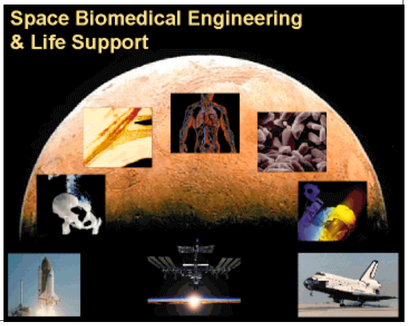
Space Biomedical Engineering
& Life Support

Motor Control

Prof. Dava Newman
March, 2006



Outline

- Higher Level Control
- Motor Control System
- A little more on Reflex Stiffness
- Optimization Principles in Motor Control
  - –Understanding the fundamental question in biomechanics
  - –Are all motor behavior optimal in some sense?
  - –Kinematic versus dynamic objective functions
- Examples

Reflexes and motor control (from TA McMahon, Muscles, Reflexes, and Locomotion, Princeton University Press, 1984)

Houk, J. C. (1989). Cooperative Control of Limb Movements by the Motor Cortex, Brainstem and Cerebellum. In Cotterill (Eds.), Modles of Brain Function Cambridge: Cambridge University Press.

Control over Movement

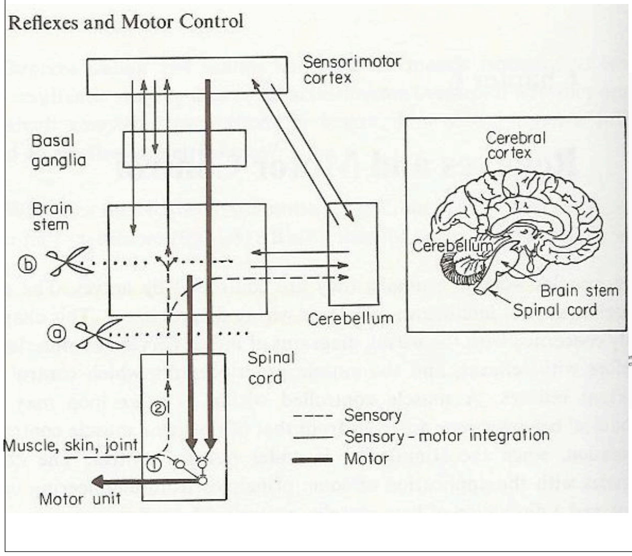
- alpha-motoneurons in motor control; without them there can be no movement! primary afferent neurons, certain interneurons, and the gamma-motoneurons
- Most of the nerve fibers that innervate a muscle are there to **sense and control** the **length** and **tension** of the muscle, not to make it contract.

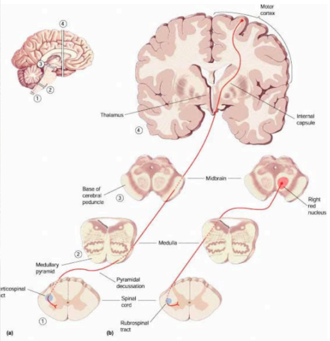
Afferent fibers	50 group Ia fibers - 50 muscle spindle primary endings 50 group II fibers - 50 muscle spindle secondary endings 40 group Ib fibers - 45 Golgi tendon organs
Efferent fibers	100 gamma-mn - 300 intrafusal muscle fibers in 50 muscle spindles 150 alpha-mn - 25,000 extrafusal muscle fibers

