The motor system

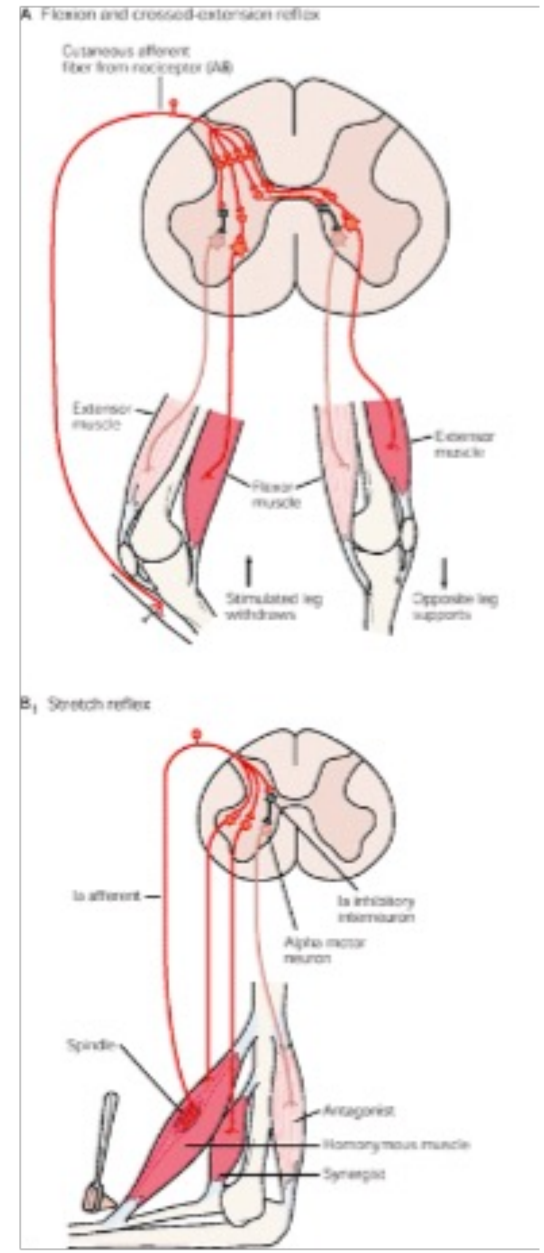
To move things is all that mankind can do…
whether in whispering a syllable or in felling a forest
C. Sherrington 1920

- 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)



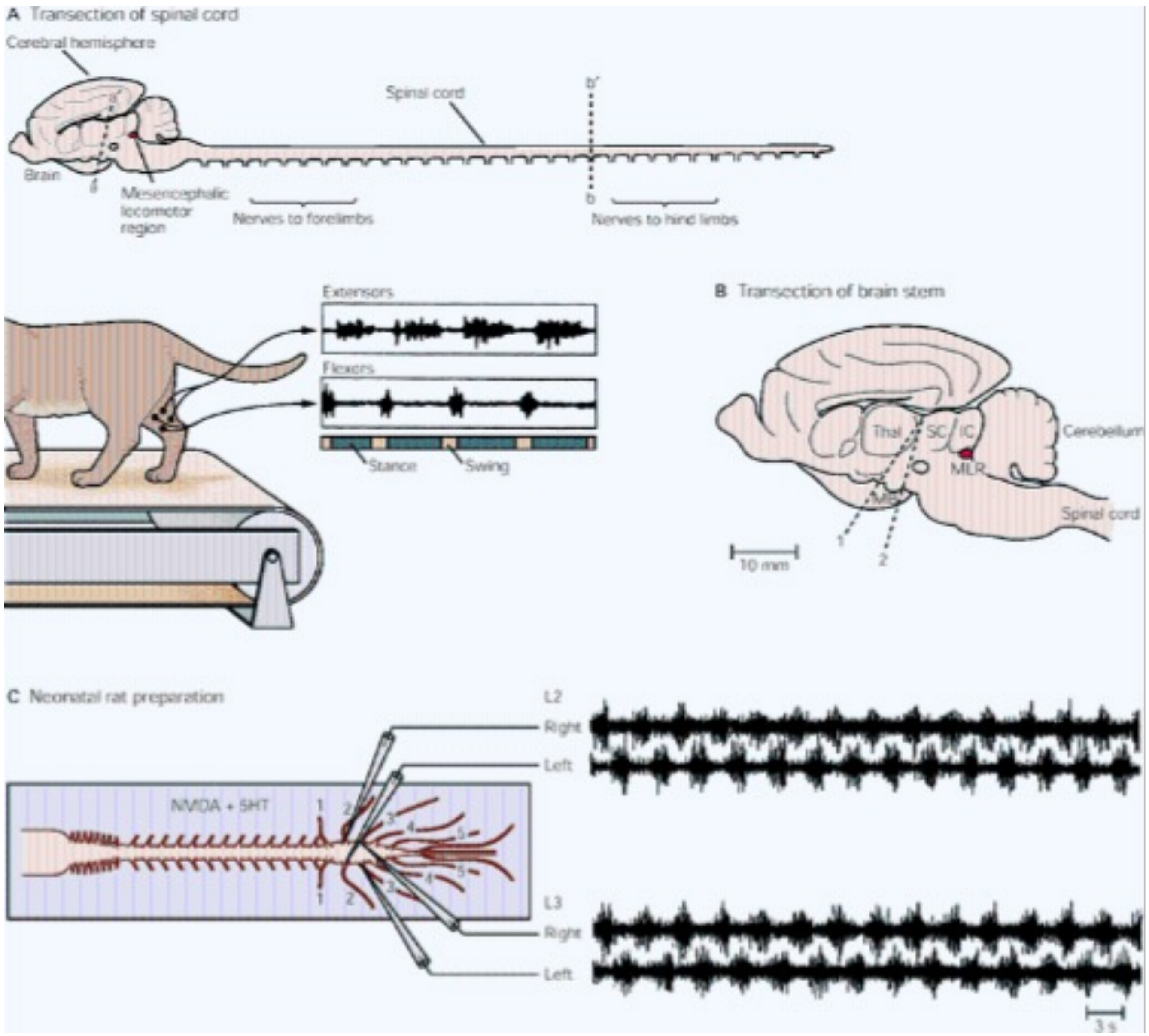
Noxious stimuli excites ipsilateral flexor, and excites contralateral extensor

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

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



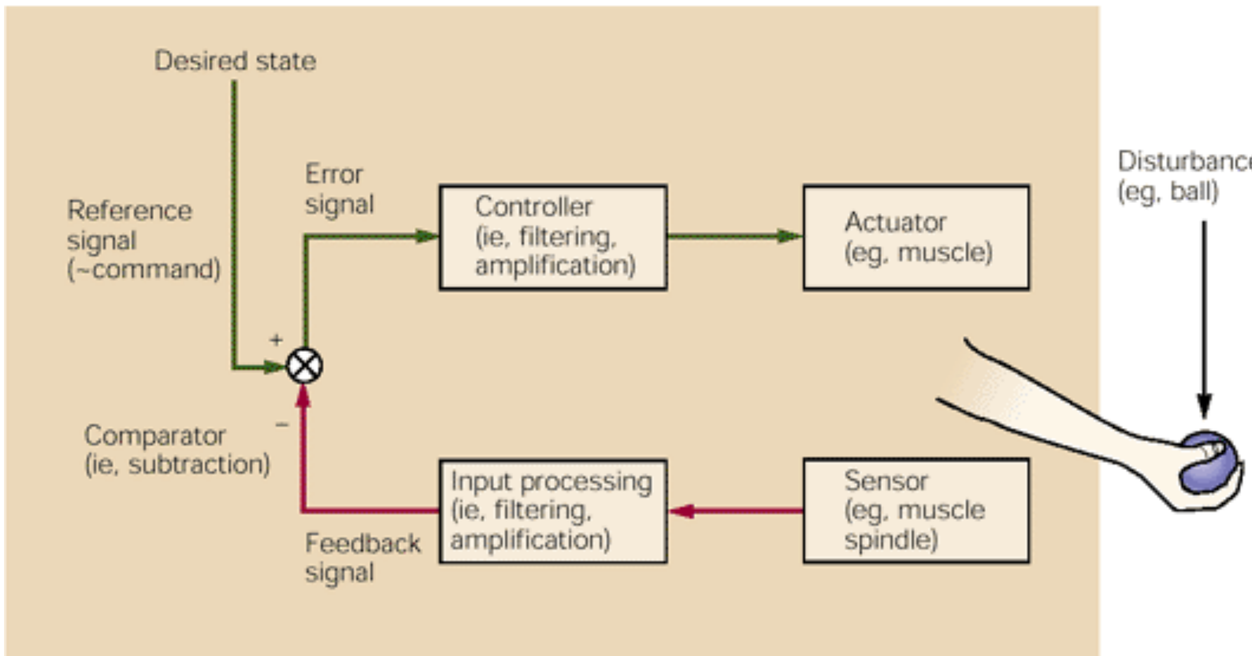
Voluntary movements: principles

Goal directed

Reaching (~120 ms)

Feedback control (error correction)

A Feedback control: command specifies desired state

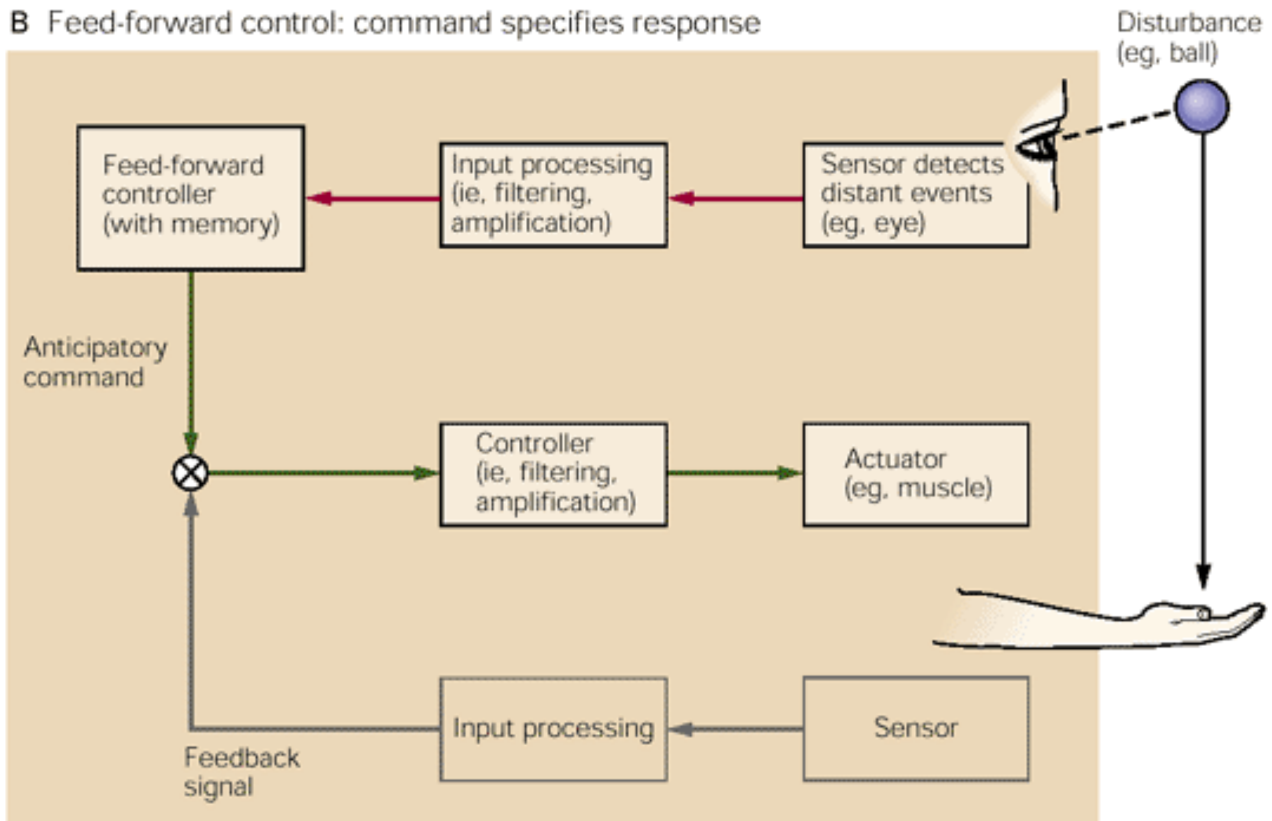


Vision
<u>Proprioception</u>

1. Gain

2. Delay (phase lag)

Feed-forward (open loop)

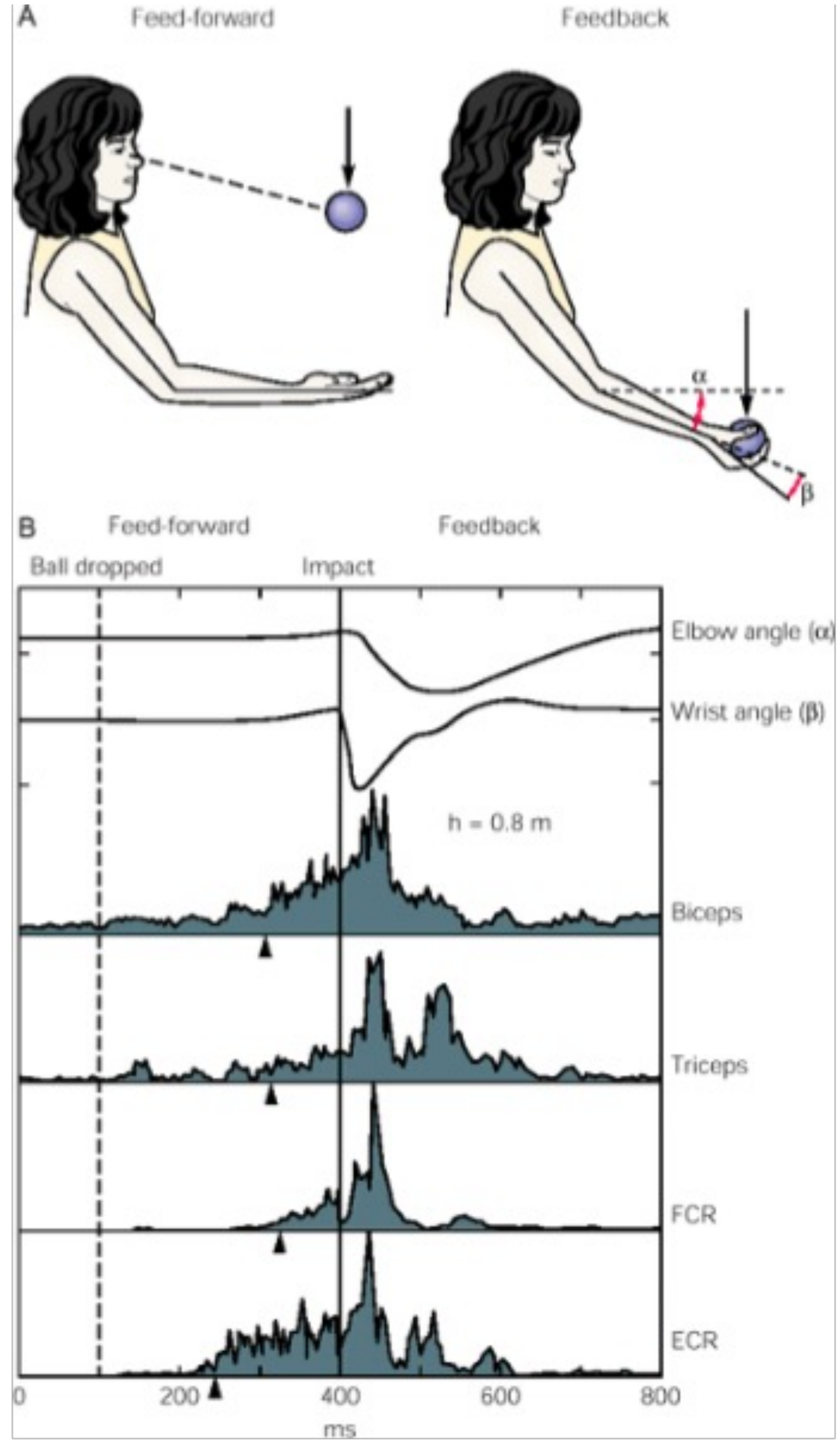


1. Very hard computationally

Feedback control (error correction)

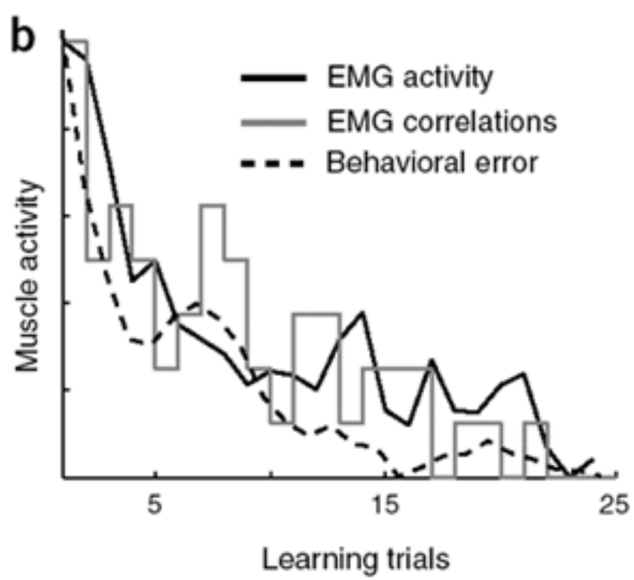
Feedforward (open loop)

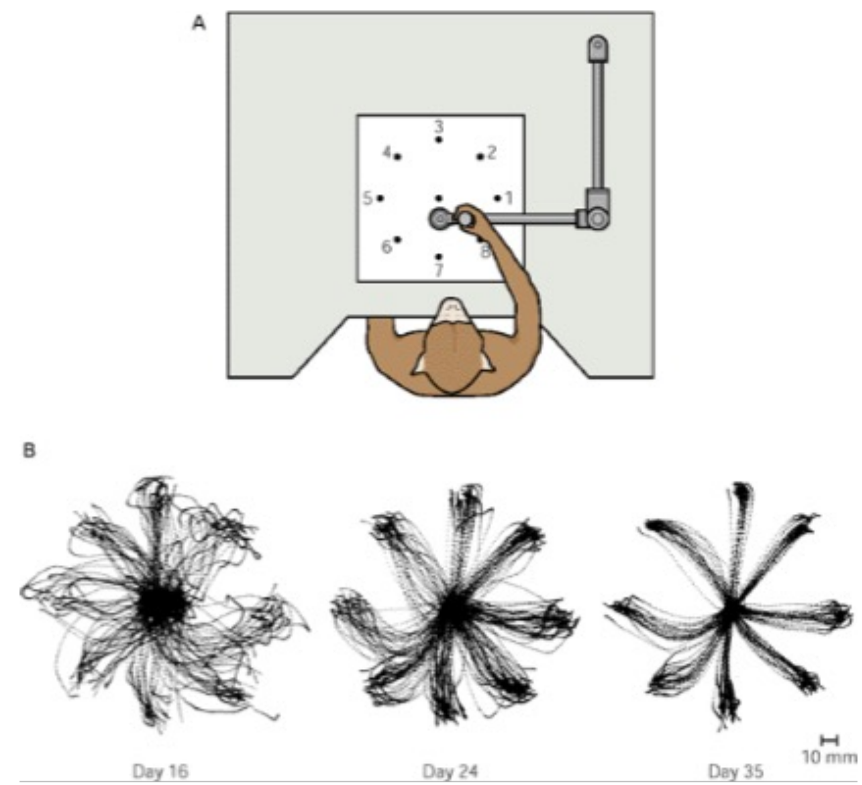
Notice onset of muscles



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).



