

# The motor system



To move things is all that mankind can do...  
whether in whispering a syllable or in felling a forest  
C. Sherrington 1920

- Principles
- Components: Muscles, Spinal cord and spinal tracts, Subcortical areas, Cortical fields.
- Learning and plasticity

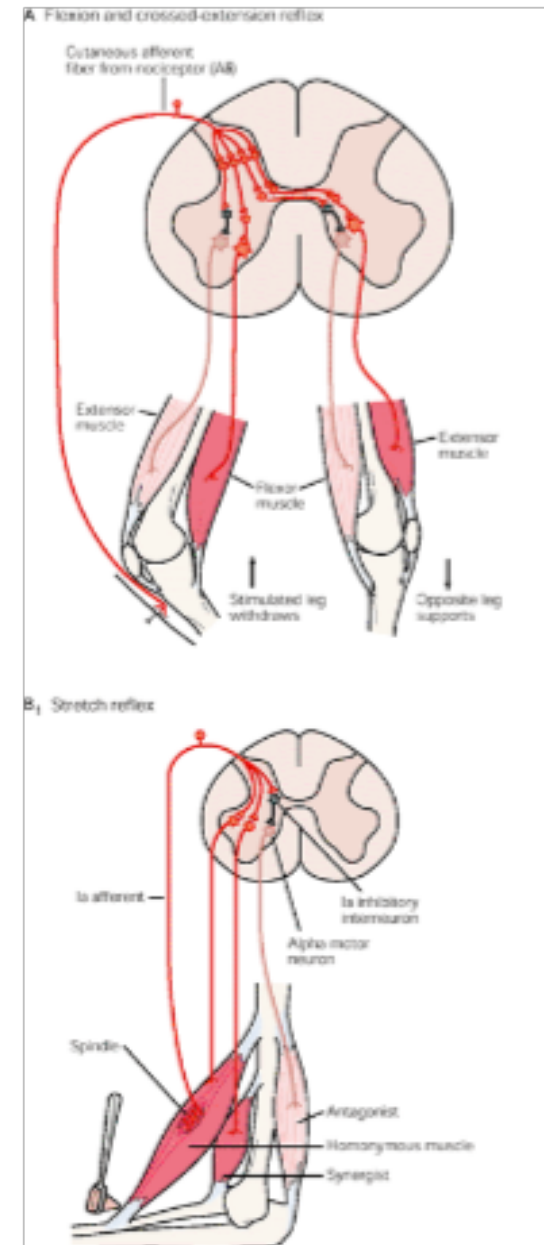
# Three main types of movements

- Reflex
- Rhythmic
- Voluntary

- **Reflex:** *involuntary* coordinated patterns of muscle contraction and relaxation elicited by peripheral stimuli (~40ms)

Noxious stimuli excites ipsilateral flexor, and excites contralateral extensor

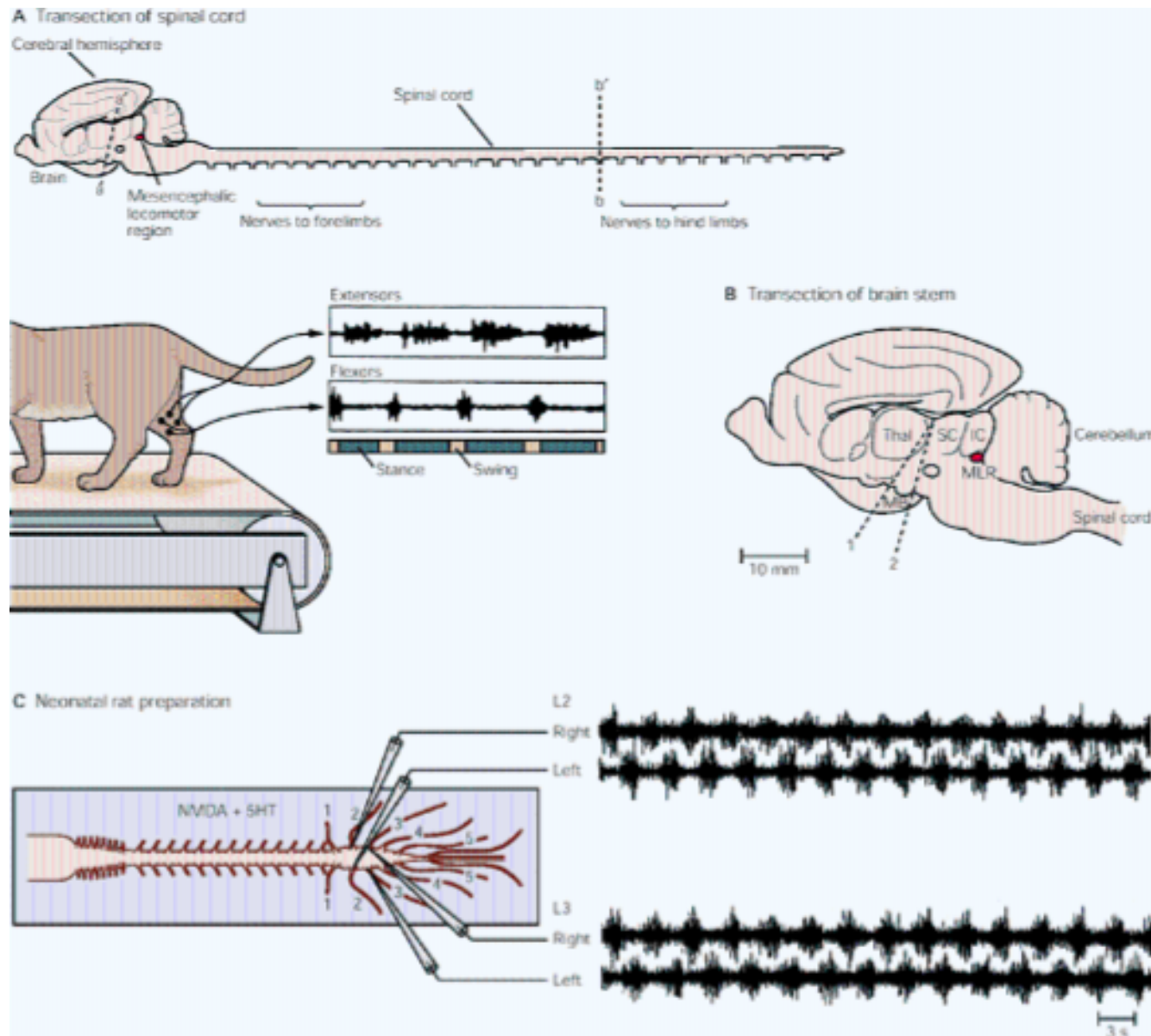
Stretch reflex: contraction of same and synergist and relaxation of antagonist



**Rhythmic:** Chewing, swallowing, and scratching, quadrupedal locomotion.

- The spinal cord and brain stem.
- Triggered by peripheral stimuli that activate the underlying circuits.

# CPG: central pattern generators



# Voluntary movements: principles

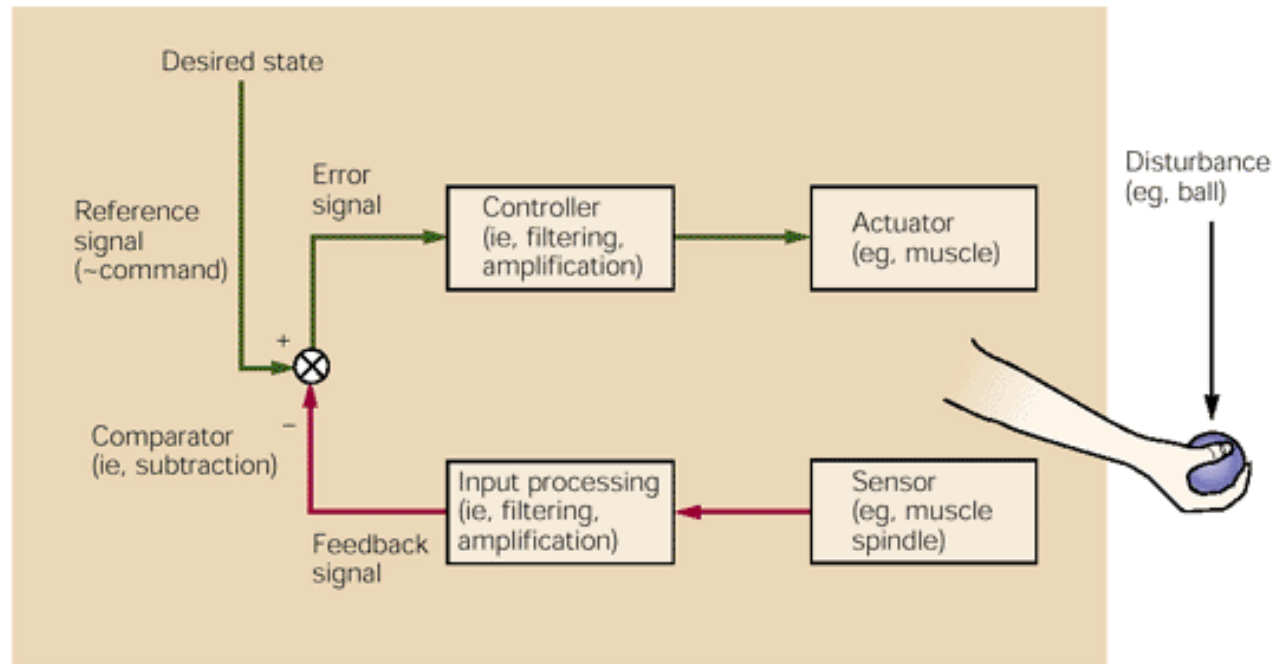
Goal directed

Reaching (~120 ms)



# Feedback control (error correction)

A Feedback control: command specifies desired state



Vision

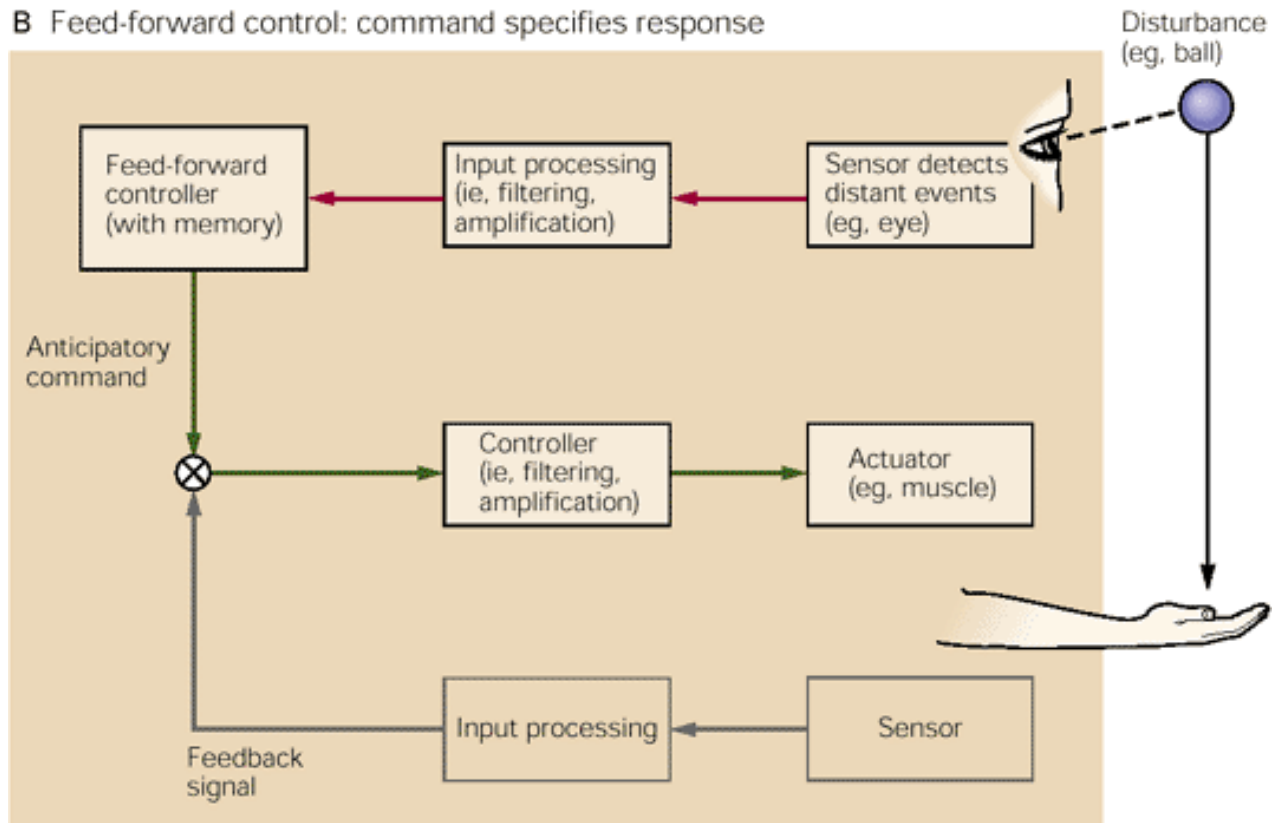
Proprioception

1. Gain

2. Delay (phase lag)

# Feed-forward (open loop)

B Feed-forward control: command specifies response

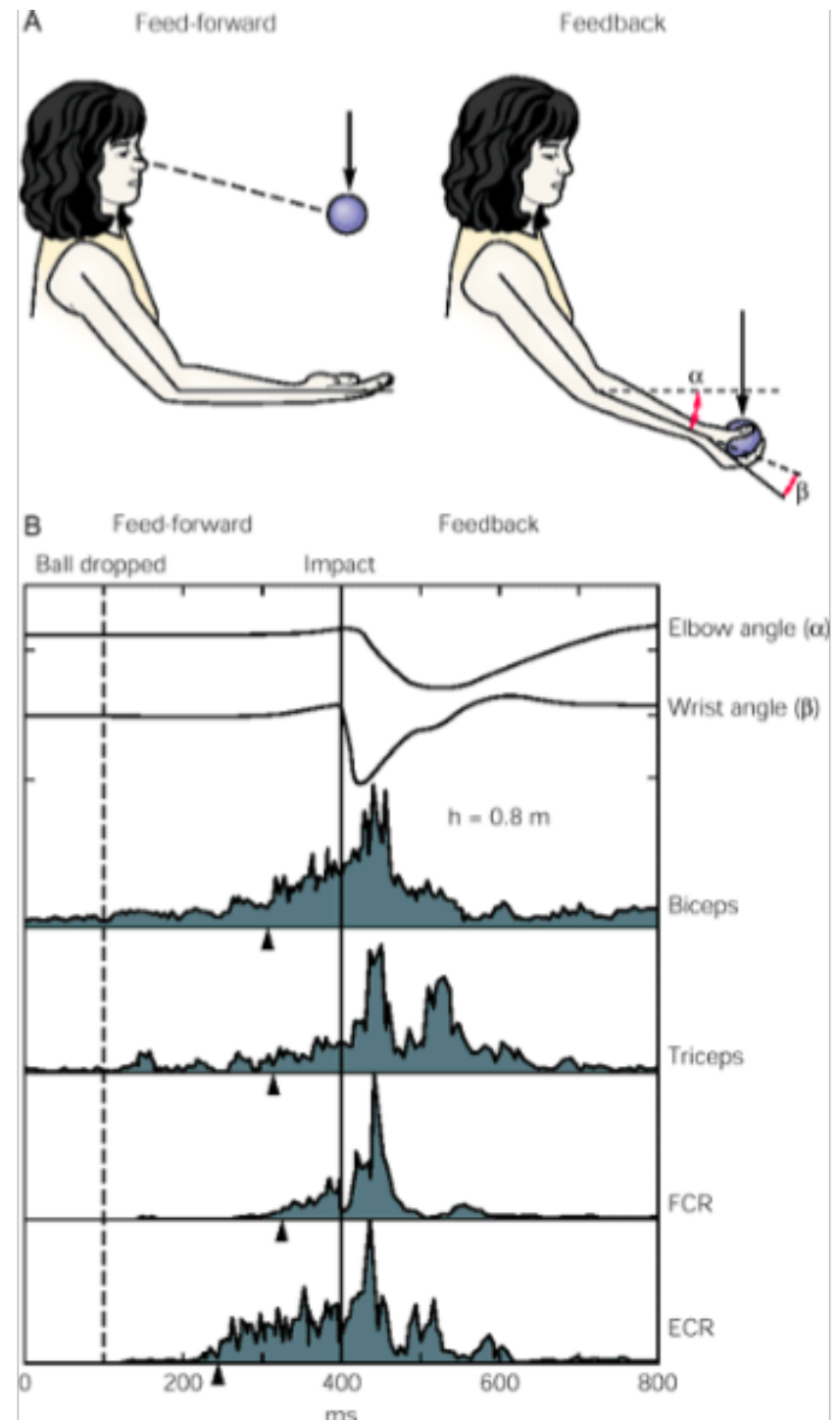


1. Very hard computationally

Feedback control (error correction)

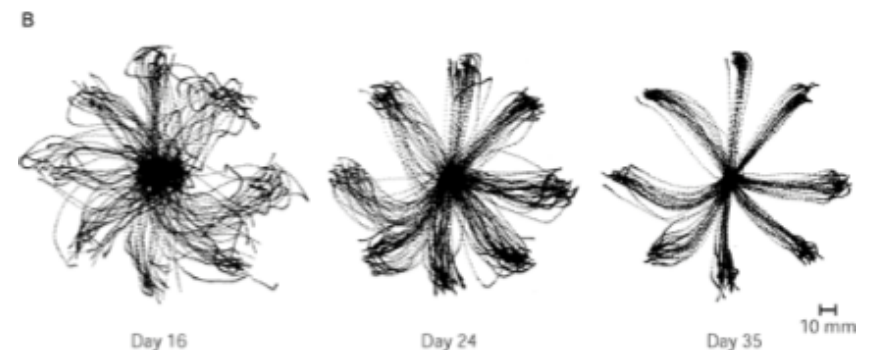
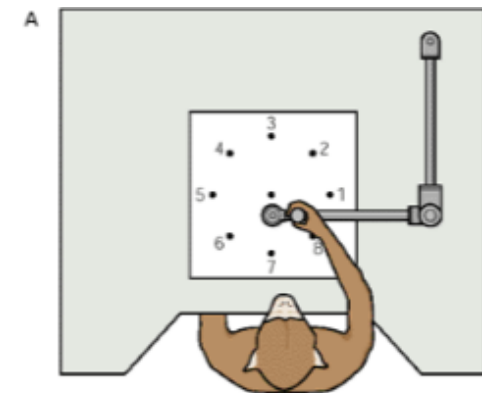
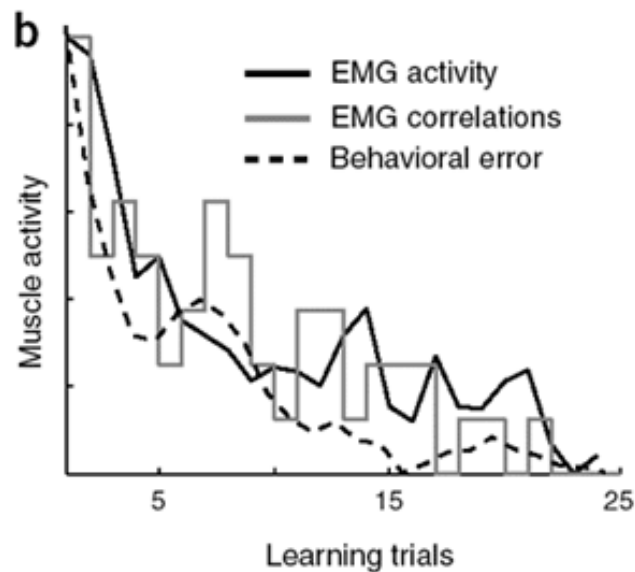
Feedforward (open loop)

