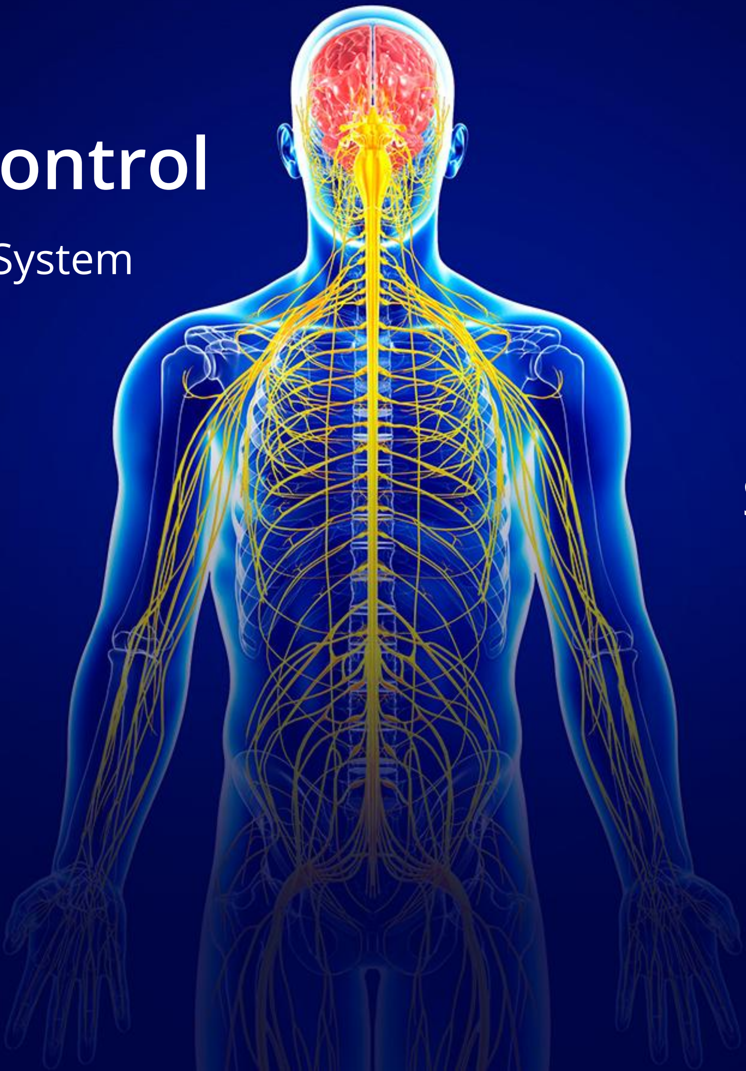
Human Motor Control

(how the Central Nervous System plans motion)



Shannon Danforth

January 2021

I got this information from two classes:

- Kinesiology 533: Neuromechanics
  - Interaction of the nervous and musculoskeletal systems during human/animal movement
  - Taught by Dan Ferris (now a professor at University of Florida)
- Mechanical Engineering 646: Mechanics and Control of Human Movement
  - Locomotor mechanics and design/control of wearable robotic systems
  - Taught by Elliott Rouse
  - In particular, a guest lecture in this class by his postdoc Tyler Clites
  - I will also use a Simulink example developed by Tyler!

What's going on behind the scenes to make this happen?

[Boston Dynamics, 2017]

Robotic control hierarchy

High-level

What is the task that we want Atlas to do?

Mid-level

What are the joint dynamics that Atlas needs to accomplish it?

Low-level

How do we deliver the appropriate amount of current to Atlas' motors to produce those dynamics?

[image from Boston Dynamics]

[Slide copied from Tyler Clites' presentation]

The same control aspects are important for human motion

[Katelyn Ohashi, UCLA Athletics, 2019]

Human control hierarchy

High-level

What task do I want to do?

Mid-level

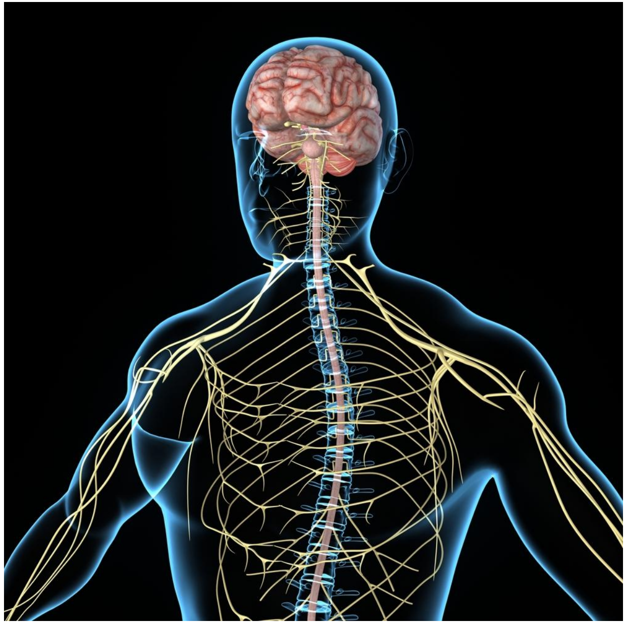
What are the joint dynamics that I need to accomplish it?

Low-level

How do I deliver the appropriate activations to my muscles to produce those dynamics?

Why do we care about how humans plan motion?

Science



[appreciategoods.com]

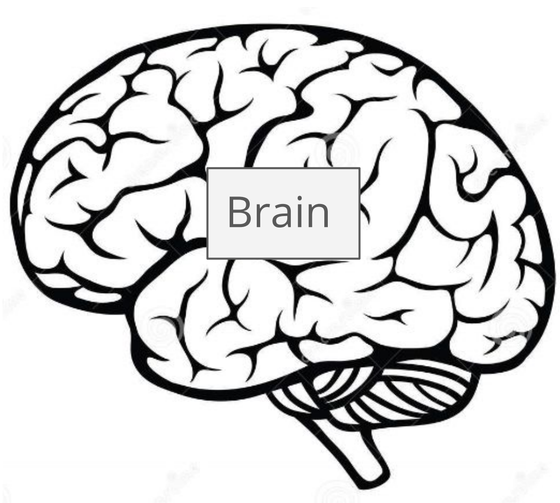
Rehabilitation

[aayushman.in]

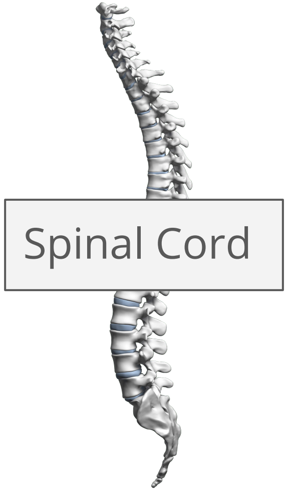
Wearable Robots

[news.engin.umich.edu]

Quick background: Central Nervous System (CNS)



- Primary processing unit
- High-level task planning
- Volitional control



- Secondary, distributed processing unit
- Low-level execution
- Reflexive control

[Bullet points from Tyler Clites' presentation]

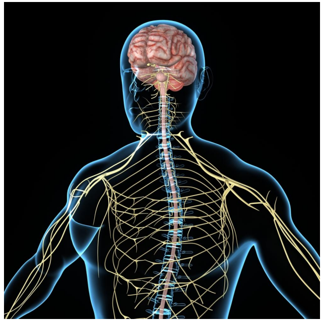
Quick background: Central Nervous System (CNS)

Brain

Spinal Cord

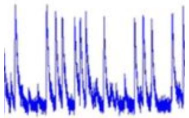
[Images from Tyler Clites' presentation]

Quick background: Muscle Activation



CNS

→



Neural Signal

→

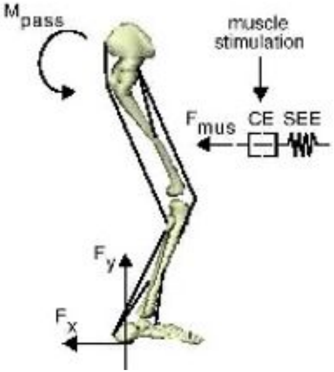
activation dynamics
(map neural input to activation signal)

Activation Processes

→

Muscle Contraction

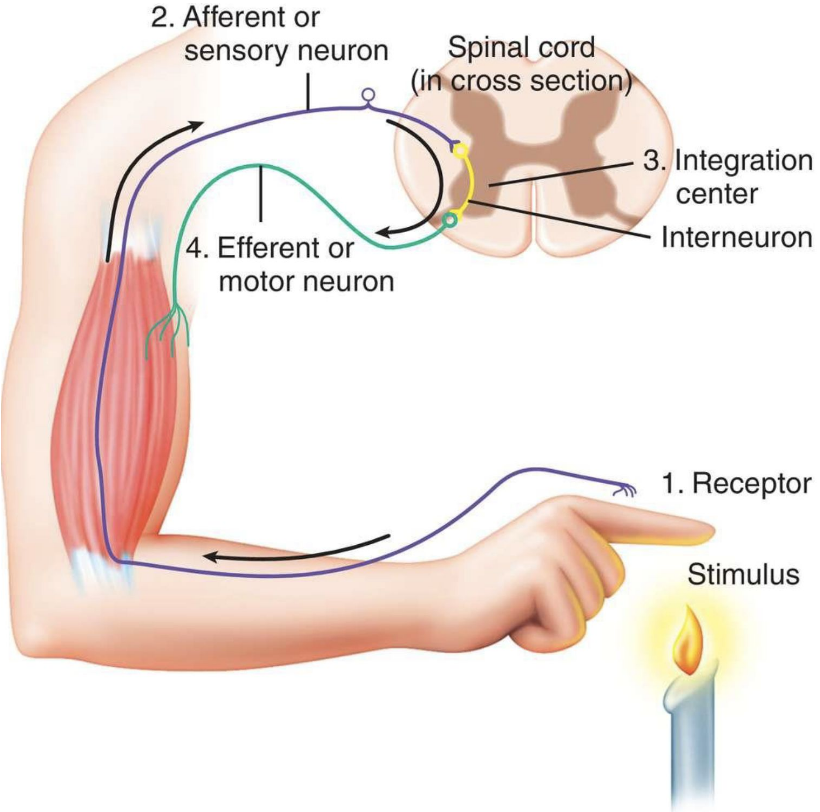
→



Physical Joint Motion

Quick background: Afferent and efferent neurons

Afferent neurons carry nerve impulses from sensory organs to the CNS



Efferent neurons carry nerve impulses from CNS to muscles

[Image from Tyler Clites' presentation]

Outline of our human motor control topics

- Low-level control
  - Feedforward
  - Feedback
  - Hybrid FF+FB
- Mid-level control
  - Inverse Kinematics and Inverse Dynamics
  - Equilibrium Point Hypothesis
  - Muscle Synergies
  - Internal Models
  - Uncontrolled Manifold Hypothesis