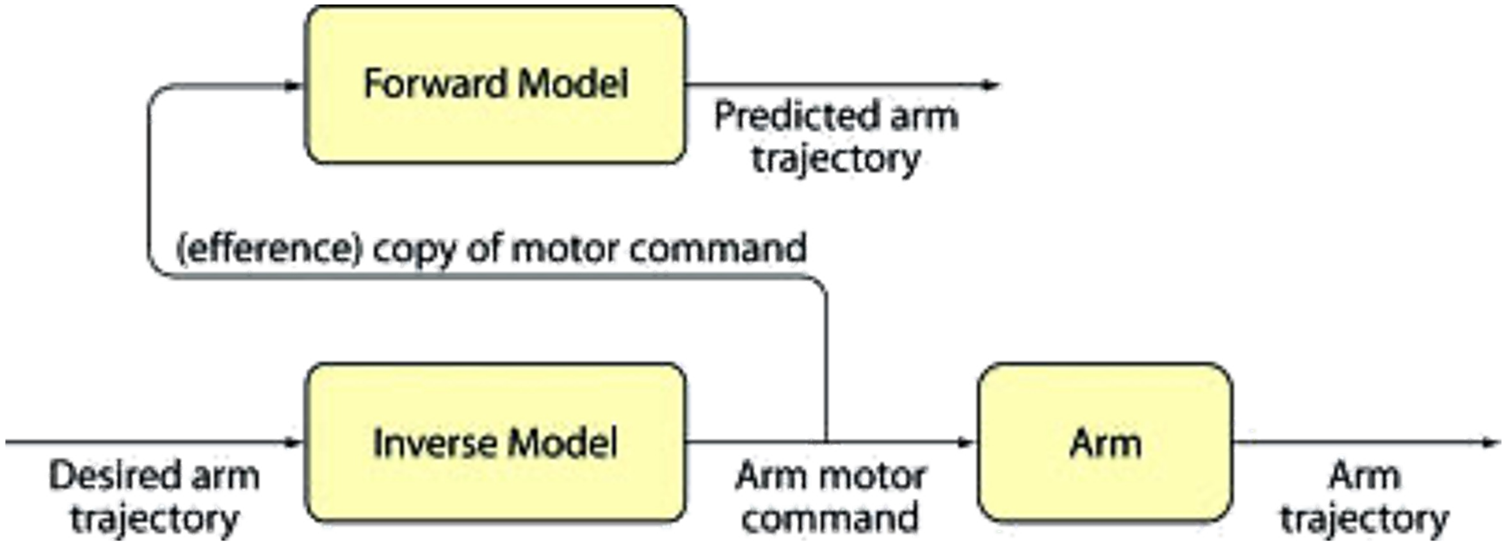


Inverse and forward internal models

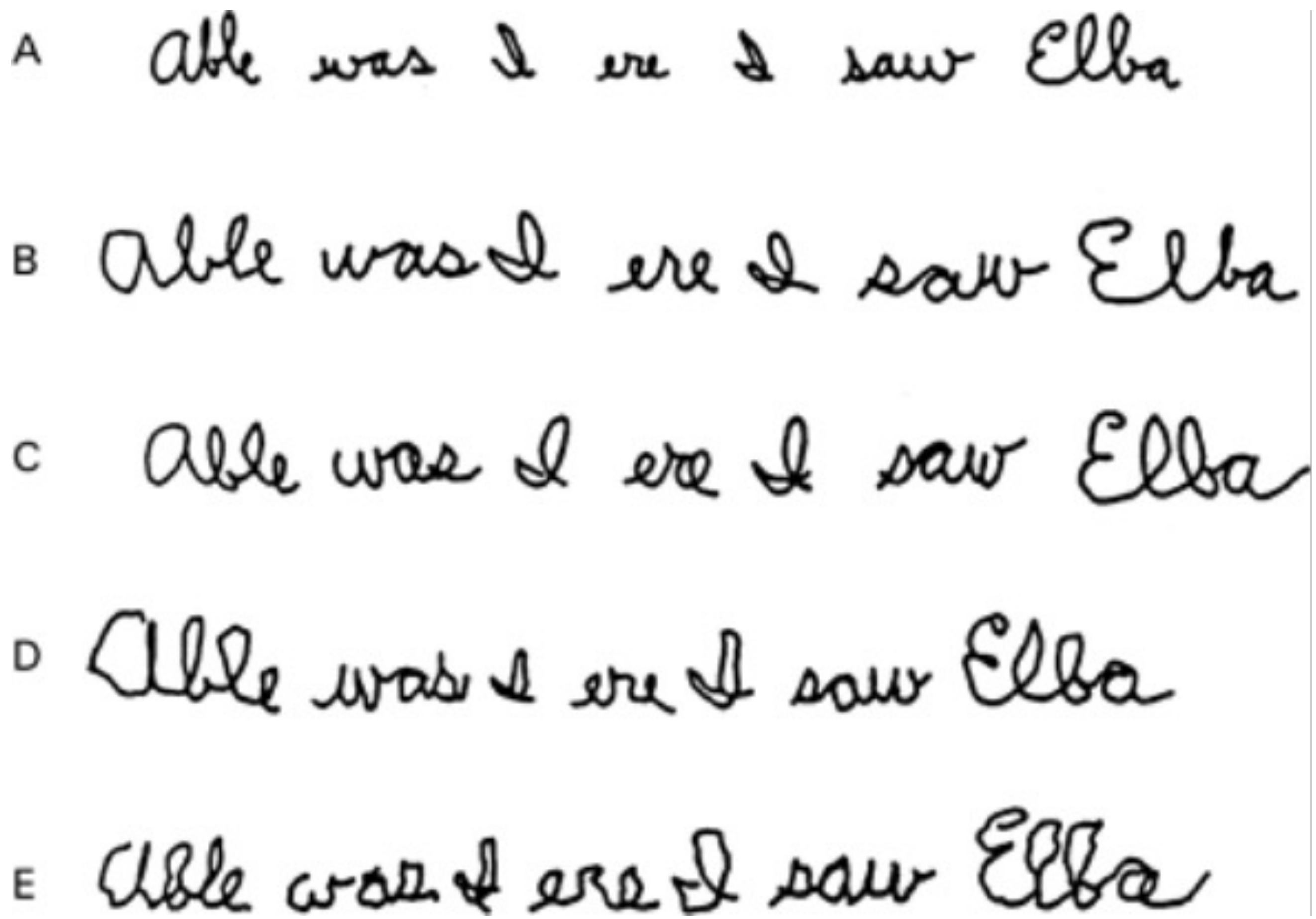
An **internal model** is used either:

- 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*).

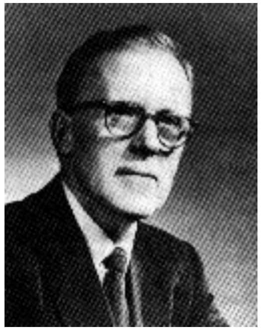


Motor programs and Invariants



Motor equivalence

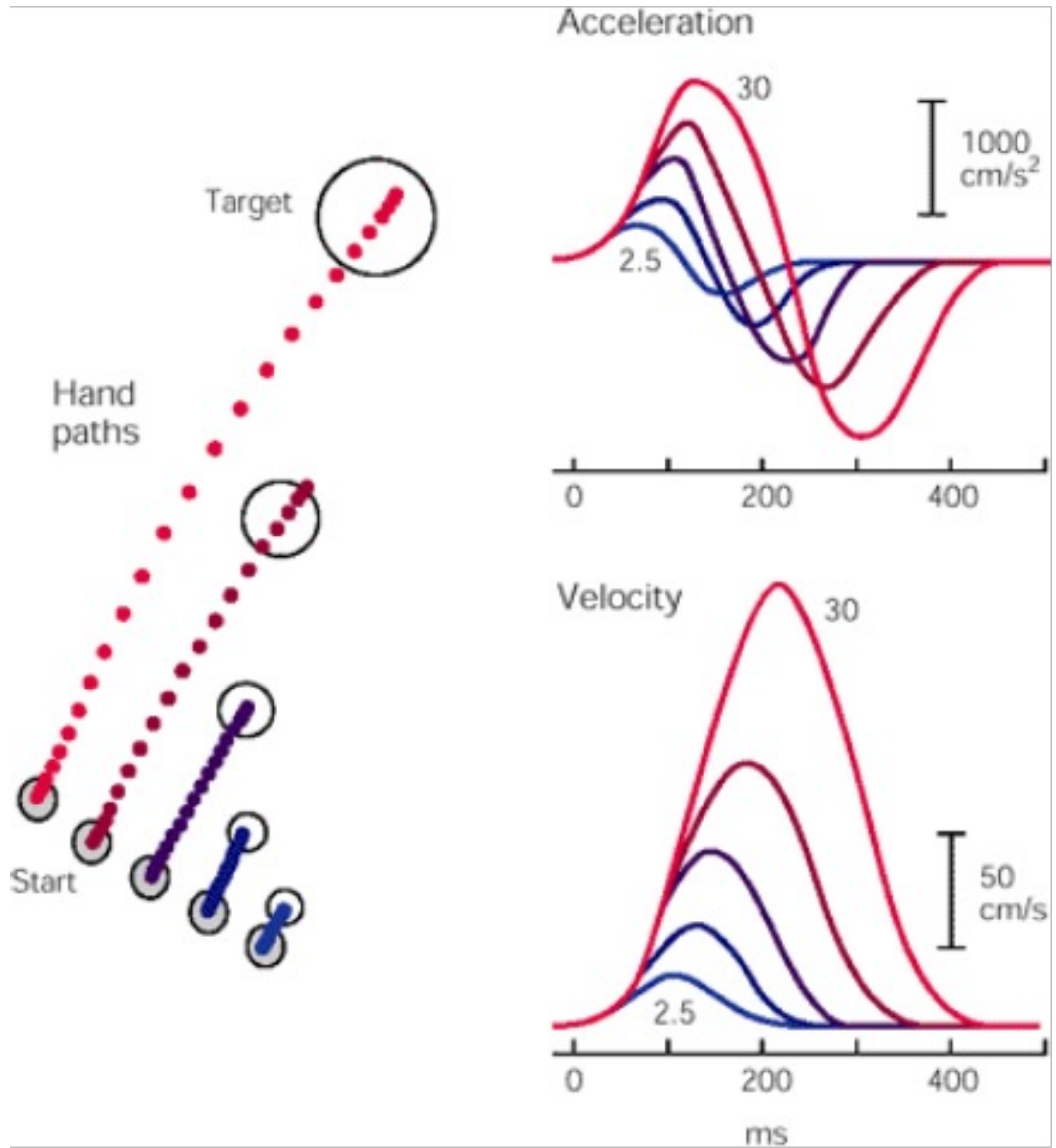
(Donald Hebb, 1950)



Pre-planning in vectors

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

Invariant time (Isochrony)

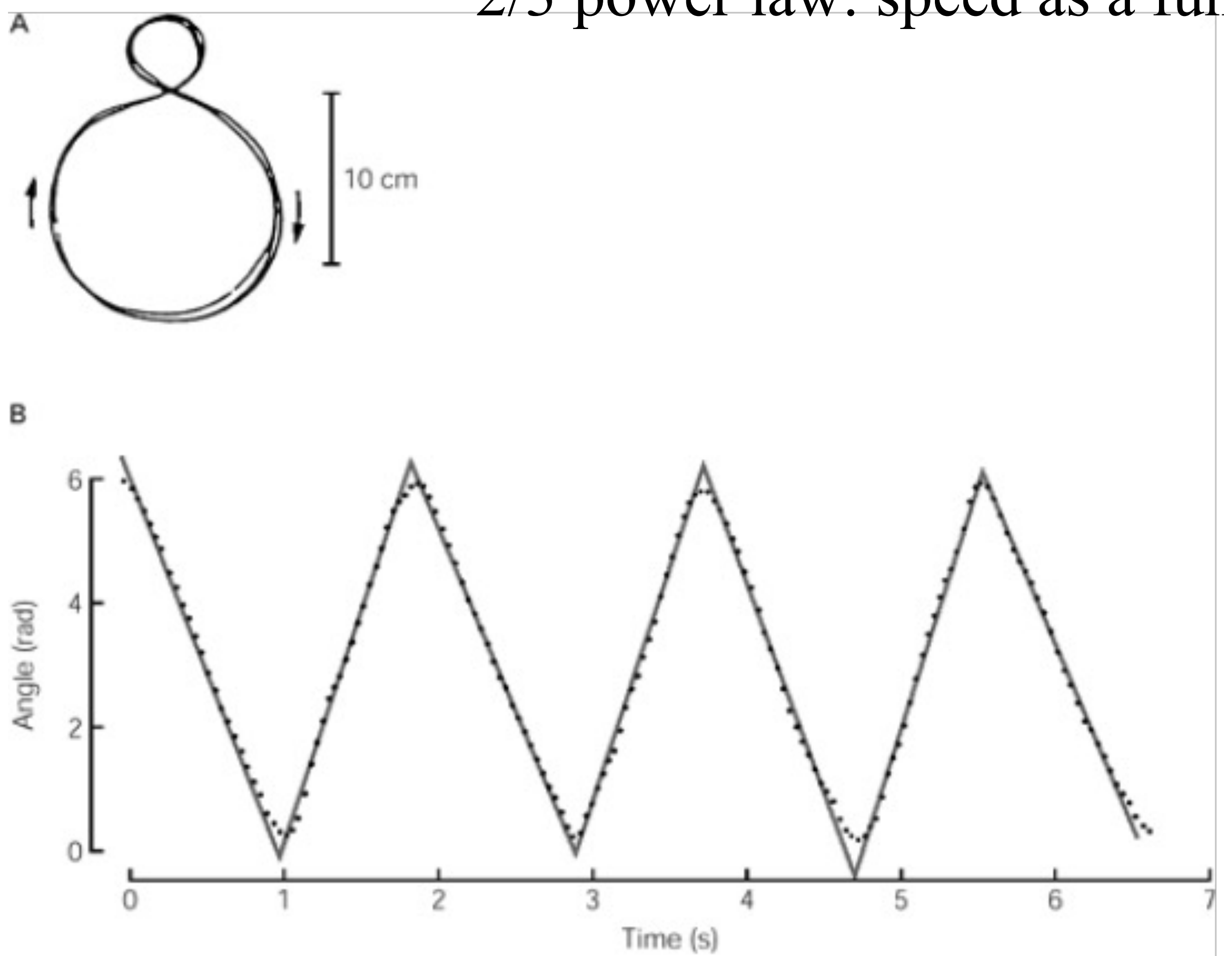


Kinematic transformation: to transform a target position into a command to the skeletal system to move the hand i.e. to convert between coordinate systems;

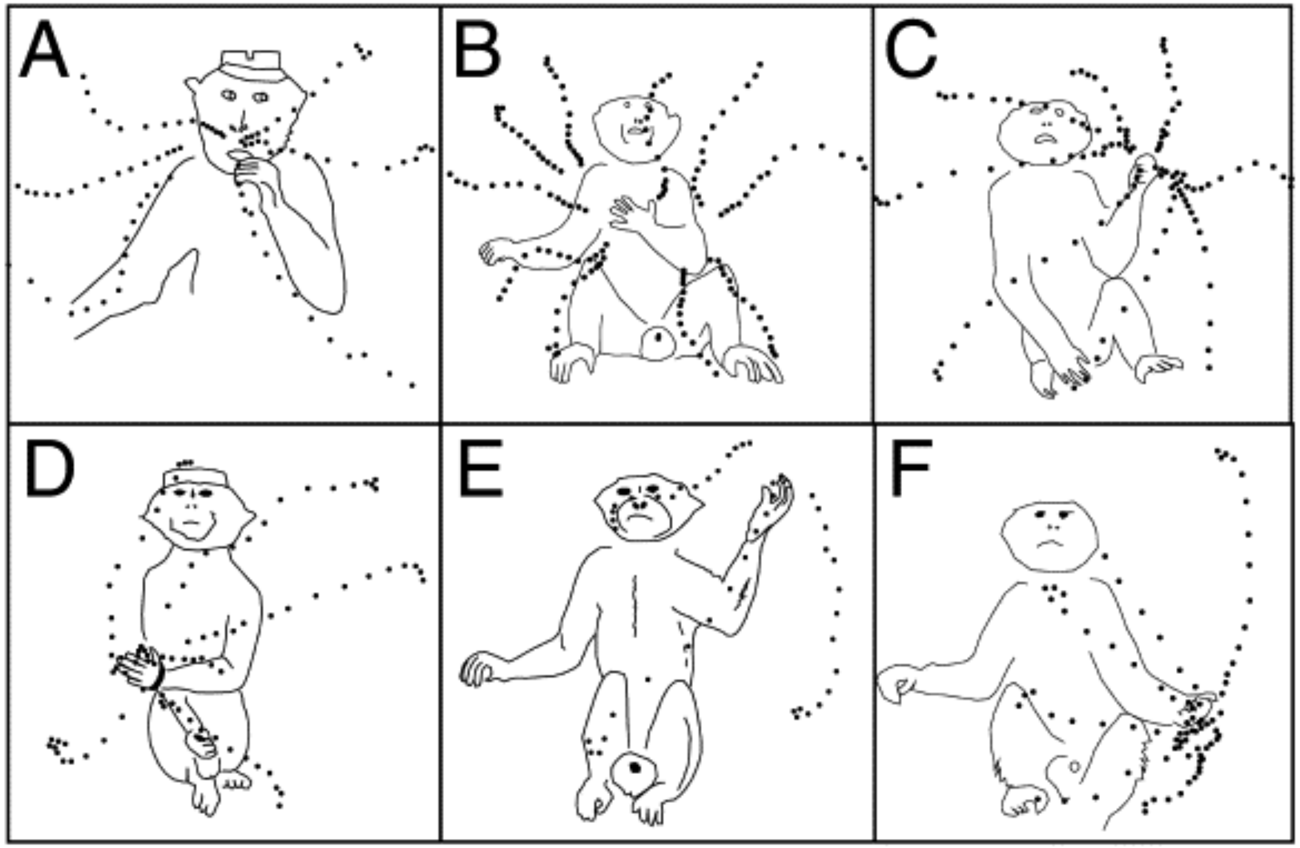
Dynamic transformation: relate motor commands to the motion of the system; in the reaching task here considered, the forces applied changed the system without changing the kinematics.