Notice onset of muscles



# Improve with practice

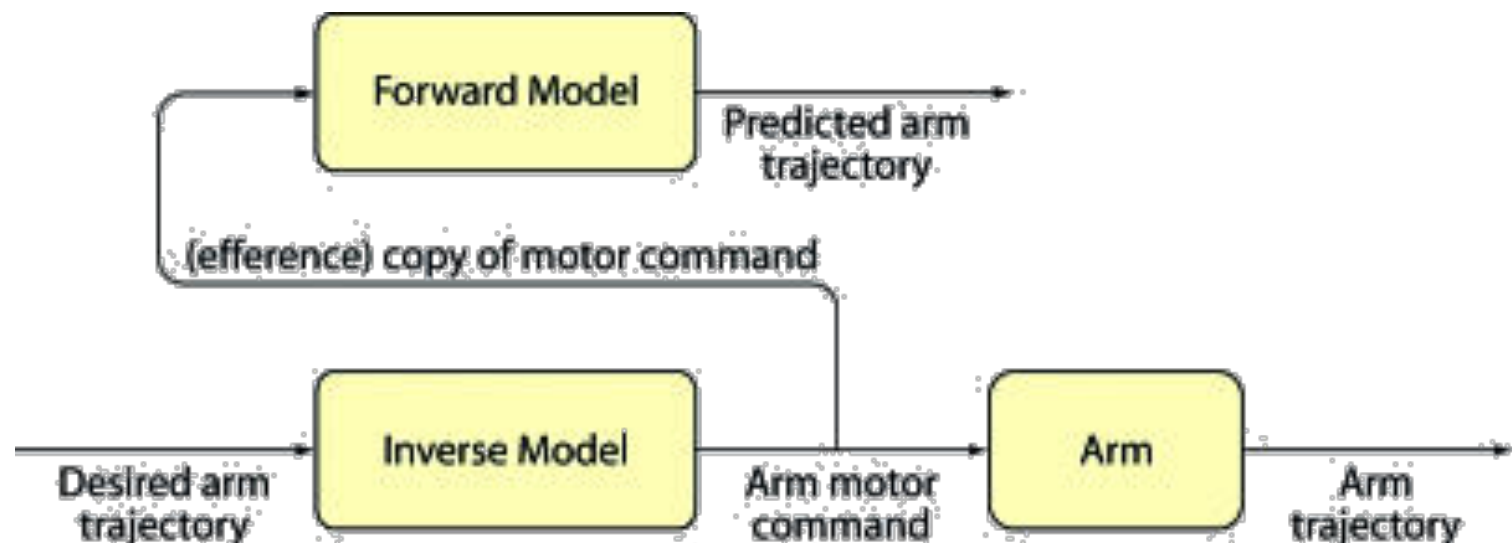
- Co-contraction of muscles
- **Internal models:** a neural representation of the relationship between the hand and the environment (how the arm would respond to the neural command).



# Inverse and forward internal models

An **internal model** is used either:

- to predict the movement consequences of a motor commands (*forward model*).
- to determine the motor commands needed to achieve a desired movement trajectory (*inverse model*).



# Motor programs and Invariants

Motor equivalence

(Donald Hebb, 1950)

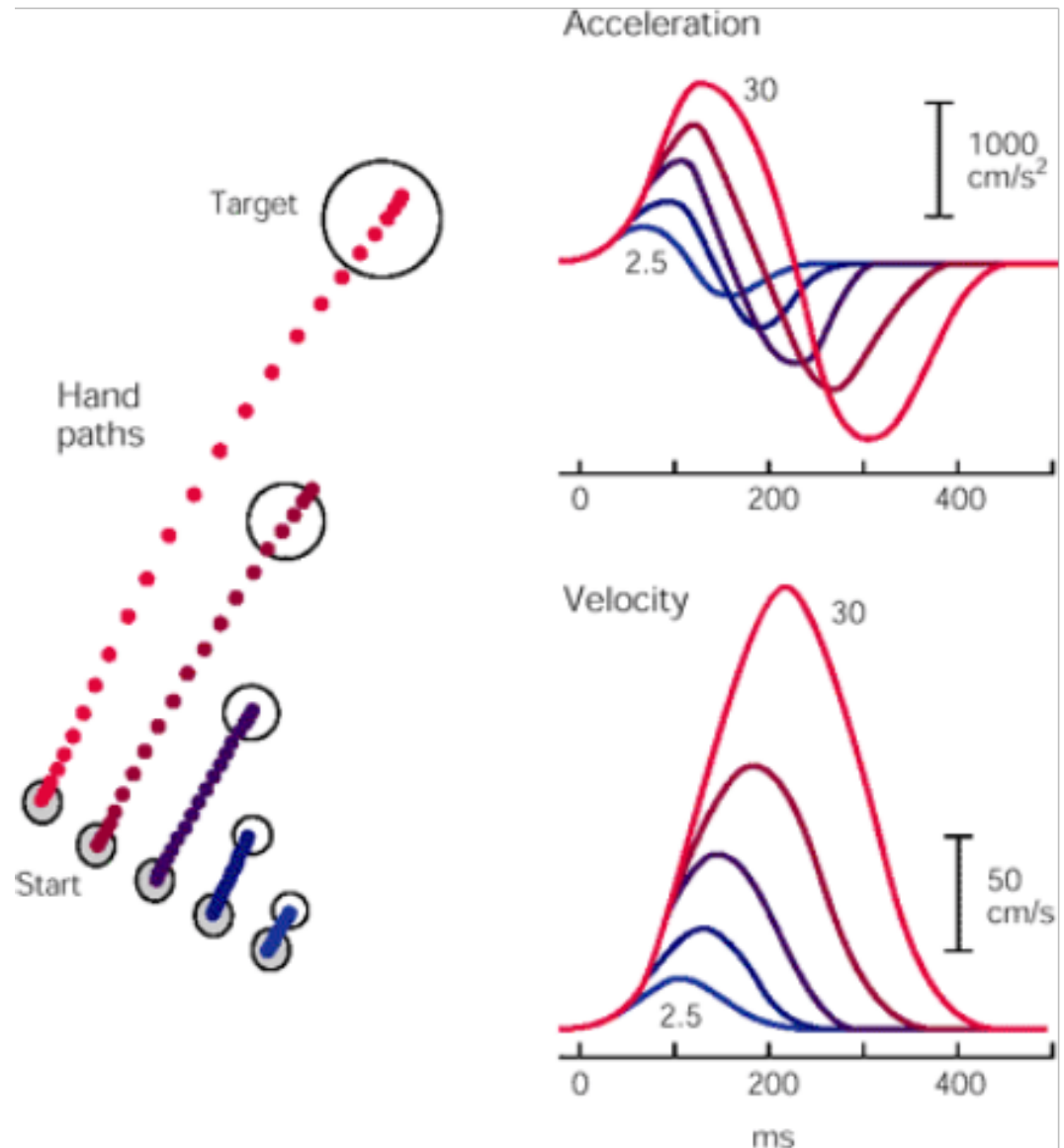


- A Able was I ere I saw Elba
- B Able was I ere I saw Elba
- C Able was I ere I saw Elba
- D Able was I ere I saw Elba
- E Able was I ere I saw Elba

# Pre-planning in vectors

Is there online visual feedback?  
No - scaling of acceleration and speed

Invariant time (Isochrony)



**Kinematic** transformation: to transform a target position into a command to the skeletal system to move the hand i.e. to convert between coordinate systems;

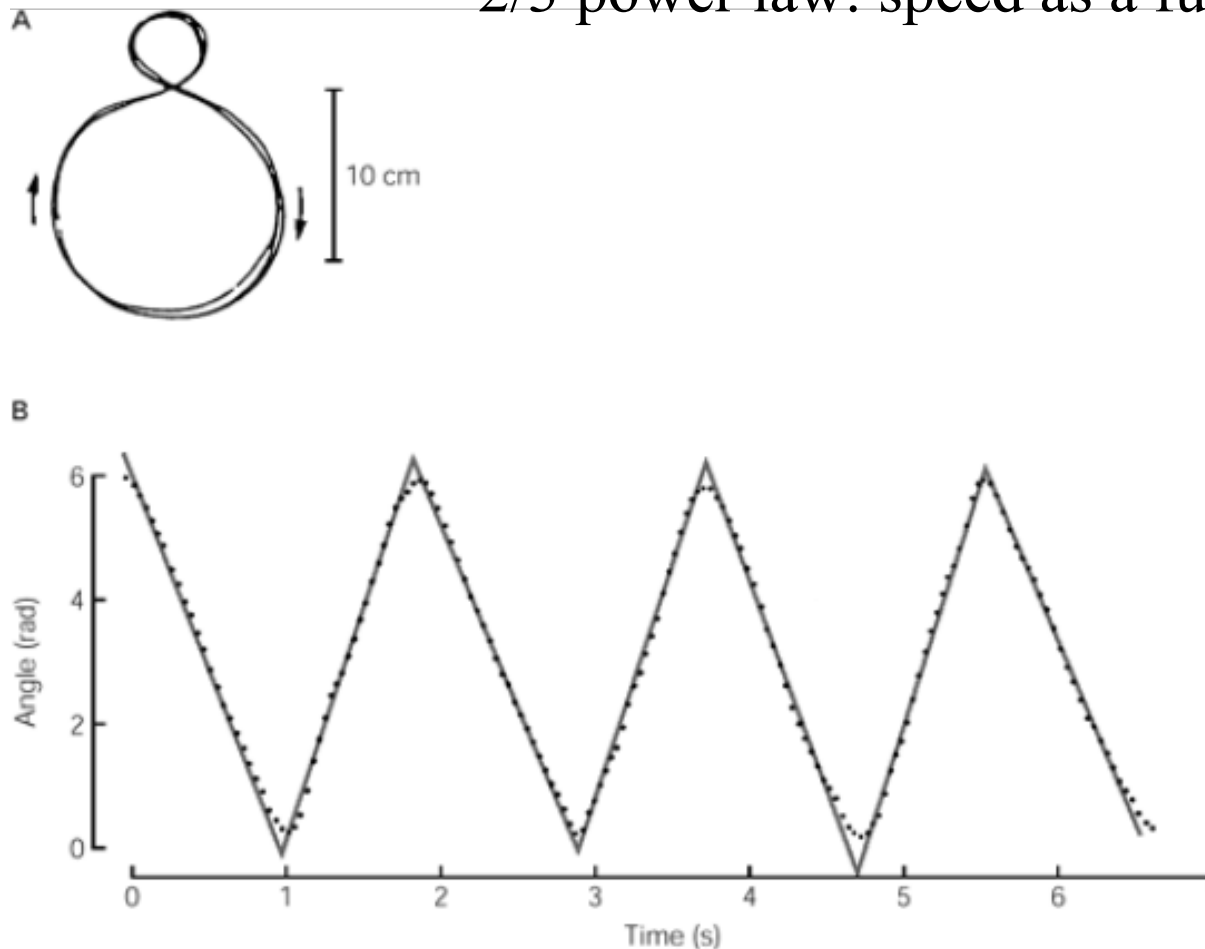
**Dynamic** transformation: relate motor commands to the motion of the system; in the reaching task here considered, the forces applied changed the system without changing the kinematics.

# Building blocks – segmentation - primitives

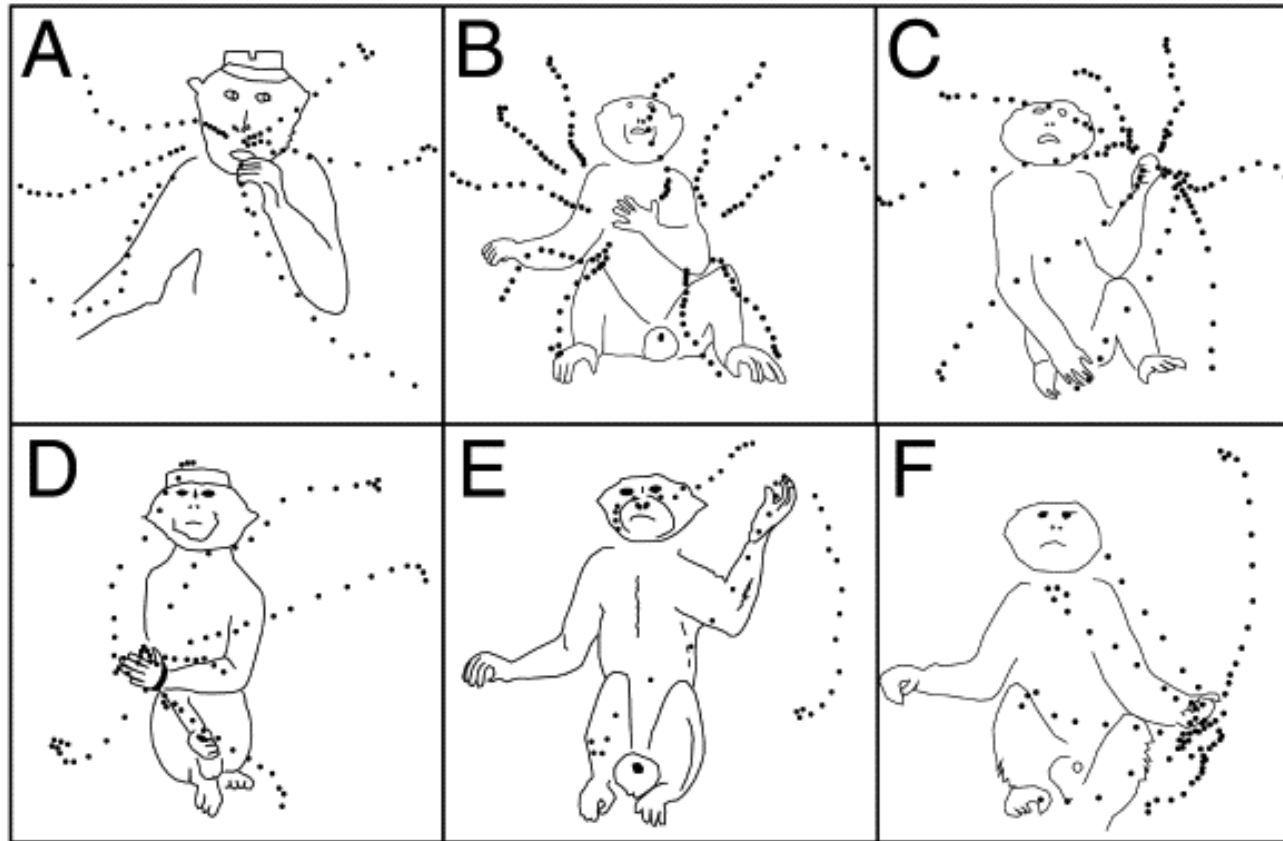
Isogony (equal angles)

Isochrony (duration independent of length)

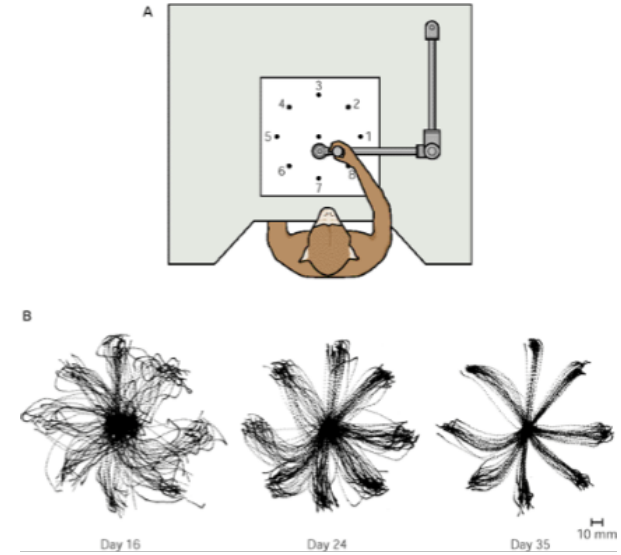
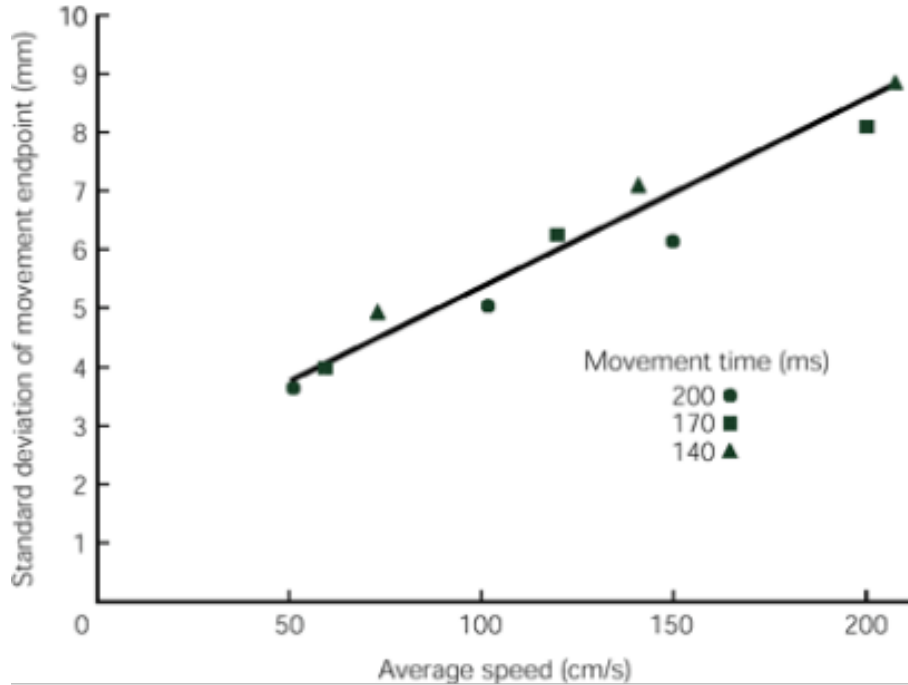
$2/3$  power law: speed as a function of curvature



