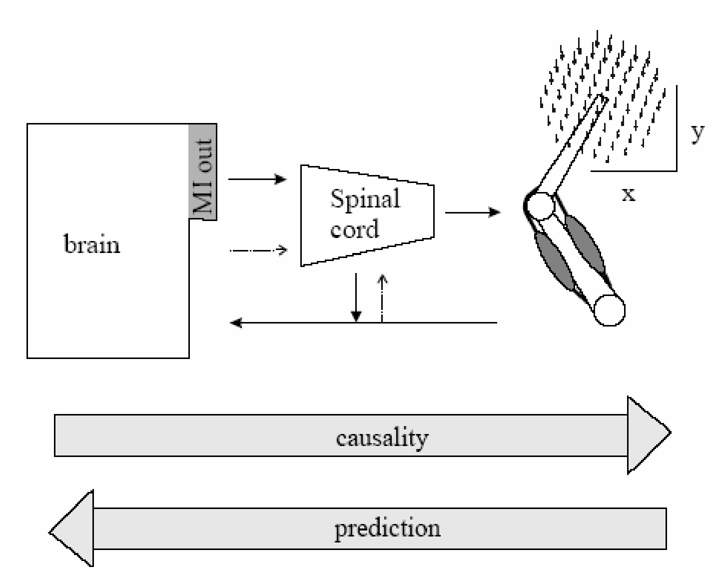
One motor cortex, two different views

2. Todorov

Direct cortical control of muscle activation in voluntary arm movements: a model

Emanuel Todorov

Gatsby Computational Neuroscience Unit, University College London, 17 Queen Square London WC1N 3 AR, UK
Correspondence should be directed to E.T. (emo@gatsby.ucl.ac.uk)

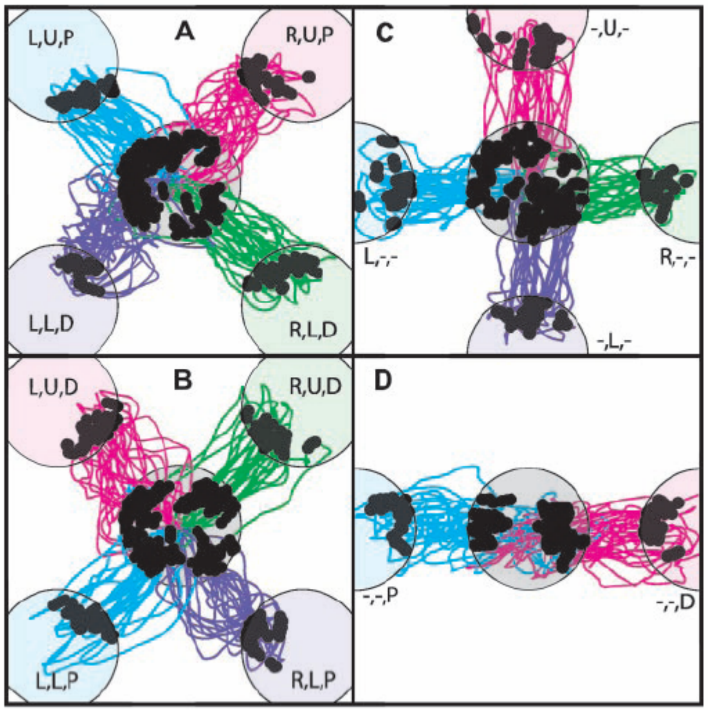


Causal flow from the MI output through spinal processing, muscle force production and multijoint mechanics **to endpoint force**.

Predictions about MI activity are obtained by 'inverting' that causal flow.

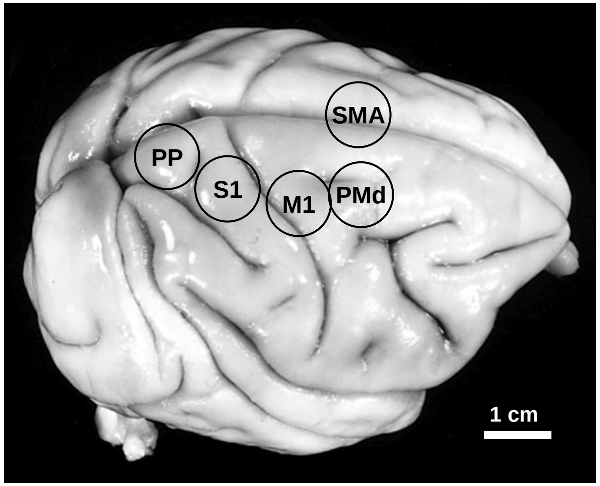
E. Todorov, Nature Neurosc. 2000

Motor prosthesis
Taylor et al., 2002

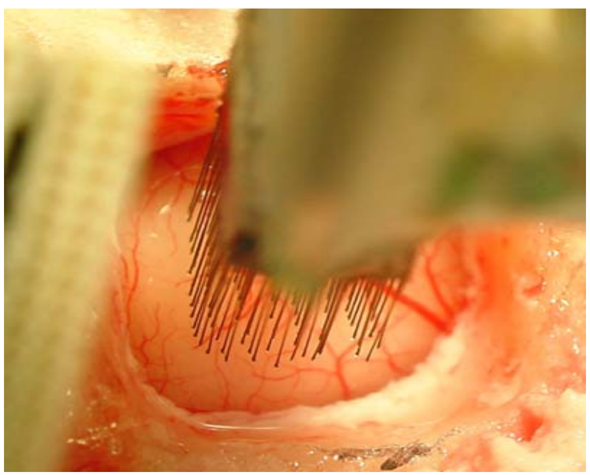


- Example of <u>continuous control</u> BMI with peri-event movement (to be discussed later in the course)
- 3D reaching movements
- Evidence of cell tuning changes in brain control movements and improvement with training (BMI induced cortical plasticity)

