

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

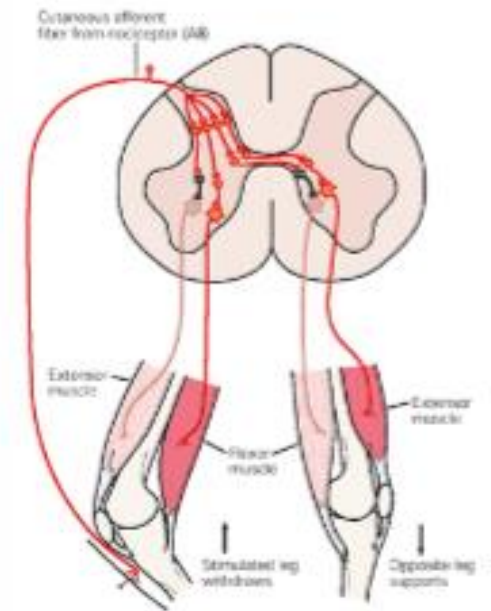
- Reflex
- Rhythmic
- Voluntary

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

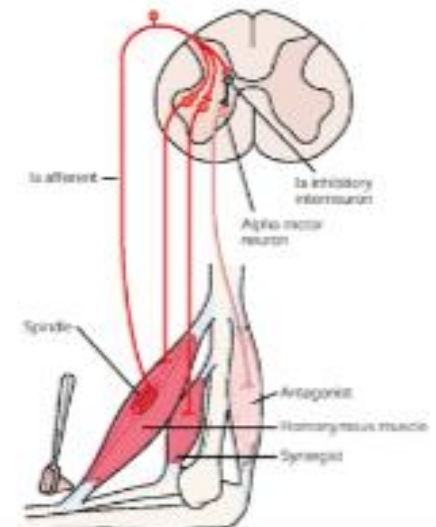
Noxious stimuli excites ipsilateral flexor, and excites contralateral extensor

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

A. Flexion and crossed-extension reflex



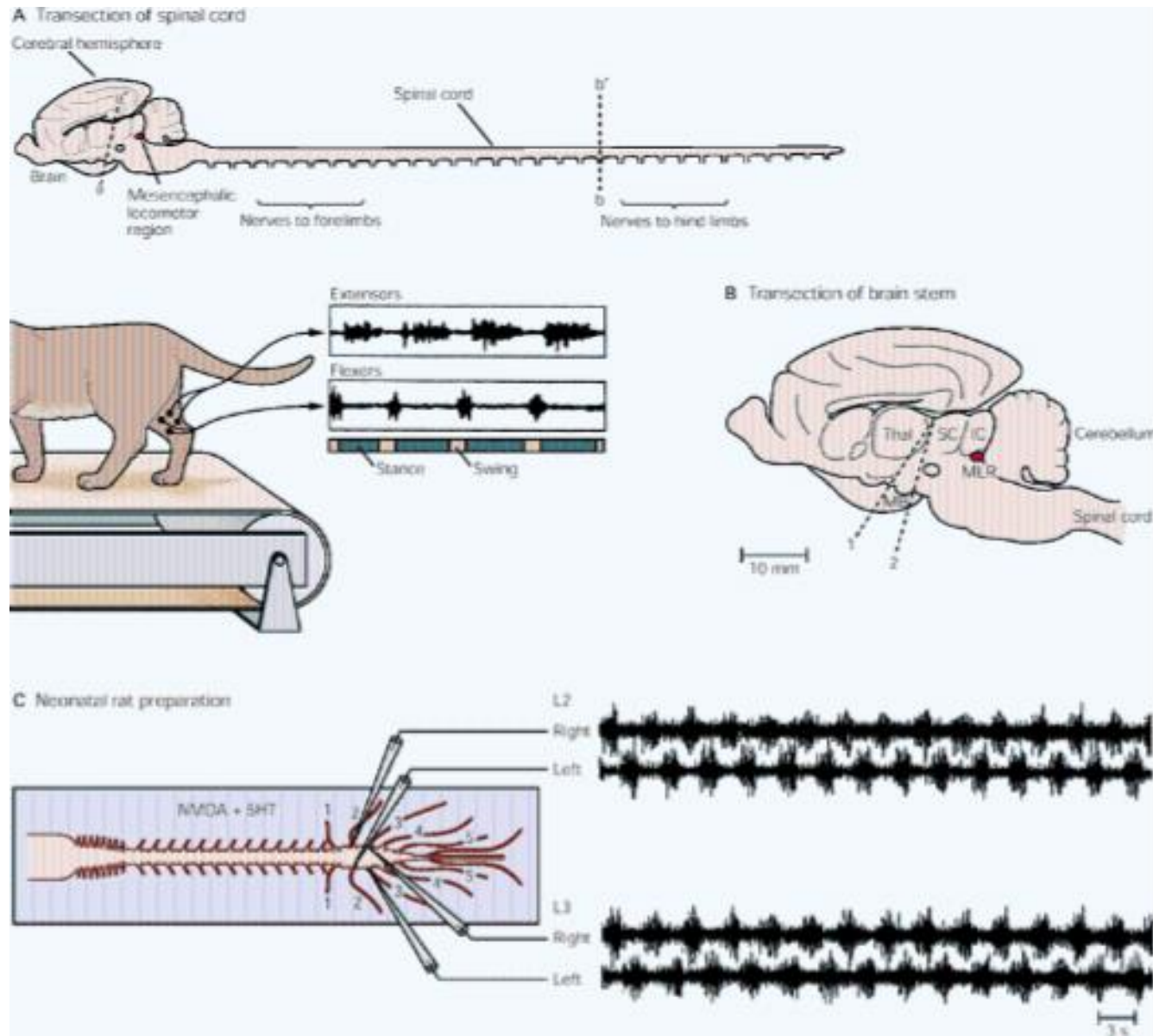
B. Stretch reflex



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

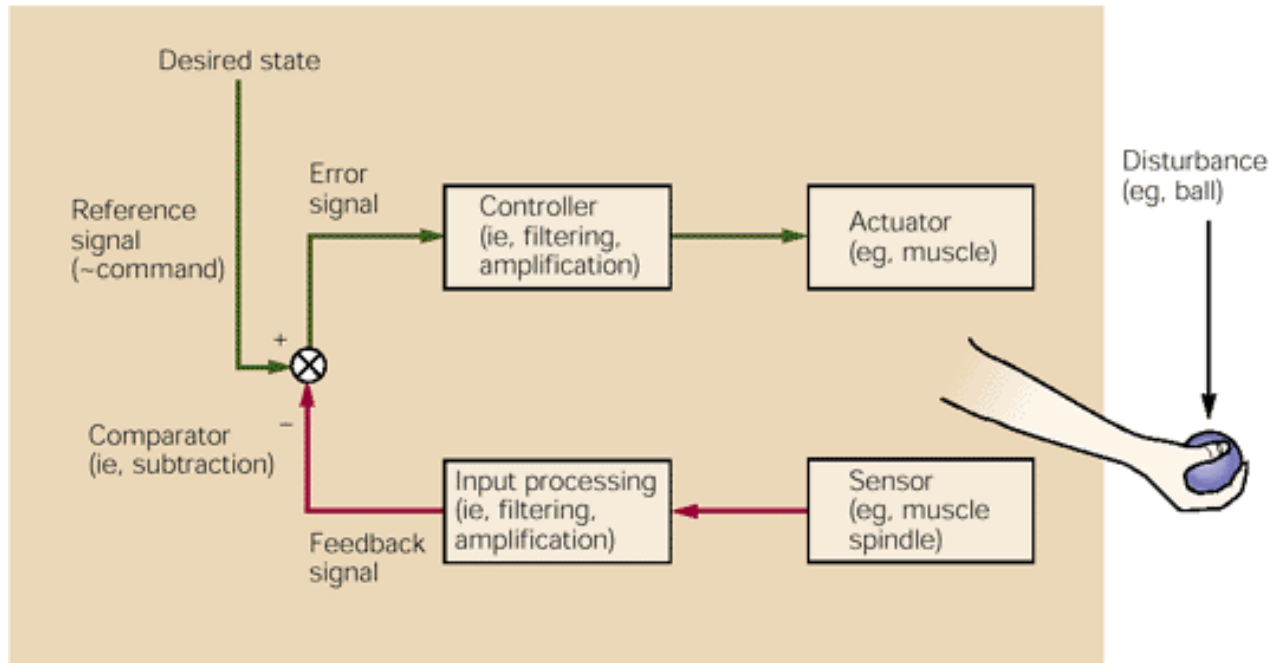
Goal directed

Reaching (~120 ms)



Feedback control (error correction)

A Feedback control: command specifies desired state



Vision

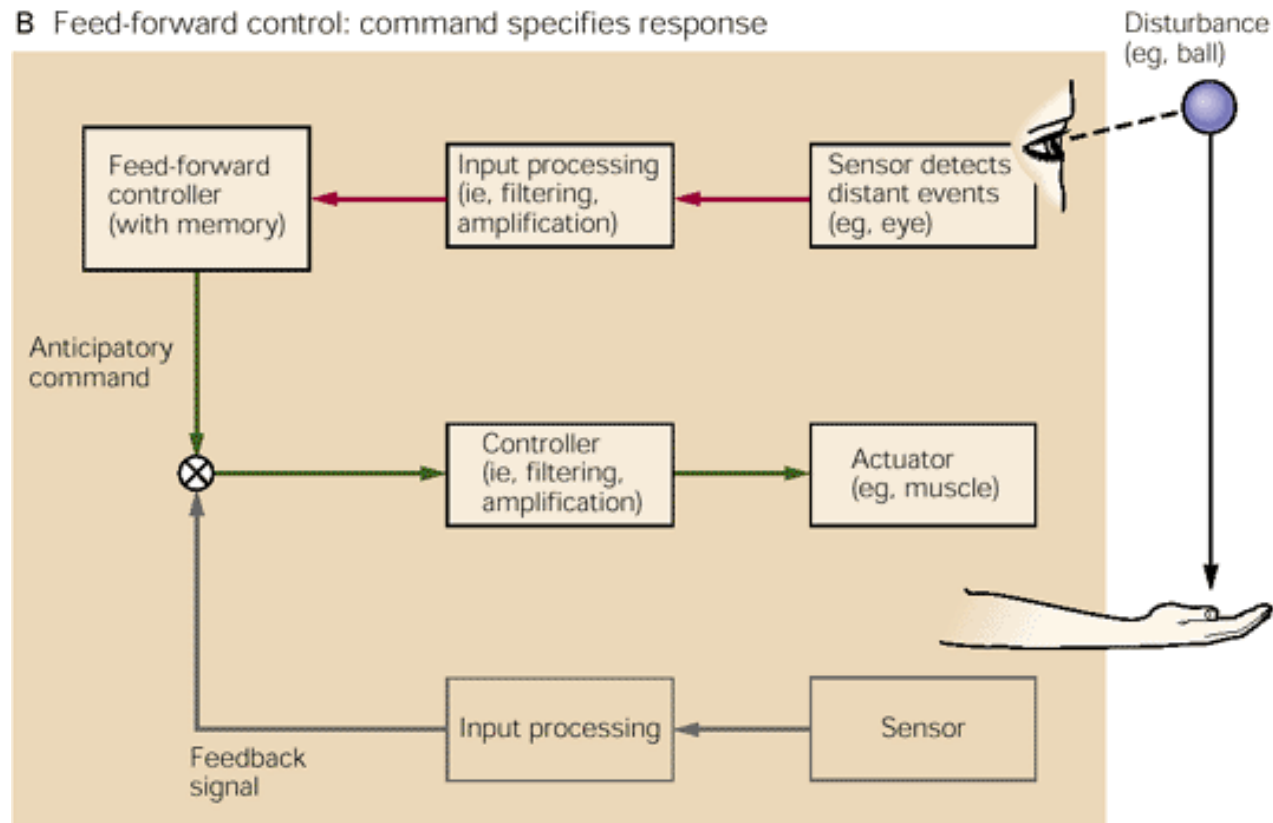
Proprioception

1. Gain

2. Delay (phase lag)

Feed-forward (open loop)