Building blocks – segmentation - primitives

Isogony (equal angles)
Isochrony (duration independent of length)
2/3 power law: speed as a function of curvature

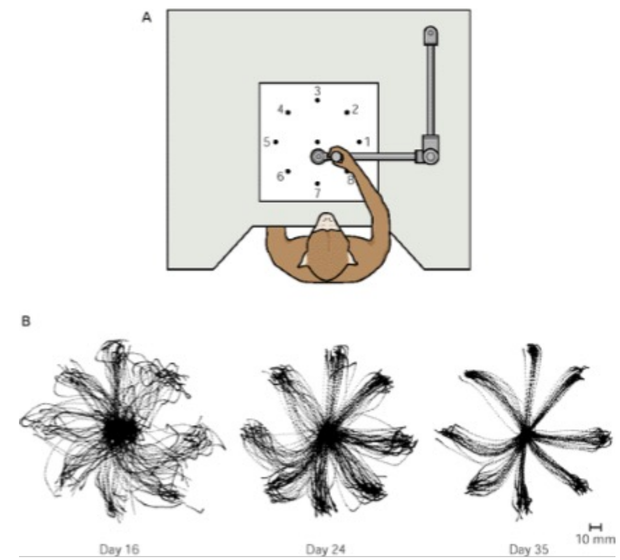


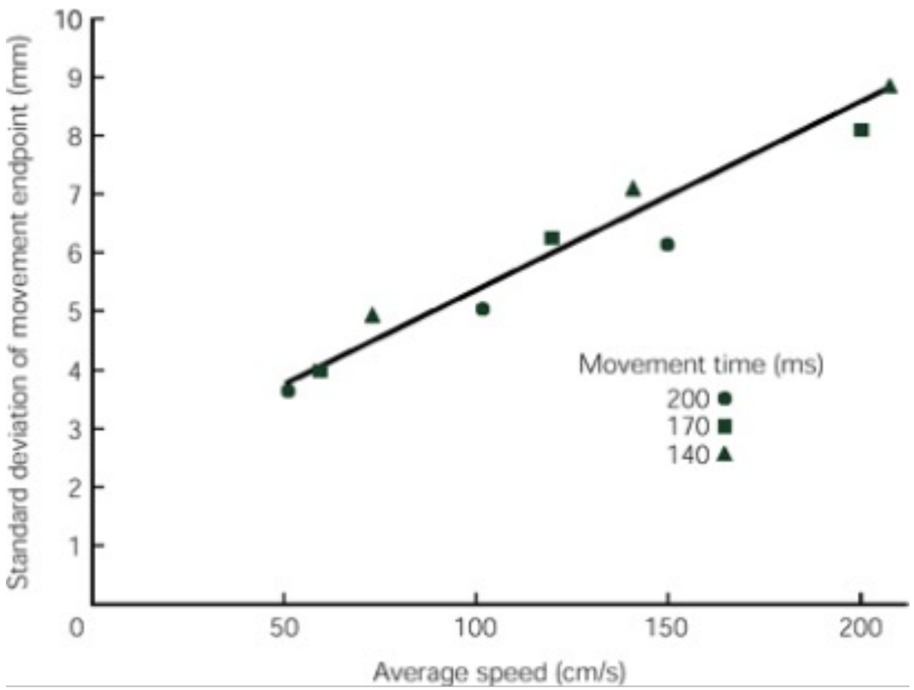
Stable behavioral gestures



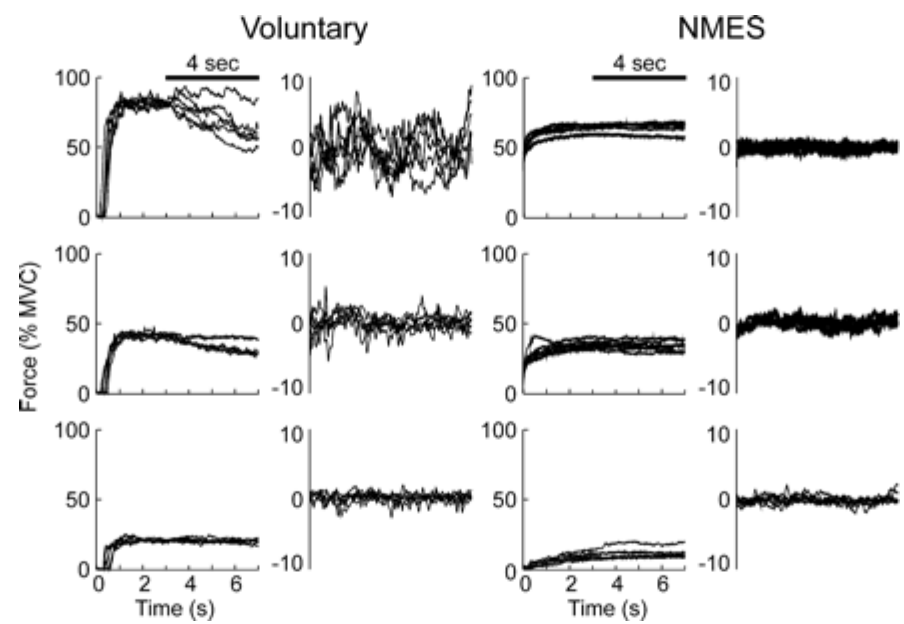
Graziano MS

Speed – accuracy tradeoff (Woodsworth, 1890)





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



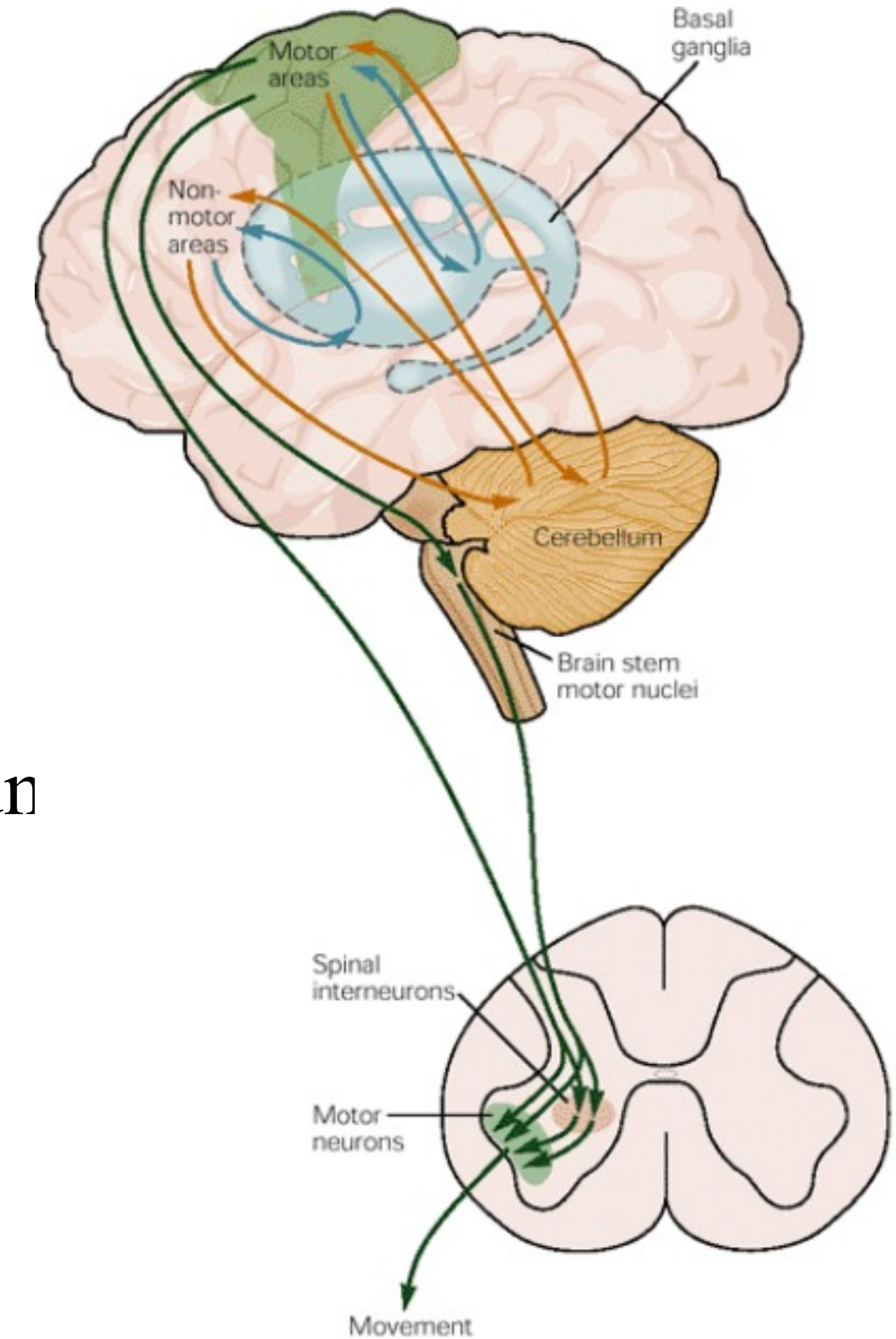
Less time for feedback corrections?
No, even without sensory feedback

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, cerebellun
- Brain stem
- Spinal tracts
- Spinal cord
- Muscles



Muscles

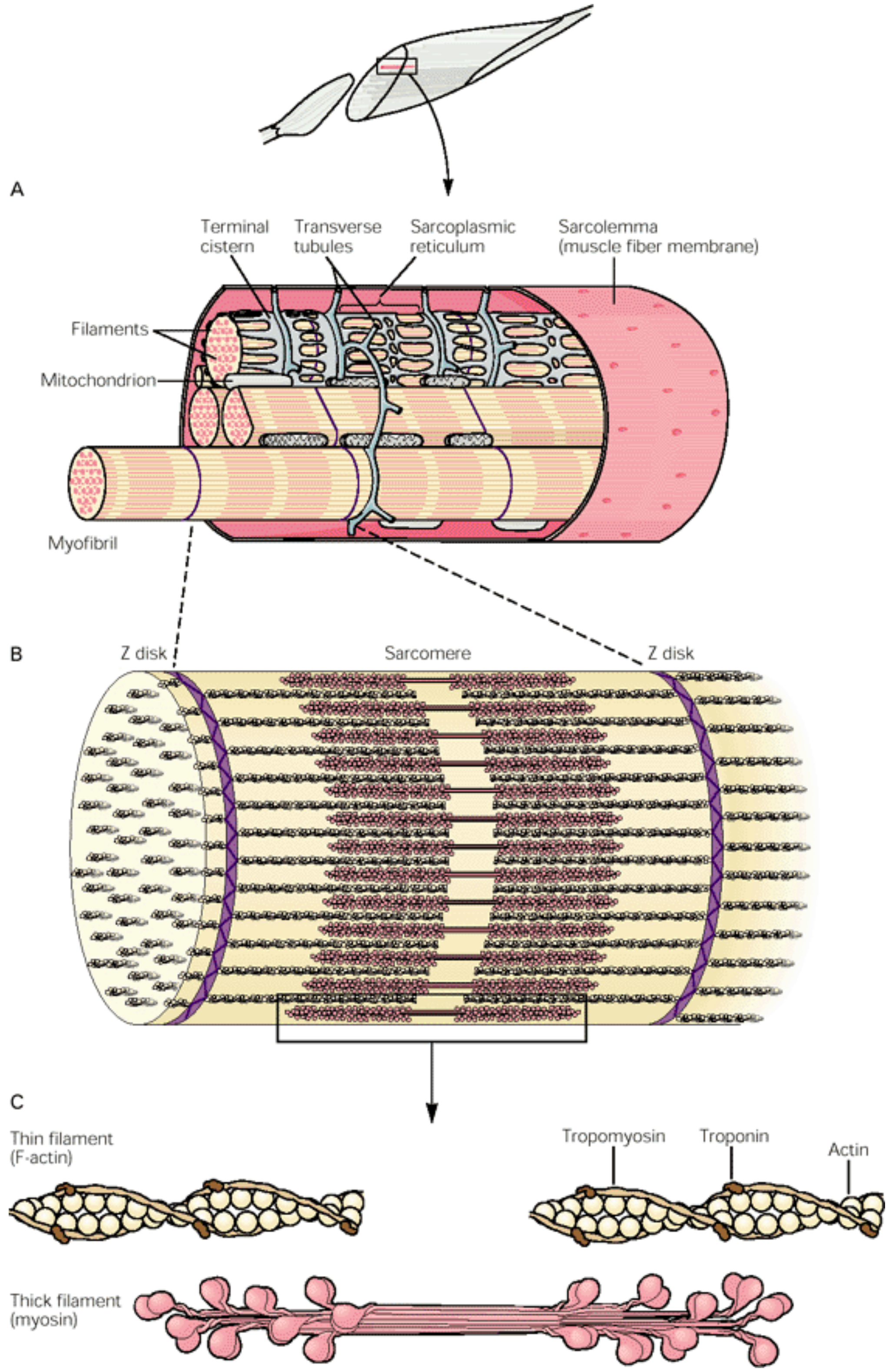
1. smooth muscles
2. cardiac muscles
3. **skeletal muscles**

Structure

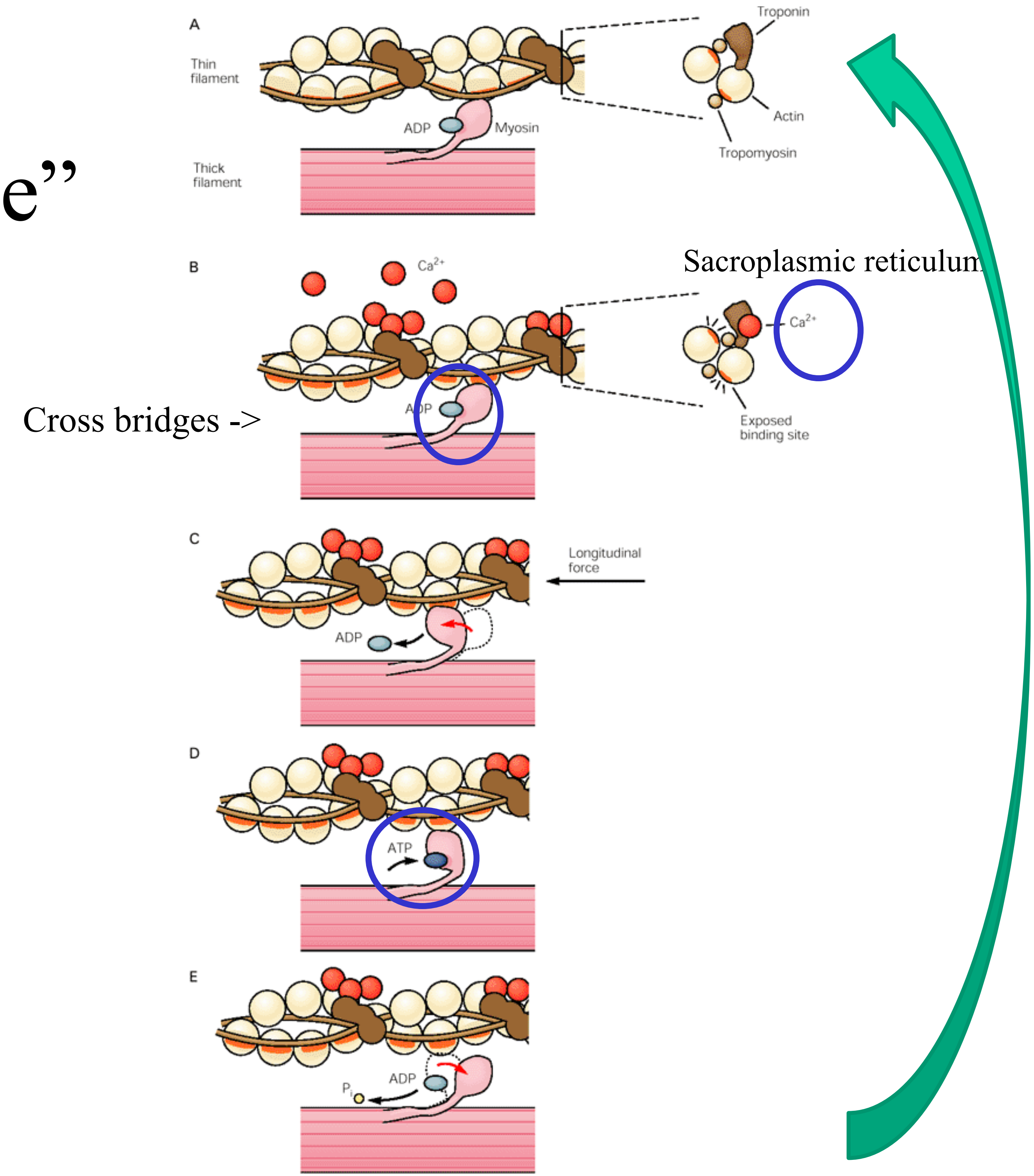
Muscle fiber

myofibril

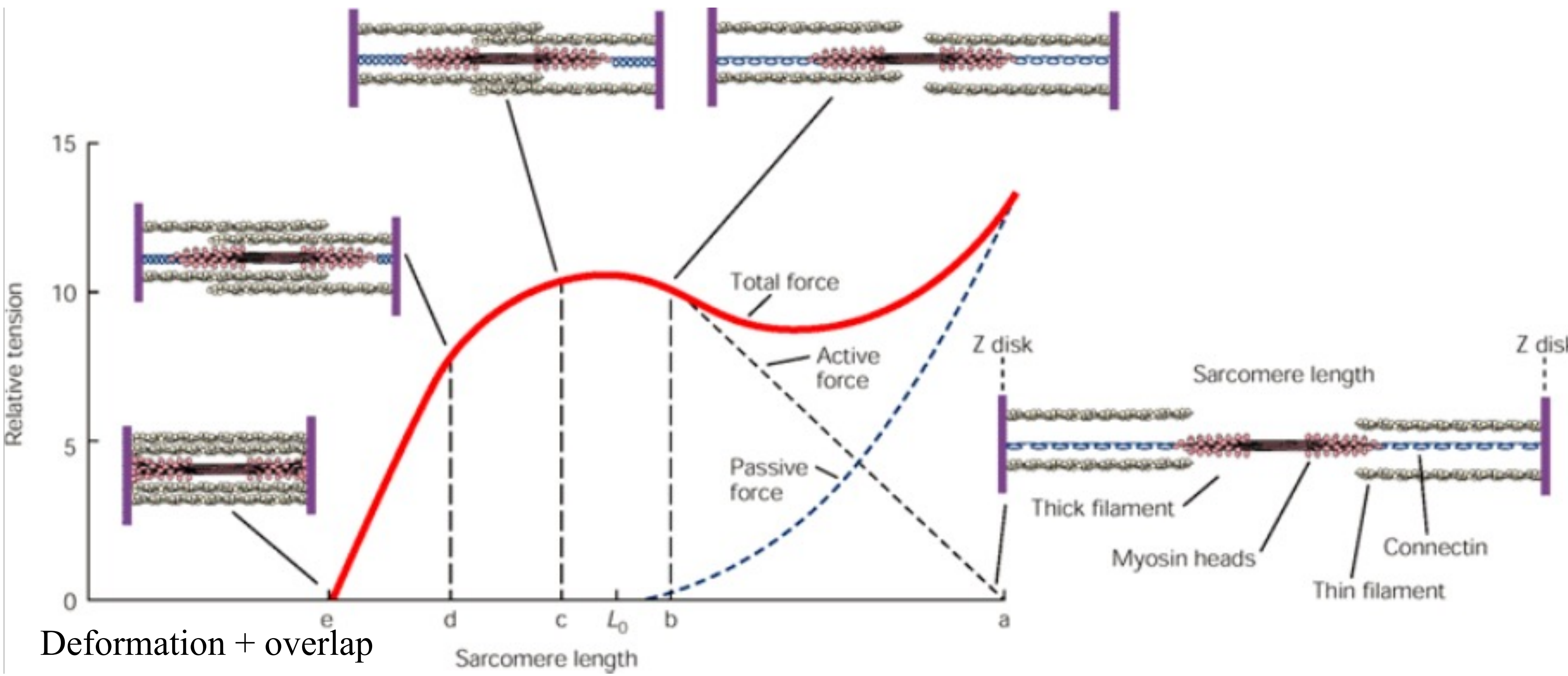
Sarcomere: functional unit



The “engine”