Higher Level Control

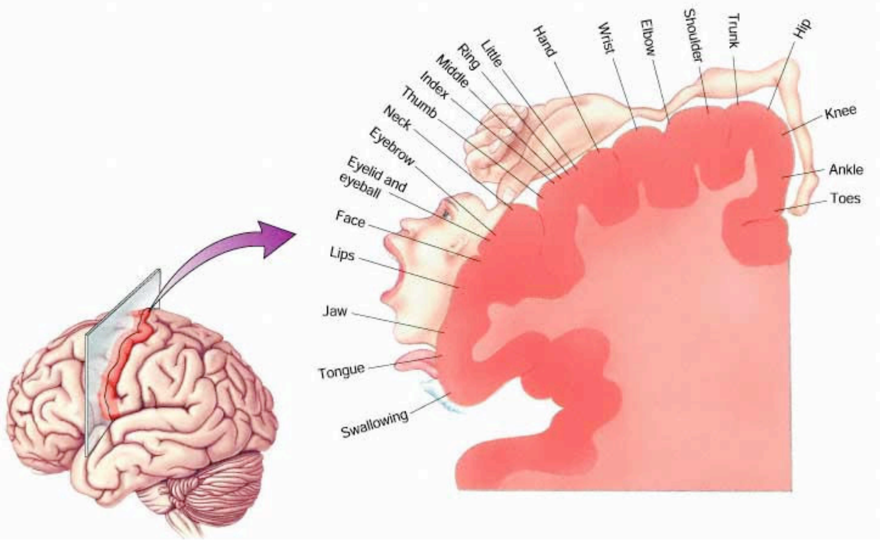
- **Spinal Cord** (transection just below brain stem)
  - Maintain **stretch** reflex, reflex **withdrawal** (pain), **scratch** reflex (tickling), extensors contract for standing posture (i.e., "chicken with their heads cut off")
  - Great deal about locomotion that is automatic & preprgrammed into spinal cord.
- **Brain Stem**
  - Decerabrate (midbrain). Preserve reflexes, and righting reflex (back or side), intact neurovestibular.
- **Sensorimotor Cortex** (and basal ganglia) top of the chain of command in the sensorimotor area of the cerebral cortex. There is a specialized area in devoted to movement of the limbs (1691, the case of a knight with a fractured skull and paralysis of the left side of the body)
  - **Basal ganglia** are a set of specialized nerve cells.
  - The fraction of the cerebral cortex controlling each part of the body is by no means proportional to the size of that part (Great graphic)
  - If the cerebral cortex is removed, the animal continues to display all the locomotion reflexes, climb, display anger, reject bad food, but cannot learn new skills
- **Cerebellum** is a major focus of incoming sensory information (muscle, skin and joint receptors).
  - The information has to do with length, force, velocity of muscles and position of joints.
  - Removed: awkward/clumsy movement, generalized integration and smoothing

Motor Control in the CNS





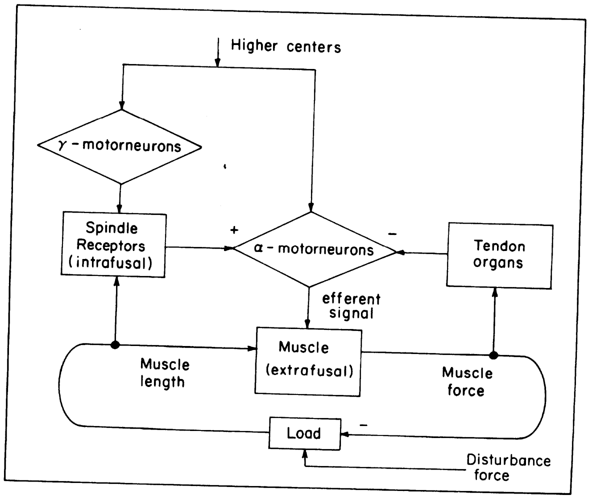
Motor Areas of the Sensorimotor Cortex



A little more on Reflex Stiffness

- Usually just talk about the monosynaptic reflex arc containing the spindle organ, but it now looks like the Golgi tendon organs also play a role in the control of muscle reflex stiffness.
- Tendon organs assumed to be the sensor in a reflex which turned off muscle activity when force rose too high (i.e., clasp-knife reflex). *decerebrate rigidity*, after a certain force level, see collapse of the limb (looks something like a clasp-knife returning into its sheath, apparently triggered by the onset of Ib afferent discharges from tendon organs.
- Tendon organs don't only respond to large forces, they are seen respond to < 0.1 g force applied directly to the base of the capsule.

Reflex Stiffness (cont.)



Stiffness regulation in the stretch reflex. Movement: alpha and gamma mn increase firing simultaneously, keeping extrafusal and intrafusal muscle fibers about the same length. If a disturbance force occurs, the change in efferent signal to the muscle is affected by afferent input from both spindle receptors and tendon organs. The spindles cause an increase in alpha activity upon muscle stretch, but the tendon organs cause a decrease in alpha activity when muscle force rises. The balance between the two provides a regulations of the reflex stiffness.

Optimization Principles:
On Models and Other Demons

What do you think of the following quotes?

- “If a kinematic objective function can be found that leads to optimal trajectories that accurately reproduce the patterns of observed behavior, it implies that the brain ignores non-kinematic factors in selecting and reproducing that behavior”
- “If a dynamic objective function can be found that leads to optimal trajectories that accurately reproduce the patterns of observed behavior, it implies that the brain considers dynamic factors in selecting and reproducing that behavior”

Optimization Principles in Motor Control

Fundamental question in biomechanics

- The human limbs are involved in a prodigious variety of tasks. Movements tend to be graceful and usually involve many limb segments
- Different tasks typically require
  - different sequencing of muscle activation and limb motion
  - different information from sensors

- How are these movements organized? Fundamental question in biomechanics: Which muscles are used and in what pattern?