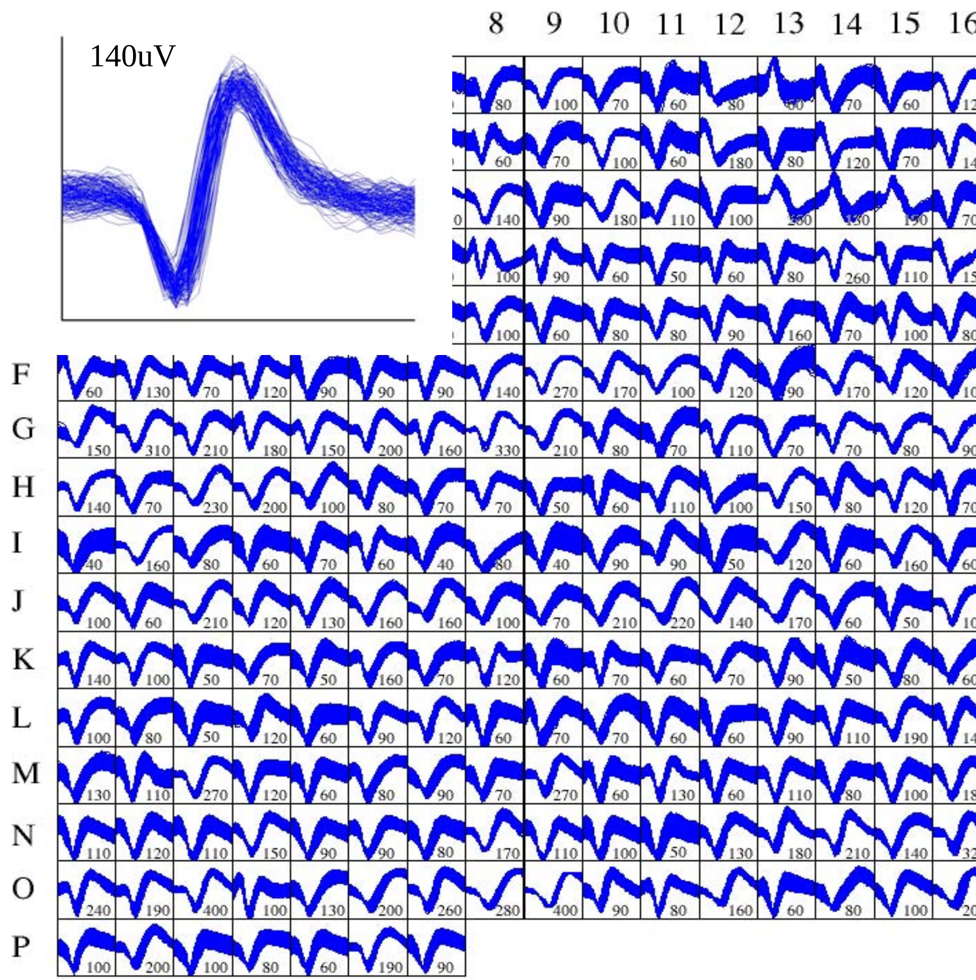
CHRONIC, MULTISITE, MULTIELECTRODE RECORDINGS



- **SMA**: supplementary motor area
- **PMd**: dorsal premotor cortex
- **M1**: primary motor cortex
- **S1**: primary somatosensory cortex
- **PP**: posterior parietal cortex (MIP)

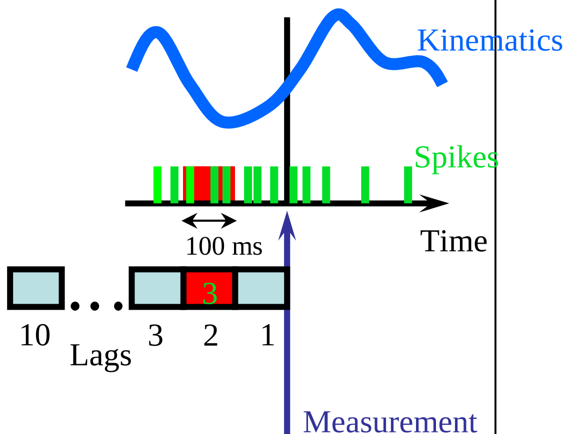


- **Materials**: Tungsten, polymide insulation, gold plated tip.
- **Separation**: 250-800μm
- **Diameter**: 35-50μm
- **Impedance**: 0.2-1 MegOhm @ 1kHz, 5nA



PNAS 100(19), 2003.