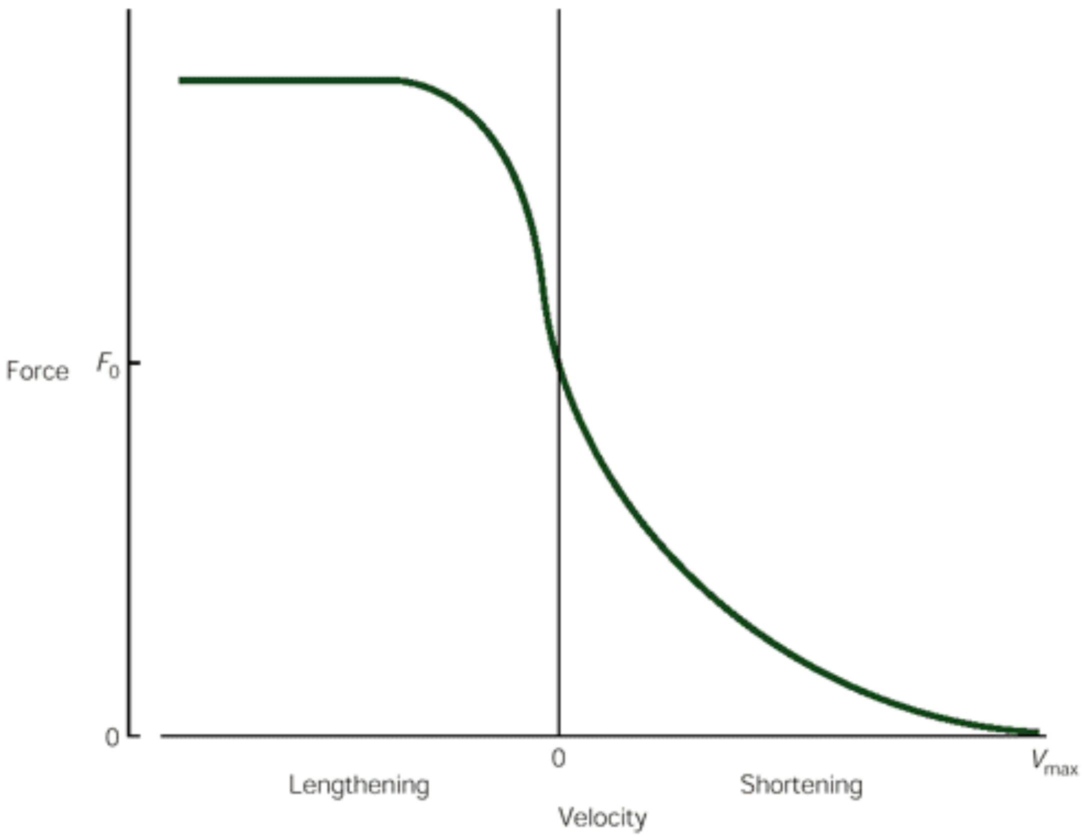

A
Thin filament
Troponin
Actin
Tropomyosin
ADP
Myosin
Thick filament
B
Ca2+
Sacroplasmic reticulum
Exposed binding site
Cross bridges ->
ADP
C
Longitudinal force
ADP
D
ATP
E
ADP
Pi

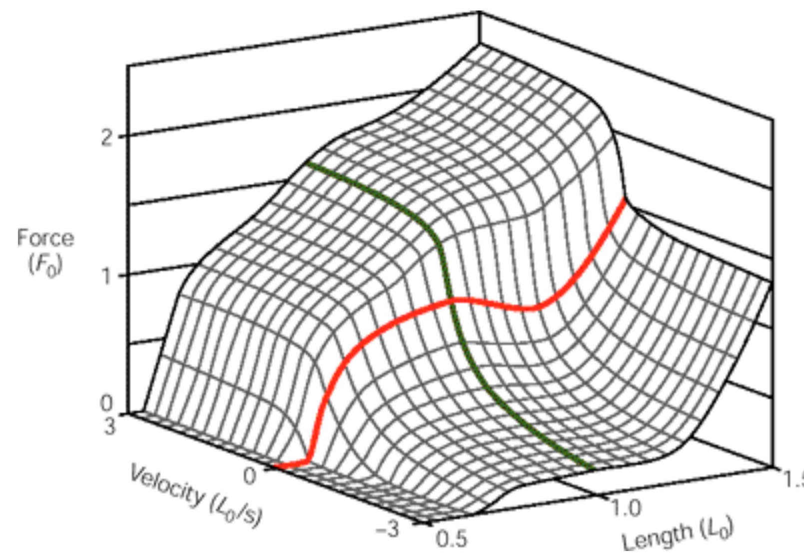
Force depends on length

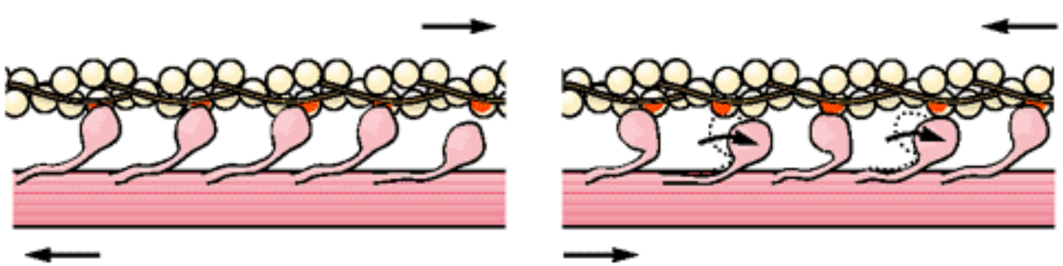


Deformation + overlap

Force depends also on velocity

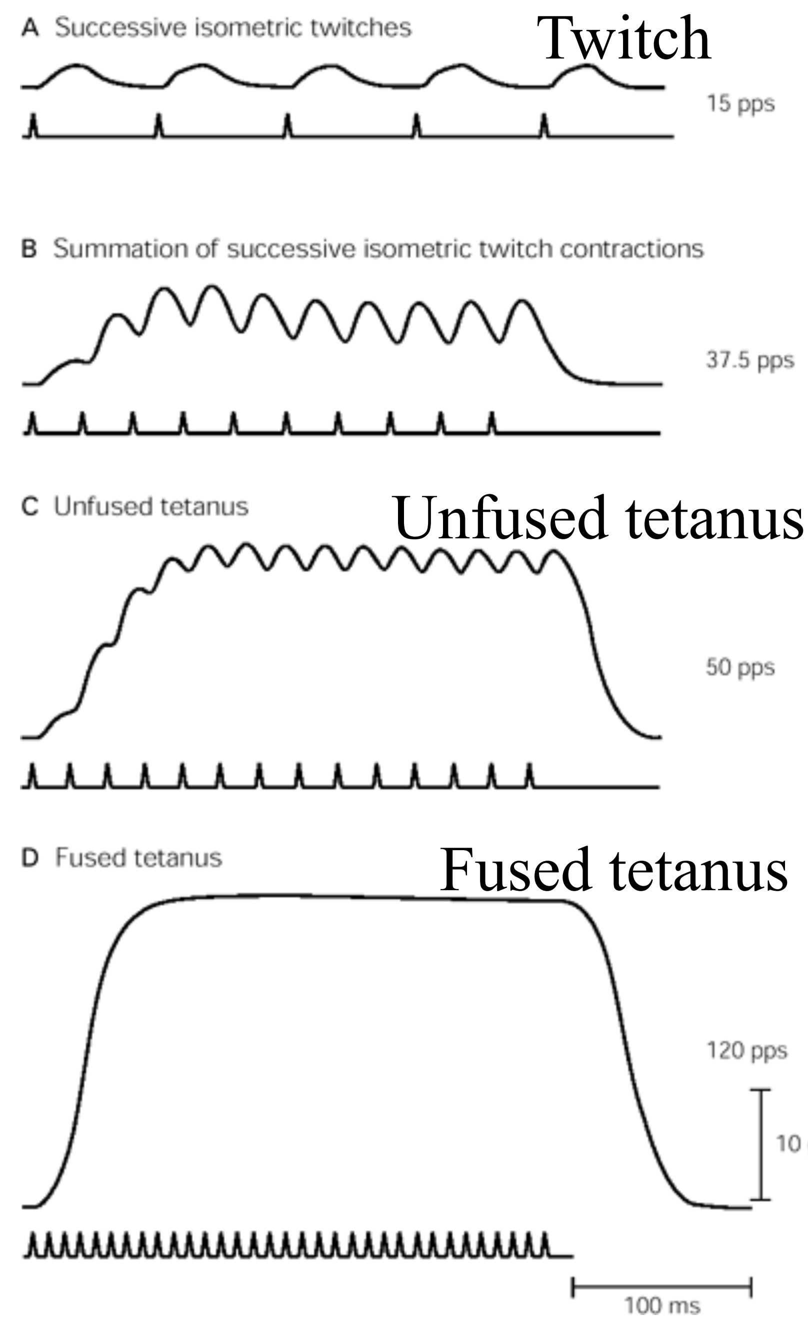




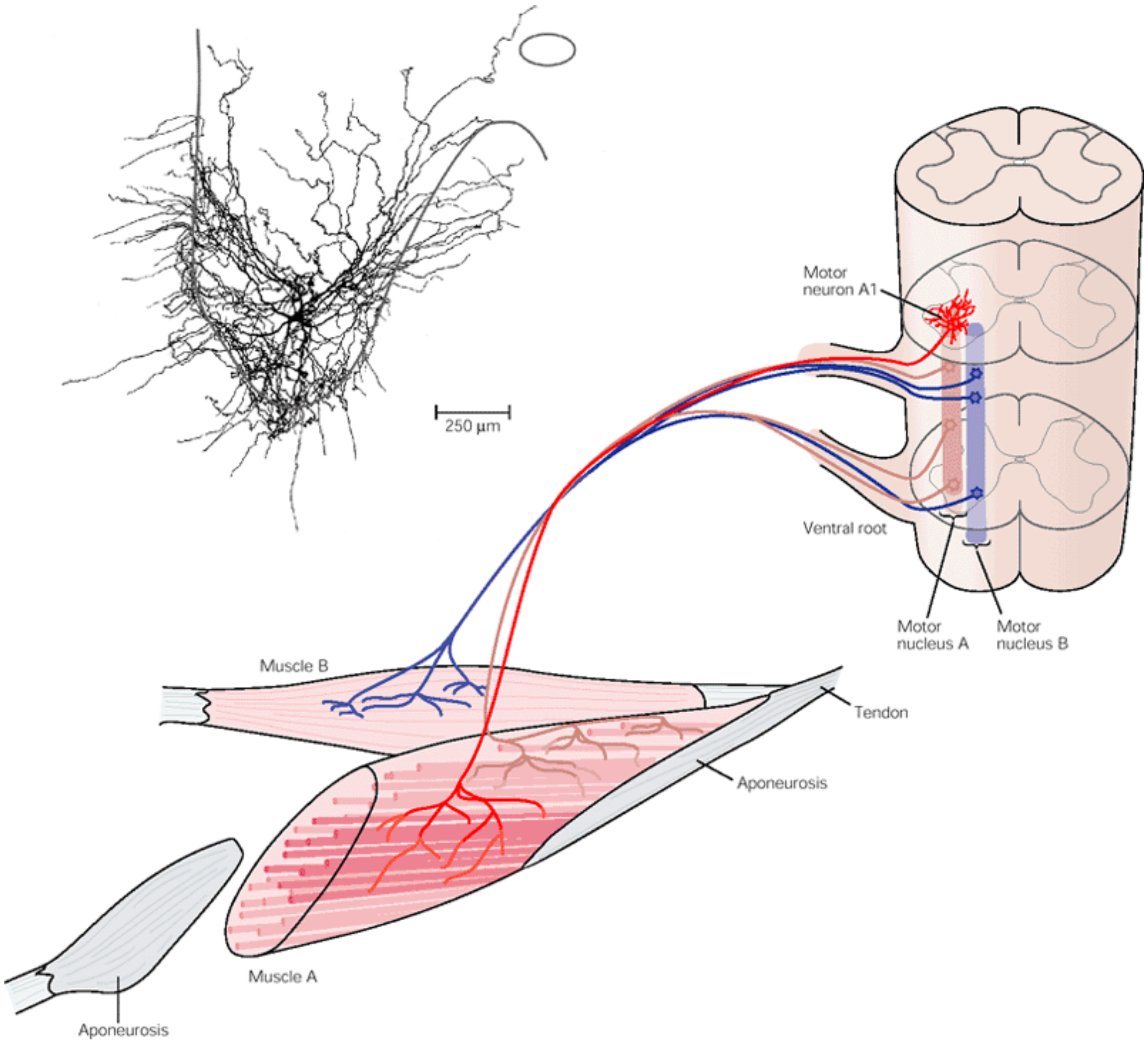


The force of a single muscle fiber is a function of

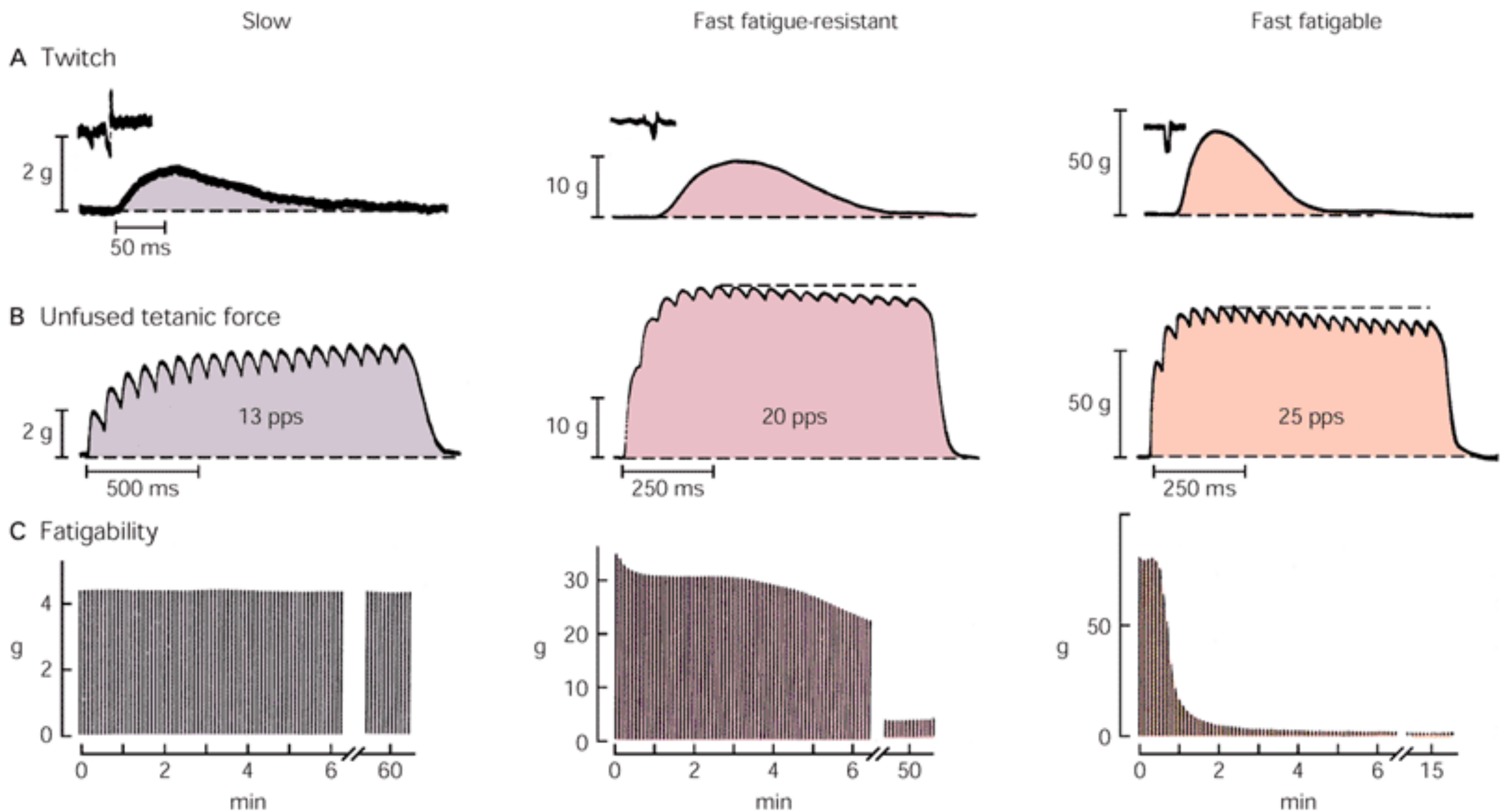
- Stimulation rate
- Stimulation pattern
- The muscle length
- The velocity of contraction
- The fiber type
- The fiber organization
- The duration of exercise - fatigue

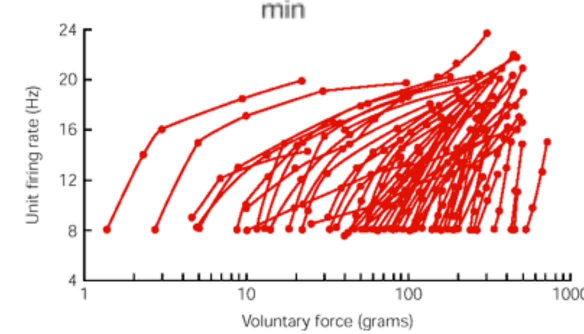


Motor unit:
motor neuron and the muscle fibers it innervates
(one to many)



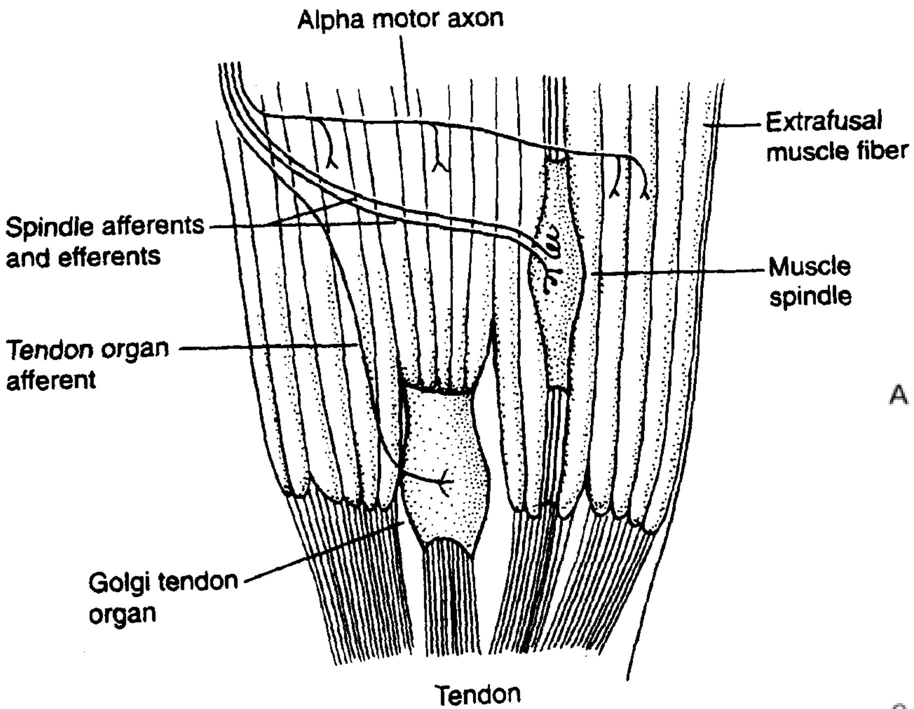
3 types of motor unit:



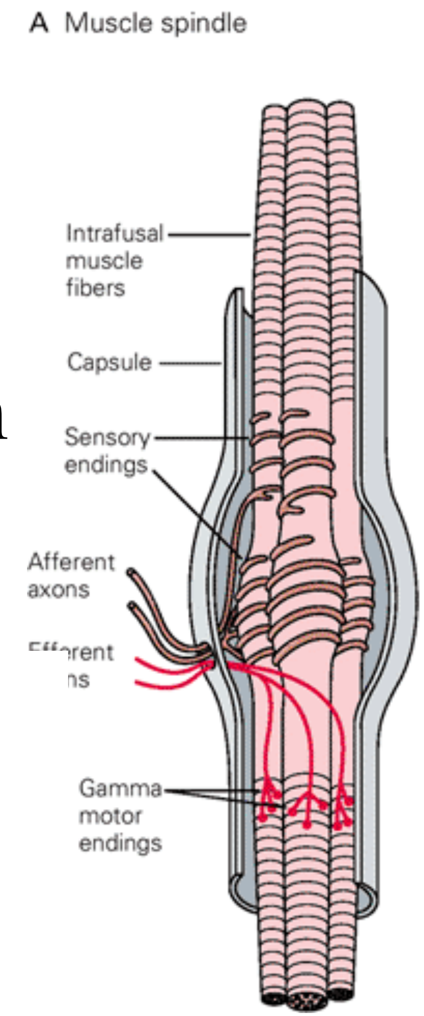


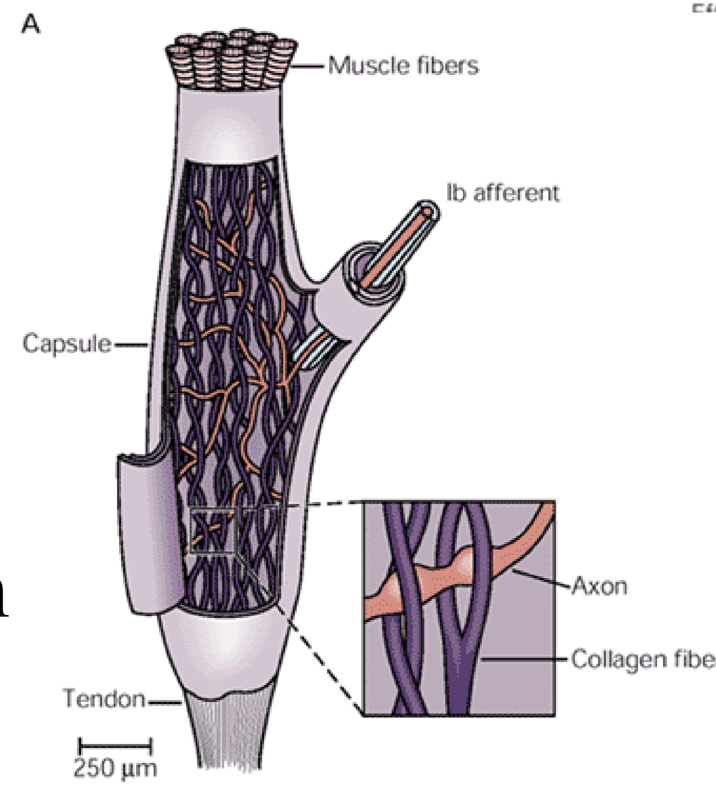
Recruited by order of force (low to high)

Muscle proprioceptive organs



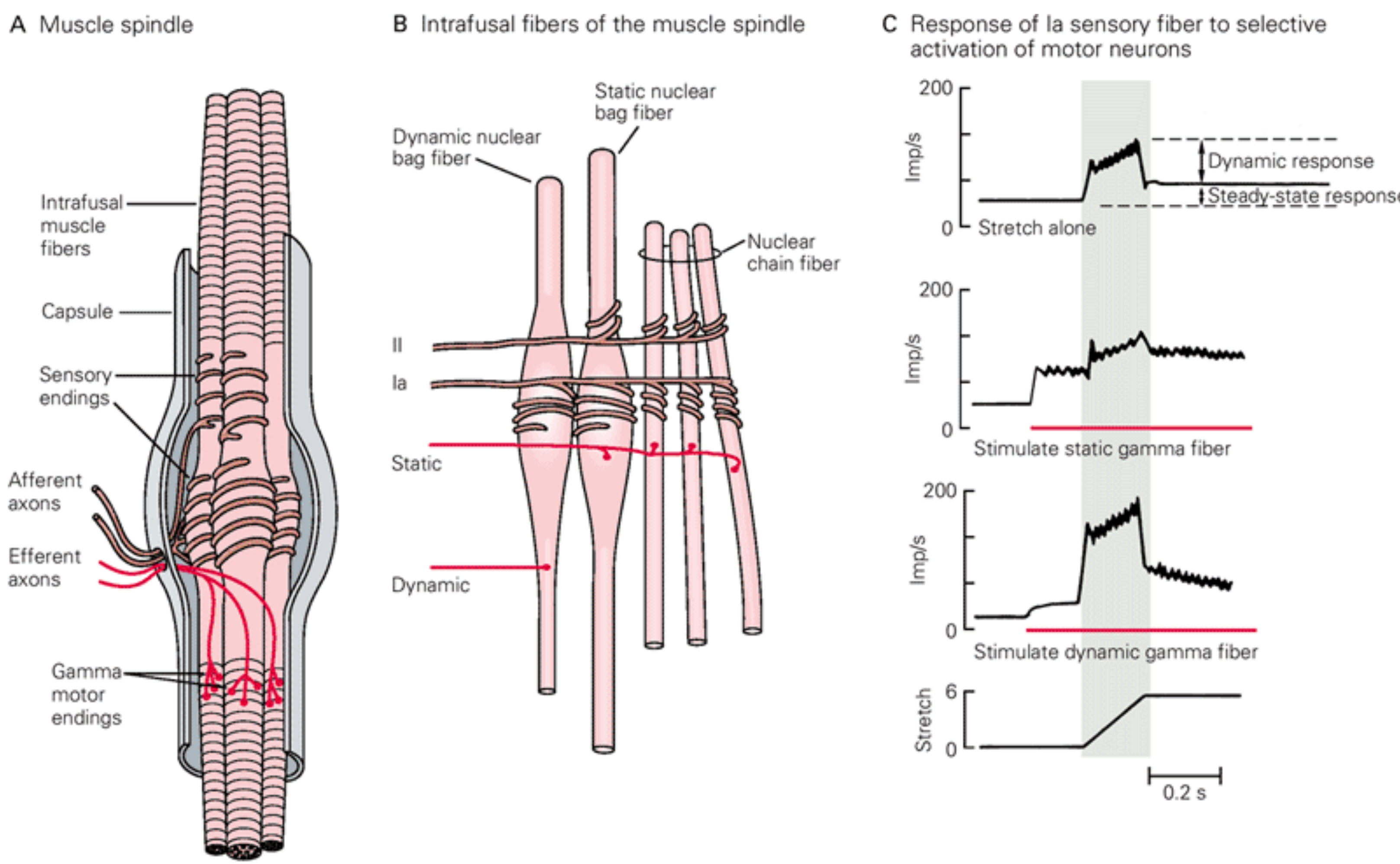
Spindle: length
Parallel



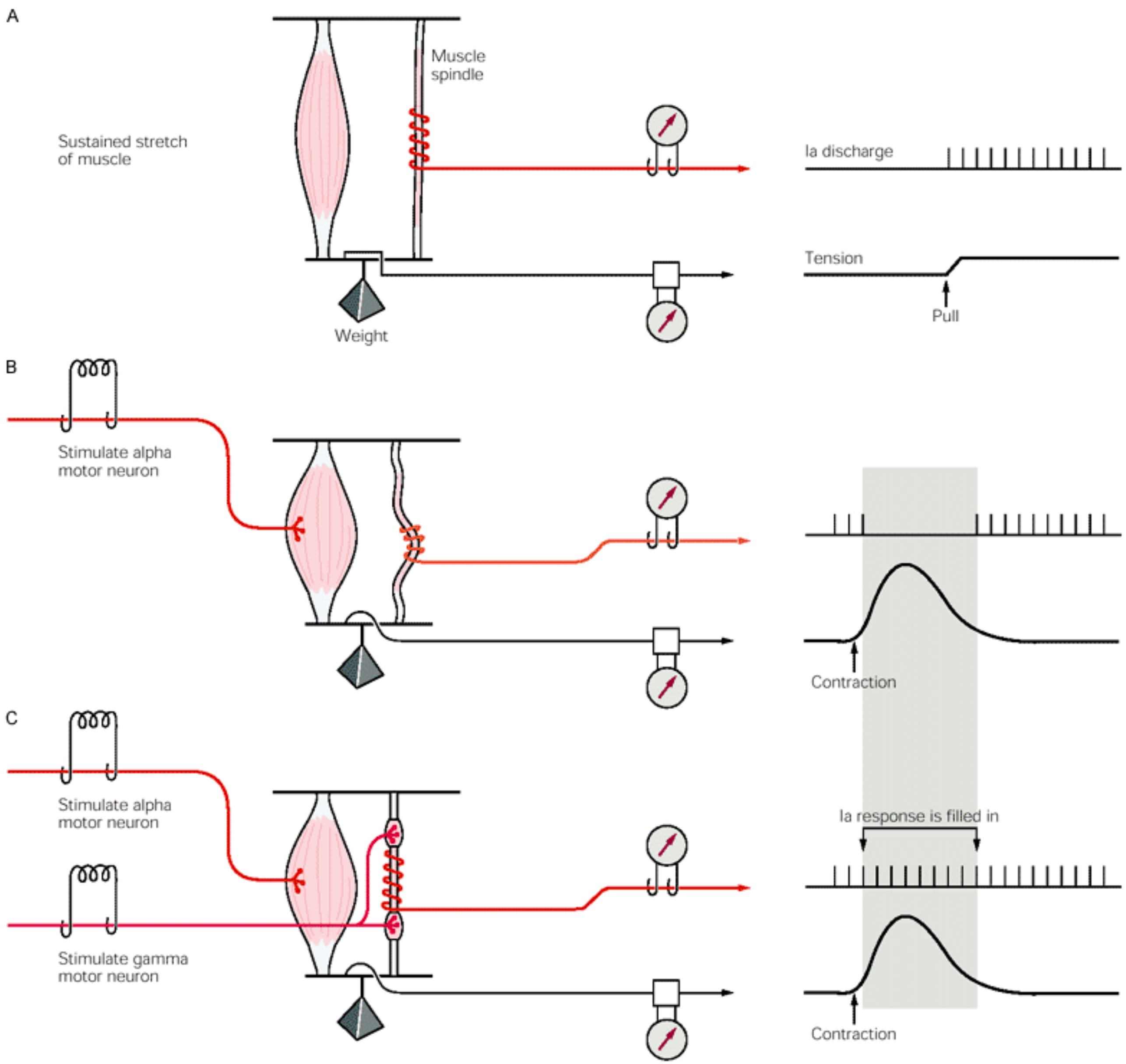


Golgi tendon: tension
Serial

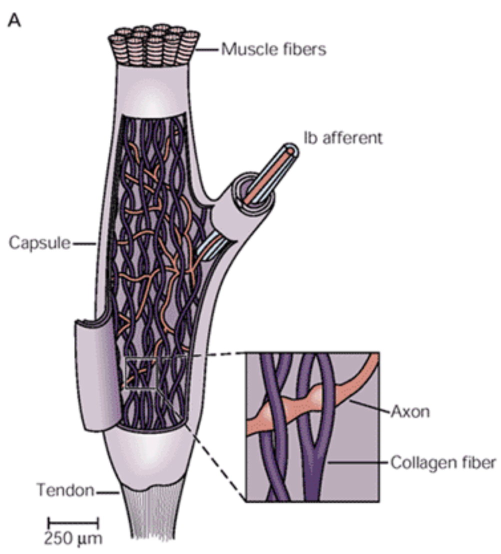
The muscle spindles are sensitive to changes in length

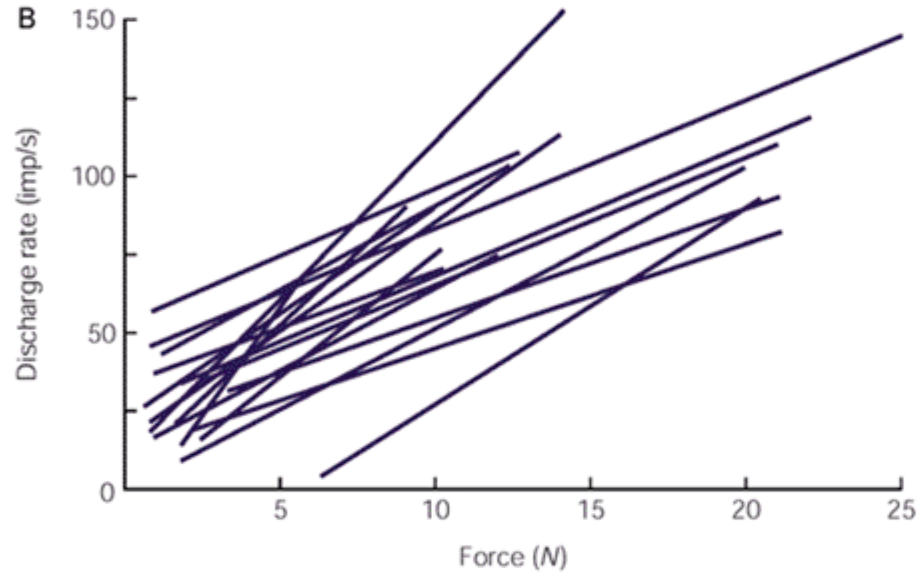


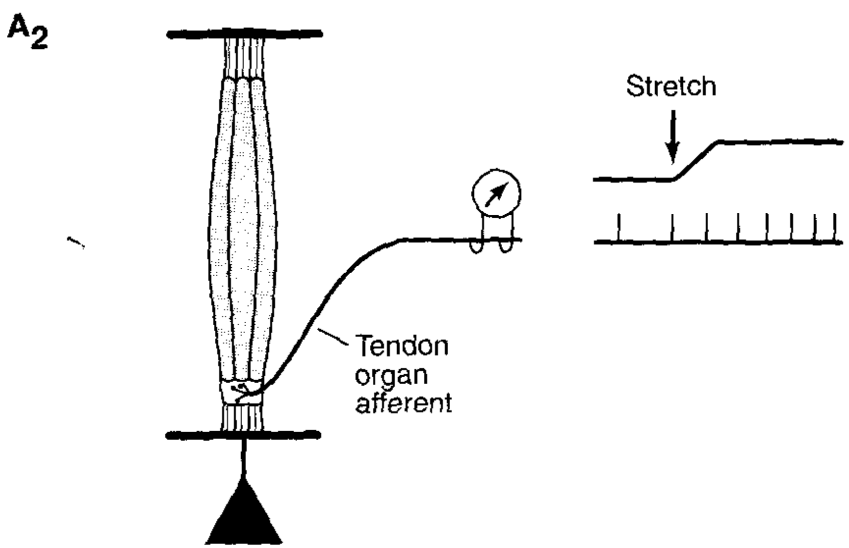
Active range can be dynamically modulated

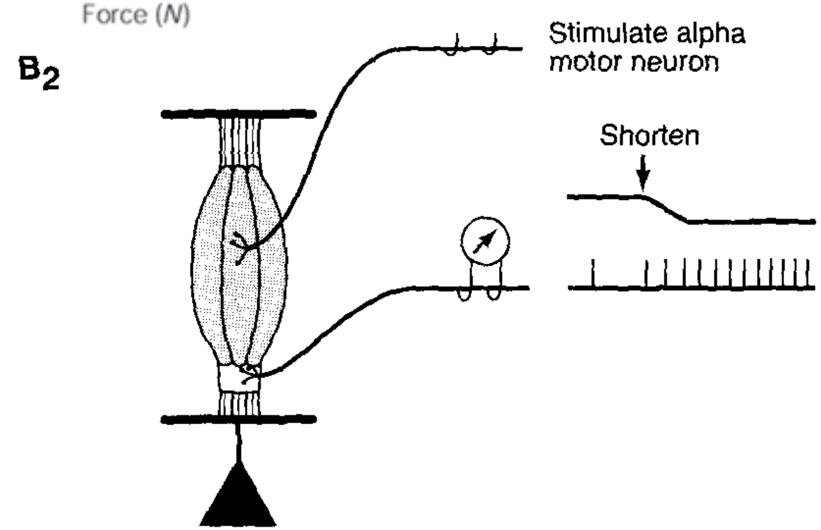


Golgi tendon organs are sensitive to the tension









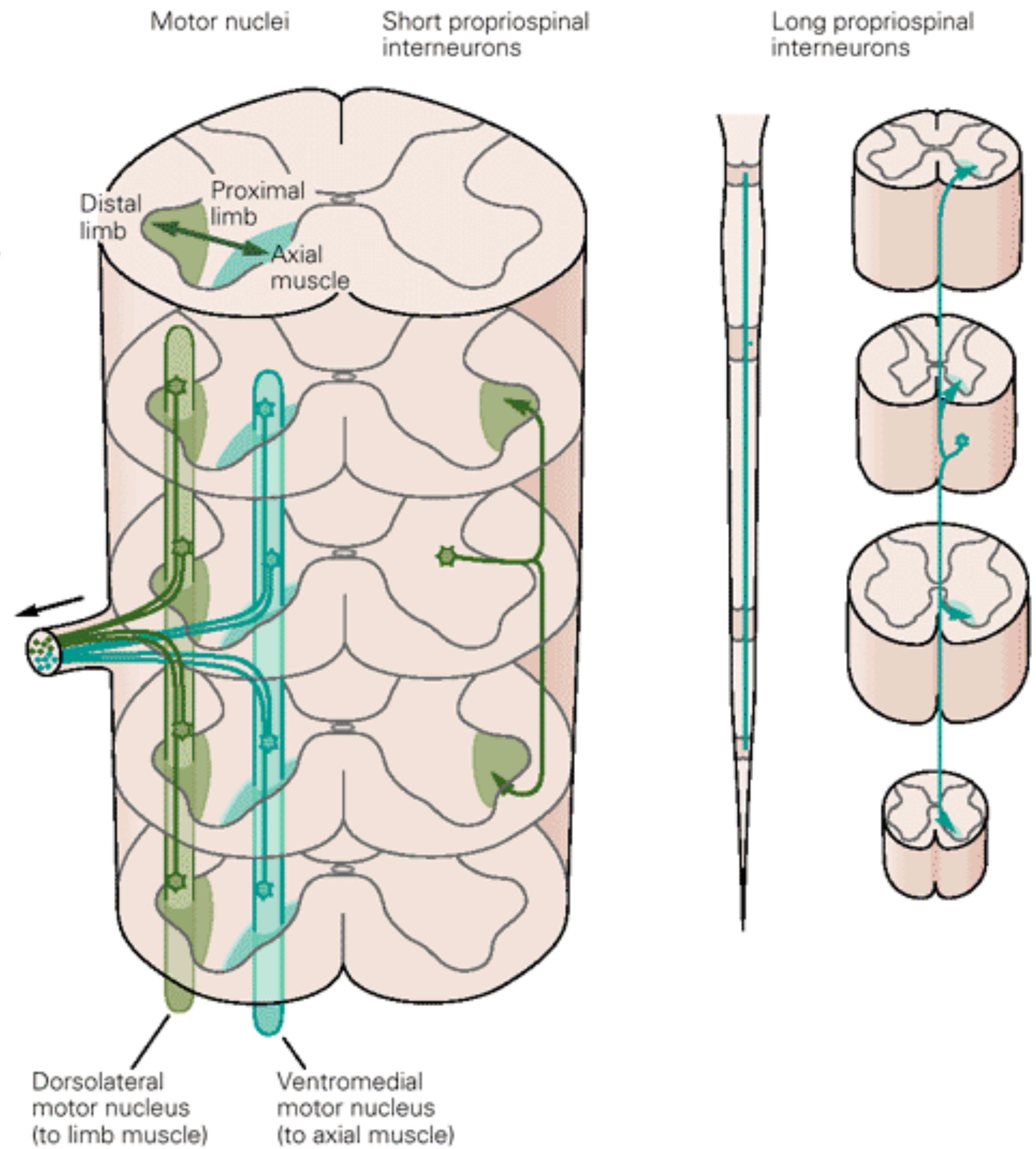
Spinal cord, Brain stem and spinal tracts