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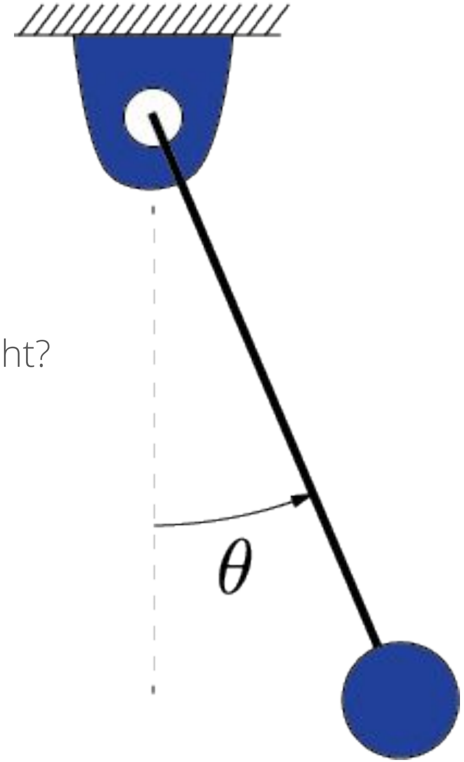
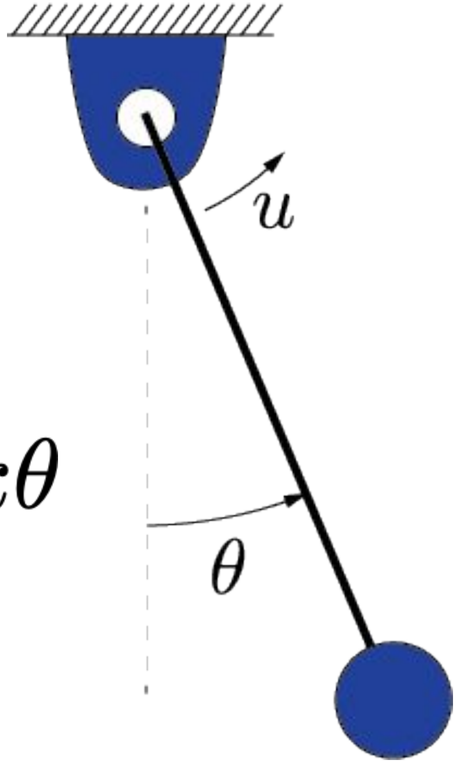
We'll use a pendulum example for low-level control

this looks enough like a human leg…right?



[Kuo A., *Motor Control*, 2002]

We'll use a pendulum example for low-level control



dynamic equation of motion:

$$u = J\ddot{\theta} + b\dot{\theta} + k\theta$$

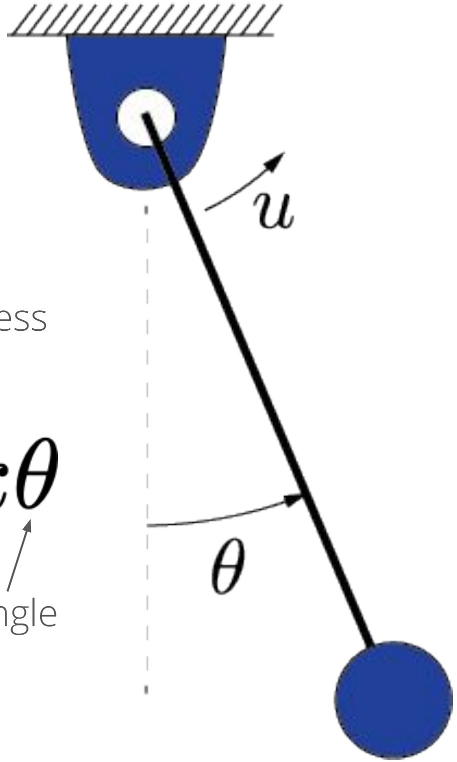
[Kuo A., *Motor Control*, 2002]

We'll use a pendulum example for low-level control

inertia, damping, stiffness

$$u = J\ddot{\theta} + b\dot{\theta} + k\theta$$

angular acceleration, angular velocity, angle



Basically, we know how this pendulum will respond to a given input u.

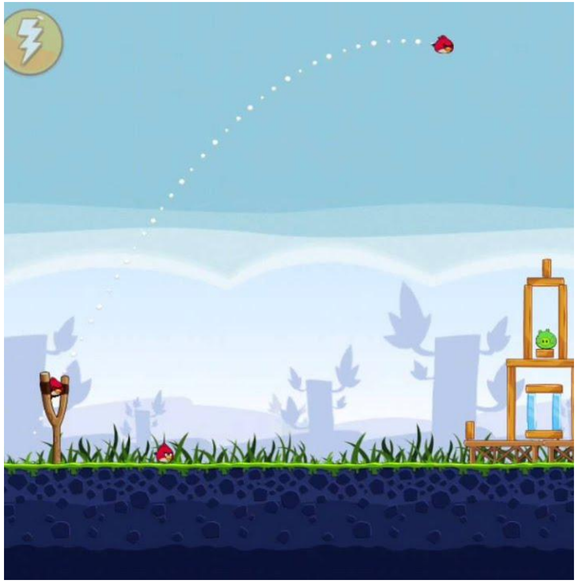
[Kuo A., *Motor Control*, 2002]

Feedforward (open-loop) control

A movement is "launched" at some target, and can't be corrected after.

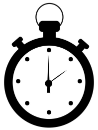
[foxsports.com]

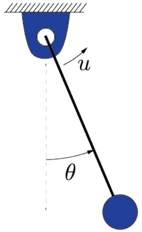
[Rocky IV]



[Angry Birds]

Ingredients of feedforward control





desired kinematics → **controller** → torque → **pendulum physics** → joint (or pendulum) state

$$(\theta, \dot{\theta}, \ddot{\theta})_{goal}$$

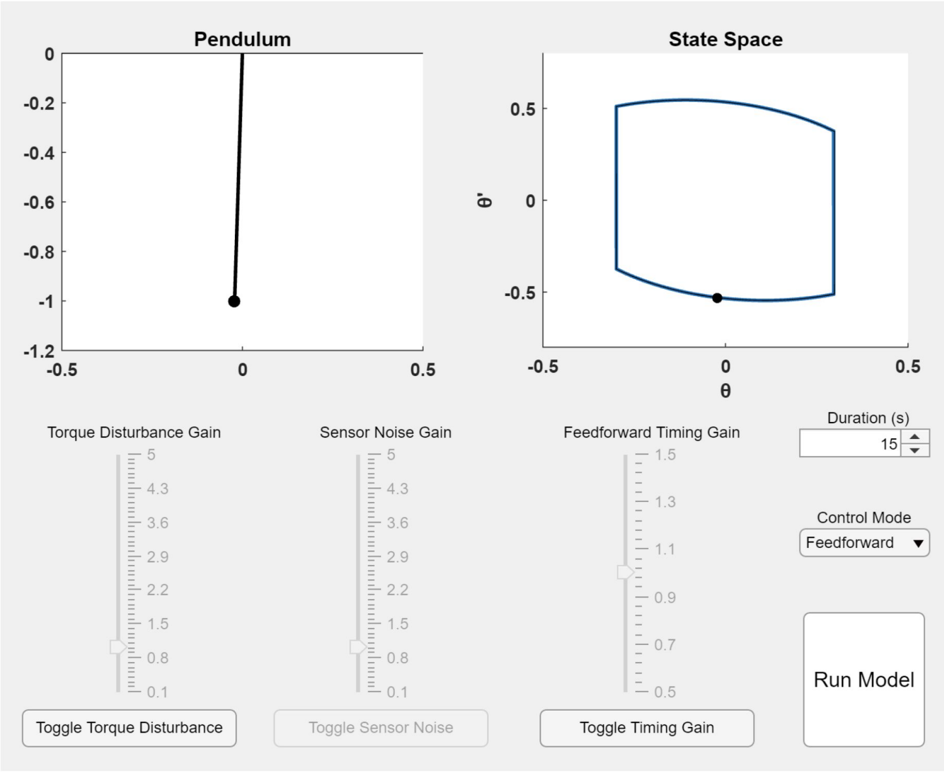
$$u$$

$$(\theta, \dot{\theta}, \ddot{\theta})_{real}$$

APPLY 5 NM OF TORQUE
FOR 3 SECONDS!

$$u = J\ddot{\theta} + b\dot{\theta} + k\theta$$

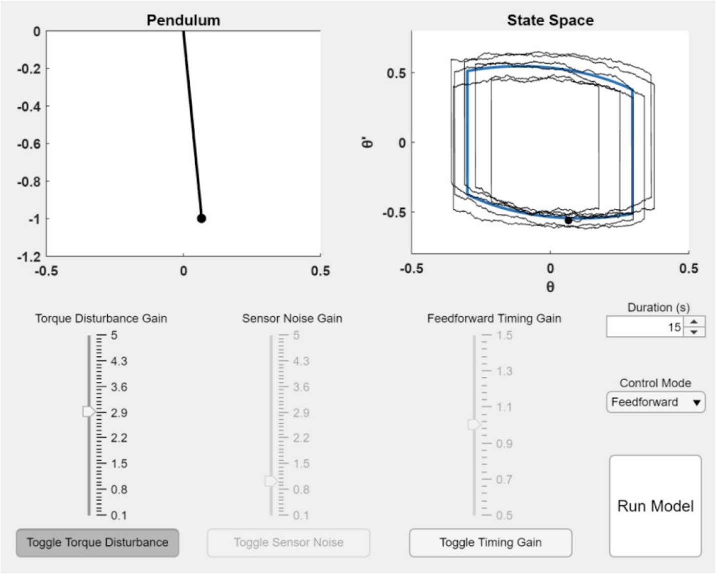
Feedforward control - Simulink demo



Feedforward control - Simulink demo takeaways

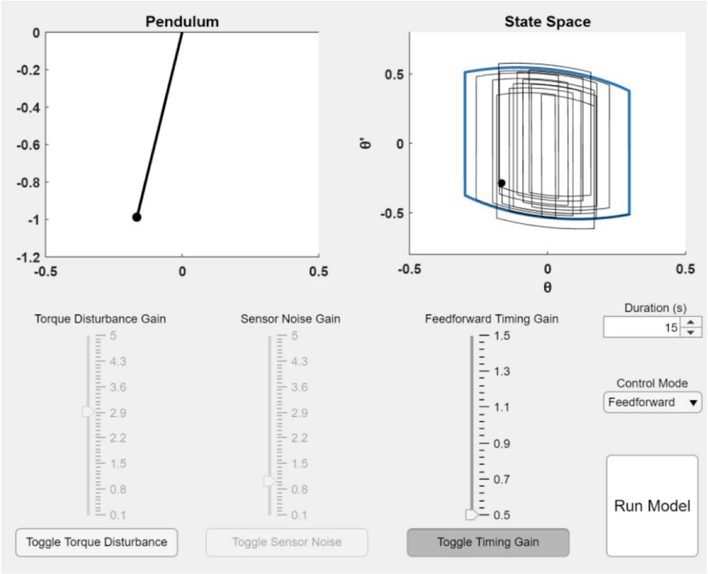
Benefits:

No dependence on sensor accuracy



Pitfalls:

Sensitive to torque disturbance and timing errors



[Simulink demo created by Tyler Clites]