[Bernstein, *The Co-Ordination and Regulation of Movement*. Pergamon Press, 1967]

Optimization Principles in Motor Control

- One widely used mathematical tool is optimization theory

  Objective: to discover principles that guide goal-directed motor behavior
- Four components to an optimization problem:
  1. An objective function that quantifies what is to be regarded as optimum (also called performance function or cost function)
  2. A dynamic system that is to be controlled
  3. A set of controls that are available for modulation
  4. An algorithm capable of finding an analytical or numerical solution (tools of variational calculus)
- Given a model of musculo-skeletal dynamics, optimization theory re-maps Bernstein's problem of choosing among an infinity of possible patterns of muscle activation into an equivalent problem of choosing among an infinity of performance criteria

Optimization Principles in Motor Control

- Optimization-based models have been developed to address the “excess degrees of freedom” problem
- Recall Bernstein question: How does the motor system select the behavior it uses from the infinite number of possibilities open to it?
  - In mathematical parlance, this is an ill-posed problem in the sense that many solutions are possible
  - For example, most limb segments are moved by a larger number of muscles than appear to be necessary
  - To reach a cup of coffee, the hand may move along an infinity of paths
- Rephrasing the central question: How does the motor system chooses values for the large number of parameters that can be controlled in order to perform a goal-oriented movement?

Optimization Principles in Motor Control

- Need to make explicit and quantitative hypotheses about the goal of motor actions
- Are all motor behavior necessarily optimal in some sense? Maybe!
- One appealing possibility is that the nervous system has evolved to select “solutions” that are indeed “optimal”: the hypotheses is that in performing a motor task, the CNS produces coordinated actions that minimize some measure of performance (effort, smoothness, etc.)

Optimization Principles in Motor Control

- Kinematics versus dynamics objective functions?
  - Kinematics refers to the time course of an object (position, velocity, acceleration, etc.)
  - Dynamics refers to variables such as forces and torques
- Even single degree of freedom can be performed in a variety of ways:
  - Path is constraint
  - Speed along the path can vary (trajectory)
- Two different types of objective functions have been proposed, they reflect the two major competing theories of motor control:

Kinematic objective function Dynamic objective function

Kinematic objective function, single-joint movements

- They are characterized by single-peaked, bell-shaped speed profiles. It was postulated (Hogan, 1984) that voluntary movements are made to be as smooth as possible
- A quantitative measure of smoothness is needed, one such measure is the squared magnitude of the jerk (rate of change of acceleration or third time derivative of position)

Kinematic objective function, single-joint movements (cont.)

$$J = \int_{t_0}^{t_1} \left(\frac{d^3\theta}{dt^3} \right)^2 dt$$

$\theta(t)$ is the joint angle. Using variational calculus, the unique time history of joint positions that minimizes this performance measure may be derived analytically

$$\theta(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 + c_4 t^4 + c_5 t^5$$

c_i are unspecified coefficients whose values are determined by the conditions at the beginning and end of movements (boundary conditions)

- When the movement is assumed to begin at rest in one position and end at rest in another, the “minimum jerk” or “maximum smoothness” movement turns out to have the smooth, uni-modal, bell-shaped velocity profile typical most experimental observations
- The maximum smoothness hypothesis is readily generalized to multi-joint motions.

Kinematic objective function, multi-joint movements

- The objective function can be written as follows in the Cartesian coordinate frame of the hand:

$$J = \int_{t_0}^{t_1} \left[\left(\frac{d^3x}{dt^3} \right)^2 + \left(\frac{d^3y}{dt^3} \right)^2 \right] \times dt$$

- Assuming the movement start and end at zero velocity from (x_0, y_0) to (x_f, y_f) at time t_f ($\tau = t/t_f$)

$$x(\tau) = x_0 + (x_0 - x_f)(15\tau^4 - 6\tau^5 - 10\tau^3)$$
$$y(\tau) = y_0 + (y_0 - y_f)(15\tau^4 - 6\tau^5 - 10\tau^3)$$

Maximum Smoothness?

