Neuromechanics of Human Motion

Brain Areas and Internal Models

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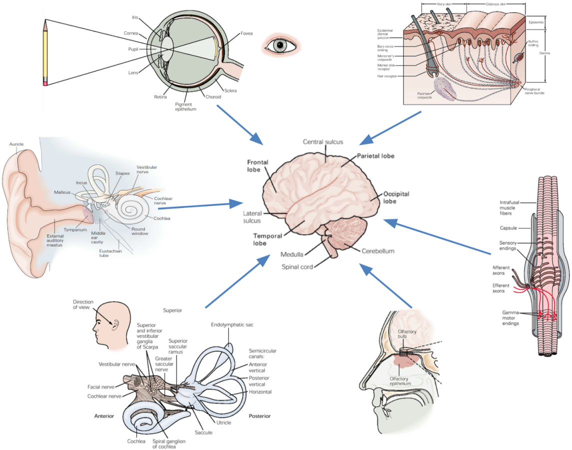
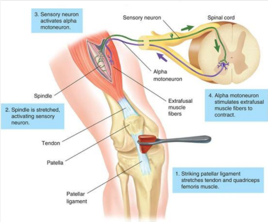
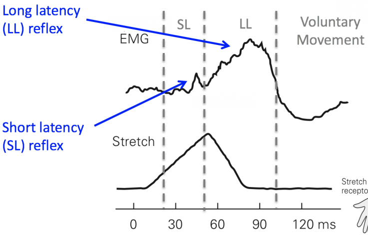
Recap — MODULE 1: Sensory Inputs

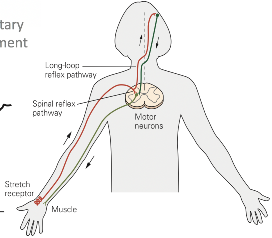


Recap — MODULE 1: Sensory Inputs

Reflexes - from simple to complex







Recap — MODULE 1: Sensory Inputs

NOISE

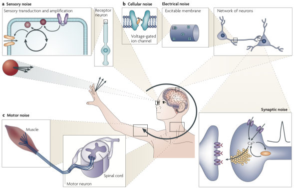
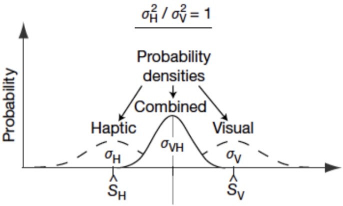
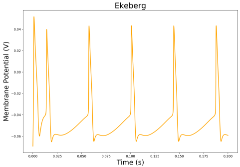
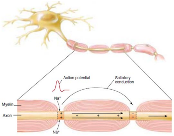


Figure 1 | **Overview of the behavioural loop and the stages at which noise is present in the nervous system.** **a** | Sources of sensory noise include the transduction of signals. This is exemplified here by a photoreceptor and its signal-amplification cascade. **b** | Sources of cellular noise include the ion channels of excitable membranes, synaptic transmission and network interactions (see BOX 2). **c** | Sources of motor noise include motor neurons and muscle. In the behavioural task shown (catching a ball), the nervous system has to act in the presence of noise in sensing, information processing and movement.



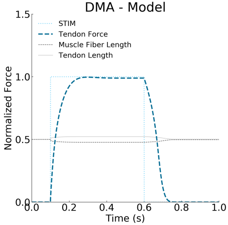
DELAYS

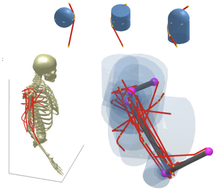


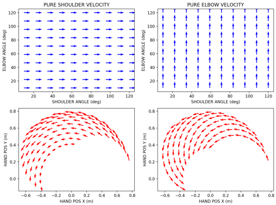


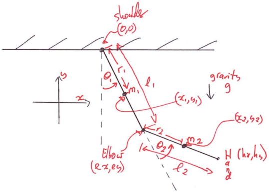
Major challenges from a control perspective

Recap — MODULE 2: Motor Outputs









Schematic of a two-joint arm in a vertical plane

Very Complex Physics!

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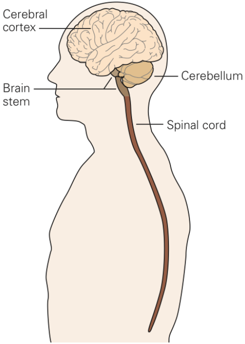
GIVEN OUR COMPLEX PHYSICS, NEURAL NOISE AND DELAYS, HOW ARE WE SO AMAZING AT MOVING???

