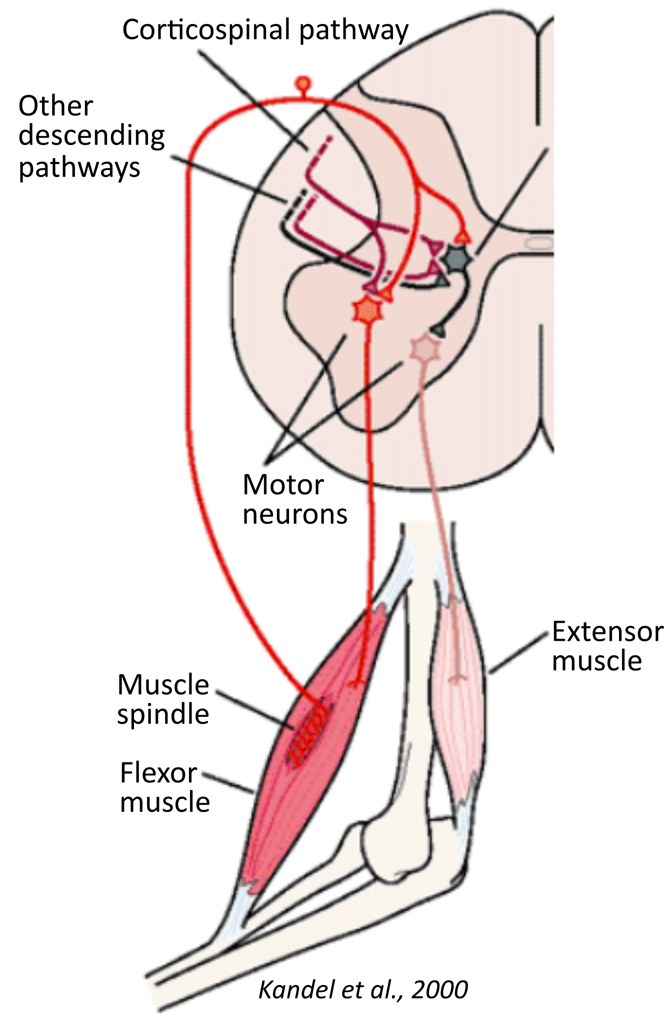
What Roboticists Need to Know About NeuroMusculoSkeletal Systems

Gerald E. Loeb, M.D.
Professor of Biomedical Engineering
Director of the Medical Device Development Facility
University of Southern California

Gerald E. Loeb

- Background
  - 1965-1973 B.A., M.D. Johns Hopkins University, internship in surgery
  - 1973-1988 Lab. Of Neural Control, National Institutes of Health
  - 1988-1999 Professor of Physiology, Queen's Univ., Canada
  - 1994-1999 Chief Scientist, Advanced Bionics Corp., Los Angeles
  - 1999-present Professor of Biomedical Engineering, Director of the Medical Device Development Facility, Univ. Southern California
  - 2008-present CEO, SynTouch LLC, Los Angeles
- Research Interests
  - Sensorimotor neurophysiology and control
  - Biomimetic prosthetic and robotic systems
- Issues in Impedance Control
  - Biological components (actuators, sensors, feedback loops) are much more nonlinear, noisy and slow than their mechatronic counterparts, yet they perform much better on unpredictable tasks and a baby can learn to use them.
  - We need to understand why if we are going to repair or replace them.

Investigating the role of muscle physiology and spinal circuitry in movement



<u>Current and recent collaborators:</u>

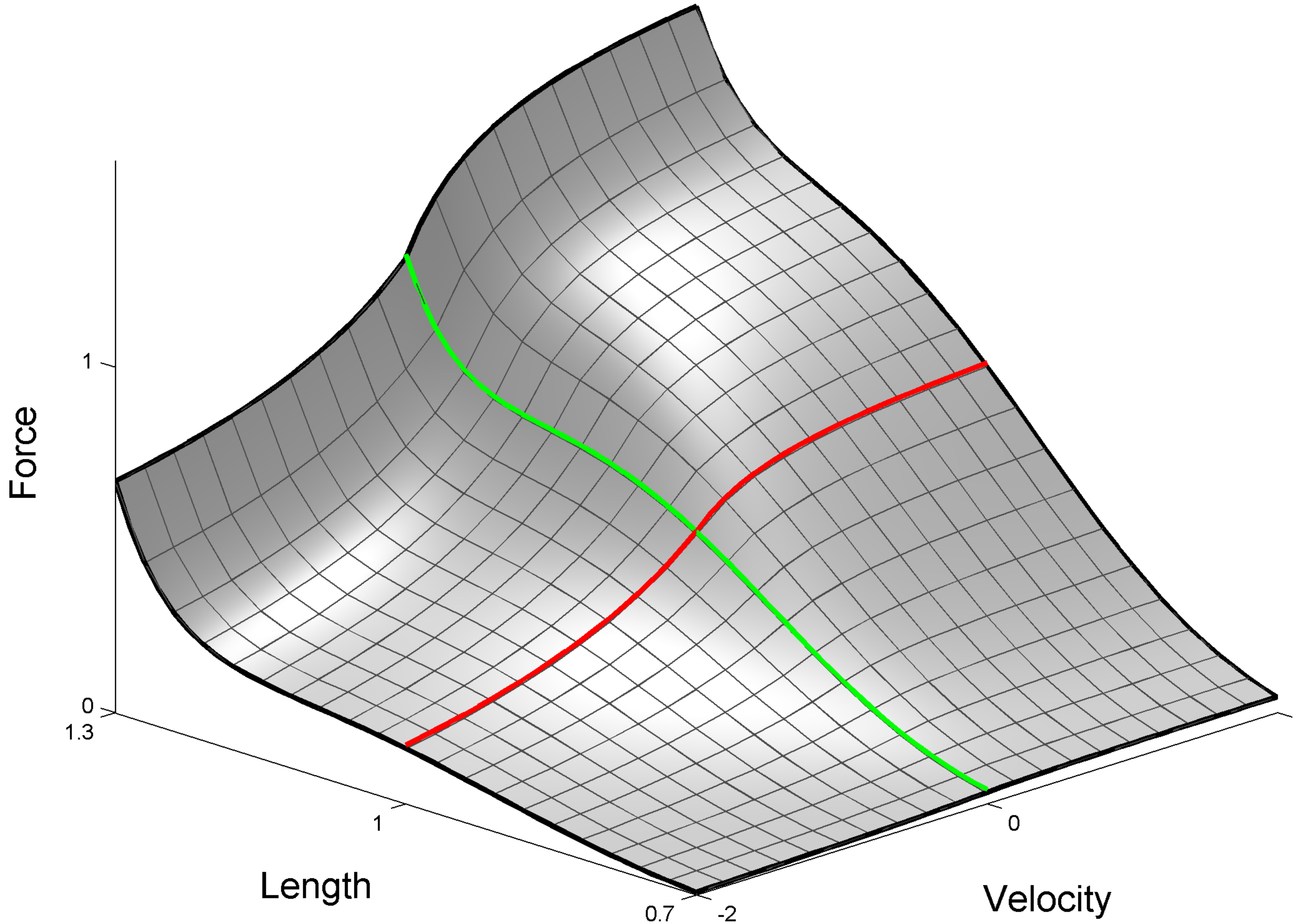
Research Asst.Professor: Dr. Rahman Davoodi

Post-doctoral fellows: Giby Raphael, Yao Li

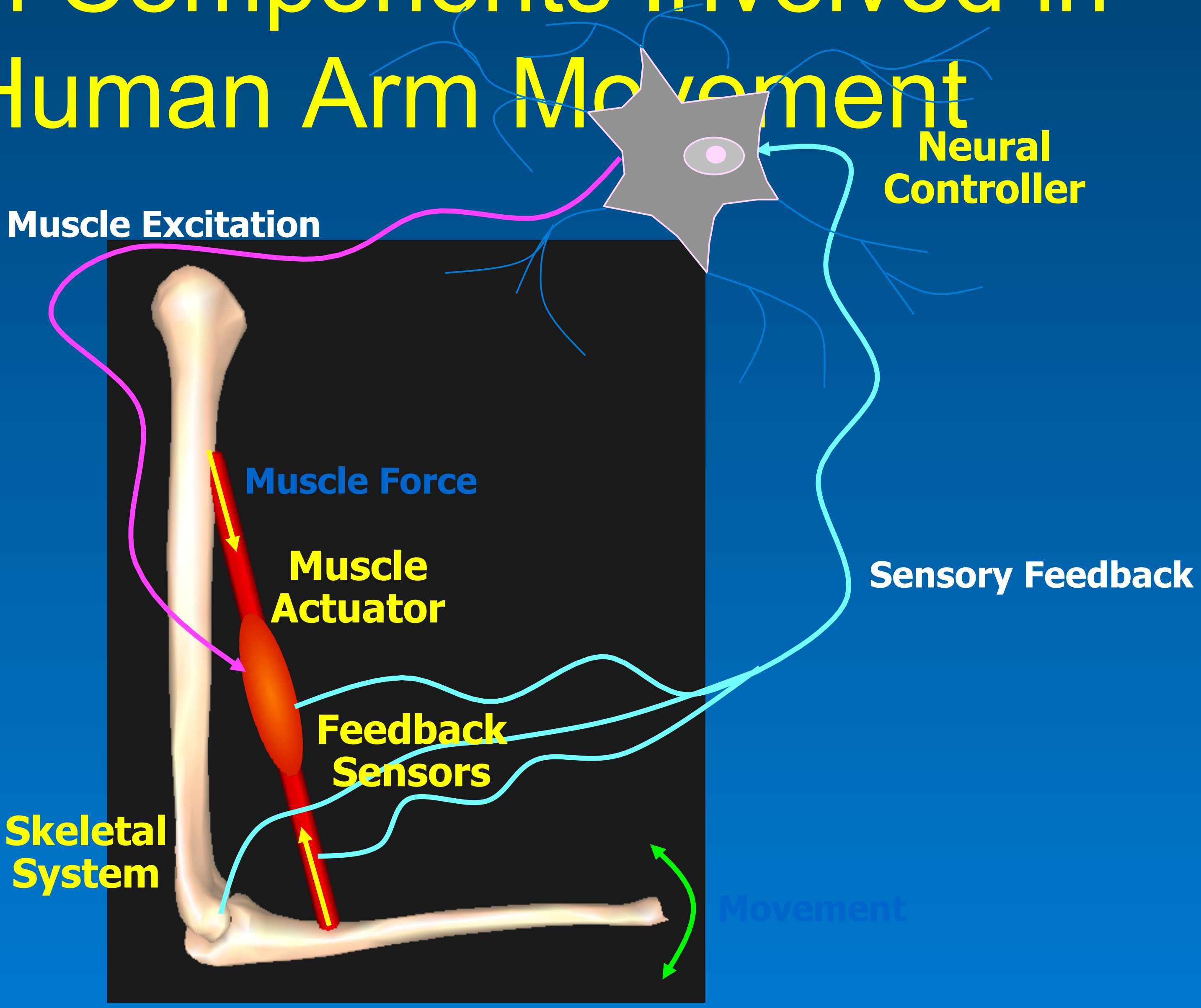
Graduate students: George Tsianos, Cedric Rustin, Jared Goodner, Katherine Quigley

Undergraduates: Norman Li, Travis Marziani, Adam Baybutt, Enrique Morales, Michelle Fung

Muscle ≠ Torque Motor



Main Components Involved in Human Arm Movement

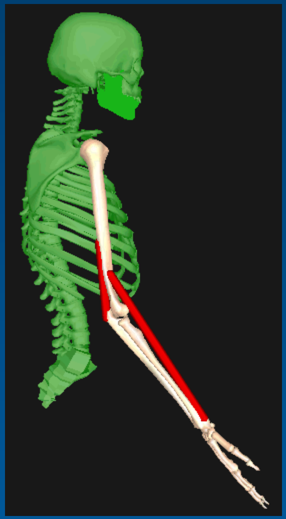


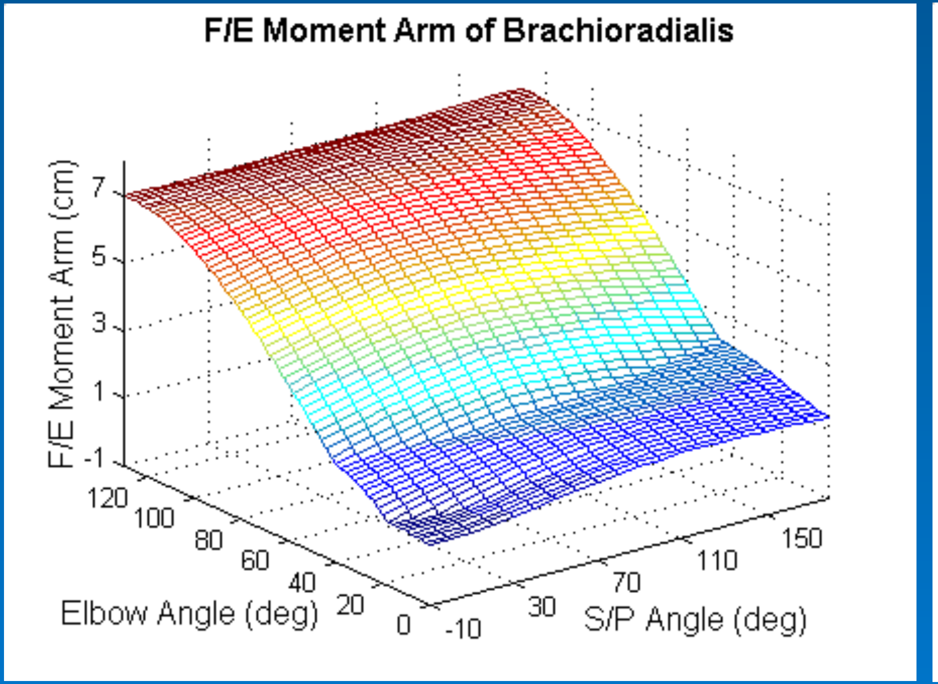
Actuator Properties: Underlying Mechanisms

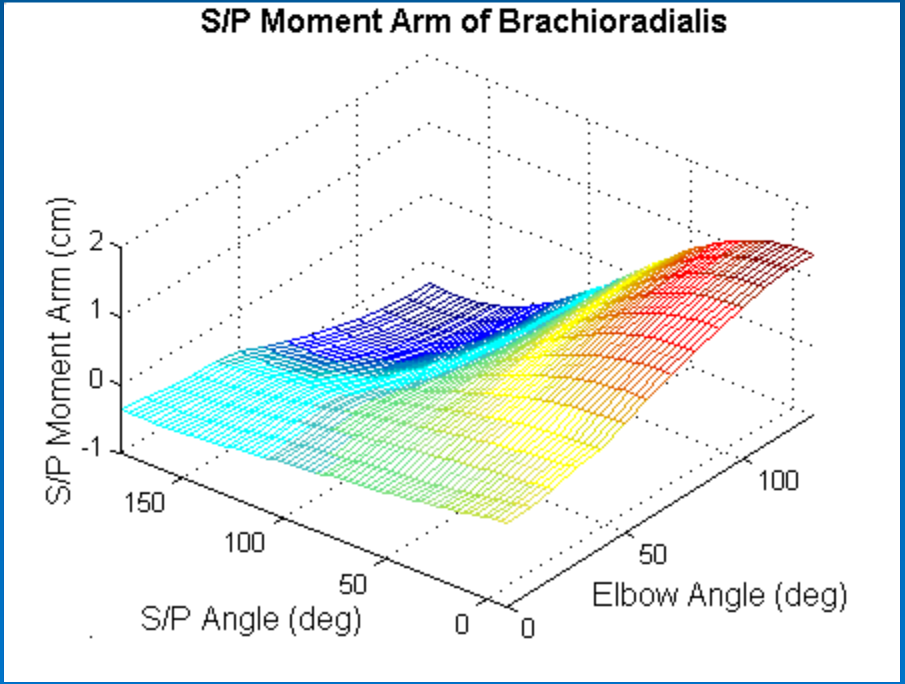
- Force – Length: Myofilament overlap
- Force – Velocity: Cross-bridge dynamics
- Force – Frequency: Calcium kinetics
- Moment – Angle: Tendon path
- Elastic Storage: Collagen ultrastructure
- Energy Transfer: Multiarticular muscles
- Impedance Control: Cocontraction

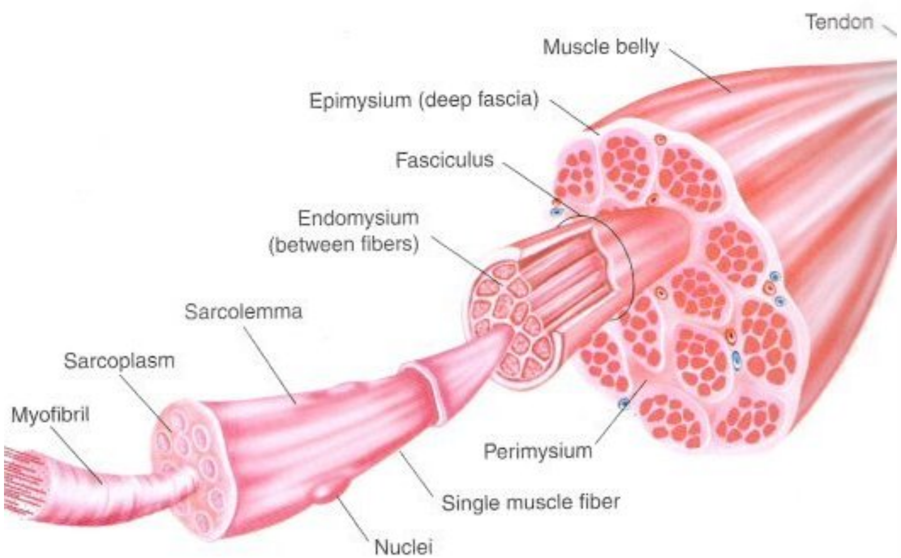
Muscle accounts for the majority of animal mass and energy consumption. The evolutionary pressures to find and exploit any advantage are huge.

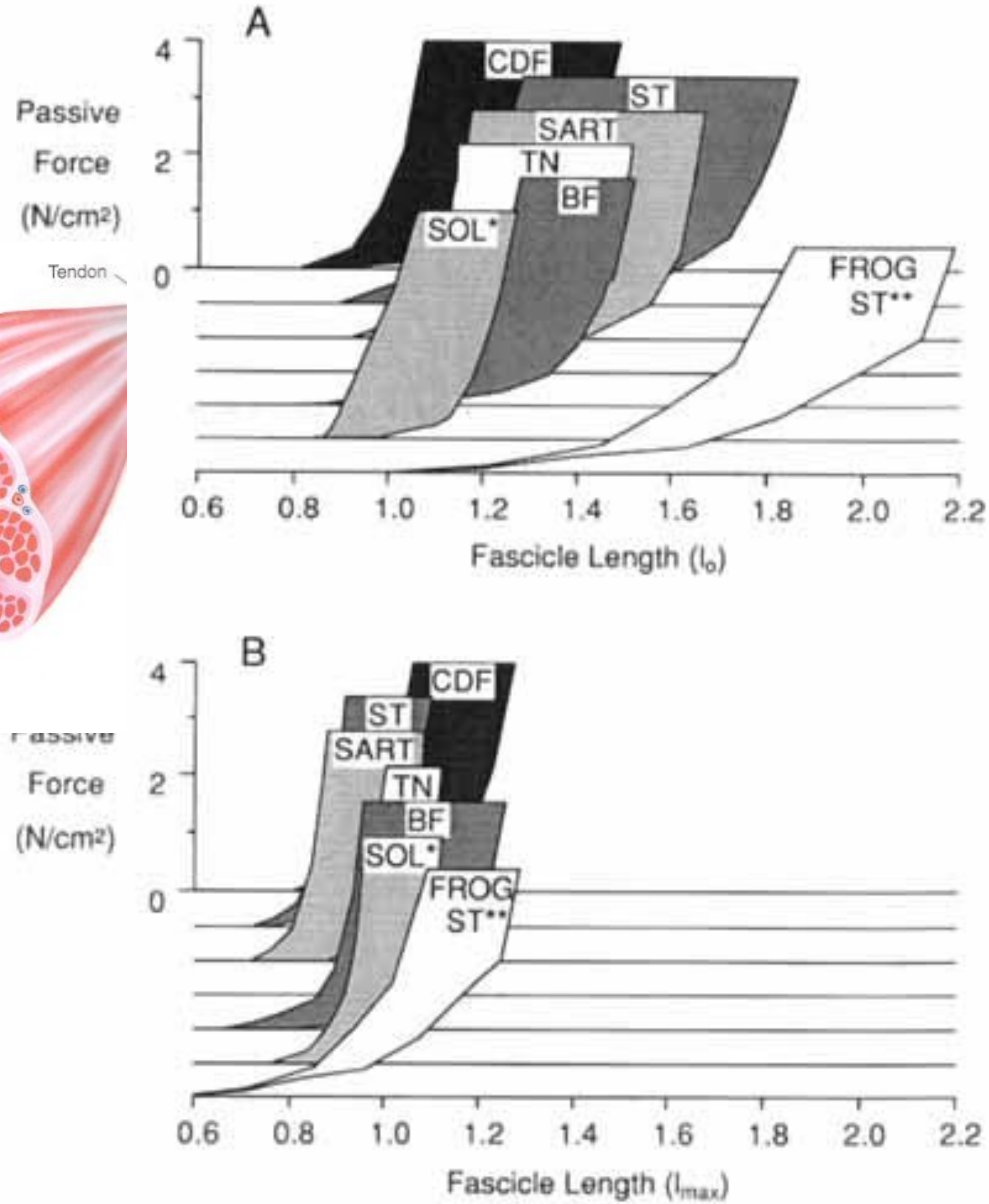
Complex Moment Arms at the Human Elbow









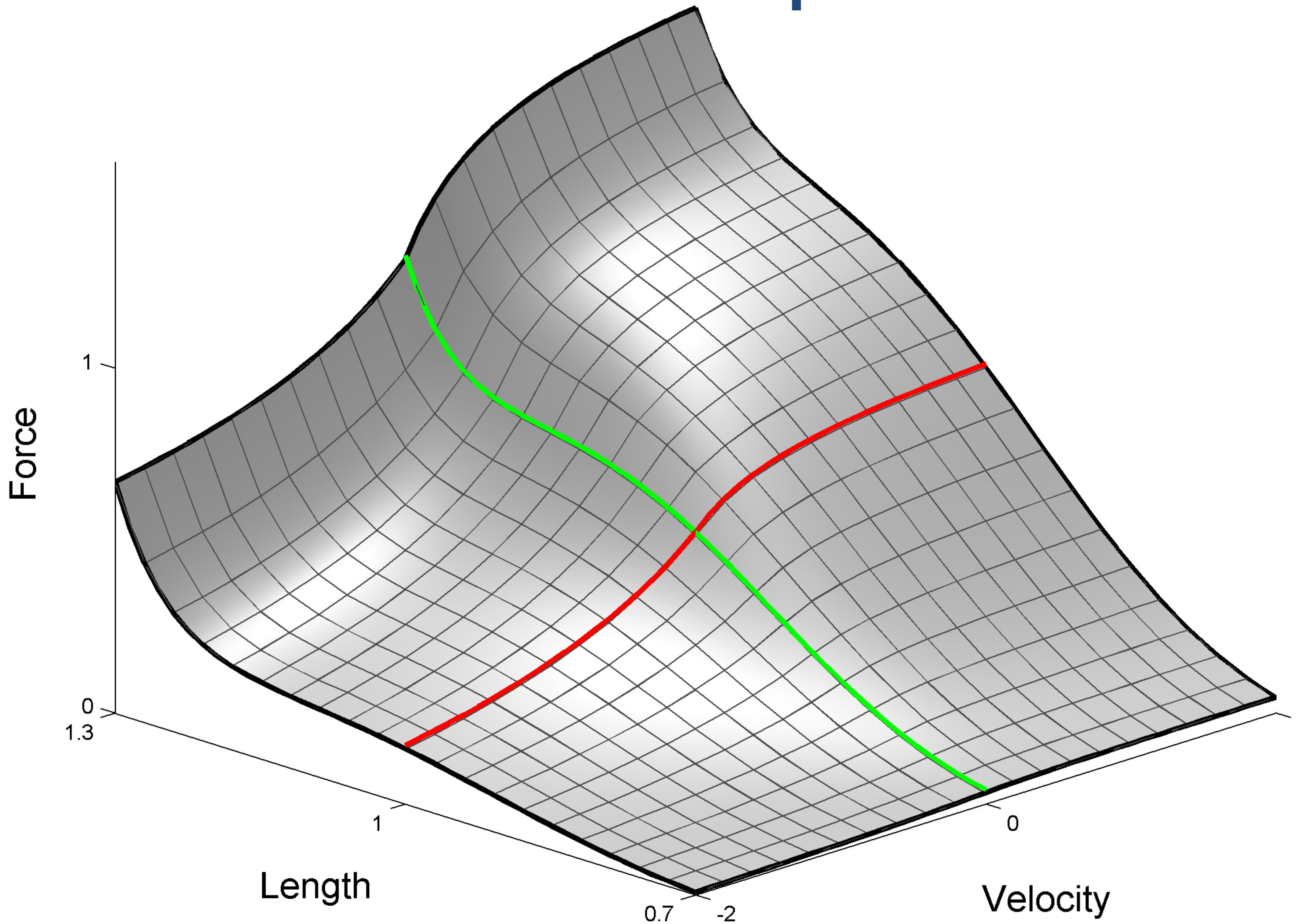


Biological Elasticity:

Nonlinear

Adaptive

Muscle ≠ Torque Motor



Virtual Muscle, based on ~20 experimental and modeling papers
with Steve Scott, Ian Brown, Milana Mileusnic, George Tsianos, et al.
Available from http://bme.usc.edu/gloeb

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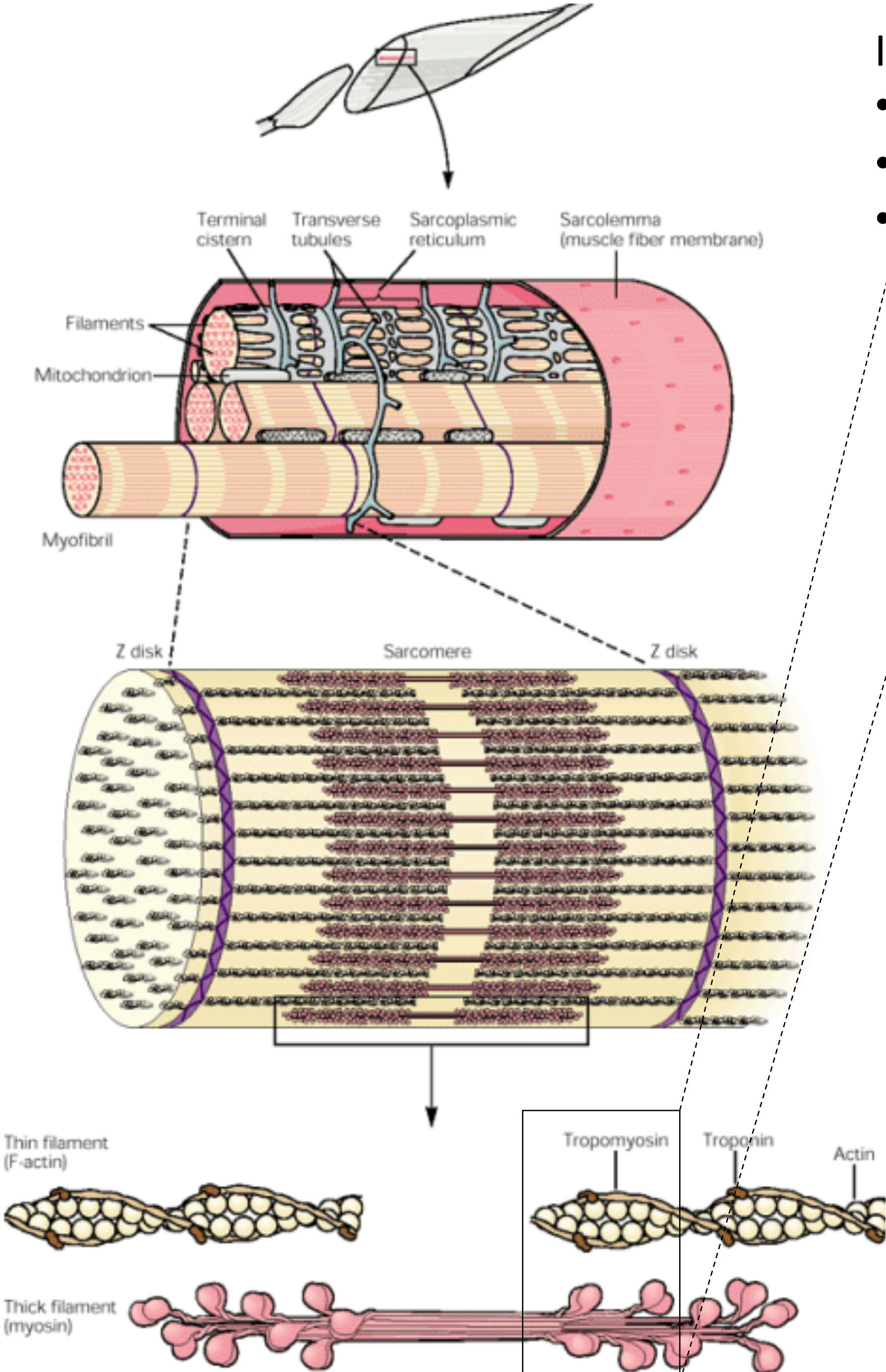
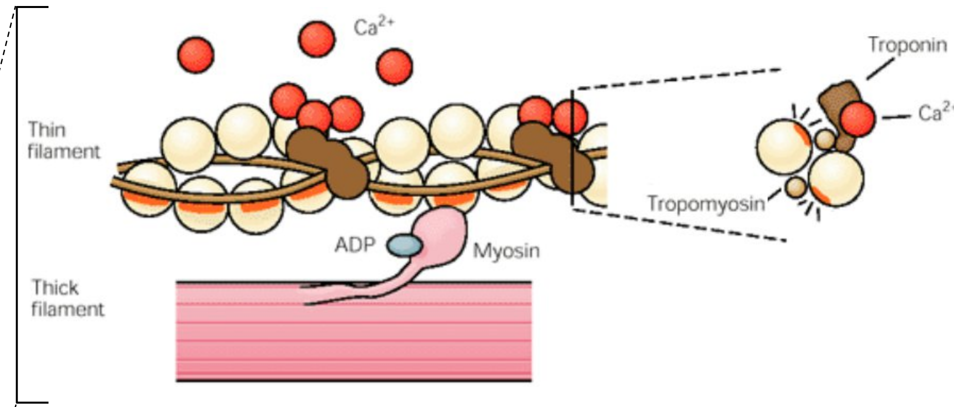
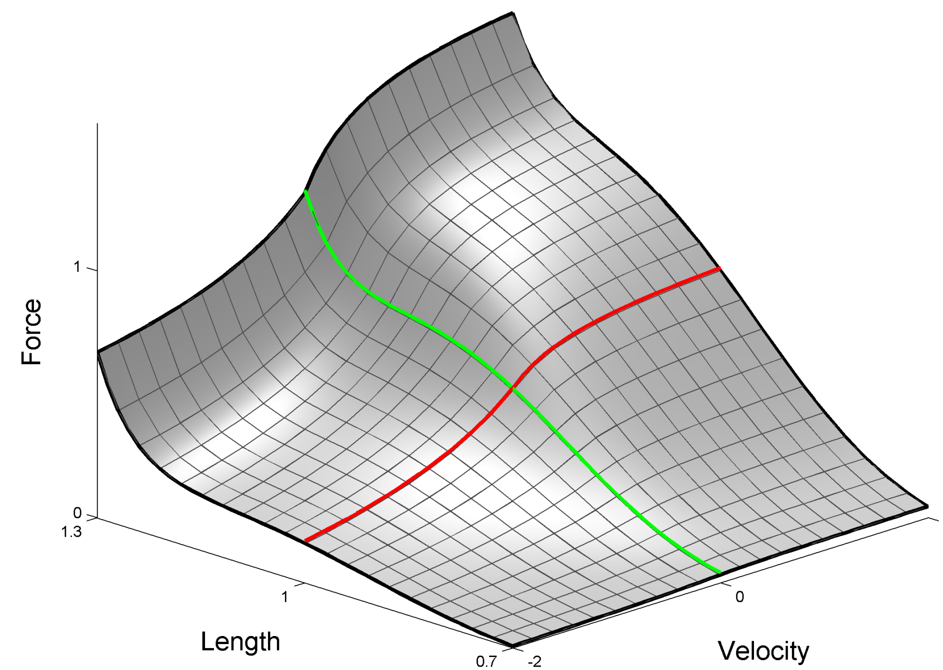
Muscle accounts for the majority of animal mass and energy consumption. The evolutionary pressures to find and exploit any advantage are huge.