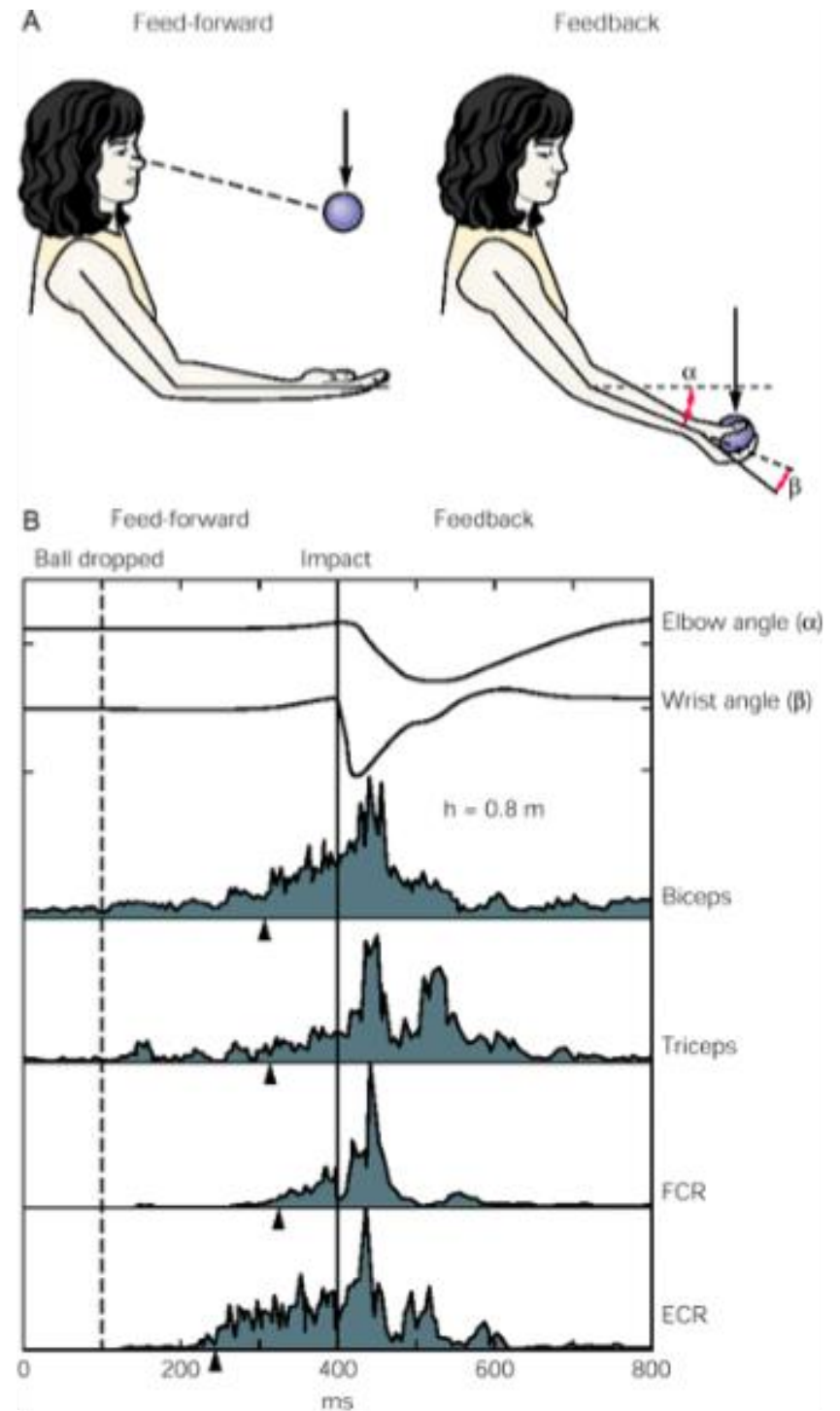
B Feed-forward control: command specifies response



1. Very hard computationally

Feedback control (error correction)

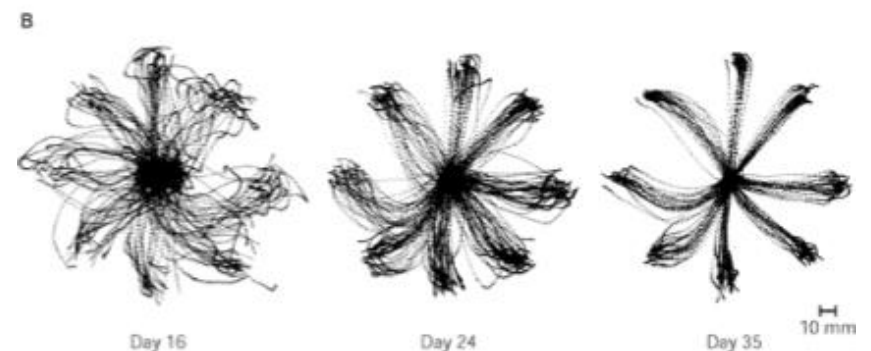
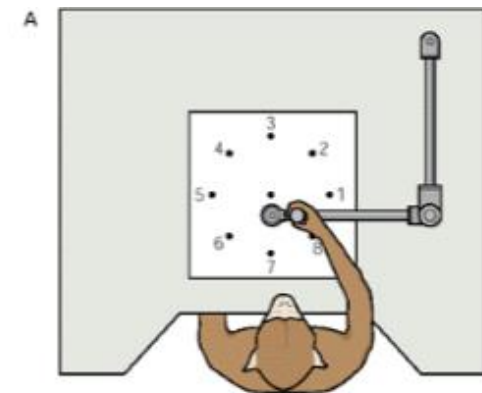
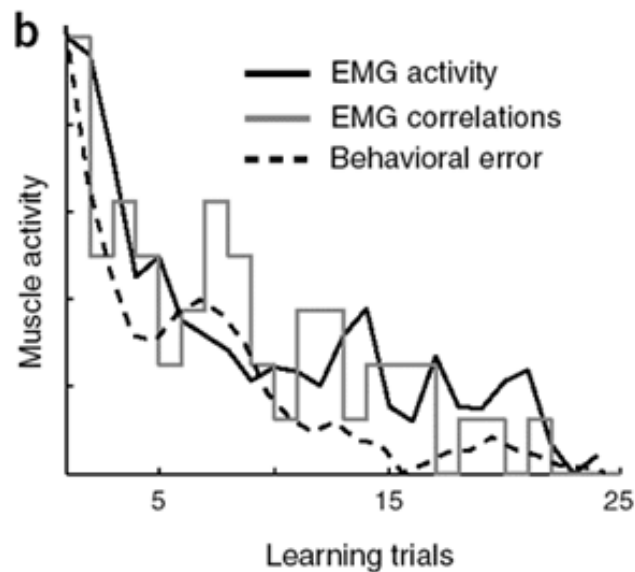
Feedforward (open loop)



Notice onset of muscles

Improve with practice

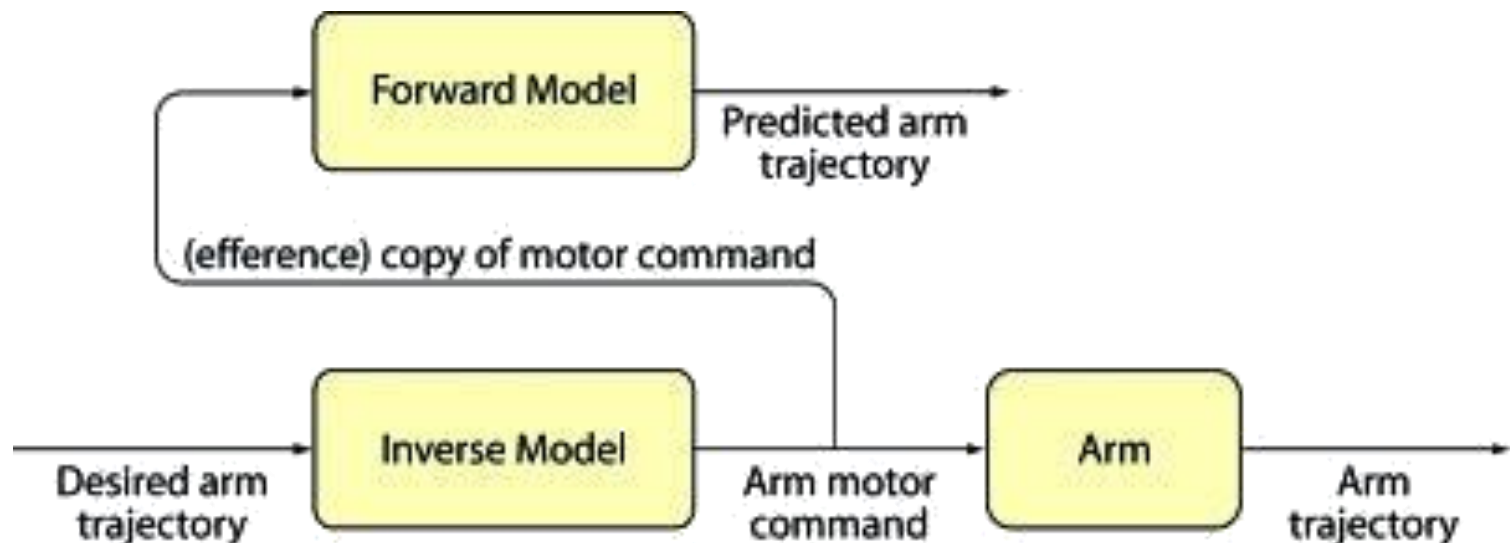
- Co-contraction of muscles
- **Internal models:** a neural representation of the relationship between the hand and the environment (how the arm would respond to the neural command).