BMI MODELING:
DECODING MOTOR OUTPUT FROM SPIKE TRAINS



motor output

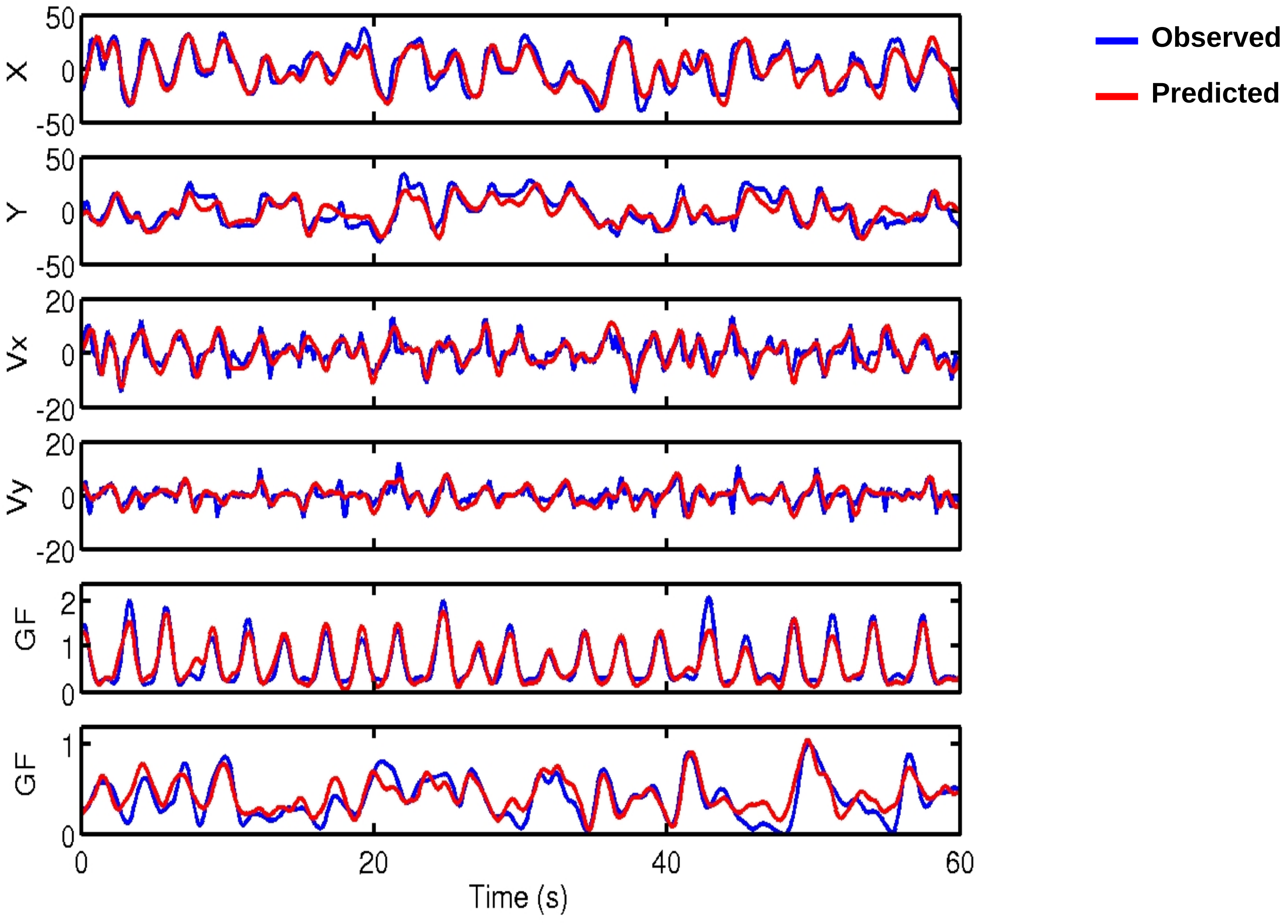
Linear regression model

$$\mathbf{y}(t) = \mathbf{b} + \sum_{u=-m}^{n} \mathbf{a}(u)\mathbf{x}(t-u) + \varepsilon(t)$$

$$\mathbf{Y}=\mathbf{XA}, \qquad \mathbf{A}=inv(\mathbf{X}^T\mathbf{X})\mathbf{X}^T\mathbf{Y}$$

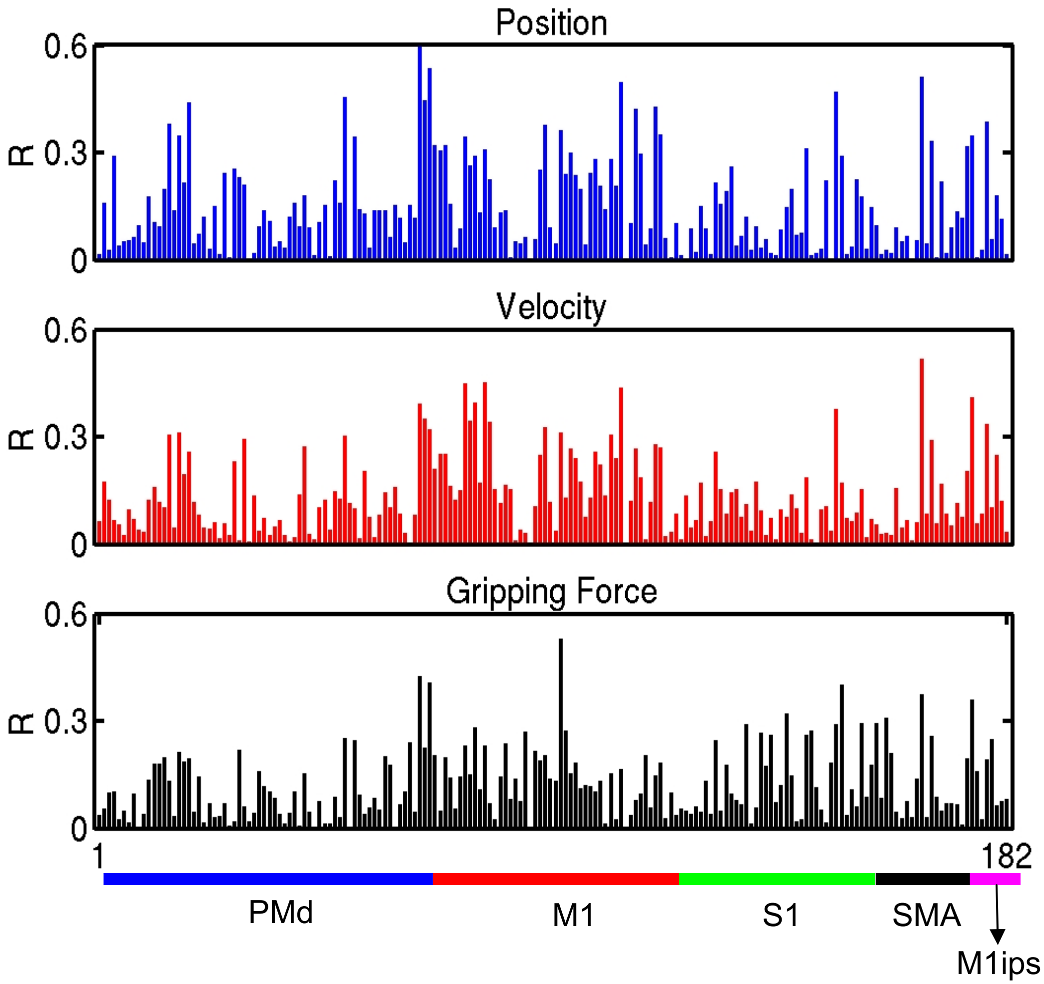
where **b** are the Y-intercepts, **a** is a set of weights required for the fitting as function of time lag ***u***, and ***ε*(*t*)** are the residual errors.