MODULE 3
Control Policies:
Brains, Biomechanics and Behaviour

Lecture Objectives — Brain Areas and Internal Models

1. Areas of the Brain: A Brief Tour
2. Internal Models
   - Interaction Moments
   - Cerebellum

A Hierarchy of Control



Cerebral Cortex

. select, plan, execute goal-directed movement

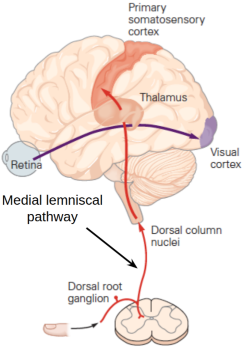
Cortical Spinal Reflexes

. contain both simple and goal-directed movement

Spinal Reflexes

. Rapid and simple reflexes

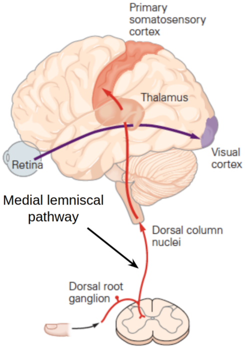
Sensory Inputs



Dorsal Column Tract

- Proprioception (spindles, GTO)
- Cutaneous
- Synapse to Thalamus

Sensory Inputs



Dorsal Column Tract

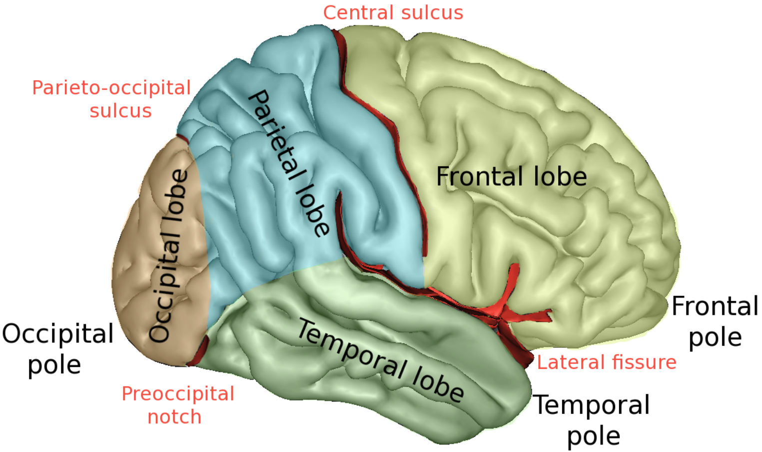
- Proprioception (spindles, GTO)
- Cutaneous
- Synapse to Thalamus

Visual Cortex

Vestibular (otolith organs, semicircular canals)

Areas of the Brain

Major Landmarks



Neural Basis of Movement

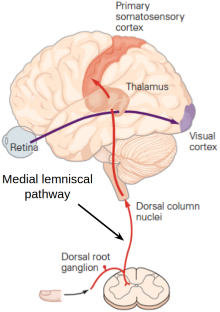
Cortical (select, plan, execute)

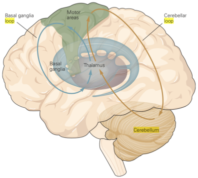
a. Parietal Lobe:
    i. Somatosensory Cortex (S1)
    ii. Posterior Parietal Cortex
b. Frontal Lobe:
    i. Premotor Cortex
    ii. Supplementary Areas
    iii. Primary Motor cortex (M1)

Subcortical

a. Thalamus
b. Basal Ganglia
c. Cerebellum

Thalamus — Subcortical



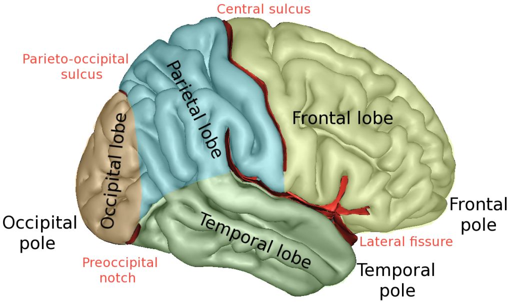


1. Major Relay Center
2. Four major groups
    a. Ventral
        - somatosensory to primary somatosensory cortex (S1)
        - Cortico-Basal Ganglia-Thalamocortical Loops
        - Cerebellar Loop

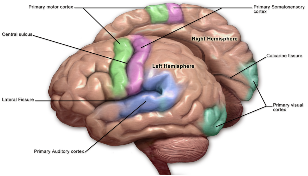
    b. Posterior (retina to visual cortex)
    c. Anterior (emotion, memory)
    d. Medial (memory)