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)

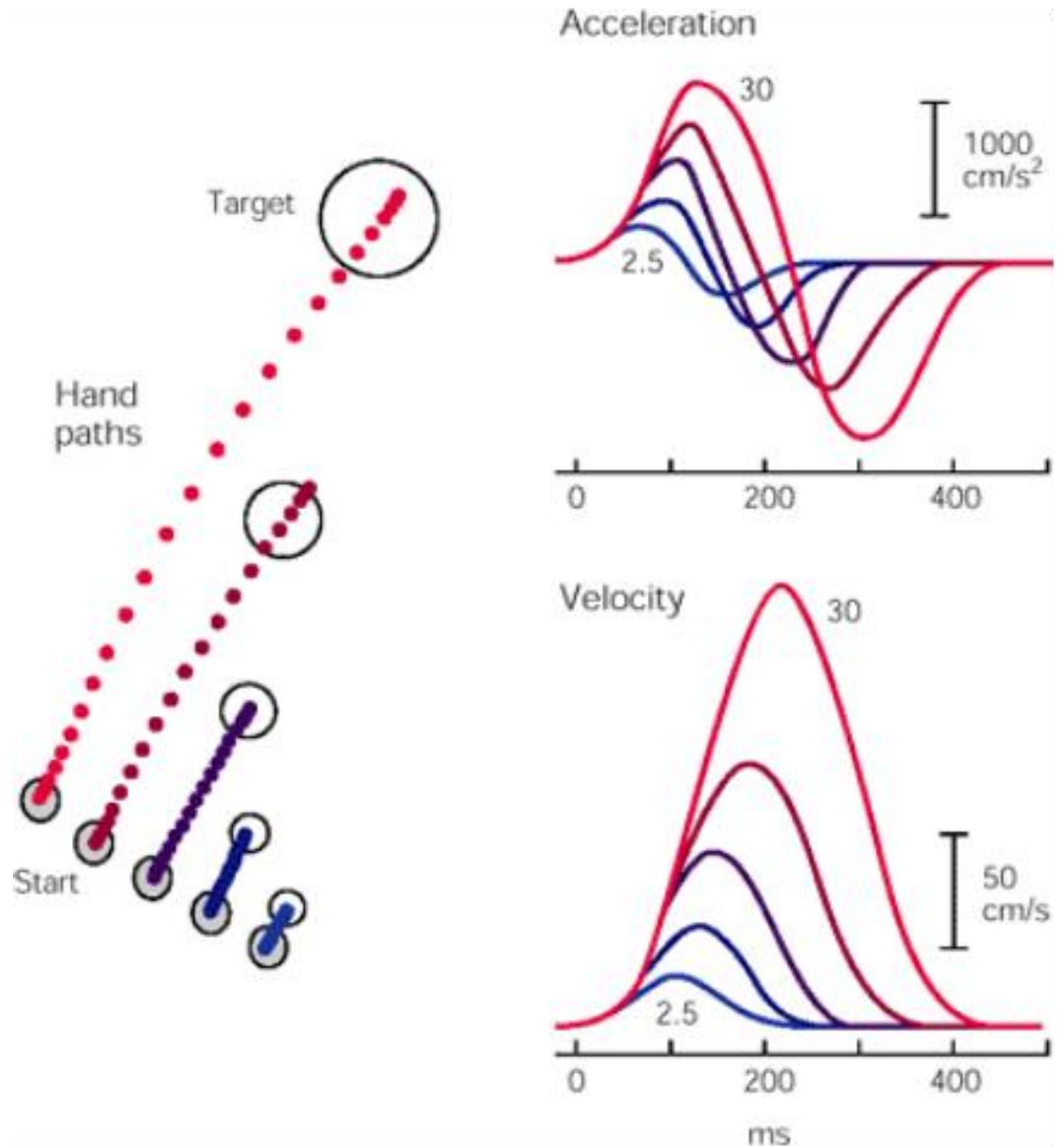


- A Able was I ere I saw Elba
- B Able was I ere I saw Elba
- C Able was I ere I saw Elba
- D Able was I ere I saw Elba
- E Able was I ere I saw Elba

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;

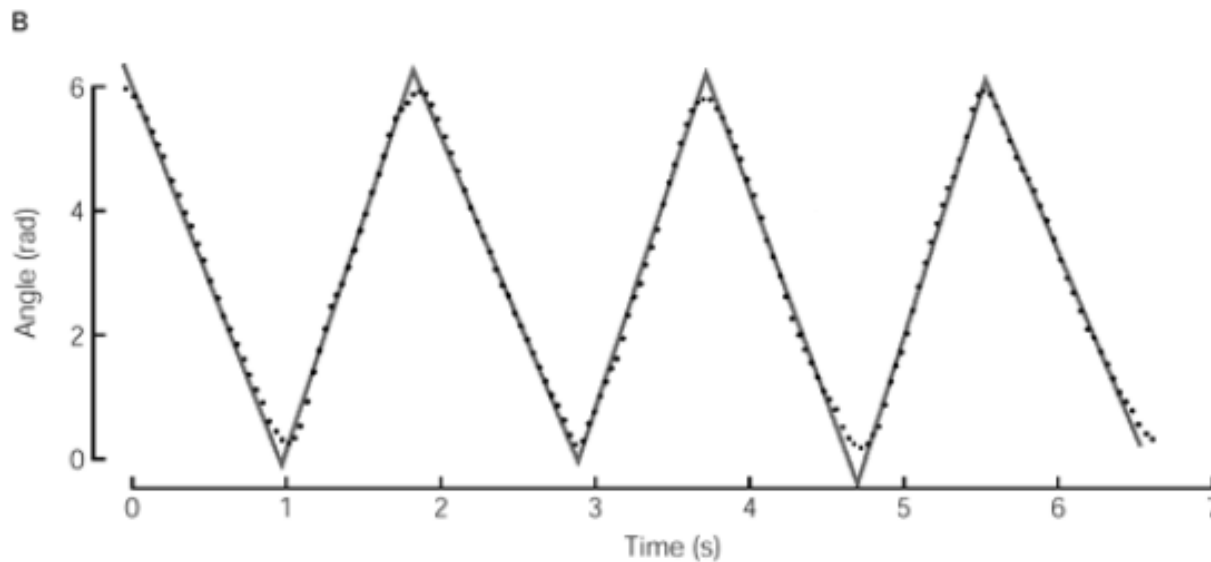
Dynamic transformation: relate motor commands to the motion of the system; in the reaching task here considered, the forces applied changed the system without changing the kinematics.

Building blocks – segmentation - primitives

Isogony (equal angles)

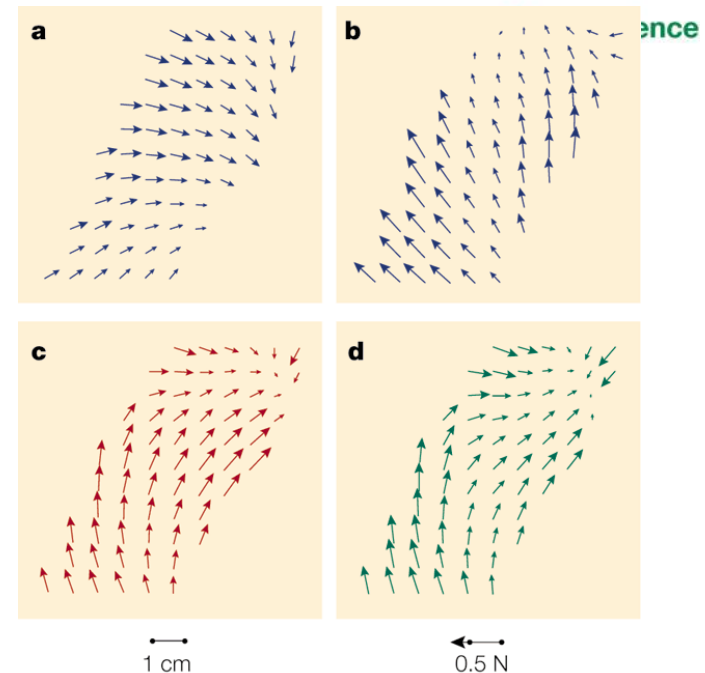
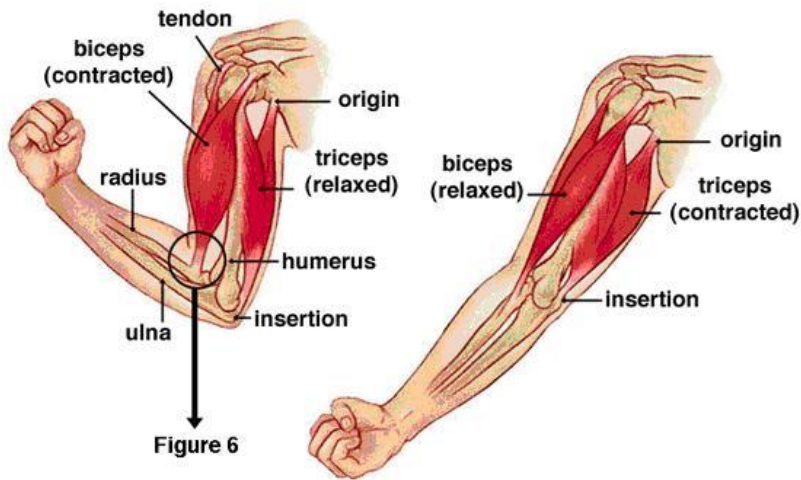
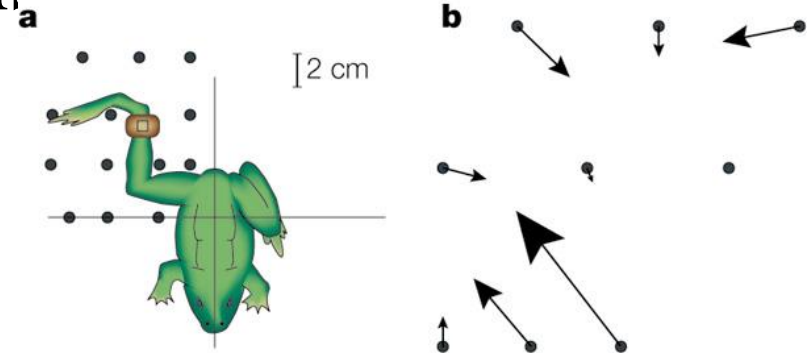
Isochrony (duration independent of length)