PREDICTIONS OF POSITION, VELOCITY, & GRIPPING FORCE



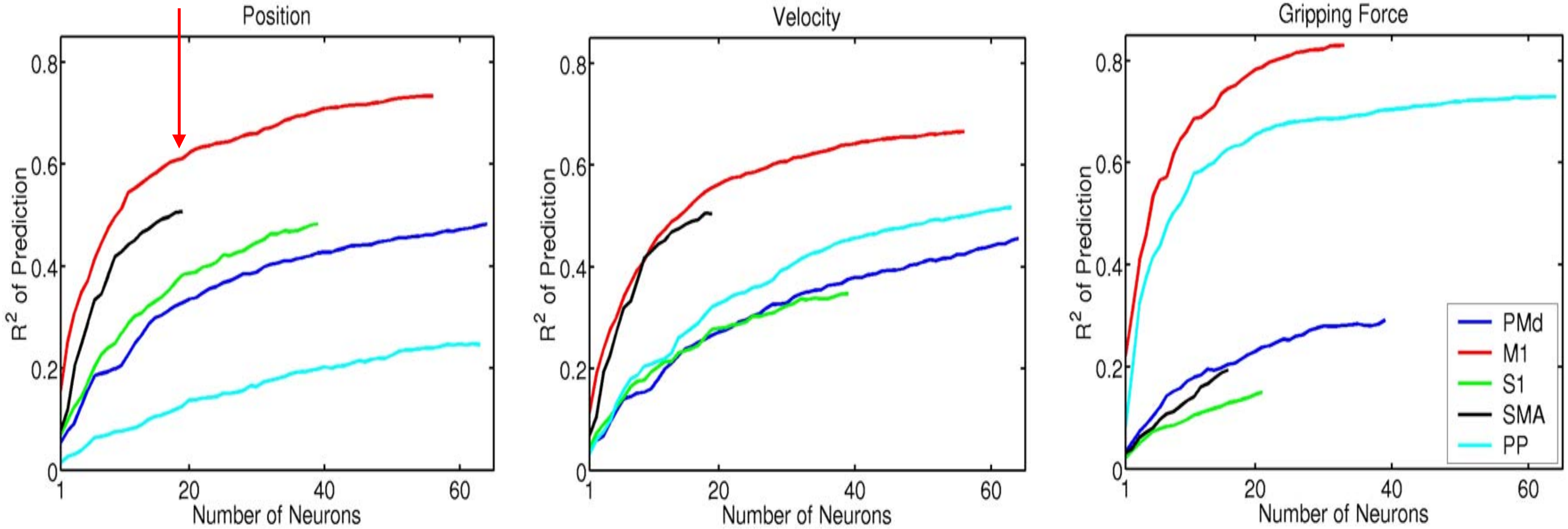
PLoS Biology 1(2), 2003.

CONTRIBUTION OF INDIVIDUAL NEURONS TO MODEL PREDICTIONS



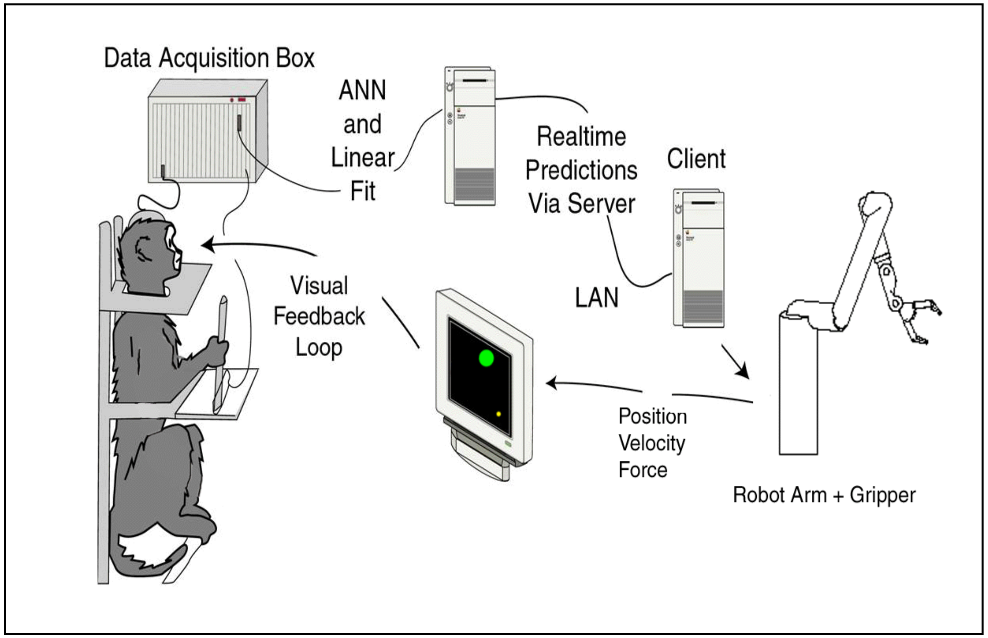
- Information distributed across fronto-parietal cortical areas
- Single neurons contribute to multiple motor parameters

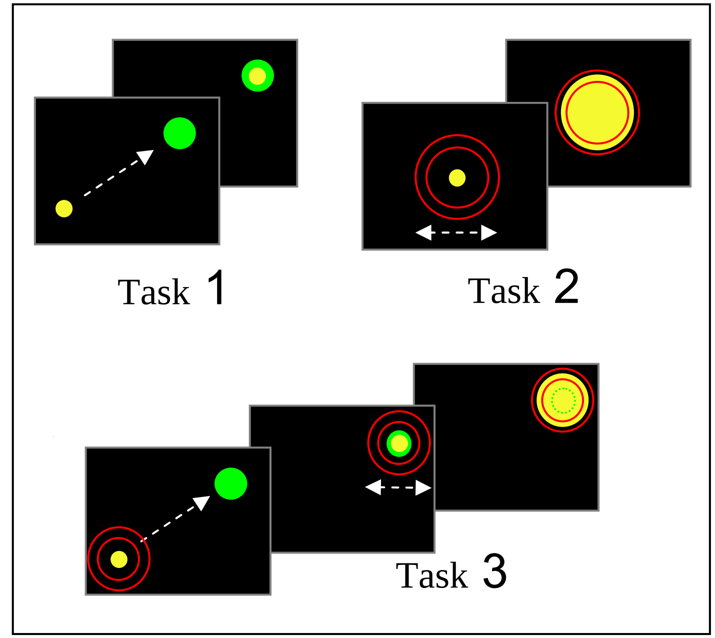
CONTRIBUTION OF DIFFERENT CORTICAL AREAS