In order to produce active force:

- Myofilaments overlap
- Myosin heads cocked
- Binding sites exposed

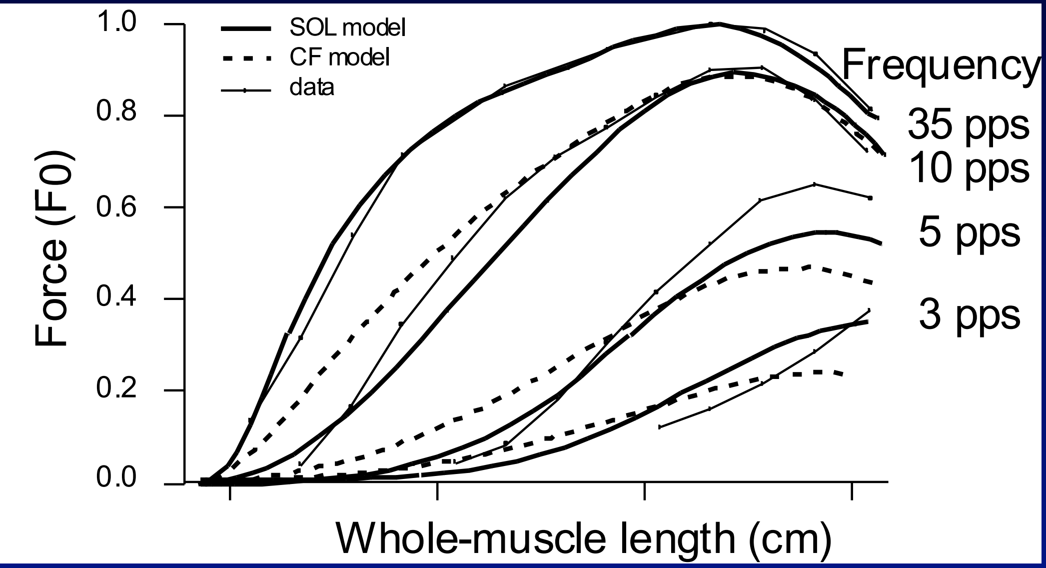


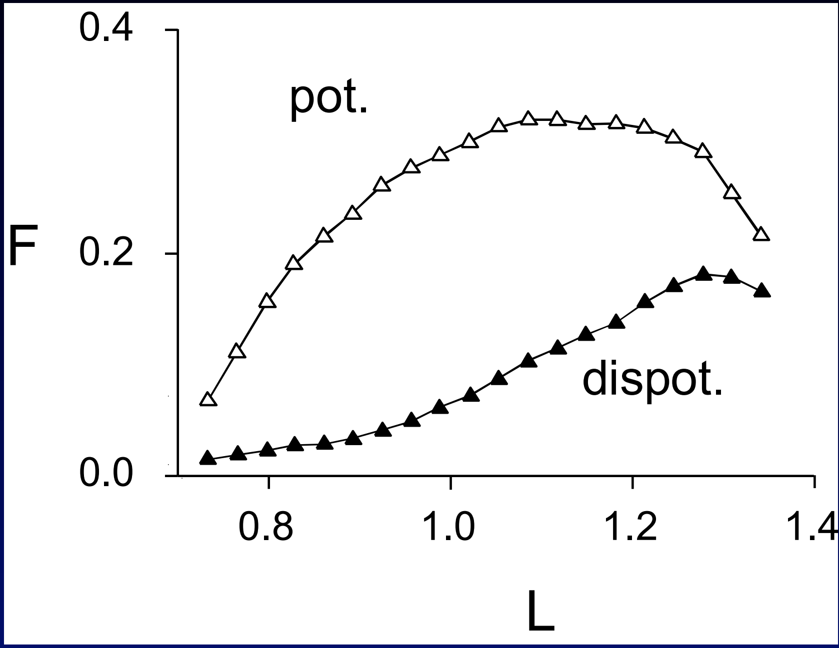


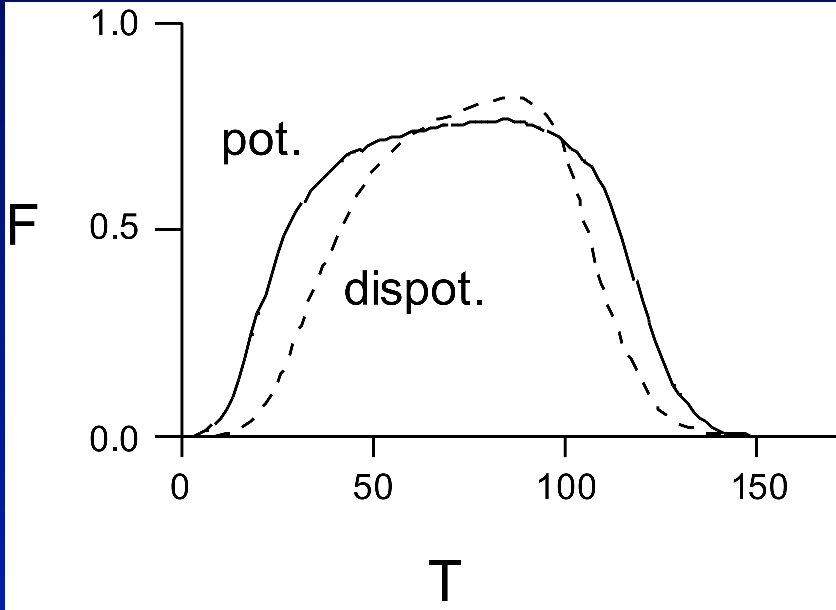


Source: Kandel ER, Schwartz JH, Jessel TM. Principles of Neural Science. 4th ed. New York (NY): McGraw-Hill; c2000. Figures 34-2a,3a; p.680

…and other nonlinear properties of muscle actuators

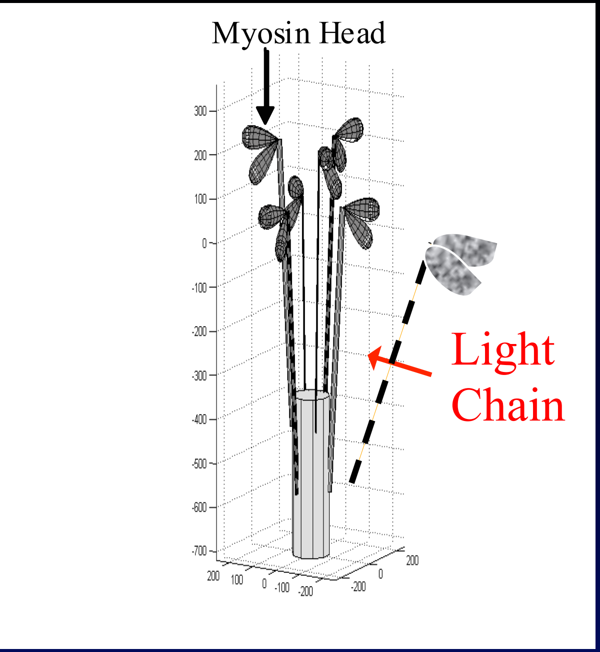


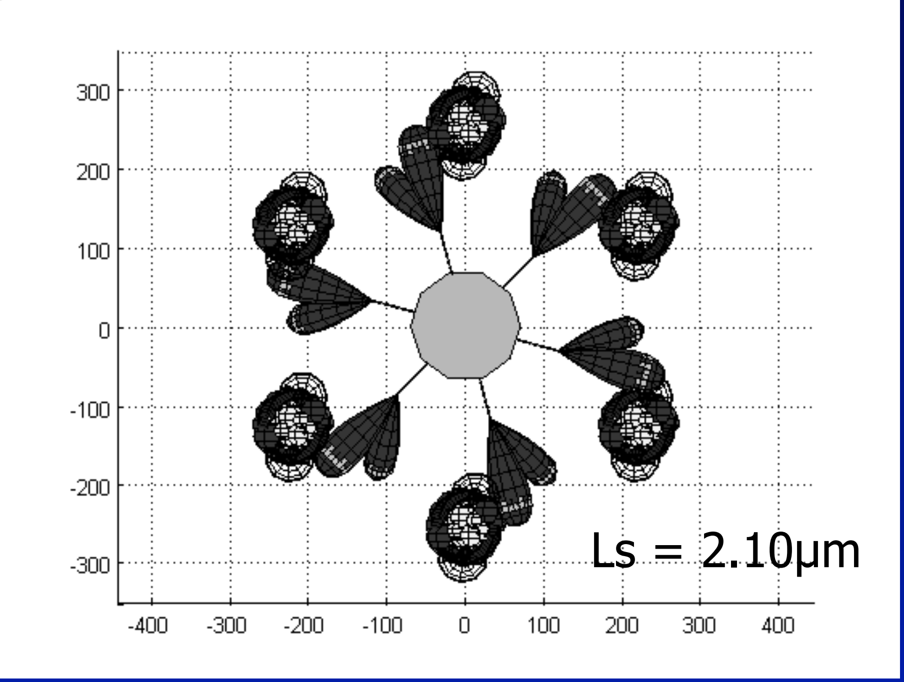


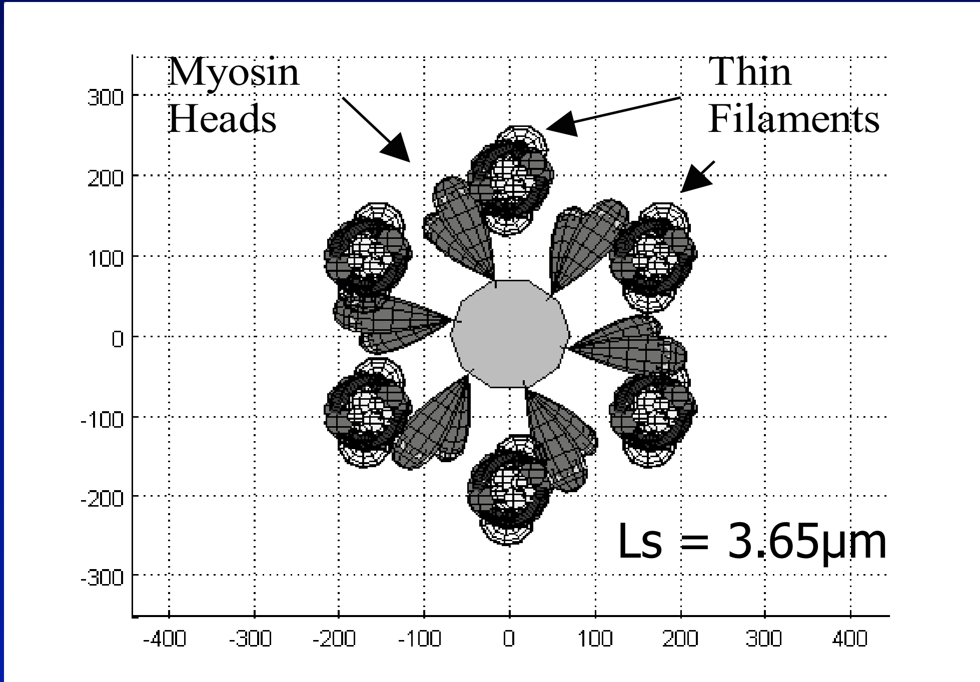


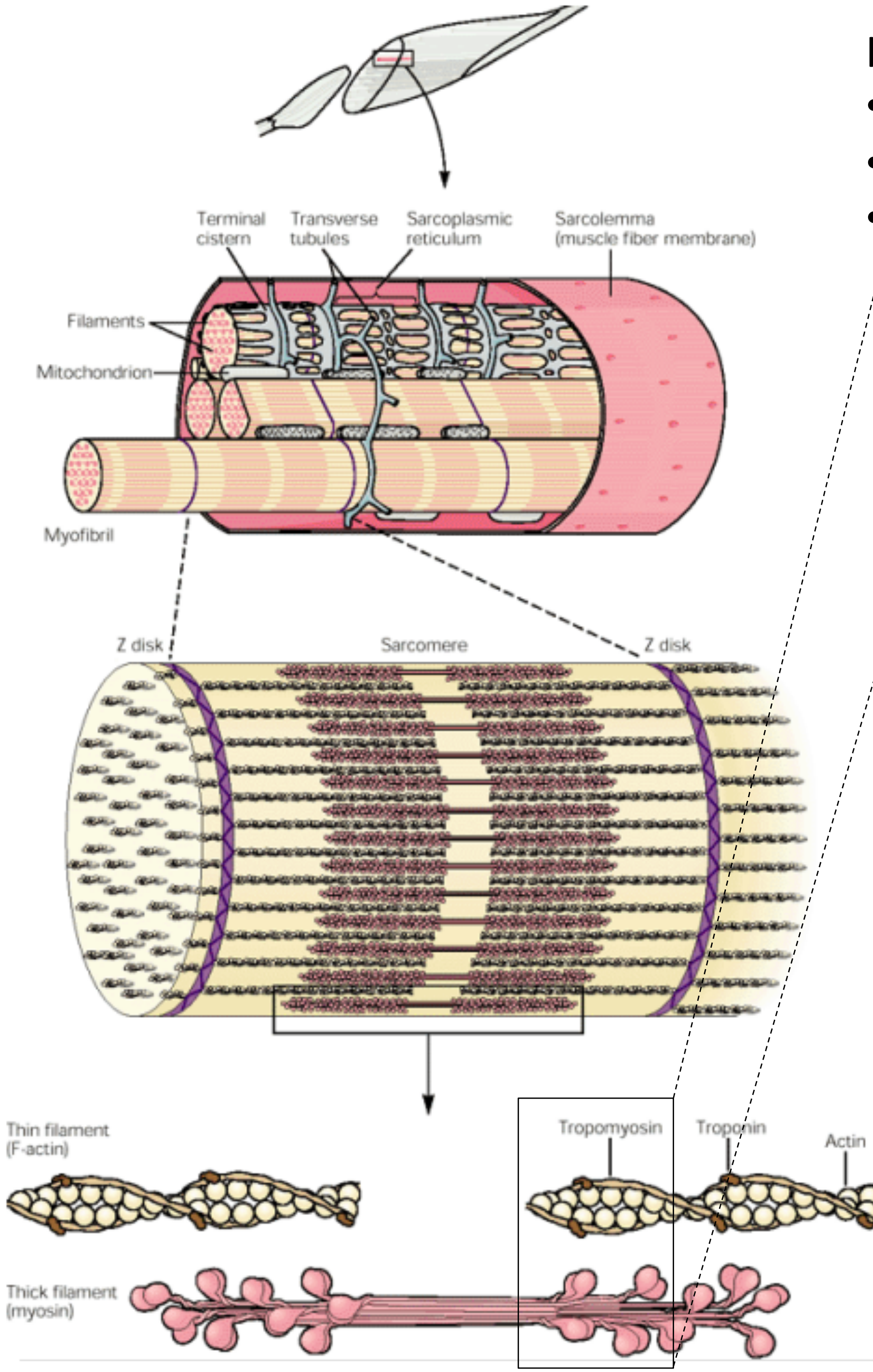
Potentiation

Myosin light-chain phosphorylation shifts resting position of myosin heads









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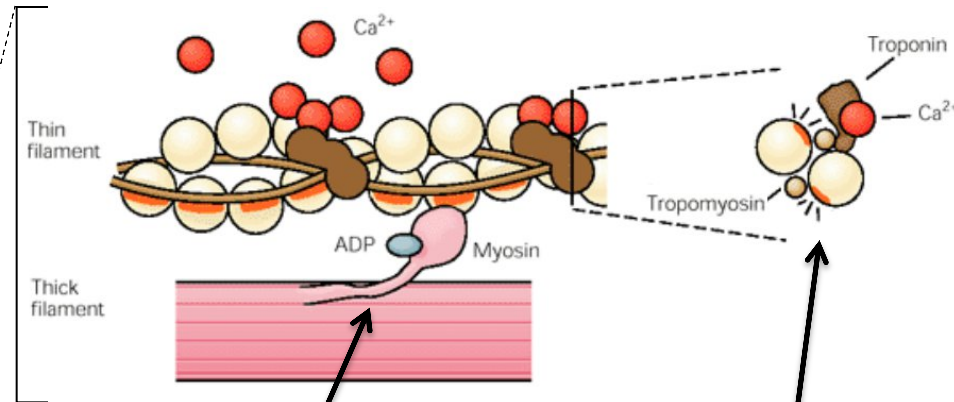


Cocked myosin head

ATP required to release myosin head and move it to the cocked state

Exposed actin site

Activation requires action potentials and calcium release;
ATP used to pump ions back.

➤ **E_{xb} depends on the number of cross-bridges and shortening velocity**

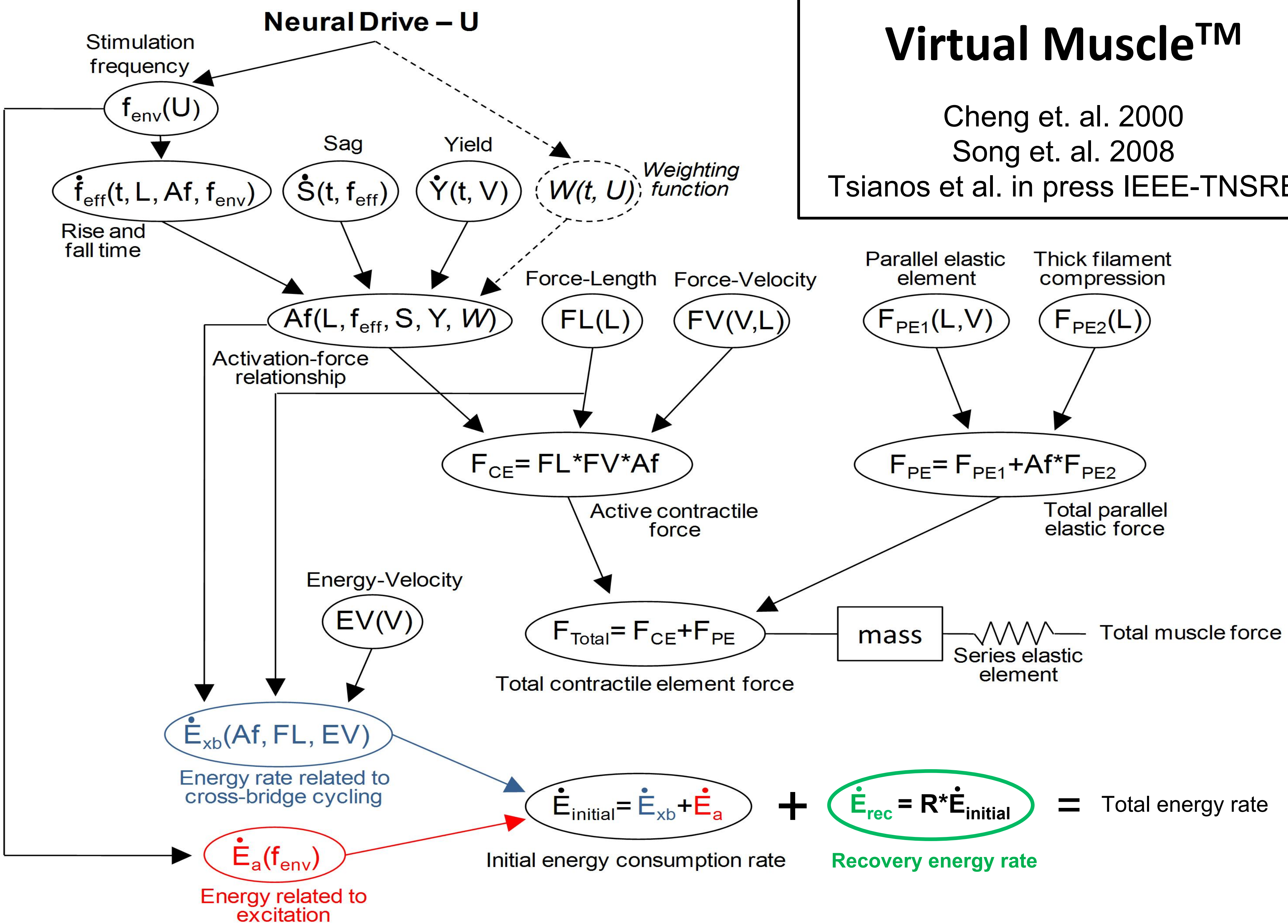
➤ **E_a depends on calcium flux in the sarcoplasm**

➤ **E_{rec} ATP and PCr replenishment results in delayed recovery heat**

Source: Kandel ER, Schwartz JH, Jessel TM. Principles of Neural Science. 4th ed. New York (NY): McGraw-Hill; c2000. Figures 34-2a,3a; p.680

Virtual Muscle™

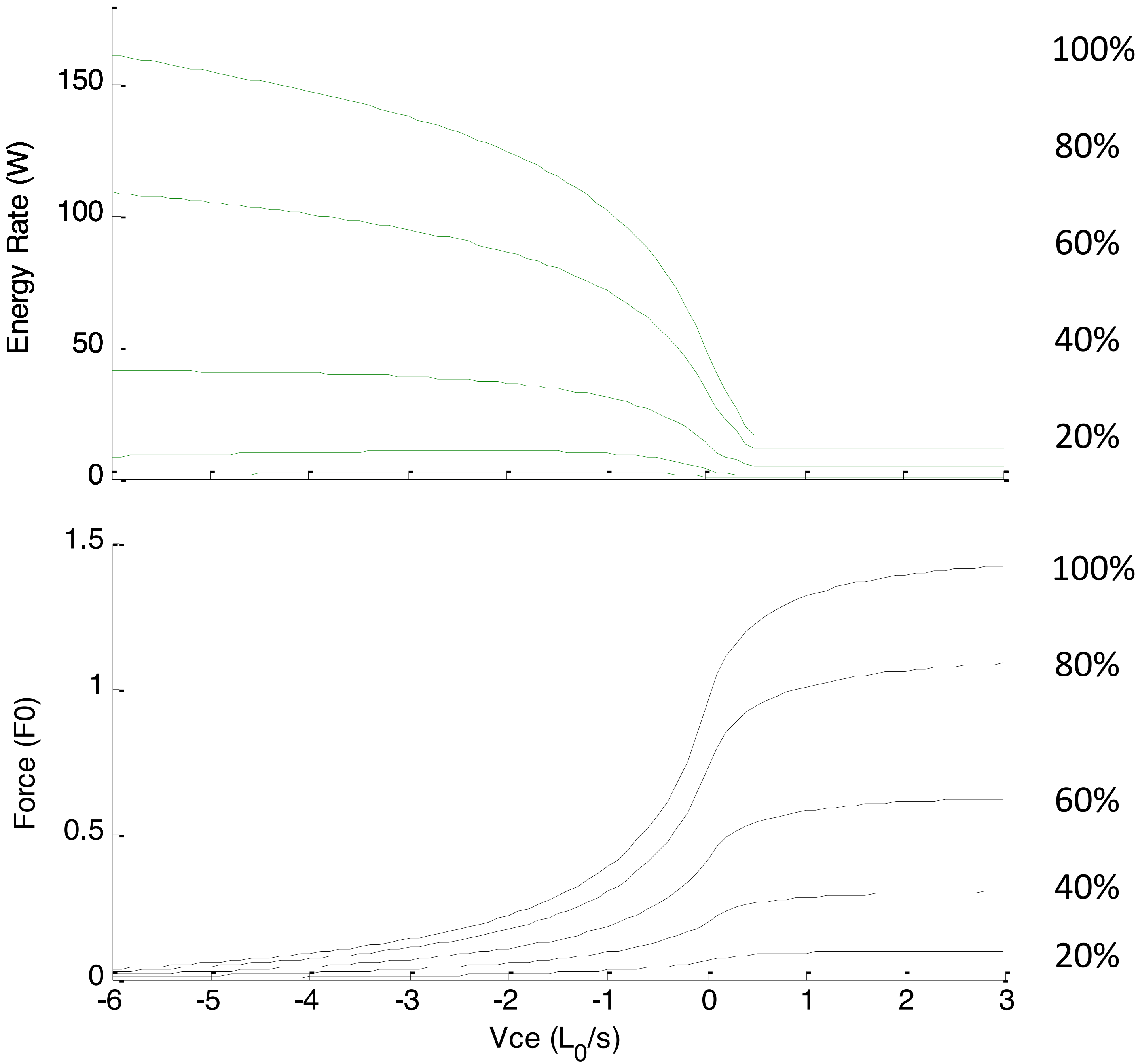
Cheng et. al. 2000
Song et. al. 2008
Tsianos et al. in press IEEE-TNSRE



Virtual Muscle
(analogous to Biceps Long)

40% Slow twitch
60% Fast twitch

Mass = 300g
F0 = 600N
L0 = 16cm

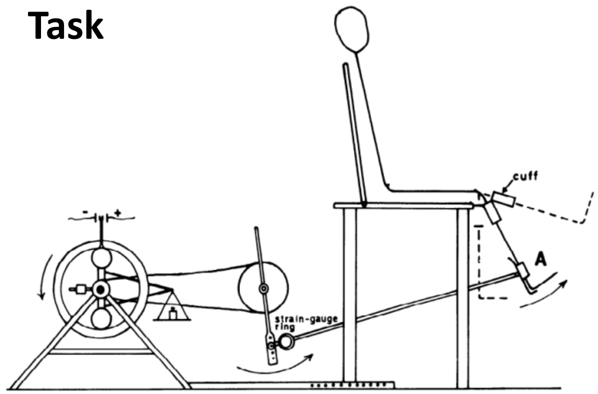


Validation of Energetics Model

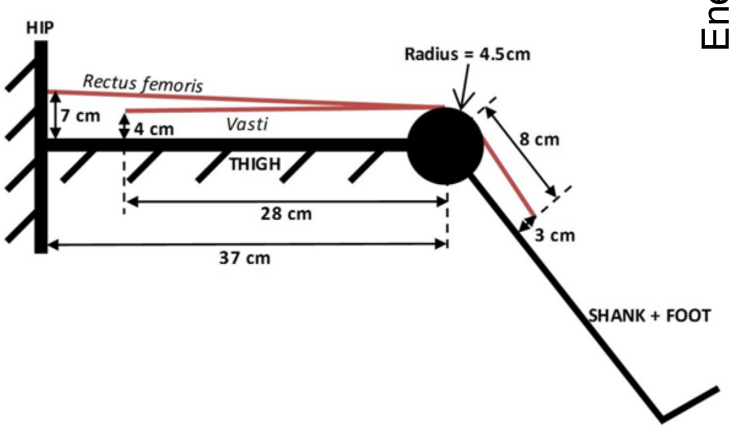
Dynamic knee extension

(Andersen et al., 1985; Gonzalez-Alonso et al., 2000)

