

Modeling and simulation in the study of Neuromuscular control of movement

Dr. Giacomo Severini

Assistant Professor in Biomedical Engineering
School of Electrical and Electronic Engineering
University College Dublin

University College Dublin

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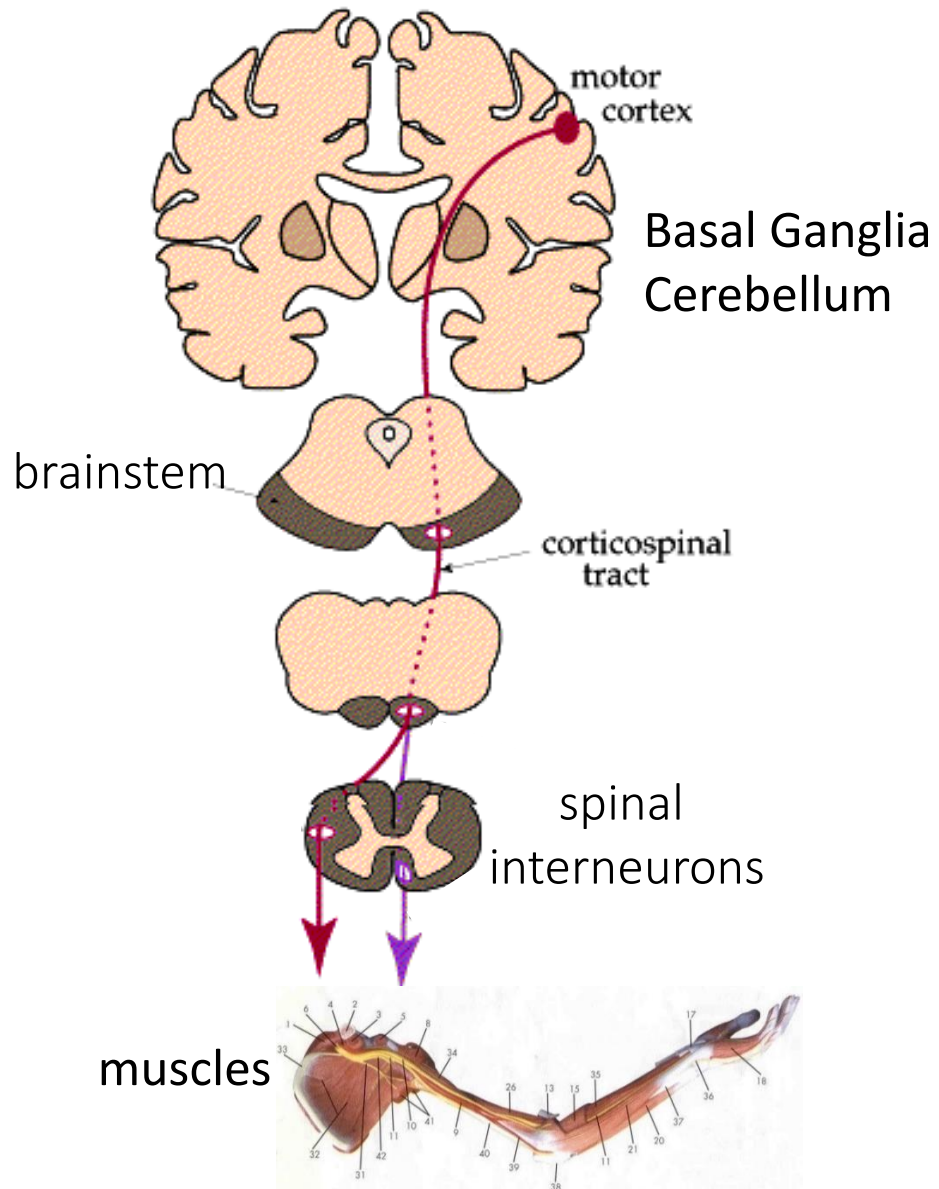
Outline

- Motor control and why modeling is needed
- Modelling and simulation in motor control, at different levels
 - Neurons
 - Muscles, kinematics and kinetics
 - Overall strategies of motor control

Neuromuscular control of movement

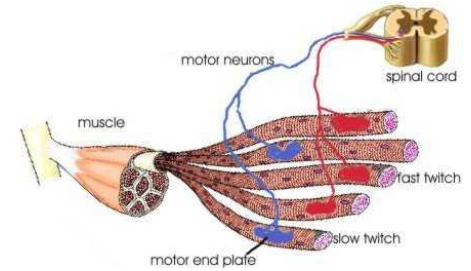
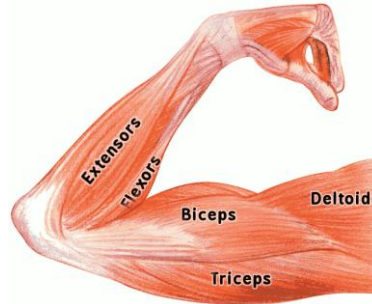
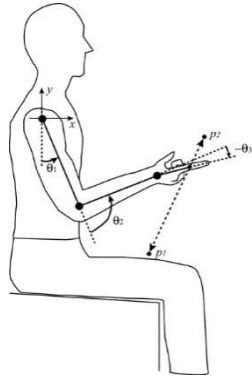
Motor control is achieved through the hierarchical interaction of several structures in the Central Nervous System

Neural mechanisms of motor execution are currently a central question in neuroscience.



A fairly complex system

The example of a Reaching Movement



7 DoFs for the arm

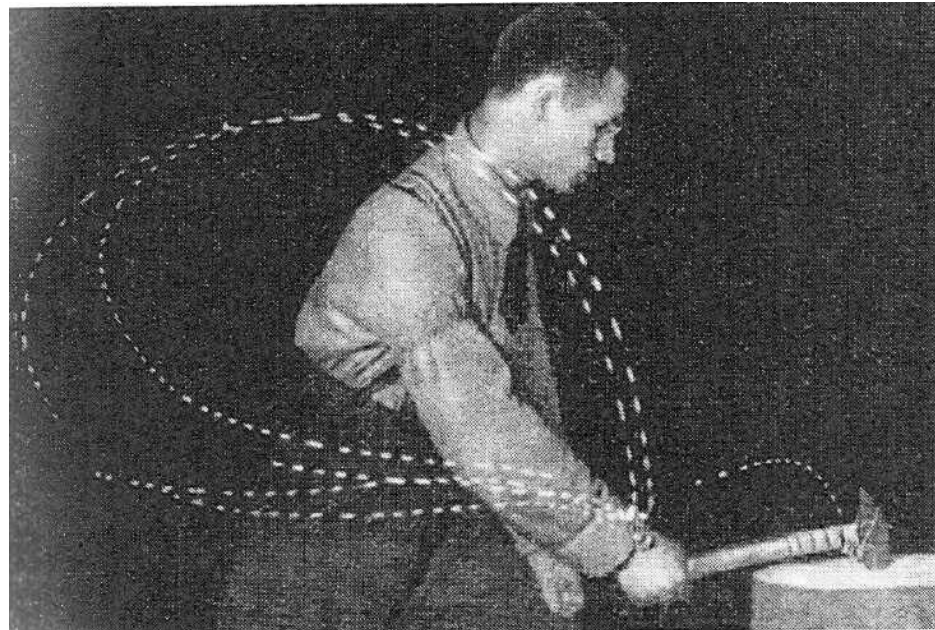
23 muscles

> 100 MUs per muscle

Billions of possible combinations of activation patterns

A system characterized by variants and invariants

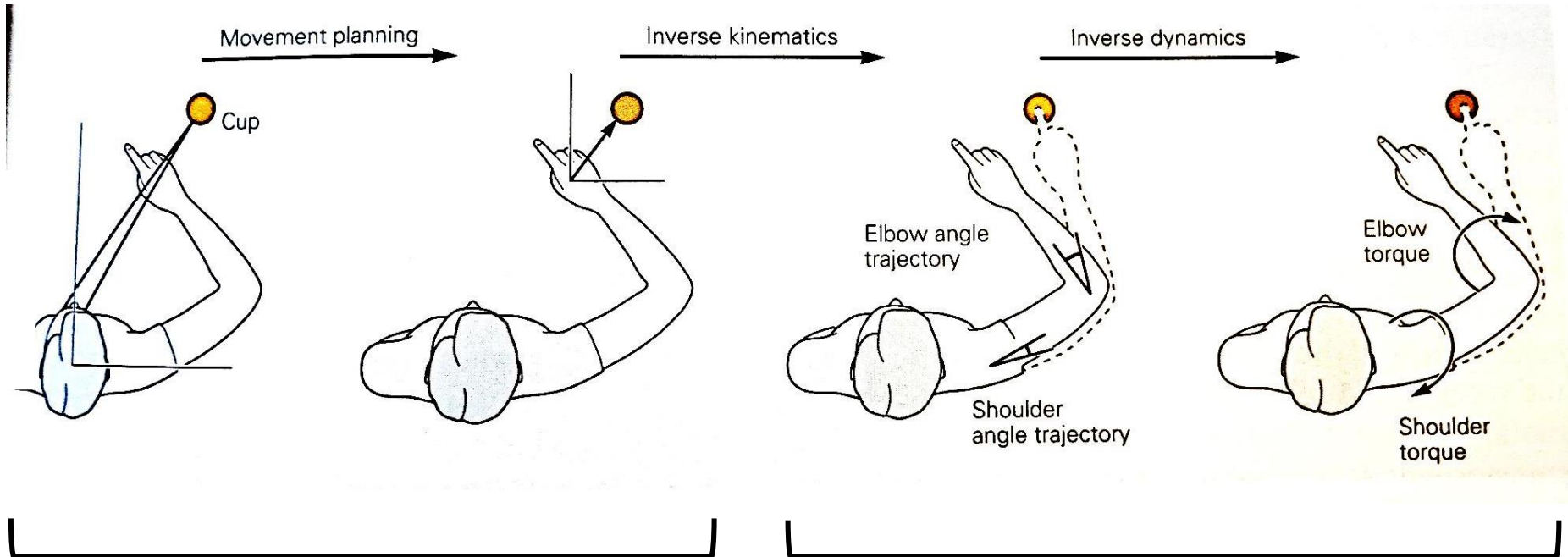
- Every movement is unique.
 - Strategies are consistent
 - Execution is somehow variable