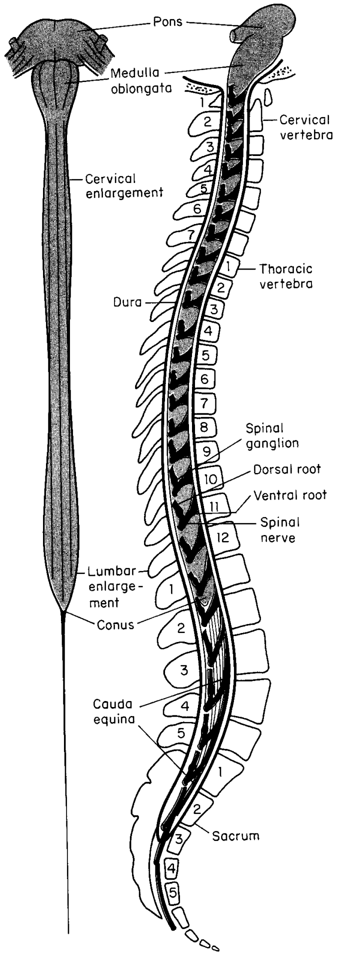
Spinal cord

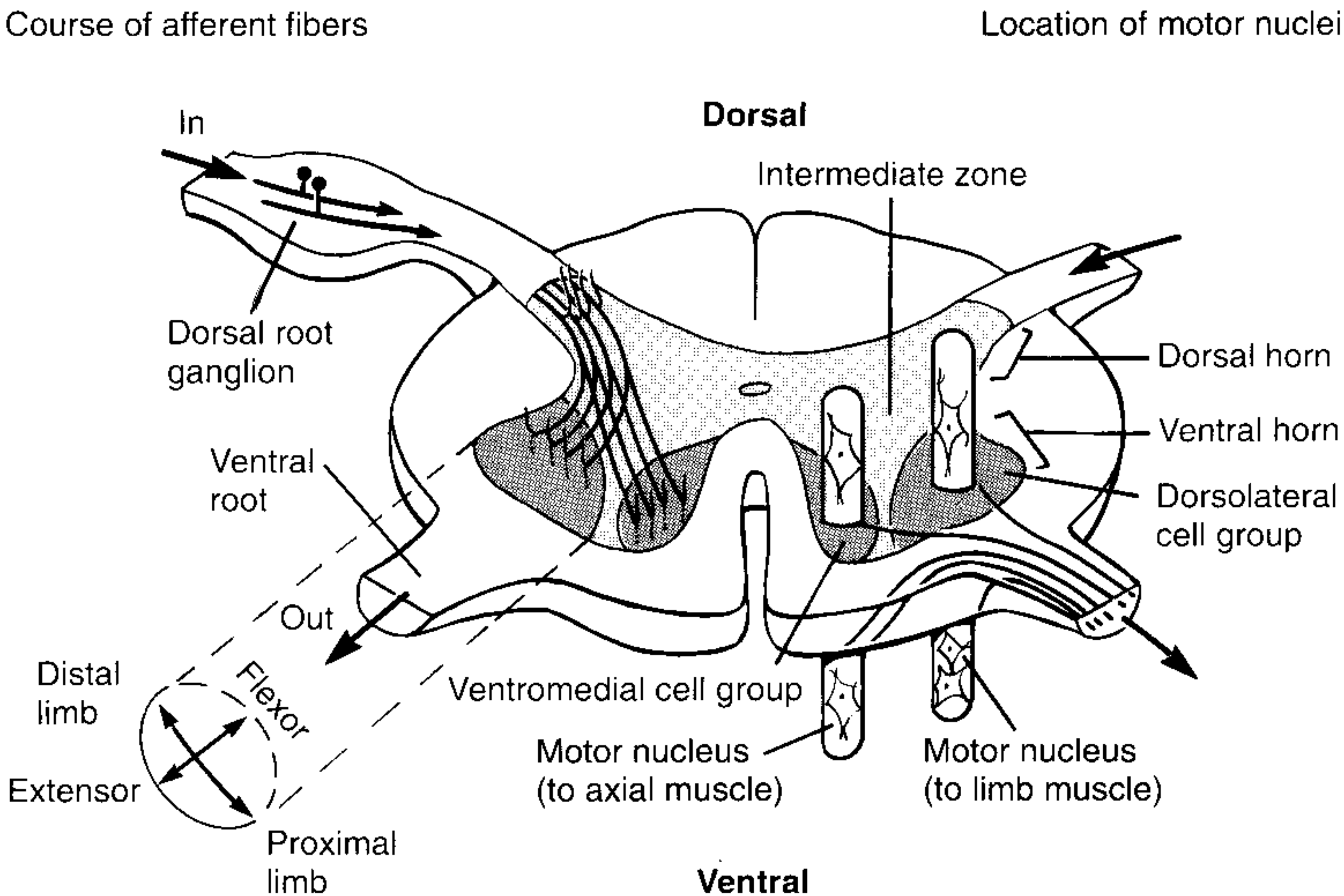
1. Local interneurons
2. Propriospinal (across segments)
3. Projection (to upper centers)
4. Motor neurons

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

Medial nuclei are long across segments
Lateral are shorter



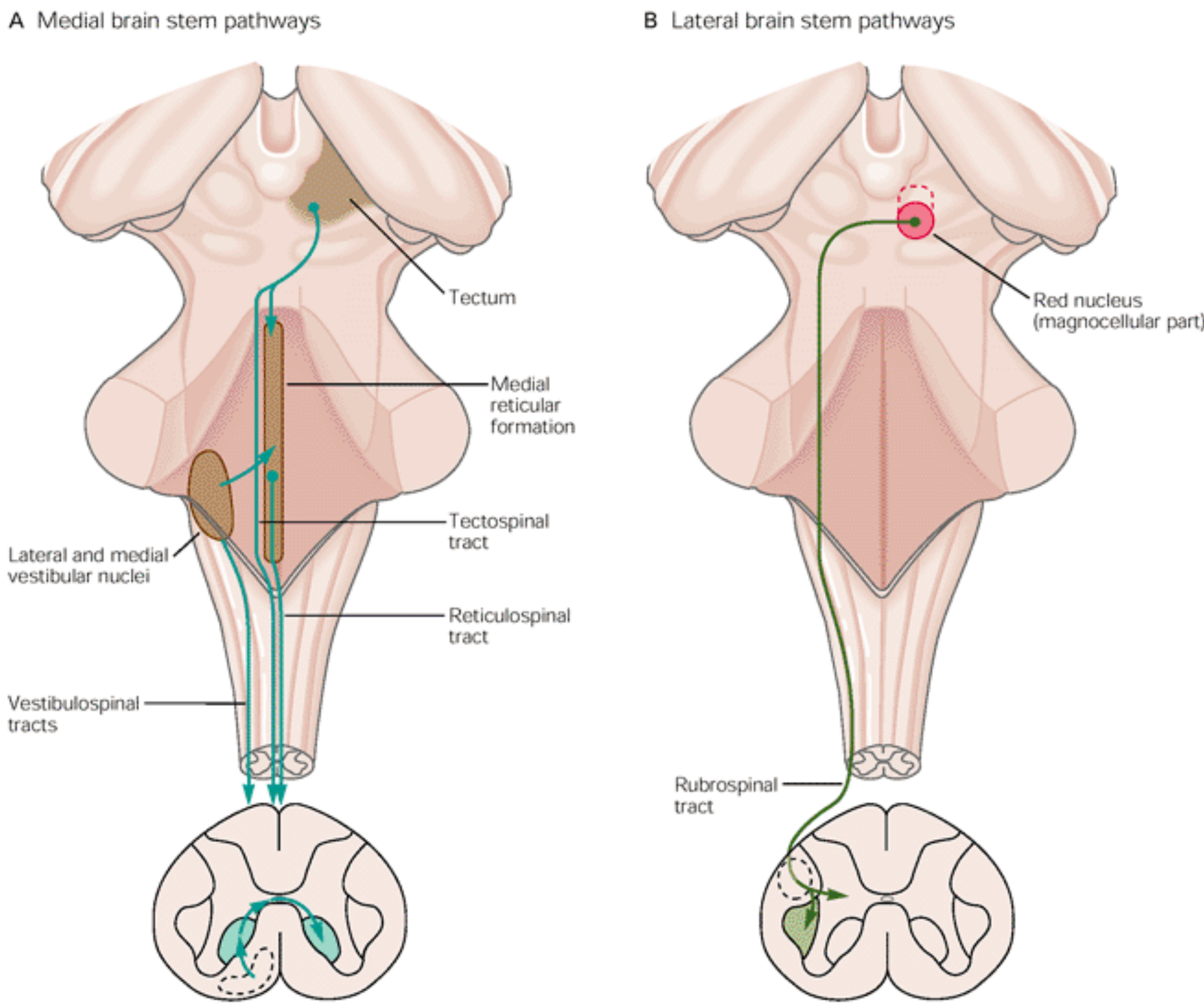

Pons
Medulla oblongata
Cervical vertebra
Cervical enlargement
Thoracic vertebra
Dura
Spinal ganglion
Dorsal root
Ventral root
Spinal nerve
Lumbar enlarge- ment
Conus
Cauda equina
Sacrum


Course of afferent fibers
Location of motor nuclei
Dorsal
In
Intermediate zone
Dorsal root ganglion
Dorsal horn
Ventral horn
Ventral root
Dorsolateral cell group
Out
Distal limb
Flexor
Extensor
Proximal limb
Ventromedial cell group
Motor nucleus (to axial muscle)
Motor nucleus (to limb muscle)
Ventral

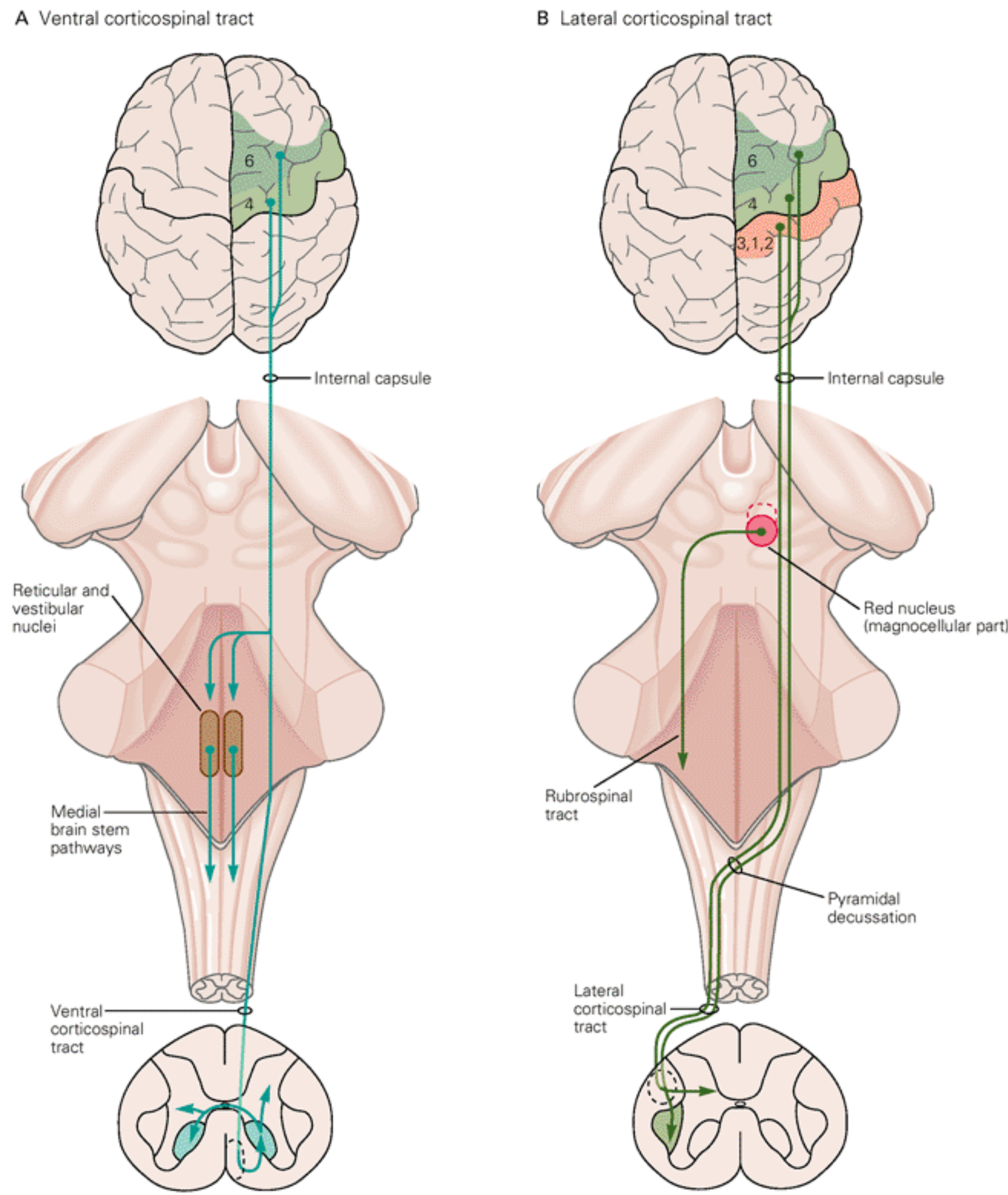
Brain stem pathways

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

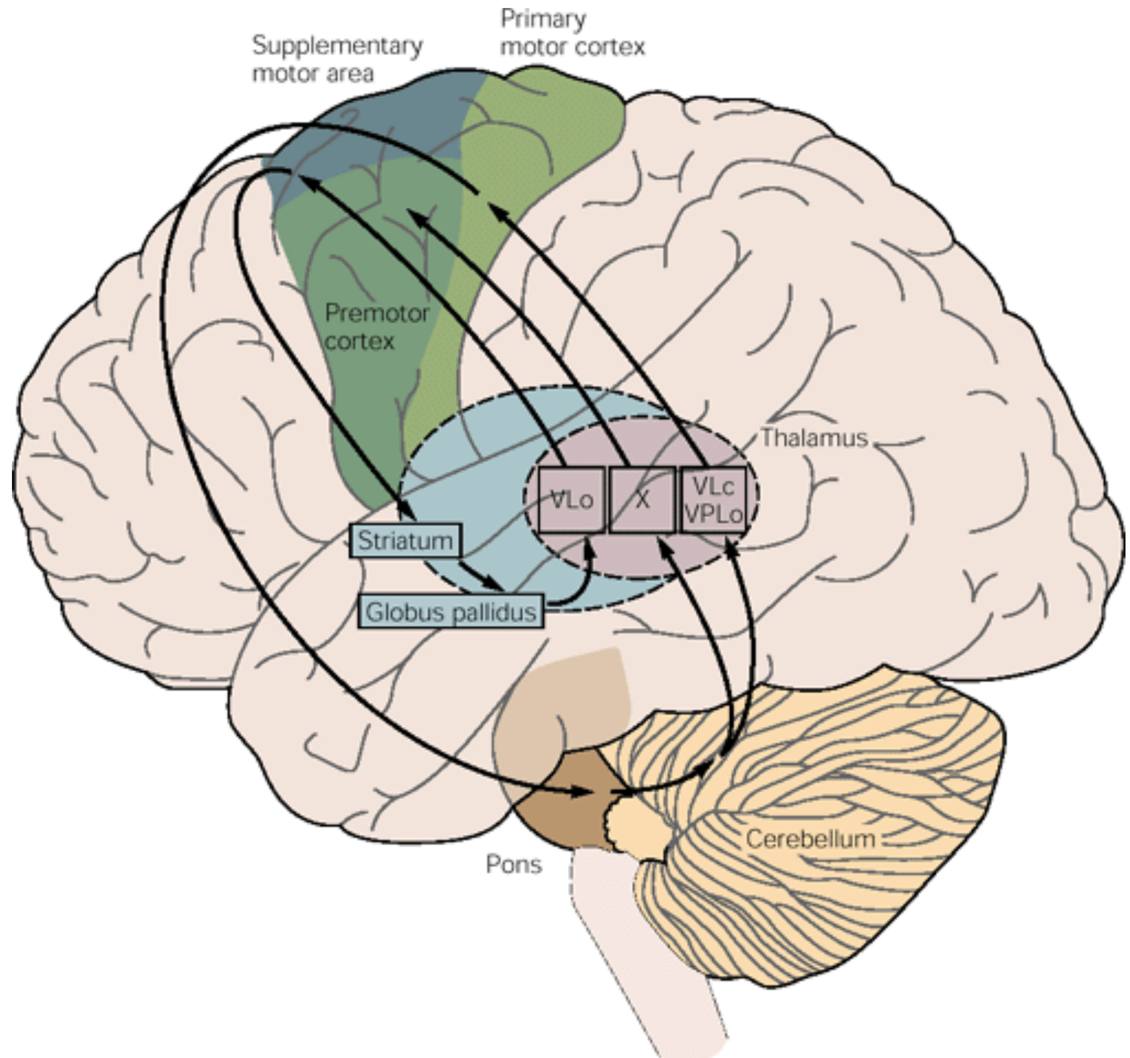
Lateral pathways (rubrospinal) terminates in dorsolateral.