- The maximum smoothness theory yields in the multi-joint movement several explicit predictions:

  1. Trajectories of the limbs are straight line paths
  2. The tangential velocity along that path is smooth and uni-modal
  3. The shape of the limb trajectories are invariant under translation, rotation, and amplitude scaling

- These predictions are in agreement with experimental observations

Limitations of the kinematic objective functions

- A troubling aspect of this theory is that it implies that at higher levels in the motor system, the brain does not take into account any dynamic considerations such as energy required, the loads on the limb segments or the force and fatigue limitations of the neuromuscular system
- In other words, it implies that the brain determines the "optimal" trajectory independently of the physical system that will generate the movement, i.e., the limb!

> "It seems very strange that the optimal trajectory of our movement is determined perfectly independent of the dynamic quantities such as arm length, payload, motor command, torque or external force, etc." Y. Uno and M. Kawato, 1989

Limitations of the kinematic objective functions (cont.)

- The trajectories derived for the minimum jerk model are invariant with respect to the region of the work-space and independent of external forces
- The minimum jerk model determines trajectories irrespective of gravity
- To circumvent this problem within the framework of optimization theory, a second type of objective functions was formulated based on dynamic variables (joint torques, muscle forces, etc.)

Dynamic Objective Function

- Models using a dynamic objective function in movements assume that the CNS solves the three following computational problems at different levels:

1. Determination of a desired trajectory
2. Transformation of visual coordinates of the desired trajectory to body coordinate
3. Generation of motor commands (forces and torques) to realize the desired trajectory

Dynamic objective function, multi-joint movements

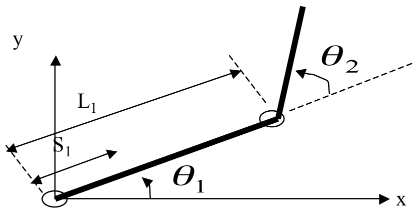
- One dynamic objective function proposed is the following:

$$J = \int_{t_0}^{t_f} \sum_{i}^{n} \left(\frac{dz_i}{dt} \right)^2 dt$$

- z_i is the motor command fed to the i-th actuator (muscle) out of n actuators

- In order to compute optimal trajectories predicted by this minimum torque change model, the dynamics equations of the musculo-skeletal system must first be specified because *J* depends on the dynamics of the controlled object

- Problem: it is difficult to describe the the musculo-skeletal system exactly because it is a complex system.
- Consider the following two-joint system:



$$z_1 = \left(I_1 + I_2 + 2M_2L_1S_1\cos(\theta_2) + M_2L_1^2\right)\times\ddot{\theta}_1 + b_1\ddot{\theta}_1$$
$$+\left(I_2 + M_2L_1S_2\cos(\theta_2)\right)\times\ddot{\theta}_2 - M_2L_1S_2\left(2\dot{\theta}_1 + \dot{\theta}_2\right)\times\dot{\theta}_2\sin(\theta_2)$$

$$z_2 = \left(I_2 + M_2L_1S_2\cos(\theta_2)\right)\times\ddot{\theta}_1 + I_2\ddot{\theta}_2 + b_2\ddot{\theta}_2$$
$$+M_2L_1S_2\left(\dot{\theta}_1\right)^2\sin(\theta_2)$$

- Since the dynamics of the multi-joint system is nonlinear, the problem of finding the unique trajectory that minimizes *J* is a nonlinear optimization problem.
- Consequently, it seems impossible to obtain analytical expression of the solution of this problem, unlike the case with the minimum jerk problem
- Predictions vs experiment
  - Trajectory depends on arm posture and external forces
  - Not always straight paths
- The minimum torque change model succeeded in reproducing observed trajectories under various conditions

---

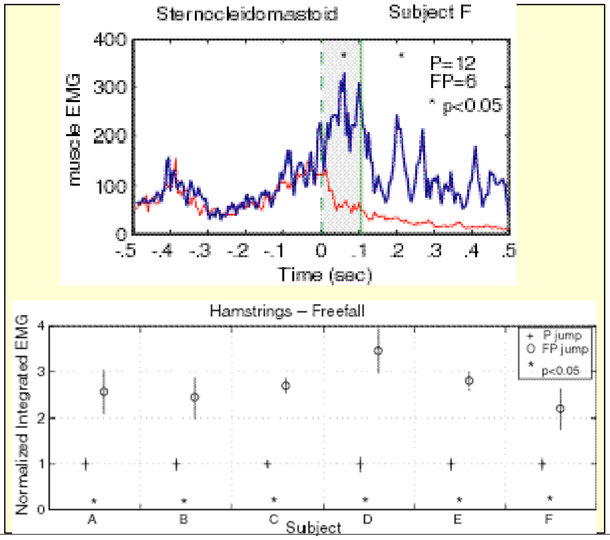
- Physiological advantage of each model: Why would the CNS want to minimize
  - torque change?
  - Jerk?