Bernstein, 1957

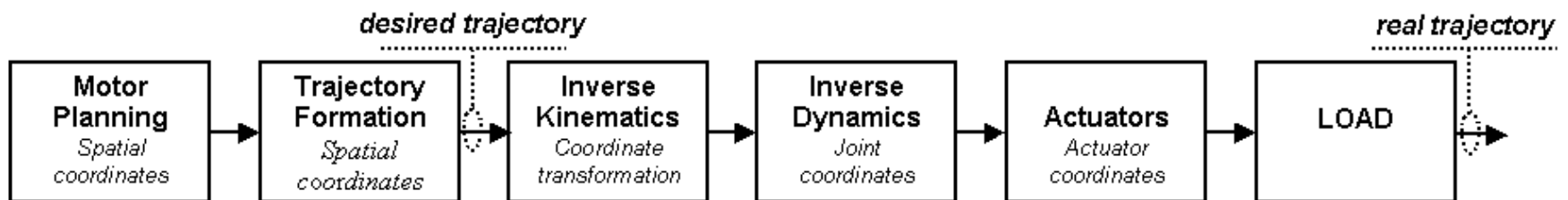
Motor planning and motor execution

Formulating task goal Planning hand trajectories Computing joint-angle pattern Computing joint torques and muscle activations



Motor planning

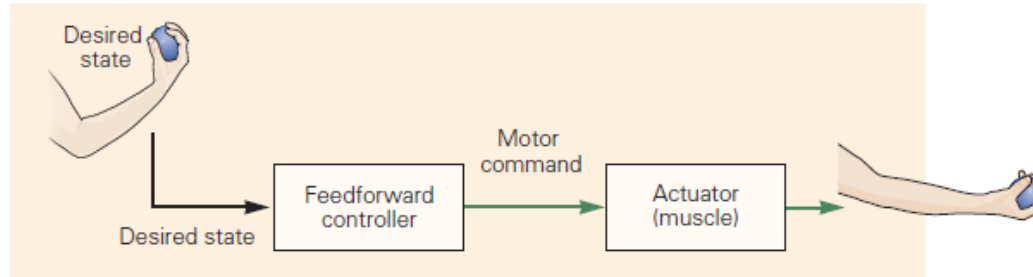
Motor execution



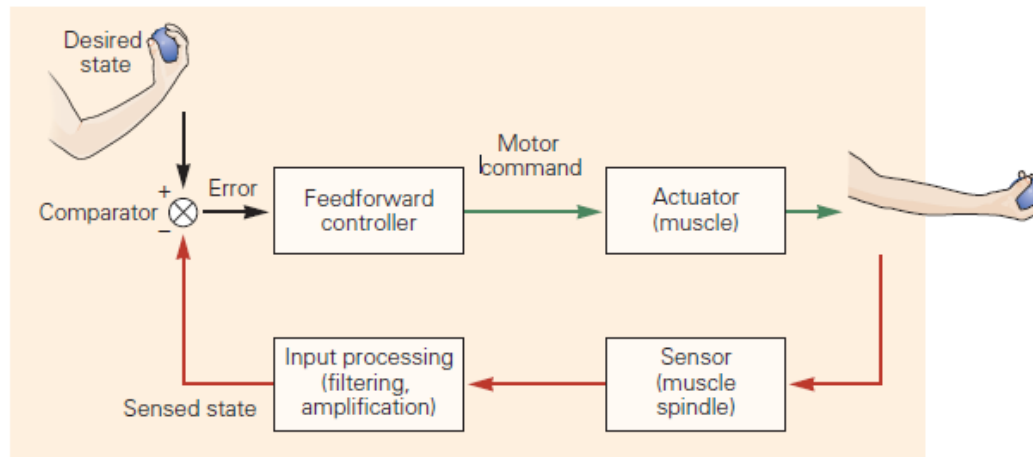
Two general strategies of motor execution