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

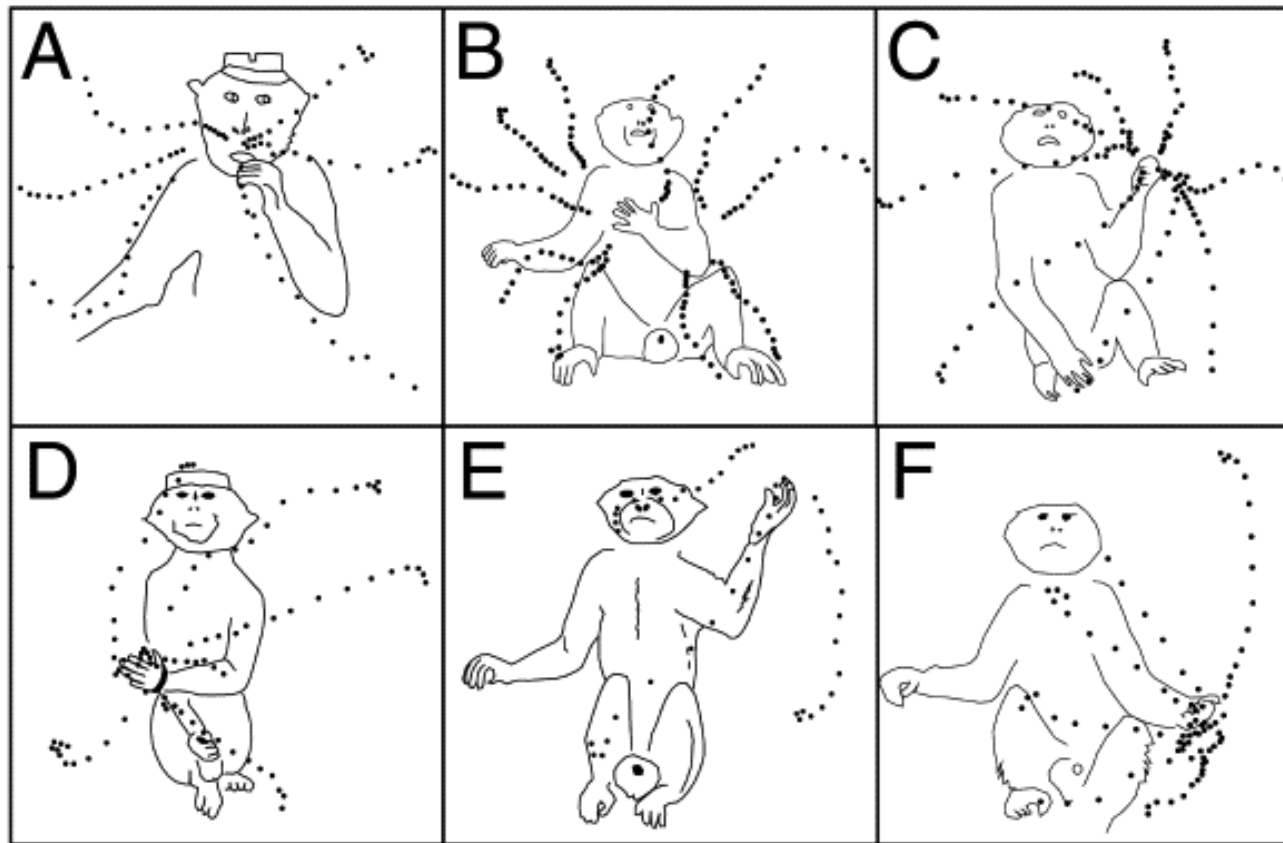


Designing a complex trajectory with limitations

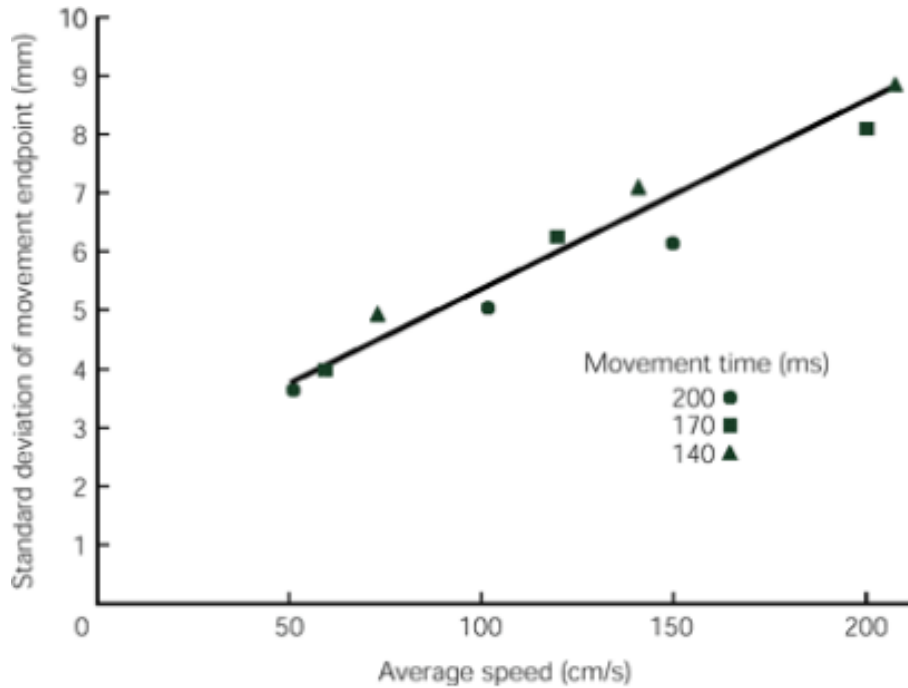
- Antagonistic muscles
- Equilibrium point trajectory



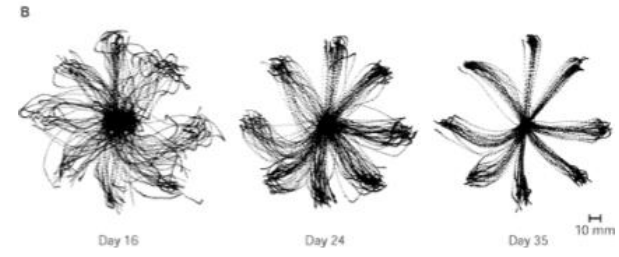
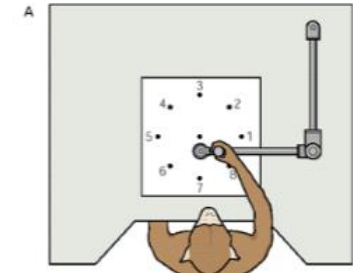
Stable behavioral gestures



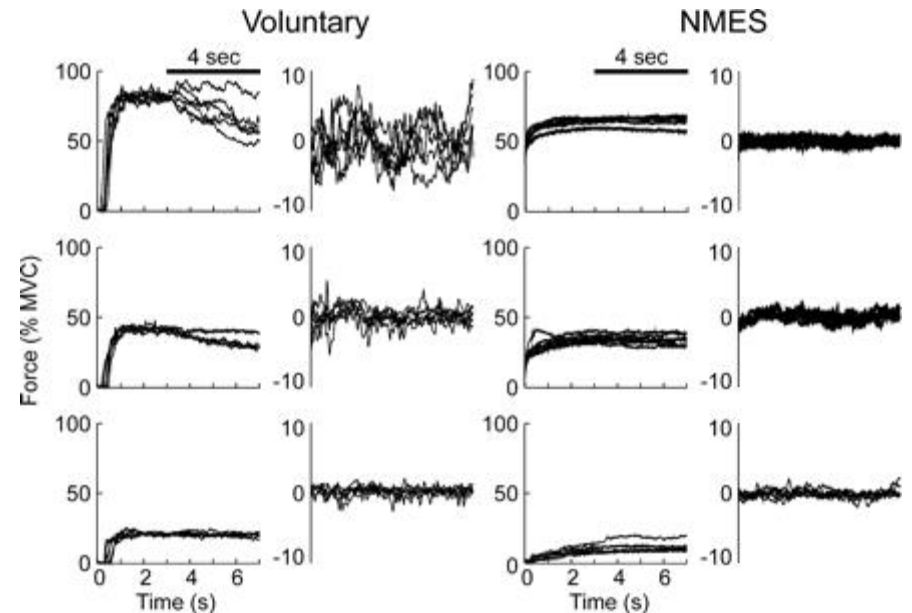
Speed – accuracy tradeoff (Woodsworth, 1890)