Example: Ground-Based Simulators

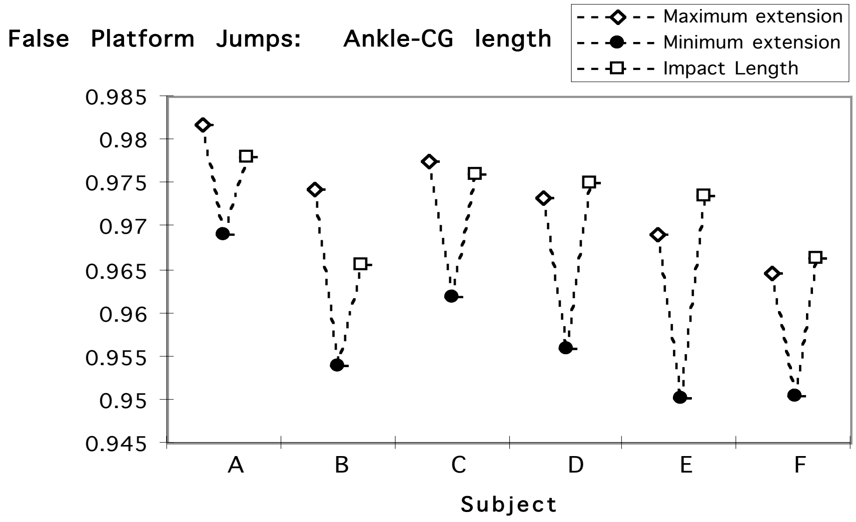
- ‘False Platform’ Experiments
- ‘Moonwalker’
- Altered Environments
- Real-time Adaptation
- Biomedical Applications

Altered Performance

P and FP EMG for time period between expected impact and FP impact



Adaptation – Freefall



Pre-Programmed Muscle Response During Downward Jumps

- Literature review
  - Engberg and Lundberg (1969)

    EMG activity during walking in cat limbs

    “EMG was triggered 5 to 10 ms prior to impact”, sort of feedforward activation “a centrally programmed event anticipating stance”
  - Melvill-Jones and Watt (1971)

    Tested the above conclusion on humans during sudden falls. Found consistent EMG burst activity beginning 75ms after drop. Concluded that “deceleration resulted from a timed burst of pre-programmed muscle activity”. Problem with this study: dropped subjects from heights up to 20cm! Activity triggered by vestibular input?
  - Greenwood and Hopkins (1976)

    Studied EMG activity during voluntary and unexpected jumps, heights up to 120cm. Findings: Two peaks of activity: 80ms after release only in unexpected jumps + consistent time before landing (related to the voluntary control of landing)

- Dyhre-Poulsen and Laursen (1980, 1983, 1985)

  Analyzed landing mechanisms and EMG activity in monkeys during downward jumps. Onset of EMG activity started occurred with great precision 80ms before landing. Still an argument against pre-programming: visual monitoring of distance during jump? Lights turned off, same activation pattern, locked to the time of expected impact

- McKinley and Smith (1983)

  Performed similar experiments on blindfolded and labyrinthectomized cats.

- Watt *et* al. (1986) plus numerous other studies

  It is widely acknowledged that microgravity exposure causes profound changes in human balance, posture control and locomotion. Watt et al. tested astronauts
  subjected to sudden drops. All subjects are “unsteady postflight”. Reaons for decrement in performance?

  Astronauts stated the floor coming up to meet them, and is there before they were ready for it

---

- The missing link: A proposed model to account for the above observations
  - The previous experiments suggest that the “flying object” has an estimate of the time of impact $\widehat{T}_{impact}$ why?
  - Prior to jump, a visual estimate of the height is performed $\widehat{H}_0$
  - What is needed to go from estimated height to estimated time of impact?

A representation of the gravity field in the sensorimotor system, or an internal g-model

$$\widehat{T}_{impact} = \sqrt{\frac{2\widehat{H}_0}{g_{CNS}}}$$

- When astronauts perform postflight jumps, one hypotheses regarding the performance decrement (other than muscle atrophy) is that internal representation of the gravity field is altered:

$$g_{CNS} < g_{true} \Rightarrow \widehat{T}_{impact} > T_{true}$$

- Hence the floor is “there before [they are] ready for it”!