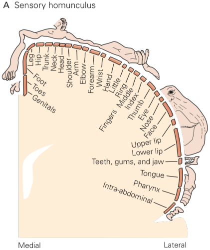
Parietal Lobe

1. Somatosensory Cortex (S1)
2. Posterior Parietal Cortex



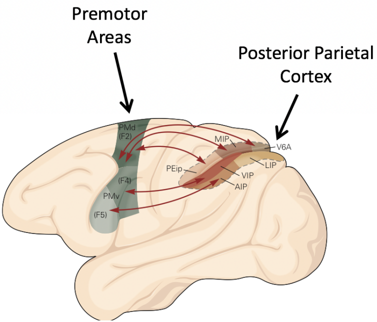
Primary Somatosensory Cortex (S1)





1. Major Role: Receive Somatosensory Feedback
2. Inputs: somatosensory signals from Thalamus
3. Homunculus (Map)
4. Outputs: M1 & posterior parietal cortex

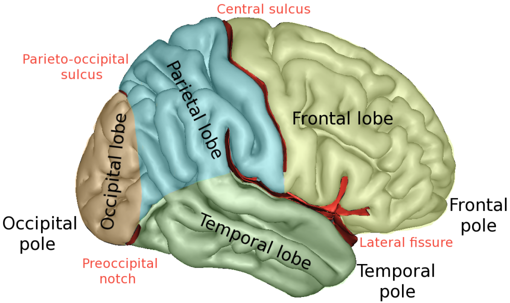
Posterior Parietal Cortex



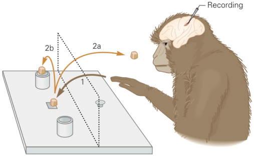
1. Major roles
   - Visually guided reaching and grasping (superior parietal cortex)
   - Multisensory integration
   - Encode purpose of action (inferior parietal cortex)
2. Inputs: thalamus, visual & auditory cortex, premotor
3. Outputs: premotor & supplementary motor areas

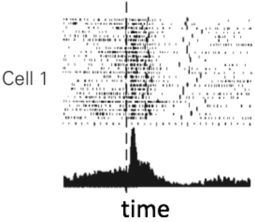
Frontal Lobe

1. premotor cortex
2. supplementary areas
3. primary motor cortex



Raster Plots

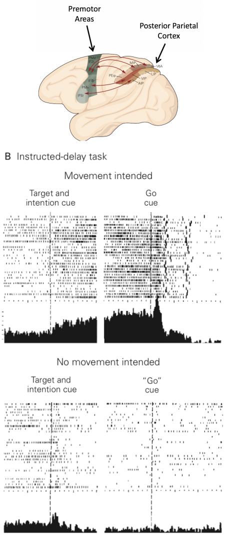




- Each line represents a single trial
- Black dot indicates neuron firing.

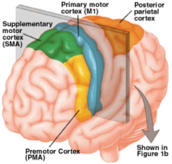
Histogram (vertical sum of all trials)

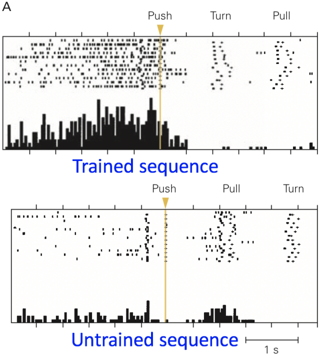
Premotor Cortex



1. Major roles
   - Movement Planning (Crammond, 2000)
   - Spatial Guidance of Movement
   - Observing Others (mirror-neurons)
   - Generate Motor Command
2. Inputs: Prefrontal cortex, M1, supplementary motor area, parietal cortex
3. Outputs: Prefrontal cortex, M1, supp. motor area, parietal cortex, thalamus, Spinal Cord

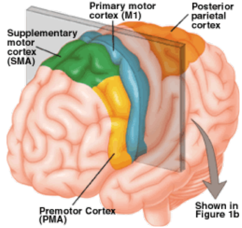
Supplementary Areas

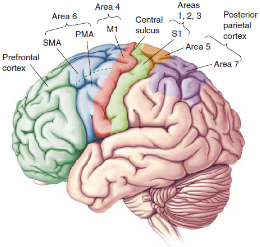




1. Major roles
   - Sequences of movements (Tanji, 2001)
   - Selecting voluntary actions
   - Postural stabilization
   - Bimanual action
2. Inputs: Premotor Cortex
3. Outputs: Premotor cortex, Sparse connections to primary motor and spine

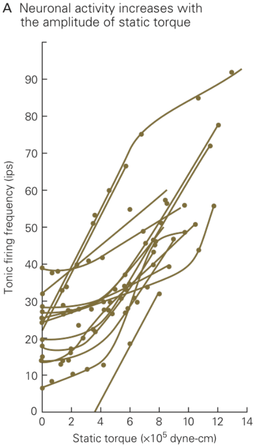
Primary Motor Cortex (M1)