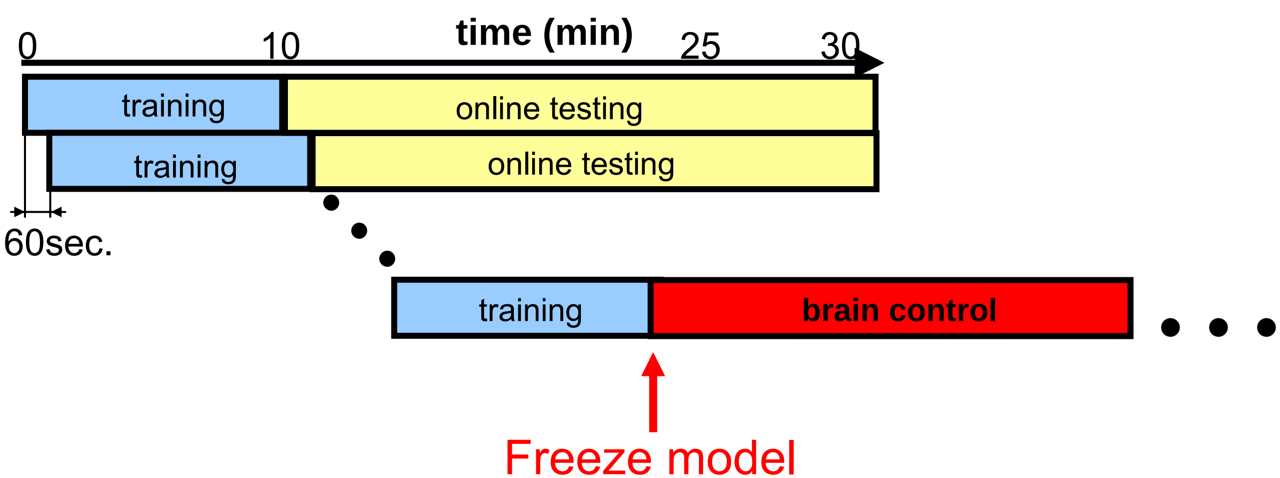


PLoS Biology 1(2), 2003.

EXPERIMENTAL SETUP & BEHAVIORAL TASKS

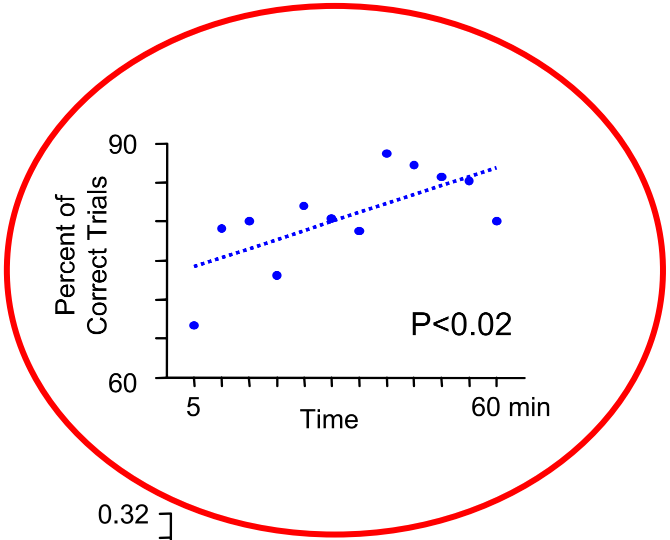


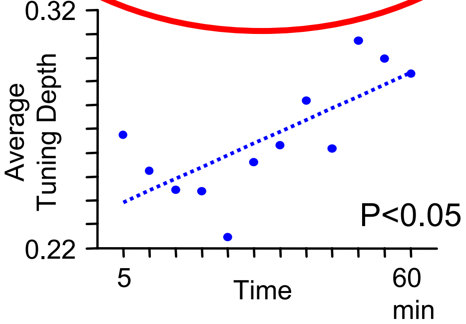




PLoS Biology 1(2), 2003.