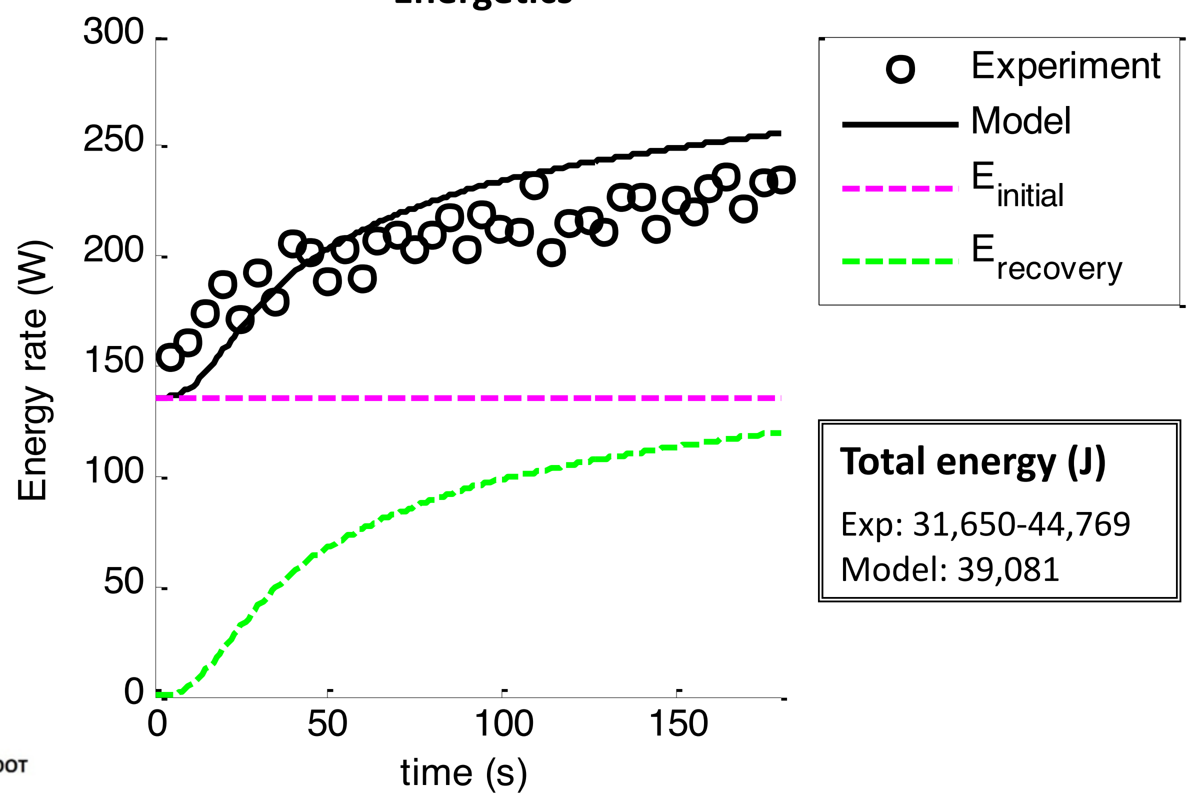
Task



Model



Energetics



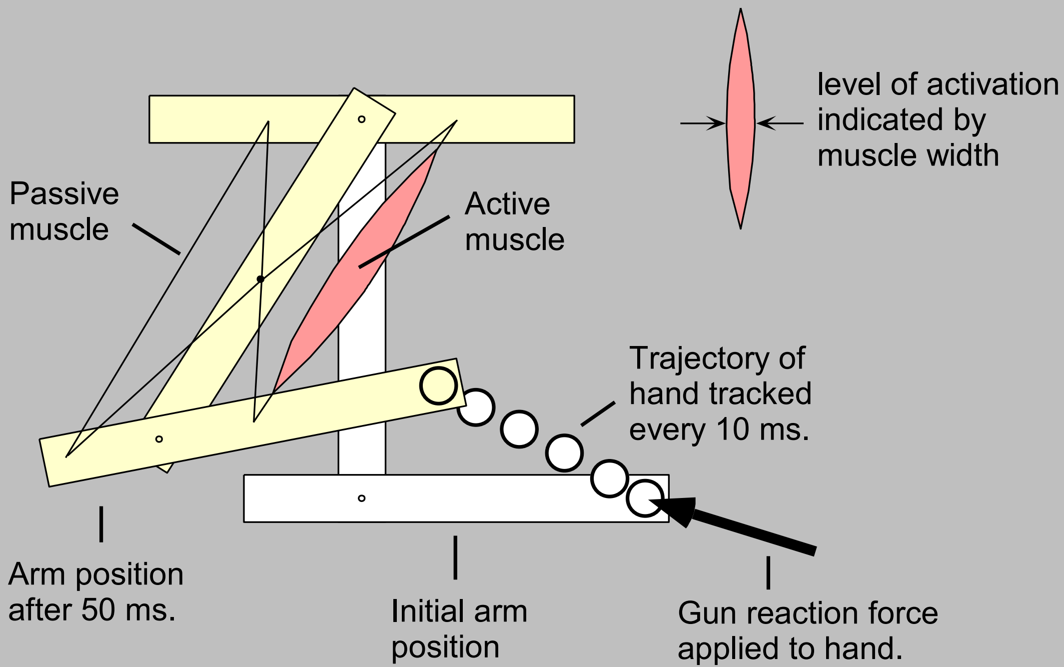
Total energy (J)

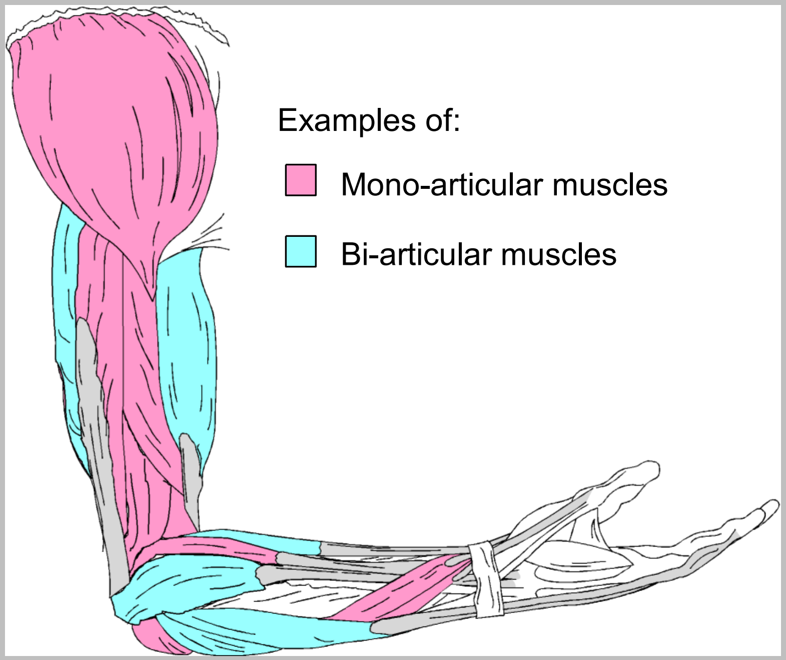
Exp: 31,650-44,769

Model: 39,081

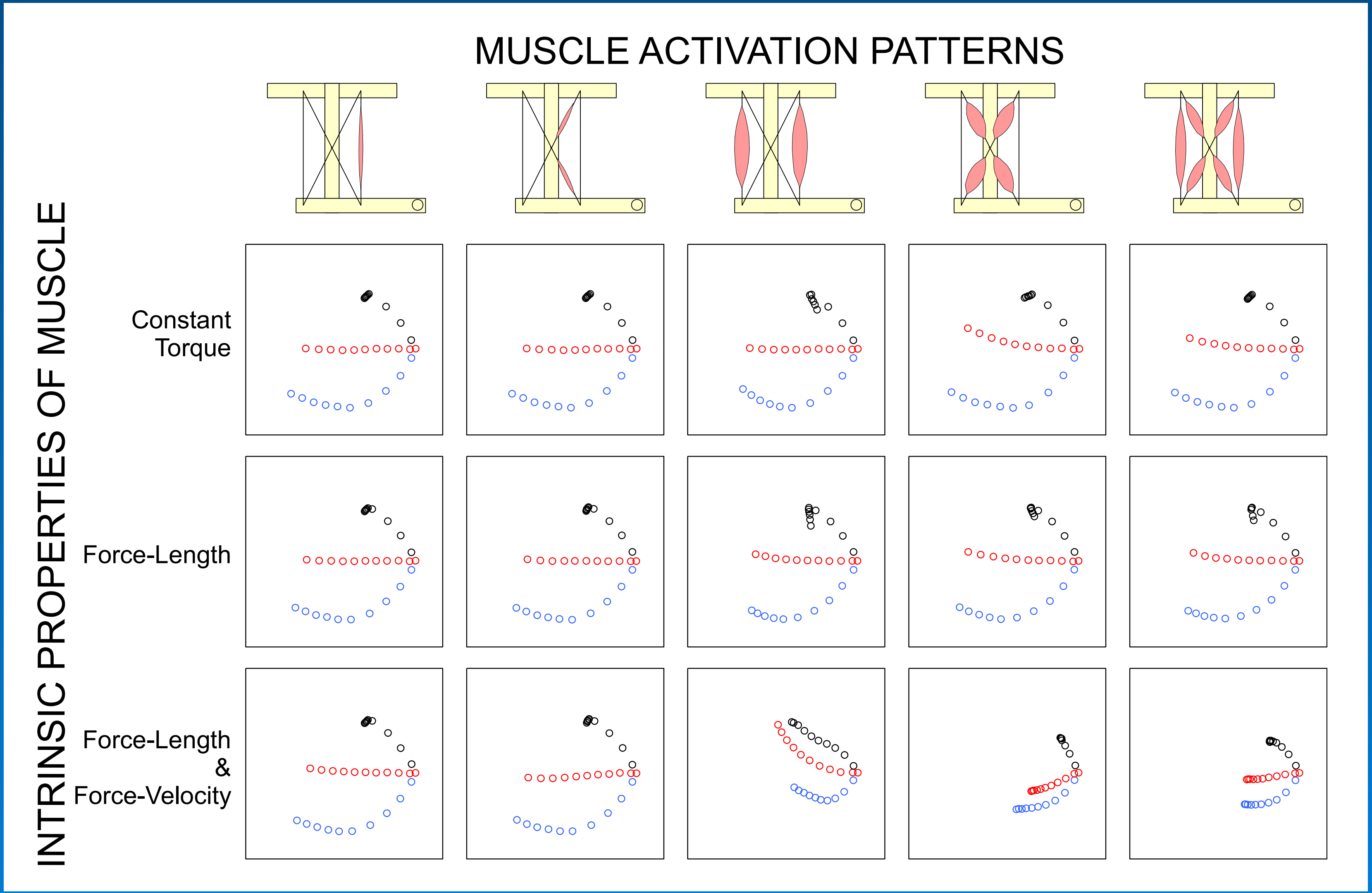
Model System to Study Preflexes

Sample Simulation (50 ms):





The Effectiveness of Preflexes



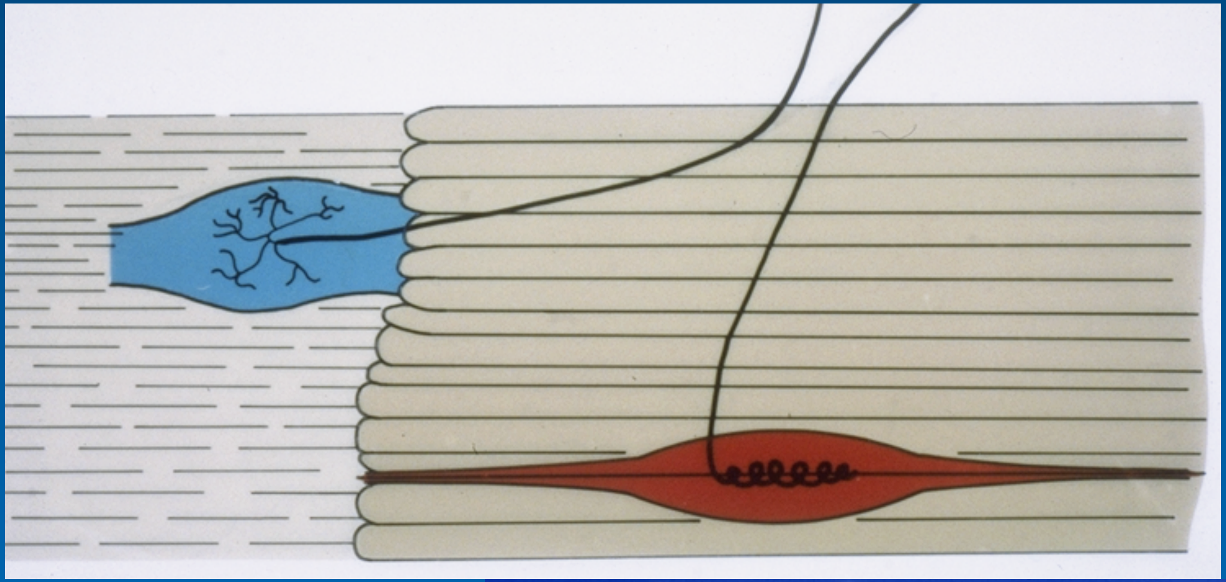
Sensing & Control: Underlying Mechanisms

- Resolution: Populations of receptors
- Dynamic Range: Predictive gain control
- Signal Processing: Integrative
- Feedback: Multimodal convergent/divergent
- Control: Programmable regulator (MIMO)

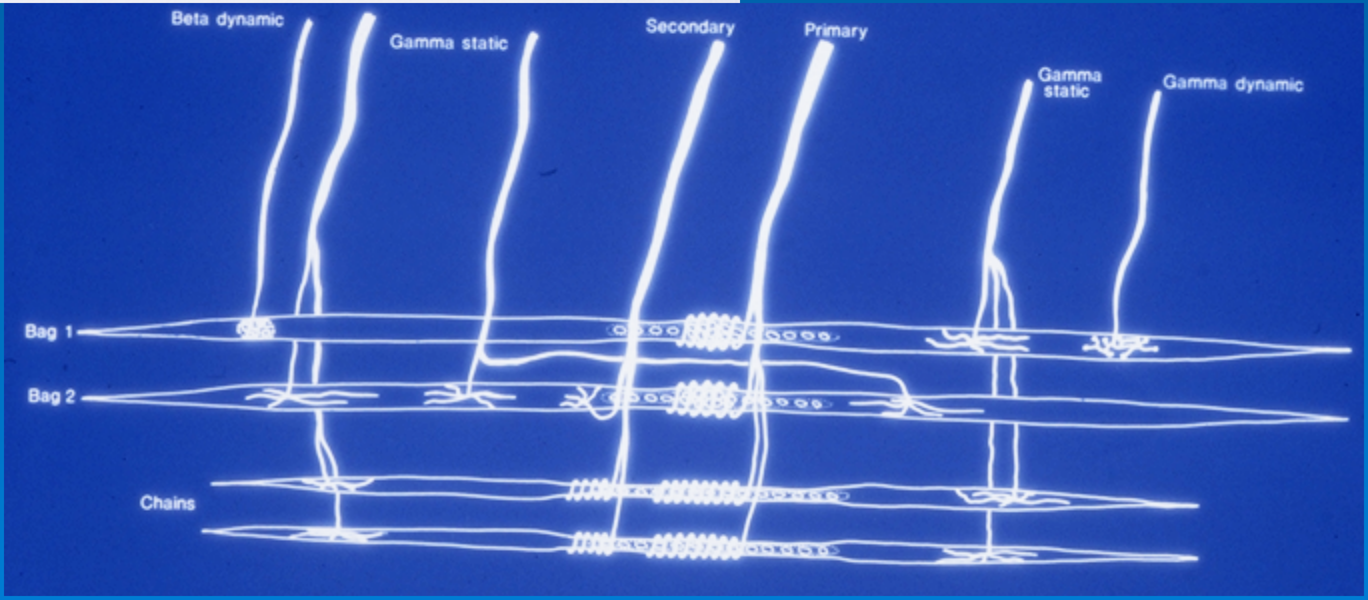
Fast & accurate movement is what distinguishes even primitive animals from plants. Servocontrol is too limited for multiarticular organisms and inverse models and optimal control are not feasible analytically.

Animals use hierarchical and "good enough" controls.

Muscles have hundreds of proprioceptive sense organs



Spindles are very complex and provide most sense of posture and movement



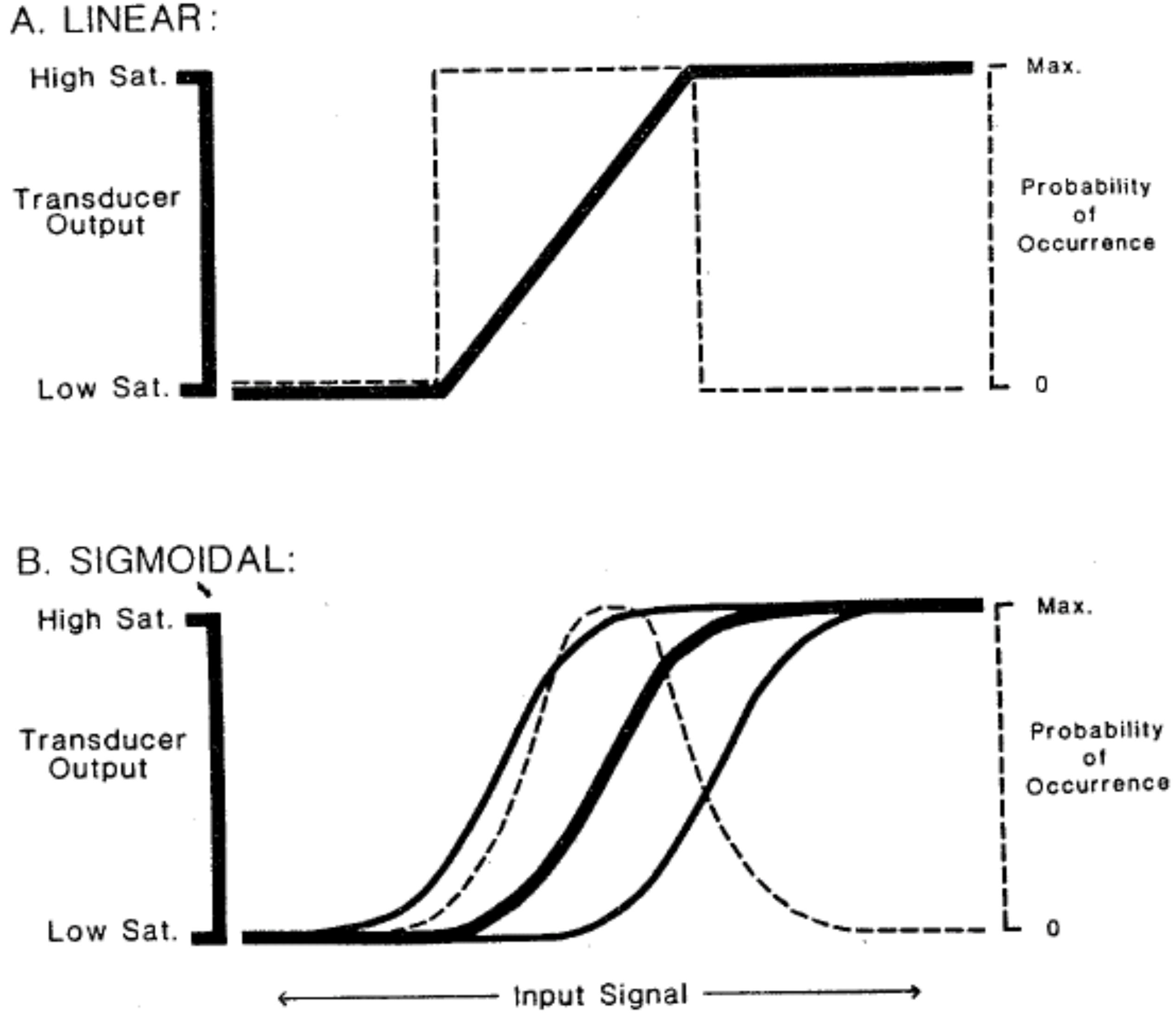
Fusimotor System as Optimal Sensor Control

$$E = n + T(S),$$

$$\Delta E = \frac{dT}{dS}\Delta S = \frac{dT}{dS}\frac{1}{P(S)} = \text{const.}$$

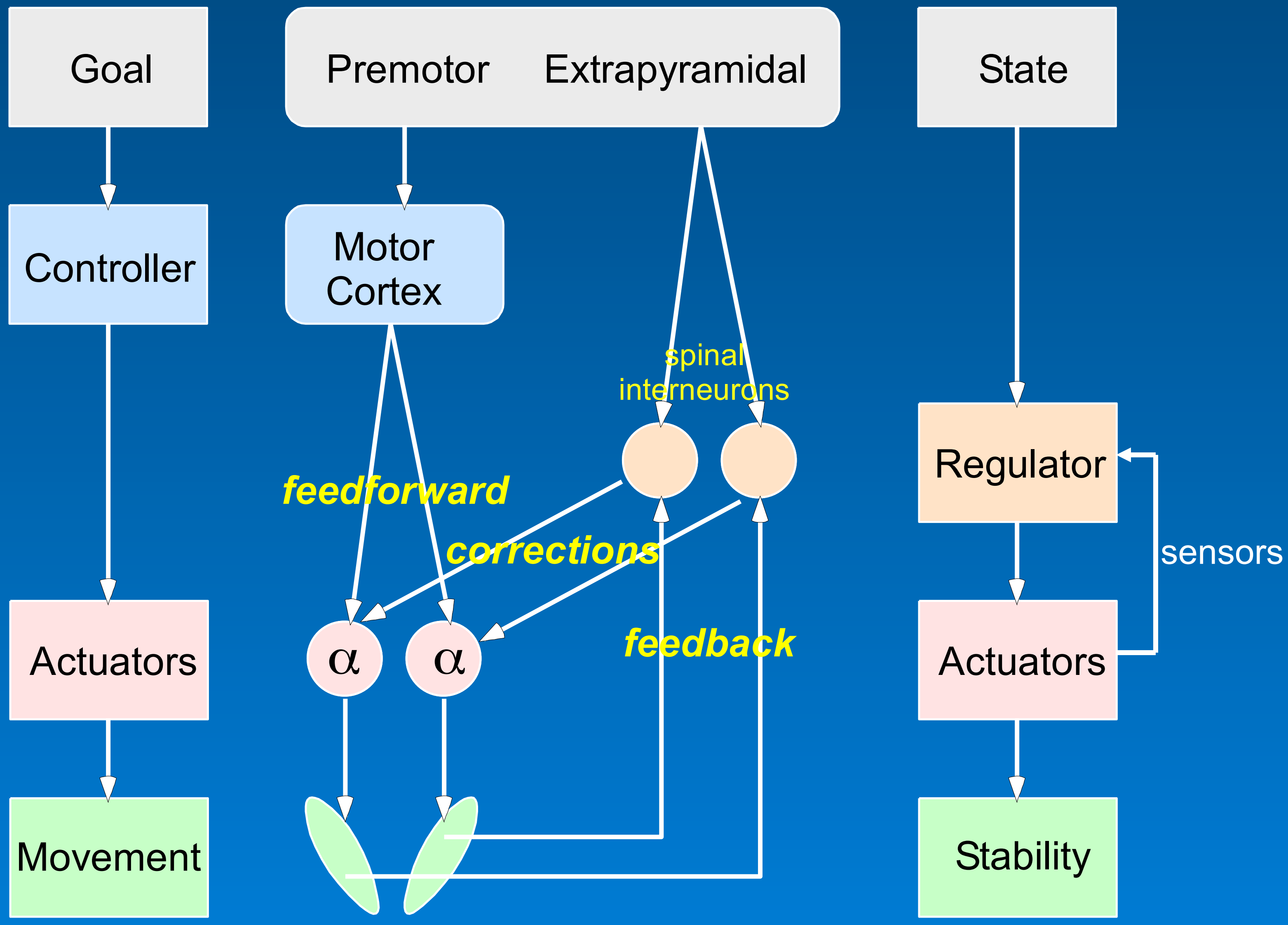
$$\frac{dT}{dS} \sim P(S)$$

$$T(S) \sim \int_{-\infty}^{S} \mathrm{P}(S)ds.$$

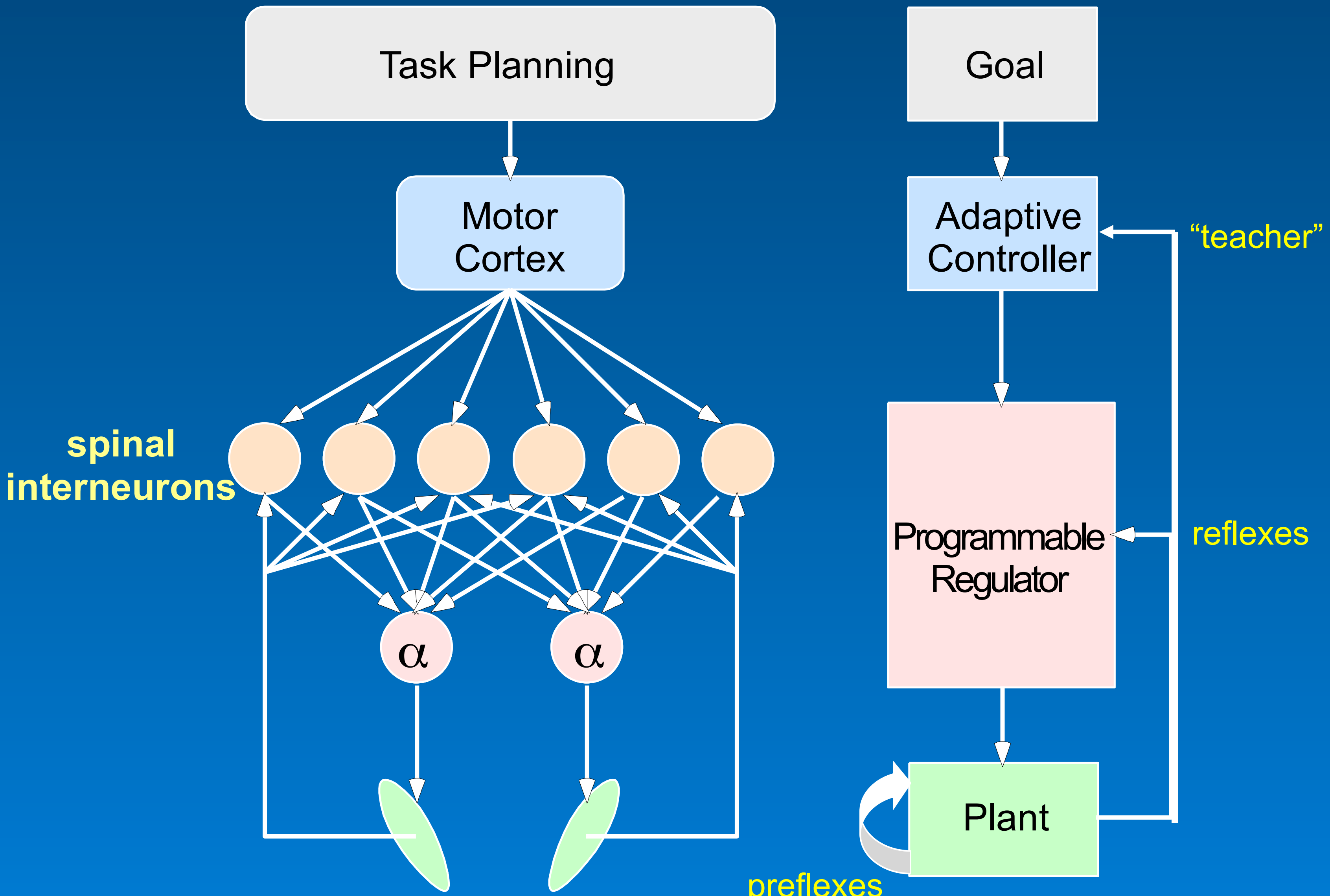


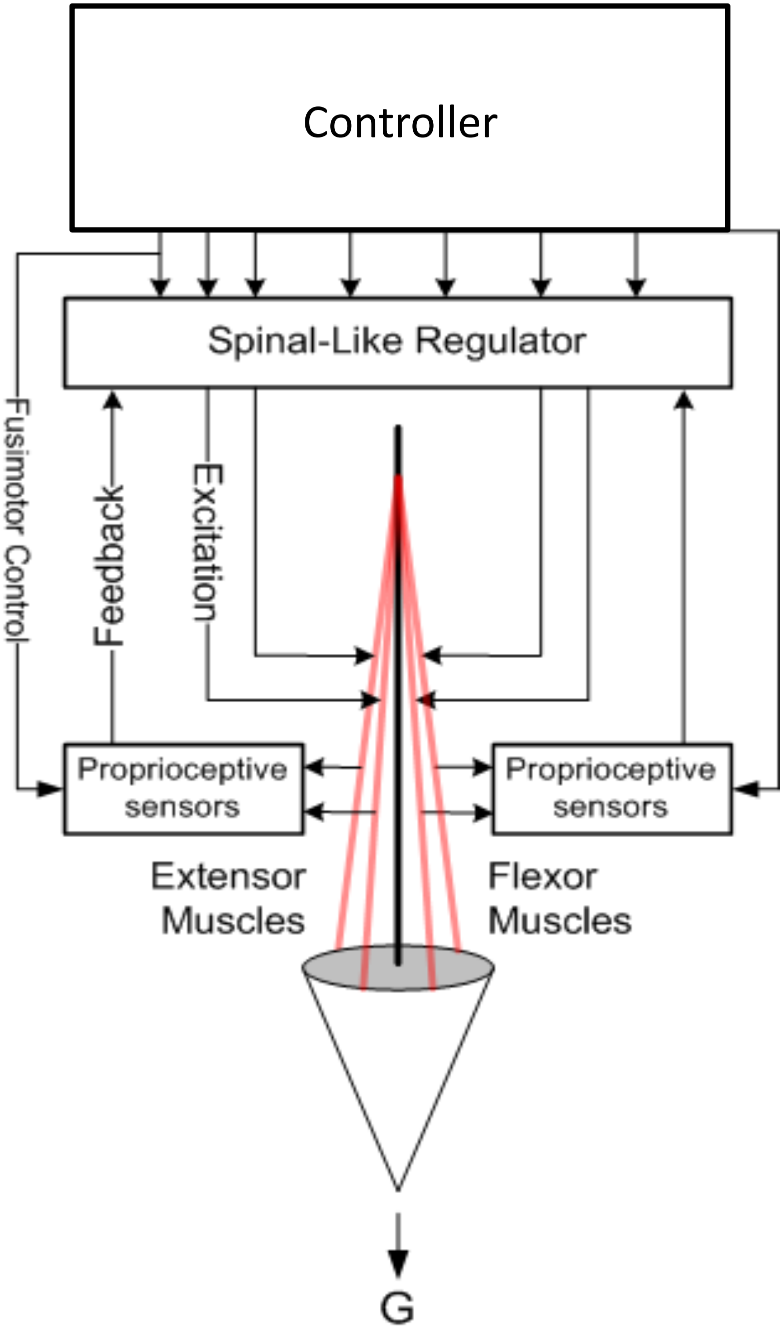
WB Marks, Appendix: Spindle Transduction Properties
in GE Loeb (1984) The Control and Responses of Mammalian Muscle Spindles During Normally Executed Motor Tasks, Exer. & Sport Sci. Revs. 12:157-204.