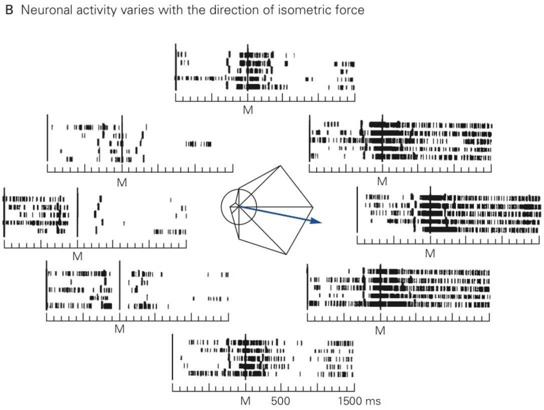




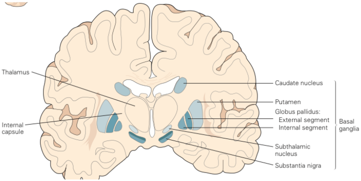
1. Major roles
   - Executes Motor Plan
   - Generate motor commands and activate muscles
   - Learning (Mussa-Ivaldi & Bizzi, 2000)
2. Inputs: Directly or indirect information from areas mentioned, cerebellum, basal ganglia
3. Outputs: Spinal Cord, Cerebellum & Basal Ganglia Loops

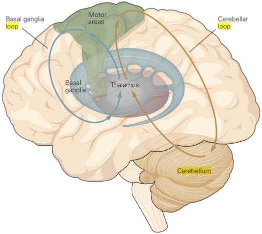
Primary Motor Cortex (M1)





Basal Ganglia — Subcortical





1. Major roles
   - Initiating movements
   - Inhibiting movements
   - Reinforcement Learning
2. Cortico-Basal Ganglia-Thalamocortical Loops
3. Dopamine
4. Next Lecture!

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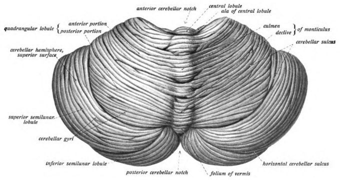
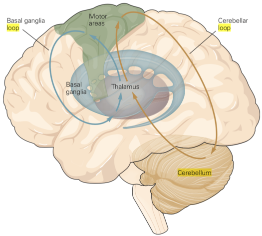
Cerebellum — Subcortical





1. Major roles
   - Coordination and Timing
   - Precision movements
   - STORE INTERNAL MODELS! (more below)
2. Inputs: Spinal cord, premotor cortex, primary motor cortex
3. Outputs: Premotor cortex and primary motor cortex (both via Thalamus), spinal cord (timing)

Fun fact: $>$ 50% neurons, $<$ 10% volume of the brain

Descending Commands from Motor Areas

1. Pyramid Tracts
   - Corticospinal tract (Betz cells) to limb and trunk muscles
   - Corticobulbar tract to facial muscles
2. Synapse to motor neurons to activate muscle

What is an Internal Model?

Internal Models

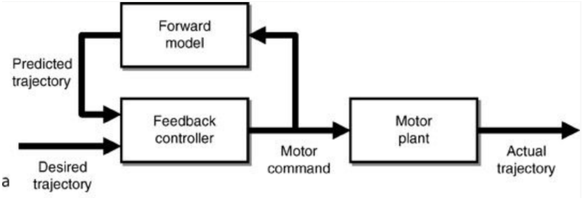
Internal Model

A stored or learned representation—via some pattern of neuronal activity—that accounts for environmental or internal dynamics

Forward vs. Inverse

Forward Internal Models

Forward Internal Model allow us to make a prediction of the trajectory that results from a particular motor command sent to a particular motor plant (Cisek, 2009)



Compensate for plant properties without waiting for actual feedback about the resulting movement to return from the periphery. Thus, a forward model can be used to implement zero-lag feedback control.

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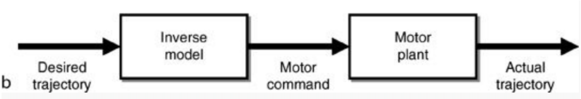
Inverse Internal Models

Inverse Internal Models allow us to generate the required motor command to produce a given desired trajectory (Cisek, 2009)



Inverse model can be used to implement accurate feedforward control

What evidence supports the notion of Internal Models???

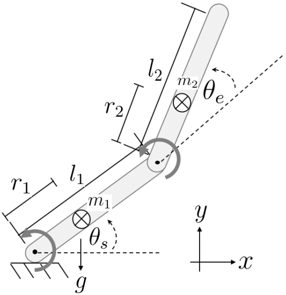
What evidence supports the notion of Internal Models???