Feedback (closed-loop) control

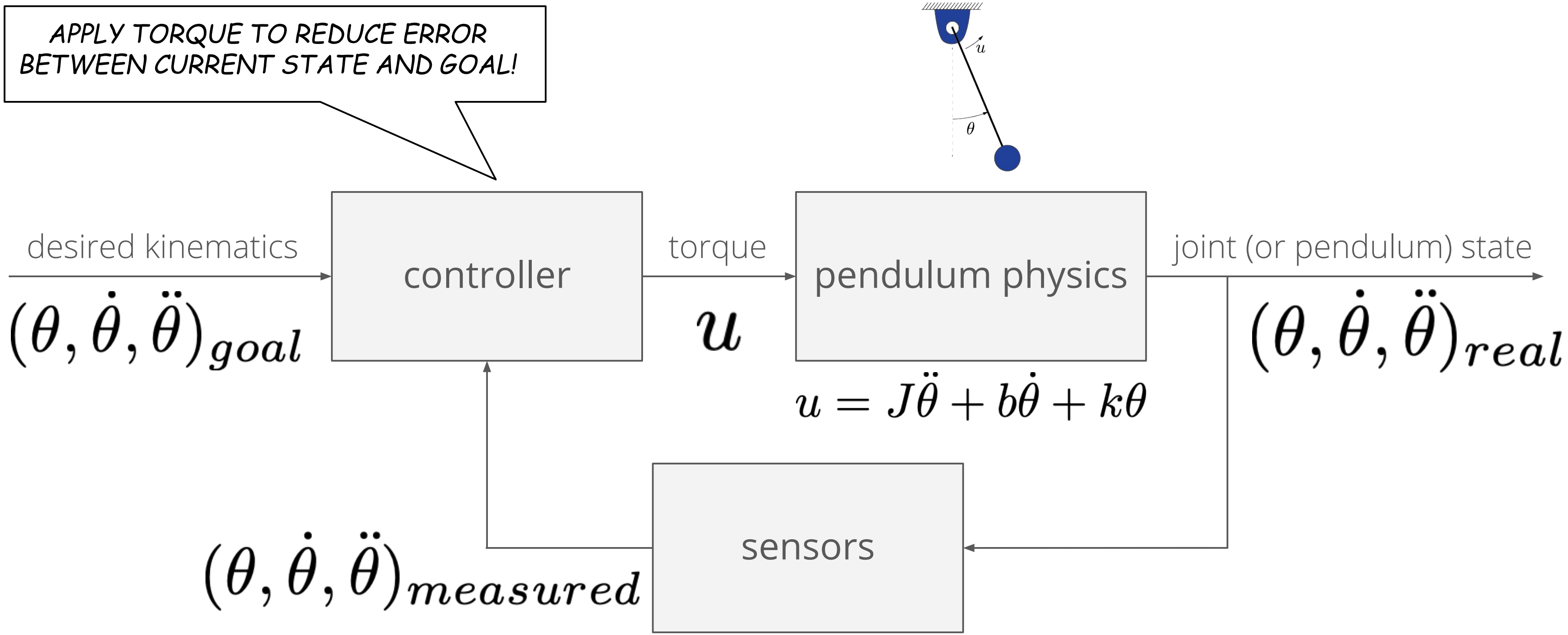
A feedback system constantly monitors its own progress and adjusts its control accordingly.

[travelers.com]

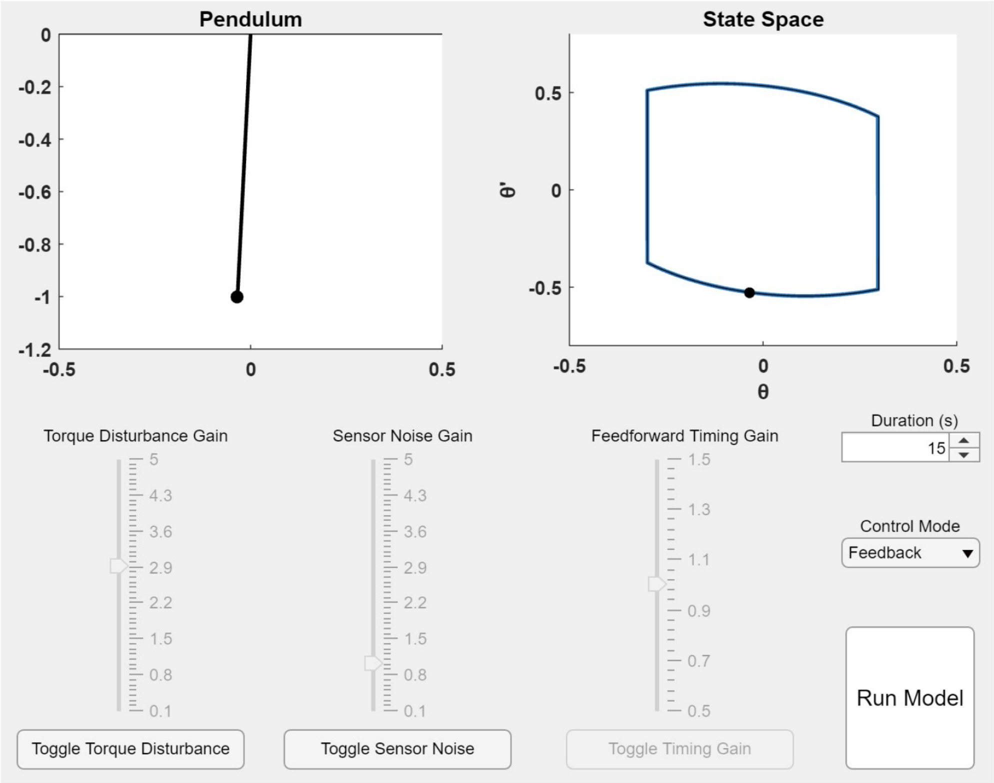
[slacklineinternational.org]

[blog.dayfire.com]

Ingredients of feedback control



Feedback control - Simulink demo

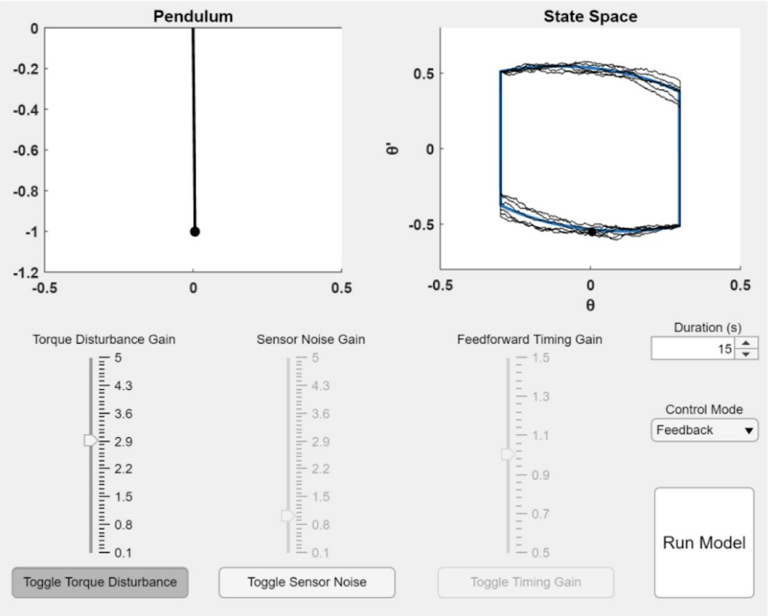


[Simulink demo created by Tyler Clites]

Feedback control - Simulink demo takeaways

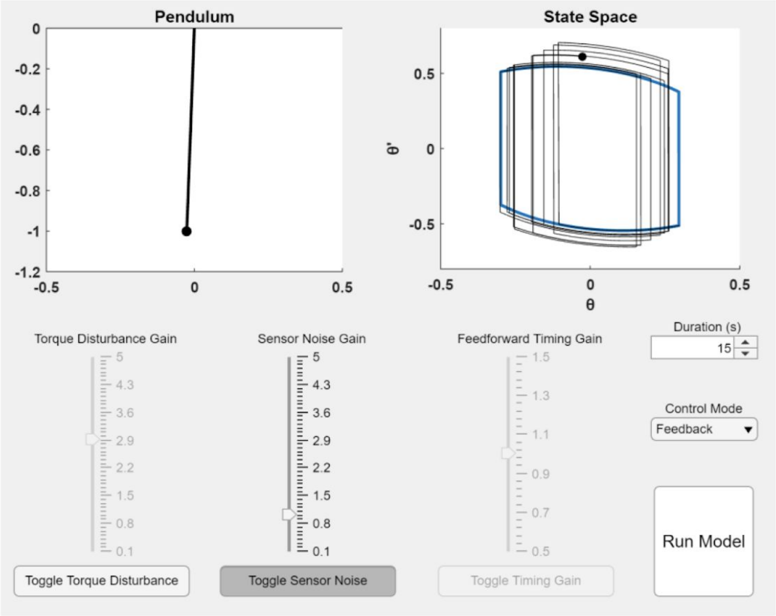
Benefits:

No dependence on timing, robust to torque disturbance

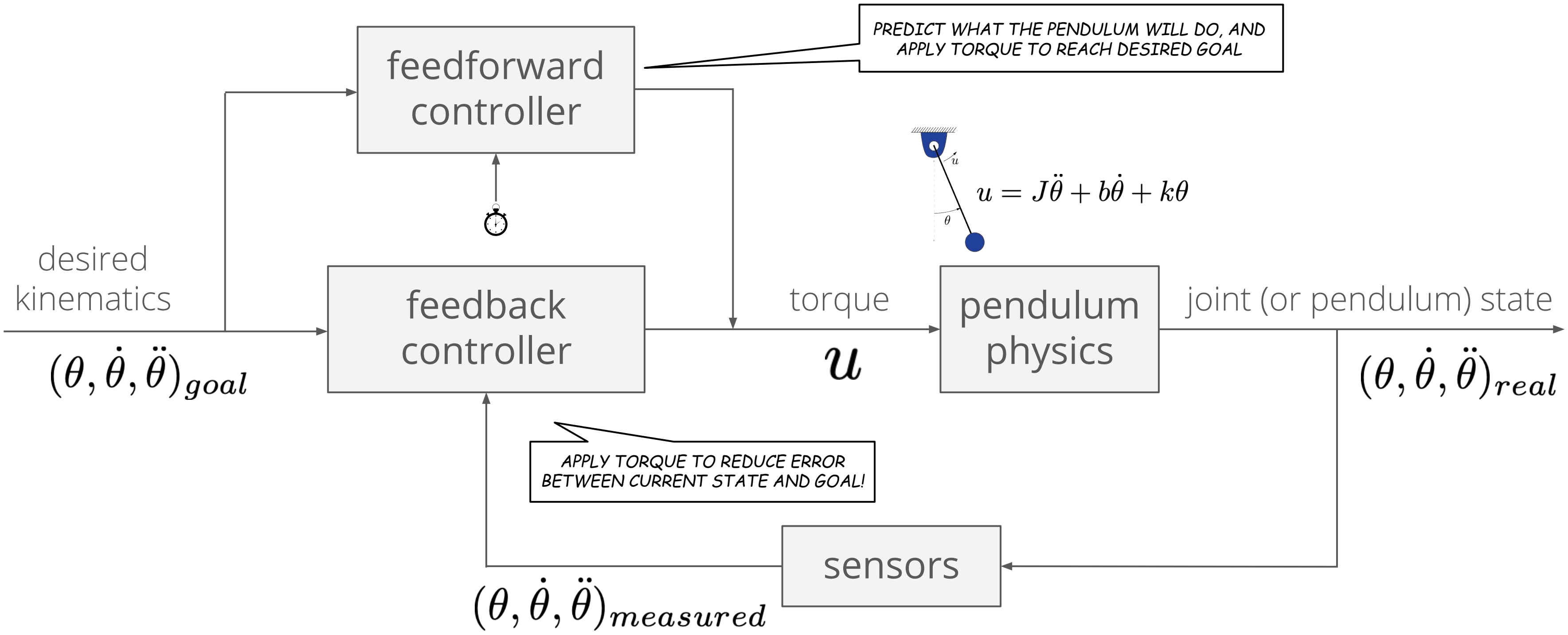


Pitfalls:

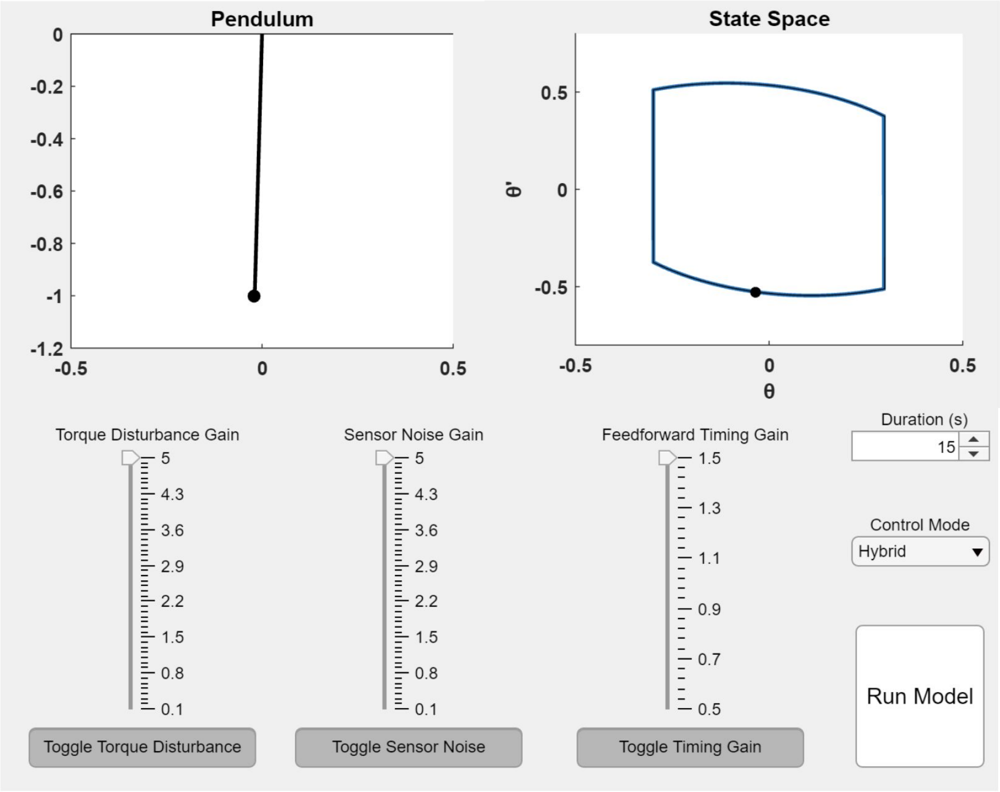
Sensitive to measurement error in sensors



Could a hybrid FF + FB approach be the best of both worlds?



Feedforward + feedback control - Simulink demo



[Simulink demo created by Tyler Clites]

Summary of low-level control

	Torque Disturbance	Timing Disturbance	Sensor Noise
Feedforward	❌	❌	✅
Feedback	✅	✅	❌
Hybrid	✅	✅	✅

Outline of our human motor control topics

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- **Mid-level control**
  - Inverse Kinematics and Inverse Dynamics
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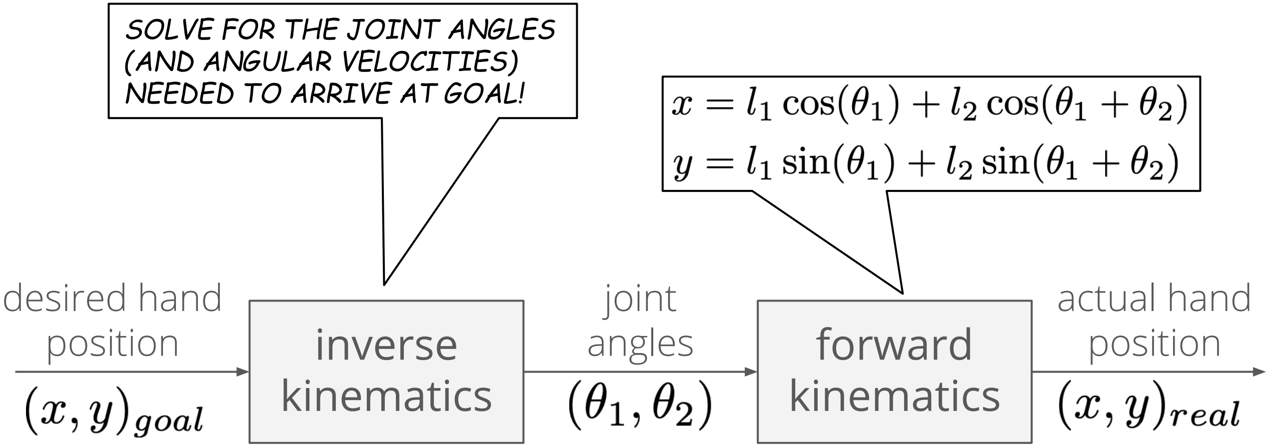
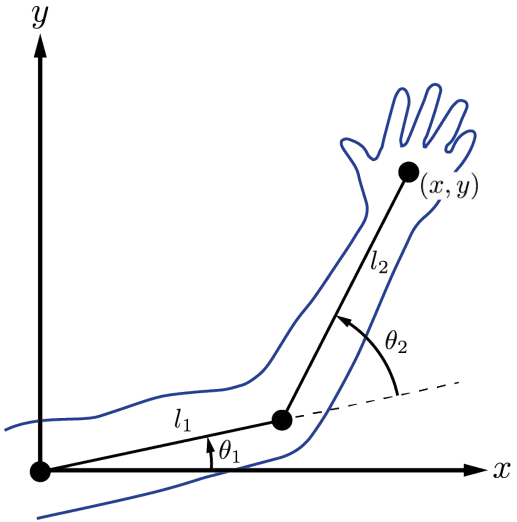
Inverse kinematics

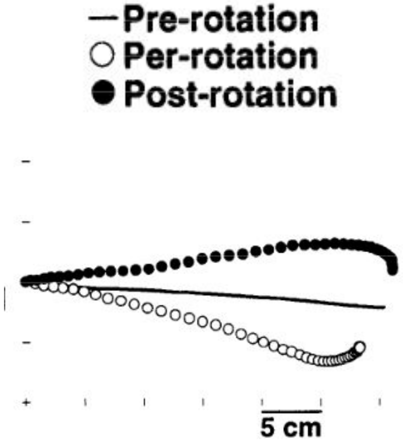
We are jointed (θ_1, θ_2) beings

in a Cartesian (x, y) world

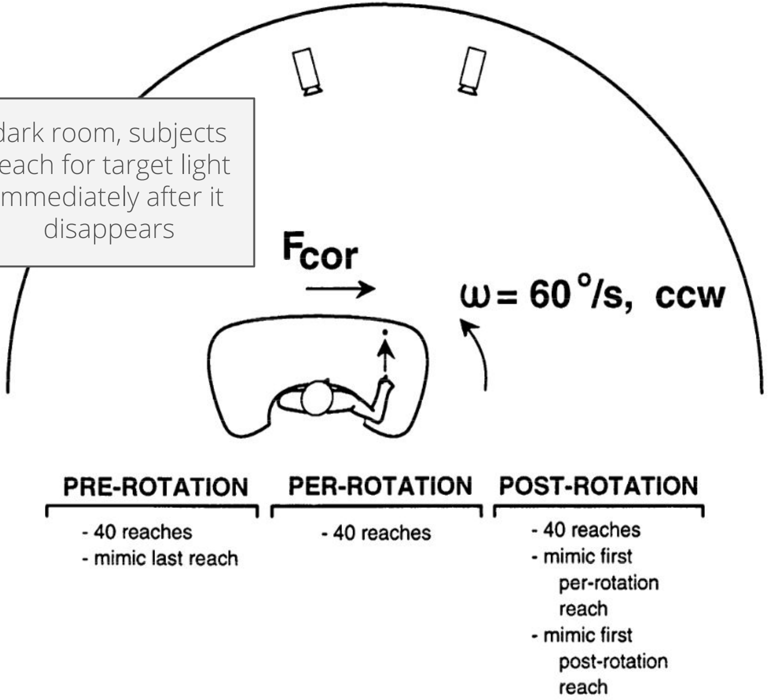


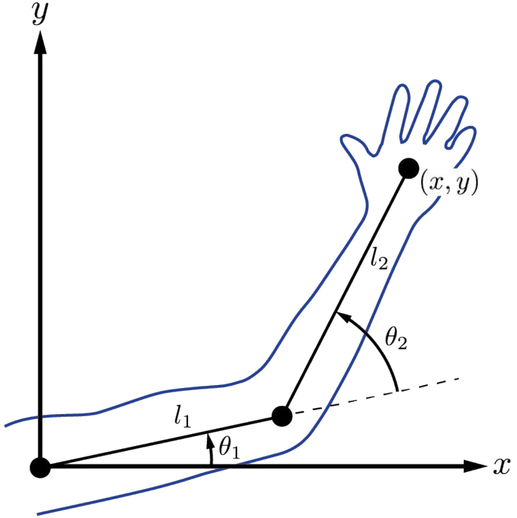


Experiment where inverse kinematics theory falls short



dark room, subjects reach for target light immediately after it disappears





[Lackner, J.R. and Dizio, P., *J. Neurophysiology*, 1994]