Feedforward and Feedback Motor Control

A Feedforward control

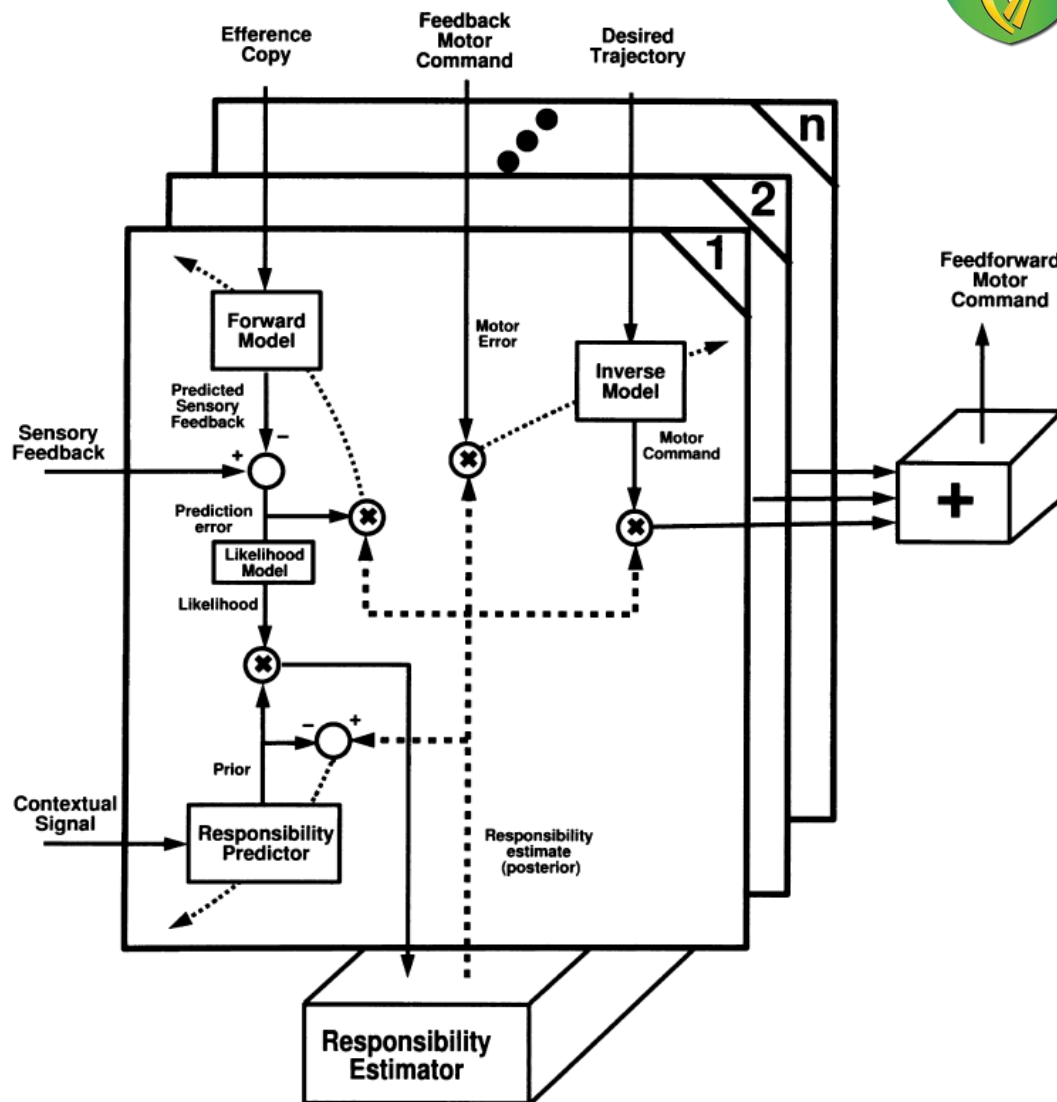


B Feedback control

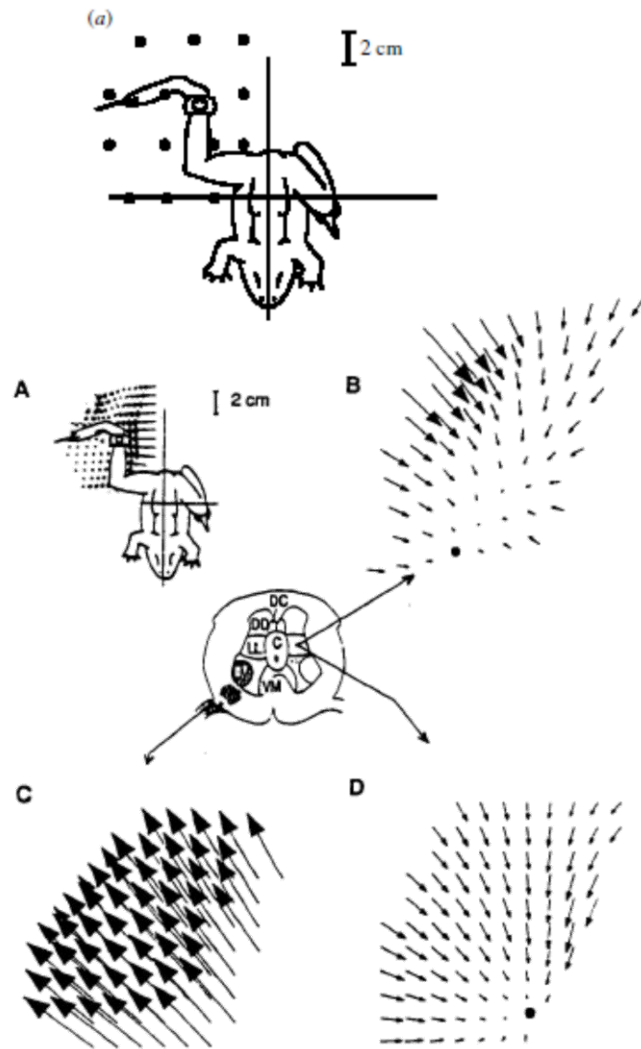


Evidence of Biological Models

- The brain employs implicit models, trained through experience, to both form feedforward commands and predict the necessity for feedback adjustment



Biological models as Hardwired circuits



Bizzi, E., Mussa-Ivaldi, F. & Giszter, S. 1991 Computations underlying the execution of movement: a biological perspective. *Science* **253**, 287^291.

The Necessity of using Modelling and Simulations in the Study of Motor Control

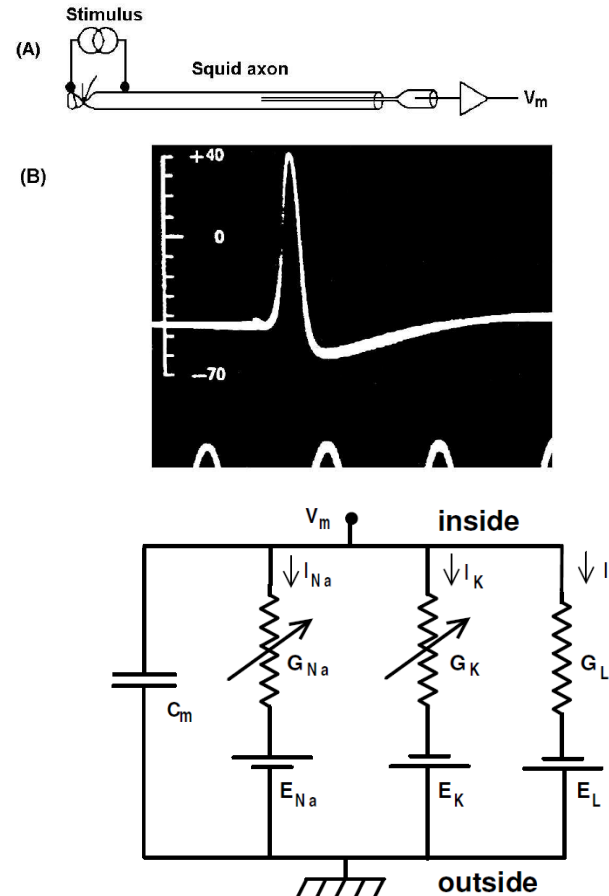
- It is actually what the brain does!
- Impossibility to measure *in-vivo* pretty much anything of what happens in the “deep” body during movement planning and execution
 - Estimate quantities (e.g. muscle forces, neuronal activity)
- Reconcile experimental data with compartmental hypotheses on specific aspects of movement execution
 - Predict behaviors

As a result, models in Neuroscience/Motor control are never fully validable

Functional vs. Biological models

Neuronal Models – from bio to circuits

- Hodgkin-Huxley neuronal model is the most common model used to represent neurons
- Derived from experiments on neurons of the Giant Squid
- The electrical behavior of the neuron is there described by a circuit (and 4 ODEs)



$$I = C_m \frac{dV_m}{dt} + \bar{g}_K n^4 (V_m - V_K) + \bar{g}_{Na} m^3 h (V_m - V_{Na}) + \bar{g}_l (V_m - V_l),$$

$$\frac{dn}{dt} = \alpha_n(V_m)(1 - n) - \beta_n(V_m)n$$

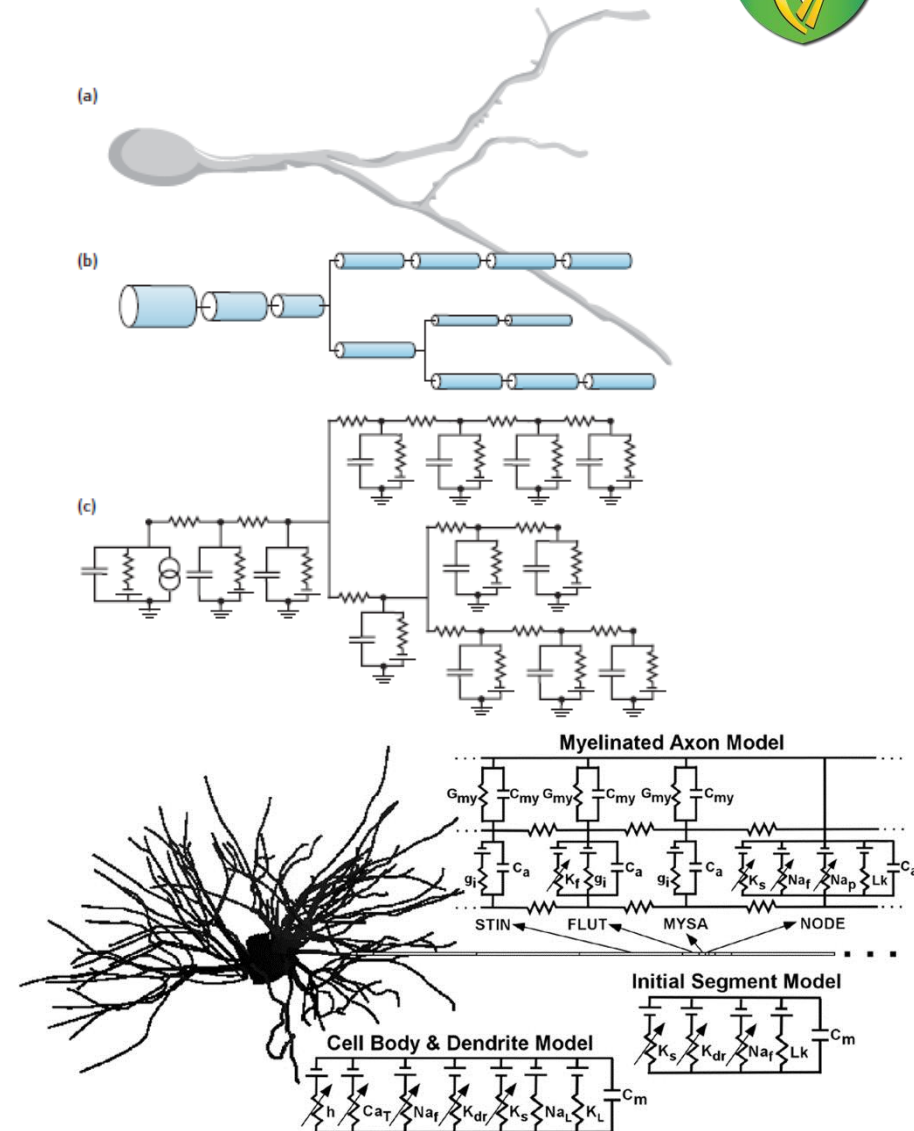
$$\frac{dm}{dt} = \alpha_m(V_m)(1 - m) - \beta_m(V_m)m$$