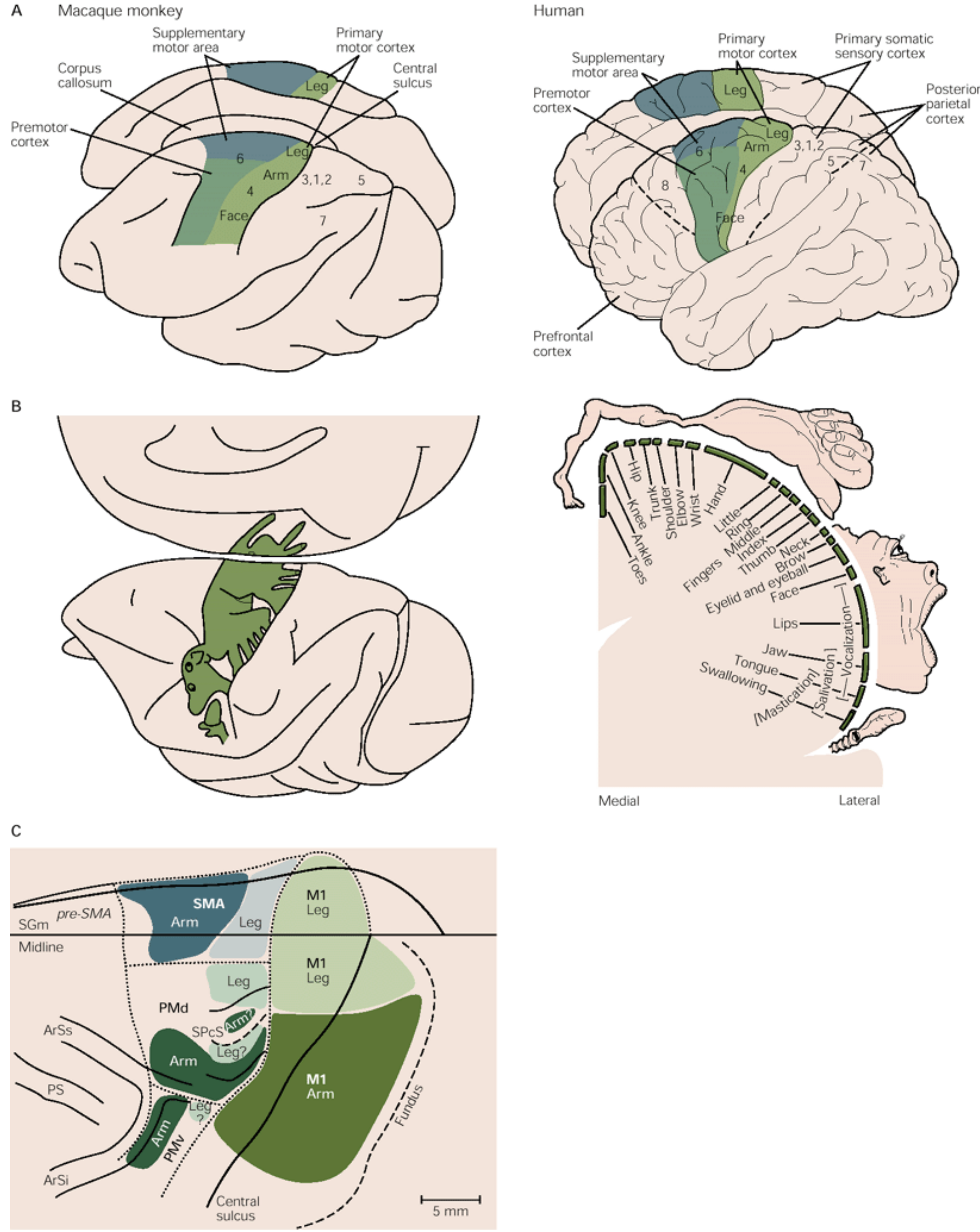
The corticospinal tract



Cortex and control of voluntary movement



Somato-topical organization



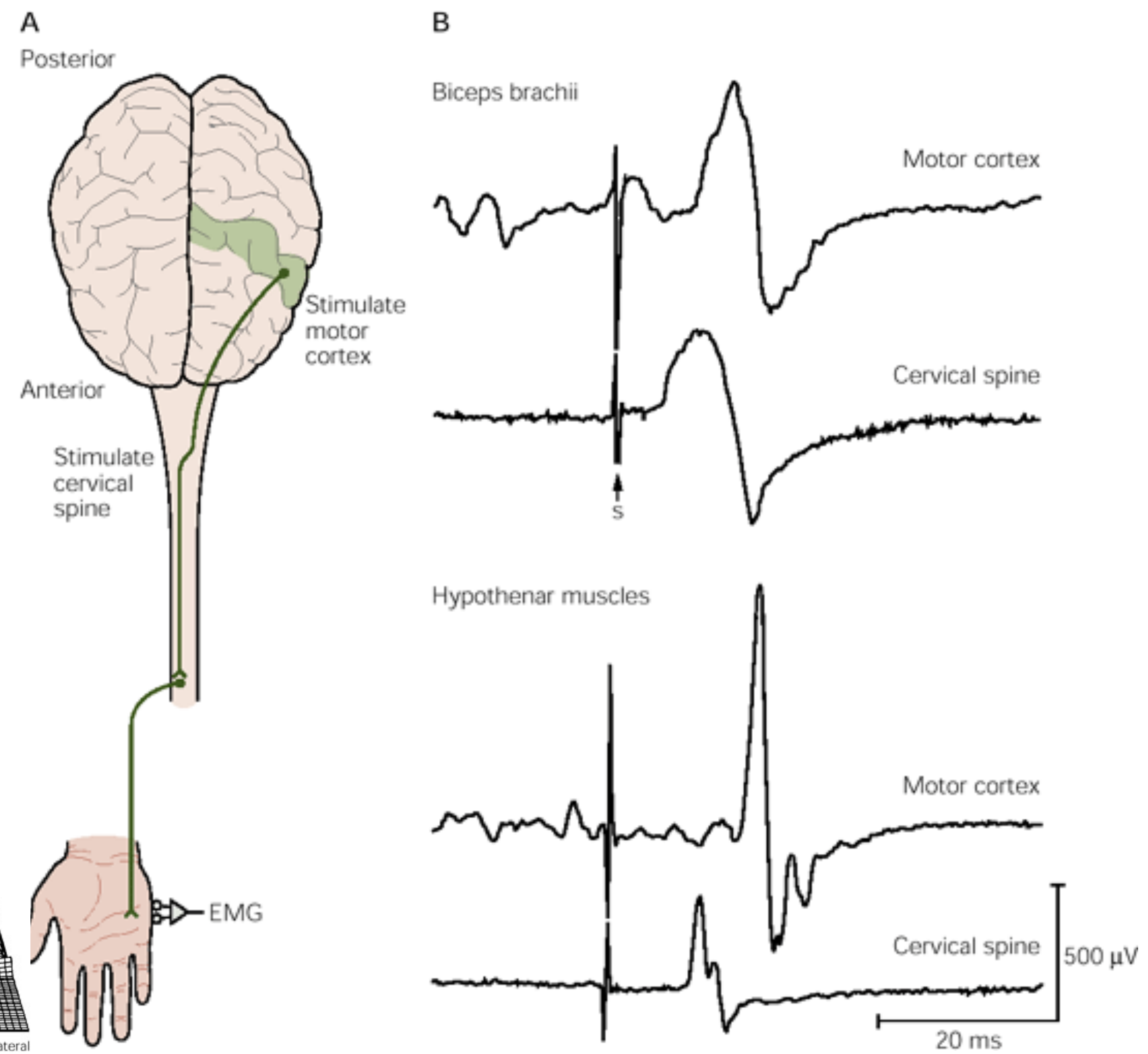
Stimulation in M1

Electrical and magnetic stimulation

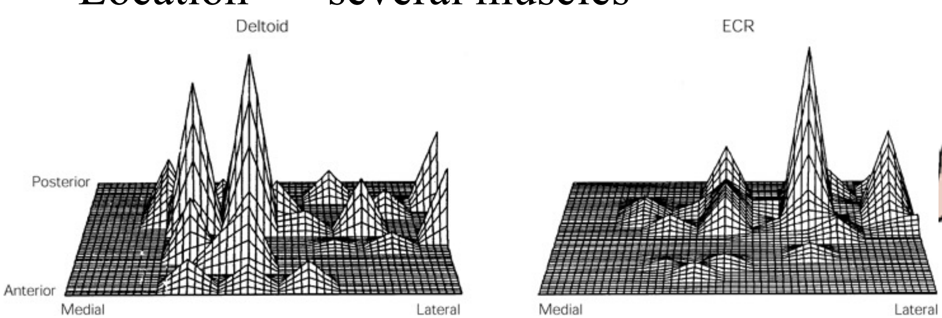
Lowest intensity

Twitch in single muscle/joint

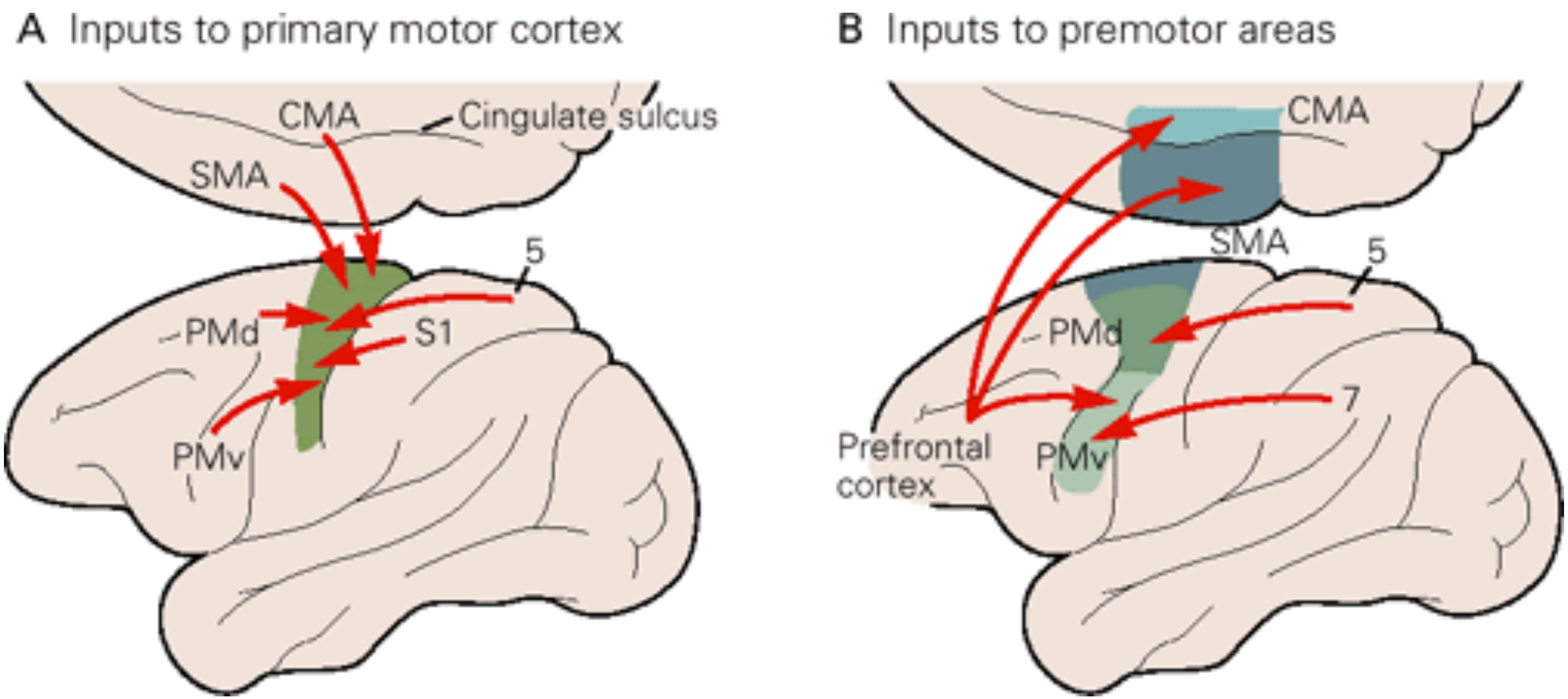
Large (Betz) cells in lamina V



Many locations -> same muscle
Location - > several muscles

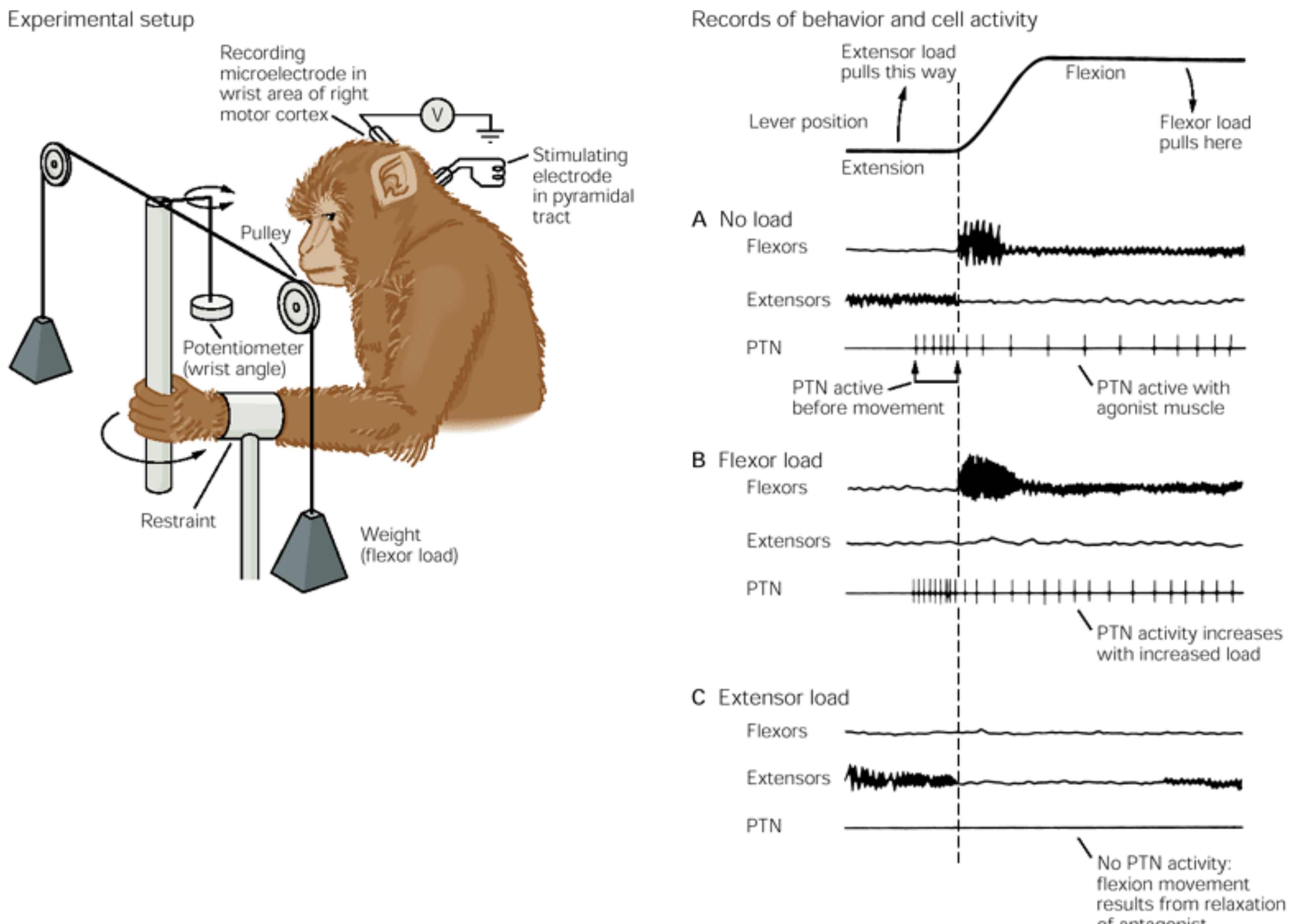


Cortical inputs

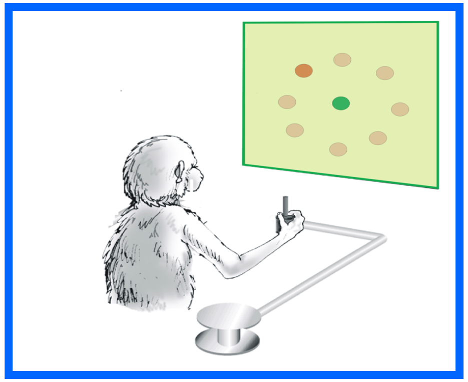


Coding of force in M1

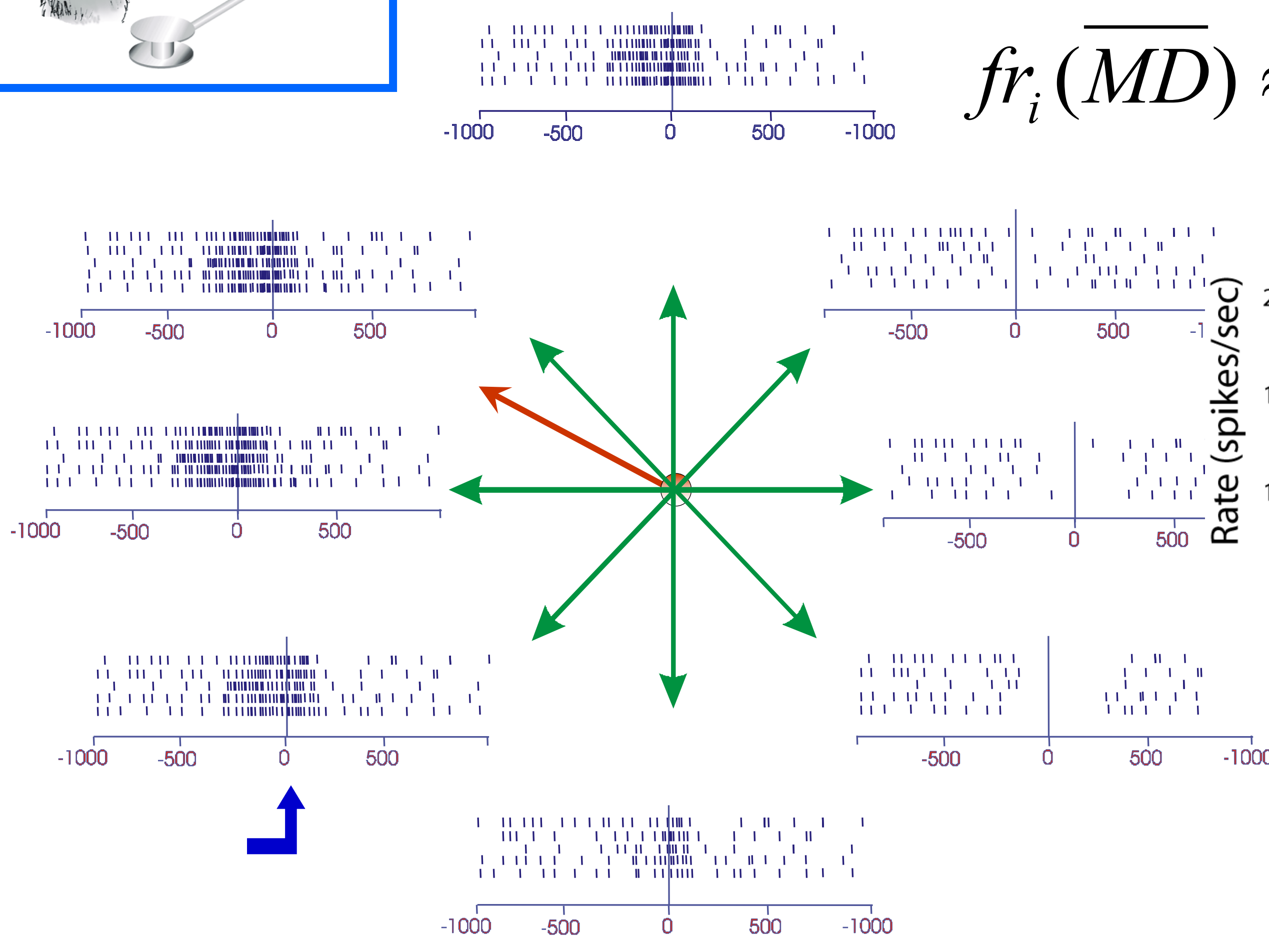
Evarts, 68

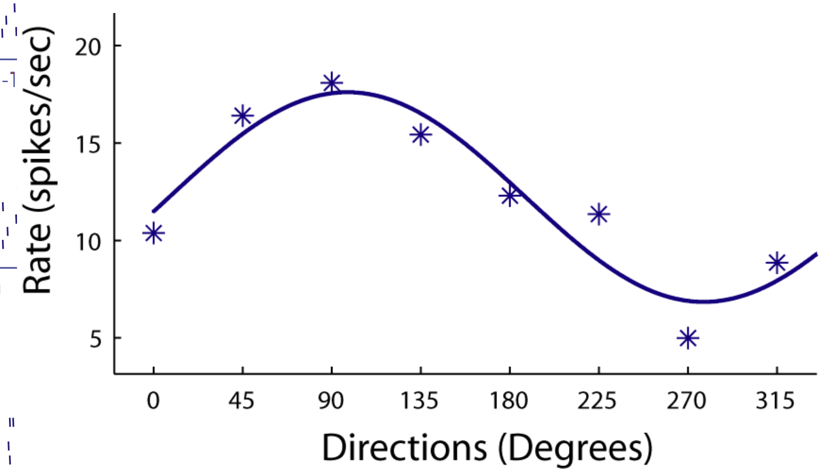


Coding of external direction



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





Georgopoulos 1982

Kinematics vs. dynamics

Extrinsic variables (end-point velocity/ position):