# Stable behavioral gestures

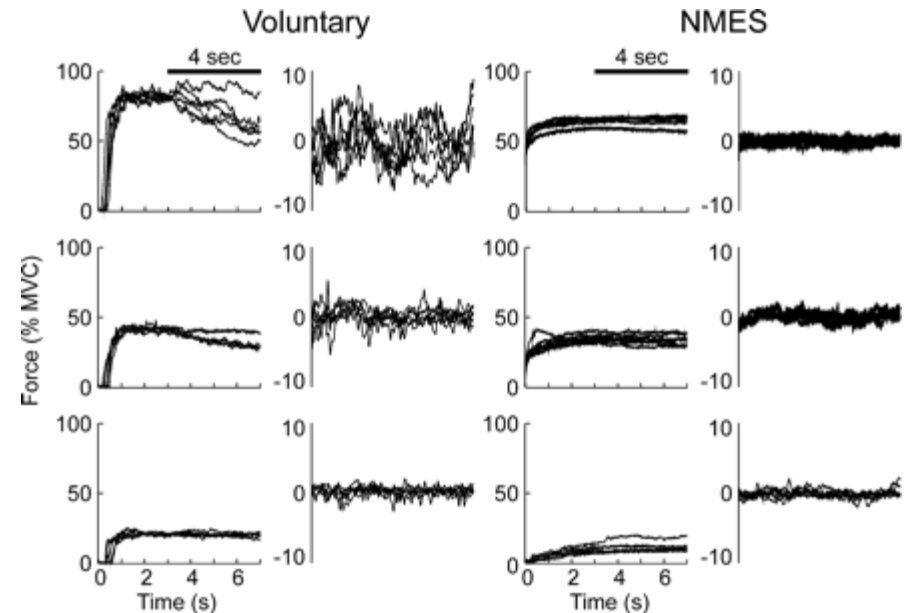


# Speed – accuracy tradeoff (Woodsworth, 1890)



Variability/noise of the components  
(neurons! much more than muscles)

Less time for feedback corrections?  
No, even without sensory feedback

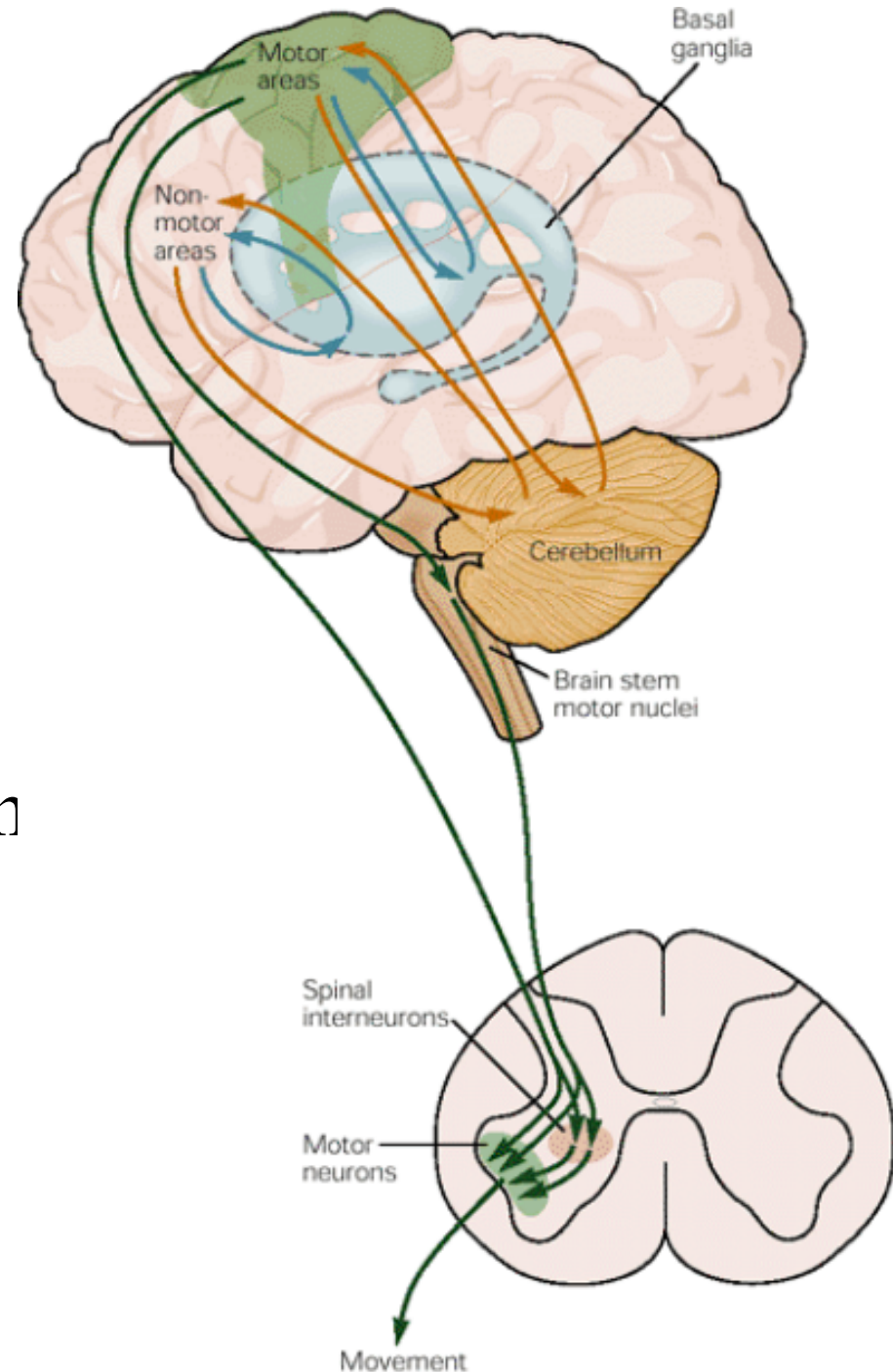


# Overcoming noise: optimization principles

- Minimum jerk (smooth acceleration)
- Minimum signal-dependent noise
- Optimal control: minimize only what is relevant, and ignore other variables.

# Hierarchical organization

- Cortex
- Basal-ganglia, cerebellum
- Brain stem
- Spinal tracts
- Spinal cord
- Muscles