$$\frac{dh}{dt} = \alpha_h(V_m)(1 - h) - \beta_h(V_m)h$$

Neuronal Models are, of course, more complex

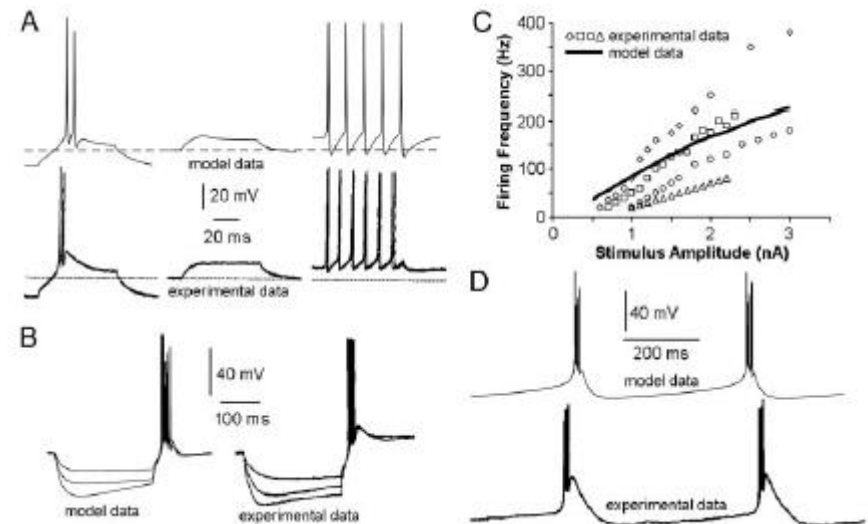
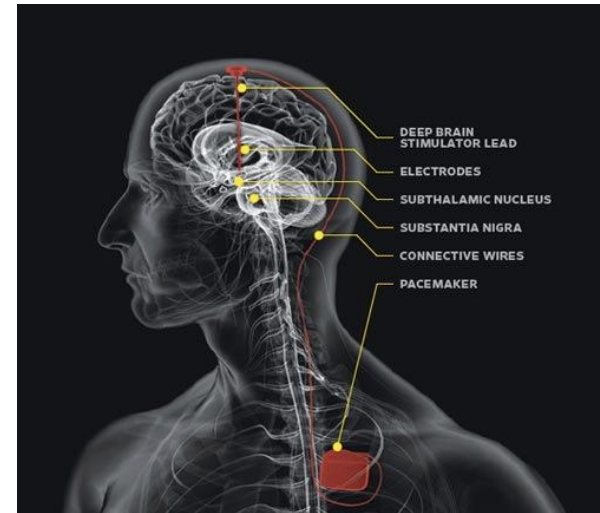


- Complex models can be derived from the knowledge (or estimation) of the physiology of each single neuron
- The accuracy of such models is critically dependent on the physiological information available to the researcher
- The simulation of small, complex networks, can have interesting applications in the field of motor control and neurorehabilitation
- Also in this case, validation is extremely “volatile”



One example – Deep Brain Stimulation

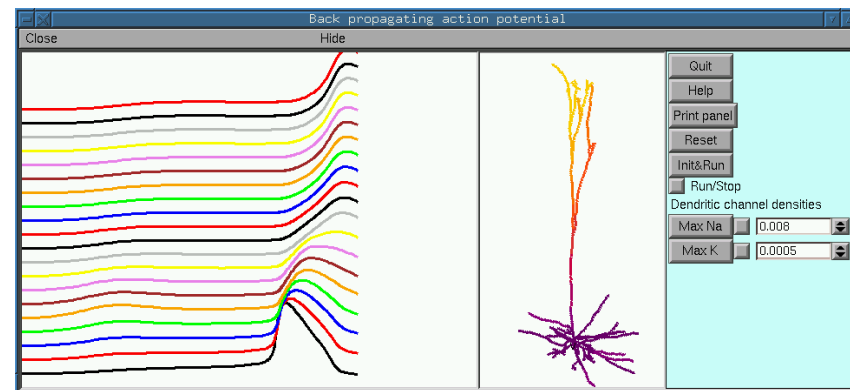
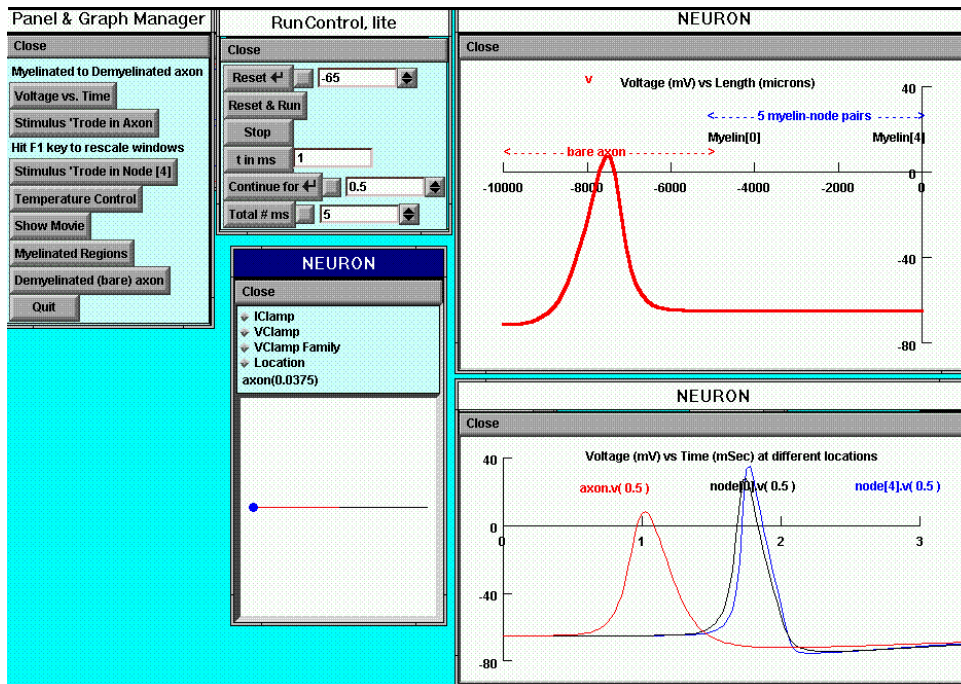
- A therapeutic approach used in the most complex cases of Parkinson's disease (but also in other applications)
- We know that applying currents to specific parts of the Thalamus attenuates the symptoms, but we don't have a clear understanding of why this happens
 - Current setting is mostly based on "Trial and Error"
- Modeling the effects of the stimulation currents on the Thalamus could then be extremely useful for maximizing the effect of the stimulation



Neuron – A Simulation tool

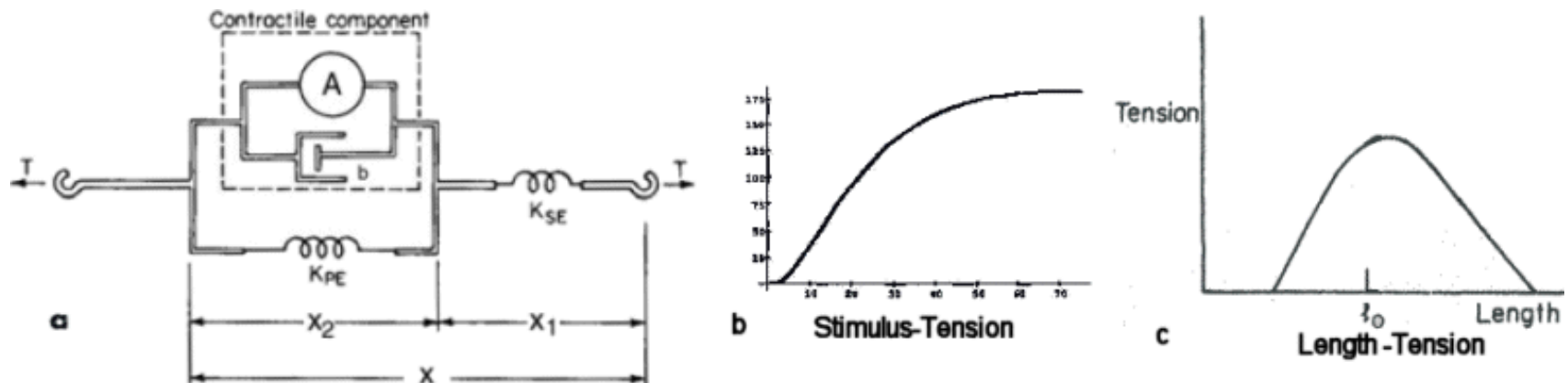


- Neuron is the most commonly used open-source simulation tool for the study of Neuronal Activity
- Different neuronal models, different complexities



Muscular Models

Hill's muscle model is the most common representation of muscle functioning



$$\dot{T} = \frac{K_{SE}}{b} \left(K_{PE} \Delta x + b \dot{x} - \left(1 + \frac{K_{PE}}{K_{SE}} \right) T + A \right)$$