Textbook Robotics & Biology



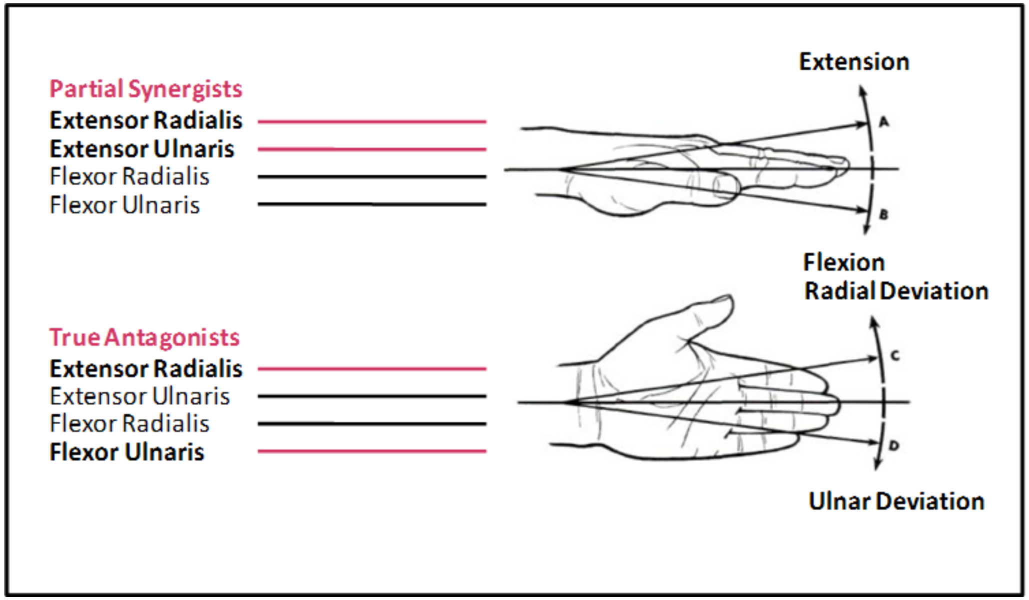
Biomimetic Hierarchical Control





Biomechanical Model
Simplified 2-axis, 4-muscle, Wrist Joint

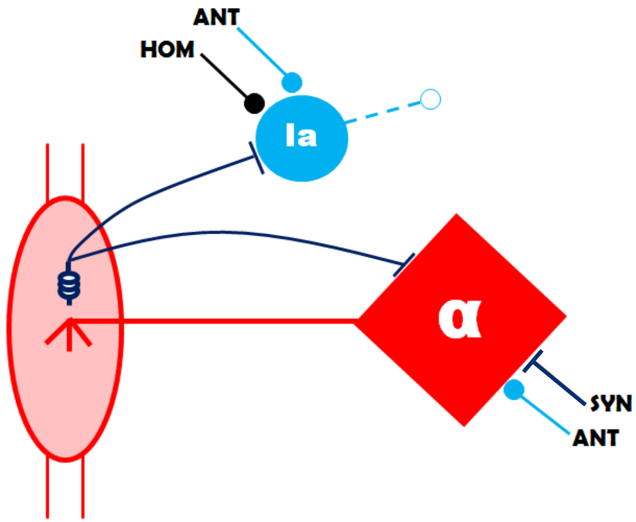
Components of the Simulation Environment
Skeletal Model *SimMechanics Toolbox, SimuLink*
Muscle Model *Virtual Muscle [Cheng, Brown, Loeb, 2000]*
Muscle Spindle Model *[Mileusnic, Brown, Lan & Loeb, 2006]*
Ensemble GTO Model *[Crago, Houk & Rymer, 1982]*
MSMS *[Davoodi et al, 2003]*



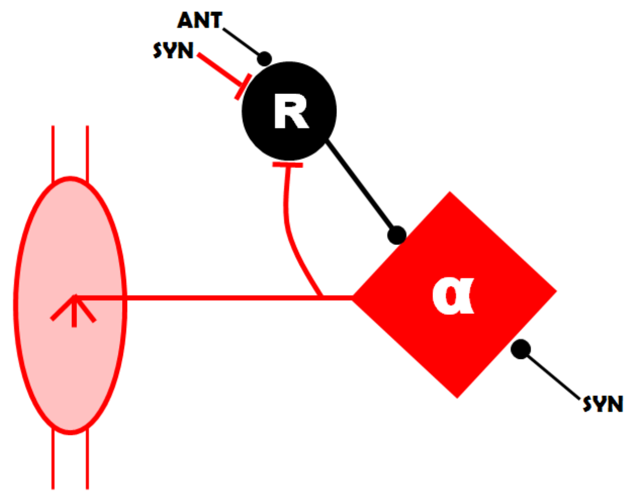
Raphael, G., Tsianos, G.A. and Loeb, G.E. Spinal-like regulator facilitates control of a two degree-of-freedom wrist. *J. Neuroscience* 30:9431-9444, July, 2010.

Classical spinal circuits

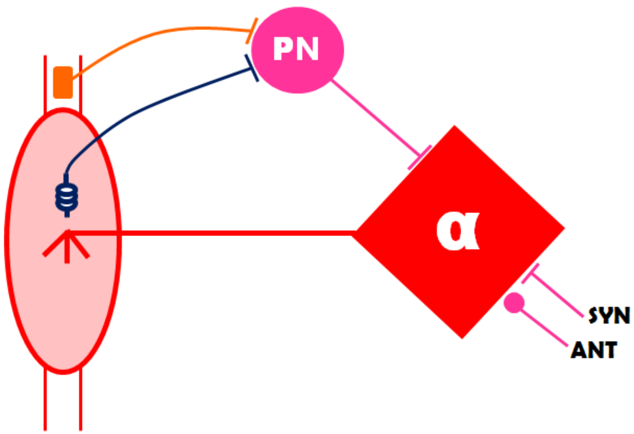
Stretch reflex and Ia inhibitory



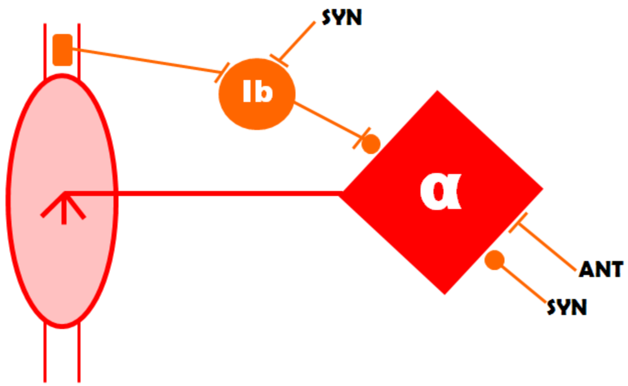
Renshaw



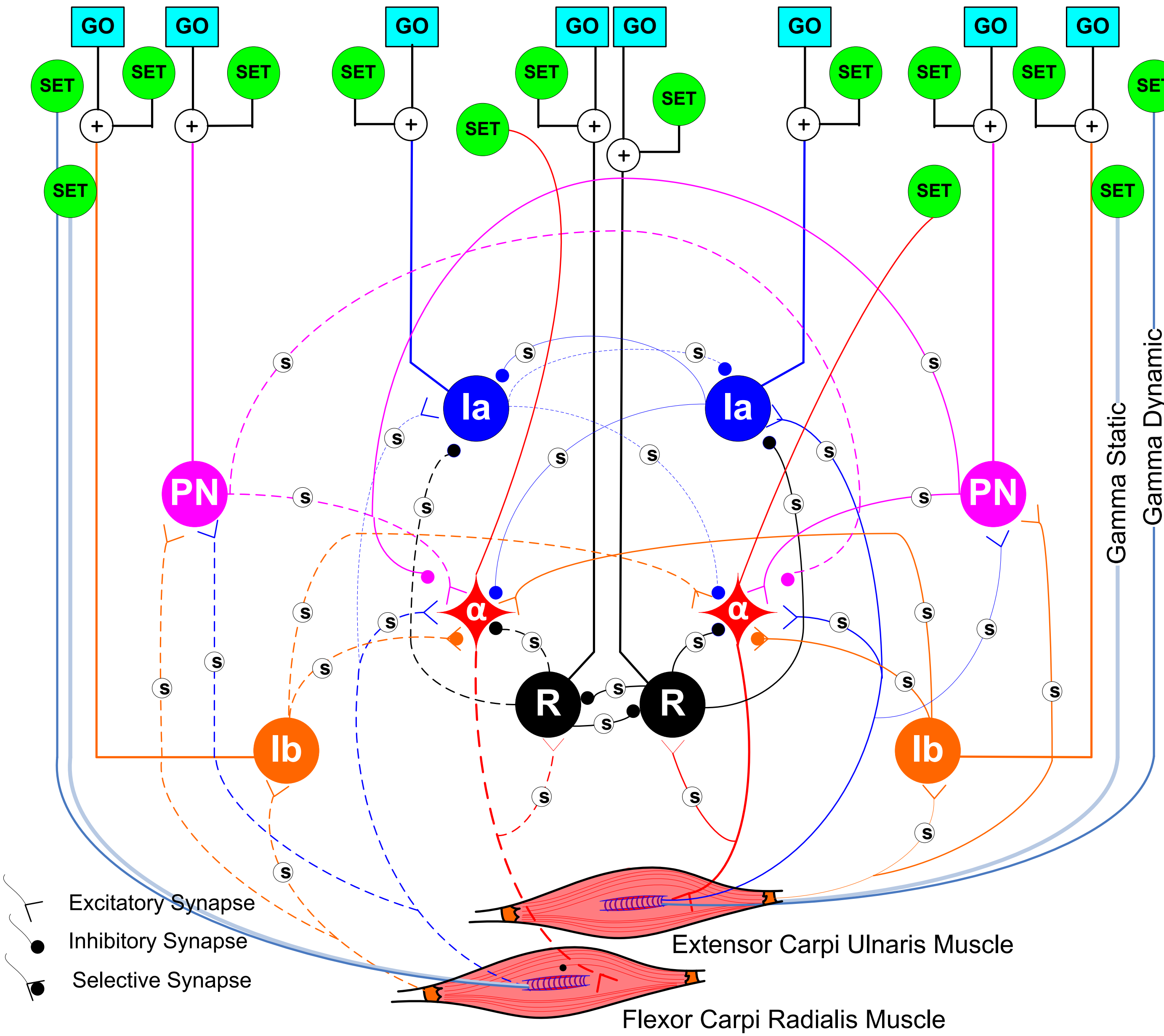
Propriospinal



Ib



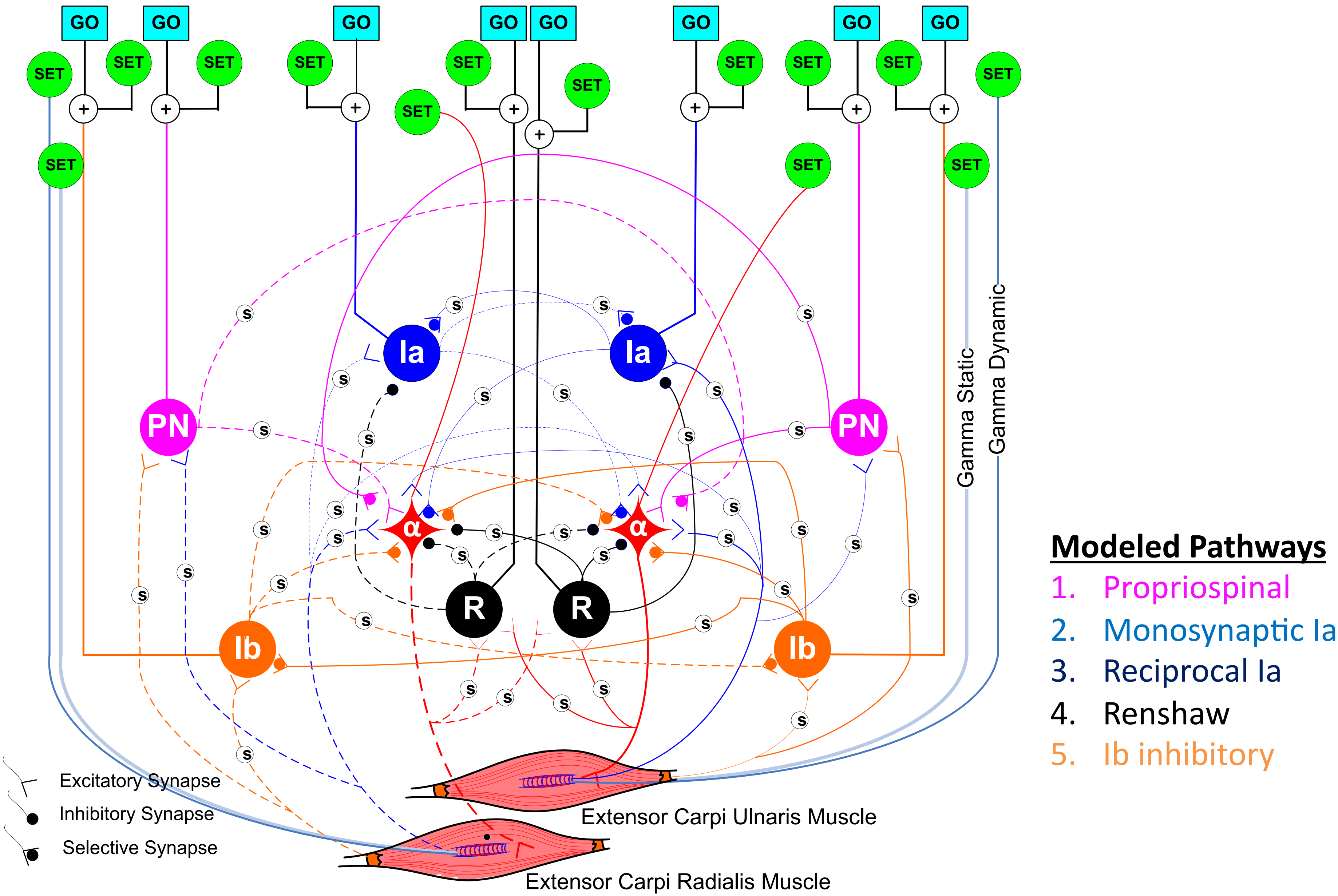
Partial view of the Integrated Spinal Cord Model
"True-Antagonists"



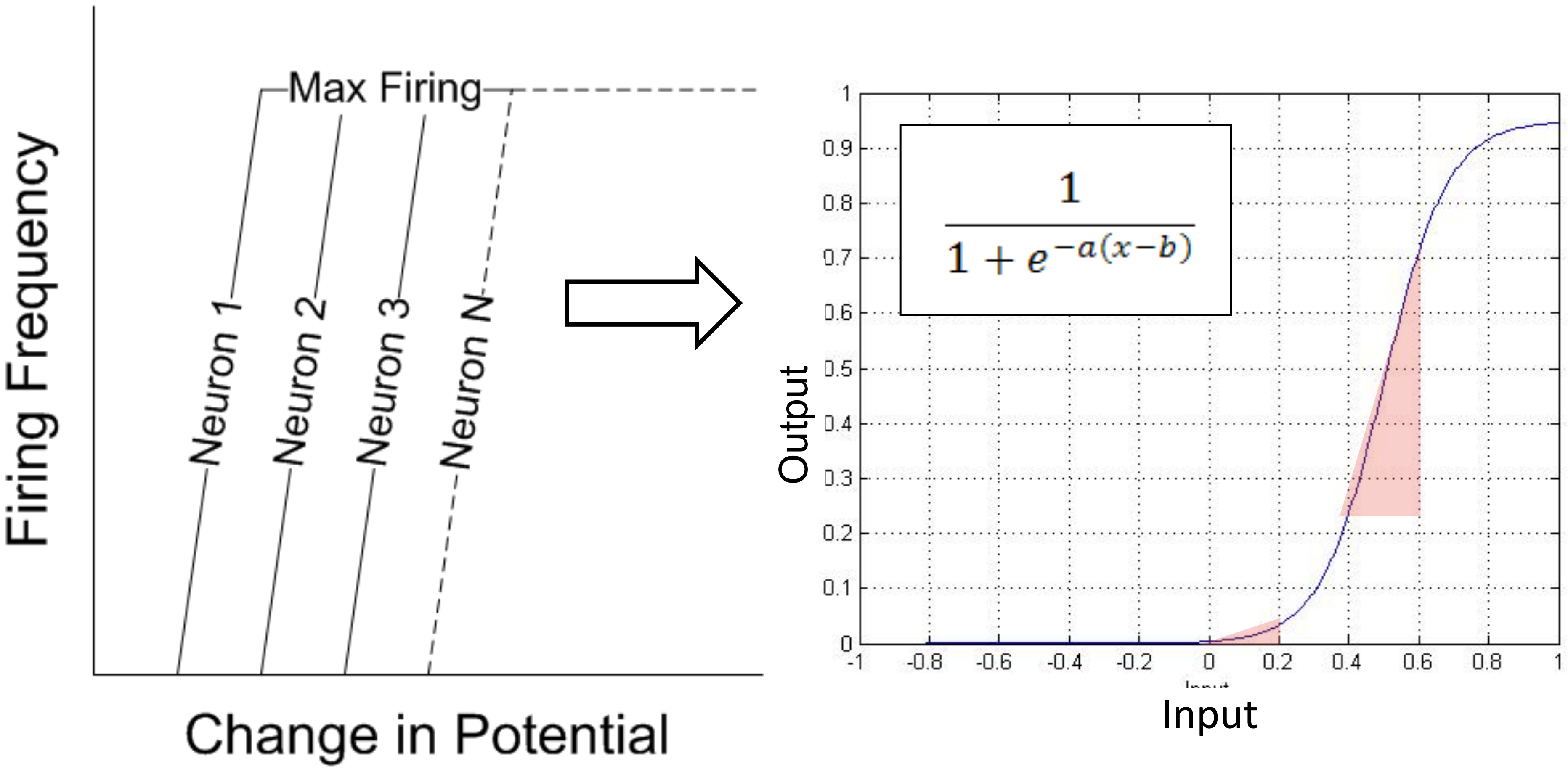
Modeled Pathways

1. Propriospinal
2. Monosynaptic Ia
3. Reciprocal Ia
4. Renshaw
5. Ib inhibitory

Partial view of the Integrated Spinal Cord Model
"Partial-Synergists"



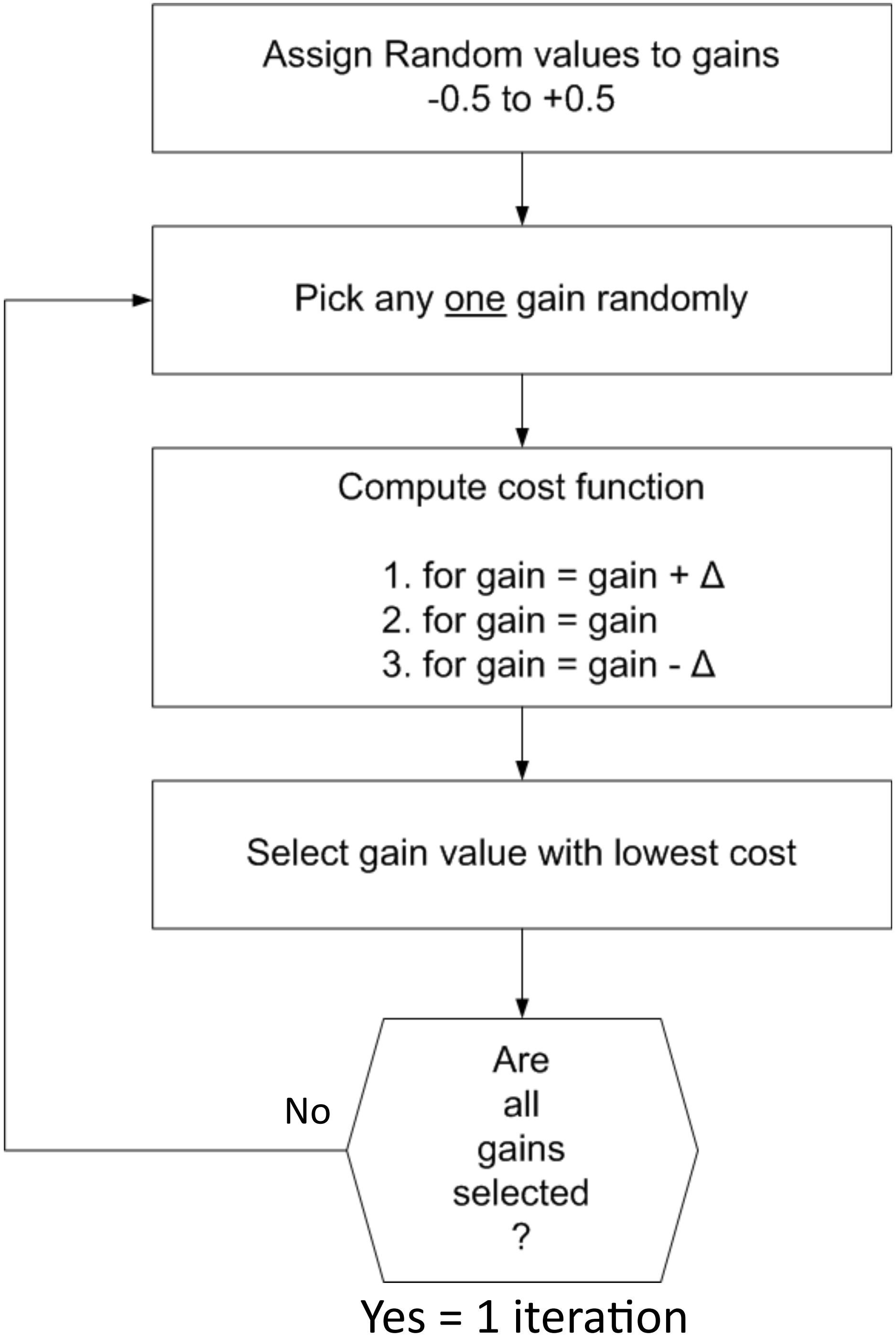
Computational Model of the Interneuron



Command Space = 184 dimensions

Constant Inputs	SET Inputs	GO Inputs
• Presynaptic Inhibition	• 140 Neural pathway gains • 8 Fusimotor inputs • Bias to 16 Interneurons & 4 Motoneurons	• Step input to 16 Interneurons

Random Gradient Descent Optimization

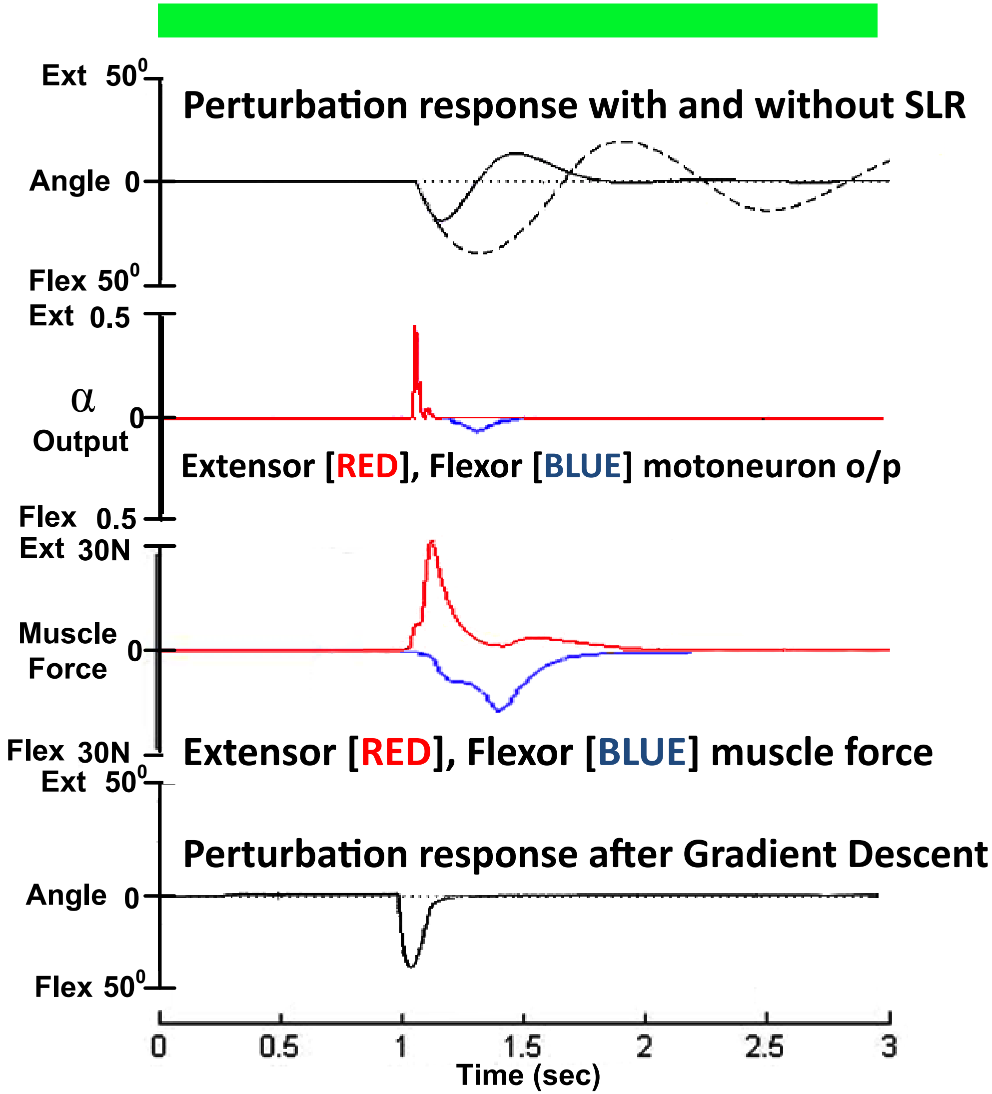


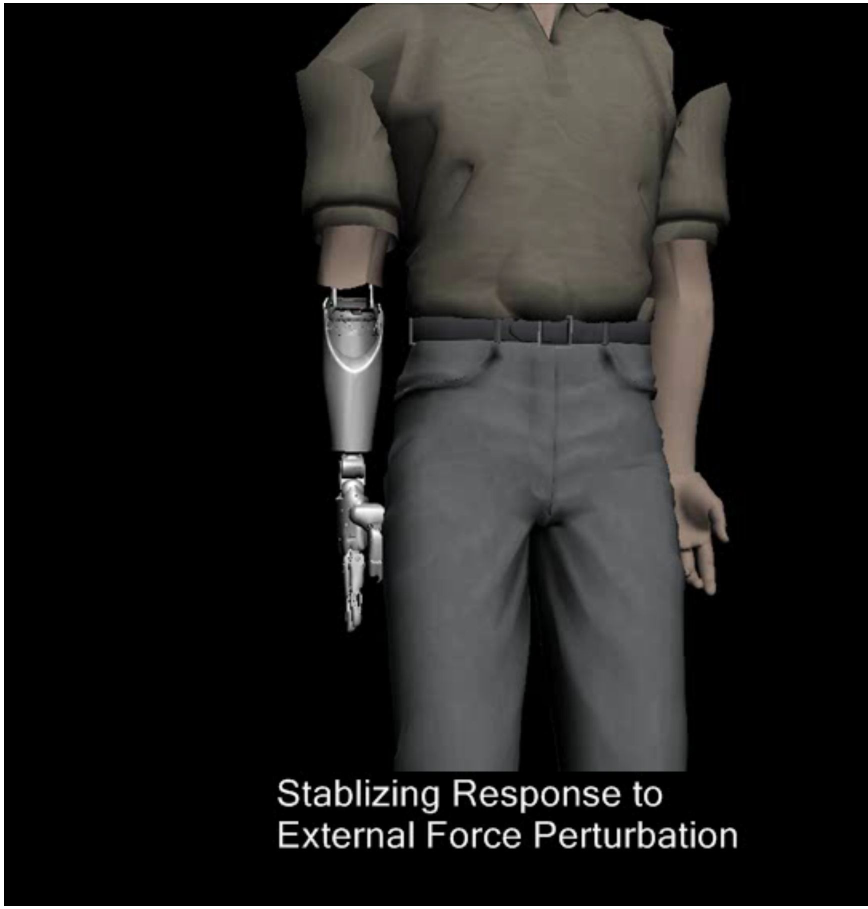
Method-1	Intuitive optimization !
Method-2	Random Gradient Descent
Method-3	Stochastic Hill Climbing