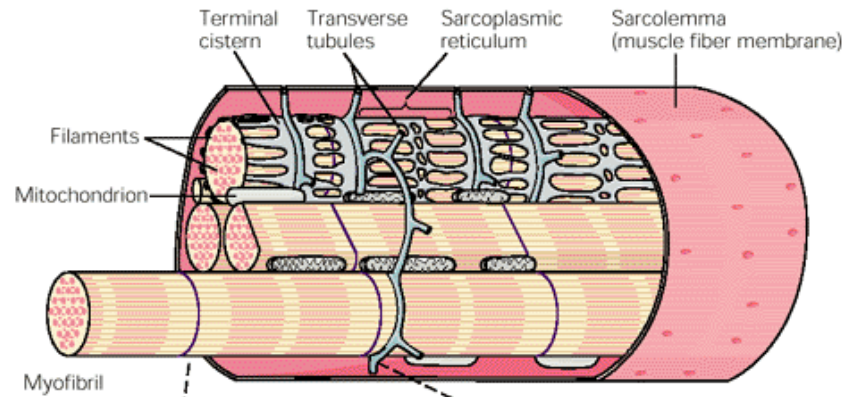
# Muscles

1. smooth muscles
2. cardiac muscles
3. **skeletal muscles**

# Structure

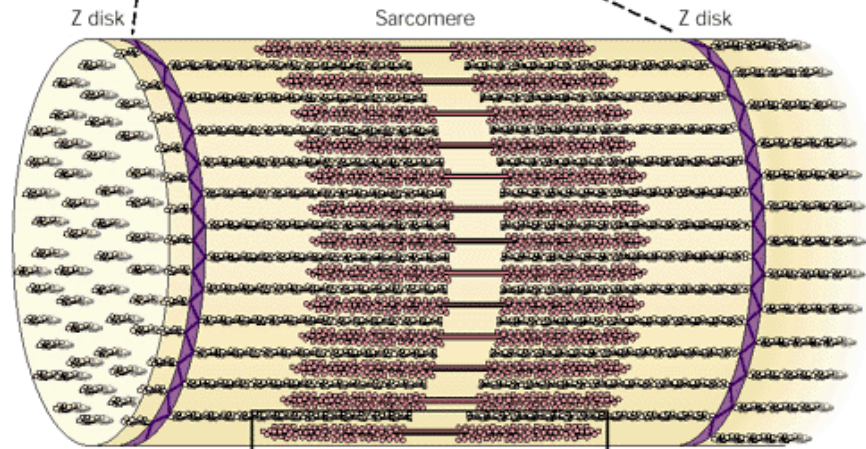
Muscle fiber

A



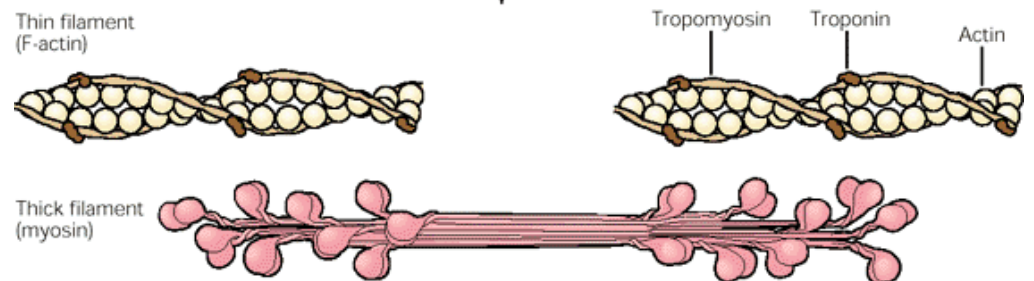
myofibril

B

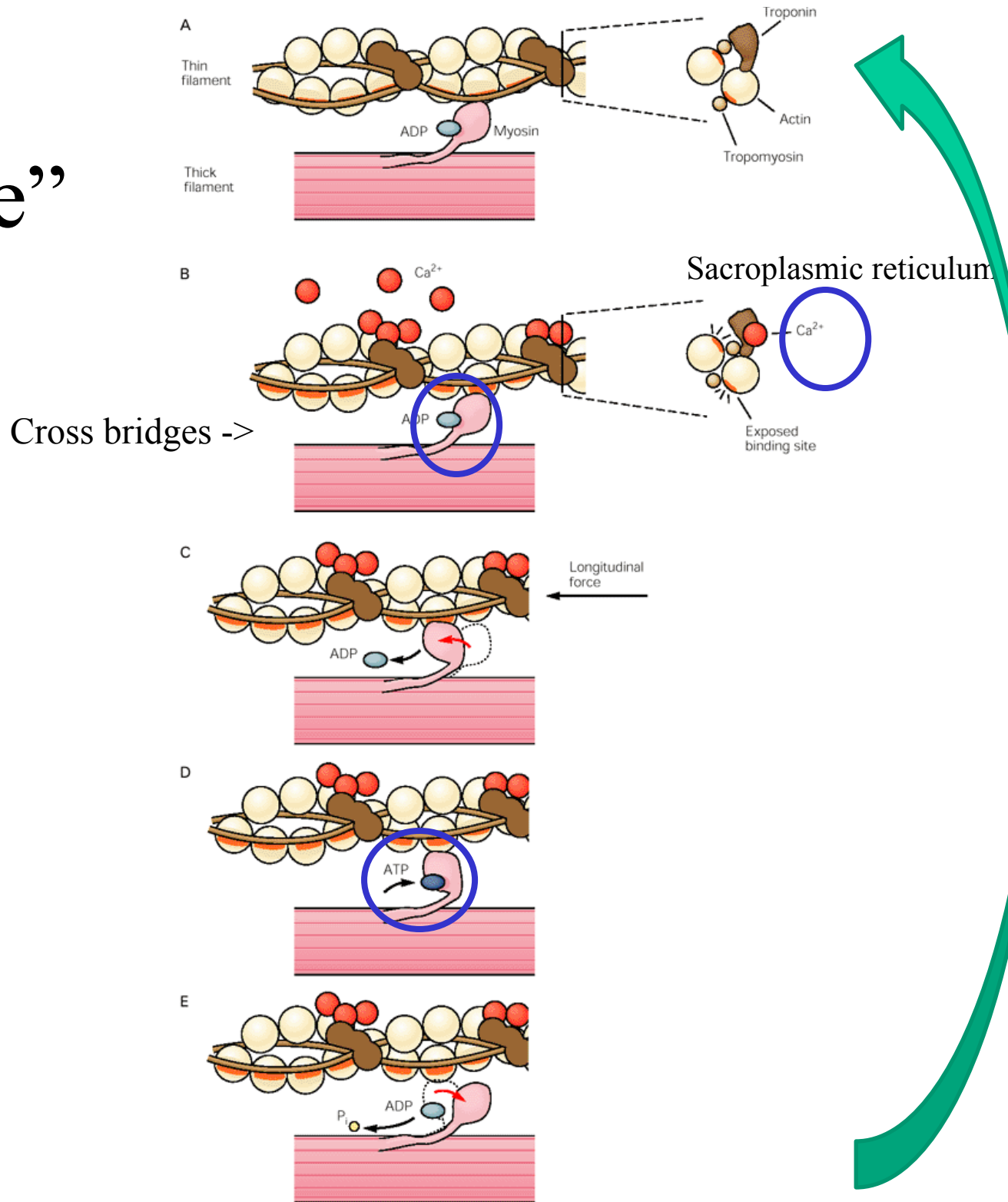


**Sarcomere: functional unit**

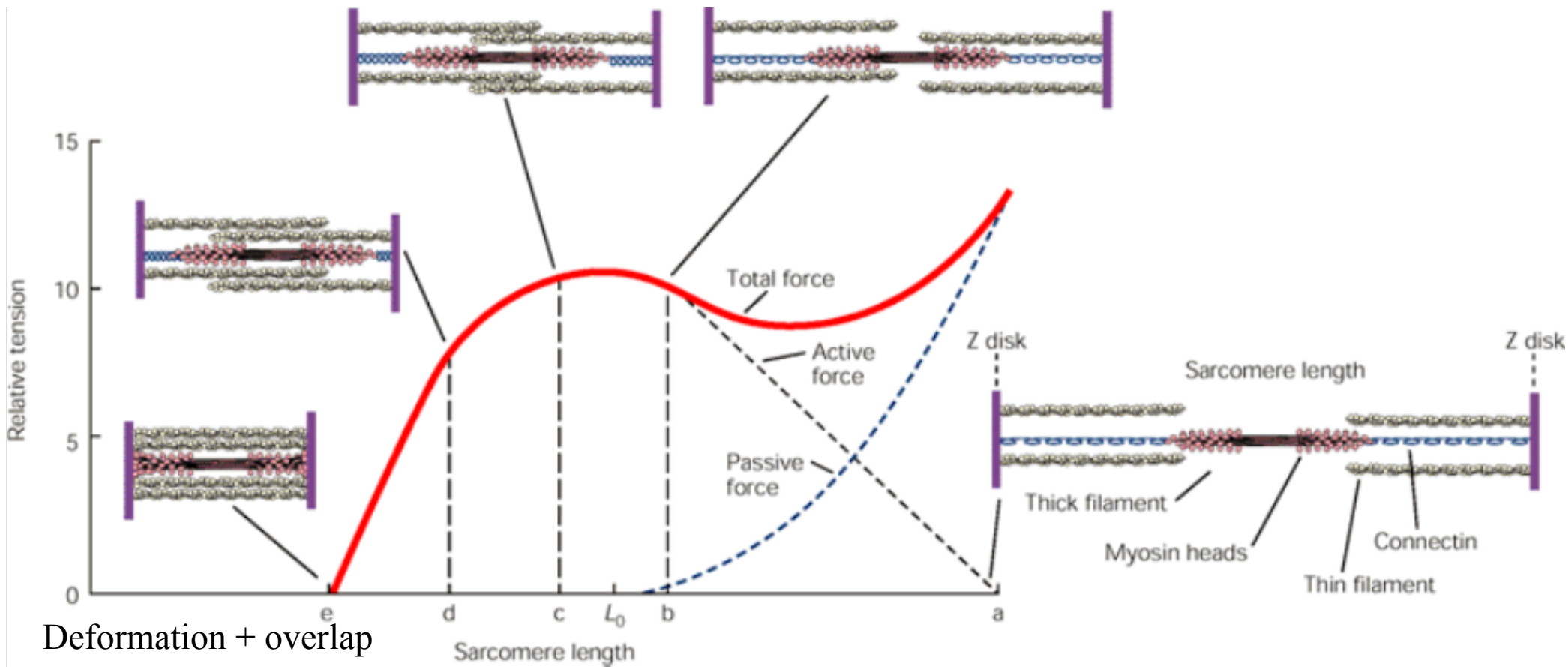
C



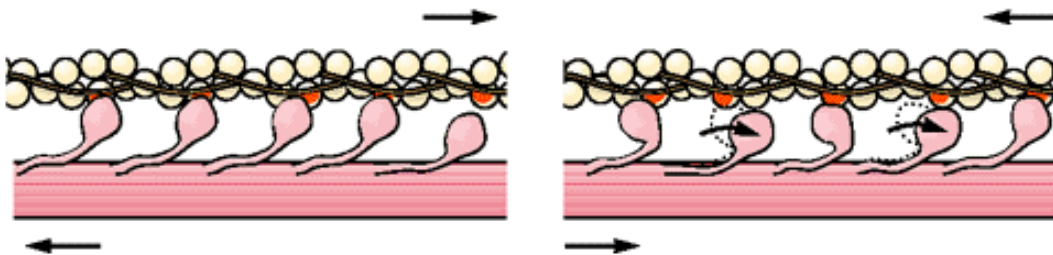
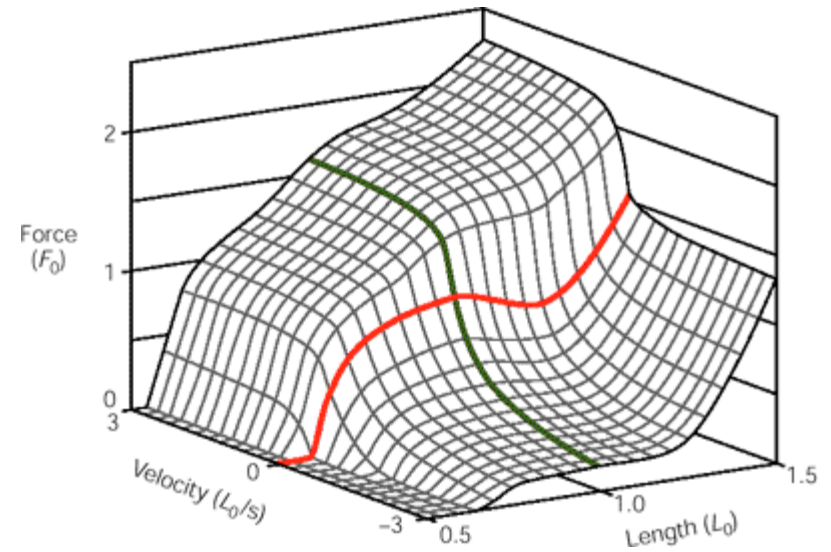
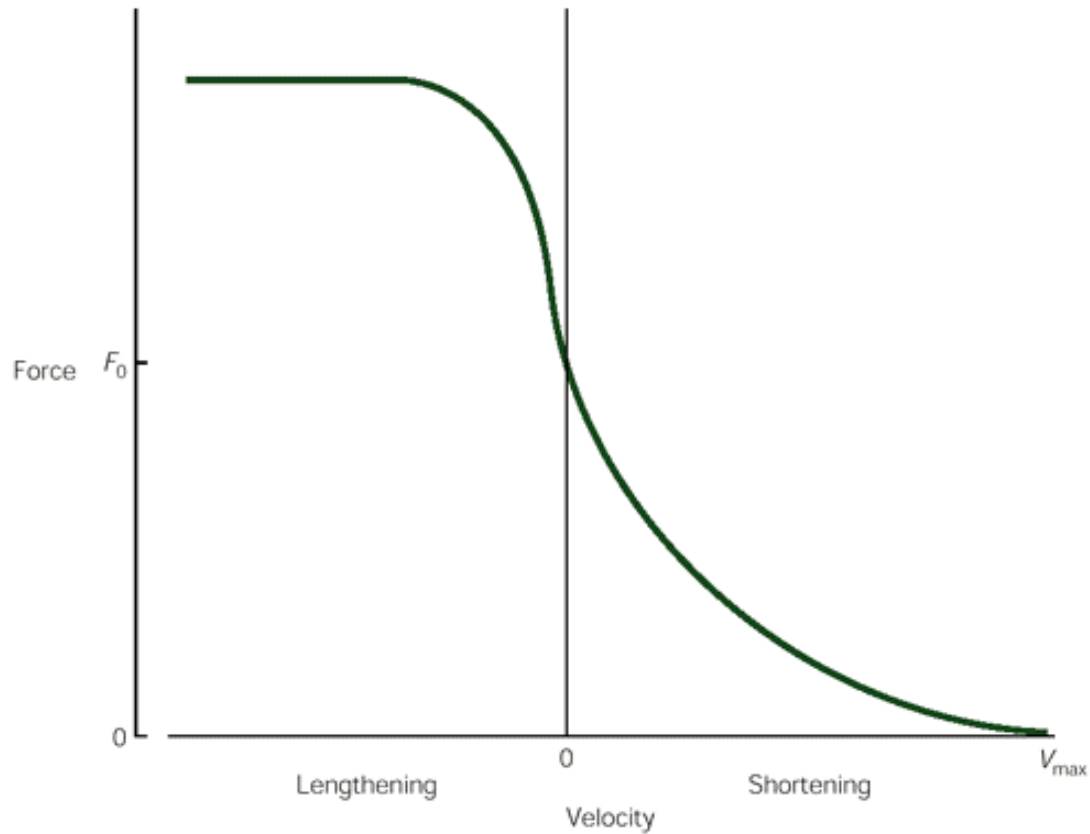
# The "engine"



# Force depends on length

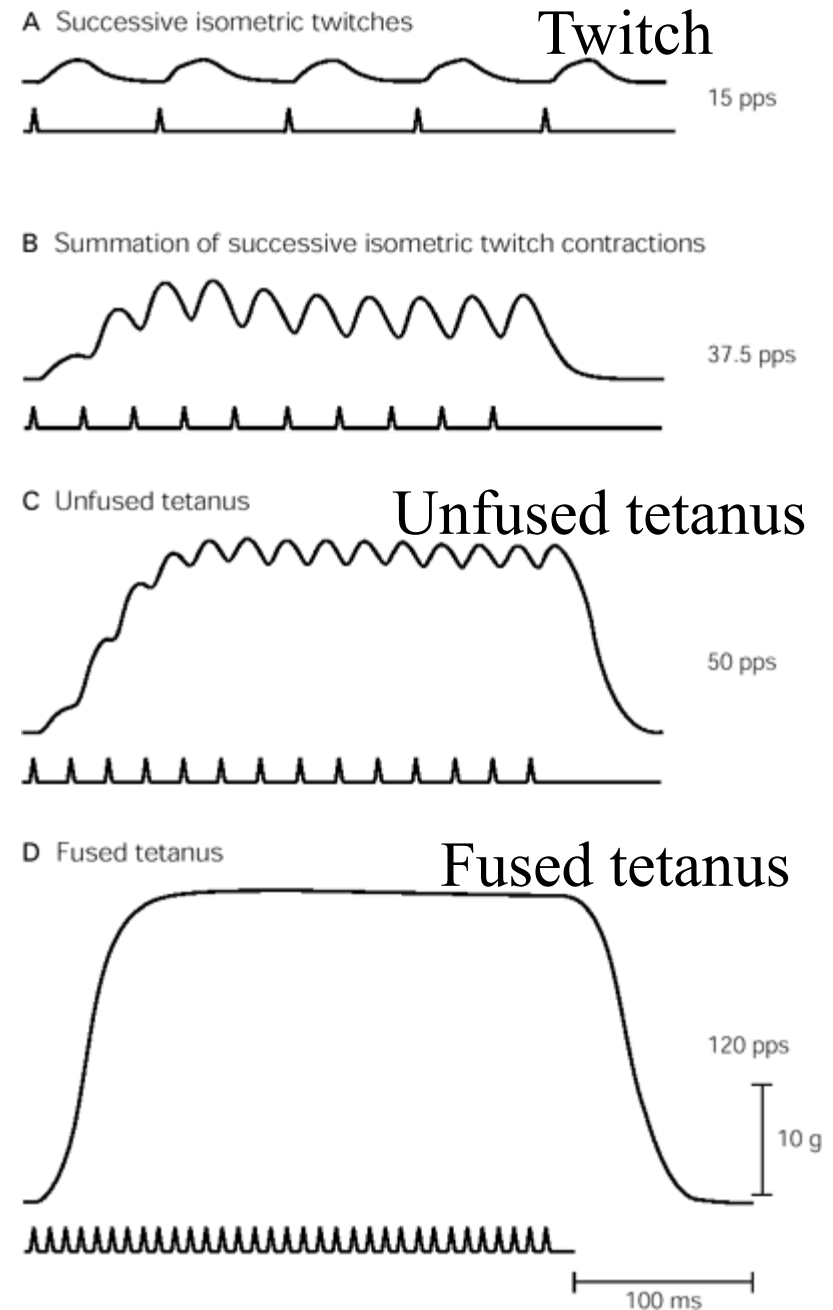


# Force depends also on velocity

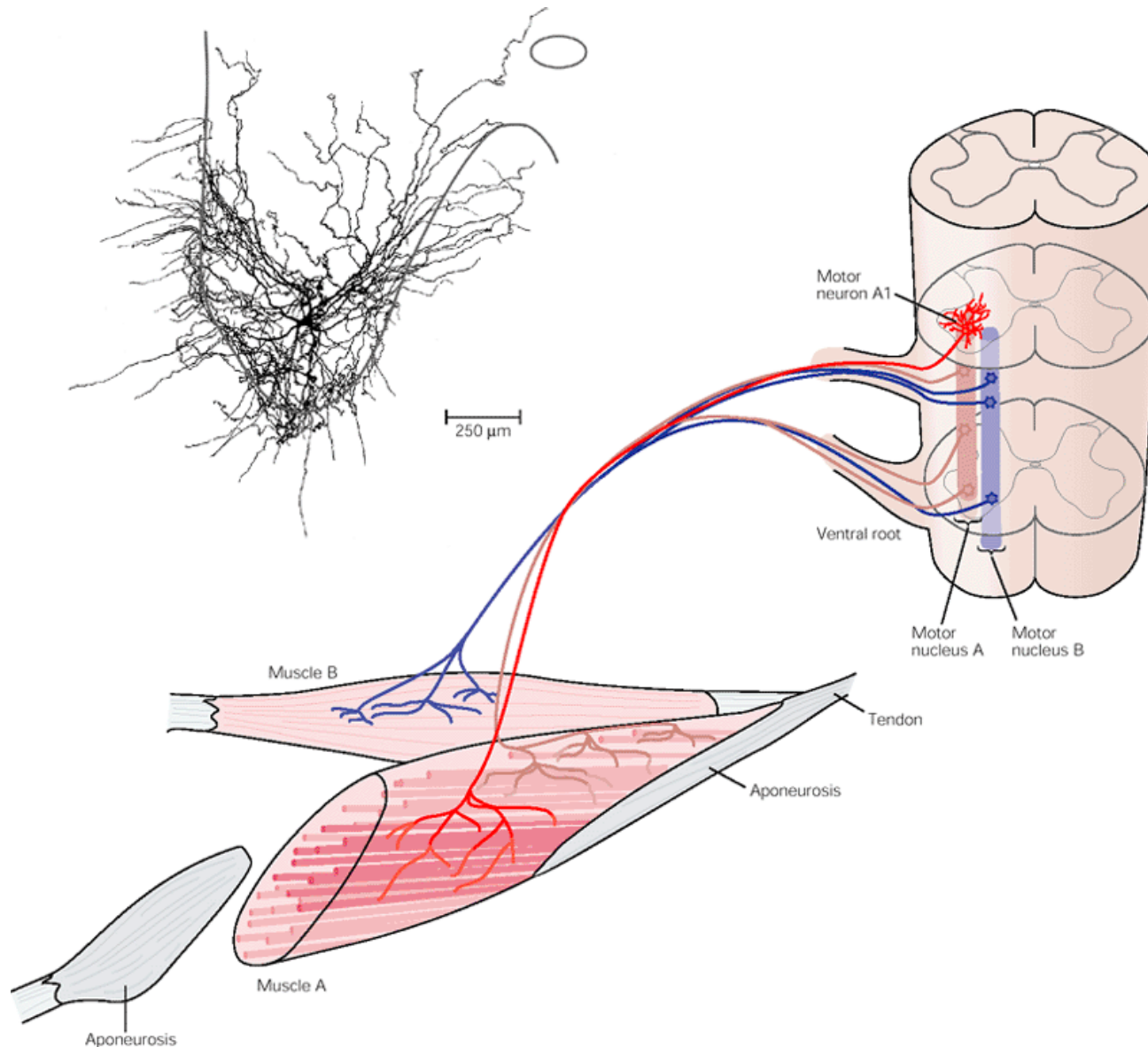


# The force of a single muscle fiber is a function of

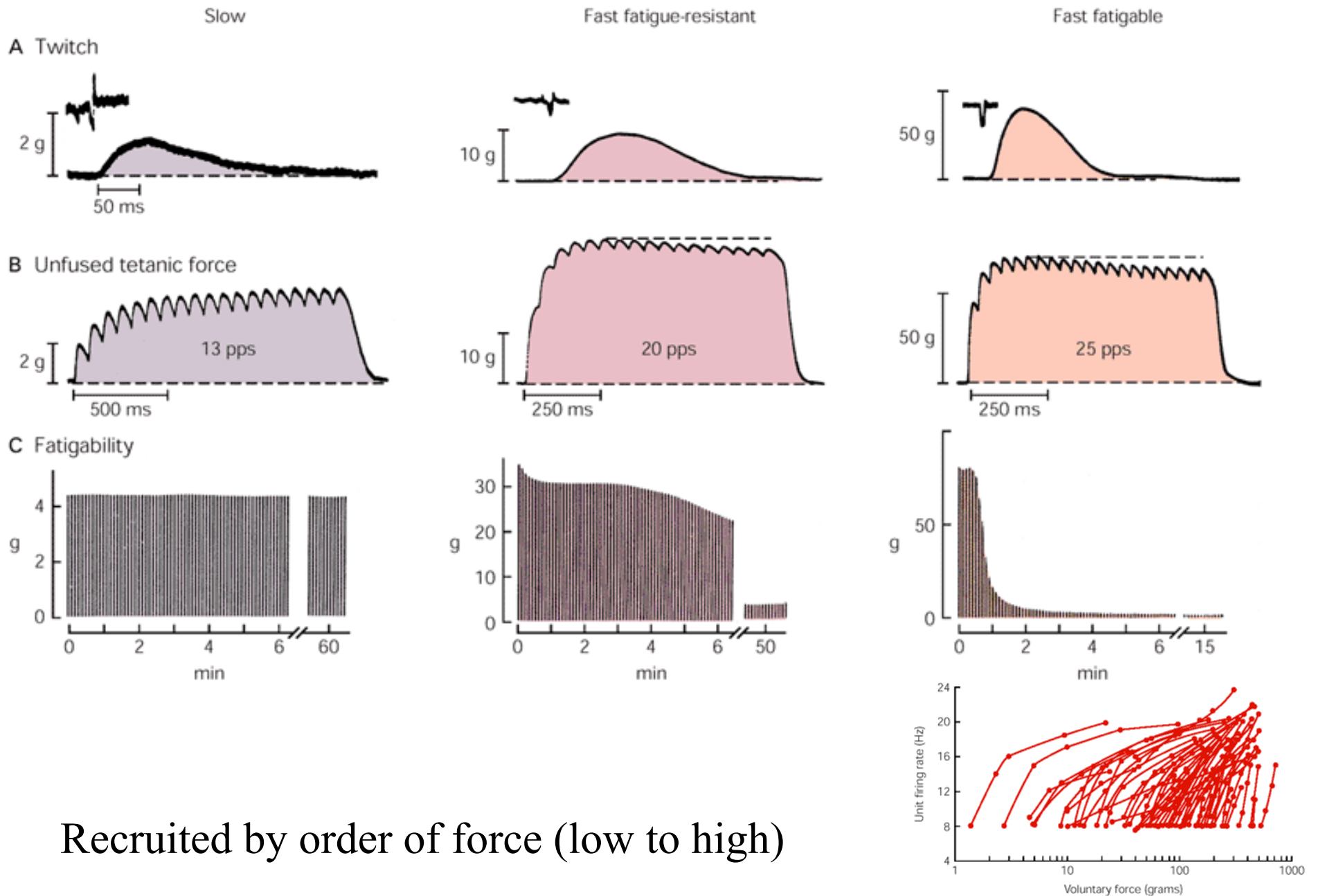
- Stimulation rate
- Stimulation pattern
- The muscle length
- The velocity of contraction
- The fiber type
- The fiber organization
- The duration of exercise - fatigue



# Motor unit: motor neuron and the muscle fibers it innervates ( one to many )

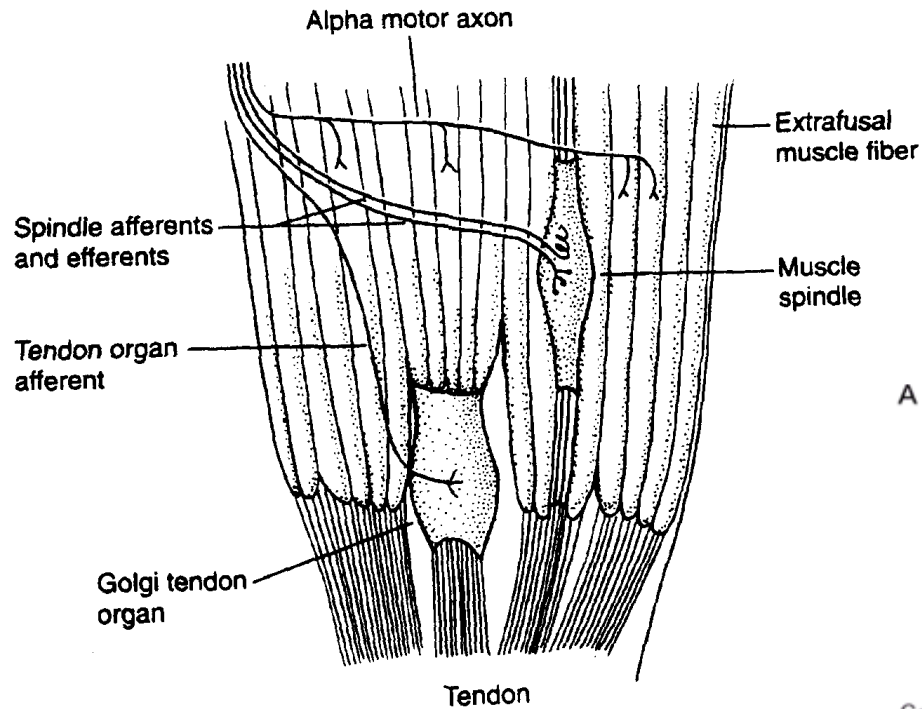


# 3 types of motor unit:



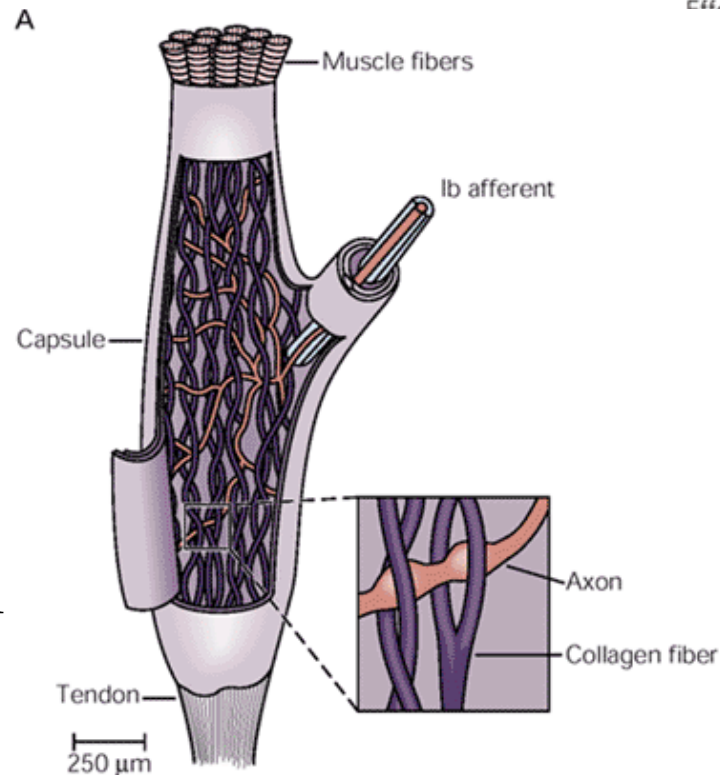
Recruited by order of force (low to high)