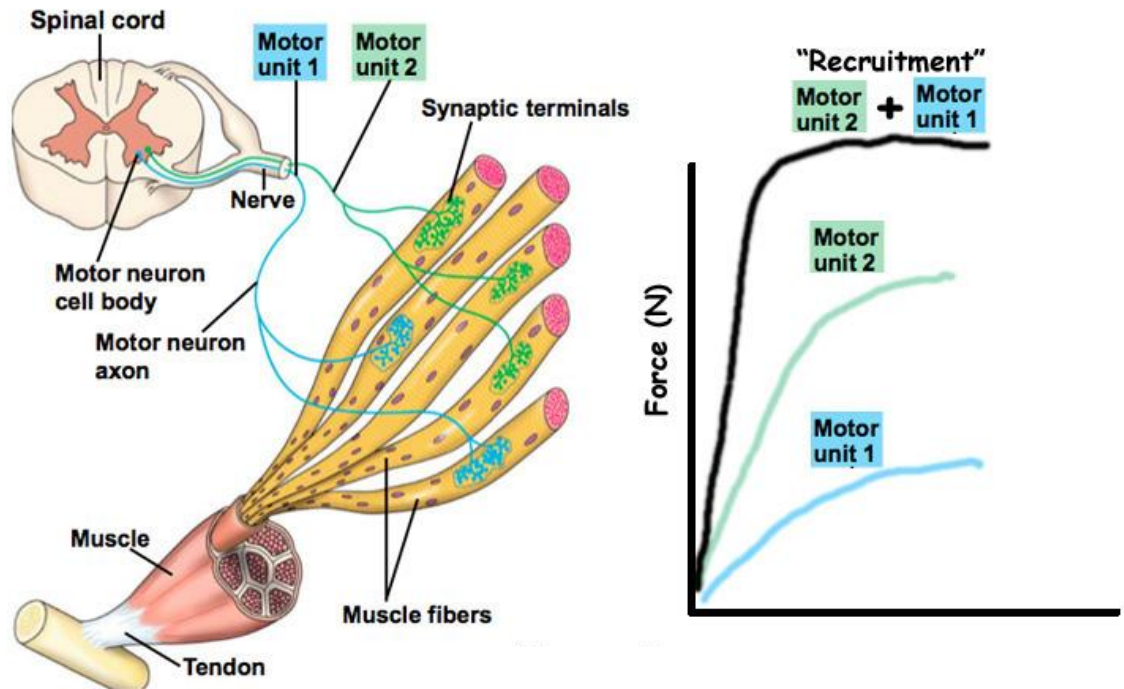
Muscle tension is a function of velocity, active force and muscular properties. The dampening parameter b is hyperbolic (force vs velocity), but is often approximated as linear (Linear Hill's model)

...but how does a muscle actually work?

Muscles are actually composed by hundreds of contractile elements all activated in a co-dependent way (Motor Units).

These units have different characteristics and are normally recruited incrementally depending on the force required from the task.

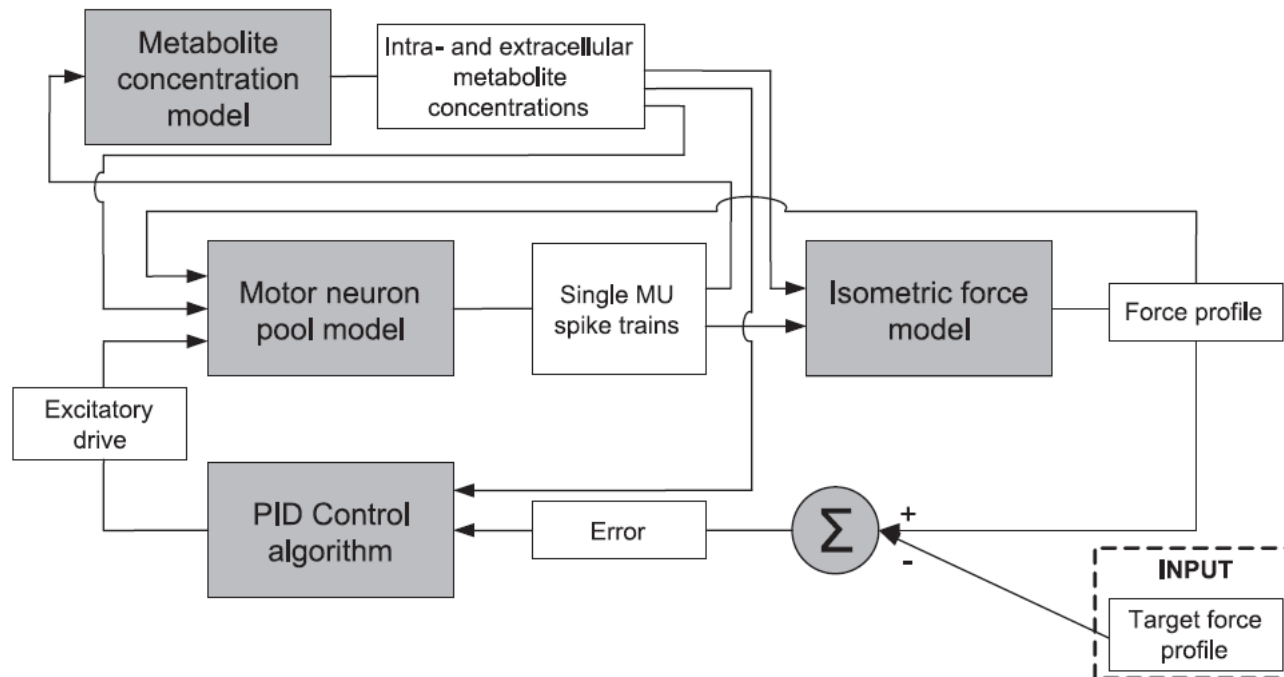
Complex models have been developed to estimate the amount of force produced by each single Motor Unit (*Fuglevand, 1993*)



A fairly more complex model

Such model include components of different nature such as:

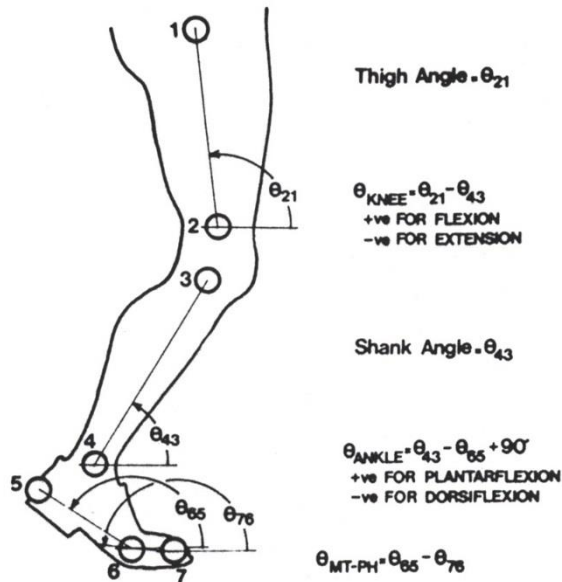
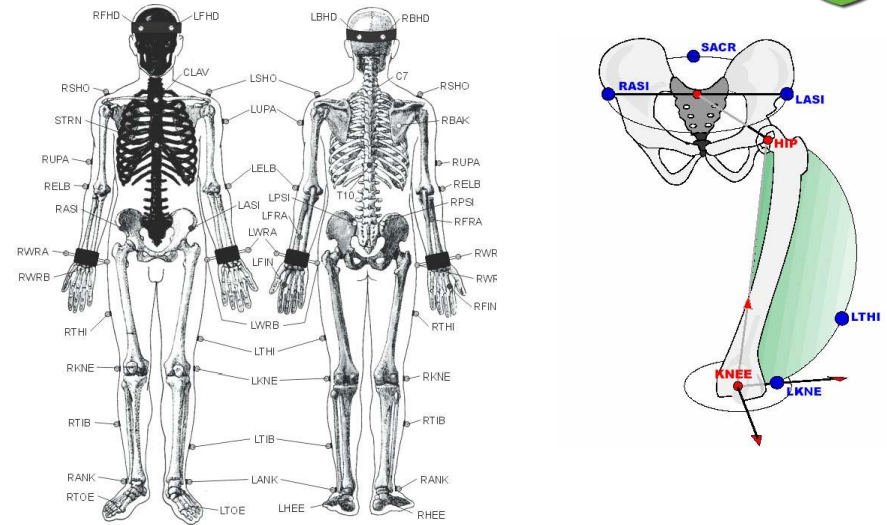
- Compartment models that describe the concentration of metabolites in the motor units
- Single motor neuron model that translate an electrical drive to a spiking behavior
- Force models that translate the spiking behavior to force



Kinematics and Kinetics Models

Empirical models that connect physical measurement (e.g. Motion Capture System) with the movement of anatomical landmarks