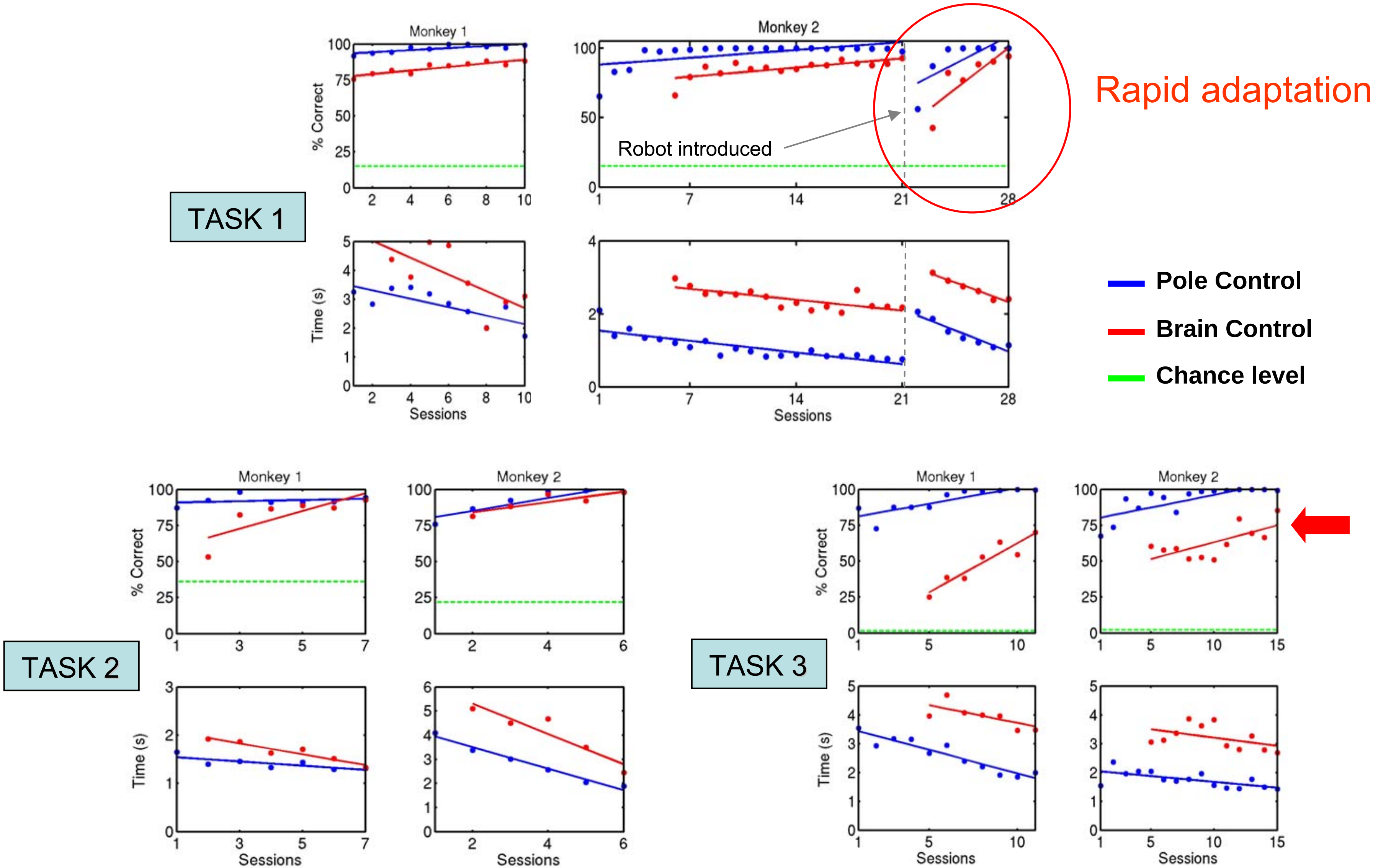
PERFORMANCE IMPROVEMENT WITHIN SESSION



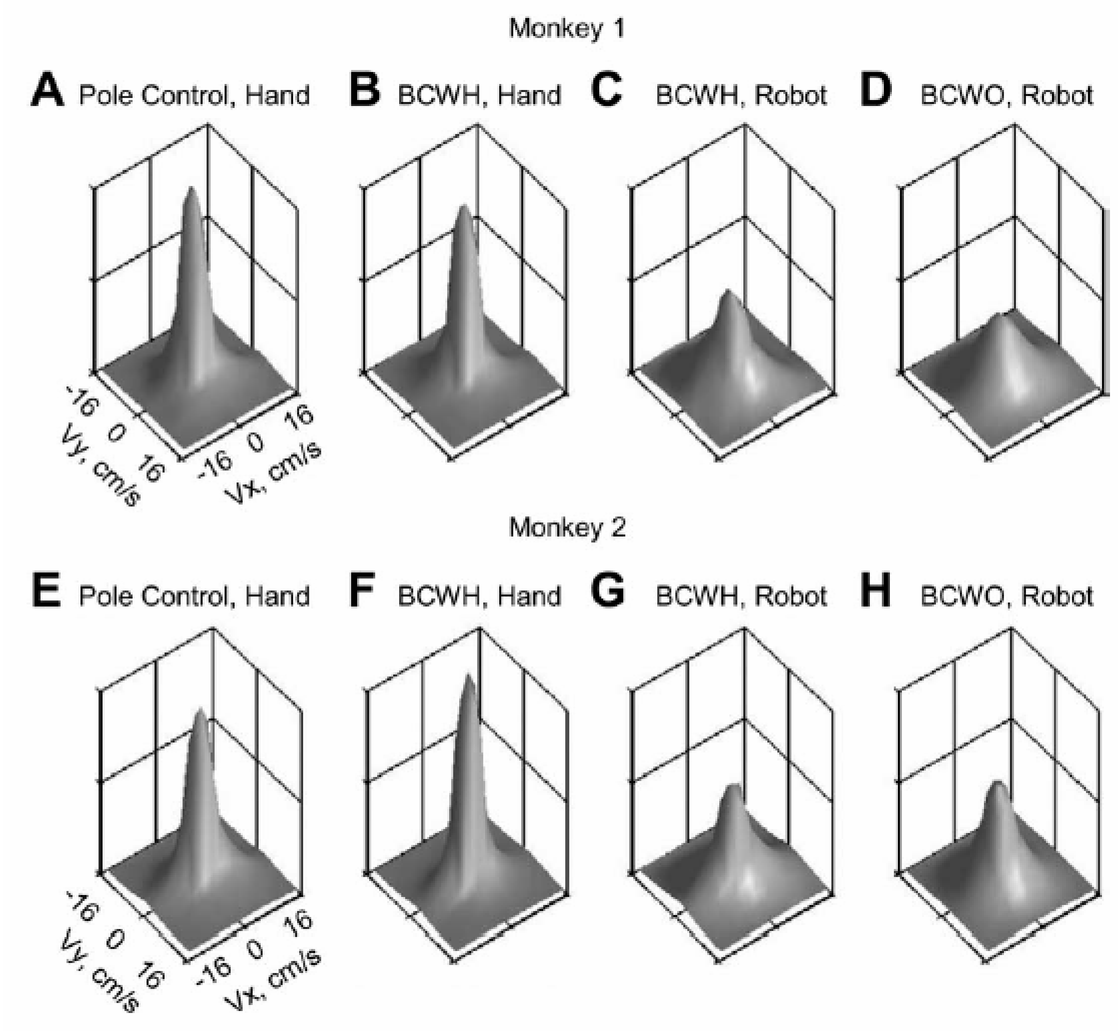


Biofeedback works!