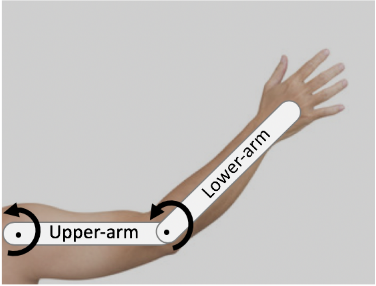
Lets consider whether the brain accounts for intersegmental dynamics (Interaction moments)

Intersegmental Dynamics

Interaction Moments

Rotational forces at one joint due to the motion of a limb segment about another joint.



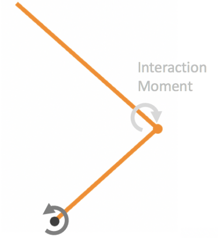


Intersegmental Dynamics

Interaction Moments

Rotational forces at one joint due to the motion of a limb segment about another joint.

Shoulder rotation causes the elbow to rotate



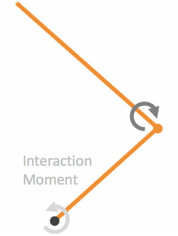
$$Q_1 \rightarrow \dot{\theta}_1, \ddot{\theta}_1 \rightarrow Q_2 \rightarrow \dot{\theta}_2, \ddot{\theta}_2$$

Intersegmental Dynamics

Interaction Moments

Rotational forces at one joint due to the motion of a limb segment about another joint.

Elbow rotation causes the shoulder to rotate



$$Q_2 \rightarrow \dot{\theta}_2, \ddot{\theta}_2 \rightarrow Q_1 \rightarrow \dot{\theta}_1, \ddot{\theta}_1$$

Equations of Motion

$$
\begin{aligned}
Q_1 =&(\mathcal{I}_1 + \mathcal{I}_2 + m_1 \cdot r_1^2 + m_2(l_1^2 + r_2^2 + 2 \cdot l_1 \cdot r_2 \cdot cos(\theta_2)))\ddot{\theta_1} + \\
&(\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta_2} - \\
&l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta_2}^2 - 2 \cdot l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta_1} \cdot \dot{\theta_2} + \\
&g \cdot sin(\theta_1) \cdot (m_2 \cdot l_1 + m_1 \cdot r_1) + g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2) \\
Q_2 =&(\mathcal{I}_2 + m_2 \cdot r_2^2)\ddot{\theta_2} + \\
&(\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta_1} + \\
&l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2)\dot{\theta_1}^2 + \\
&g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2)
\end{aligned}
$$

Elbow Moments arising from Shoulder Movement

$$
\begin{aligned}
Q_1 =& (\mathcal{I}_1 + \mathcal{I}_2 + m_1 \cdot r_1^2 + m_2(l_1^2 + r_2^2 + 2 \cdot l_1 \cdot r_2 \cdot cos(\theta_2)))\ddot{\theta}_1 + \\
& (\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta}_2 - \\
& l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta}_2^2 - 2 \cdot l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta}_1 \cdot \dot{\theta}_2 + \\
& g \cdot sin(\theta_1) \cdot (m_2 \cdot l_1 + m_1 \cdot r_1) + g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2) \\
Q_2 =& (\mathcal{I}_2 + m_2 \cdot r_2^2)\ddot{\theta}_2 + \\
& (\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta}_1 + \\
& l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2)\dot{\theta}_1^2 + \\
& g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2)
\end{aligned}
$$

Shoulder Moments arising from Elbow Movement

$$
\begin{aligned}
Q_1 = & (\mathcal{I}_1 + \mathcal{I}_2 + m_1 \cdot r_1^2 + m_2(l_1^2 + r_2^2 + 2 \cdot l_1 \cdot r_2 \cdot cos(\theta_2)))\ddot{\theta_1} + \\
& (\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta_2} - \\
& l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta_2}^2 - 2 \cdot l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta_1} \cdot \dot{\theta_2} + \\
& g \cdot sin(\theta_1) \cdot (m_2 \cdot l_1 + m_1 \cdot r_1) + g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2) \\
Q_2 = & (\mathcal{I}_2 + m_2 \cdot r_2^2)\ddot{\theta_2} + \\
& (\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta_1} + \\
& l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2)\dot{\theta_1}^2 + \\
& g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2)
\end{aligned}
$$