Not 100% precise, but good enough

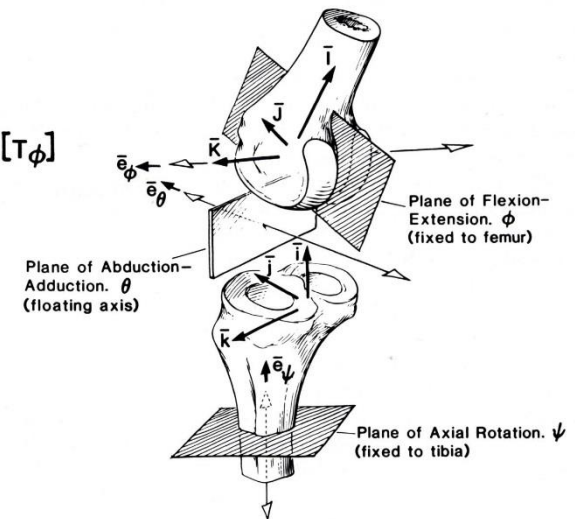


Kinematics

$$\bar{r}_1 = [T] \bar{\rho} + \bar{r}_0$$

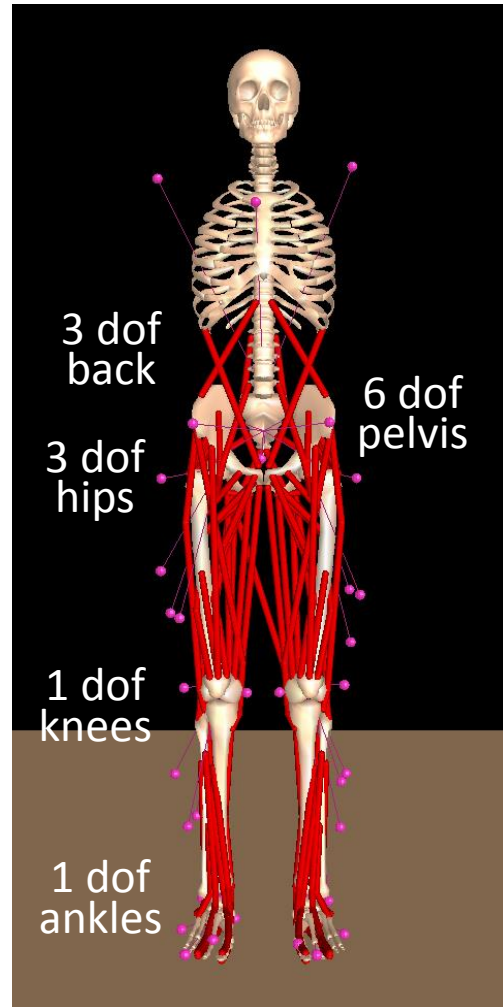
where

$$[T] = [T_\psi] [T_\theta] [T_\phi]$$



Kinetics

Simulation tools in the study of motor control – OpenSim



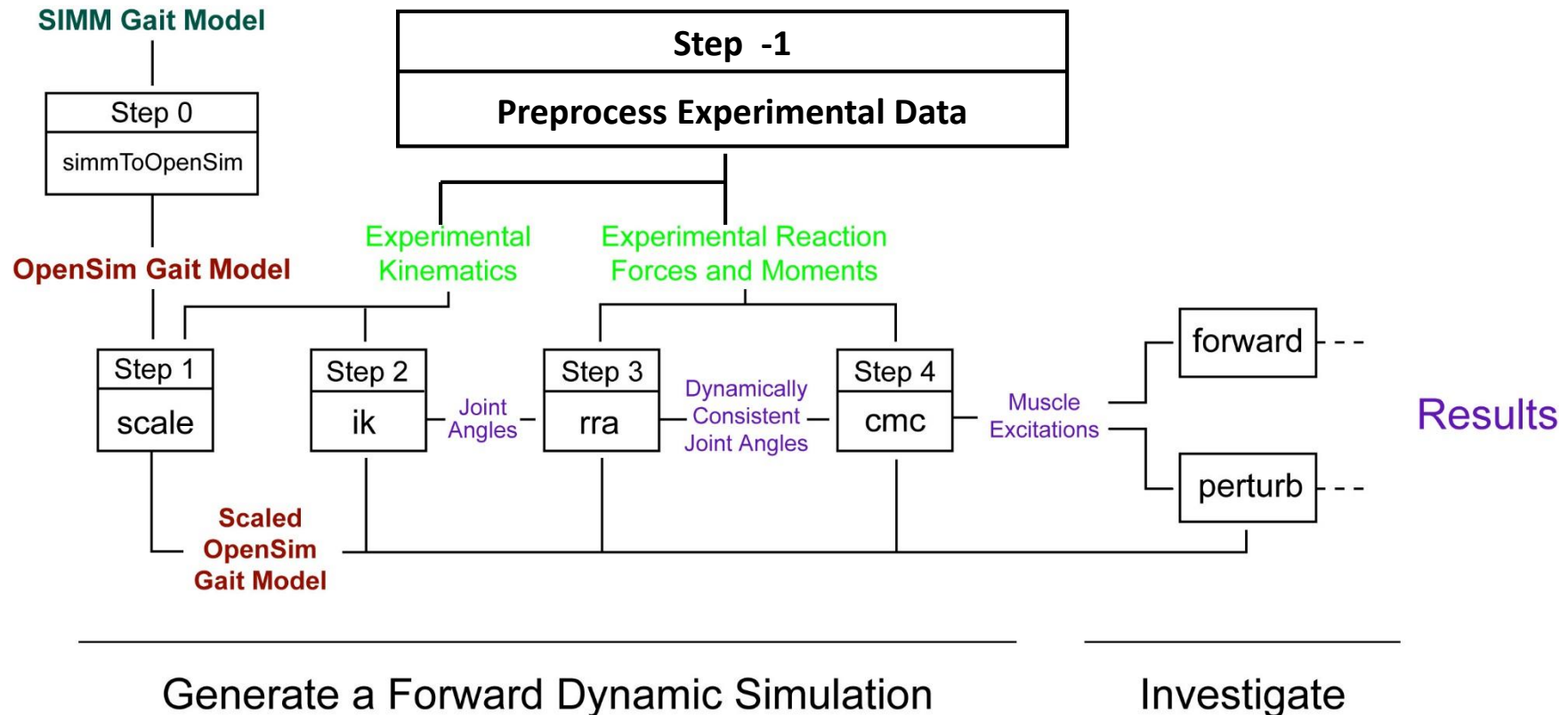
78 kg, 1.78 m

19 DOF, 92 Muscles (Delp, 1990)



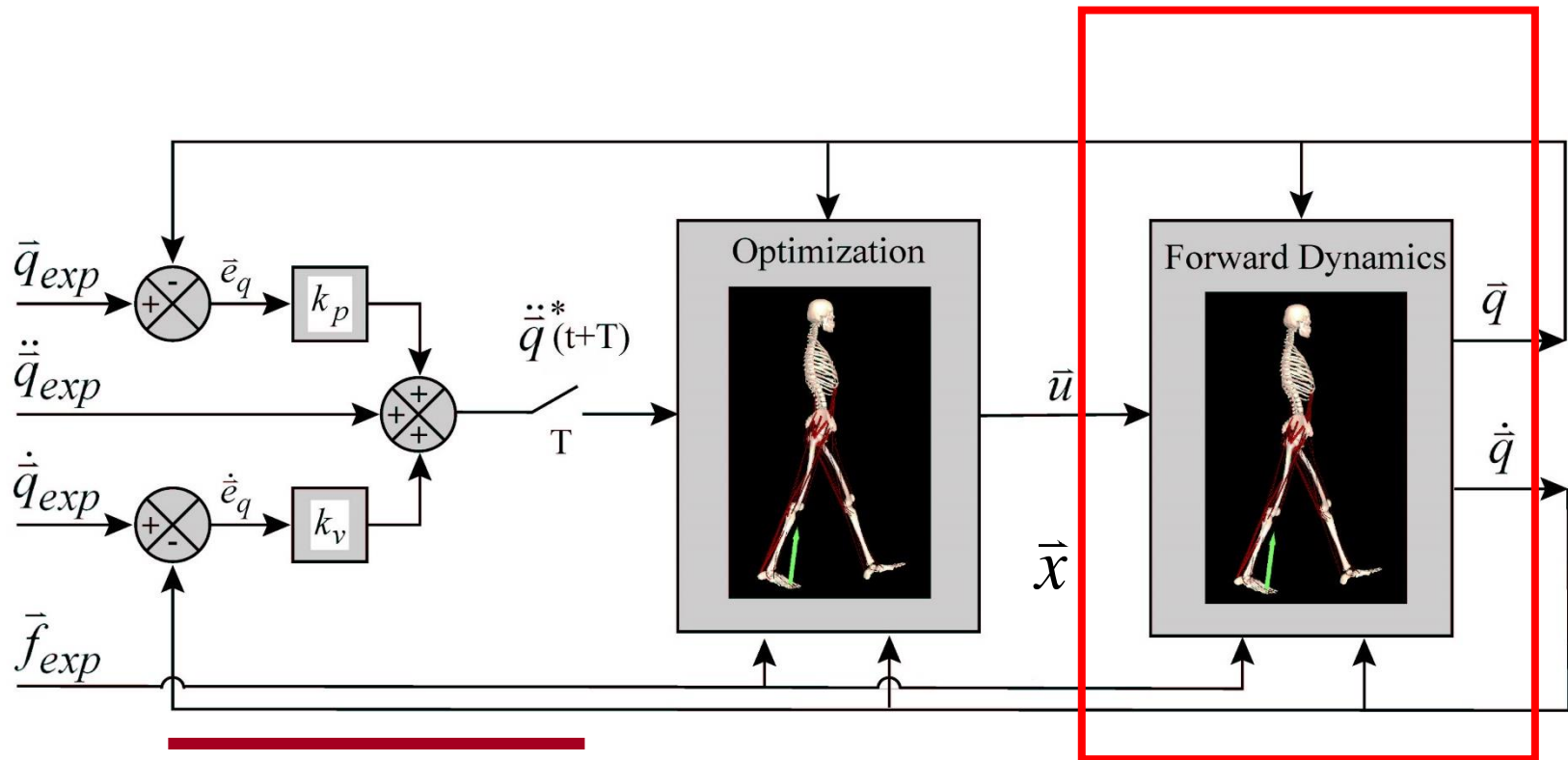
Adapted from OpenSim website

OpenSim workflow



Adapted from OpenSim website

OpenSim workflow