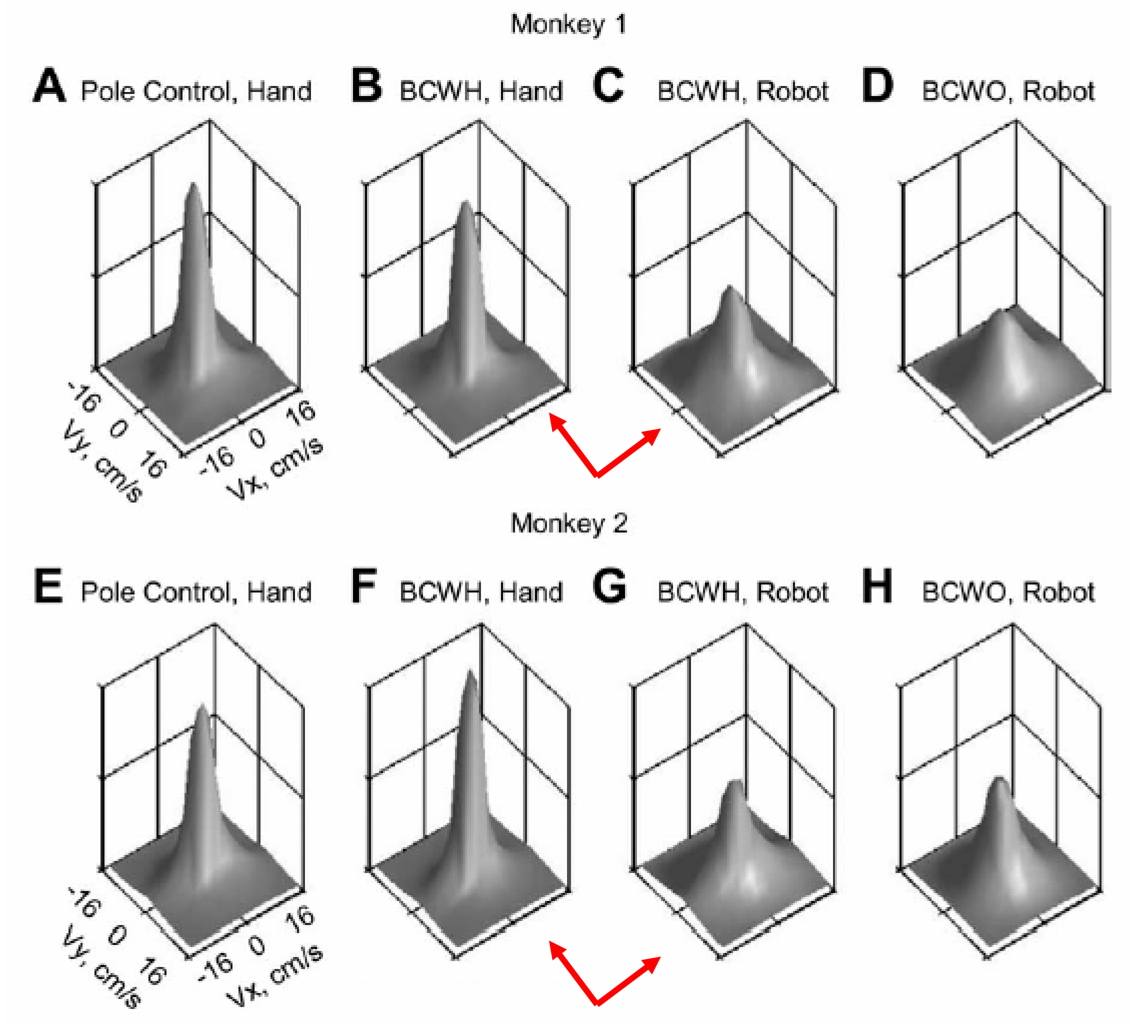
CHANGES IN PERFORMANCE WITH LEARNING



PLoS Biology 1(2), 2003.

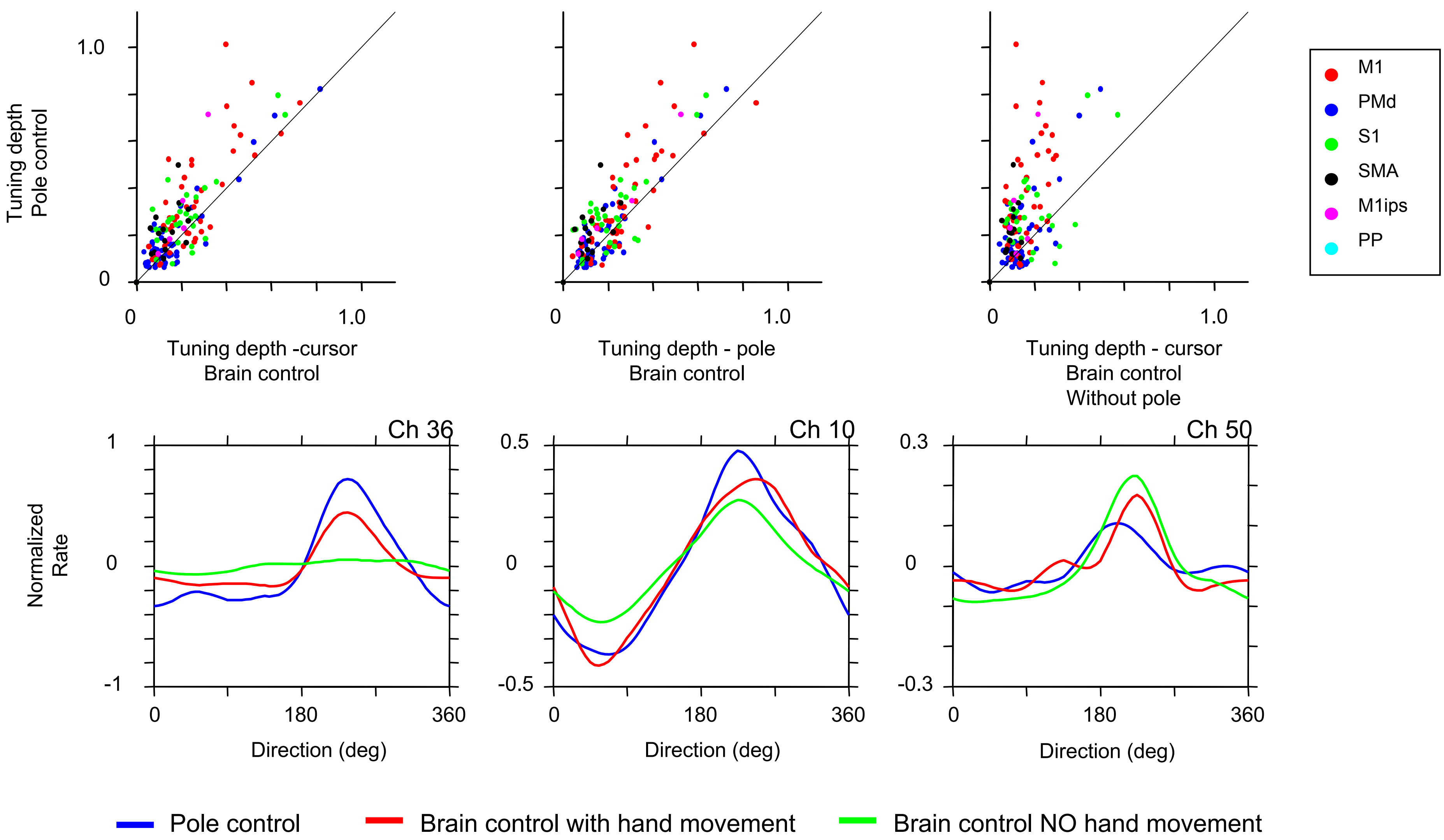


Q. What can be learned from the monkeys' behavior?



Reduced frequency of low velocities may reflect **BMI difficulty for posture control**