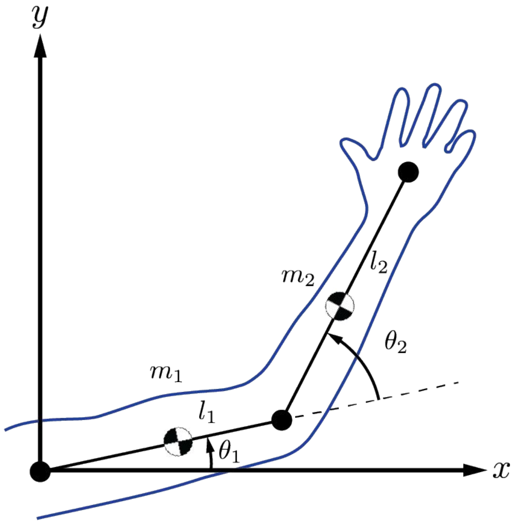
Inverse dynamics

Similar, but with torques and forces

$$\tau_1 = \ddot{\theta}_1\left(I_1 + I_2 + m_2 l_1 l_2 \cos\theta_2 + \frac{m_1 l_1^2 + m_2 l_2^2}{4} + m_2 l_1^2\right)$$
$$+ \ddot{\theta}_2\left(I_2 + \frac{m_2 l_1 l_2}{2}\cos\theta_2 + \frac{m_2 l_2^2}{4}\right)$$
$$- \dot{\theta}_2^2 \frac{m_2 l_1 l_2}{2}\sin\theta_2 - \dot{\theta}_1\dot{\theta}_2 m_2 l_1 l_2 \sin\theta_2$$
$$+ g\left(\frac{m_2 l_2}{2}\cos(\theta_1 + \theta_2) + l_1\left(\frac{m_1}{2} + m_2\right)\cos\theta_1\right)$$
$$\tau_2 = \ddot{\theta}_1\left(I_2 + \frac{m_2 l_1 l_2}{2}\cos\theta_2 + \frac{m_2 l_2^2}{4}\right) + \ddot{\theta}_2\left(I_2 + \frac{m_2 l_2^2}{4}\right)$$
$$+ \dot{\theta}_1^2 \frac{m_2 l_1 l_2}{2}\sin\theta_2 + g\frac{m_2 l_2}{2}\cos(\theta_1 + \theta_2)$$

PHYSICS!

desired motion pattern $(\theta_1, \theta_2)_{goal}$ → **inverse dynamics** → joint torques (τ_1, τ_2) → **forward dynamics** → actual motion pattern $(\theta_1, \theta_2)_{real}$



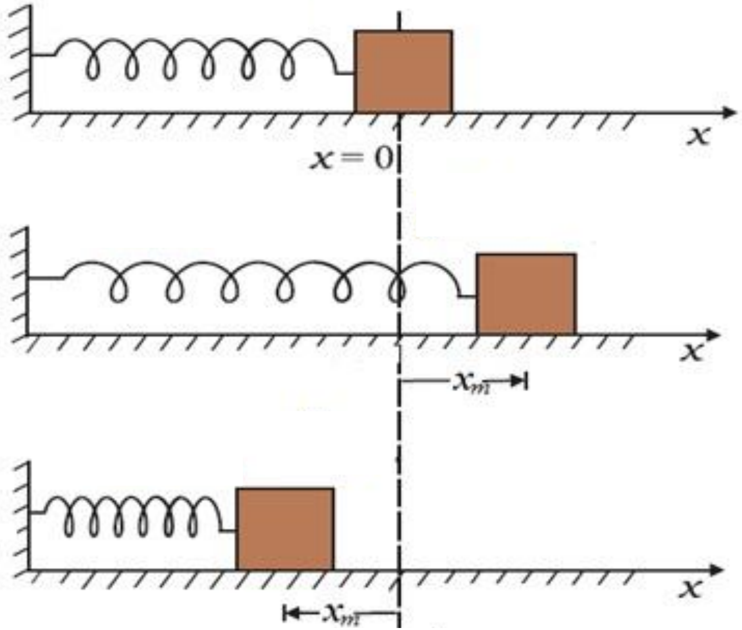
Equilibrium Point Hypothesis

Main idea: when we identify a goal for our end effector (e.g., reaching our hand to a desired location), we set an equilibrium point for our joints. If we're perturbed, we will settle back on the equilibrium point.

spring equilibrium position

elongated

compressed



ROAHM LAB

[Image adapted from examfear.com]

EMBiR Lab
Evolution and Motion of Biology and Robotics

Equilibrium Point Hypothesis - supporting experiment

Deafferented monkeys without visual feedback can still move to a desired target, even when a disturbance is applied

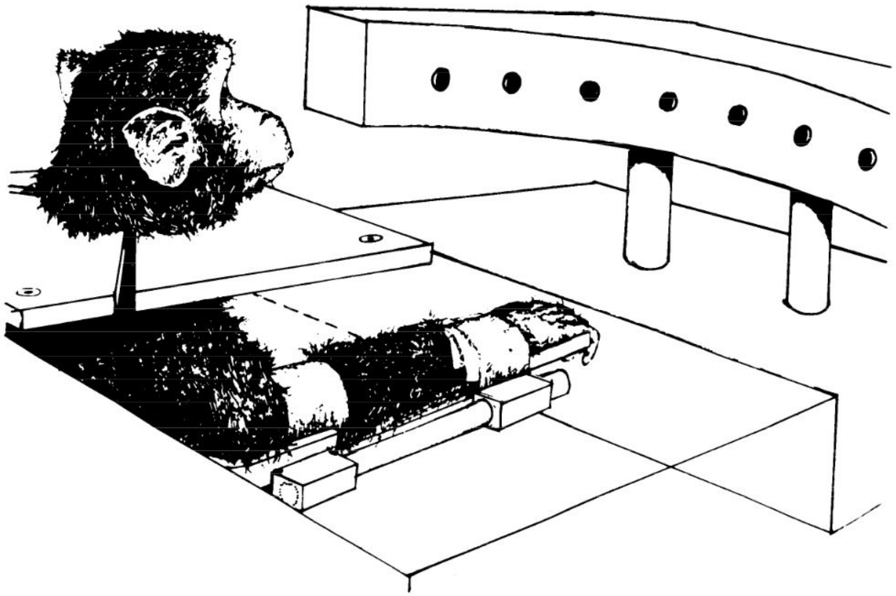
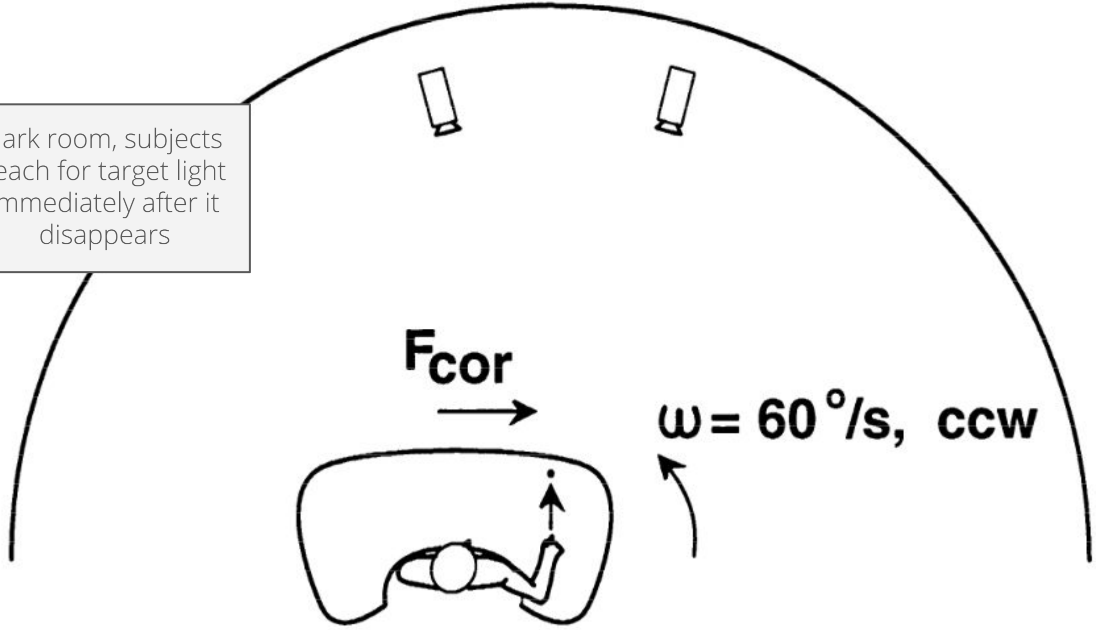


FIG. 1. Monkey set up in arm apparatus. Arm is strapped to splint, which pivots at elbow. Target lights are mounted in perimeter arc at 5° intervals. During experimental session, the monkey was not permitted to see its arm, and the room was darkened.

EPH doesn't hold up for the rotating room experiment...

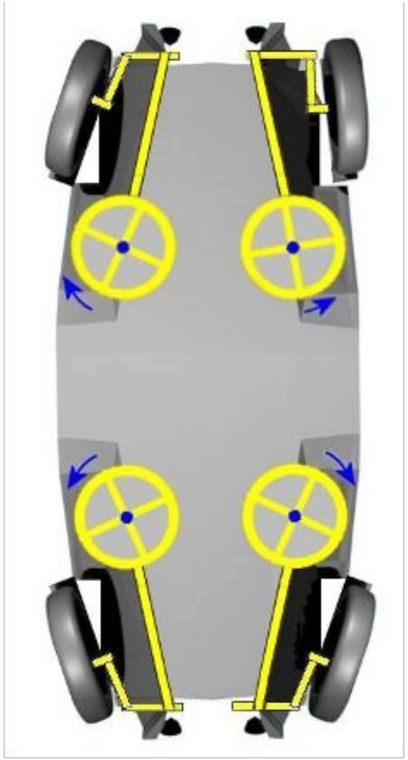
dark room, subjects reach for target light immediately after it disappears



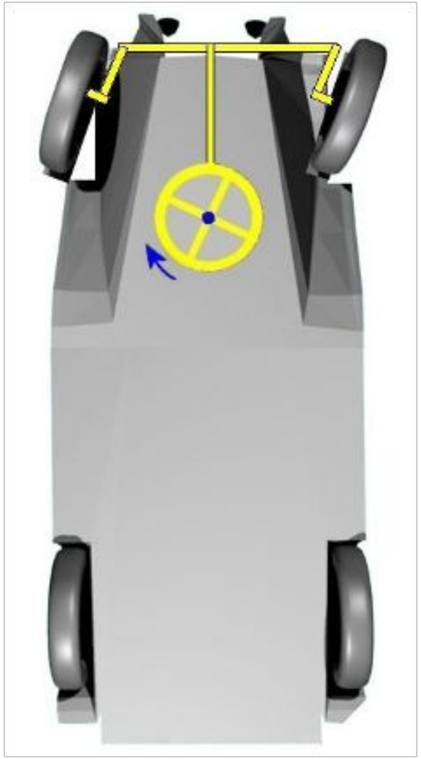
[Lackner, J.R. and Dizio, P., *J. Neurophysiology*, 1994]