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



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

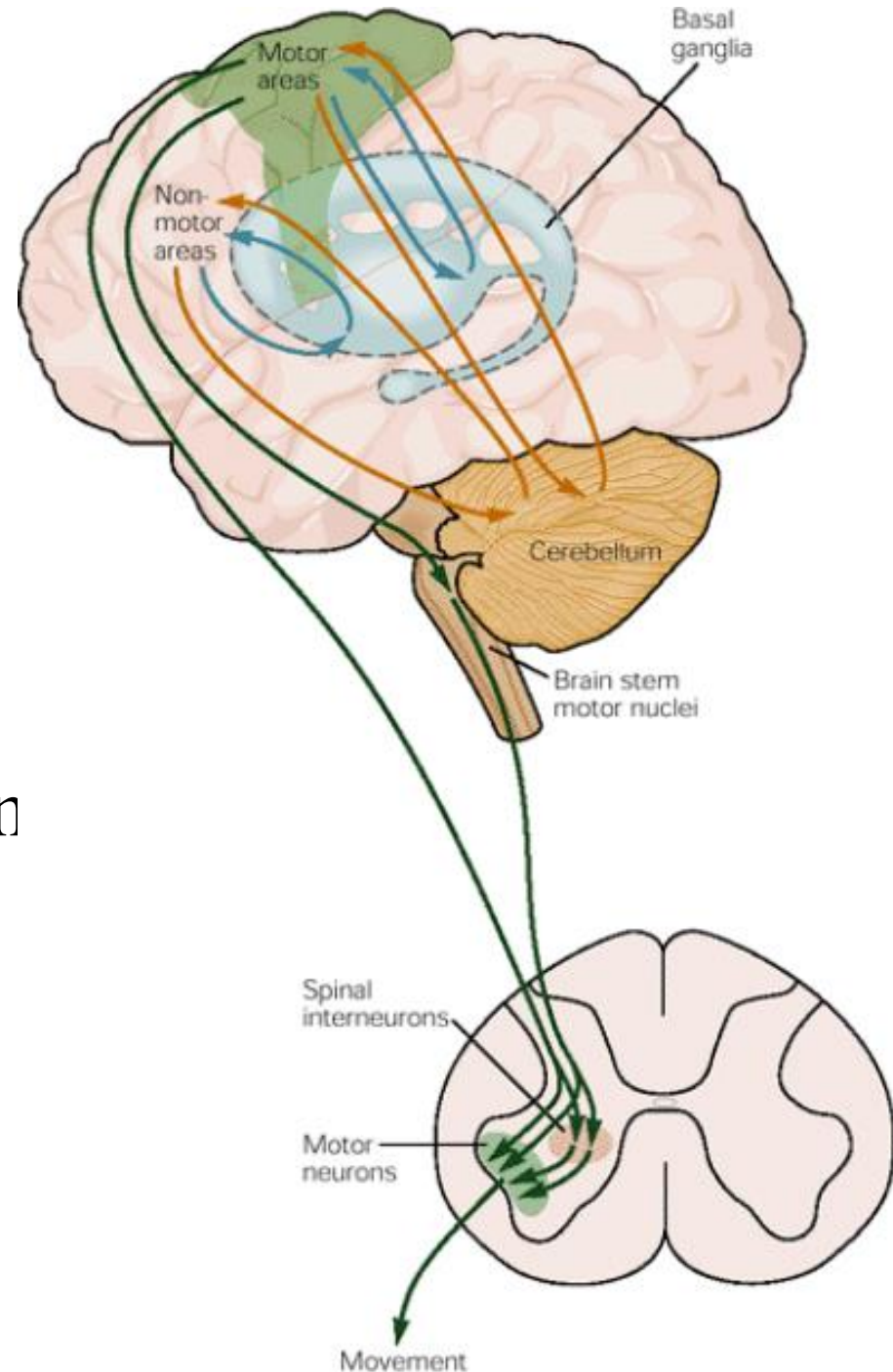


Overcoming noise: optimization principles

- 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

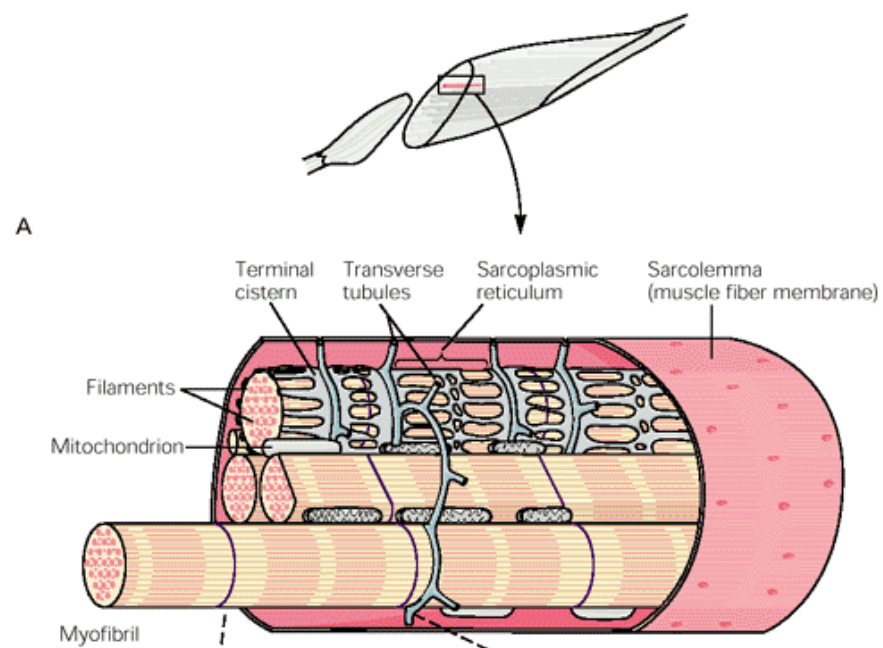


Muscles

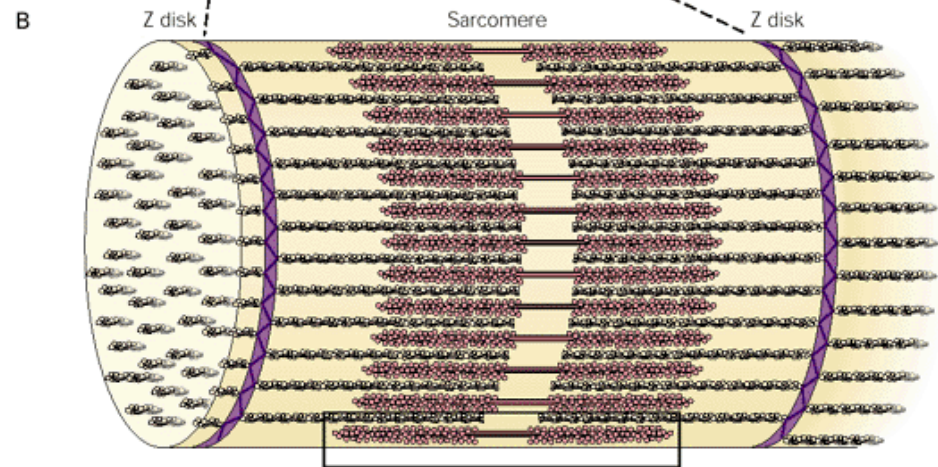
1. smooth muscles
2. cardiac muscles
3. **skeletal muscles**