Interaction Moment Terms

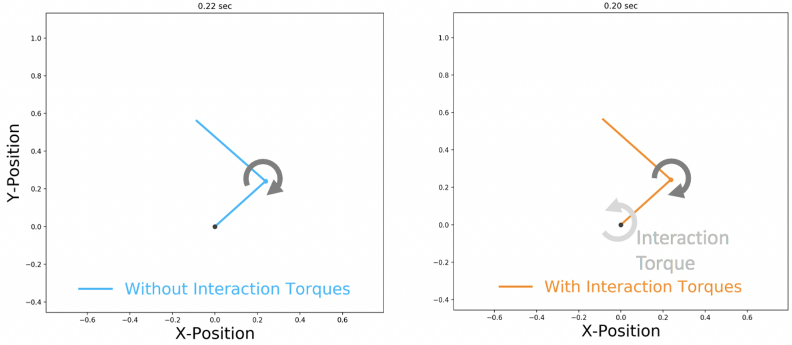
$$
\begin{aligned}
Q_1 =& (\mathcal{I}_1 + \mathcal{I}_2 + m_1 \cdot r_1^2 + m_2(l_1^2 + r_2^2 + 2 \cdot l_1 \cdot r_2 \cdot cos(\theta_2)))\ddot{\theta_1} + \\
& (\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta_2} - \\
& l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta_2}^2 - 2 \cdot l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta_1} \cdot \dot{\theta_2} + \\
& g \cdot sin(\theta_1) \cdot (m_2 \cdot l_1 + m_1 \cdot r_1) + g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2) \\
Q_2 =& (\mathcal{I}_2 + m_2 \cdot r_2^2)\ddot{\theta_2} + \\
& (\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta_1} + \\
& l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2)\dot{\theta_1}^2 + \\
& g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2)
\end{aligned}
$$

Interaction Moment Terms

$$
\begin{aligned}
Q_1 =& (\mathcal{I}_1 + \mathcal{I}_2 + m_1 \cdot r_1^2 + m_2(l_1^2 + r_2^2 + 2 \cdot l_1 \cdot r_2 \cdot cos(\theta_2)))\ddot{\theta_1} + \\
& (\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta_2} - \\
& l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta_2}^2 - 2 \cdot l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2) \cdot \dot{\theta_1} \cdot \dot{\theta_2} + \\
& g \cdot sin(\theta_1) \cdot (m_2 \cdot l_1 + m_1 \cdot r_1) + g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2) \\
Q_2 =& (\mathcal{I}_2 + m_2 \cdot r_2^2)\ddot{\theta_2} + \\
& (\mathcal{I}_2 + m_2[r_2^2 + l_1 \cdot r_2 \cdot cos(\theta_2)])\ddot{\theta_1} + \\
& l_1 \cdot m_2 \cdot r_2 \cdot sin(\theta_2)\dot{\theta_1}^2 + \\
& g \cdot m_2 \cdot r_2 \cdot sin(\theta_1 + \theta_2)
\end{aligned}
$$

Interaction Moment — Simulation 1

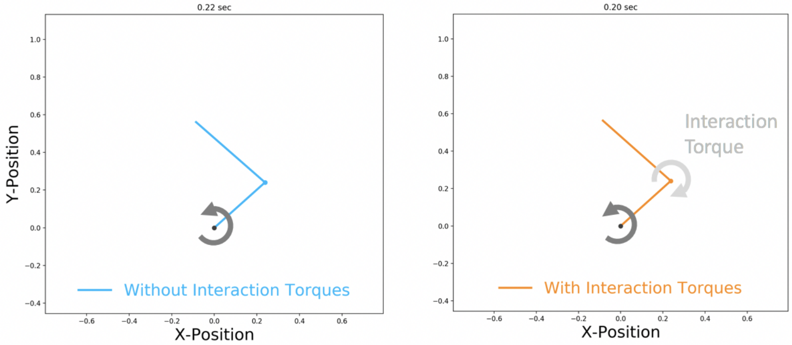
$$Q_2 \rightarrow \dot{\theta}_2, \ddot{\theta}_2 \rightarrow Q_1 \rightarrow \dot{\theta}_1, \ddot{\theta}_1$$



Elbow rotation leads to shoulder rotation

Interaction Moment — Simulation 2

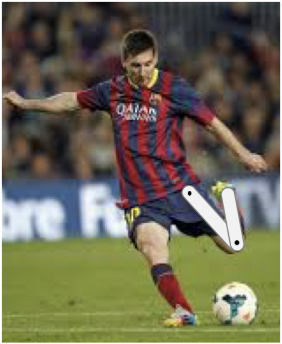
$$Q_1 \rightarrow \dot{\theta}_1, \ddot{\theta}_1 \rightarrow Q_2 \rightarrow \dot{\theta}_2, \ddot{\theta}_2$$



Shoulder rotation leads to elbow rotation

University of Delaware

Why Care About Interaction Moments?



1. Rapid actions $\rightarrow$ High Interaction Moments
2. Pitching needs millisecond precision (Hore et al., 2011)

Does the Brain Account for Interaction Moments?