# Muscle proprioceptive organs

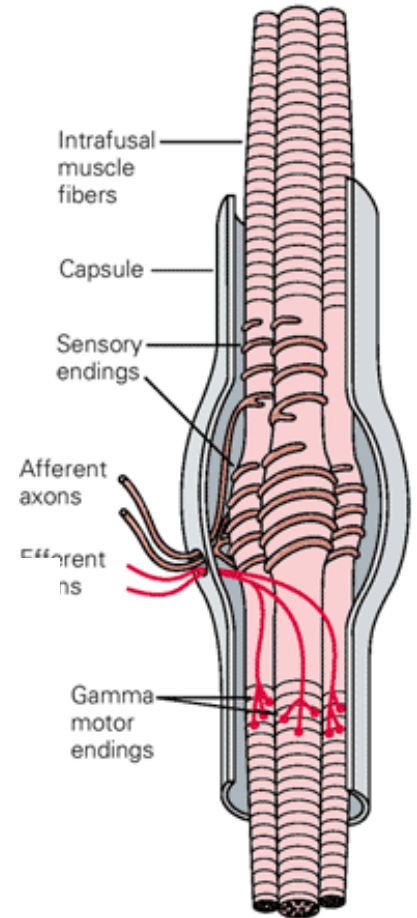


Golgi tendon: tension  
Serial

Spindle: length  
Parallel

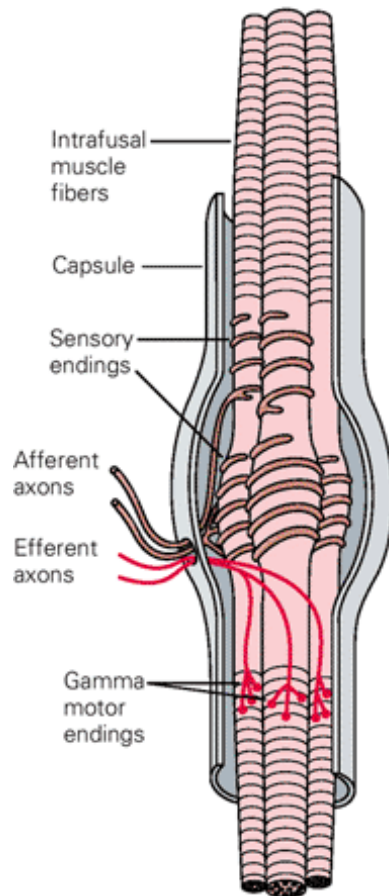


A Muscle spindle

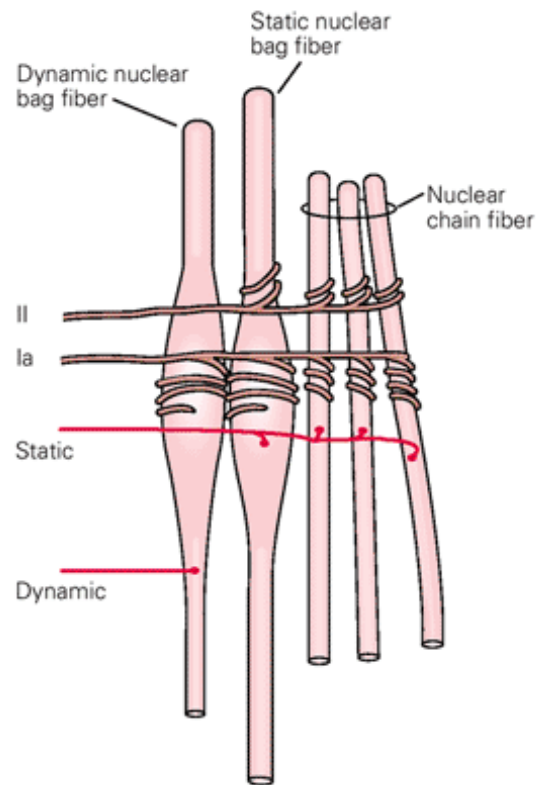


# The muscle spindles are sensitive to changes in length

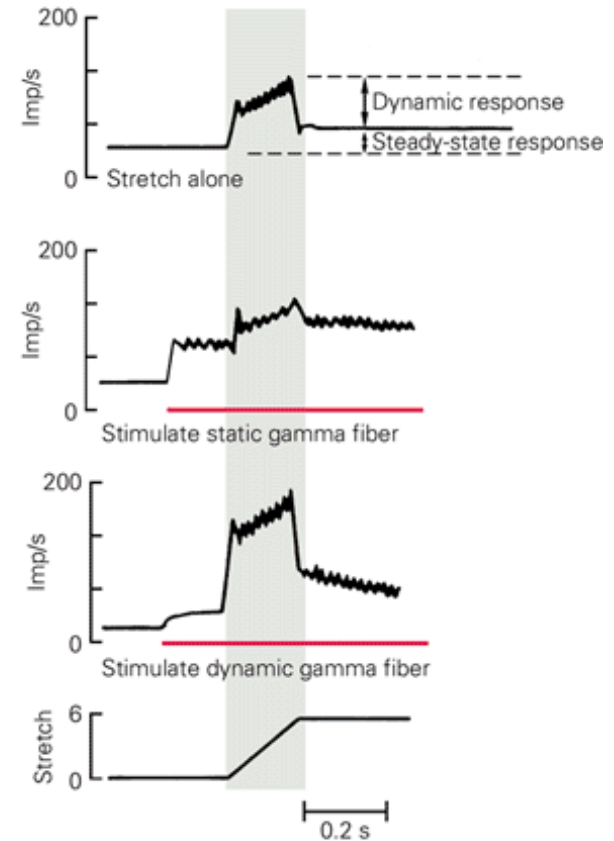
A Muscle spindle



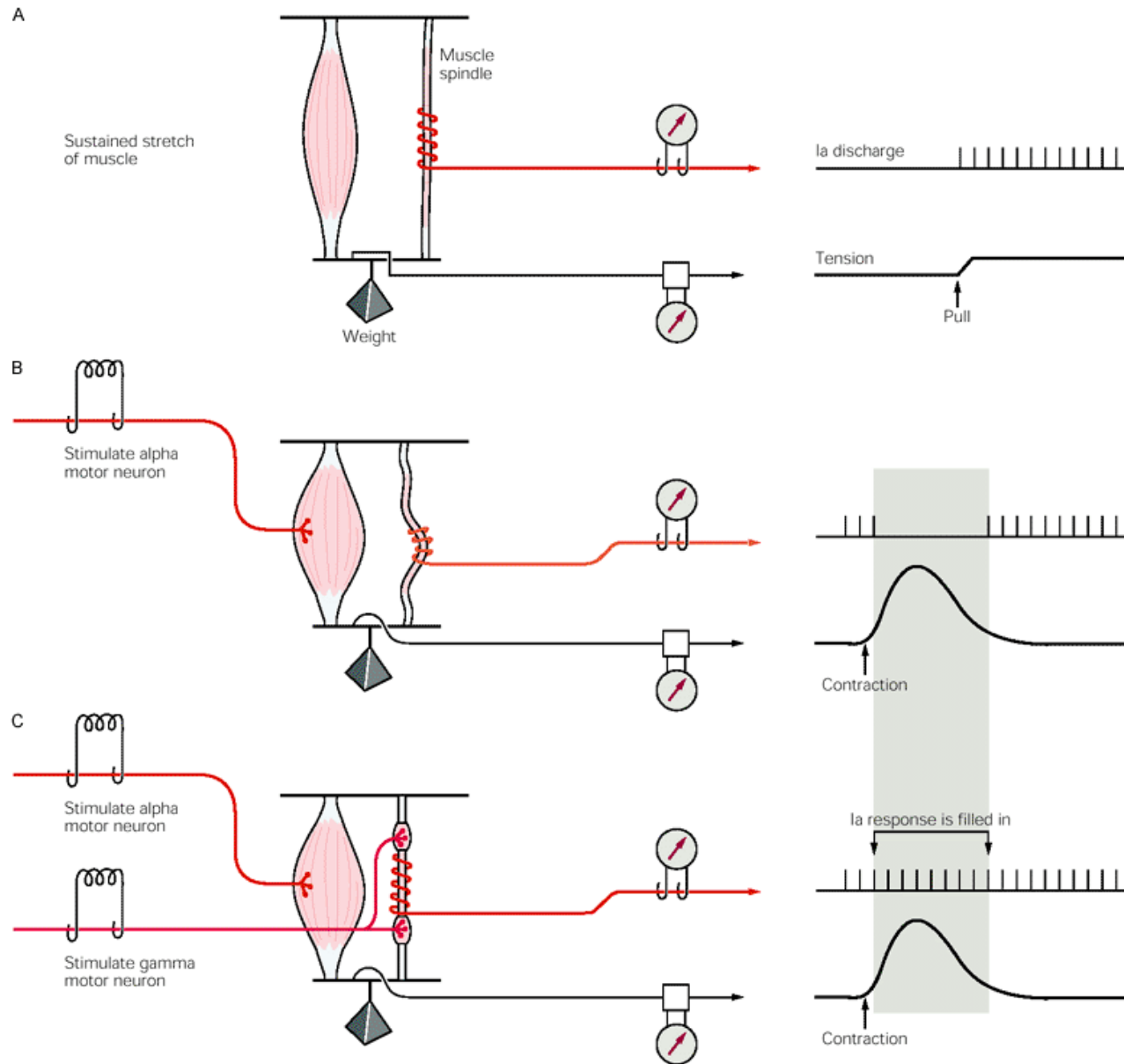
B Intrafusal fibers of the muscle spindle



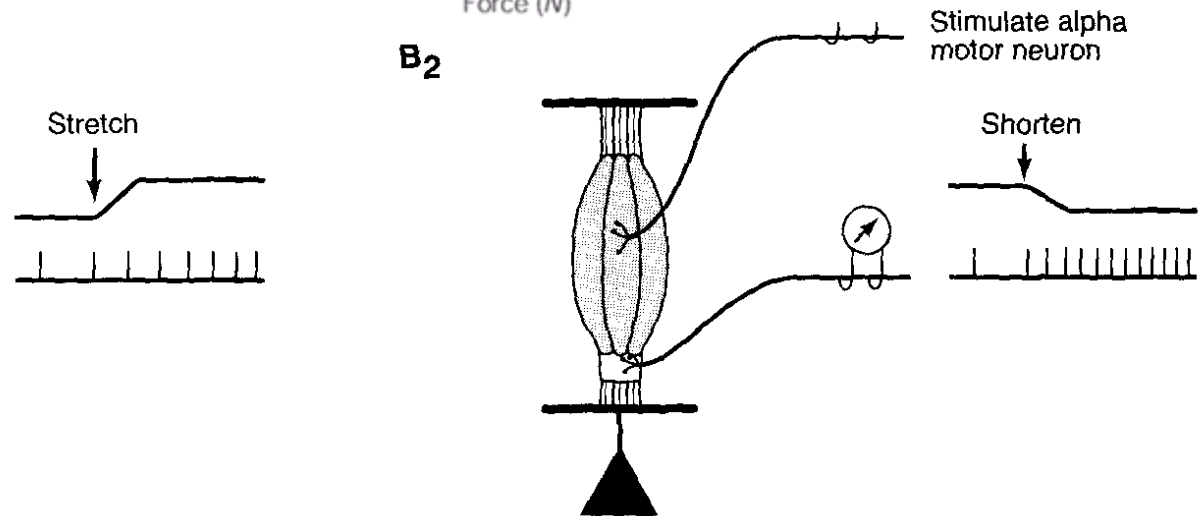
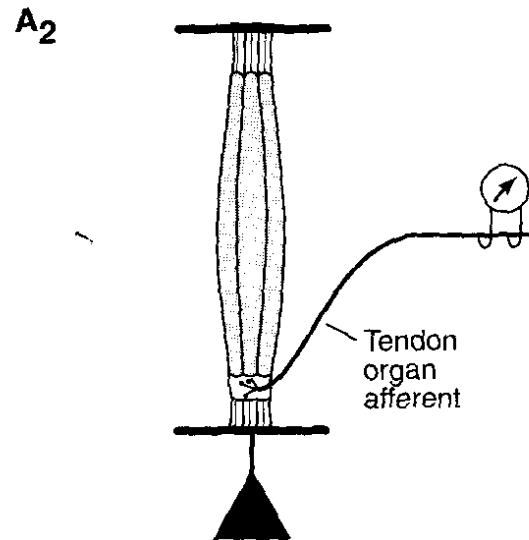
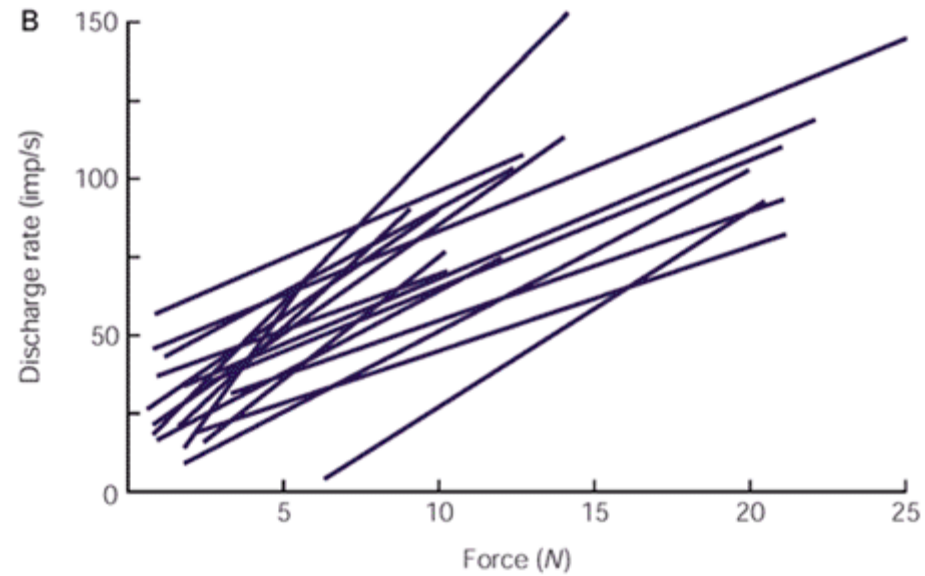
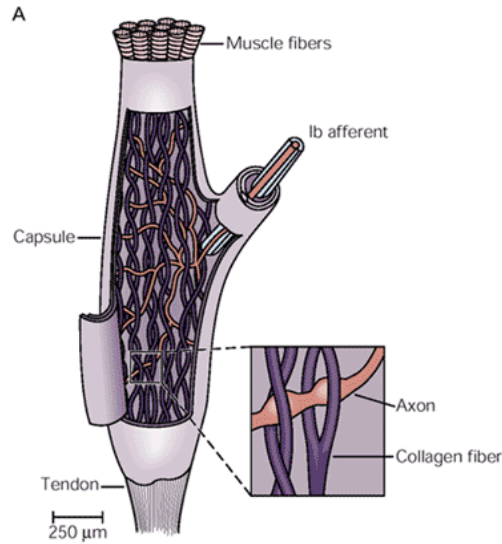
C Response of Ia sensory fiber to selective activation of motor neurons



# Active range can be dynamically modulated



# Golgi tendon organs are sensitive to the tension



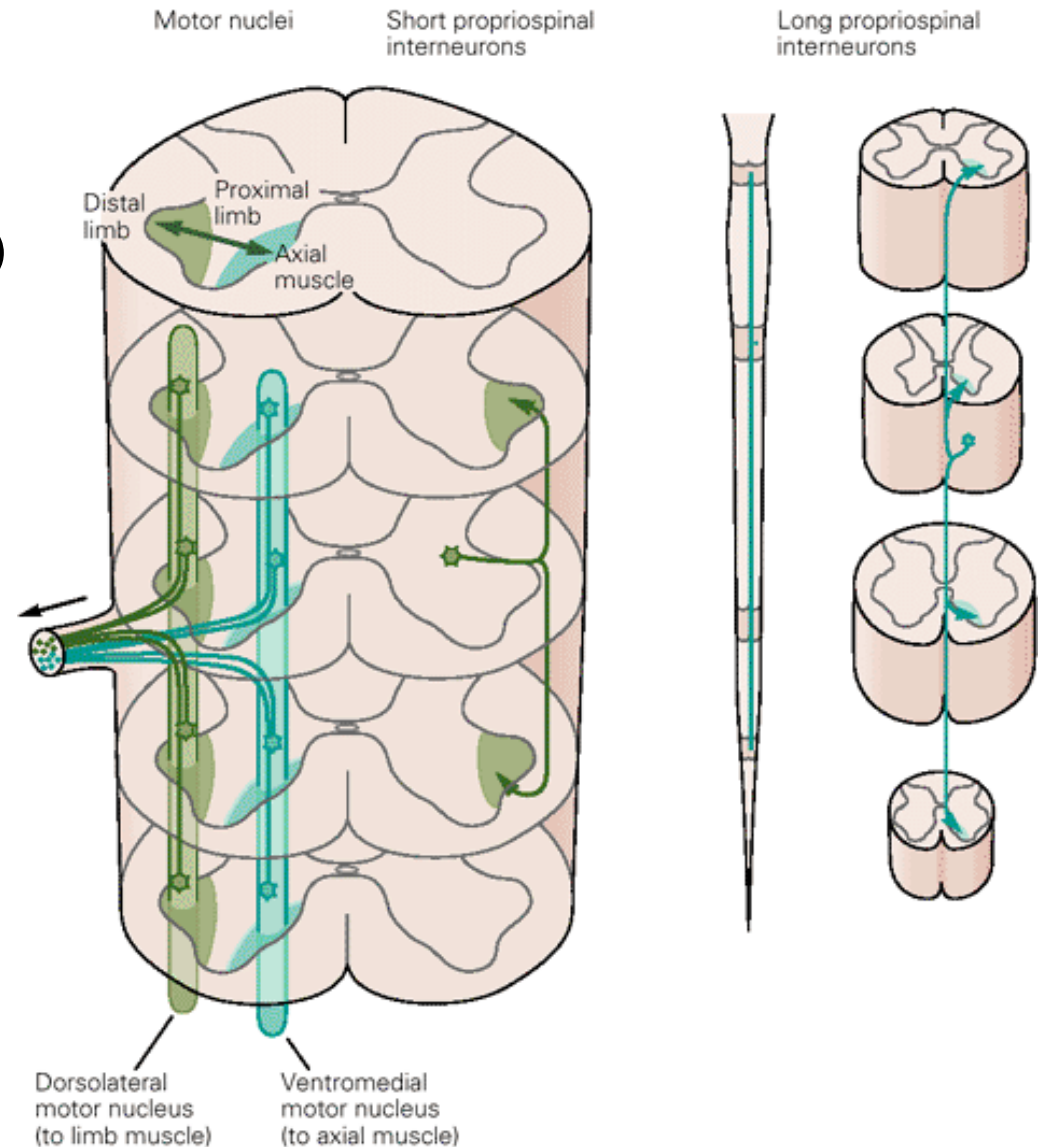
# Spinal cord, Brain stem and spinal tracts