Structure

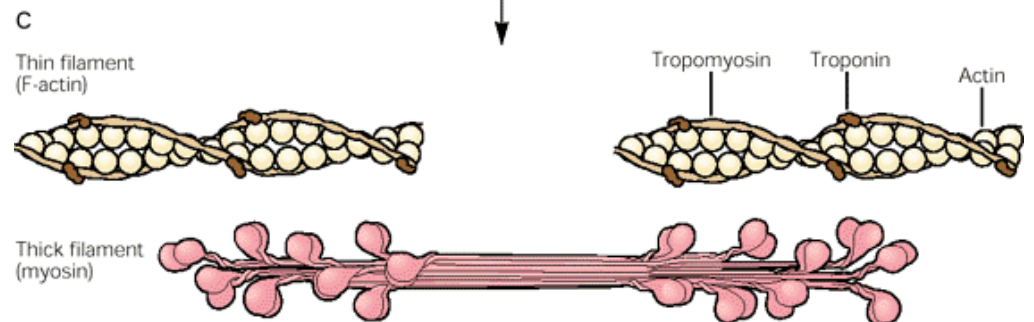
Muscle fiber



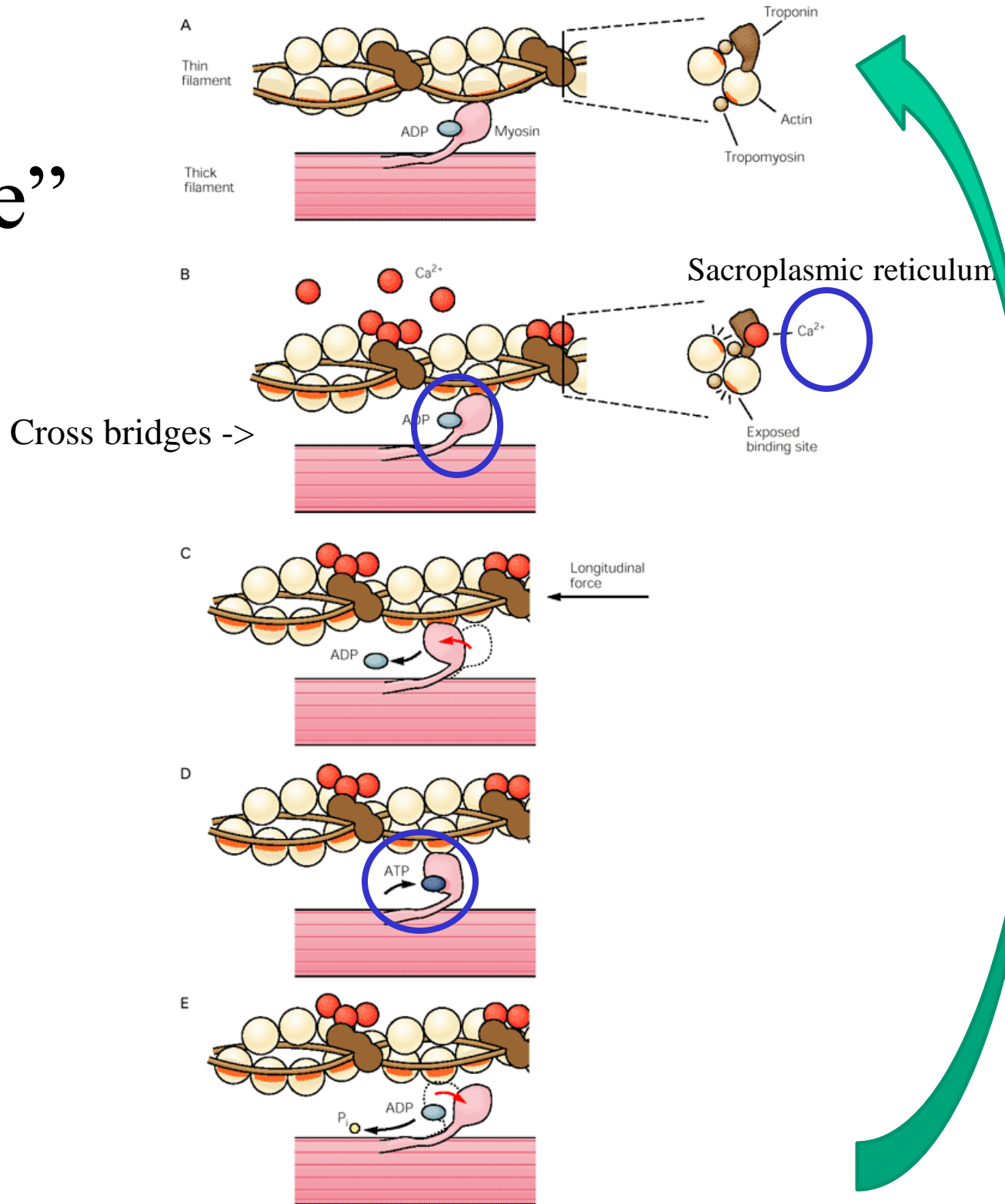
myofibril



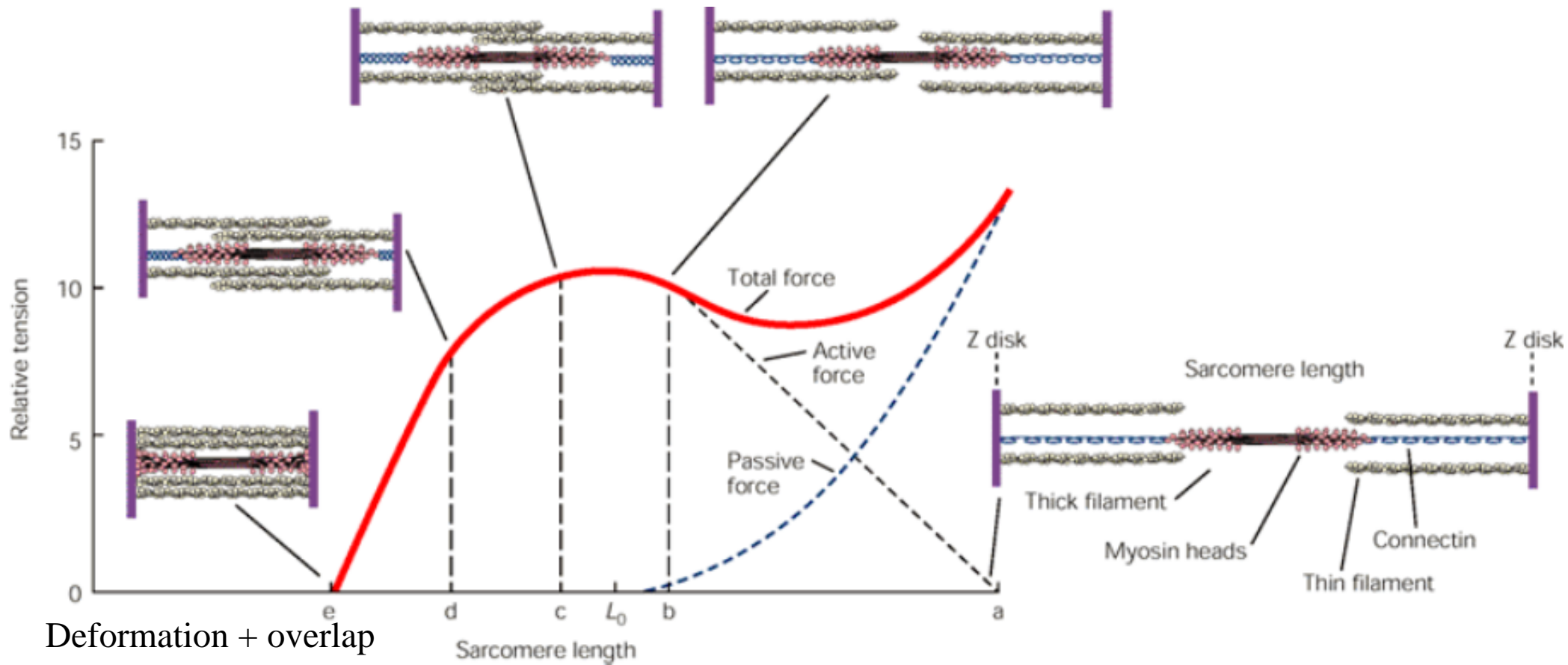
Sarcomere: functional unit



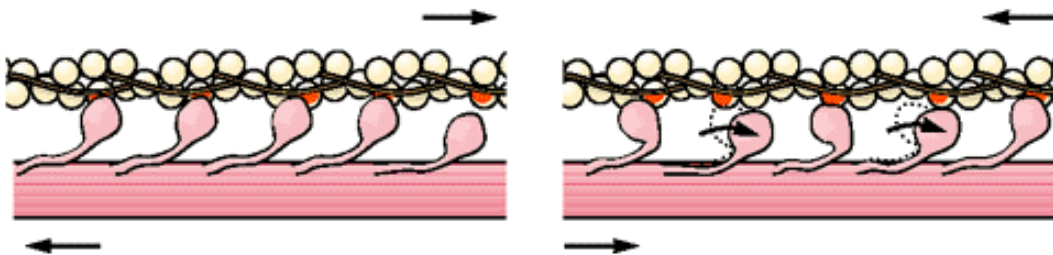
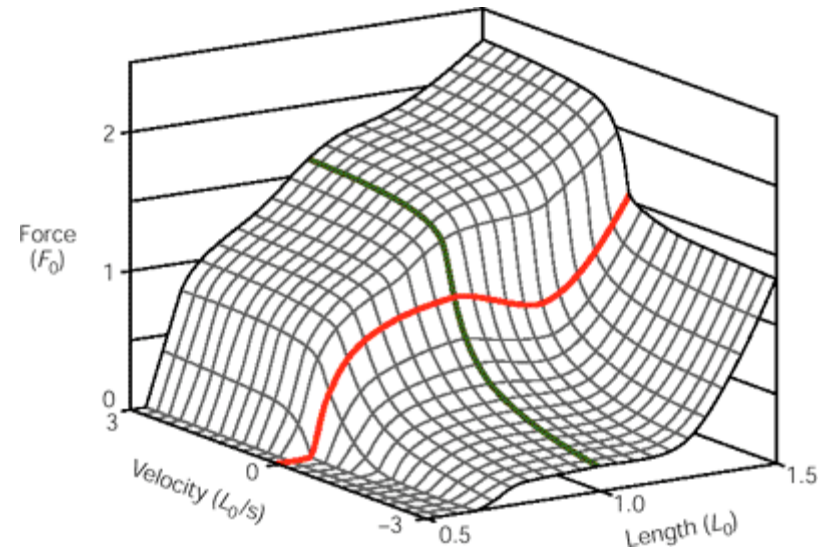
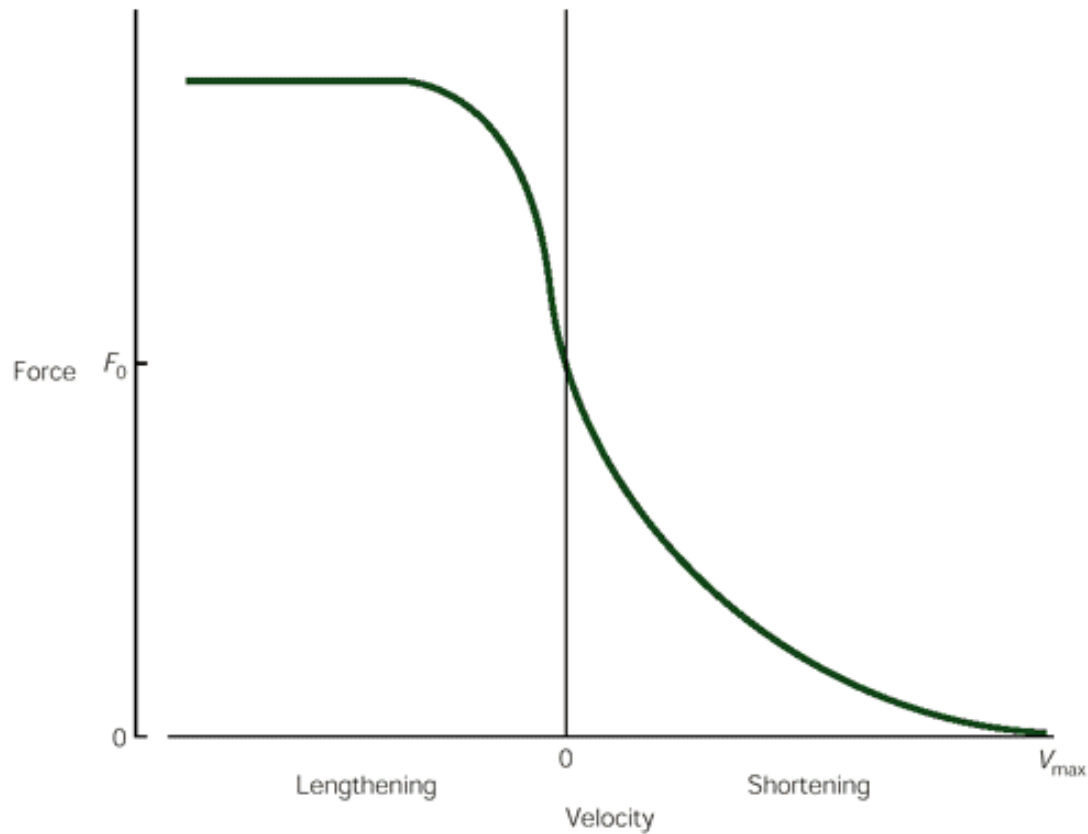
The "engine"