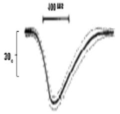
Cost Function :

$$\int (Desired\ state - Actual\ state)^2$$

Task 1: Stabilizing response to external force perturbation



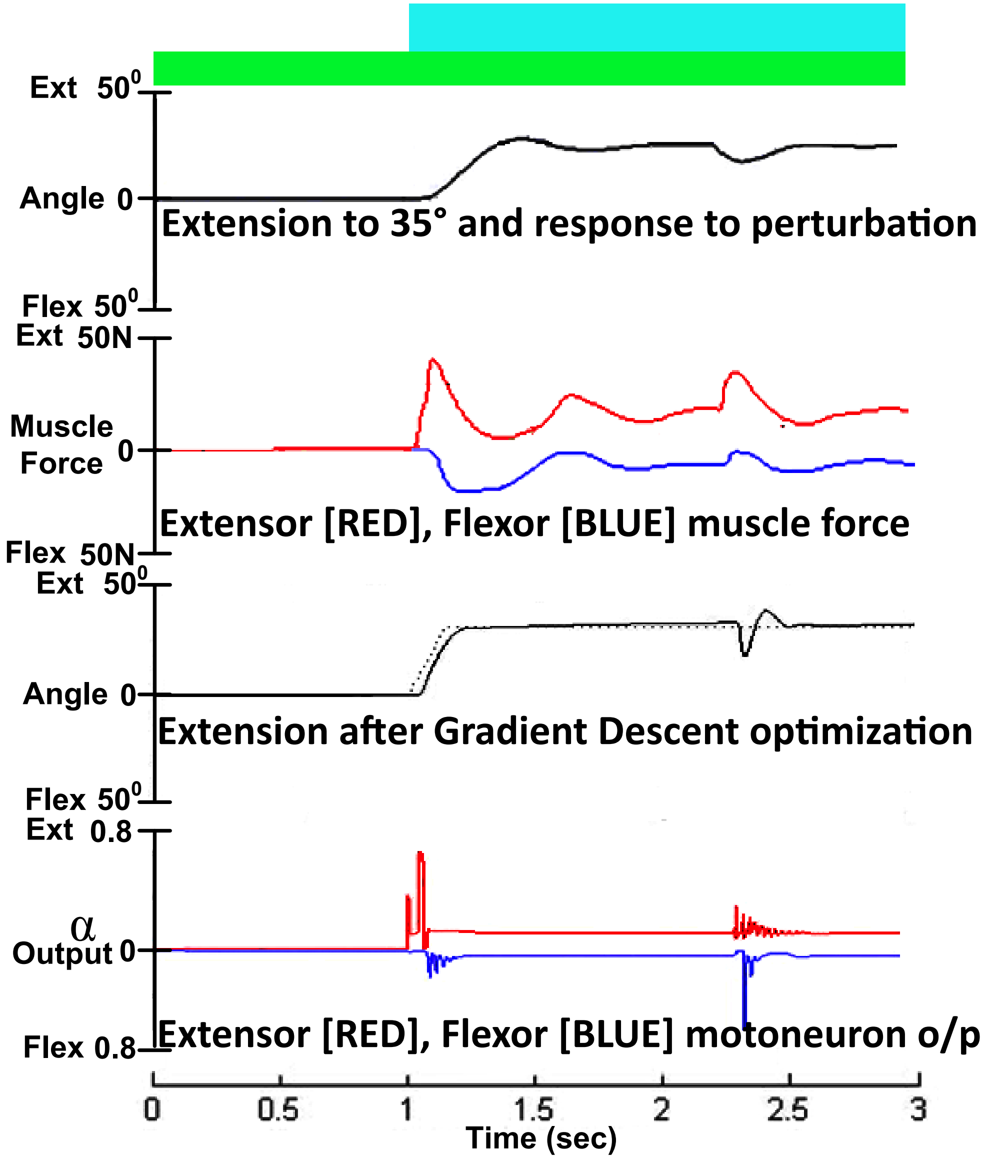


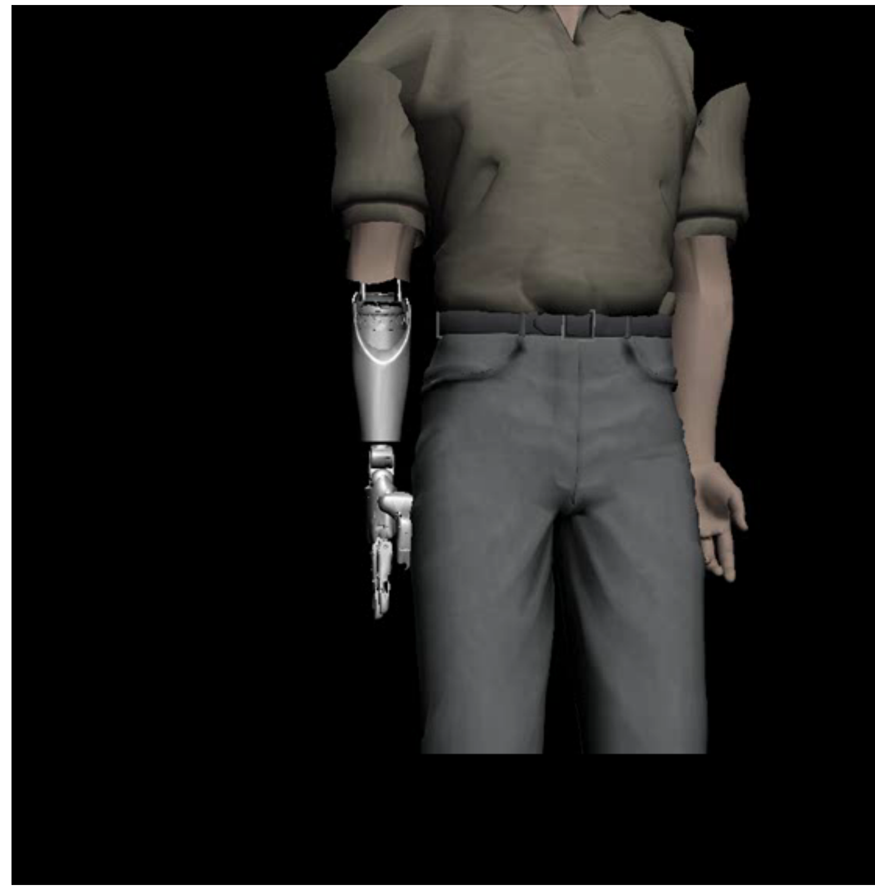


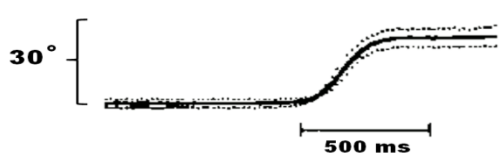
Liles S L 1985 J Neurophysiology

Activity of neurons in putamen during active and passive movements of wrist

Task 2: Rapid voluntary movement to a position target



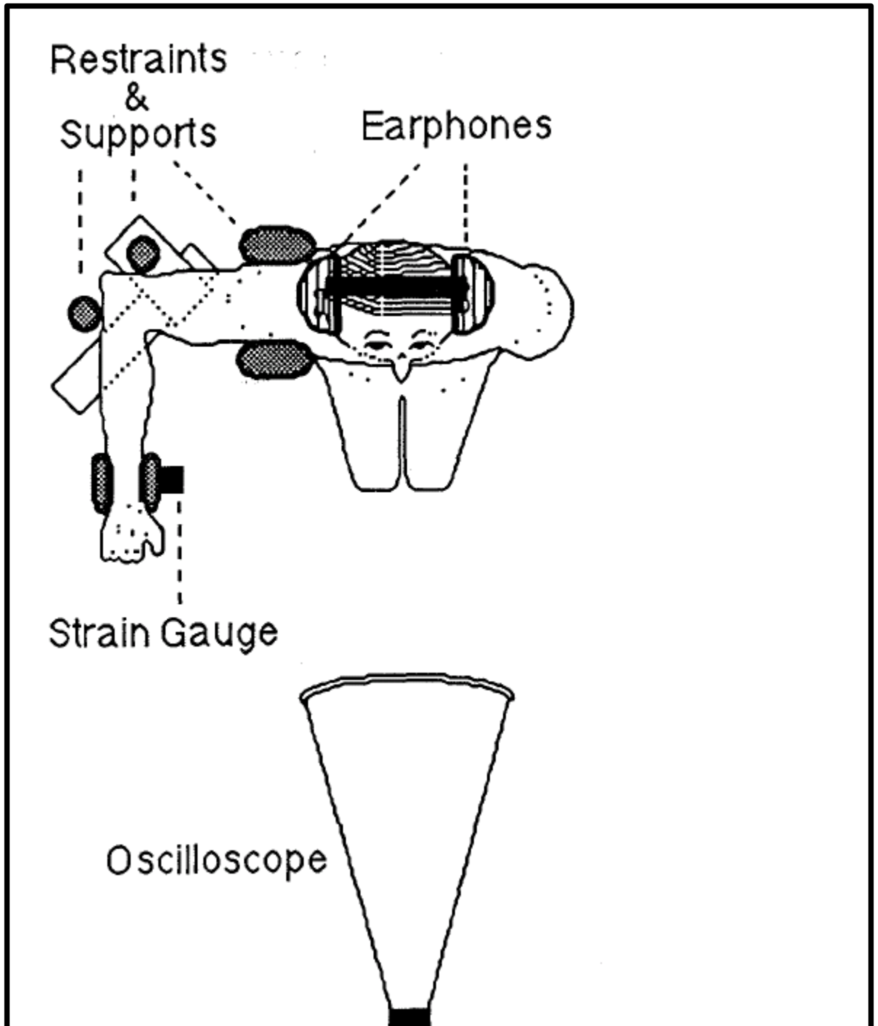




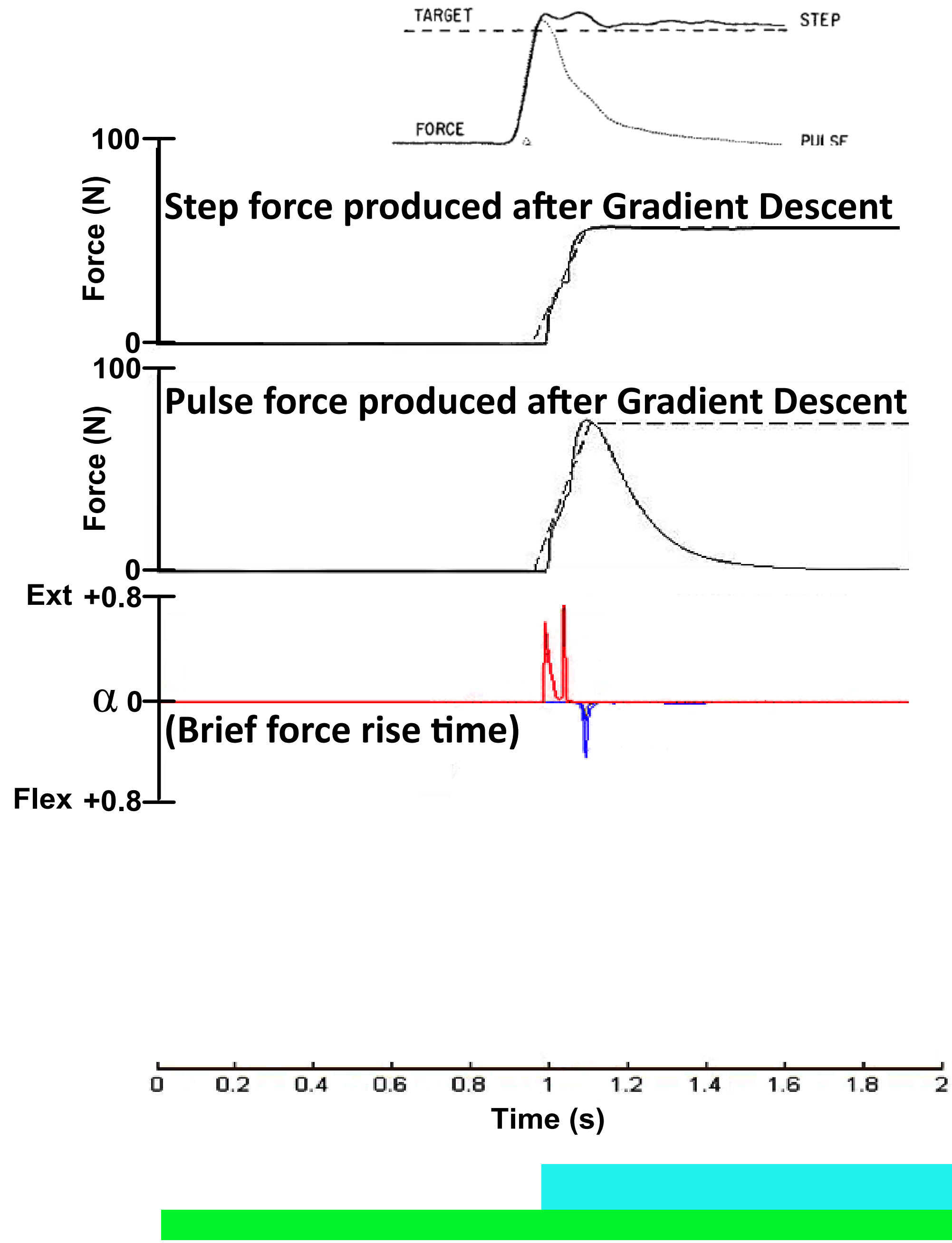
Liles S L 1985 *J Neurophysiology*

Activity of neurons in putamen during active and passive movements of wrist

Task 3: Voluntary isometric force to a target level

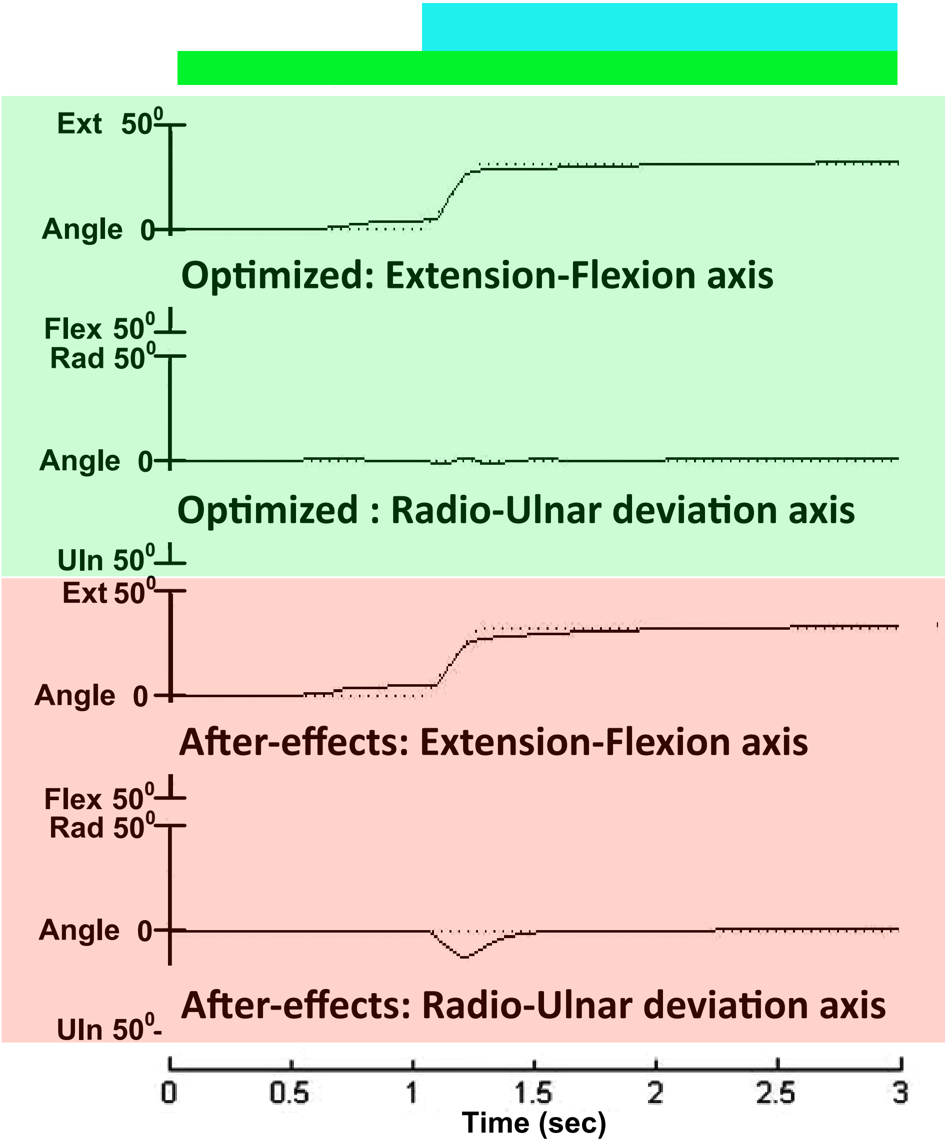


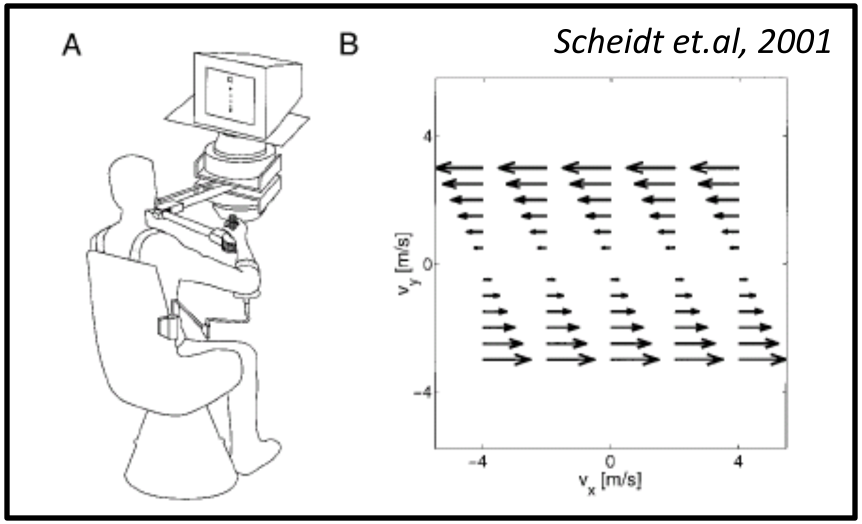
Ghez C and Gordon J 1987 Trajectory control in targeted force impulses I. Role of opposing muscles *Exp. Brain Res*. **67** 225-240

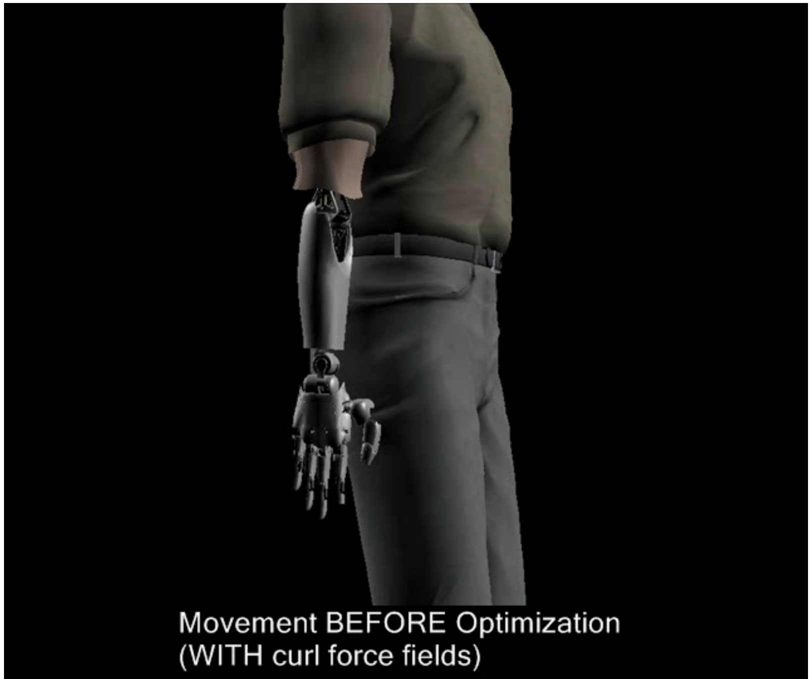


Task 4: Adaptation to viscous curl force fields

Experiments: Kluzik 2008, Scheidt 2001; 2000; Diedrichsen 2005; Flanagan 1999; Hwang 2005; Karniel 2002, etc!