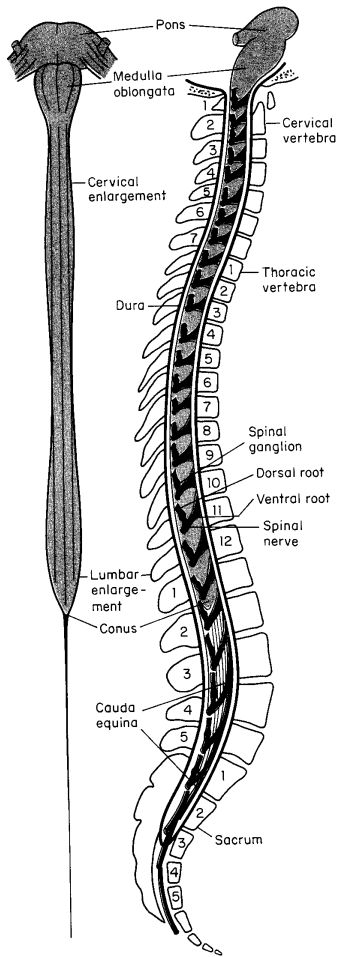
# Spinal cord

1. Local interneurons
2. Propriospinal (across segments)
3. Projection (to upper centers)
4. Motor neurons

**Motor nuclei:** cell bodies of motor neurons that innervate a muscle.

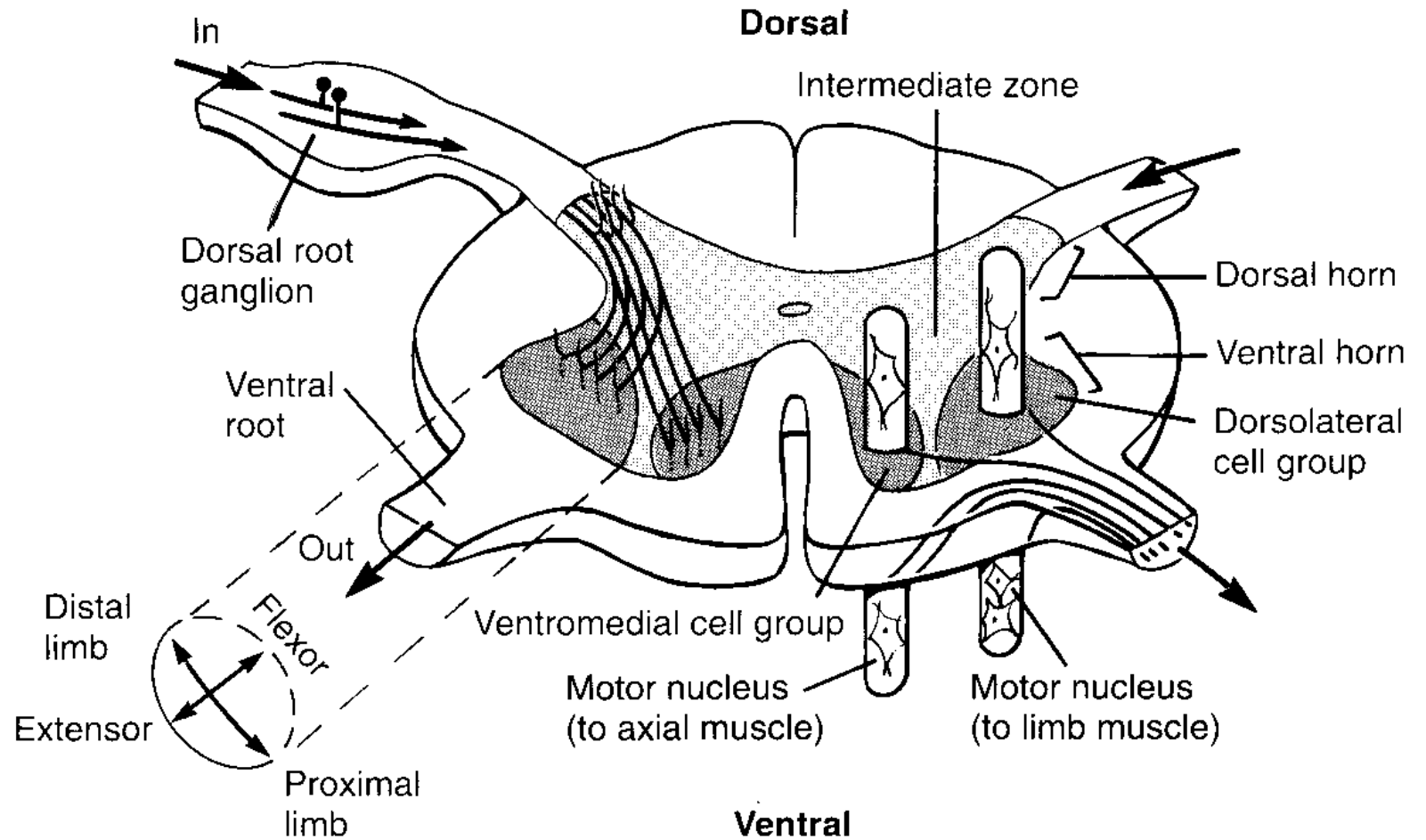
Medial nuclei are long across segments  
Lateral are shorter





Course of afferent fibers

Location of motor nuclei

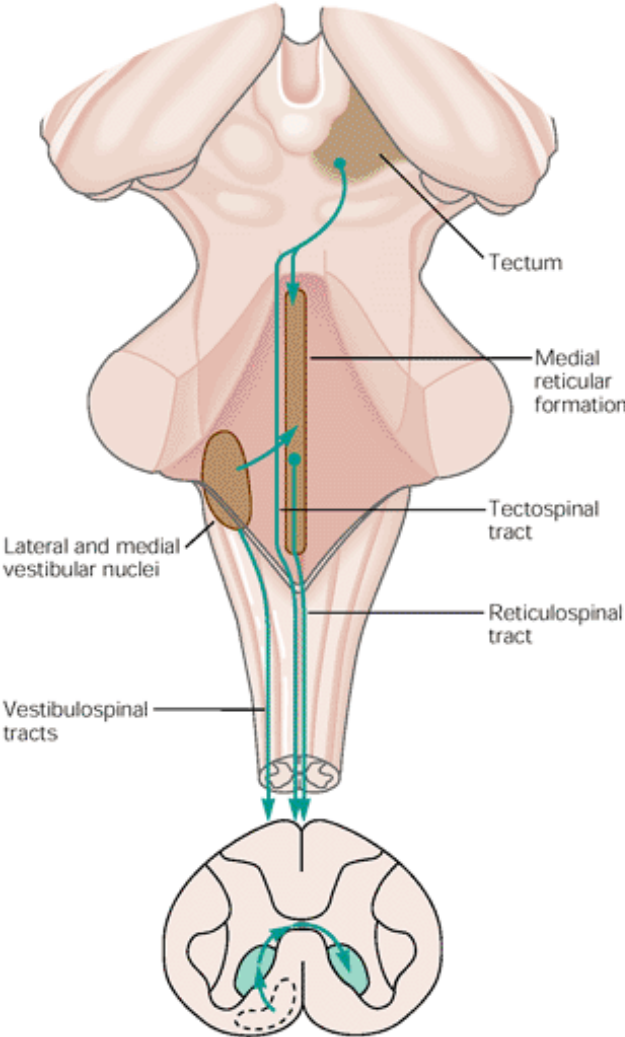


# Brain stem pathways

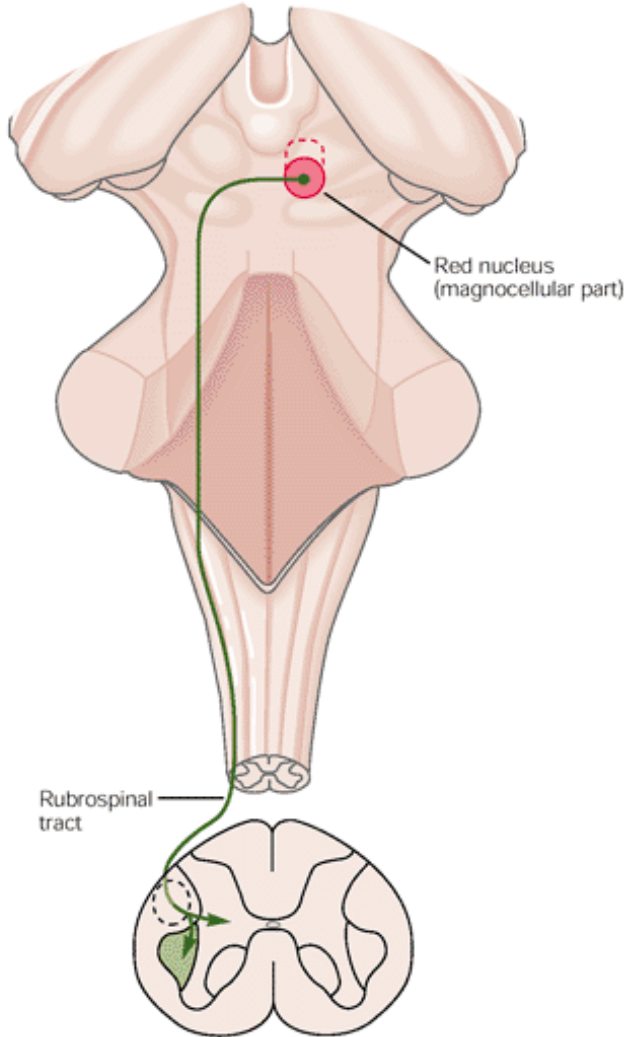
**Medial** pathways (vestibulospinal, reticulospinal, tectospinal), terminates in ventromedial (axial) for postural control.