Step 1: Compute Desired Accelerations (PD Control)

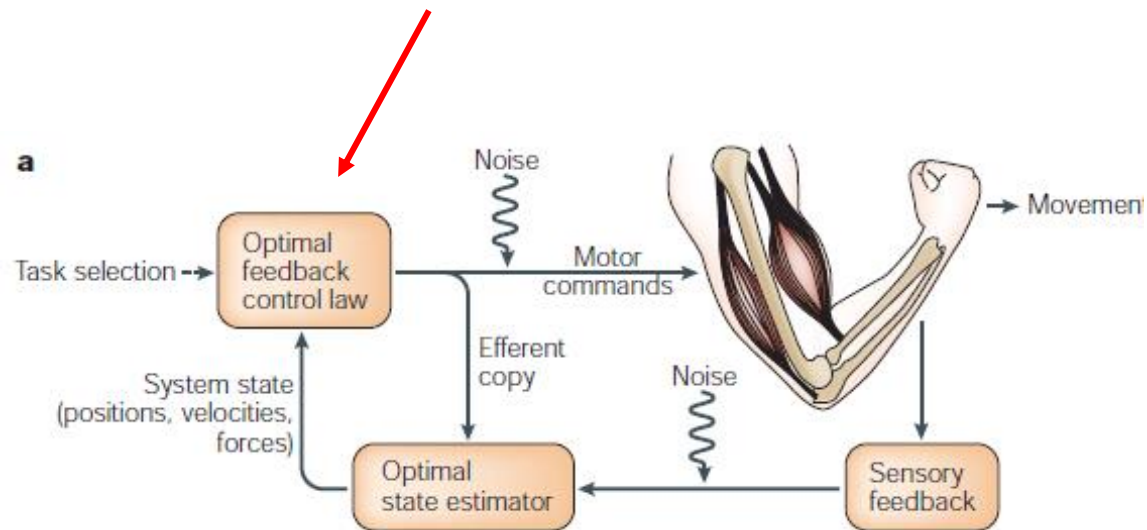
Step 2: Solve for Muscle Excitations (static optimization)

Step 3: Integrate from t to $t+T$

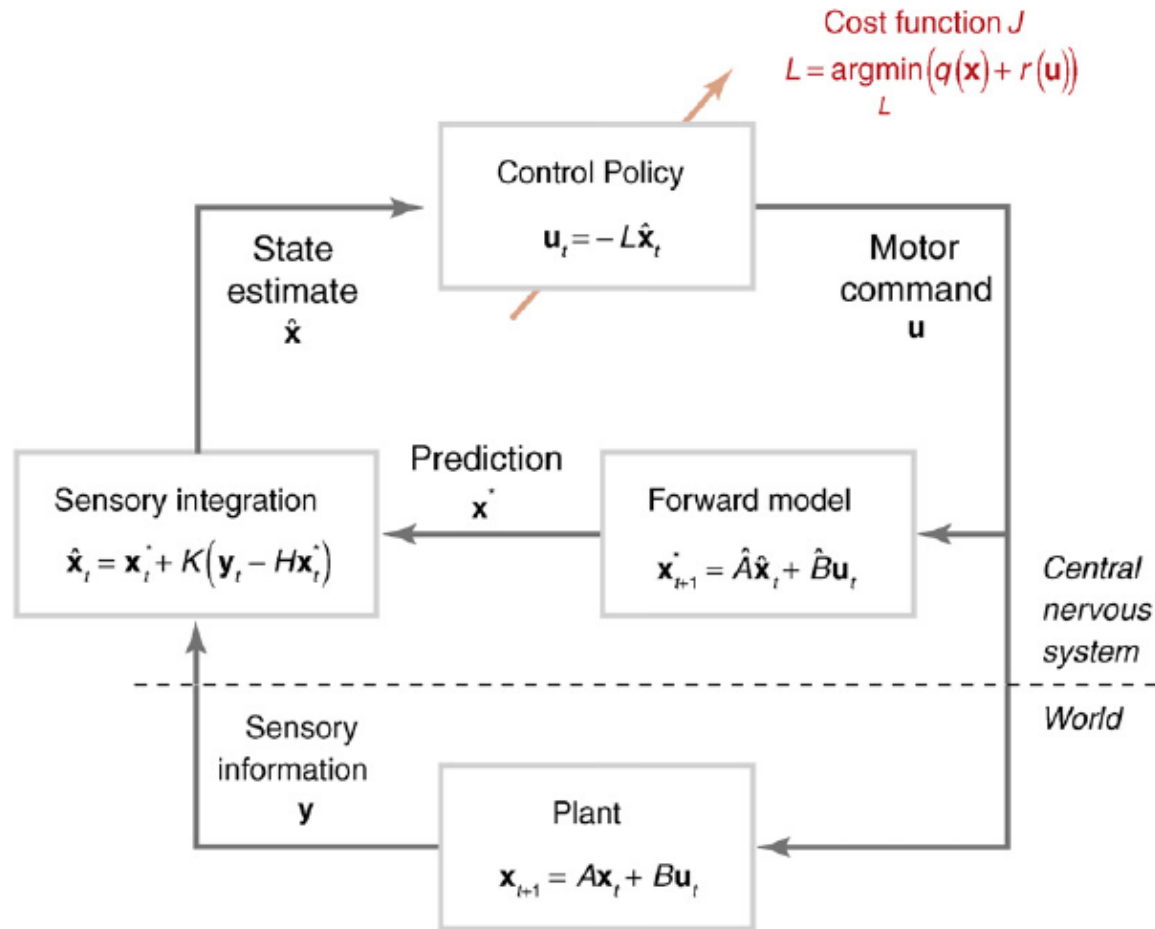
Modelling and Simulation for the development of Theoretical Behavioural Models

Control is achieved as the minimization of a cost function (e.g. precision, energy efficiency), through the estimation of an optimal state and the adjustment of feedback gains using a “minimum intervention principle”

This is the key problem!