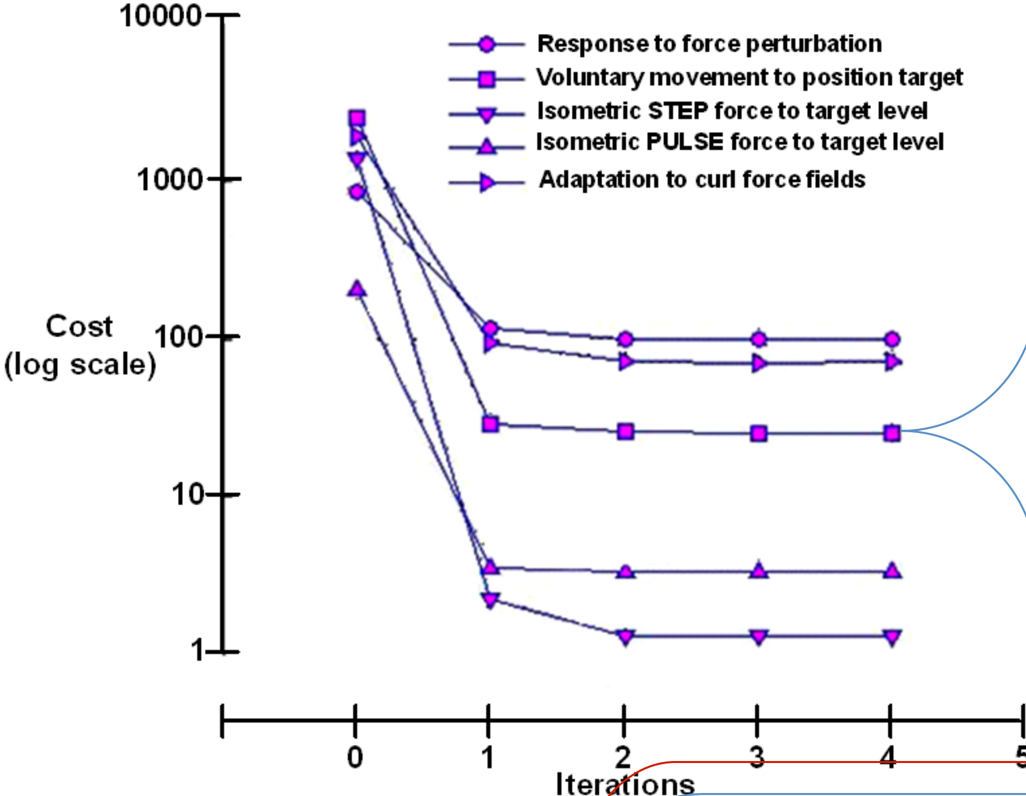




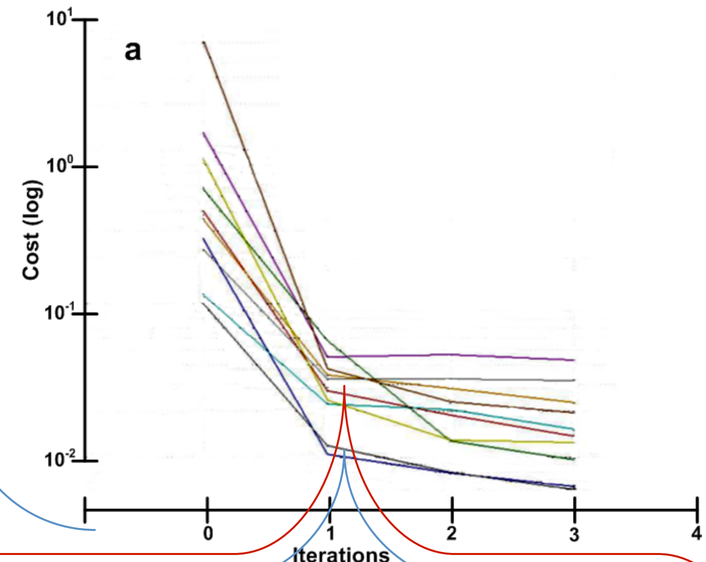


Learning Curves

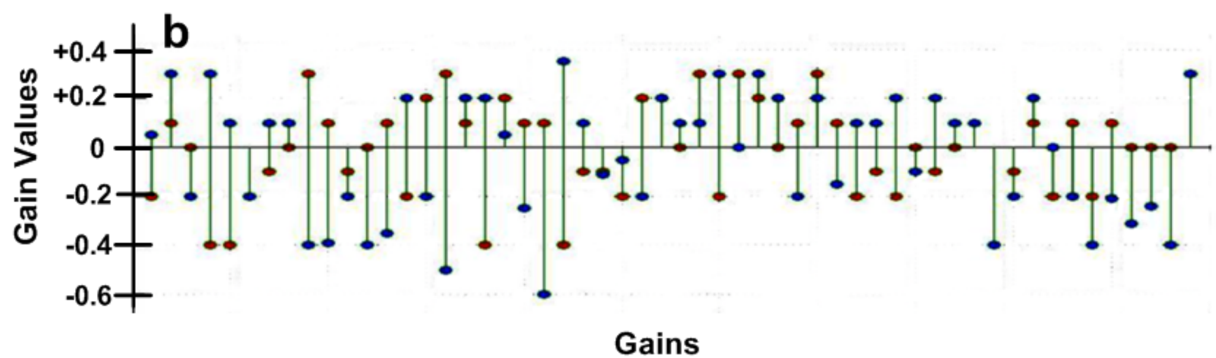
Typical learning curves for all tasks



Random starting conditions for rapid movement

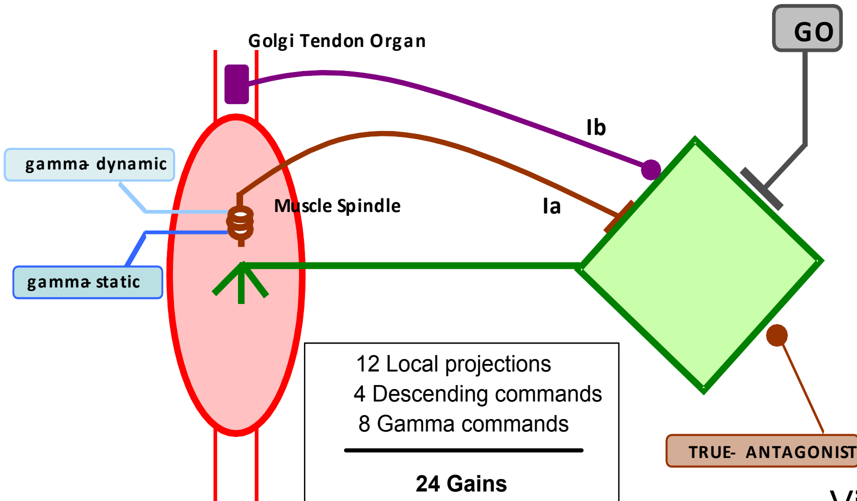


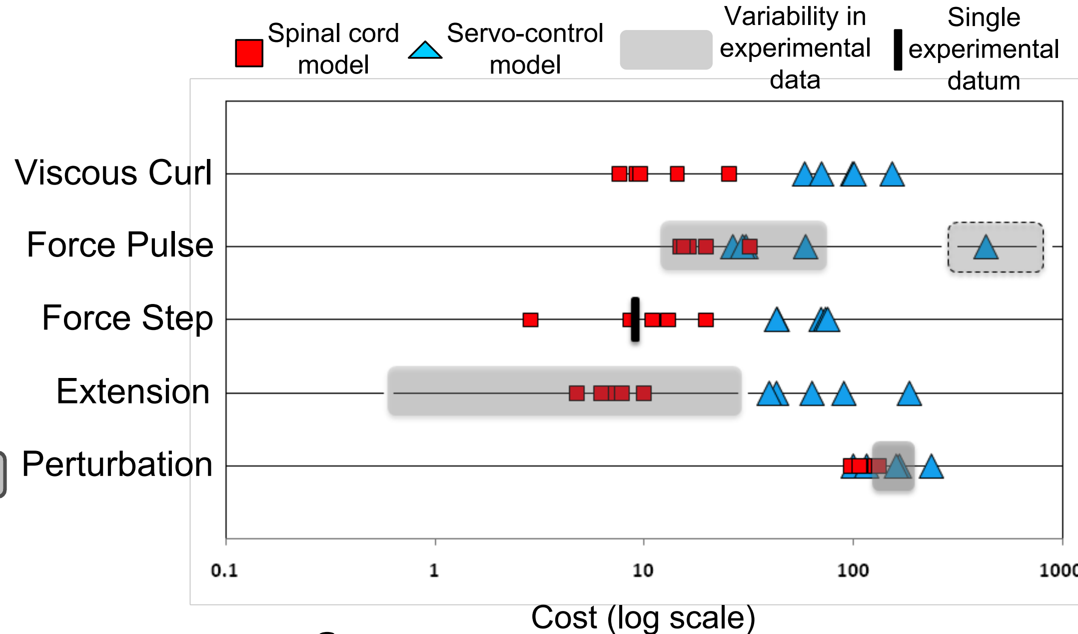
Analysis of gain values



Conclusion:
many local
“good enough”
minima

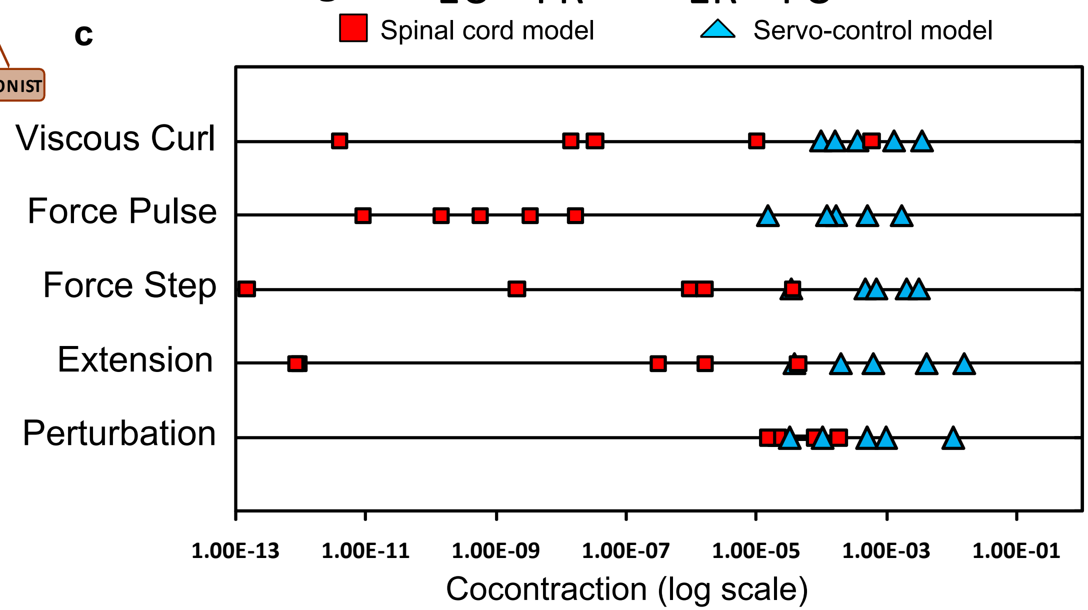
Comparison with Servo-Control



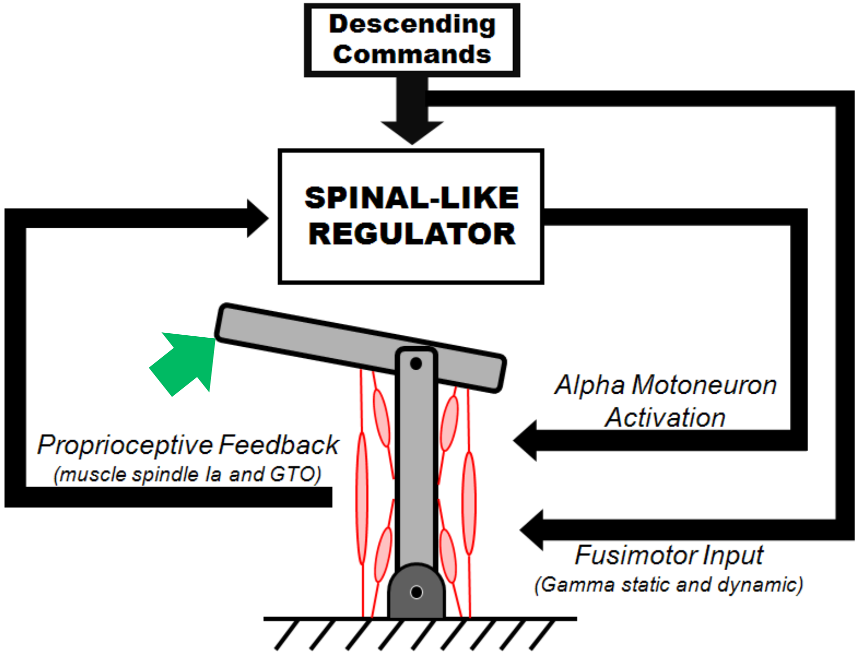


$$\int (\text{state}^* - \text{state})^2 \; dt$$

$$\int (\alpha_{EU}\alpha_{FR} + \alpha_{ER}\alpha_{FU}) \; dt$$

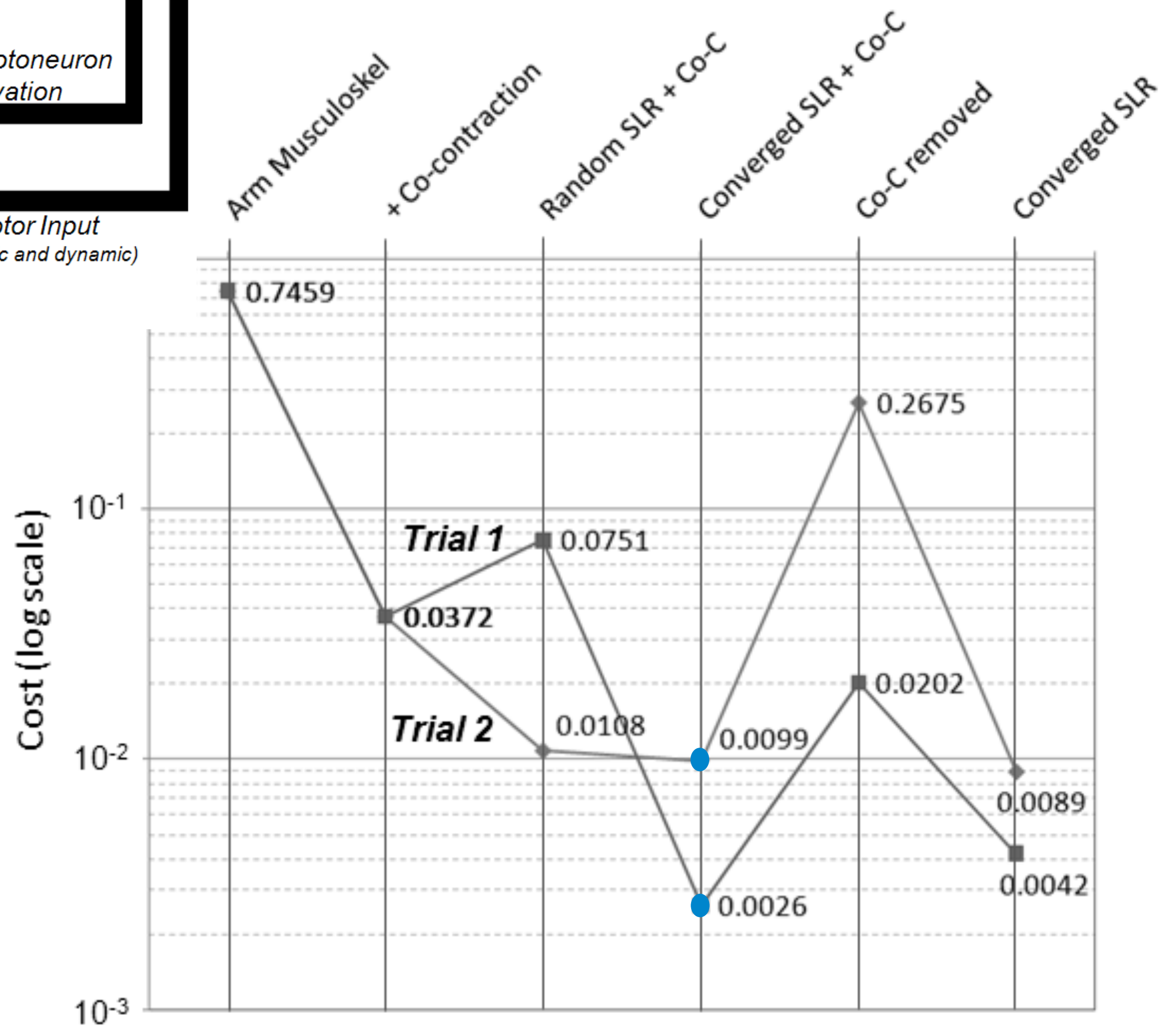


SLR Controller for Planar Elbow-Shoulder Musculoskeletal System



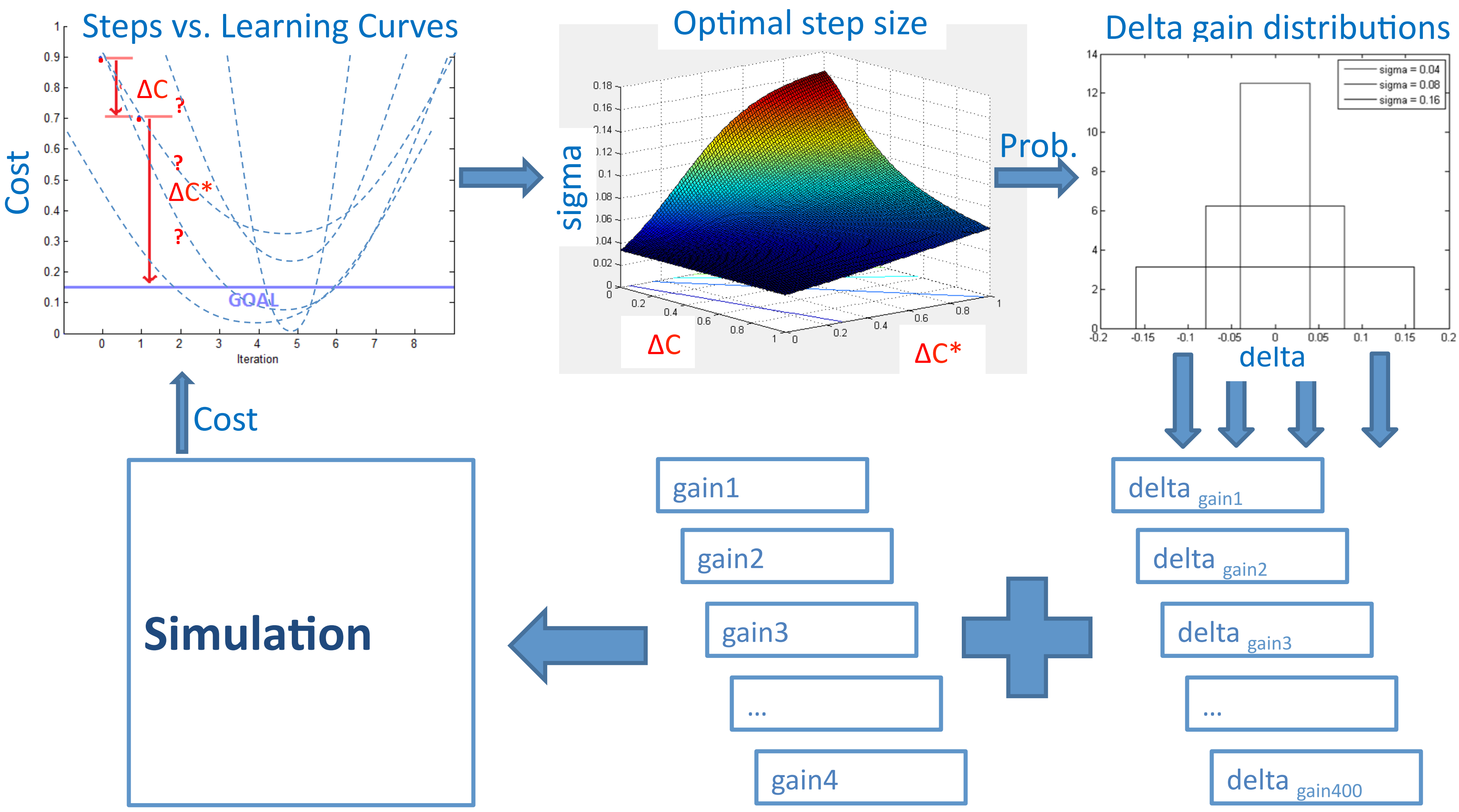
Learning to Resist **Sudden Perturbing Force**

100N x 10ms

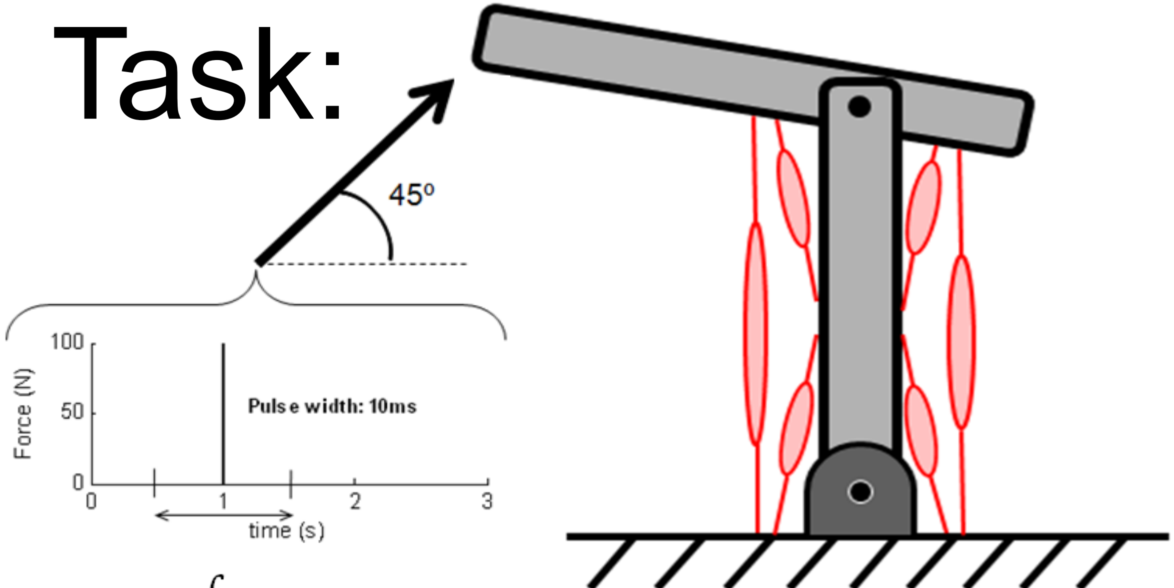


BioSearch™ Corticospinal Learning Algorithm

Hypothesis: Landscape has so many "good enough" local minima that a Random Walk is a viable learning process

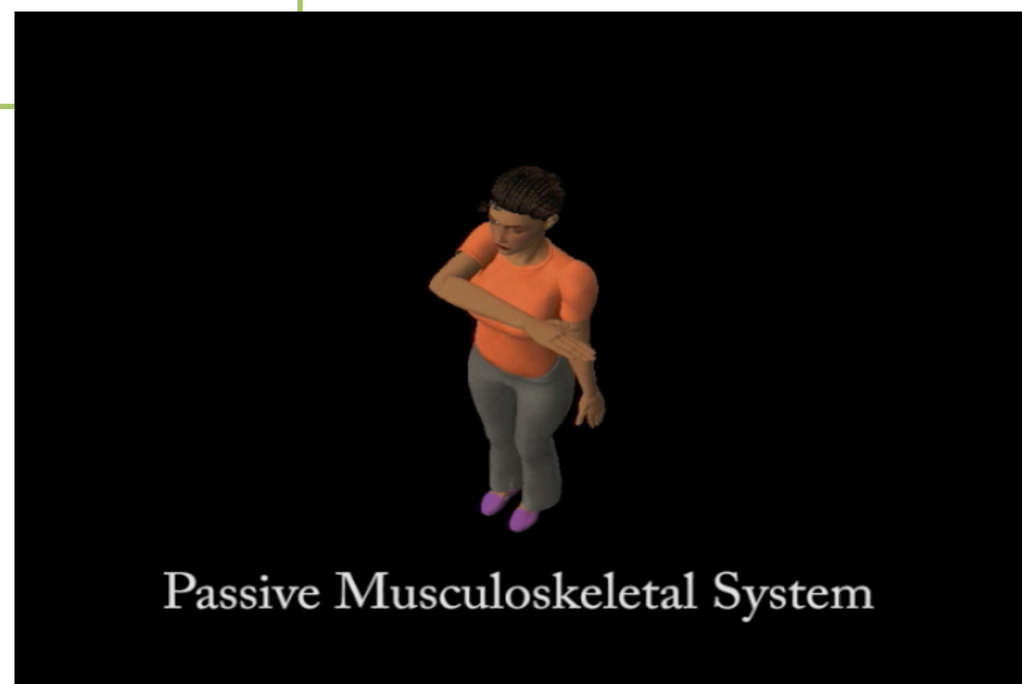


Task:

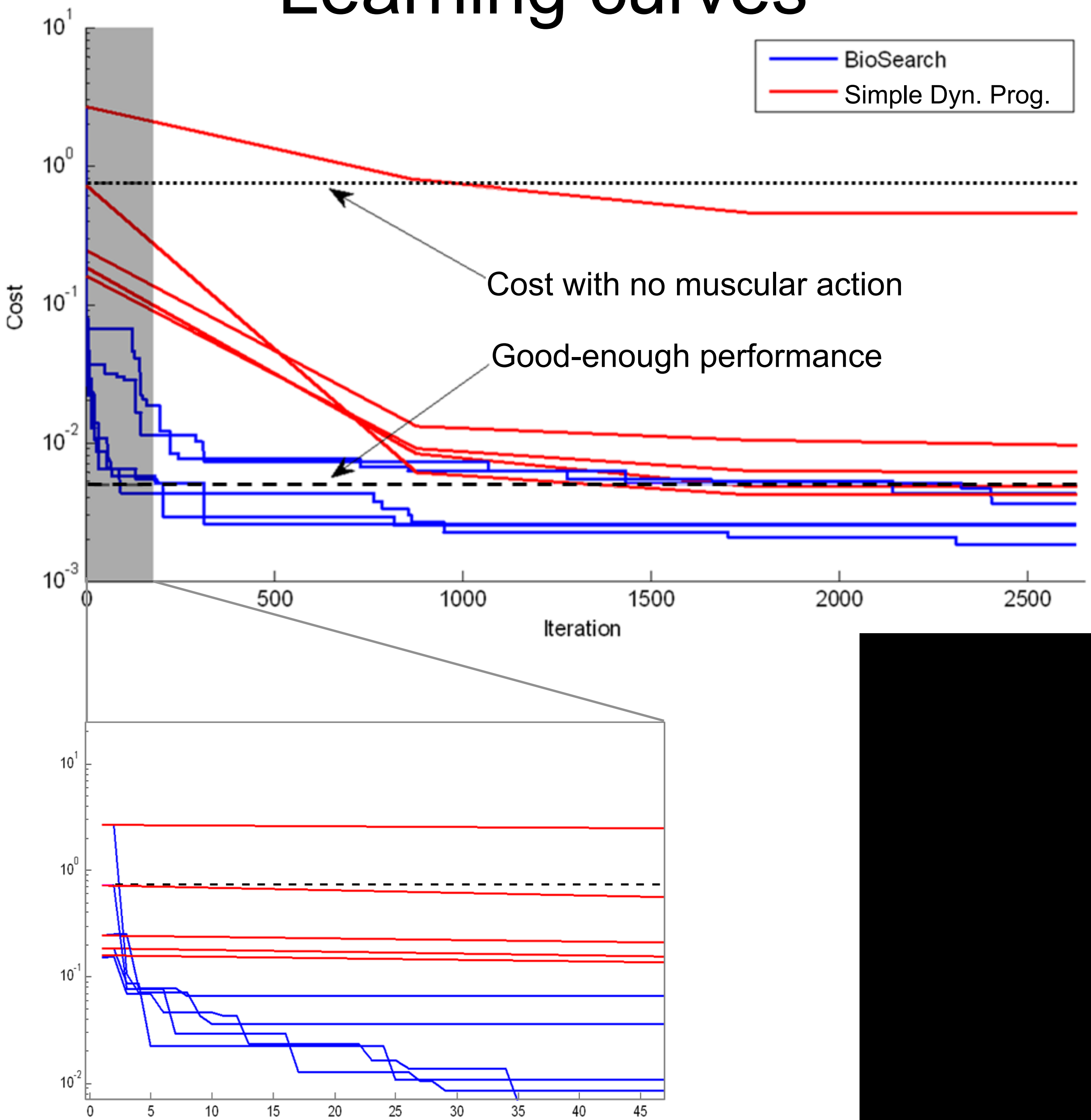


$$Cost = \int (Endpoint\ deviation\ from\ initial\ position)^2\, dt$$

SET the gains of the SLR to resist an impulsive perturbation at the endpoint.

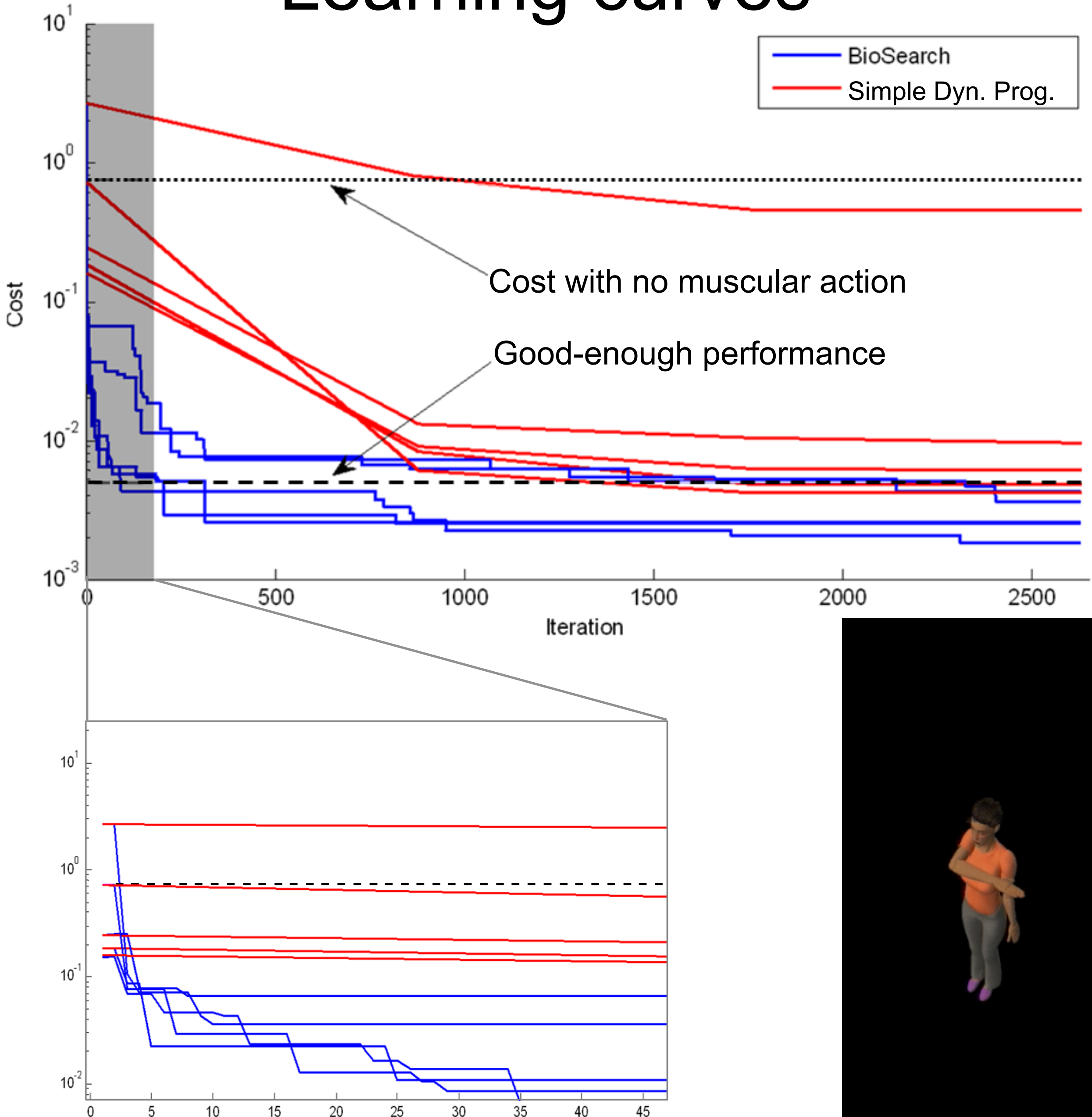


Learning curves

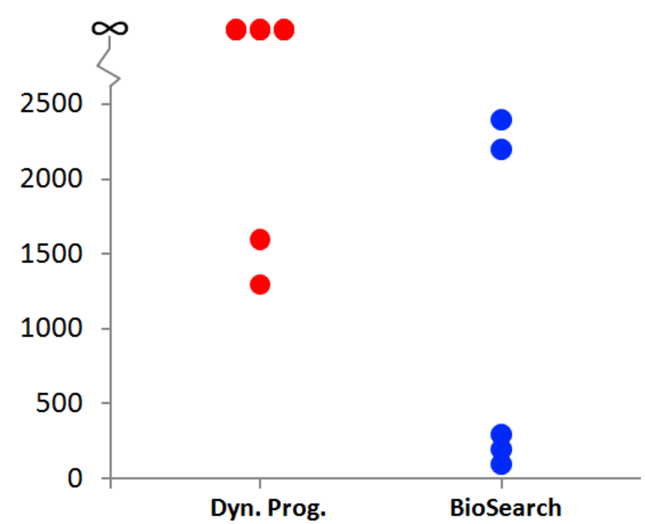


Jared Goodner, George Tsianos, Yao Li

Learning curves

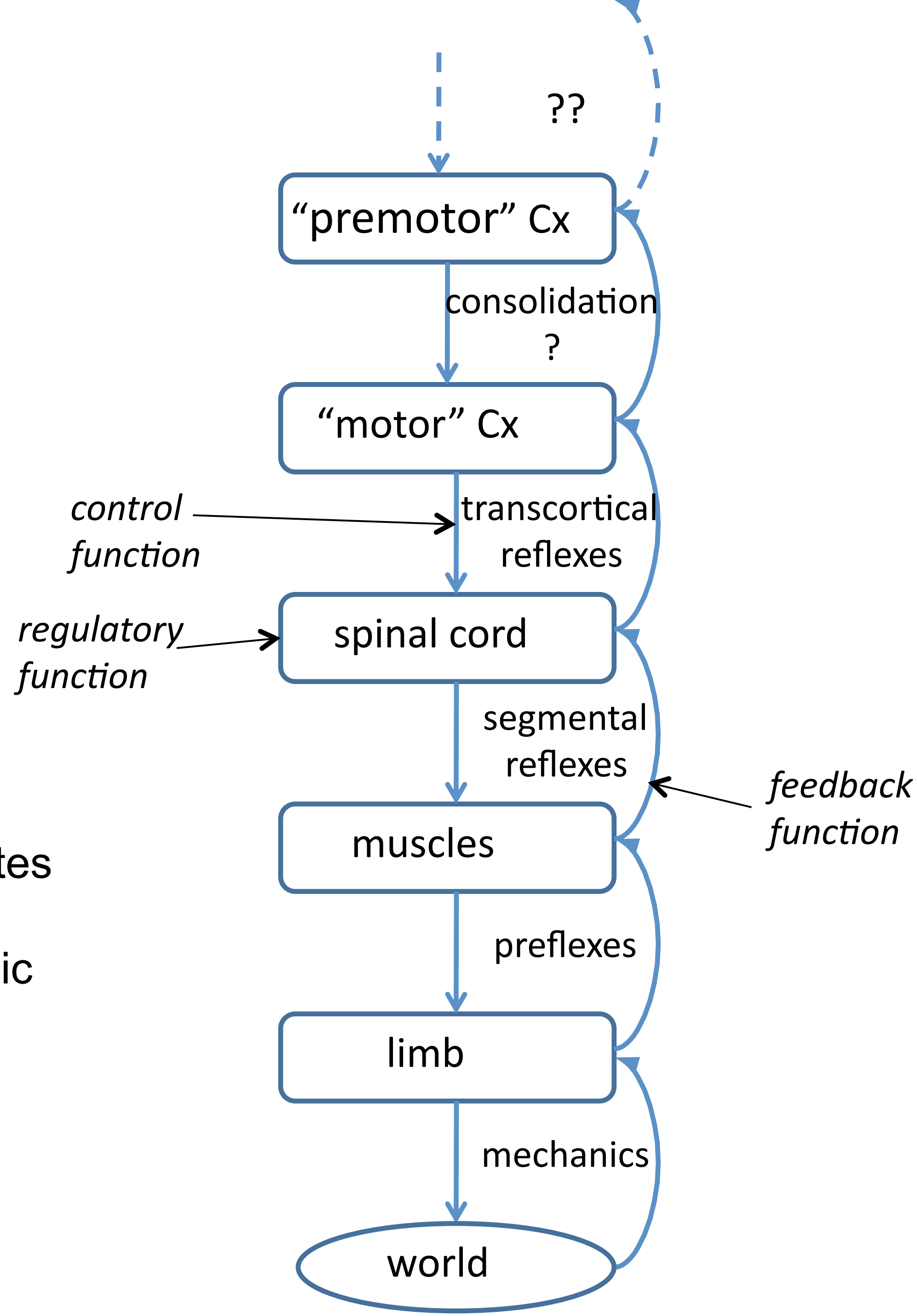


Convergence rate



Jared Goodner, George Tsianos, Yao Li

Hierarchical Control Updated



Each control stage operates on a lower stage whose local feedback and intrinsic properties constitute a regulator that is programmed by its controller.