**Lateral** pathways (rubrospinal) terminates in dorsolateral.

A Medial brain stem pathways

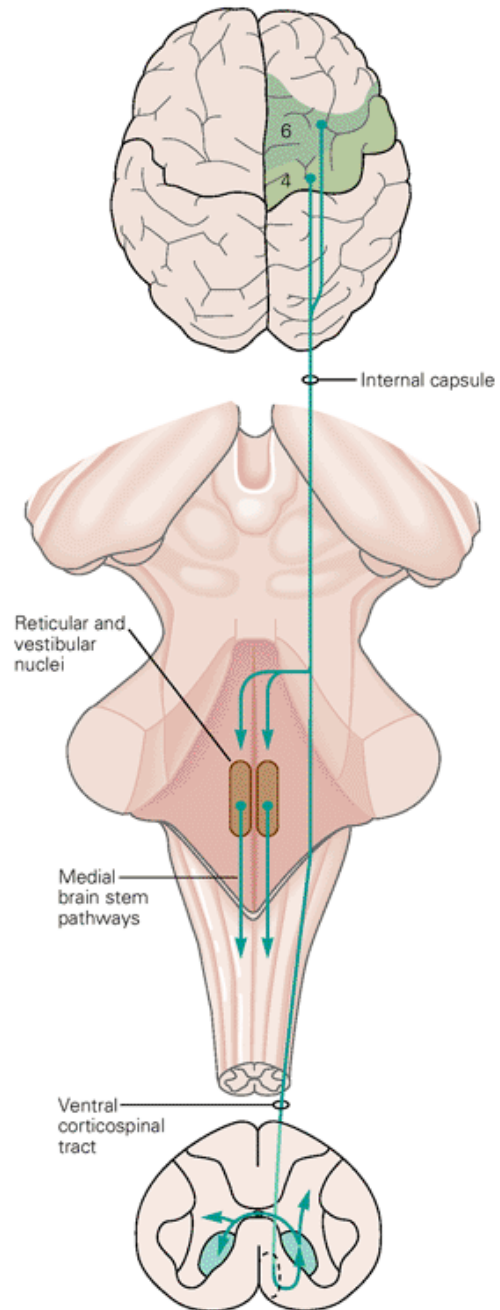


B Lateral brain stem pathways

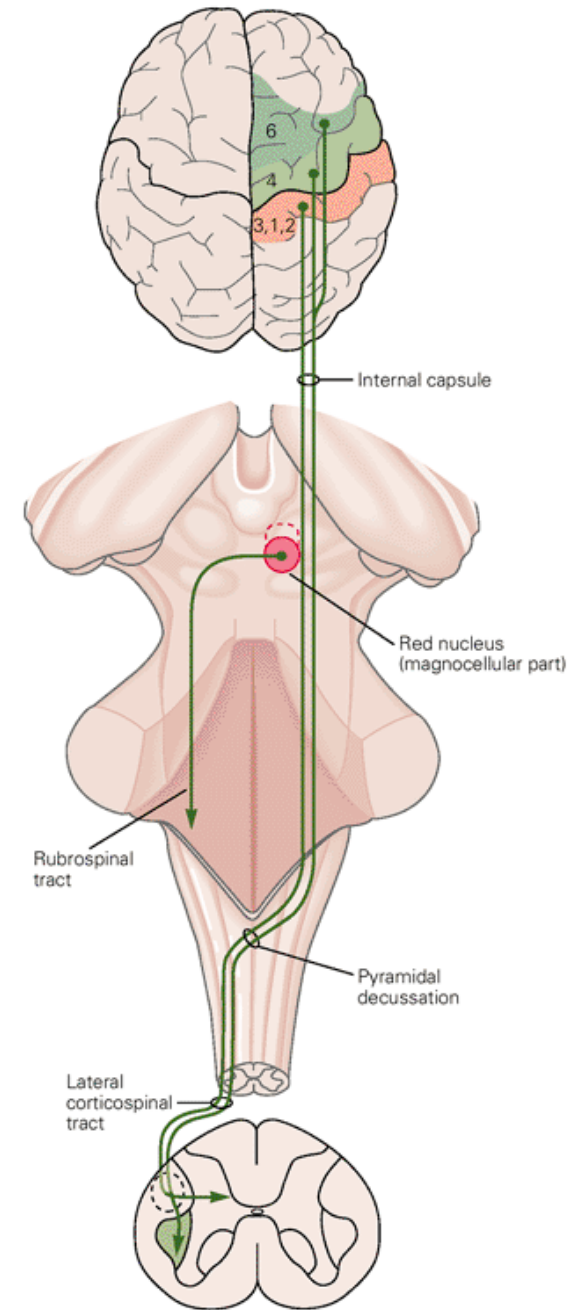


# The corticospinal tract

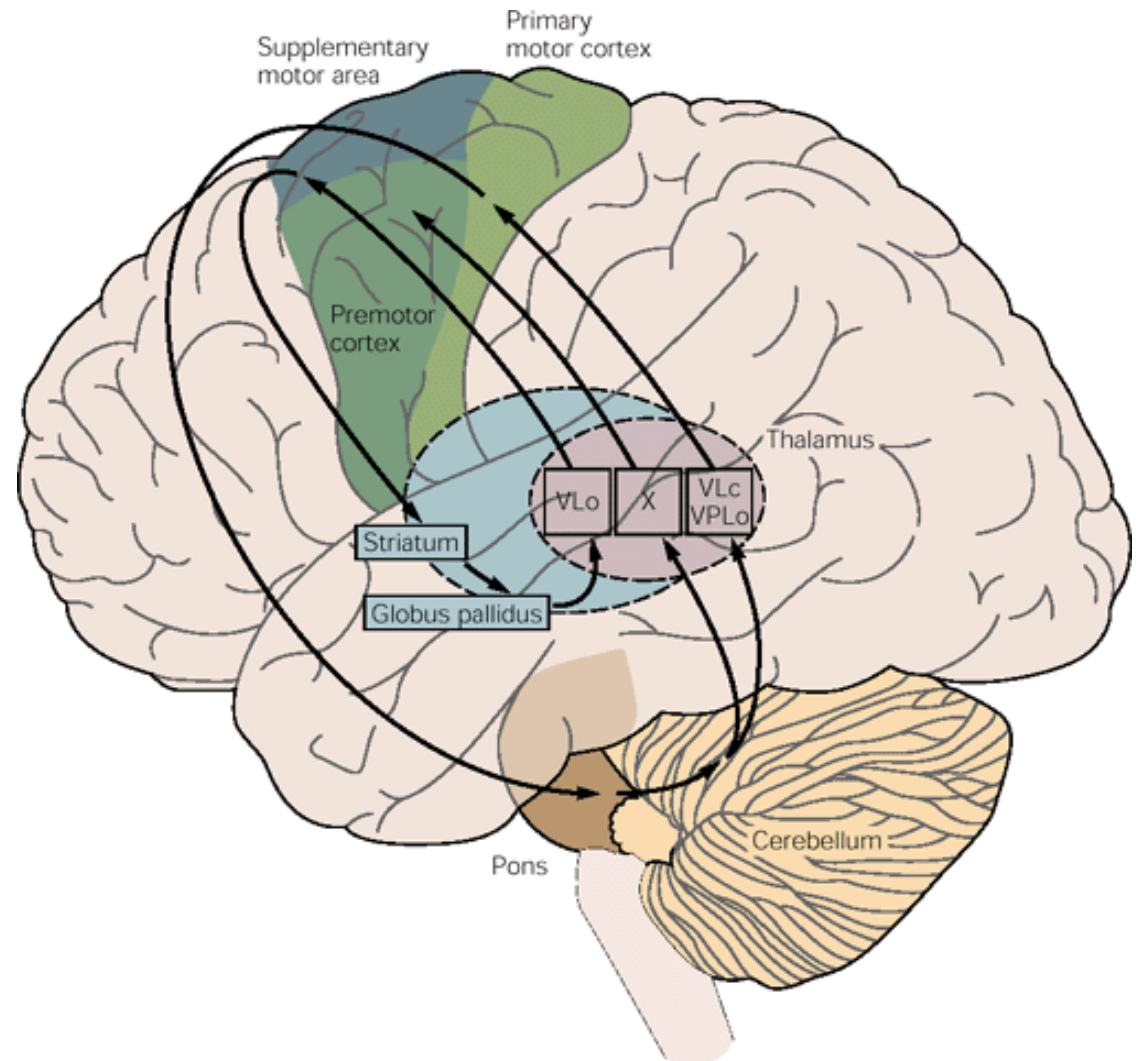
A Ventral corticospinal tract

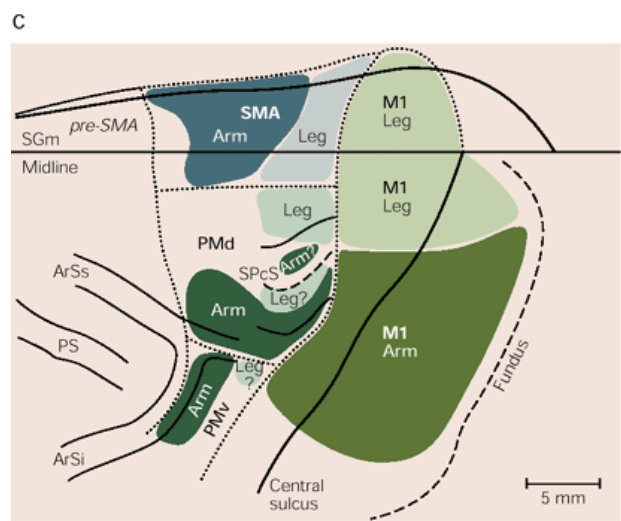
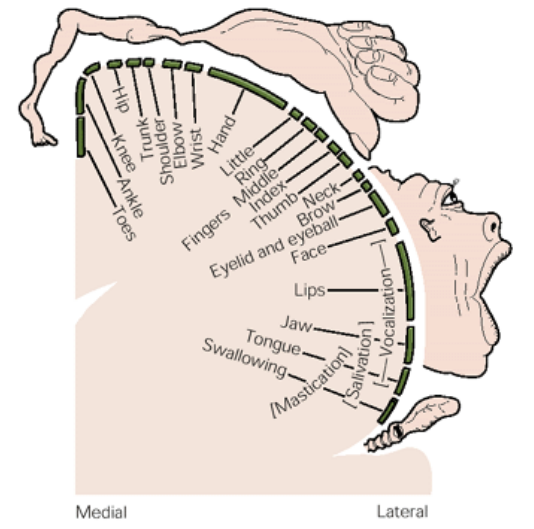
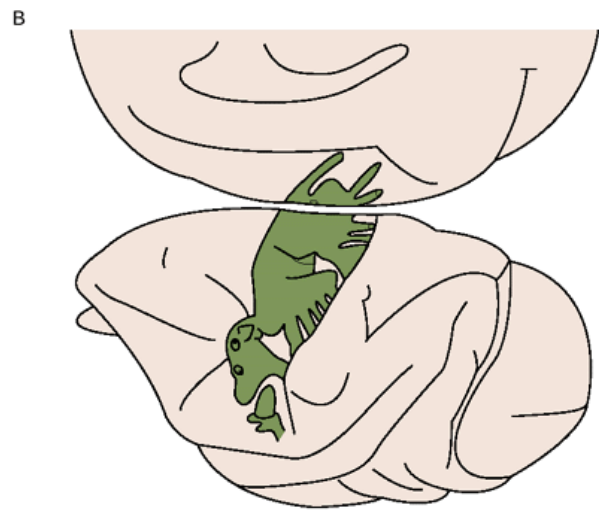
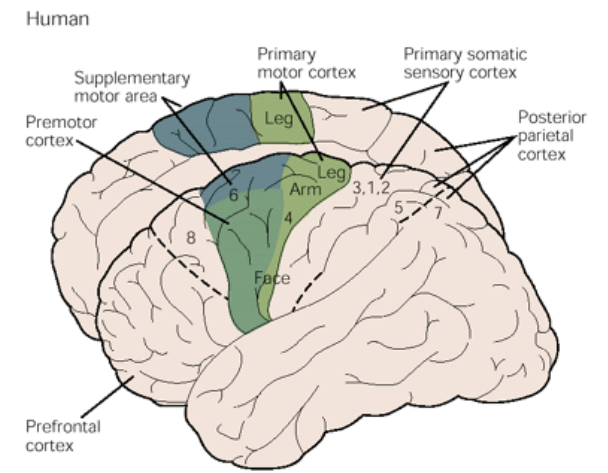
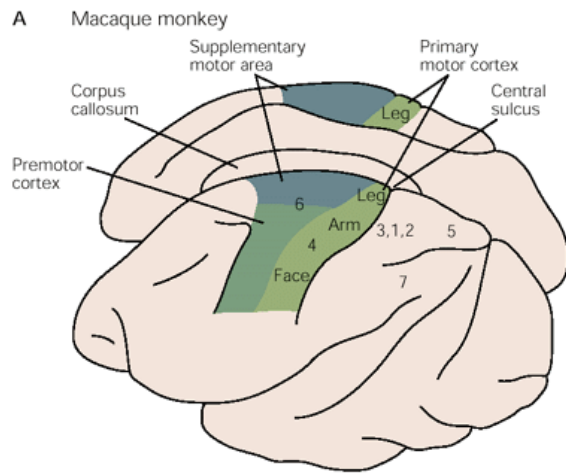


B Lateral corticospinal tract



# Cortex and control of voluntary movement





# Somato-topical organization

# Stimulation in M1

Electrical and magnetic stimulation

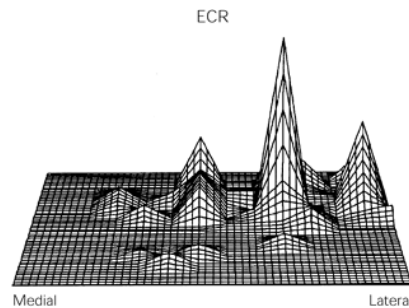
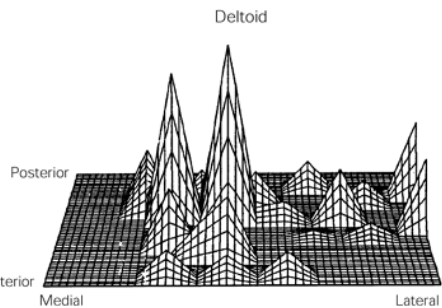
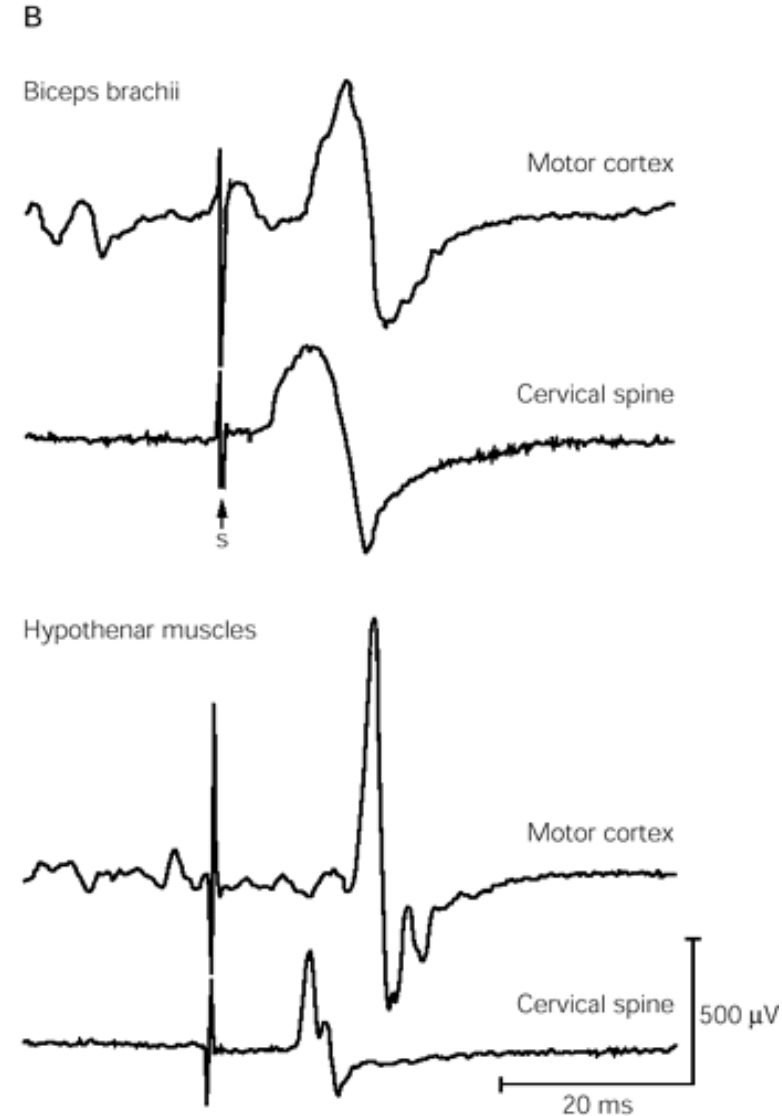
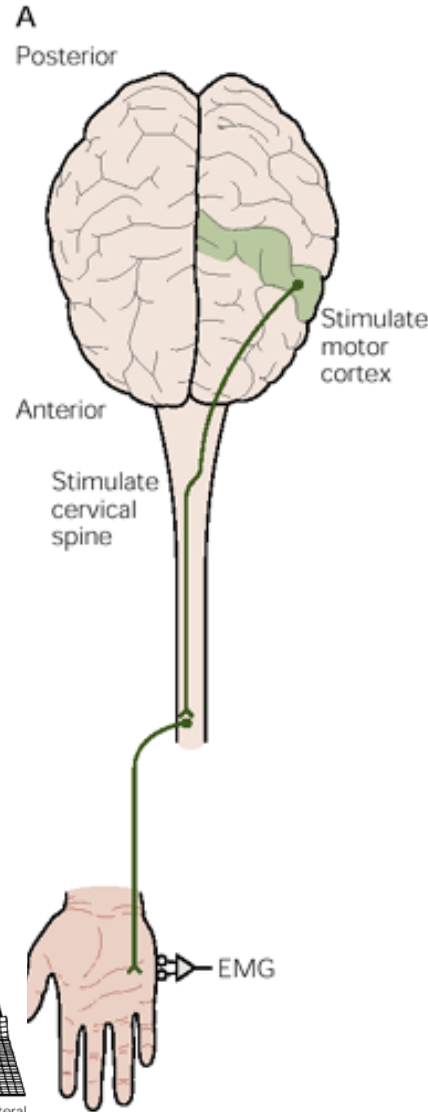
Lowest intensity

Twitch in single muscle/joint

Large (Betz) cells in lamina V

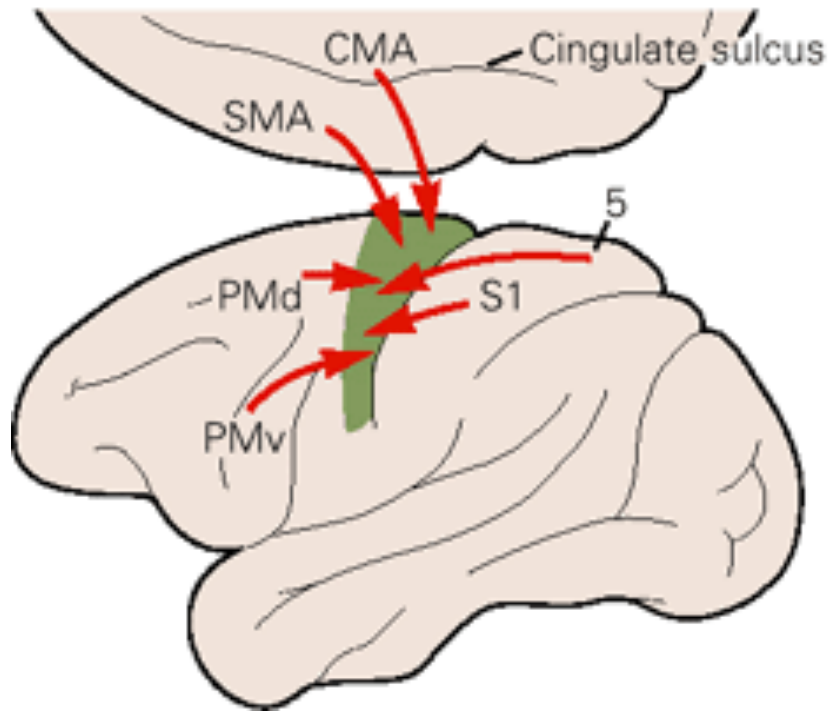
Many locations -> same muscle

Location - > several muscles

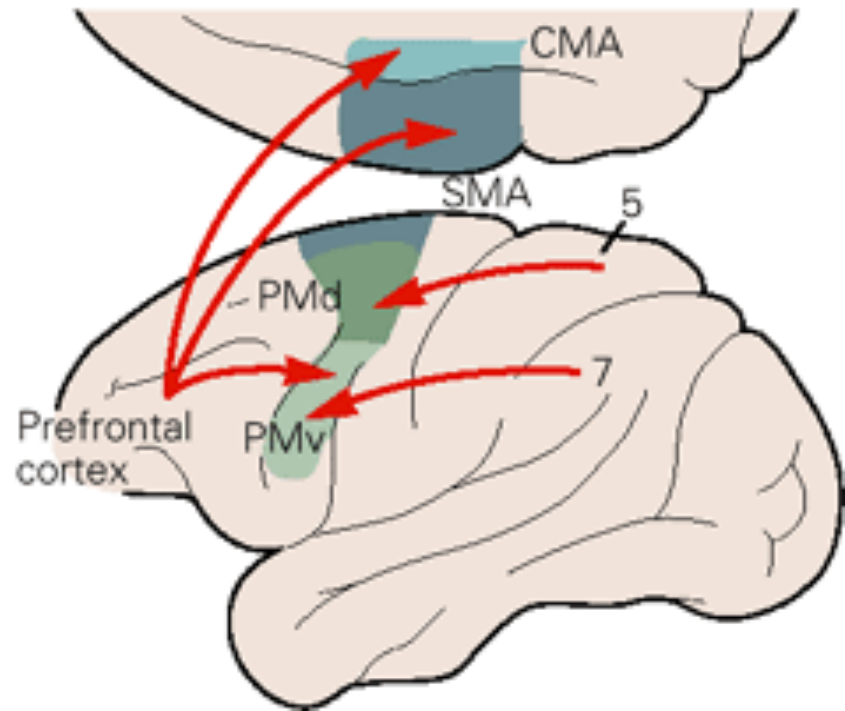


# Cortical inputs

A Inputs to primary motor cortex



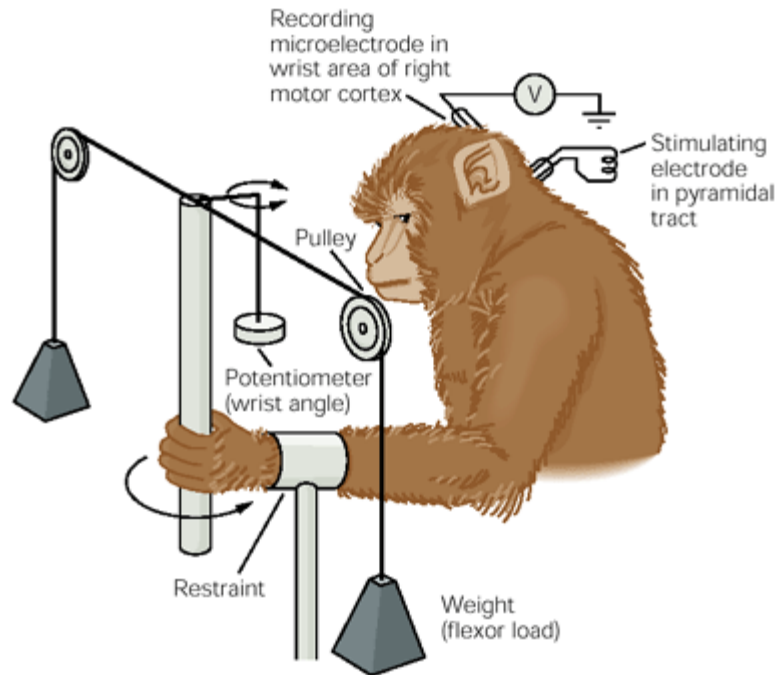
B Inputs to premotor areas



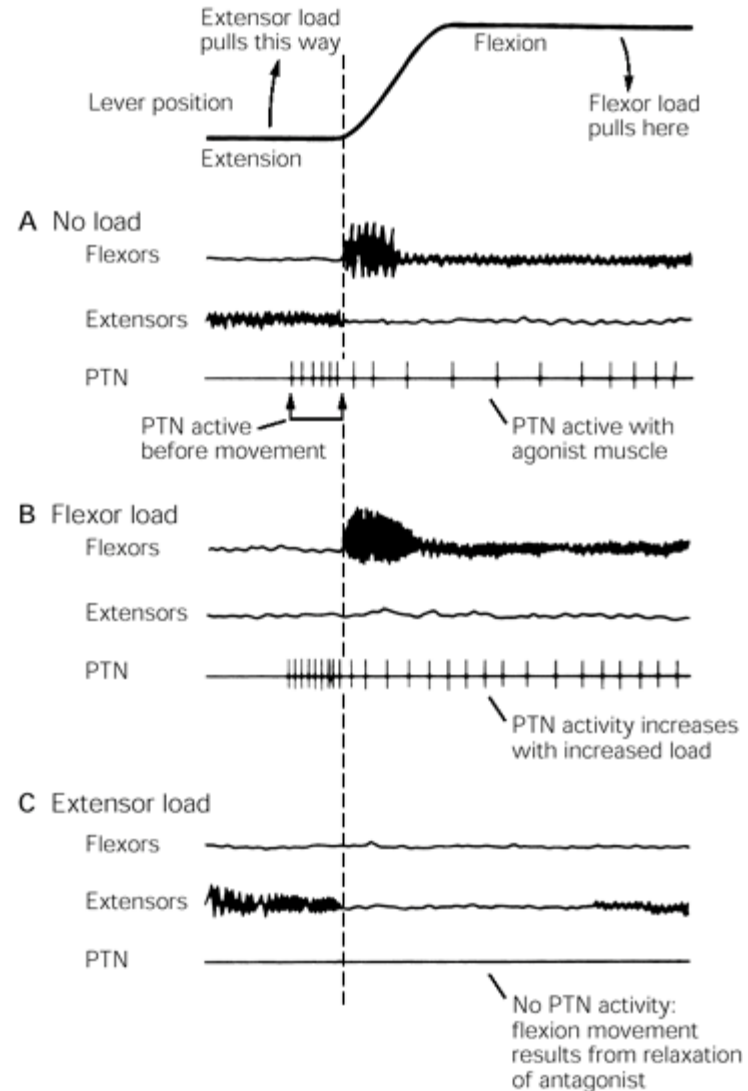
# Coding of force in M1

Evarts, 68

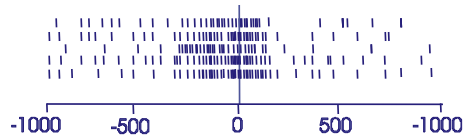
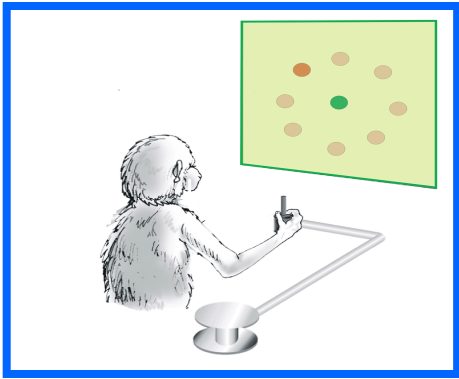
Experimental setup