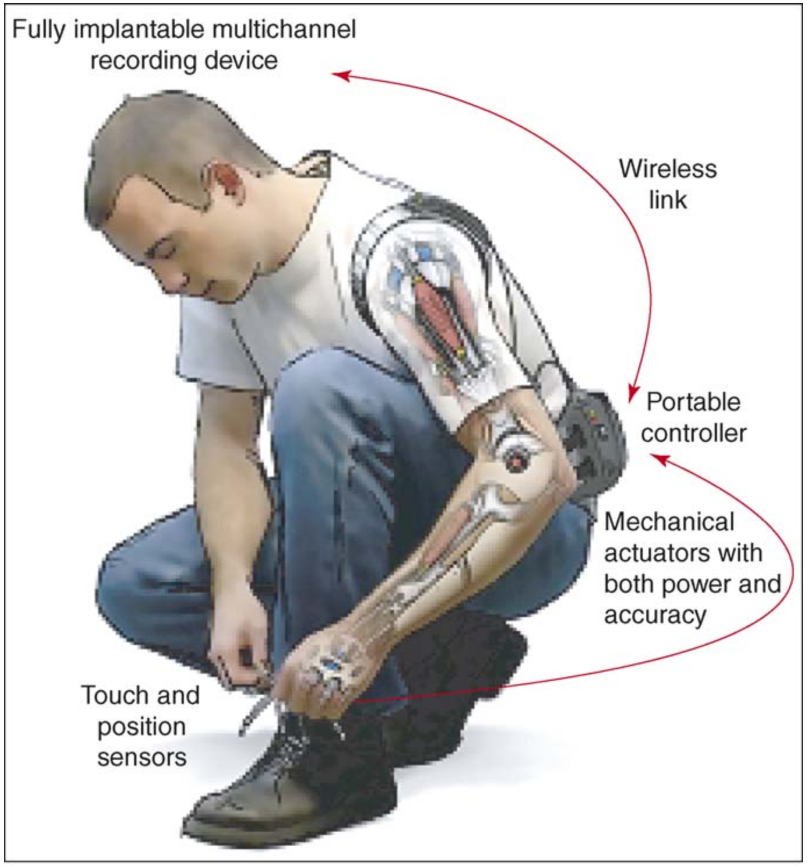
CHANGES IN DIRECTIONAL TUNING



PLoS Biology 1(2), 2003.

DISCUSSION

ULTIMATE GOAL



Trends in Neurosc. (Lebedev & Nicolelis, 2006)

So what do we need to get here?

Discussion

- Why do we need dynamics in BMIs?
  - Isn’t kinematics enough?
    - i.e. taking advantage of motors, power, etc to resist perturbations (e.g. by increasing Z)

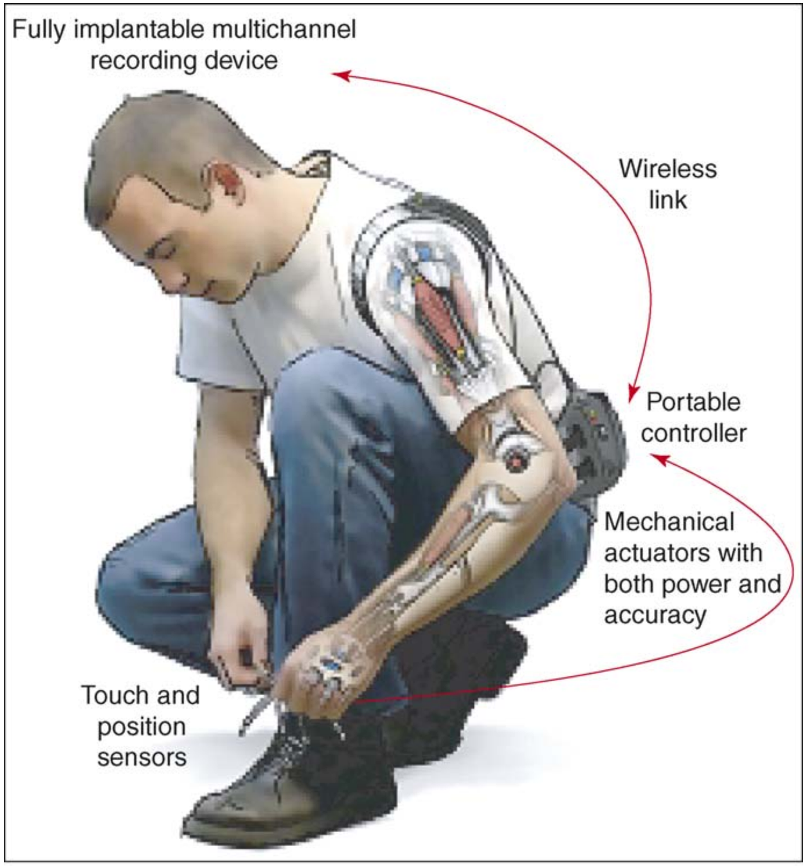
Discussion

- Why do we need dynamics in BMIs?
  - Isn't kinematics enough?
    - i.e. taking advantage of motors, power, etc to resist perturbations (e.g. by increasing Z)
- Problem! → unstable tasks, tasks that will require low impedance…
  - How does the robot know **how** the user wants to interact with the object/environment?

    → We need impedance control!

DISCUSSION

ULTIMATE GOAL



Trends in Neurosc. (Lebedev & Nicolelis, 2006)