Plenty of evidence

1. Hollerbach, J. M., & Flash, T. (1982). Biological cybernetics, 44(1), 67-77.
2. Hasan, Z., & Karst, G. M. (1989). Experimental Brain Research, 76(3), 651-655.
3. Virji-Babul, N., & Cooke, J. D. (1995). Experimental brain research, 103(3), 451-459.
4. Sainburg, R. L., Ghilardi, M. F., Poizner, H. & Ghez, C. (1995). Journal of Neurophysiology, 73(2), 820-835.
5. Gribble, P. L., & Ostry, D. J. (1999). Journal of Neurophysiology, 82(5), 2310-2326.
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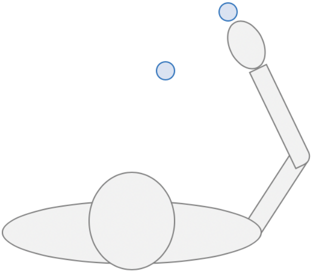
7. Koshland, G. F., Galloway, J. C., & Nevoret-Bell, C. J. (2000). Journal of neurophysiology, 83(5), 3188-3195.
8. Bastian, A. J., Martin, T. A., Keating, J. G., & Thach, W. T. (1996). Journal of Neurophysiology, 76(1), 492-509.

Pure Elbow Moment — Gribble (1999)



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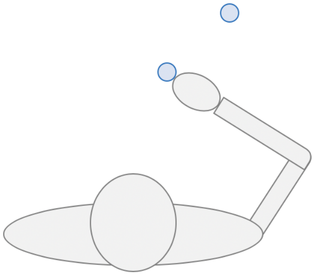

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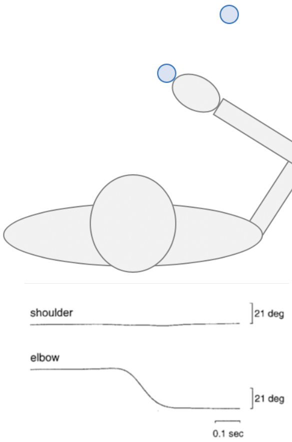

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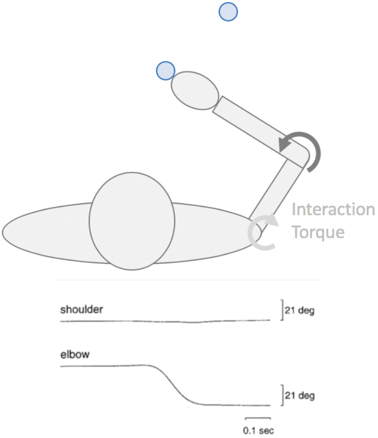

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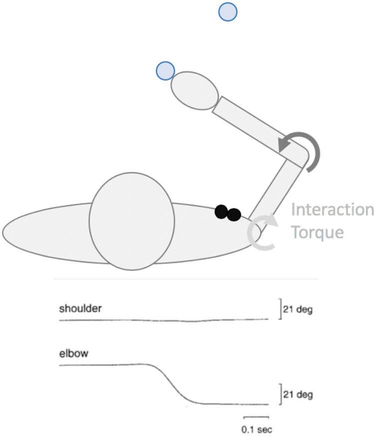

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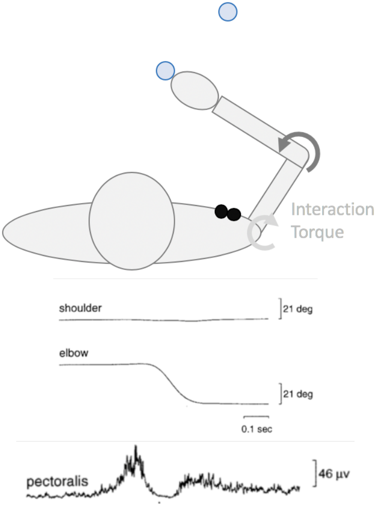
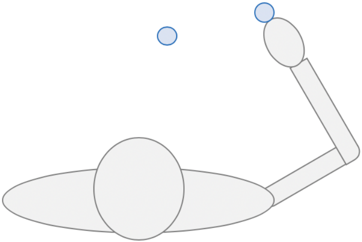


Pure Shoulder Moment — Gribble (1999)



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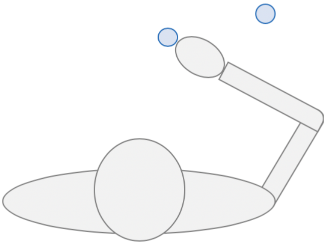
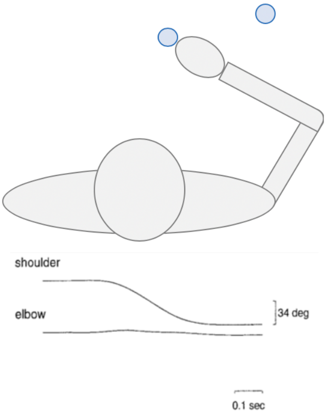