Anthropomorphic Design

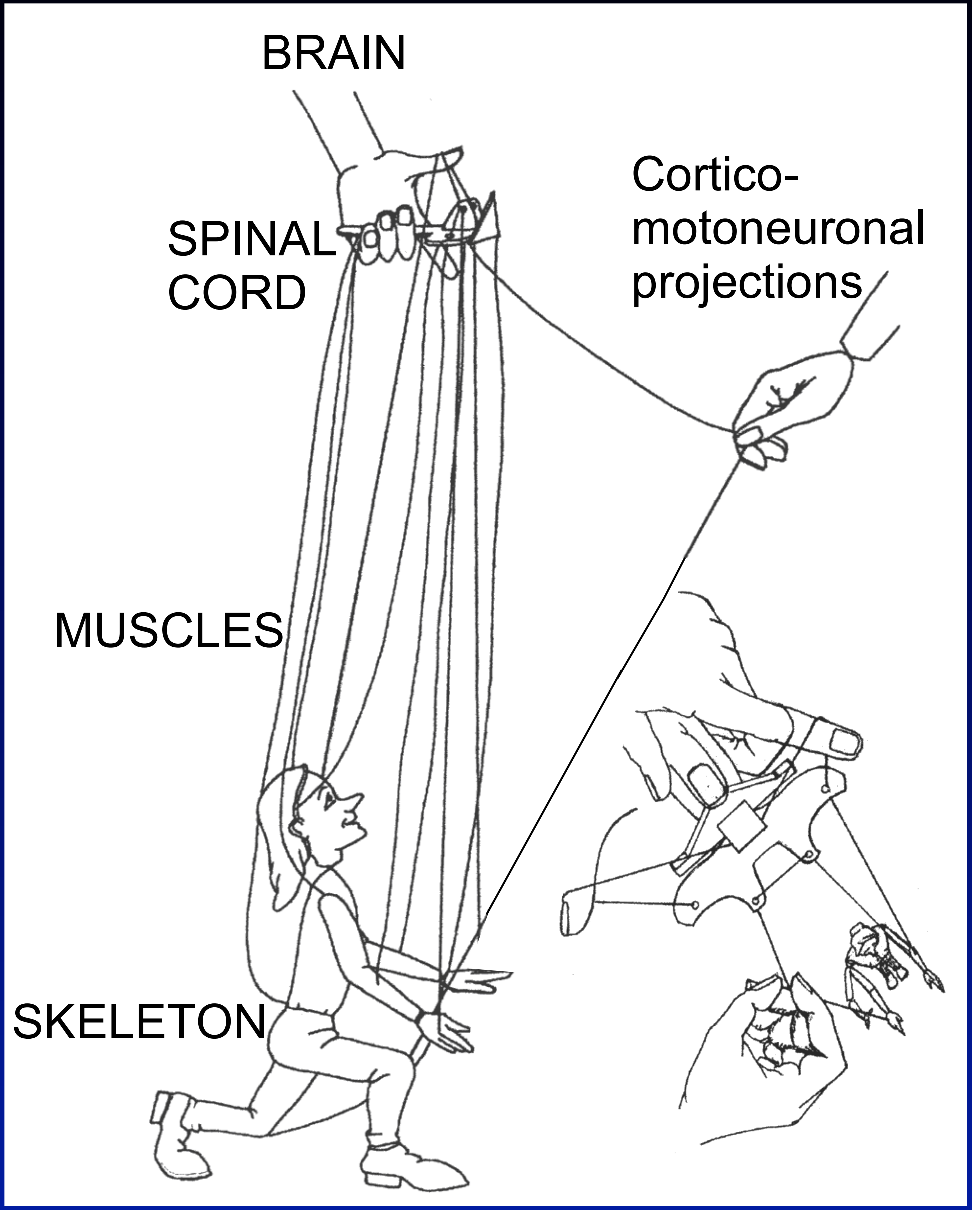
- ○ Copy as many details of biological constructs as possible.
- ○ Hope that the machine does something useful.

Biomimetic Design

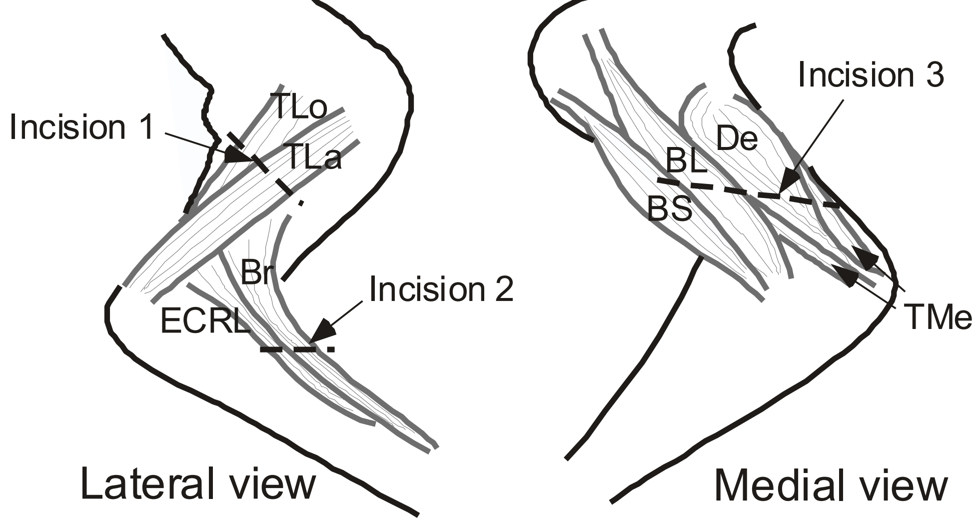
- ✓ Identify utility of each biological design feature.
- ✓ Understand principle of operation of the design feature.
- ✓ Build a machine based on that principle of operation.
- ✓ Demonstrate human-like capabilities enabled by that design feature.

Valid Analogy?

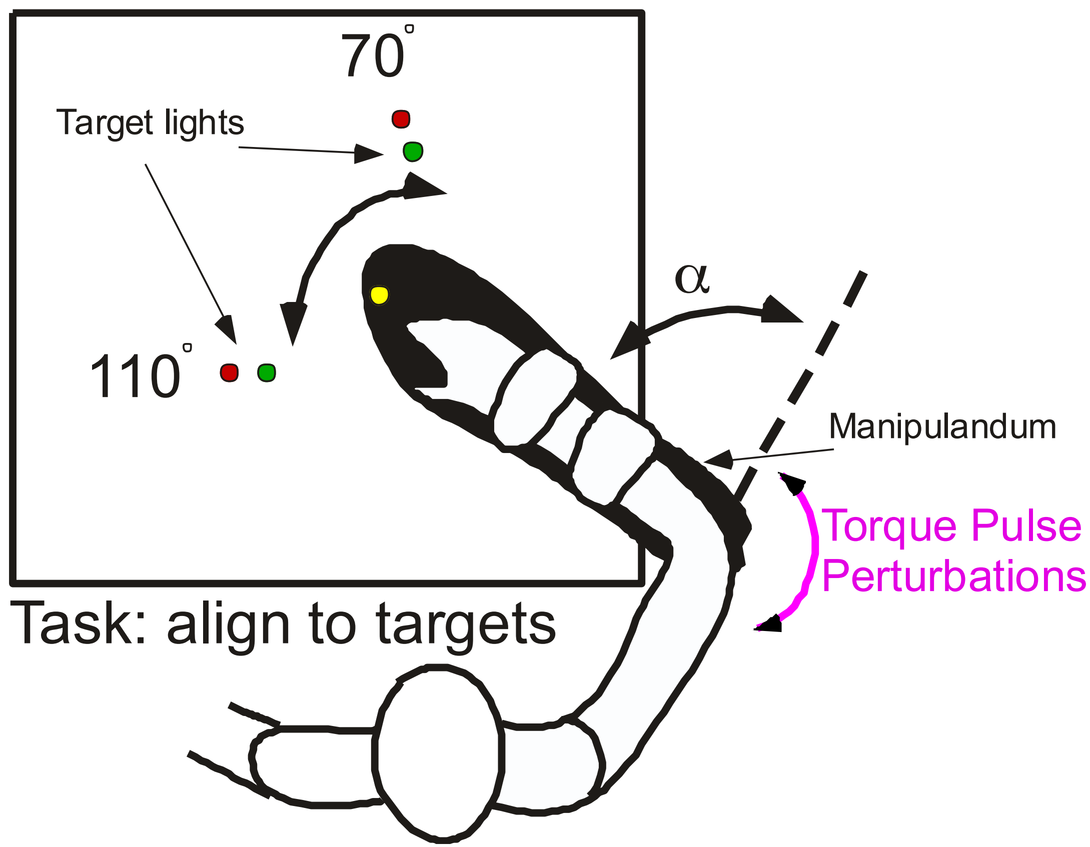
Theory of Computation for the Spinal Cord



Using a Musculoskeletal Model To Interpret Motor Control Strategies In a Forearm Pointing Task



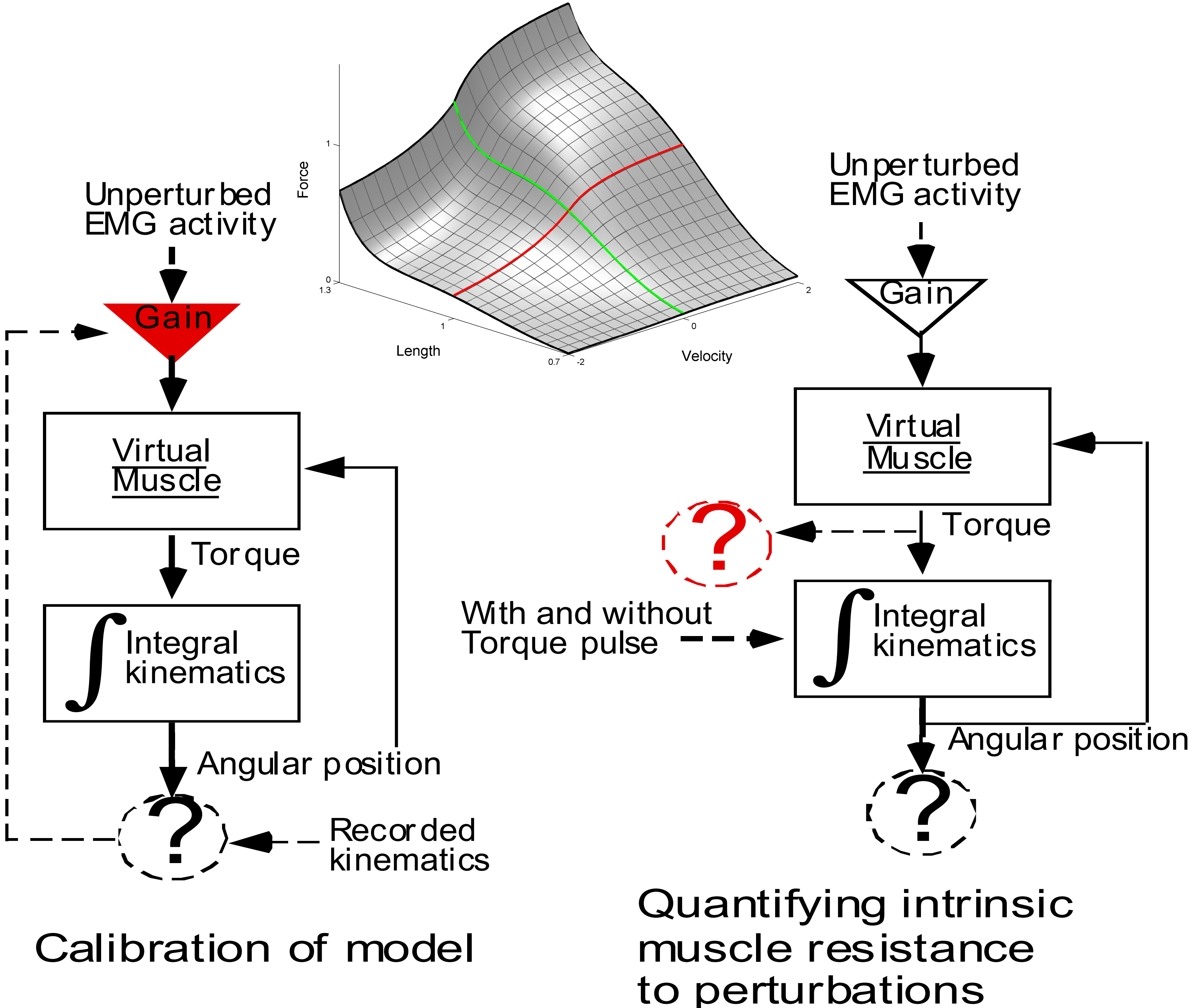
EMG recordings & muscle models



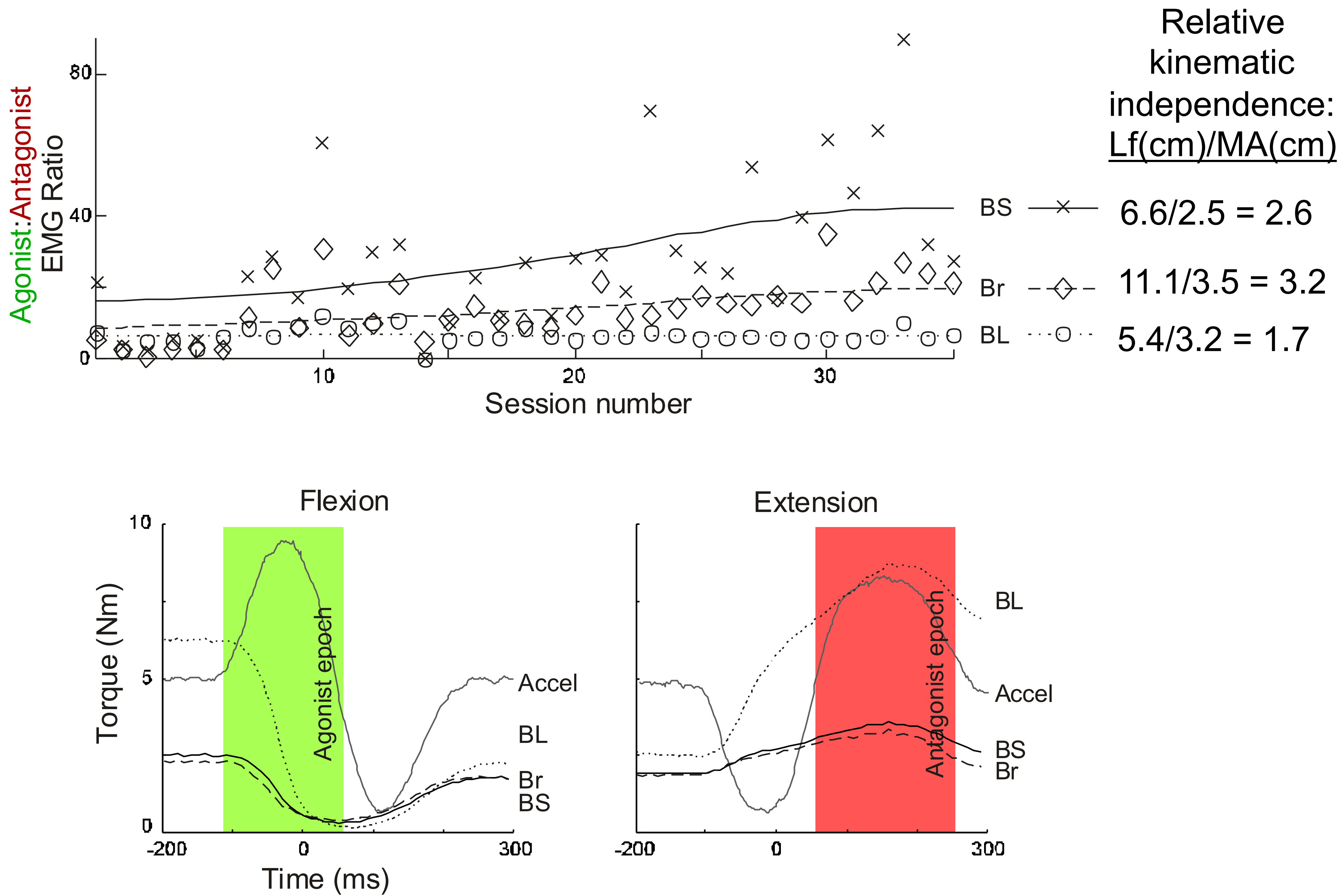
Cheng & Loeb (in prep.);

Cheng, Brown & Loeb (2000)
Virtual Muscle,
J. Neurosci. Meth.
101:117-130

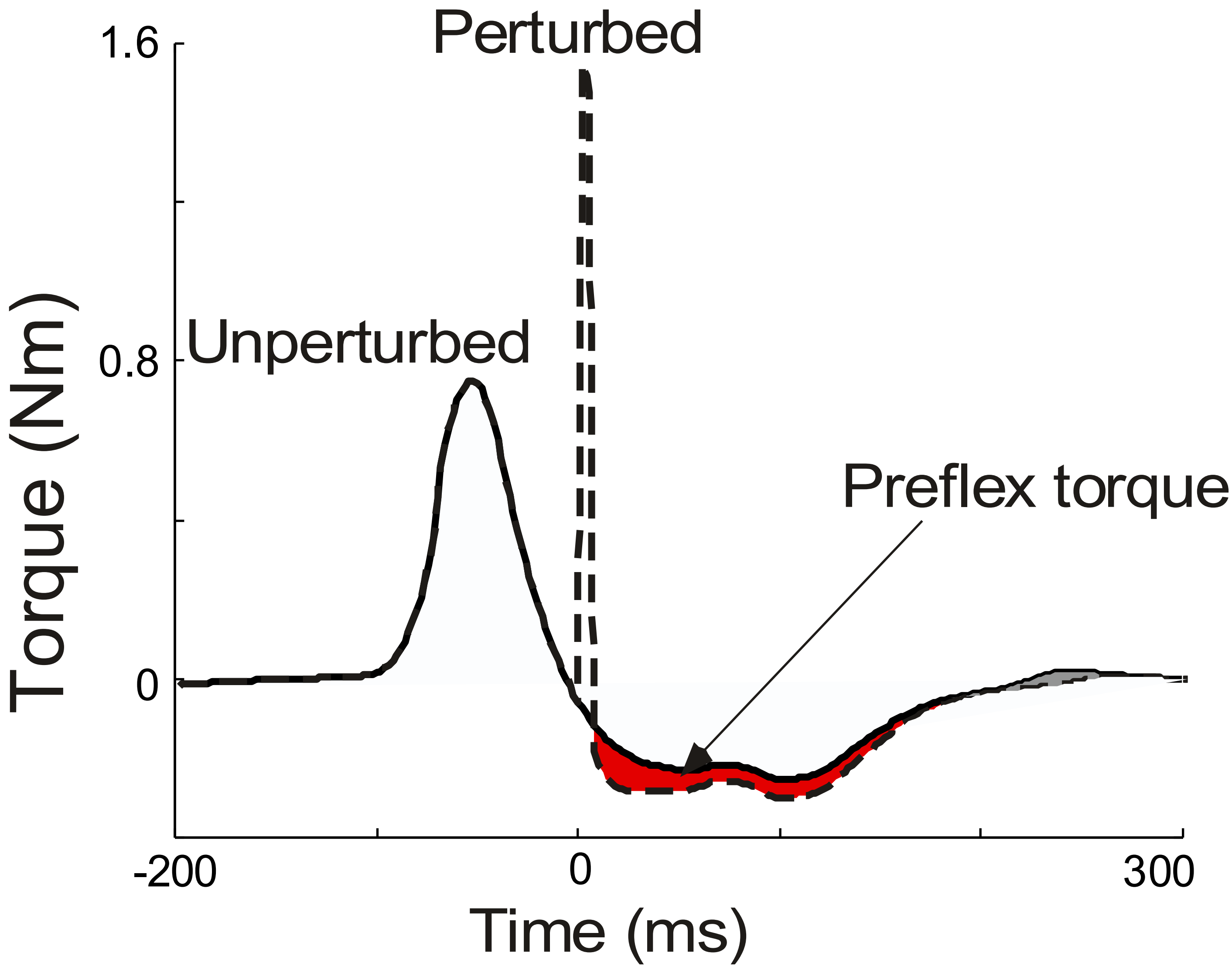
http://ami.usc.edu (Projects, BION)


Force
1
0
1.3
1
0.7
Length
-2
0
2
Velocity
Unperturbed EMG activity
Gain
Virtual Muscle
Torque
Integral kinematics
Angular position
?
Recorded kinematics
Calibration of model
Unperturbed EMG activity
Gain
Virtual Muscle
?
Torque
With and without Torque pulse
Integral kinematics
Angular position
?
Quantifying intrinsic muscle resistance to perturbations

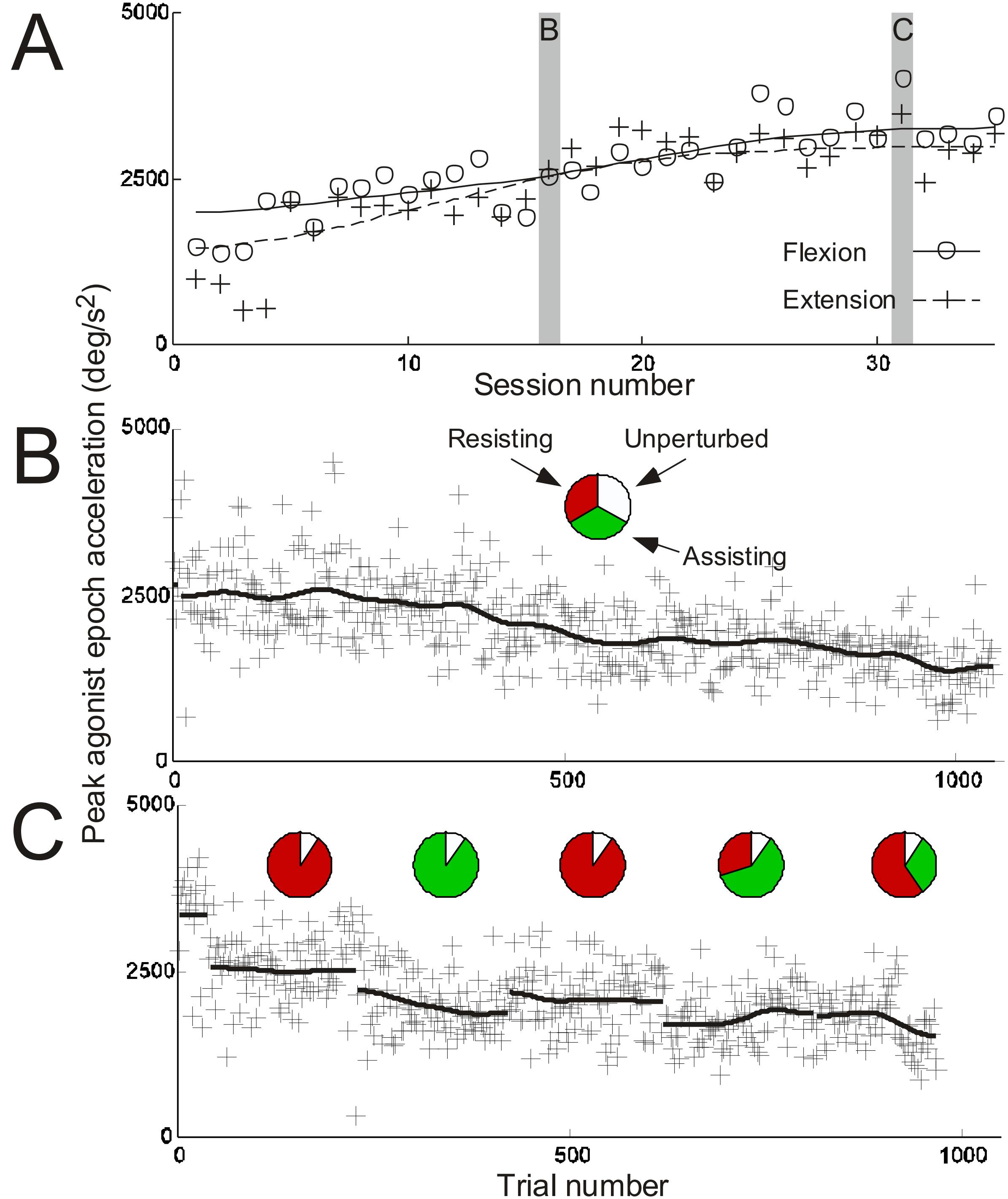
Not all synergists are created equal.



Muscles are smart.