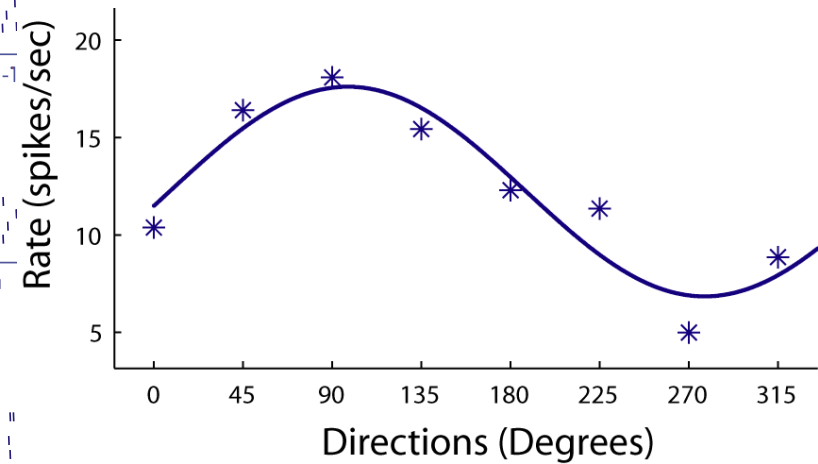
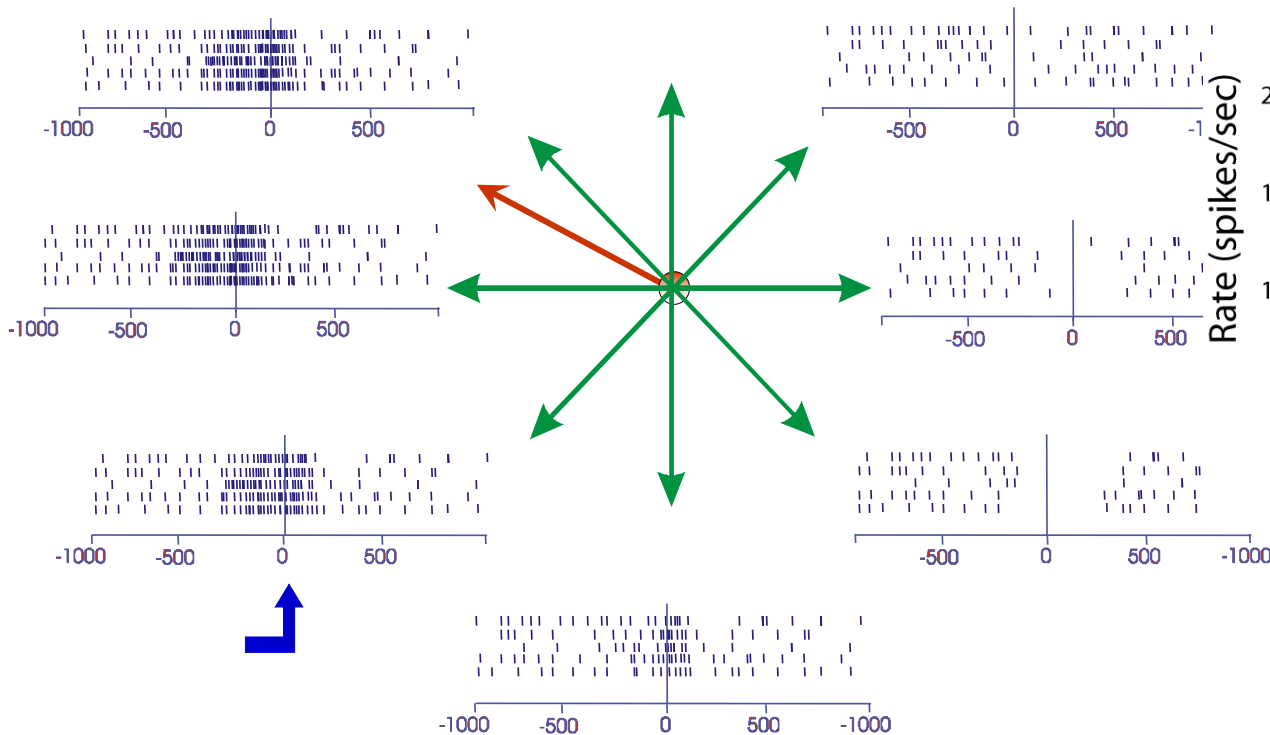
Records of behavior and cell activity



# Coding of external direction



$$fr_i(\overline{MD}) \approx b_i + k_i \cos(\theta_i - \theta_{MD})$$



Georgopoulos 1982

# Kinematics vs. dynamics

Extrinsic variables (end-point velocity/ position):

- Relative to torso

- Relative to eye

- Relative to shoulder

Intrinsic coordinates:

- Muscles shortening velocity

- Muscles tension

Joints' velocity, torque, power.

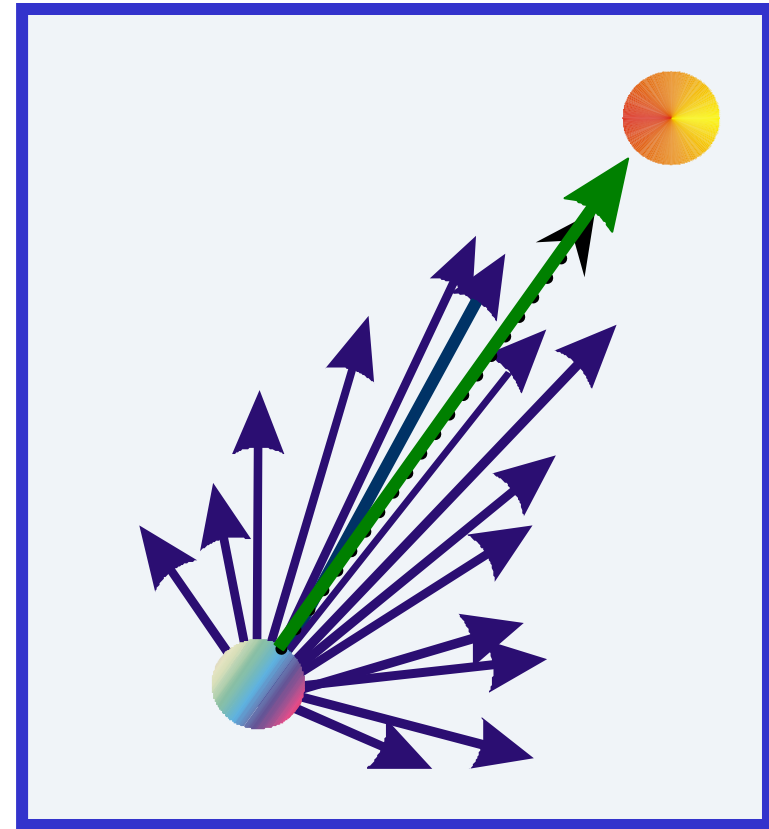
# The population vector

If:

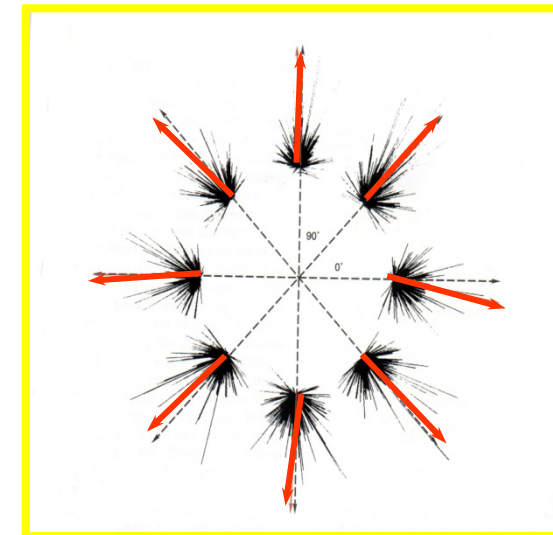
- Many cells “care” about direction of movement
- Cells are tuned “cosine like” with a preferred direction
- Preferred directions are uniformly distributed

Then:

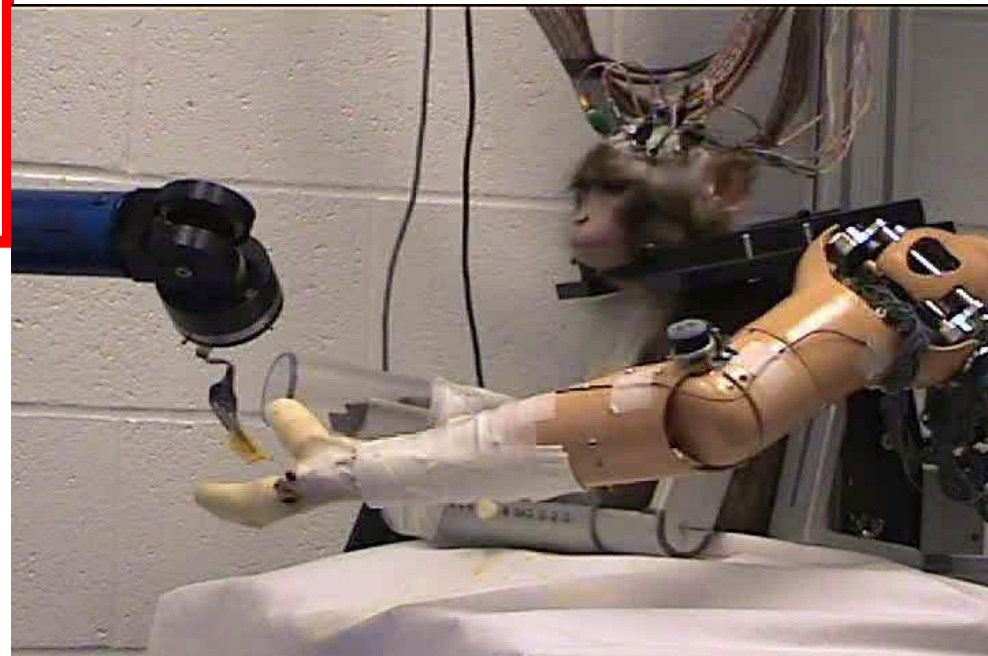
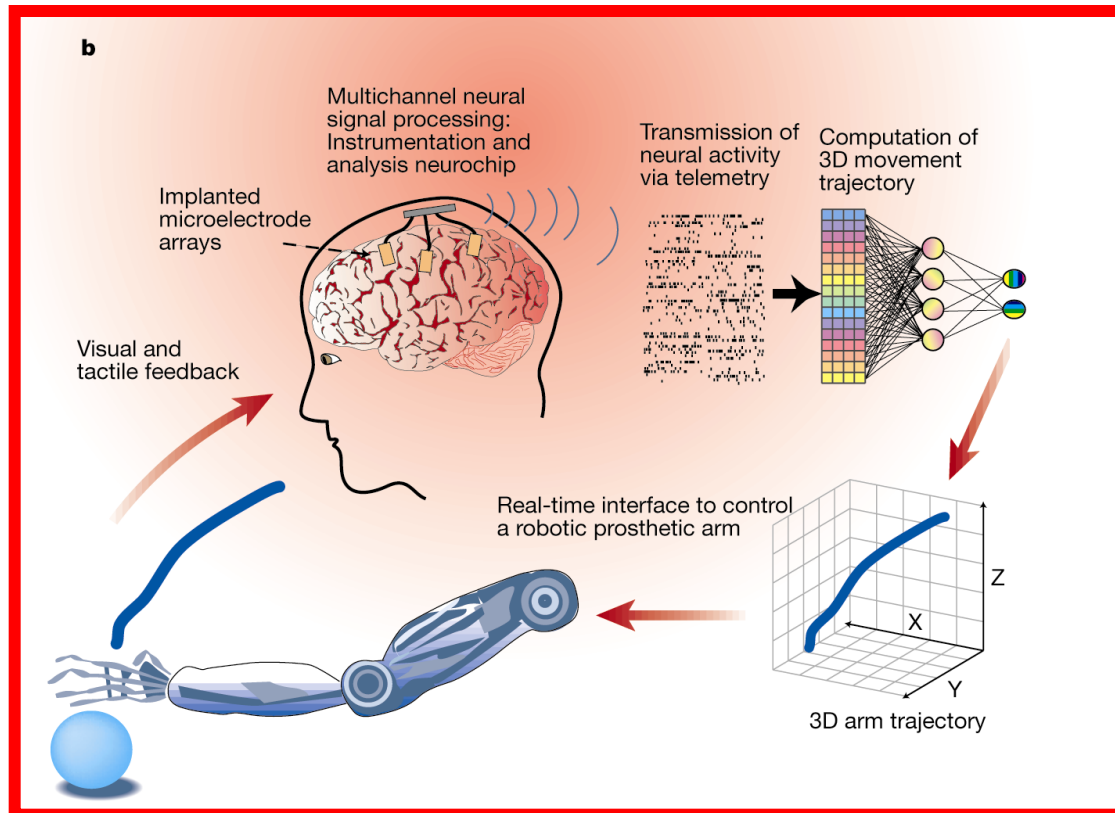
The actual movement can be estimated in Cartesian coordinates by a linear combination of weighting the preferred directions with the actual firing rate



$$\overline{MD} \approx PV = \sum_{i=1}^N w_i \overline{C}_i$$



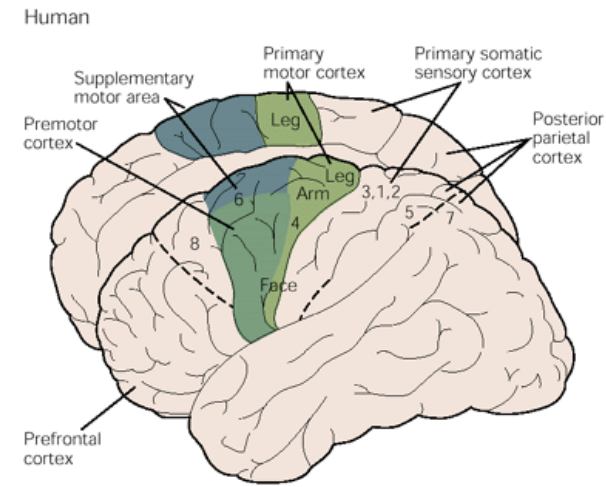
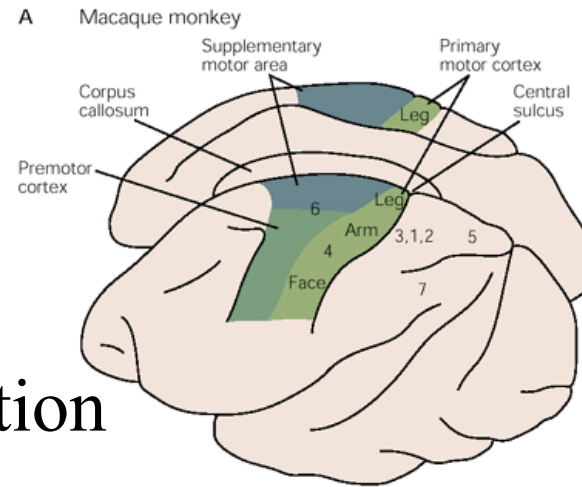
# What can we do with it? Neural prostheses



Schwartz AB

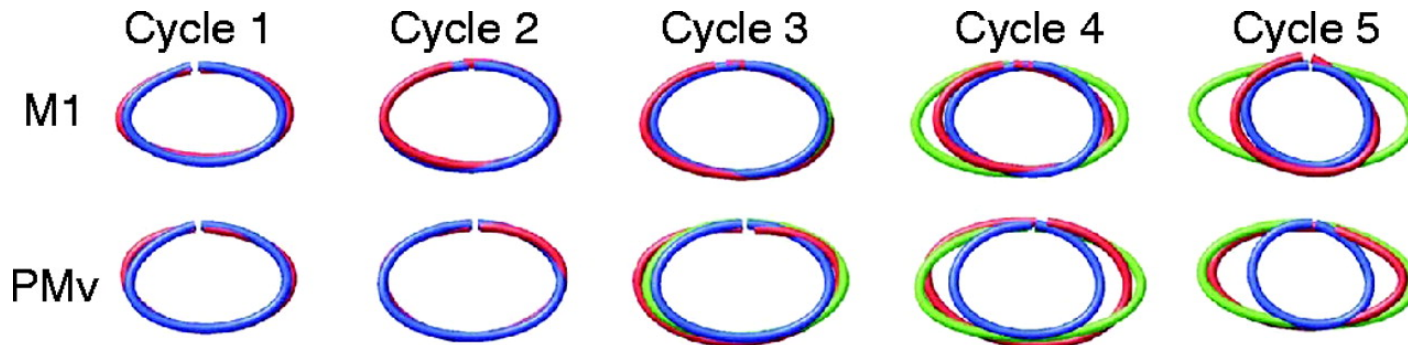
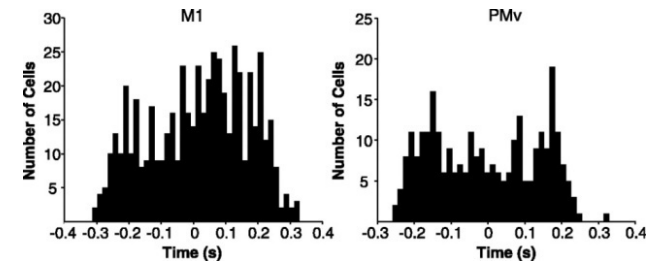
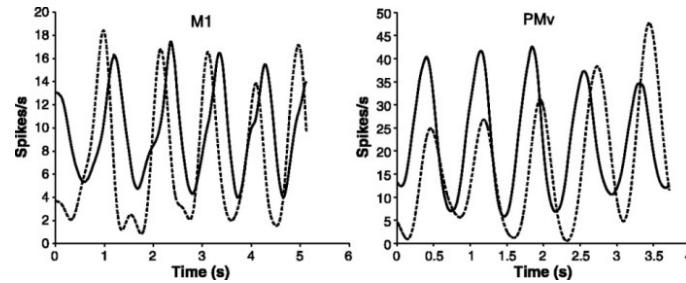
# Premotor areas

Premotor dorsal (PMd), premotor ventral (PMv), supplementary motor area (SMA), cingulate (CMA)



- Multi-joint representation
- Complex, meaningful
- Sensorimotor transformations
- Preparatory (set) activity
- Bimanual coordination (SMA)
- Sequence learning (SMA)
- Self-initiation (PMv, SMA) vs. cue-driven (PMd)
- Language, theory of mind

# Representation of plan and execution



Illusion task trajectories. Top row is five cycles from M1 units. Bottom row is from the PMv. The hand trajectory is blue, cursor trajectory is green, and neural trajectory is red. Each displayed trajectory is the mean across five repetitions

# The basal Ganglia