Muscle Synergies

controlling each wheel separately



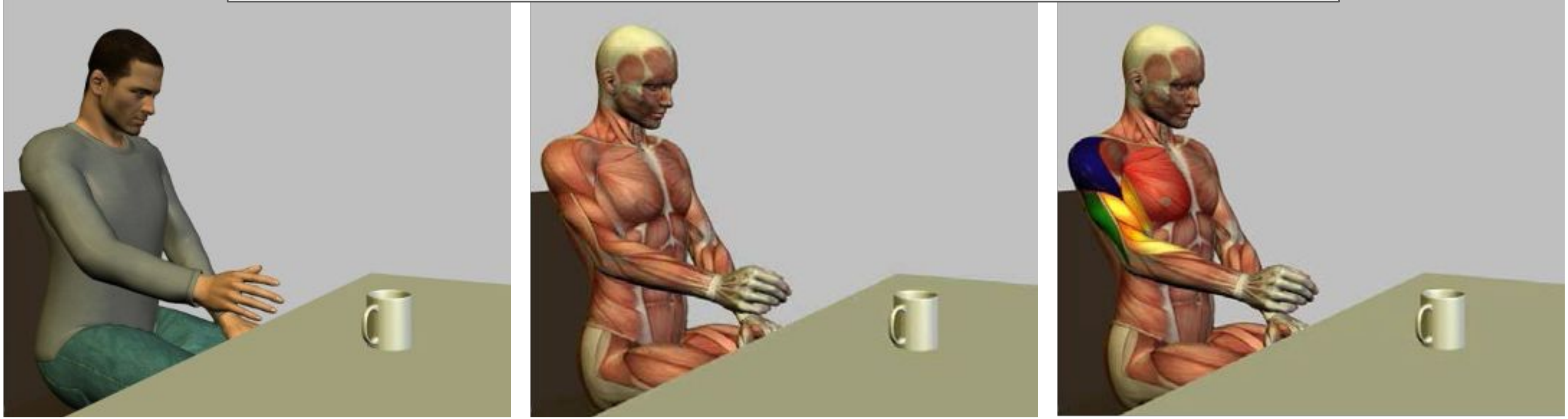
vs.



reducing degrees of freedom by coordinating wheels as a group

Muscle Synergies

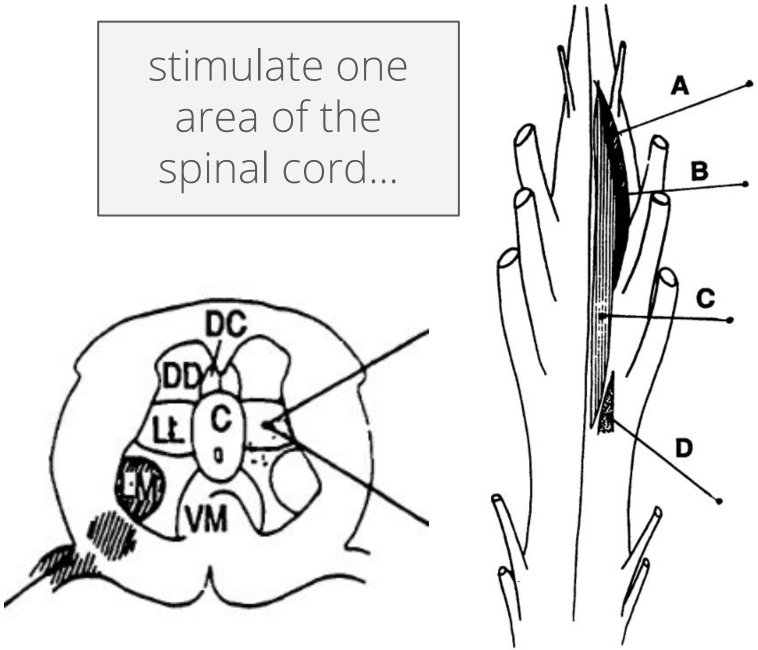
control can be simplified by grouping muscles into functional units

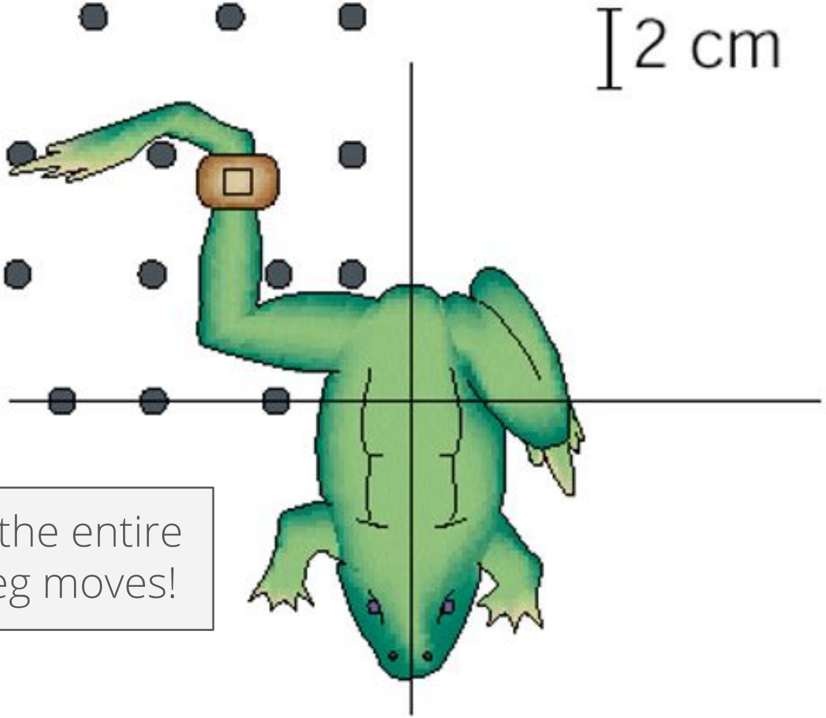


[Images from Dan Ferris' presentation]

Muscle Synergies - cool frog experiment

stimulate one area of the spinal cord...



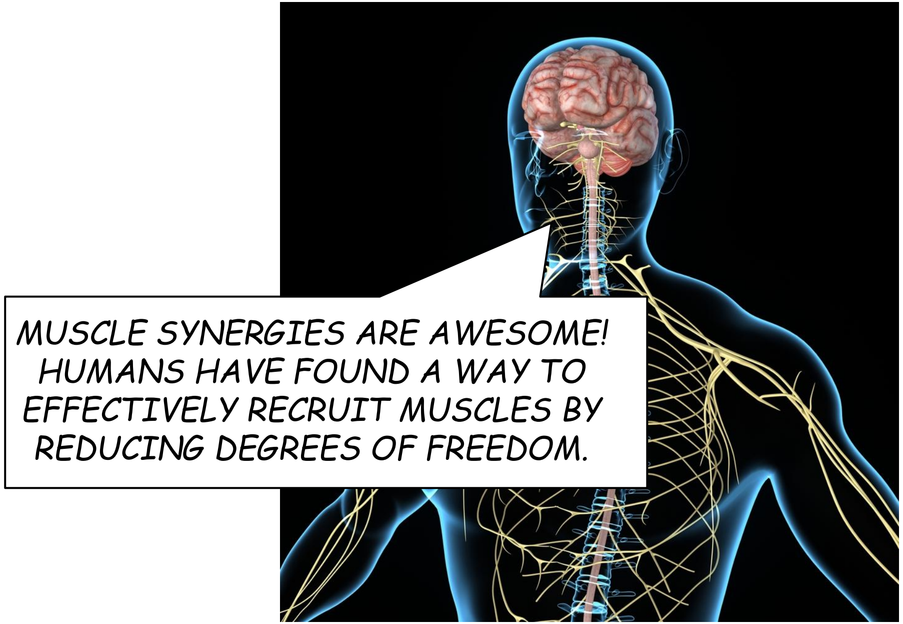


...and the entire frog leg moves!

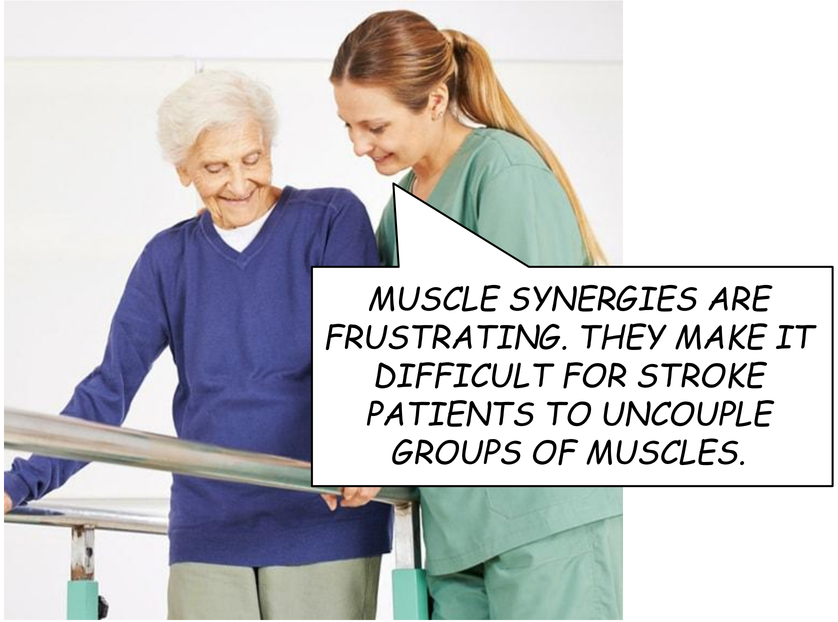
[Bizzi, E. et al., *Science*, 1991]