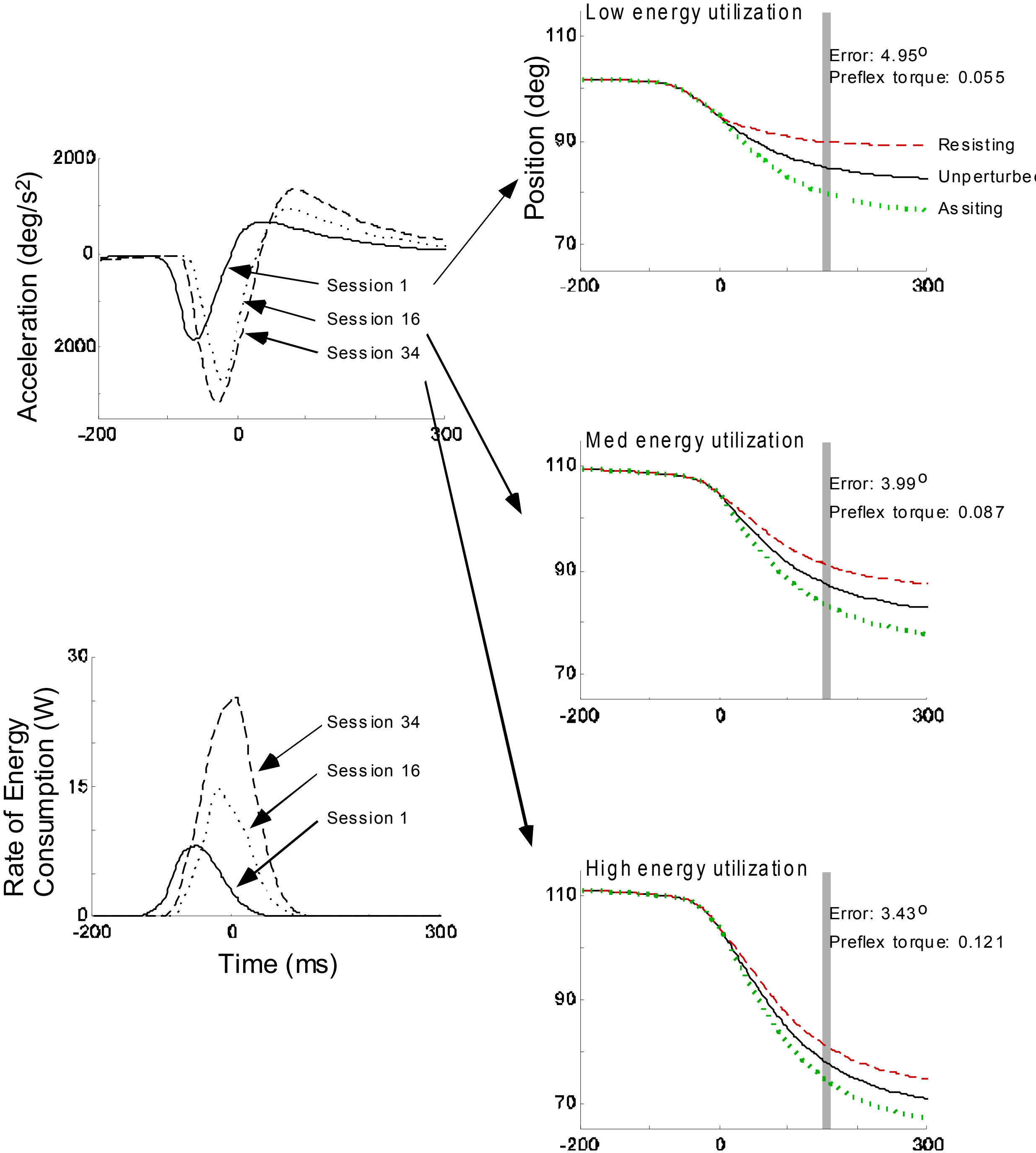
Even inertia can be smart

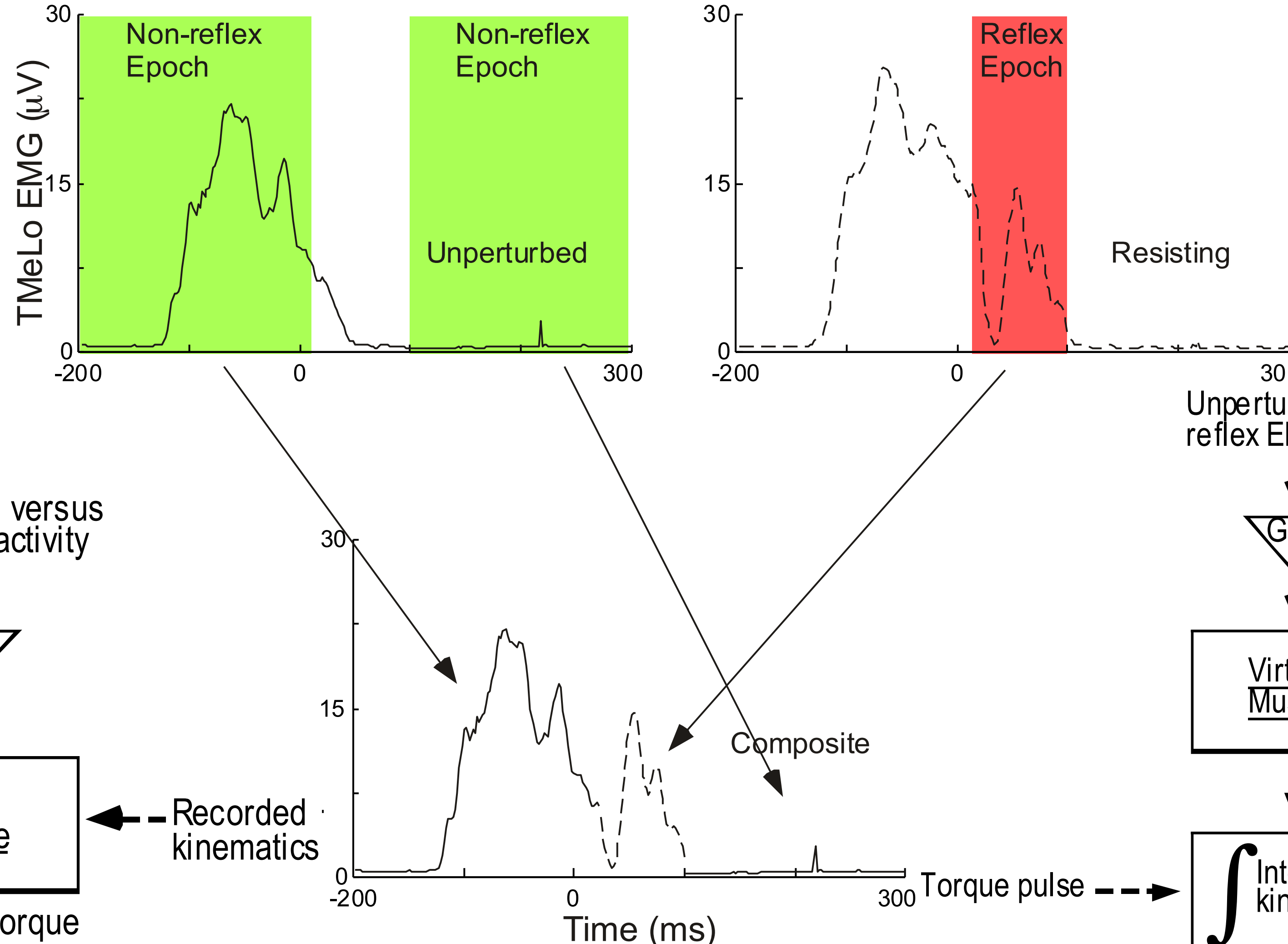


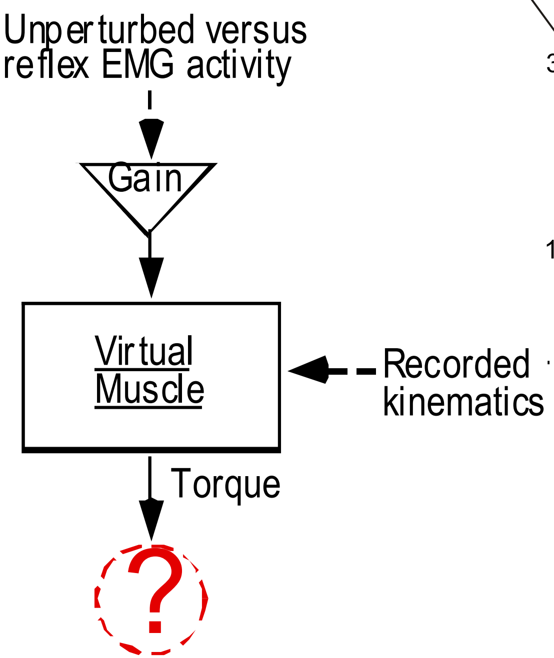
Impulse $\Delta\Gamma \cdot t$

Momentum $J \cdot \dot{\omega}$

But momentum and preflexes have fixed costs

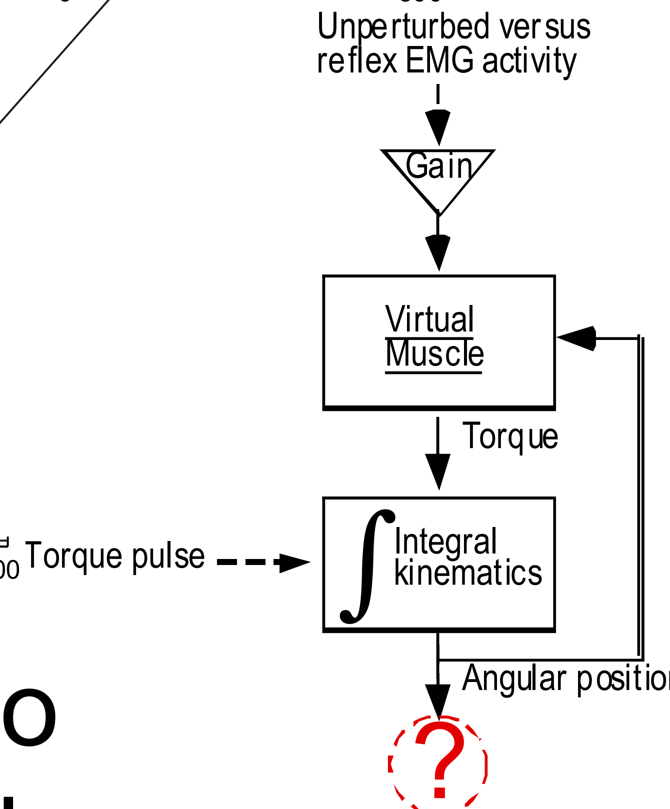






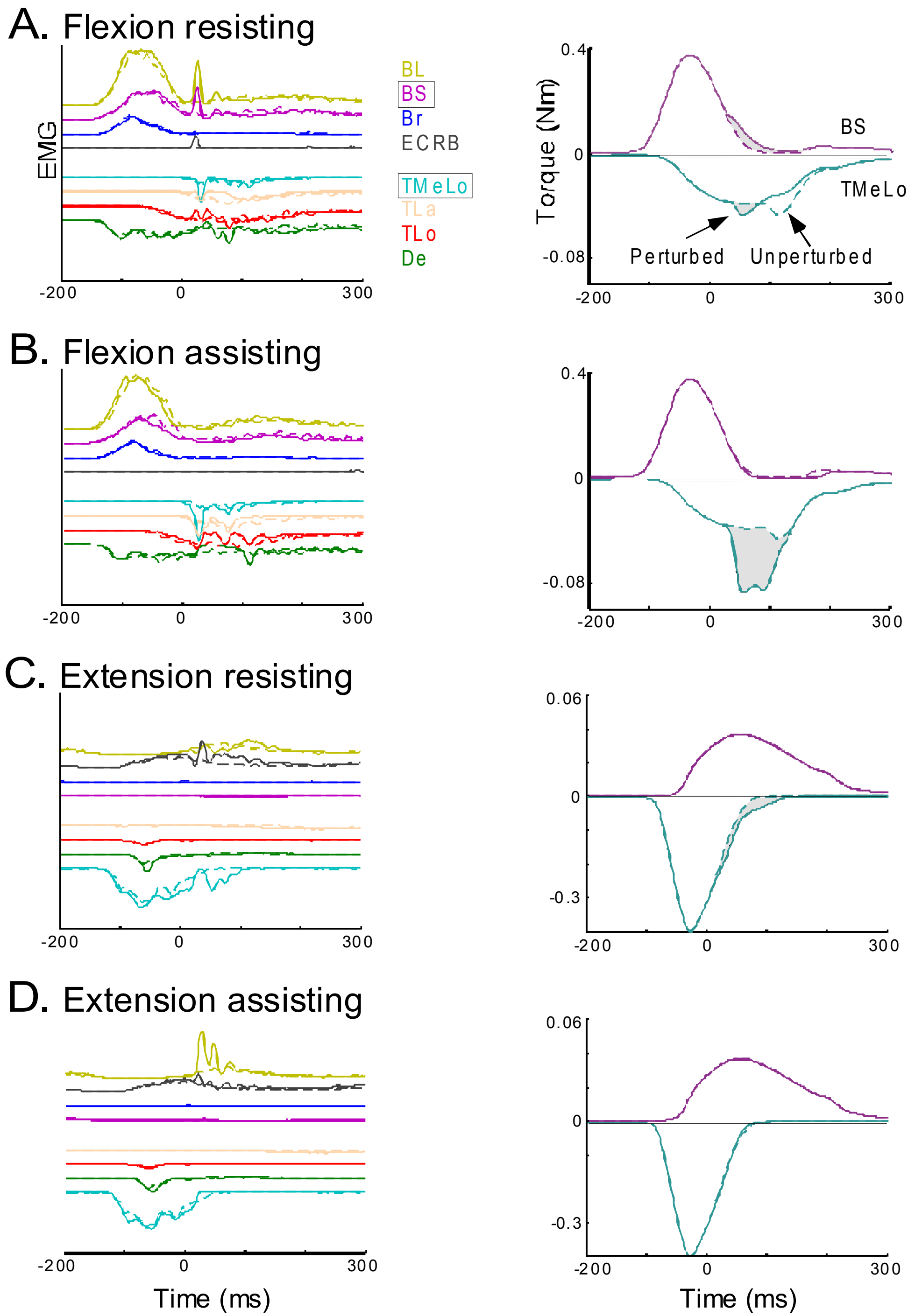
Quantifying reflex effects of individual muscles

Use Model to Understand Reflexes



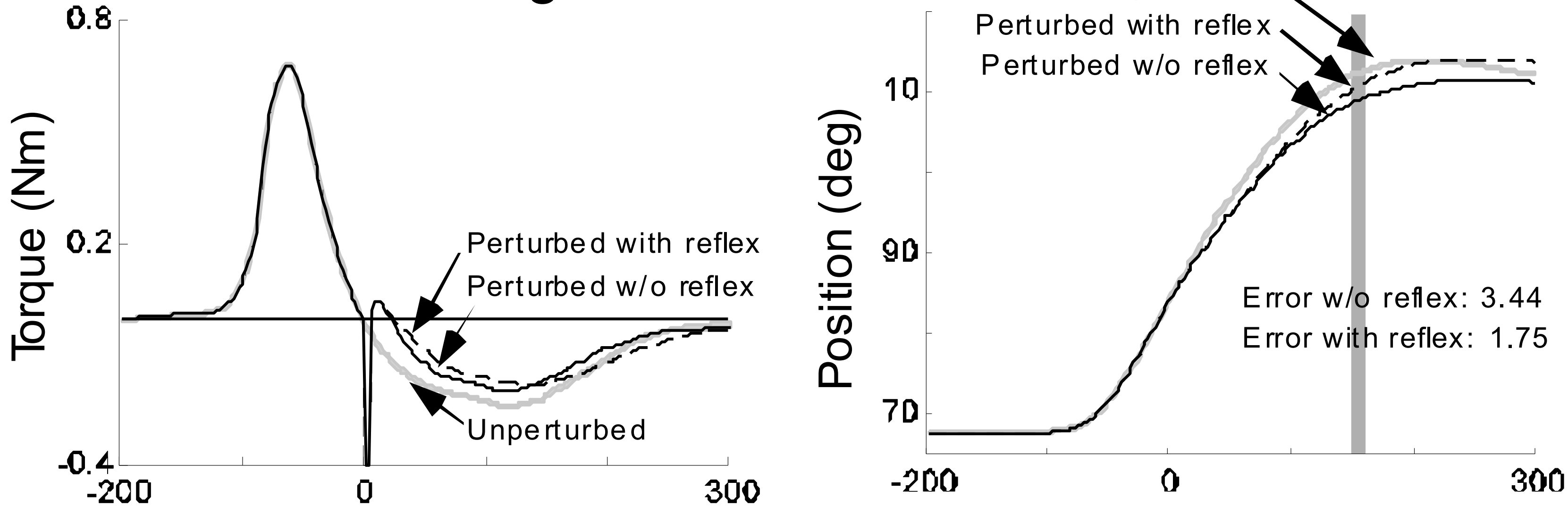
Effectiveness of reflexes in controlling perturbations

They look like reflexes. Are they important?

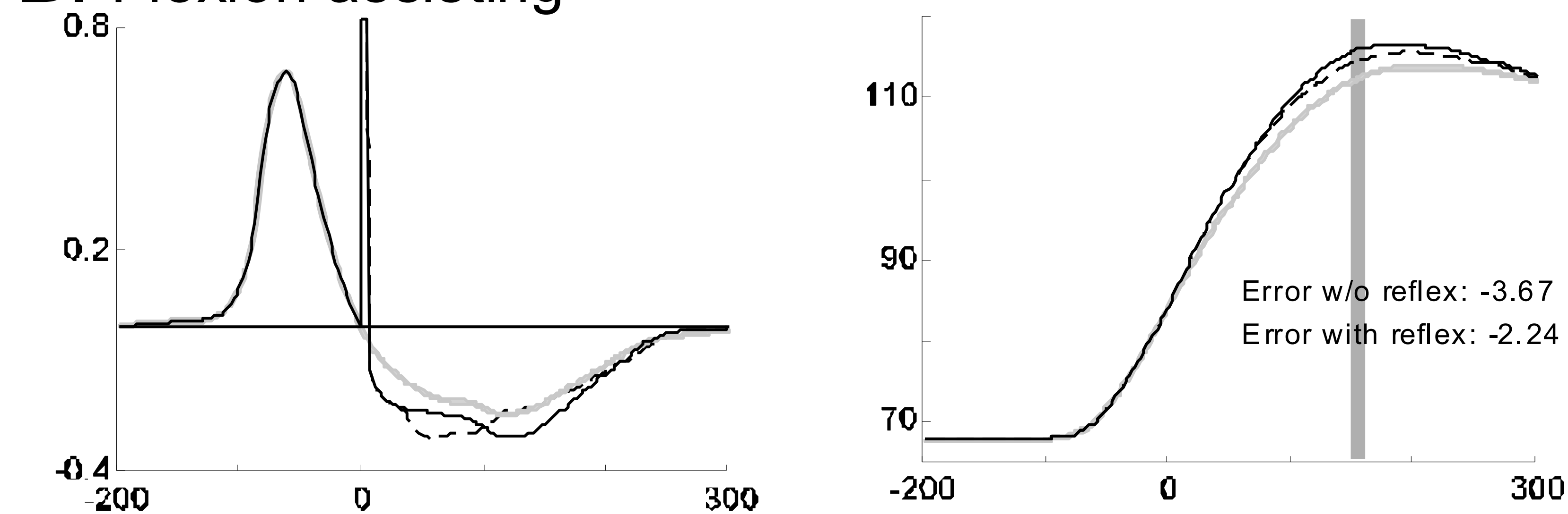


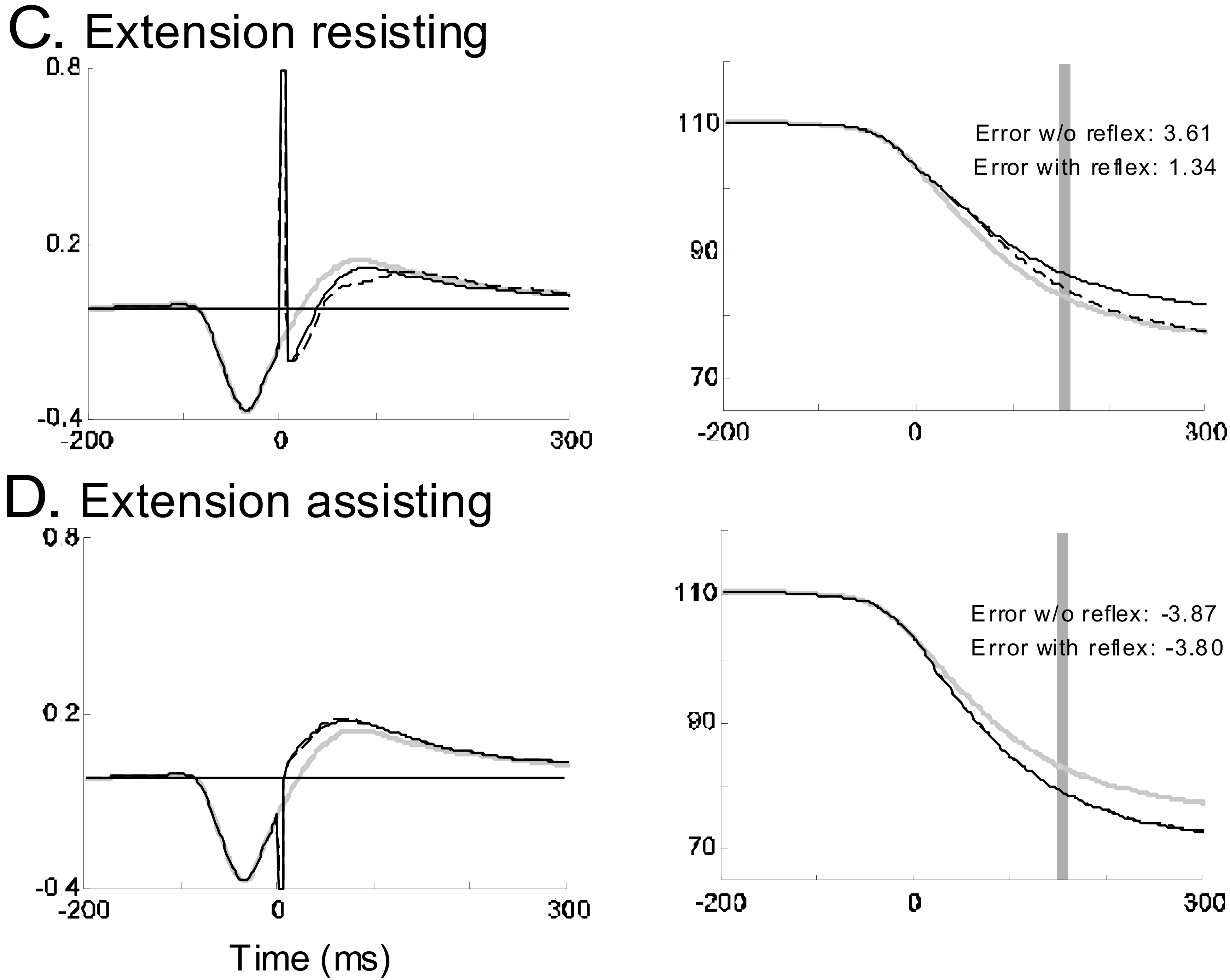
Preflexes alone don't cut it.

A. Flexion resisting

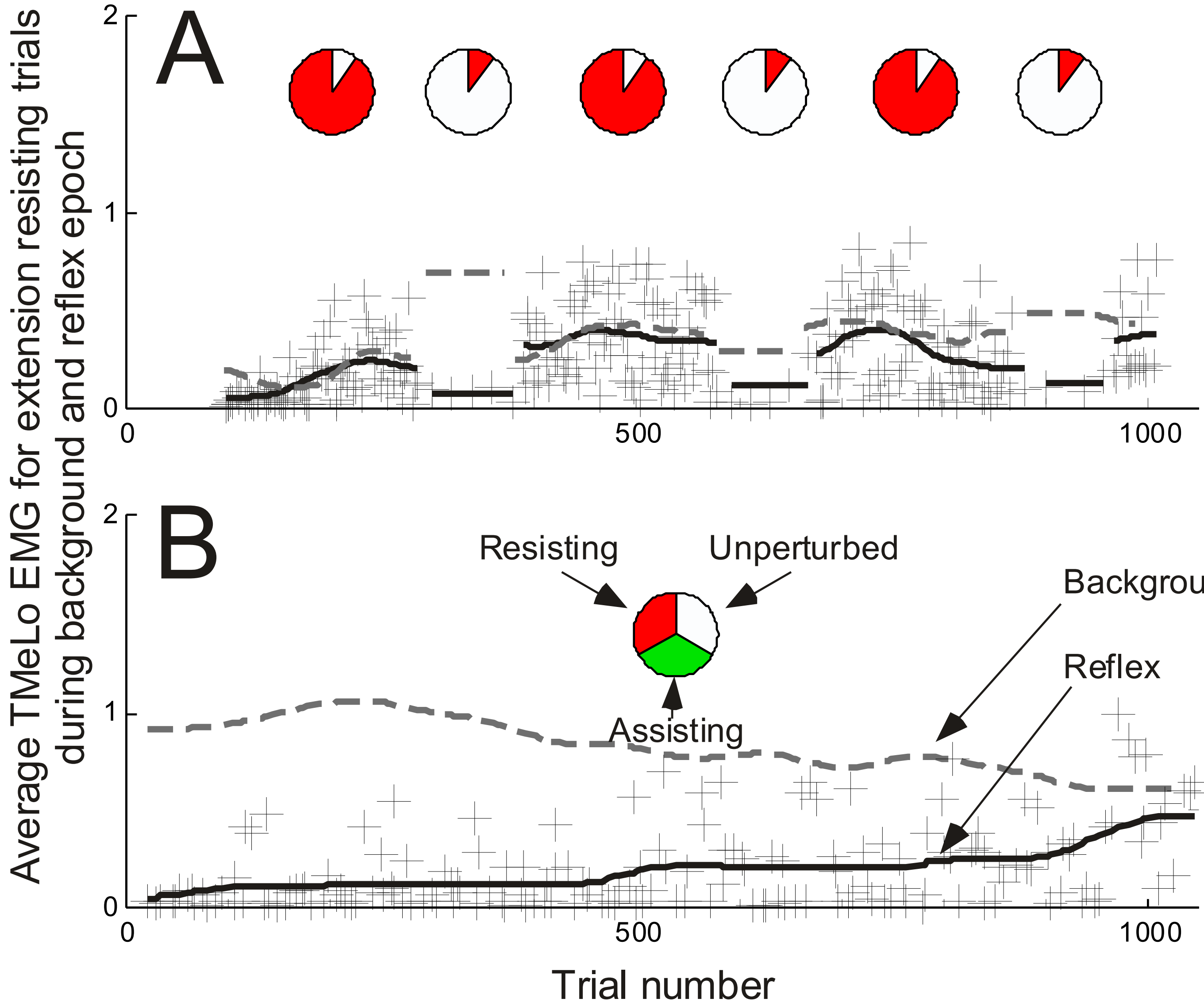


B. Flexion assisting

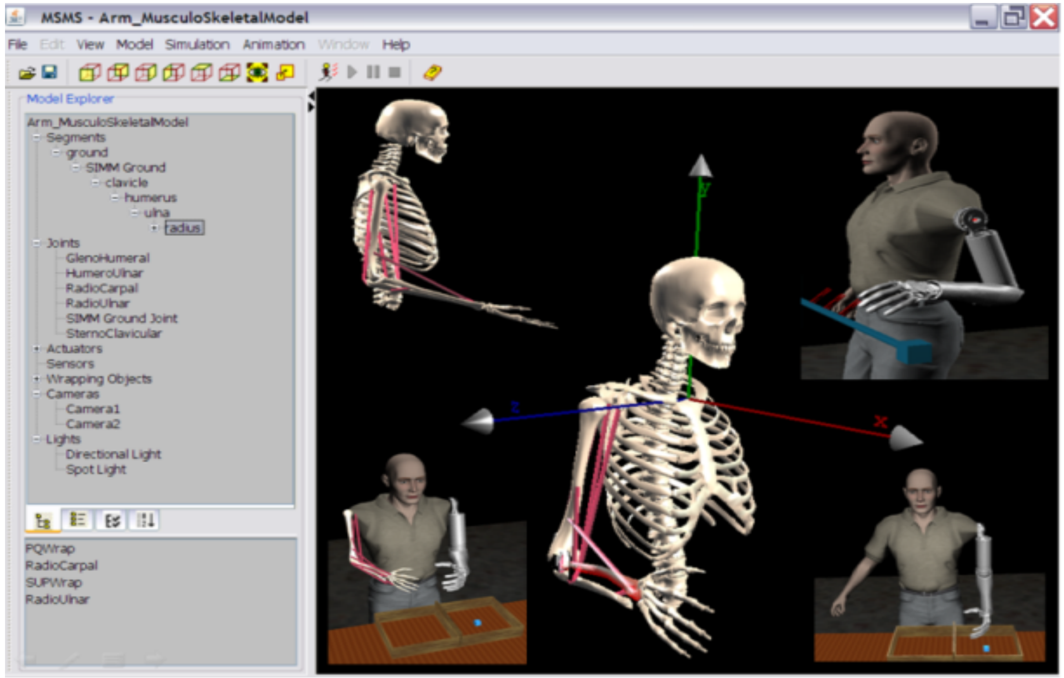



C. Extension resisting
0.8
0.2
-0.4
-200
0
300
110
90
70
-200
0
300
Error w/o reflex: 3.61
Error with reflex: 1.34
D. Extension assisting
0.8
0.2
-0.4
-200
0
300
Time (ms)
110
90
70
-200
0
300
Error w/o reflex: -3.87
Error with reflex: -3.80

Are reflexes selectively controlled?



MSMS: Main Goals and Features



- **Provides interactive tools for modeling musculoskeletal and prosthetic limbs and the task environments**

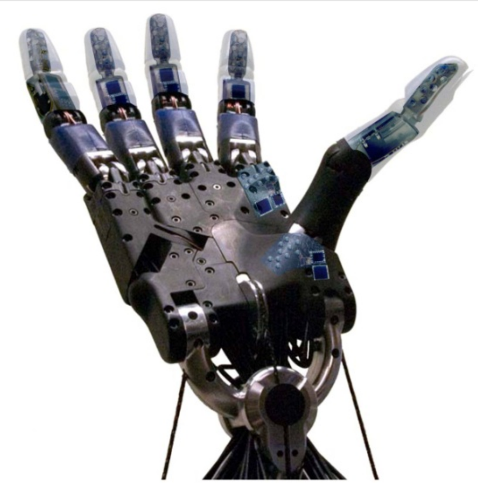
- **Simulates the models to predict limb's movement caused by neural controllers and external forces**

- **Simulates the models in real-time VR environments with the human or non-human primate subject in the loop**

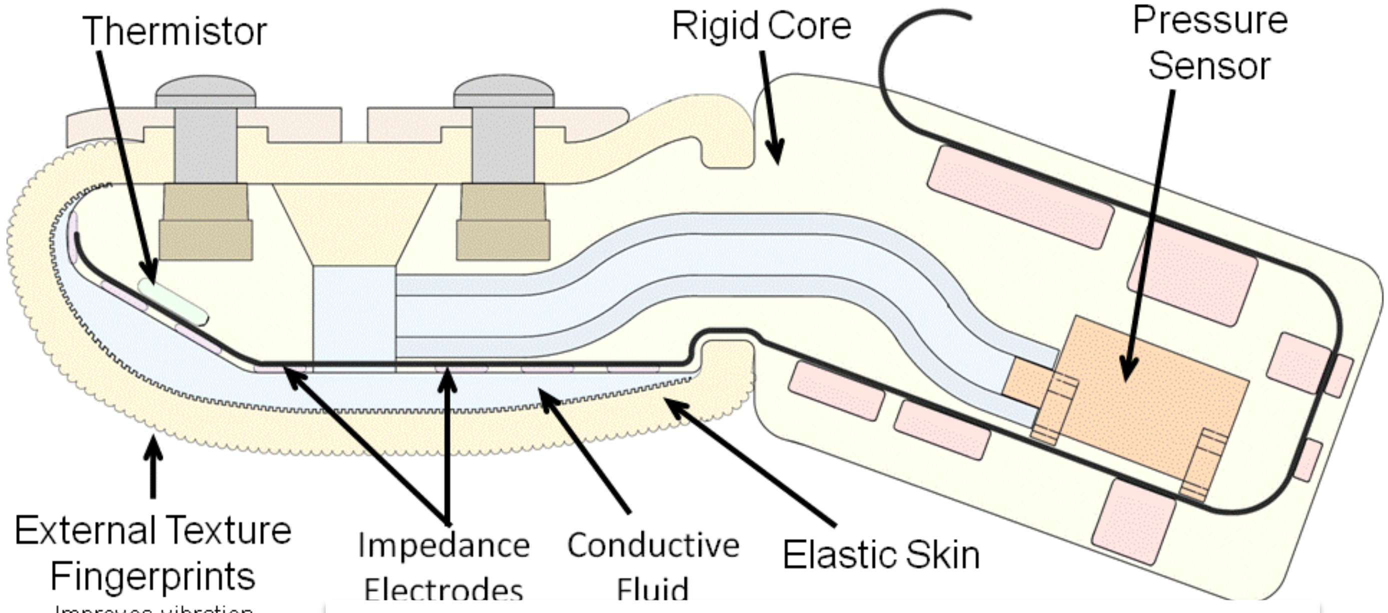
Development since 1999 led by Dr. Rahman Davoodi

Medical Device Development Facility, University of Southern California

Challenge: Can we endow mechatronic prosthetic & robotic hands with haptic abilities?



BioTAC®



Answer: Biomimetic tactile sensors

- Contact with object deforms skin and fluid, changing electrode impedances
- Heat flux into object identifies material properties
- Skin sliding over textures generates vibration spectra recorded by pressure sensor