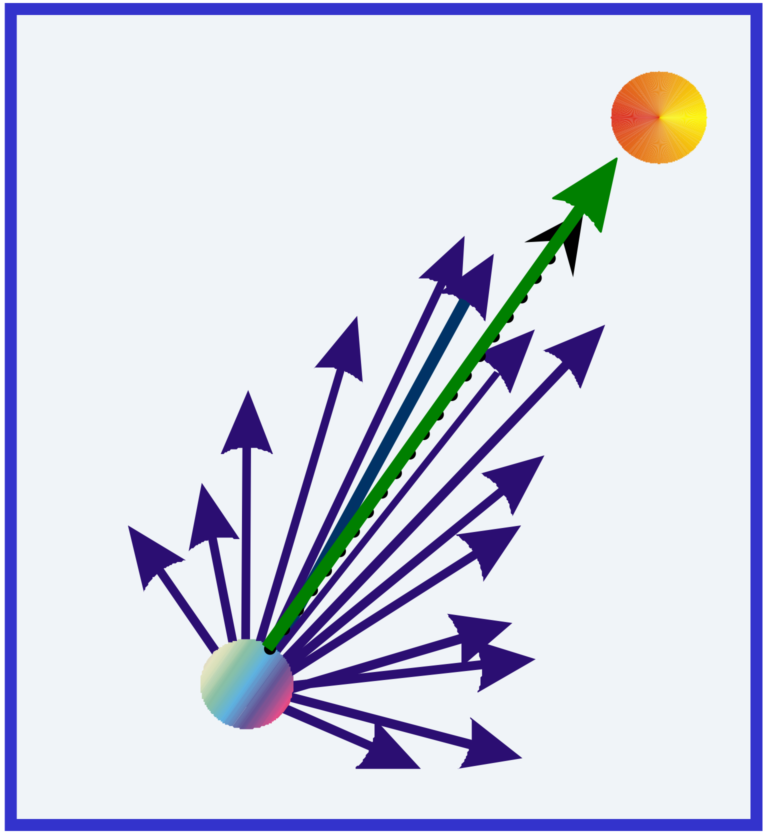
- Relative to torso
- Relative to eye
- Relative to shoulder

Intrinsic coordinates:

- Muscles shortening velocity
- Muscles tension

Joints’ velocity, torque, power.

The population vector



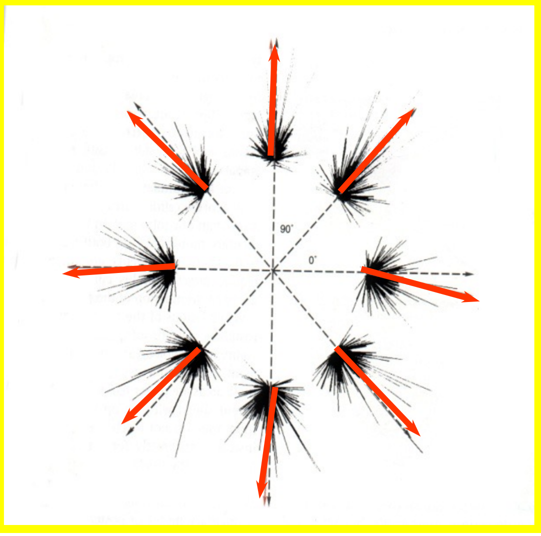
If:

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

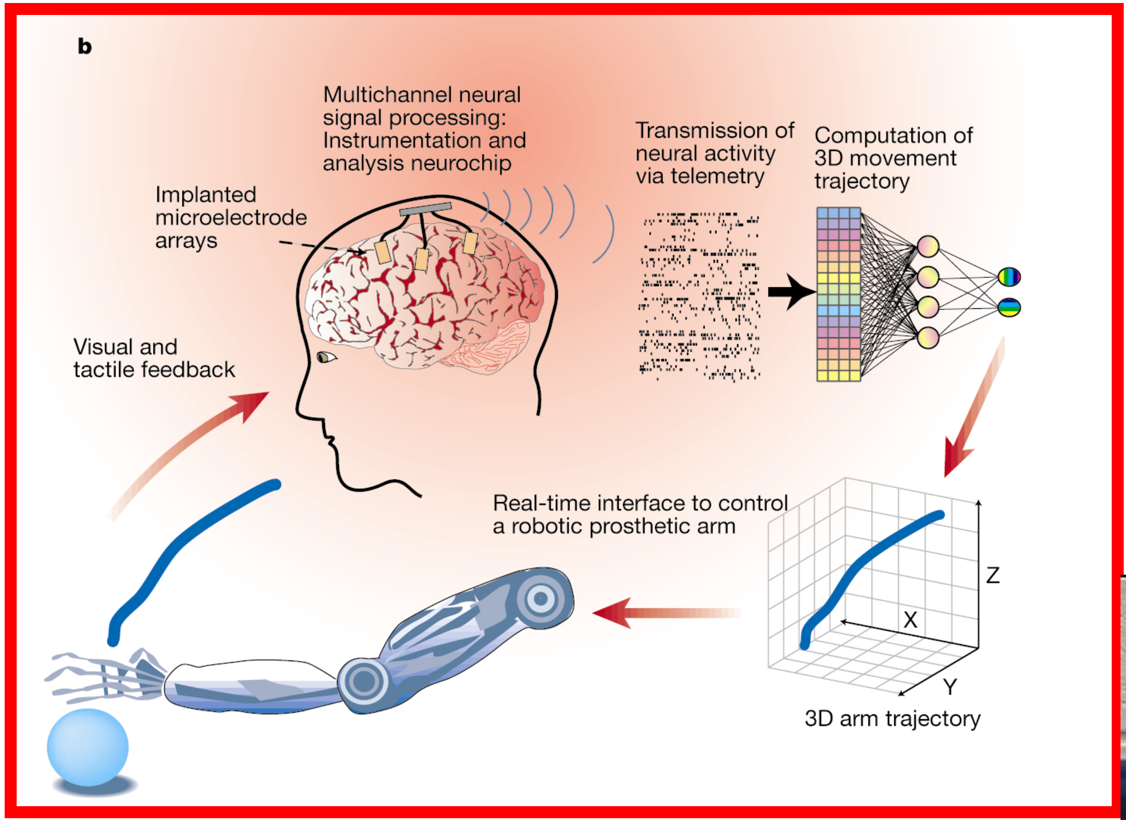
$$\overline{MD} \approx PV = \sum_{i=1}^{N} w_i \overline{C}_i$$

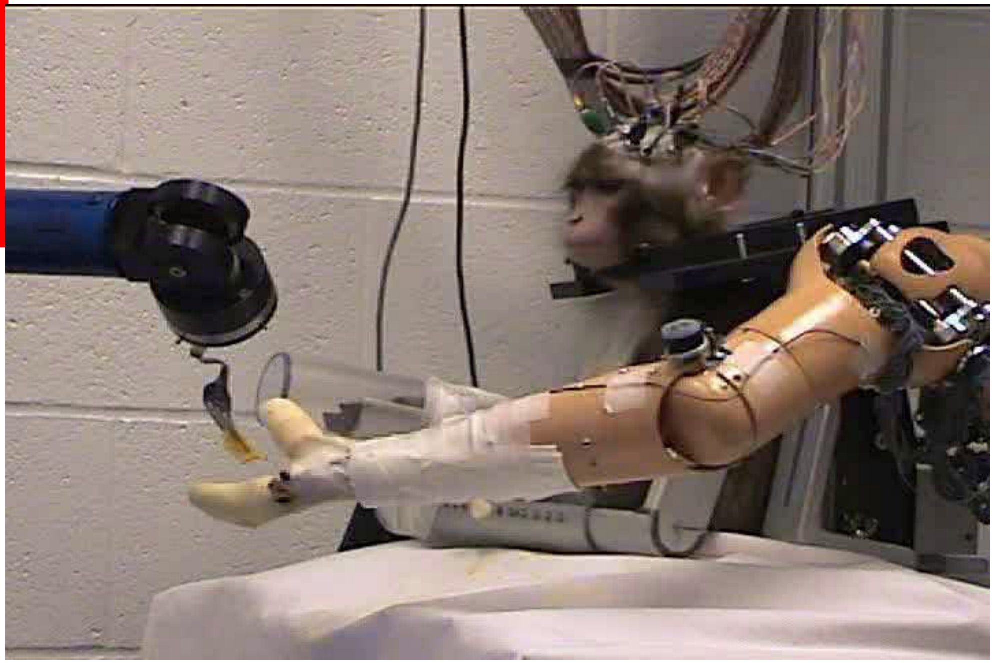
Then:

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



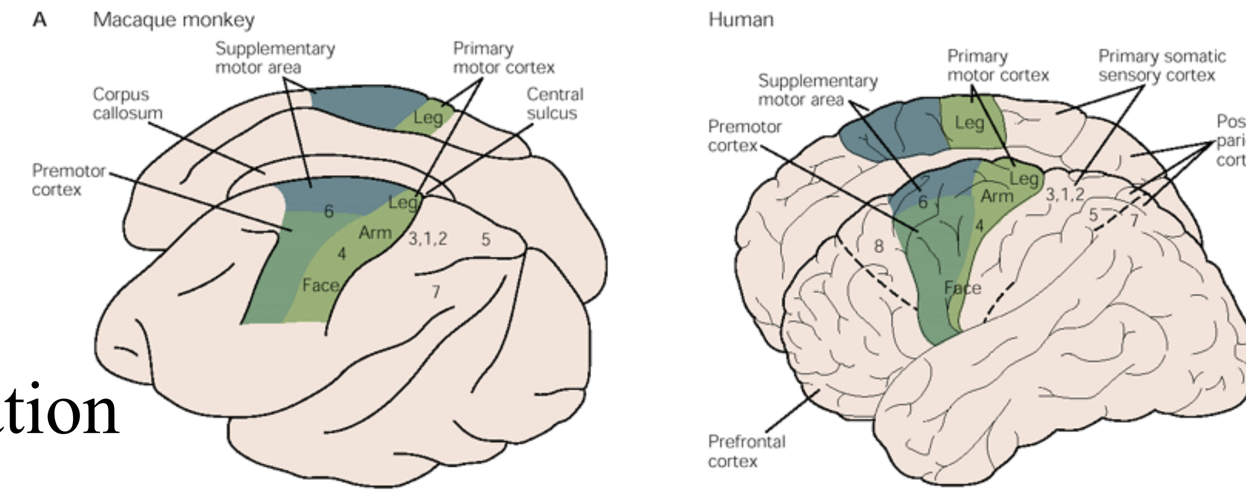
What can we do with it? Neural prostheses





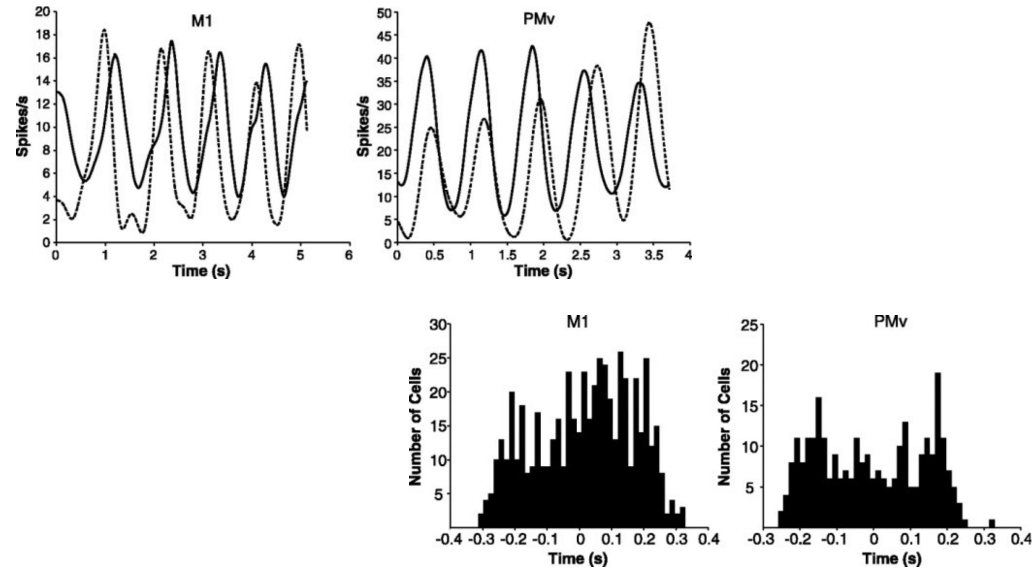
Schwartz AB

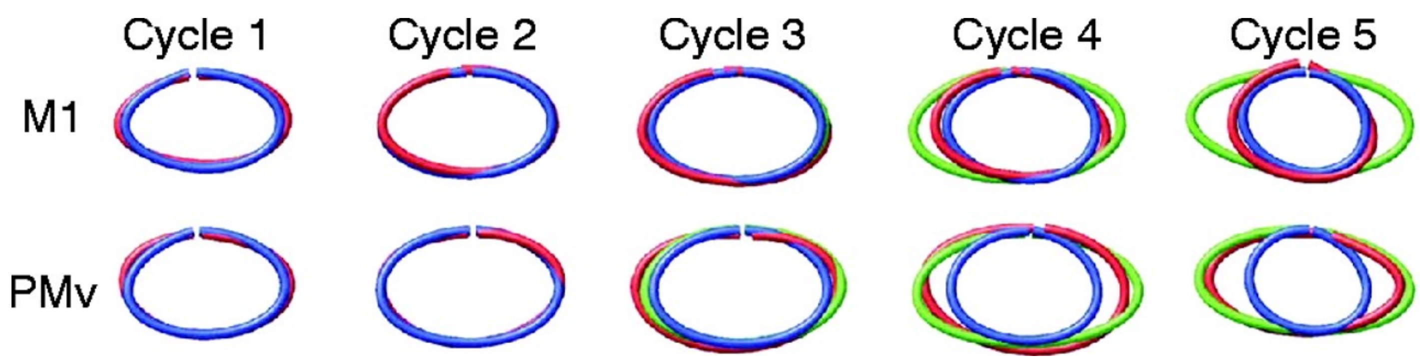
Premotor areas
Premotor dorsal (PMd), premotor ventral (PMv), supplementary motor area (SMA), cingulate (CMA)



– 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

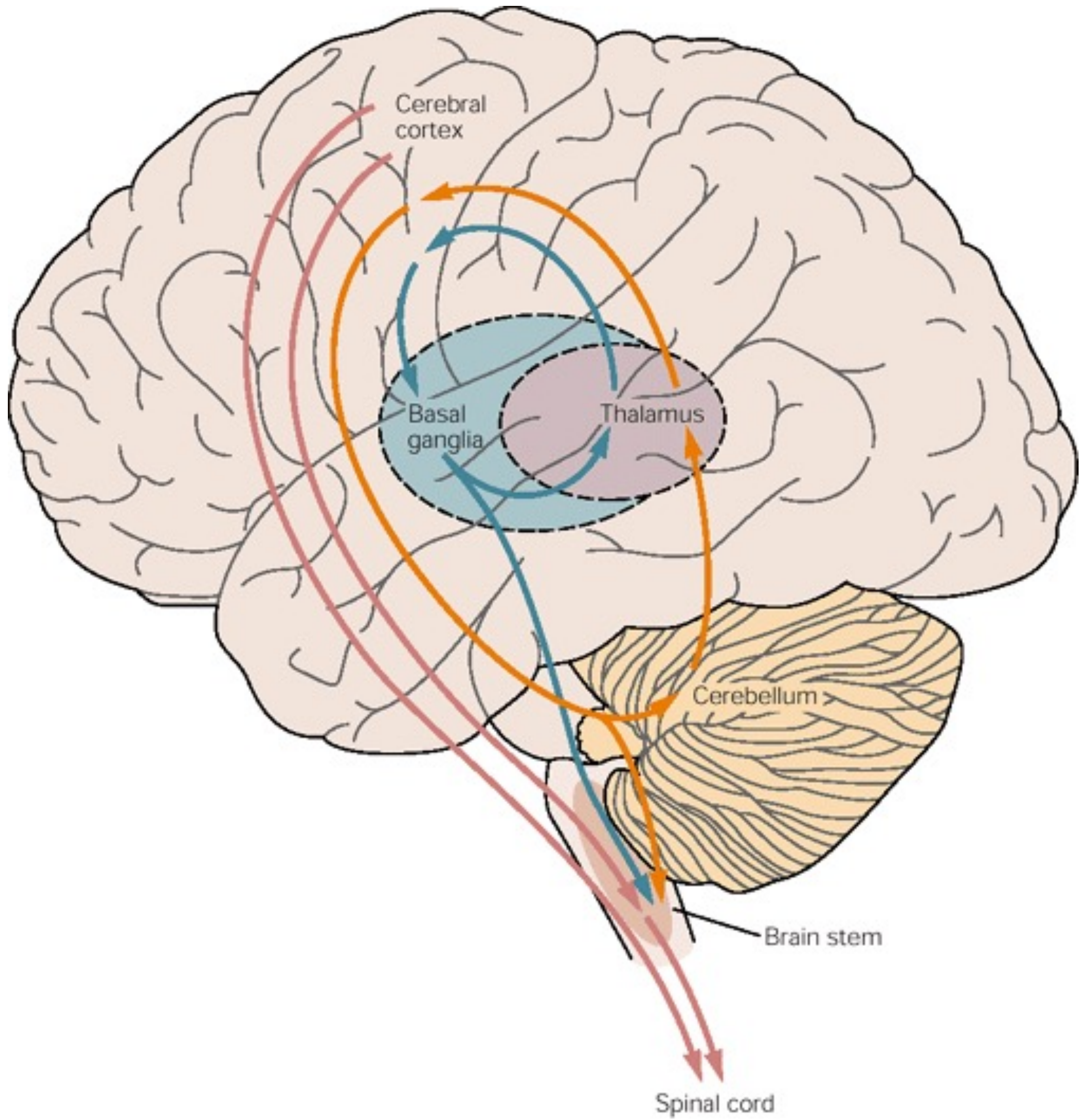




Illusion task trajectories. Top row is five cycles from M1 units. Bottom row is from the PMv. The hand trajectory is blue, cursor trajectory is green, and neural trajectory is red. Each displayed trajectory is the mean across five repetitions

Andy Schwartz

The basal Ganglia



Deep-Brain-Stimulation