Muscle Synergies - viewpoints depending on field

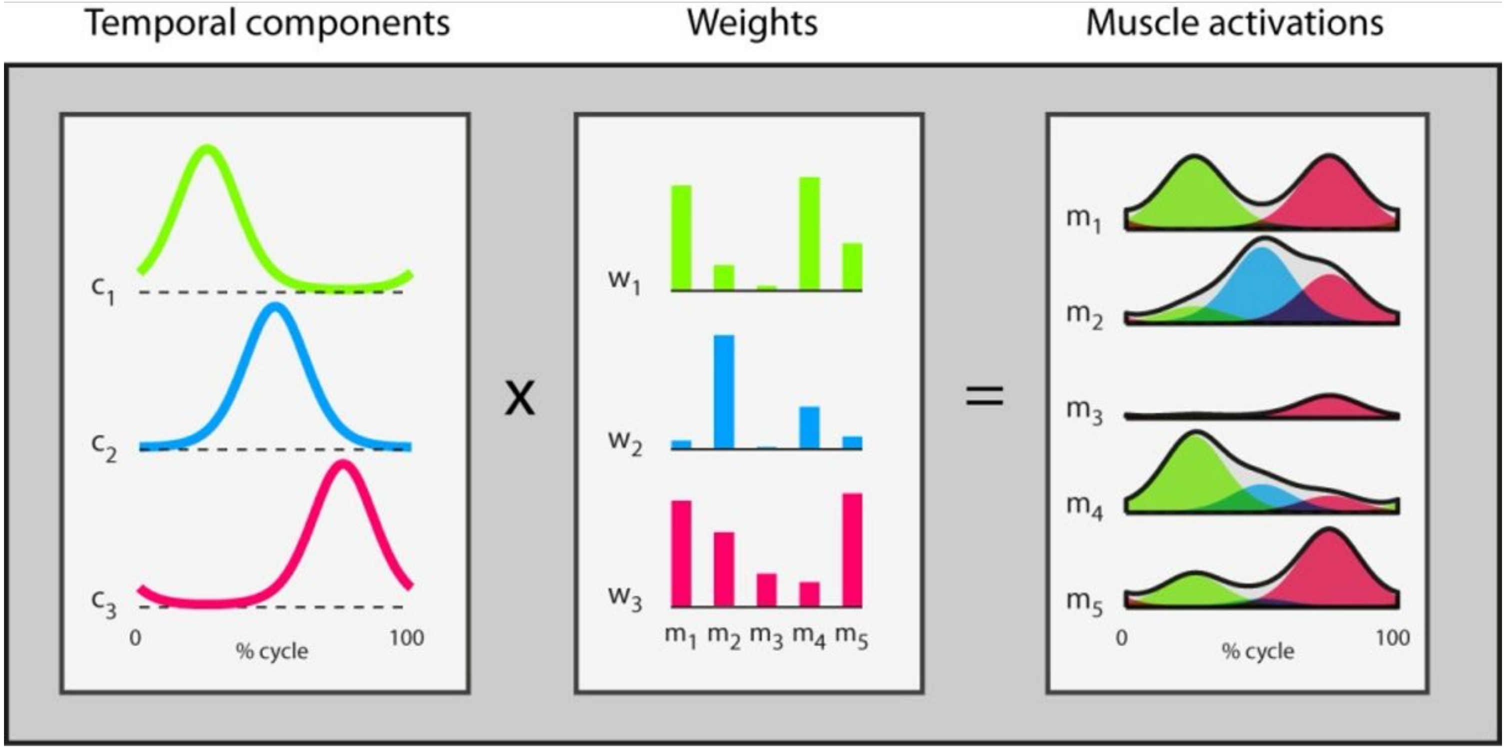
neuroscience



neurorehabilitation

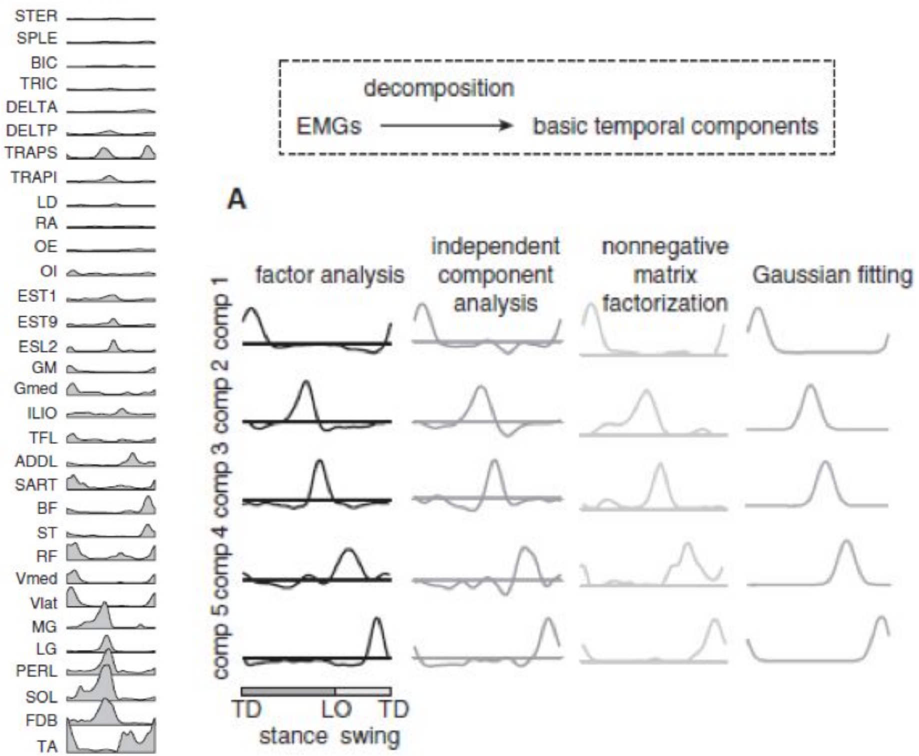


Muscle Synergies - EMG decomposition



[Image from Dan Ferris' presentation]

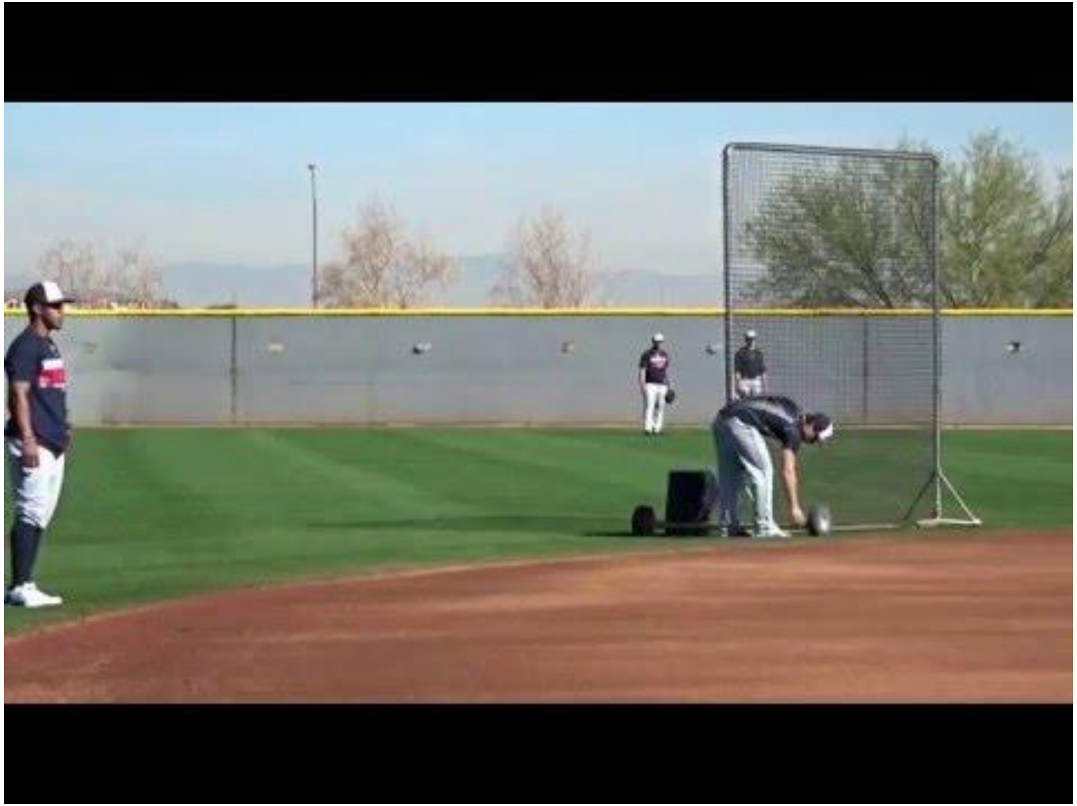
Muscle Synergies - EMG decomposition



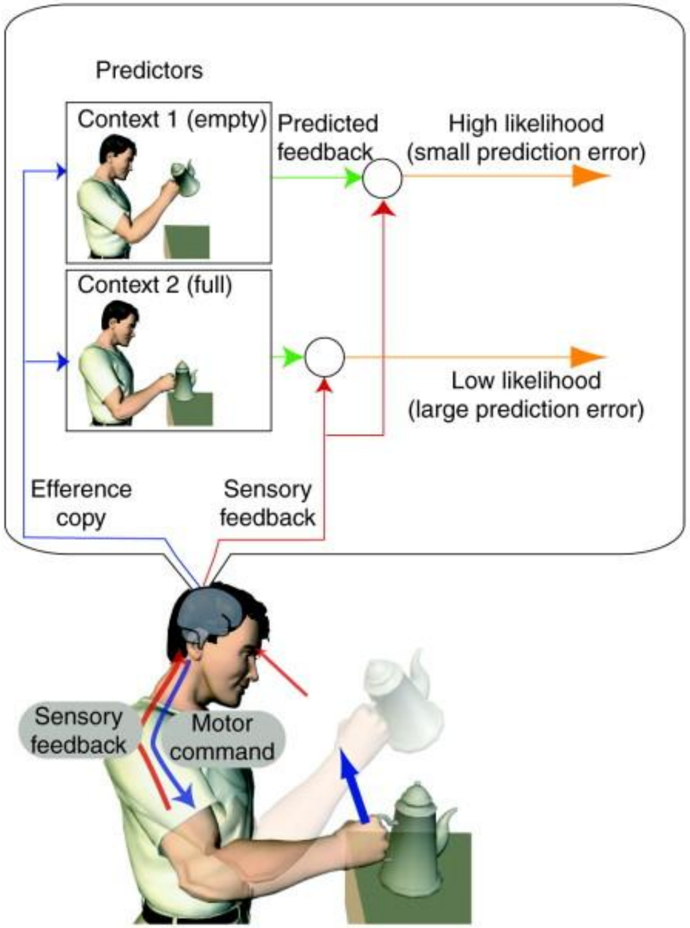
- EMG from stroke patients needed fewer components
- EMG from children needed fewer components than EMG from adults

[Cappellini, G. et al., *J. Neurophysiology*, 2006]

Internal Models



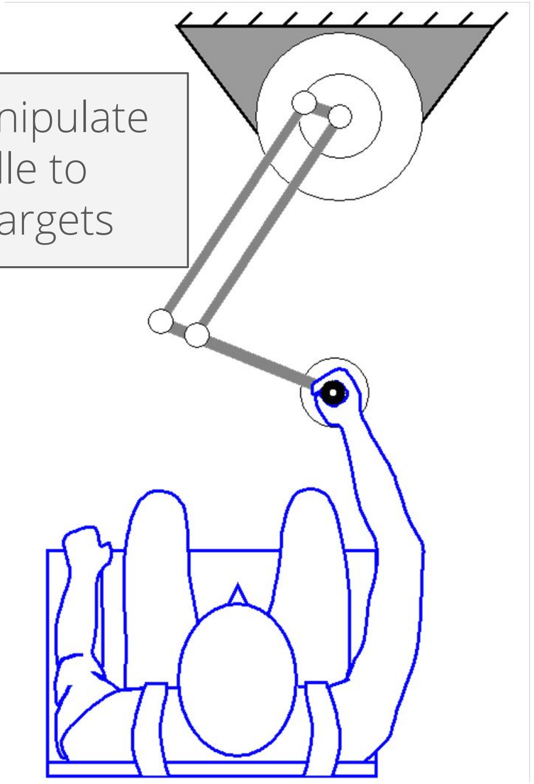
Internal Models

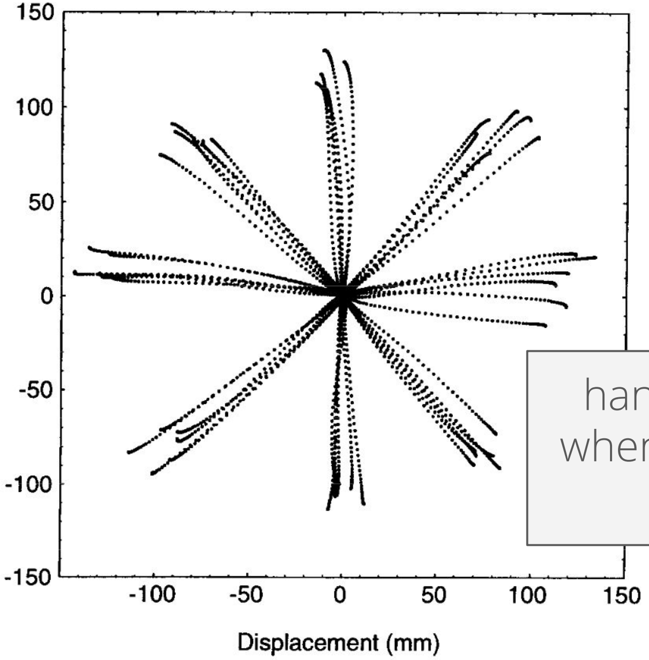


[Wolpert, D.M. and Flanagan, J.R., *Current Biology*, 2001]