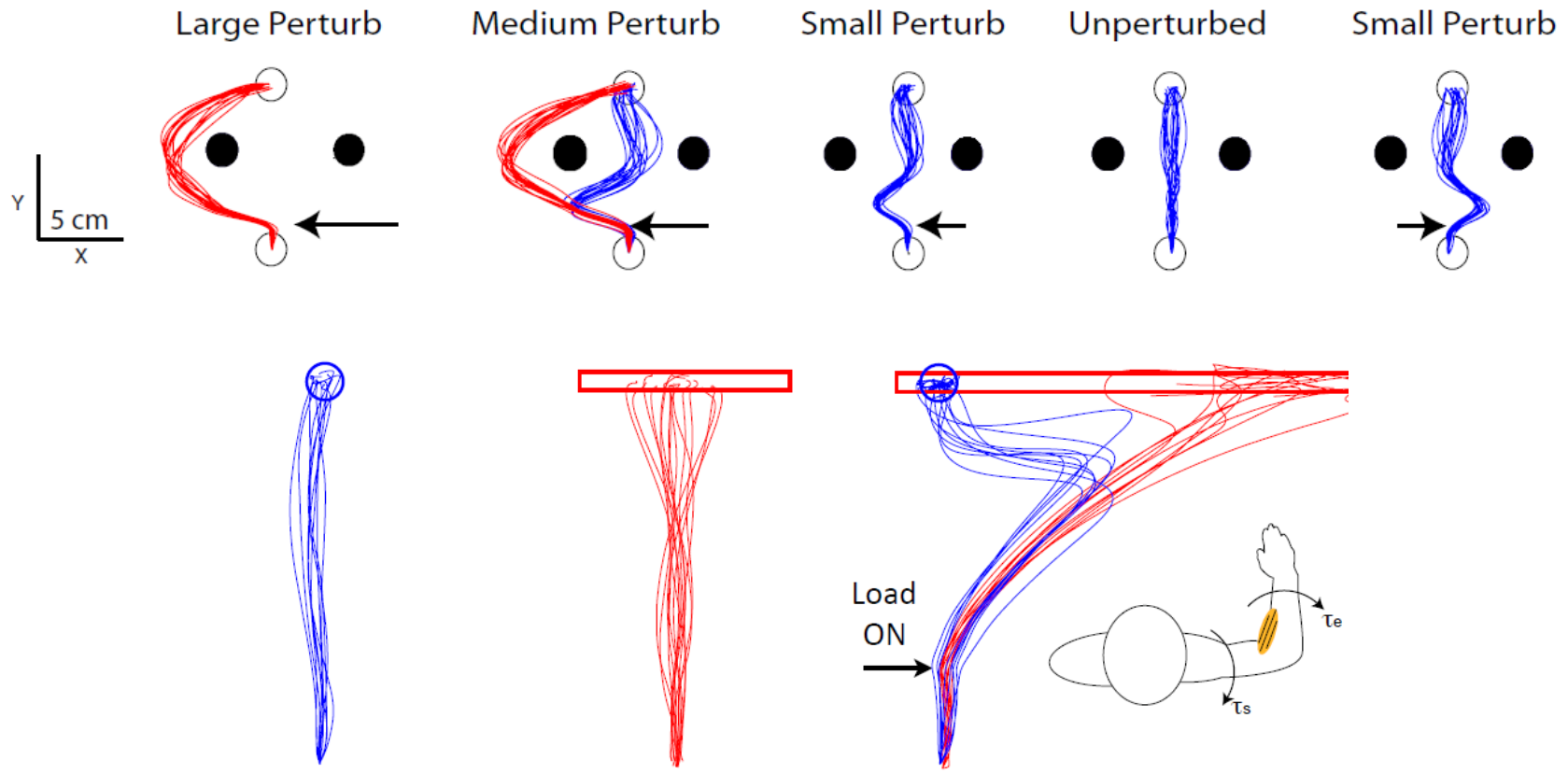
Optimal Feedback Control



Optimal Feedback Control – evidences

Correction depend on task dependent cost functions and on the cost-to-go

Optimal Feedback Control Model



Optimal Feedback Control – an example



A practical example -> Bidimensional perturbed reaching (Todorov et al. 2007)

$$d\mathbf{p}(t) = \mathbf{v}(t)dt$$

$$md\mathbf{v}(t) = (\mathbf{a}(t) - b\mathbf{v}(t))dt$$

$$\tau d\mathbf{a}(t) = (\mathbf{u}(t) - \mathbf{a}(t))dt + M(\mathbf{u}(t))d\mathbf{w}(t).$$

$$\mathbf{x}(t) = [\mathbf{p}(t); \mathbf{v}(t); \mathbf{a}(t); \mathbf{p}^*(t)],$$

$$d\mathbf{x}(t) = (A\mathbf{x}(t) + B\mathbf{u}(t))dt + C(\mathbf{u}(t))d\mathbf{w}(t),$$

Cost function: encourages endpoint accuracy, stopping at the target and energy consumption

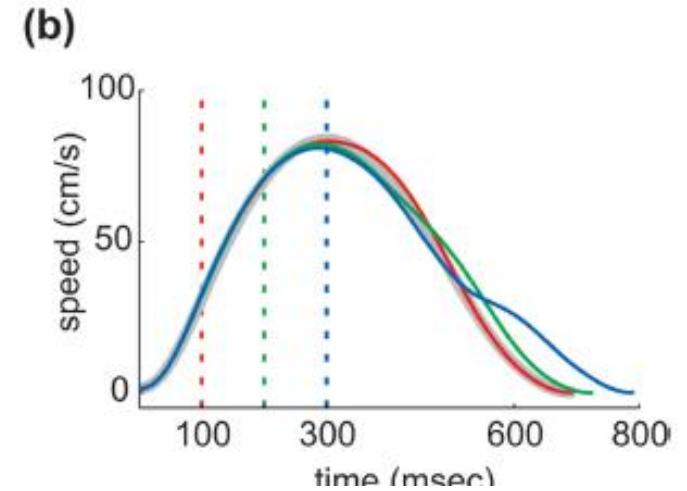
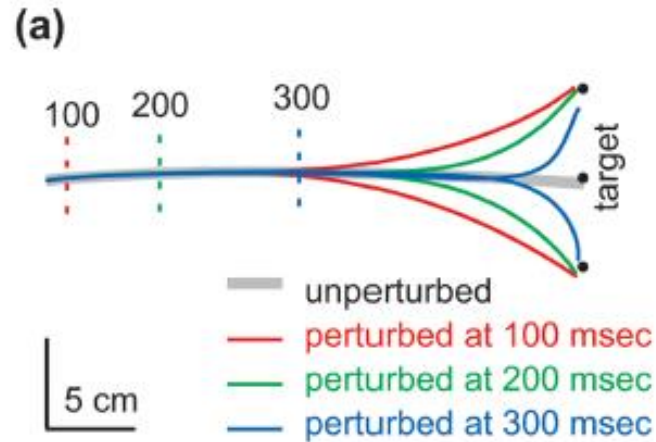
$$\|\mathbf{p}^*(t_f) - \mathbf{p}(t_f)\|^2 + w_{\text{stop}}(\|\mathbf{v}(t_f)\|^2 + \|s_a\mathbf{a}(t_f)\|^2) + w_{\text{energy}} \int_0^{t_f} \|\mathbf{u}(t)\|^2 dt.$$

Control law, with time variant gains and estimates of velocity and actuation (from noisy sensory feedback and efferent copy) can be reduced to

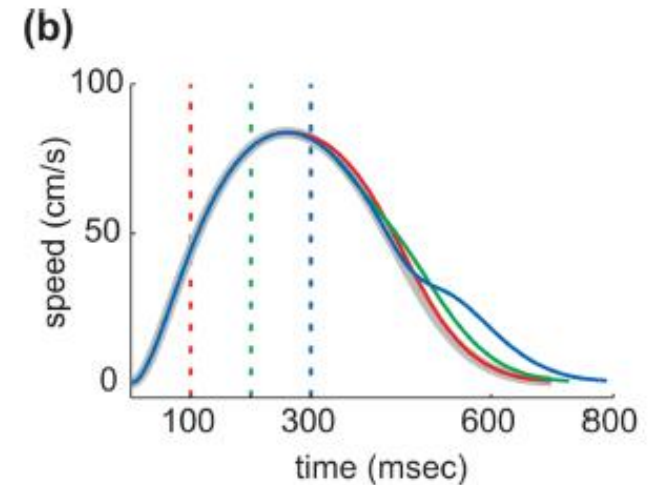
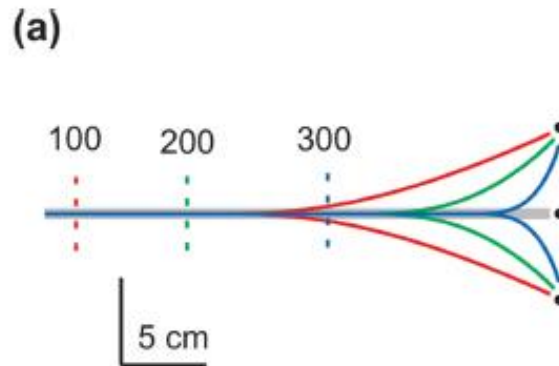
$$\mathbf{u}(t) = k_p(t)(\mathbf{p}^*(t) - \hat{\mathbf{p}}(t)) - k_v(t)\hat{\mathbf{v}}(t) - k_a(t)\hat{\mathbf{a}}(t),$$

Optimal Feedback Control – results

Empirical
results



Results from
simulation



Optimal Feedback Control – taking things further – MuJoCo, a simulation tool



Contact-Invariant optimization:
adding the cost of point of contact
in the mix, given a pre-defined
physical plant

Simulation environment MuJoCo
developed at WSU



Discovery of complex behaviors through Contact-Invariant Optimization

Igor Mordatch, Emo Todorov and Zoran Popovic

Movement Control Laboratory and GRAIL
University of Washington

SIGGRAPH 2012

Emo Todorov's lab, University of Washington

Take home messages

- Modeling and simulation are paramount in the study of motor control and are applicable at different (in every sense) levels.
 - We cannot cut people and measure!
- Our model are never fully exact neither fully validable, but, in the better cases, allow for reliable estimation of neuronal/muscular/behavioral dynamics
- Open software is becoming now the trend, and several new software have been developed in the past years.



Thank You for Your Attention!