Pure Shoulder Moment — Gribble (1999)



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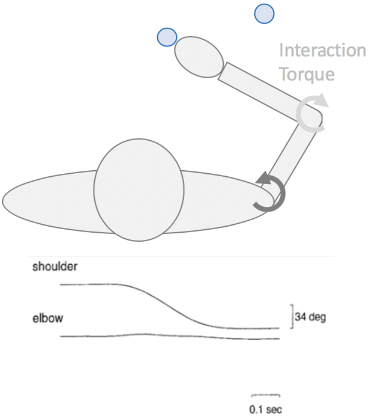

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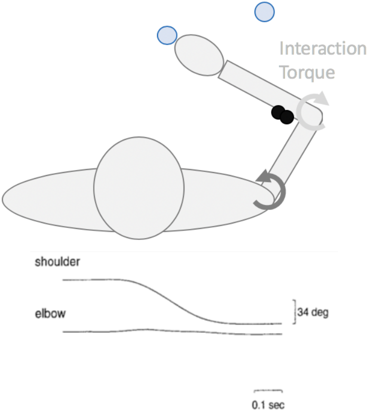

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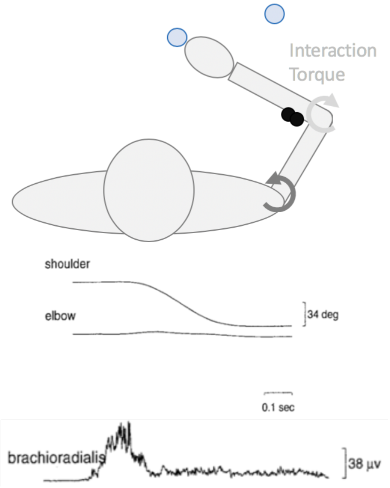

THE BRAIN PLANS FOR INTERACTION MOMENTS!!!

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Suggests the nervous system stores a representation of these dynamics.

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Where is this information stored?

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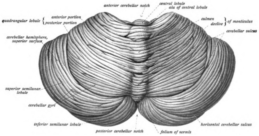
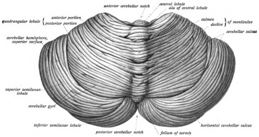
Cerebellum



Internal Models and the Cerebellum



Cerebellar Ataxia

Cerebellar Ataxia

Movement Disorder caused by damage to the cerebellum

Causes

1. Stroke
2. Trauma
3. Excessive alcohol

Symptoms

1. Intention tremor
2. Dysmetria: lack of coordination (under and overshoot targets during reaching or eye saccades)

Cerebellar Ataxia

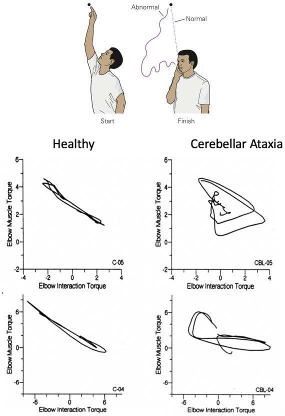
DEMO: Finger to Nose Test

Cerebellar Ataxia

DEMO: Finger to Nose Test

Click Me: Link

Cerebellum and Interaction Moments
Bastian et al., 1996



Cerebellum and Interaction Moments
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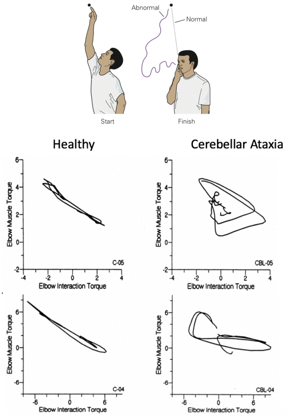

$$Q = EMT = M\ddot{\theta} + C + G$$

THE CEREBELLUM STORES NEURAL REPRESENTATIONS OF DYNAMICS!

THE CEREBELLUM STORES NEURAL REPRESENTATIONS OF DYNAMICS!

1. Cerebellum $\rightarrow$ Large projections (connections) with Primary Motor Cortex (M1)
2. M1 sends descending motor commands to muscles

Summary

1. Areas of the Brain
   - Major Roles
   - Interpret Raster Plots
2. Define Internal Model
3. Define Interaction Moments
4. Link between cerebellum and internal models

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TAKE HOME:

The brain stores an a neural representation of our biomechanics that aids in generating coordinated movement behaviour.

Questions???

Homework

1. Simulate a 2-link arm *with* and *without* Interaction Moments

Next Class

1. Reinforcement Learning
2. Basal Ganglia