Internal Models - supporting experiment

subjects manipulate this handle to specified targets



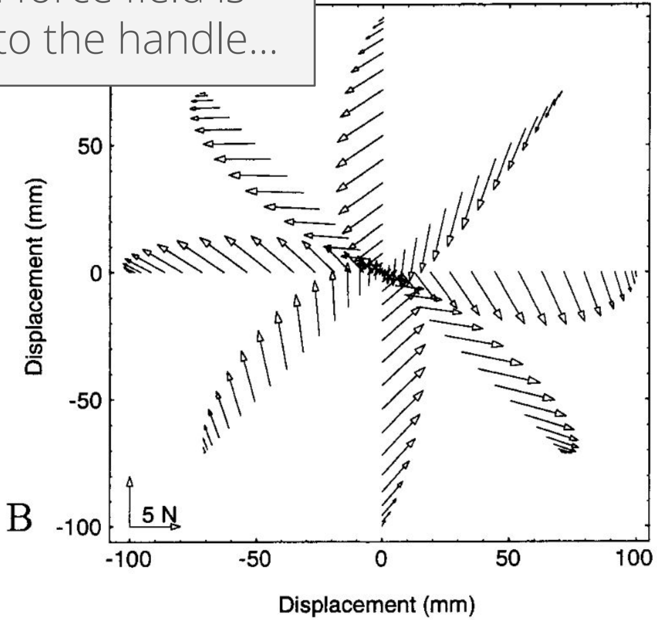


handle trajectories when no disturbance is applied

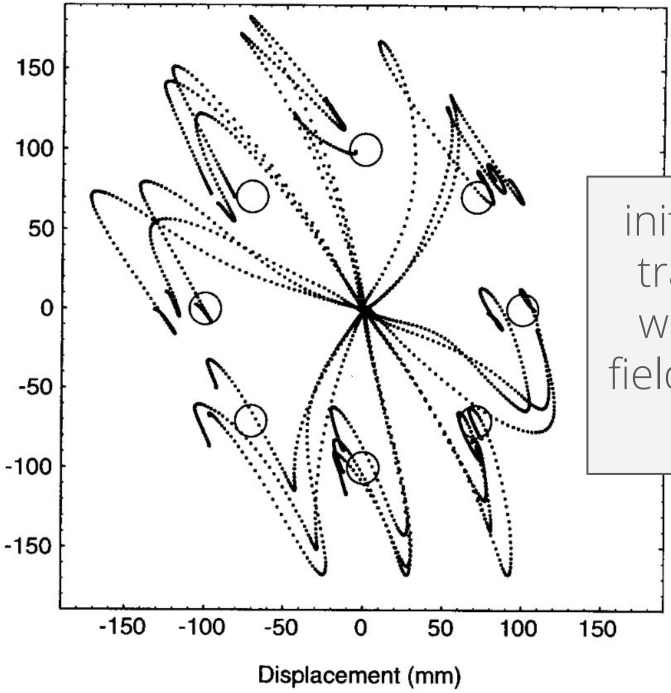
[Shadmehr, R. and Mussa-Ivaldi, F.A., *J. Neuroscience*, 1994]

Internal Models - supporting experiment

then, a force field is applied to the handle...



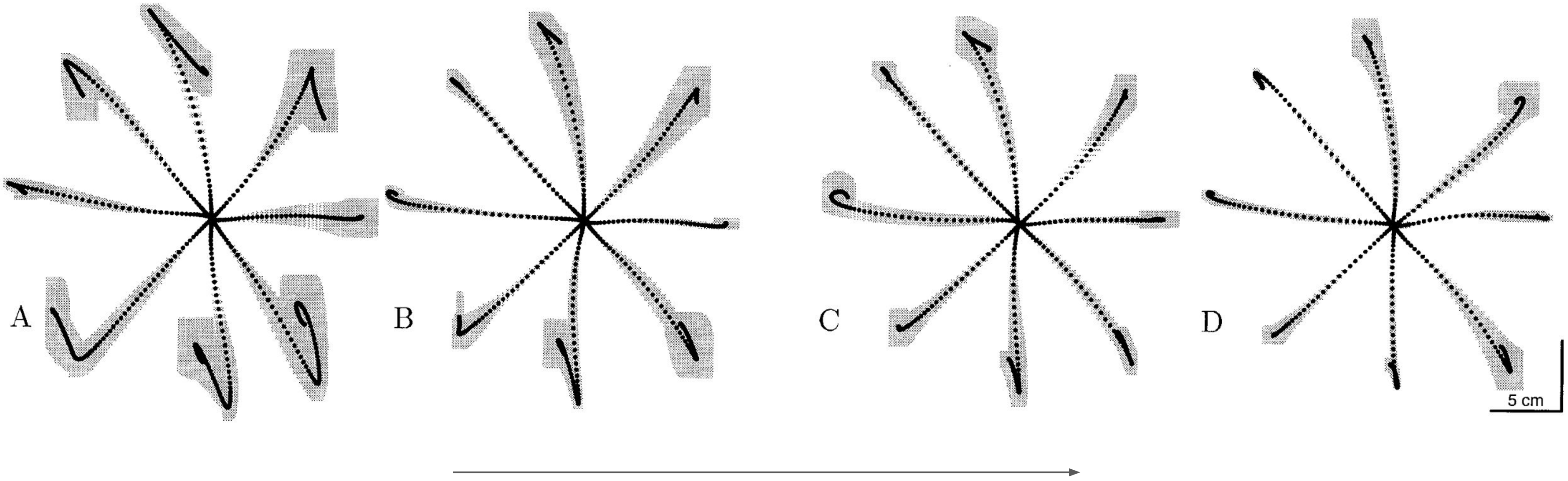
B, Forces acting on the hand while making reaching movements in the left workspace of Figure 2 from the center to targets about the circumference of a circle. Movements are simulated as being minimum jerk with a period of 0.5 sec and amplitude of 10 cm.



initial handle trajectories when force field is applied

[Shadmehr, R. and Mussa-Ivaldi, F.A., *J. Neuroscience*, 1994]

Internal Models - supporting experiment

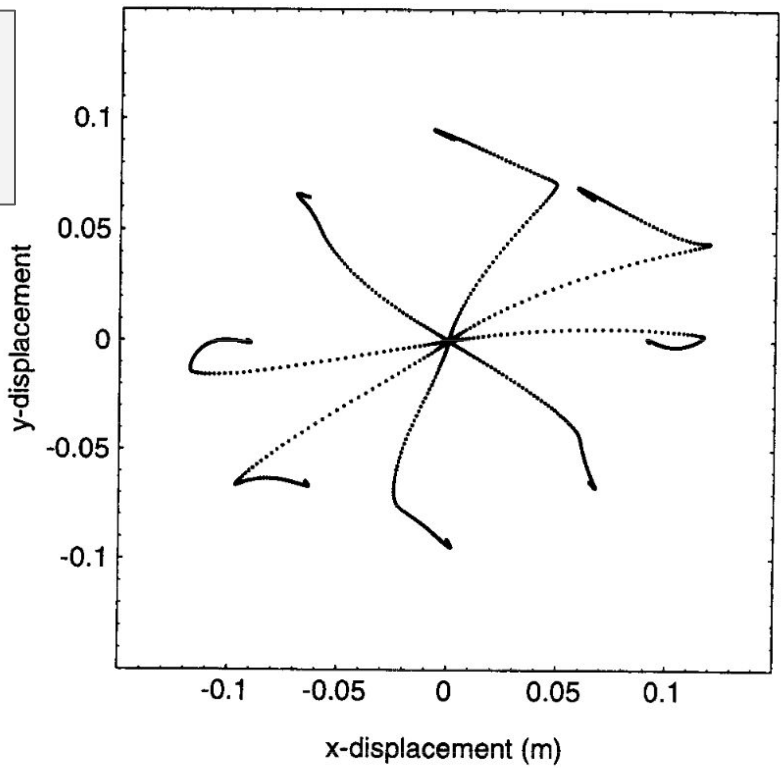


improvement (updating internal model) over time...

[Shadmehr, R. and Mussa-Ivaldi, F.A., *J. Neuroscience*, 1994]

Internal Models - supporting experiment

when the force field was removed…



…subjects had to train themselves the opposite way!

[Shadmehr, R. and Mussa-Ivaldi, F.A., *J. Neuroscience*, 1994]

Uncontrolled Manifold Hypothesis

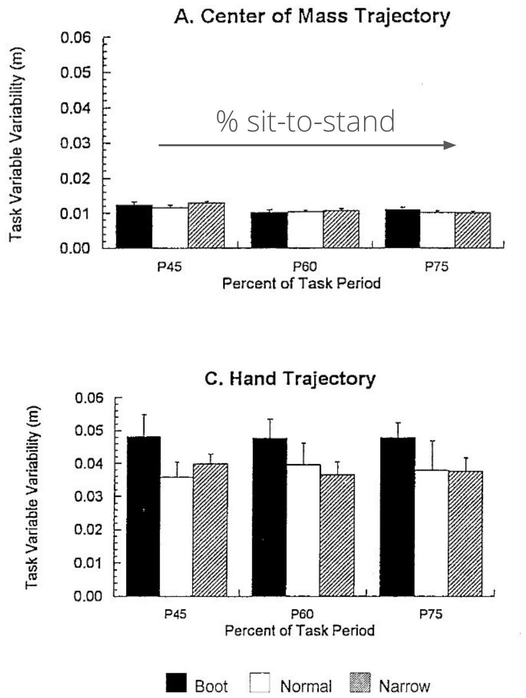
large variability in joint angles and velocities

Small variability in where the hammer lands

[Image from theindependent.com]

Uncontrolled Manifold Hypothesis

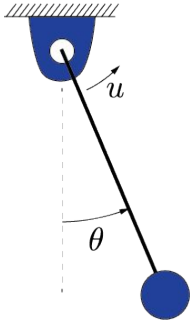
- The nervous system controls some degrees of freedom (DOFs), but may care less about other DOFs
- This hypothesis states that the variance within a given task is confined to a subspace of DOFs that can preserve task performance
- The subspace is called the uncontrolled manifold (UCM)
- Example UCM: During sit-to-stand, all combinations of lower-limb joint angles that together place the center of mass in a certain position



[Scholz, J.P. and Schöner, G., *Exp. Brain Research*, 1999]

In conclusion.... Science is hard!!

- Low-level control
    - Feedforward
    - Feedback
    - Hybrid FF+FB
- Mid-level control
    - Inverse Kinematics and Inverse Dynamics
    - Equilibrium Point Hypothesis
    - Muscle Synergies
    - Internal Models
    - Uncontrolled Manifold Hypothesis



So many cool experiments about human/animal motor control, so many different ways to interpret them...