Force depends on length

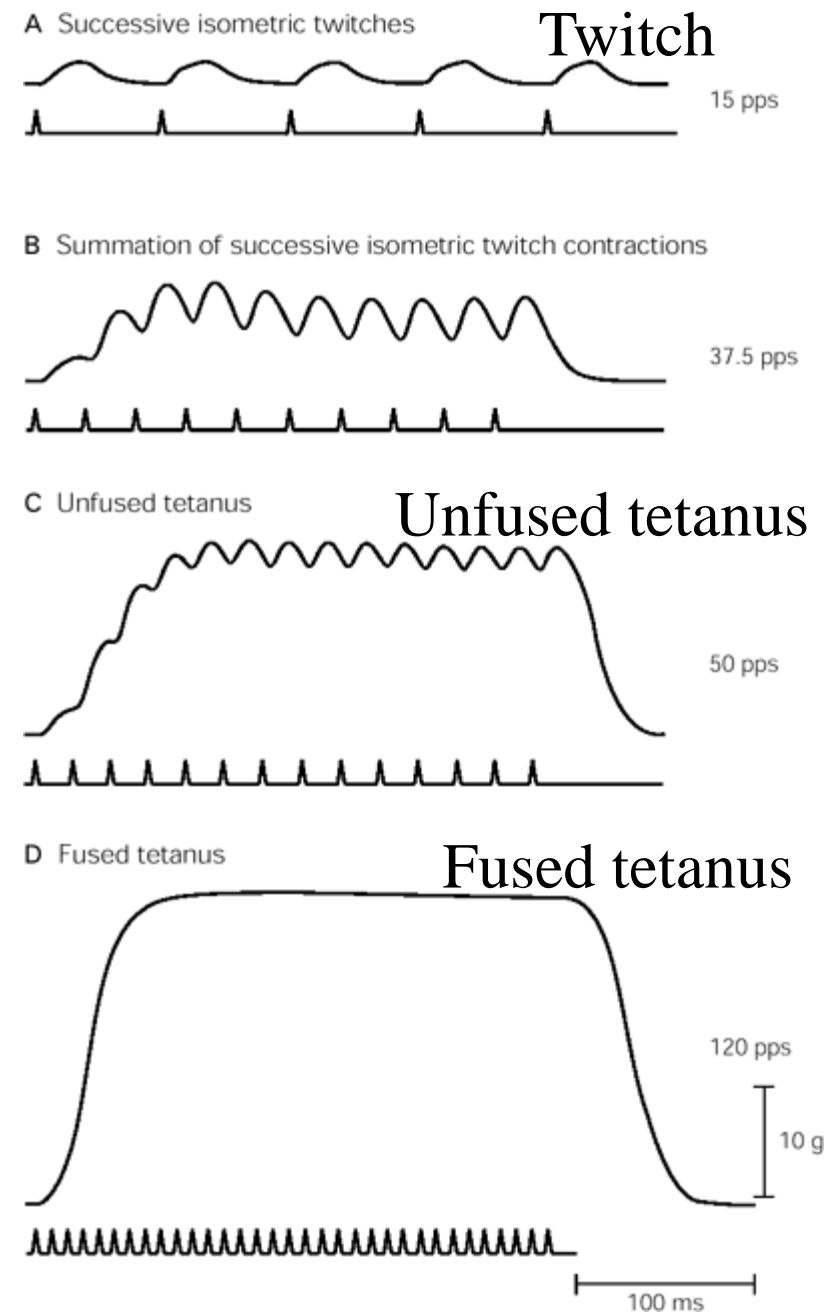


Force depends also on velocity

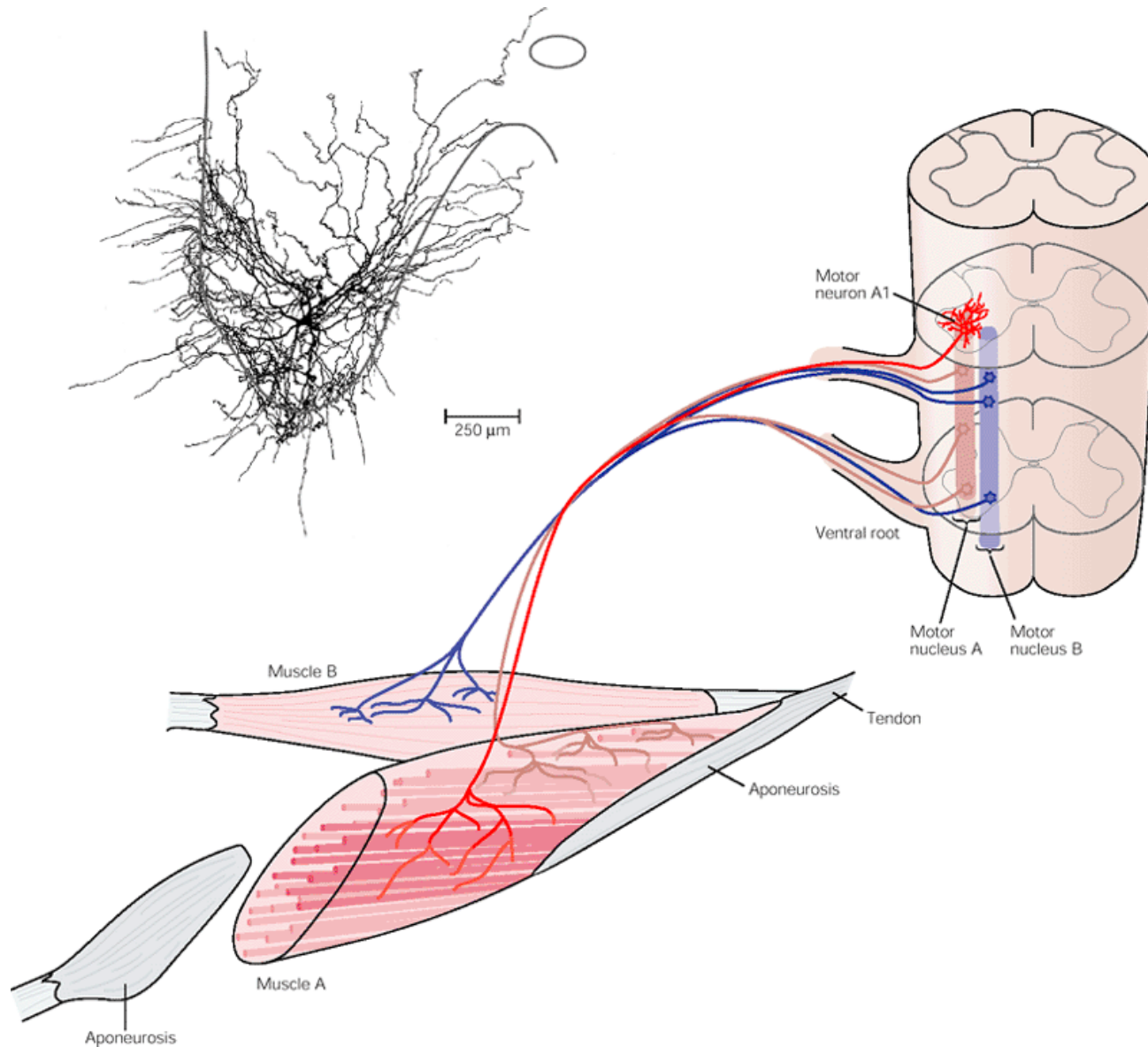


The force of a single muscle fiber is a function of

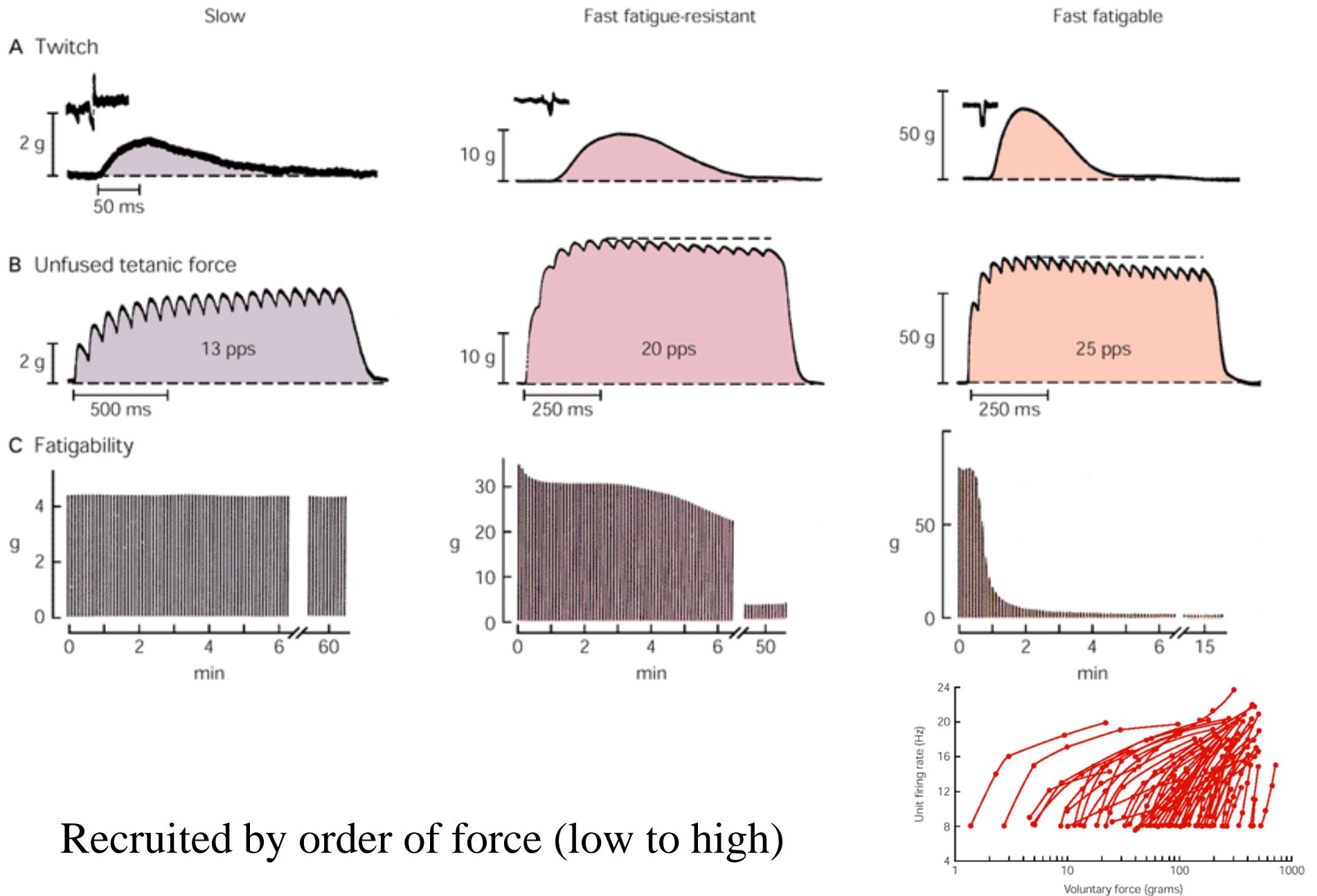
- Stimulation rate
- Stimulation pattern
- The muscle length
- The velocity of contraction
- The fiber type
- The fiber organization
- The duration of exercise - fatigue



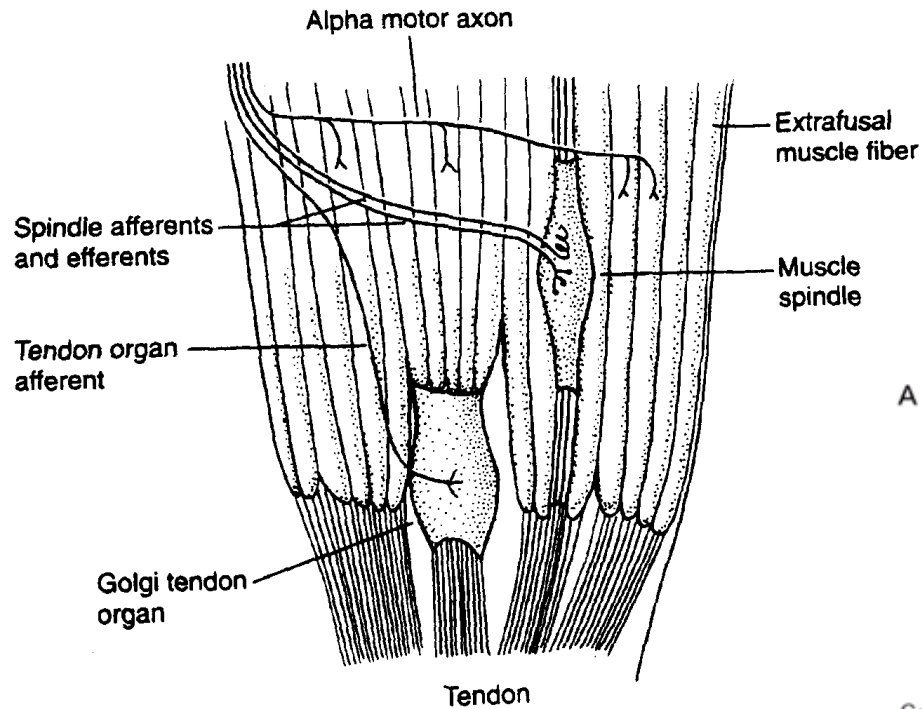
Motor unit: motor neuron and the muscle fibers it innervates (one to many)



3 types of motor unit:

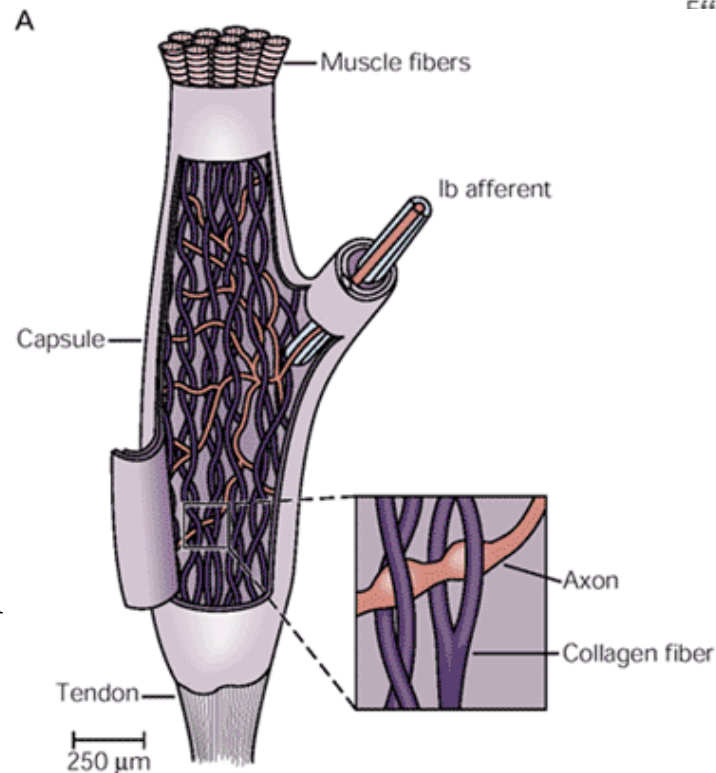


Muscle proprioceptive organs

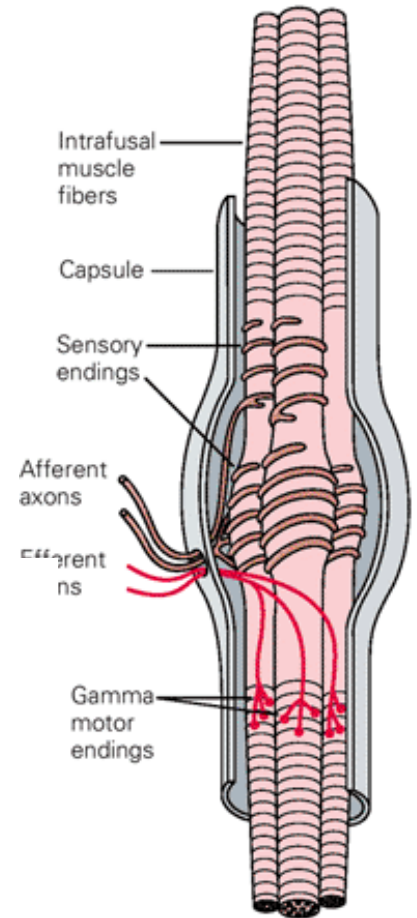


Golgi tendon: tension
Serial

Spindle: length
Parallel

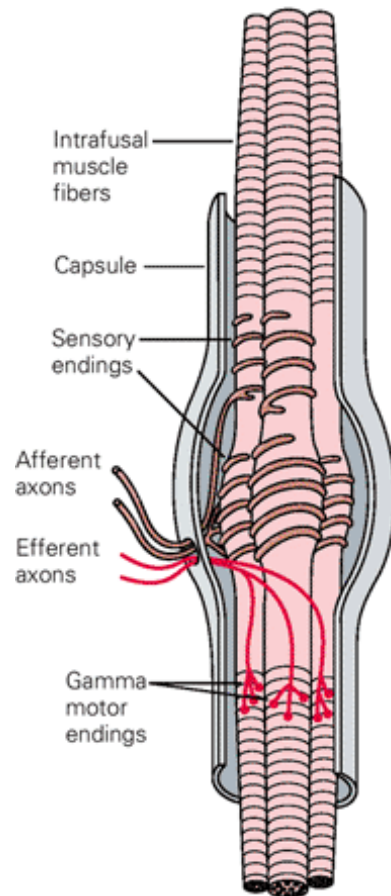


A Muscle spindle

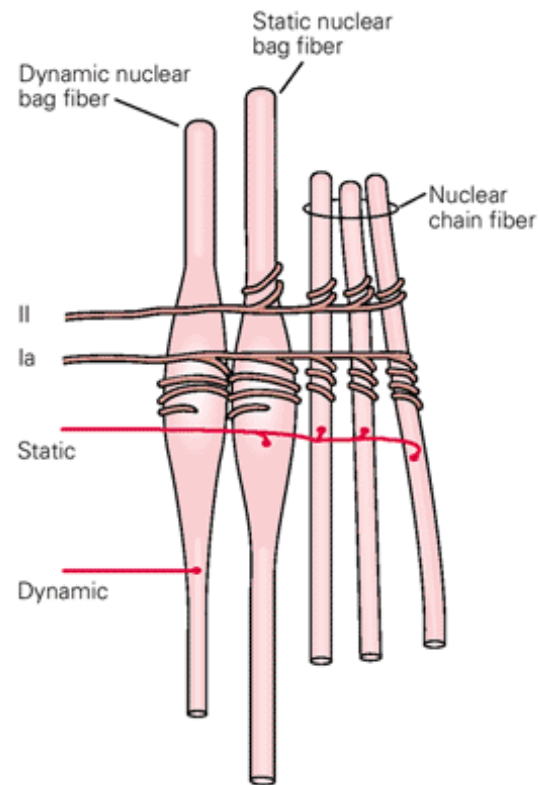


The muscle spindles are sensitive to changes in length

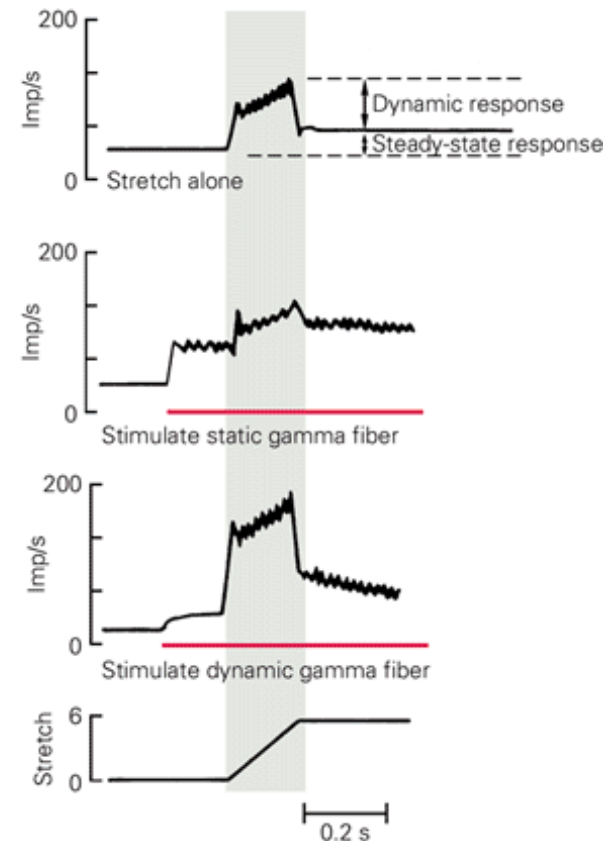
A Muscle spindle



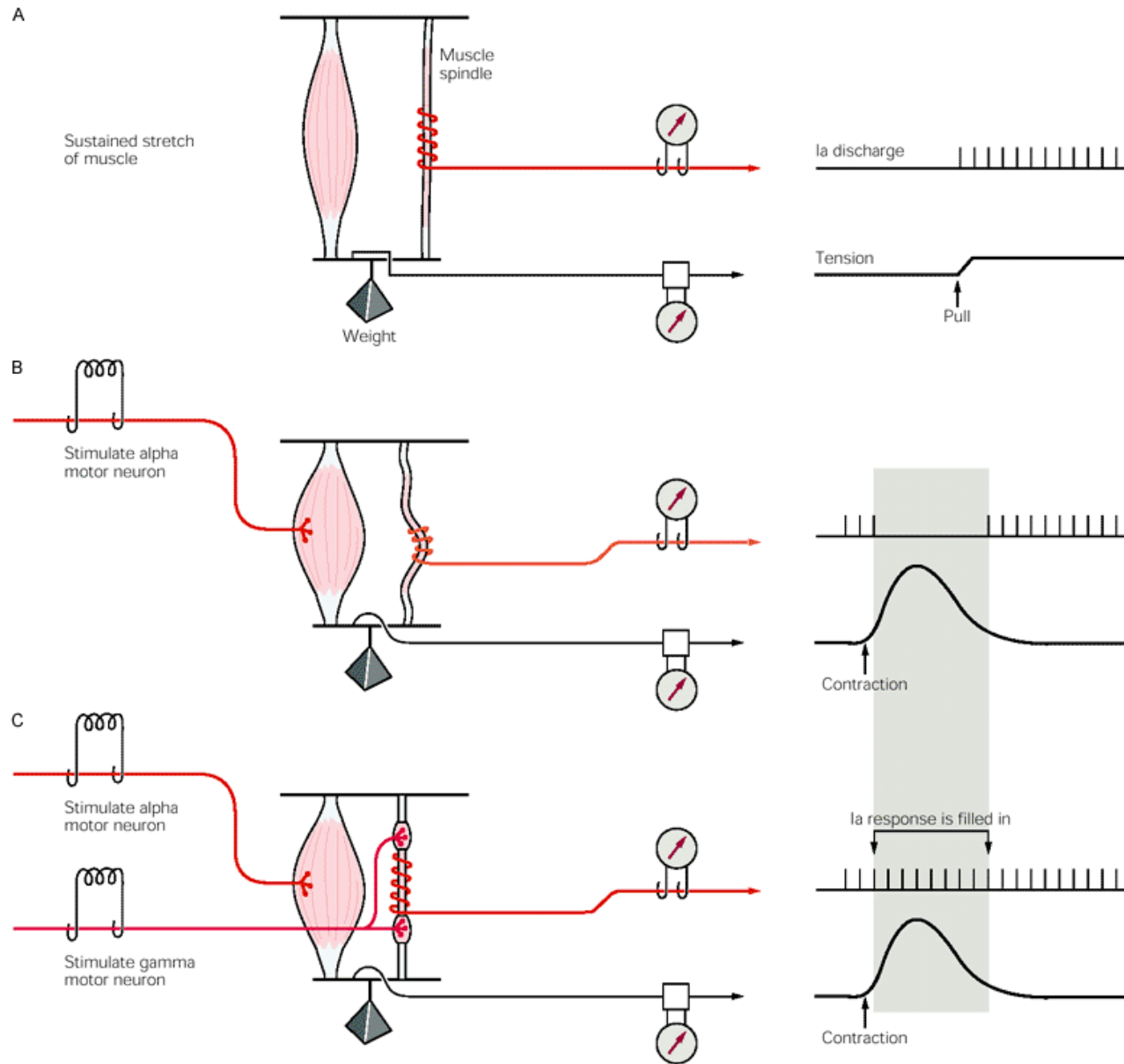
B Intrafusal fibers of the muscle spindle



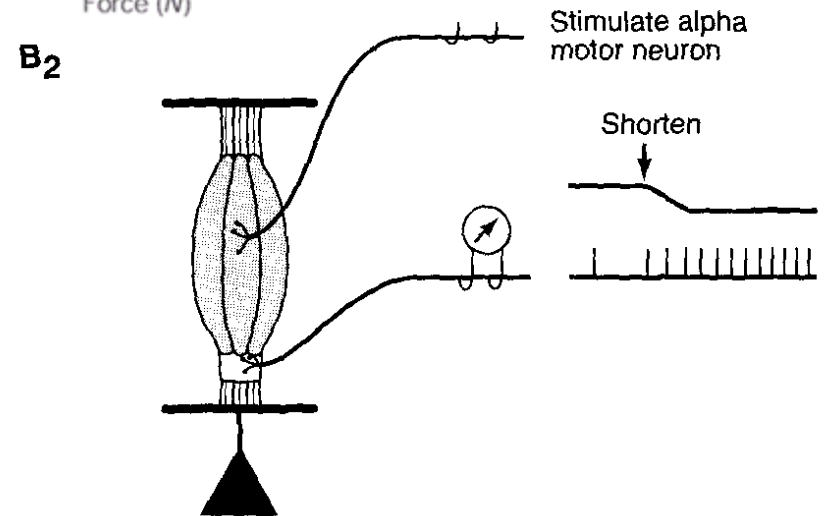
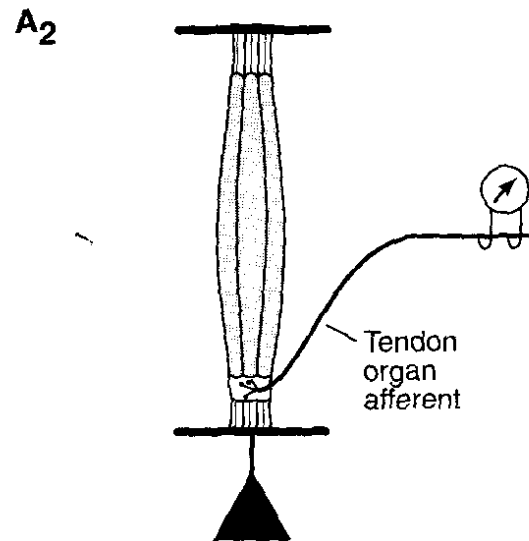
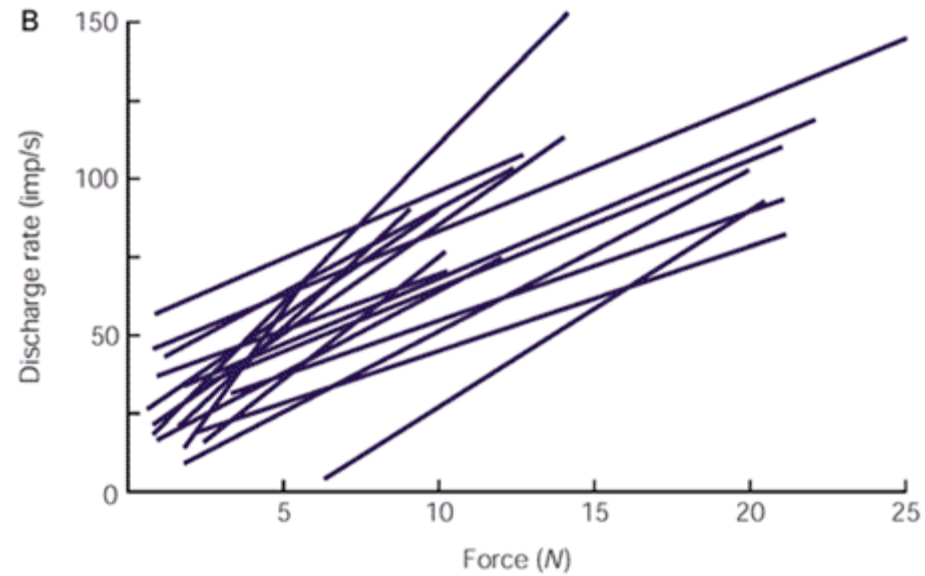
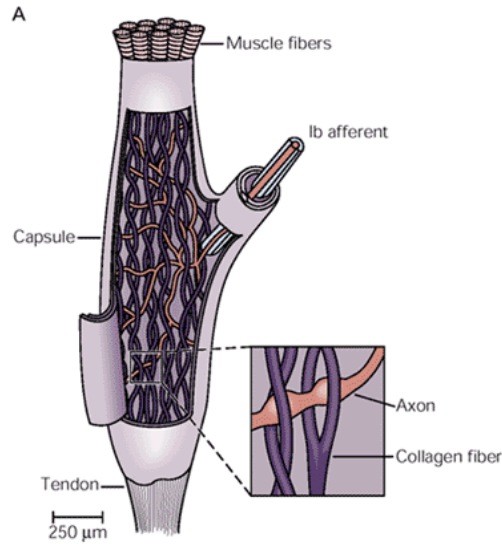
C Response of Ia sensory fiber to selective activation of motor neurons



Active range can be dynamically modulated



Golgi tendon organs are sensitive to the tension



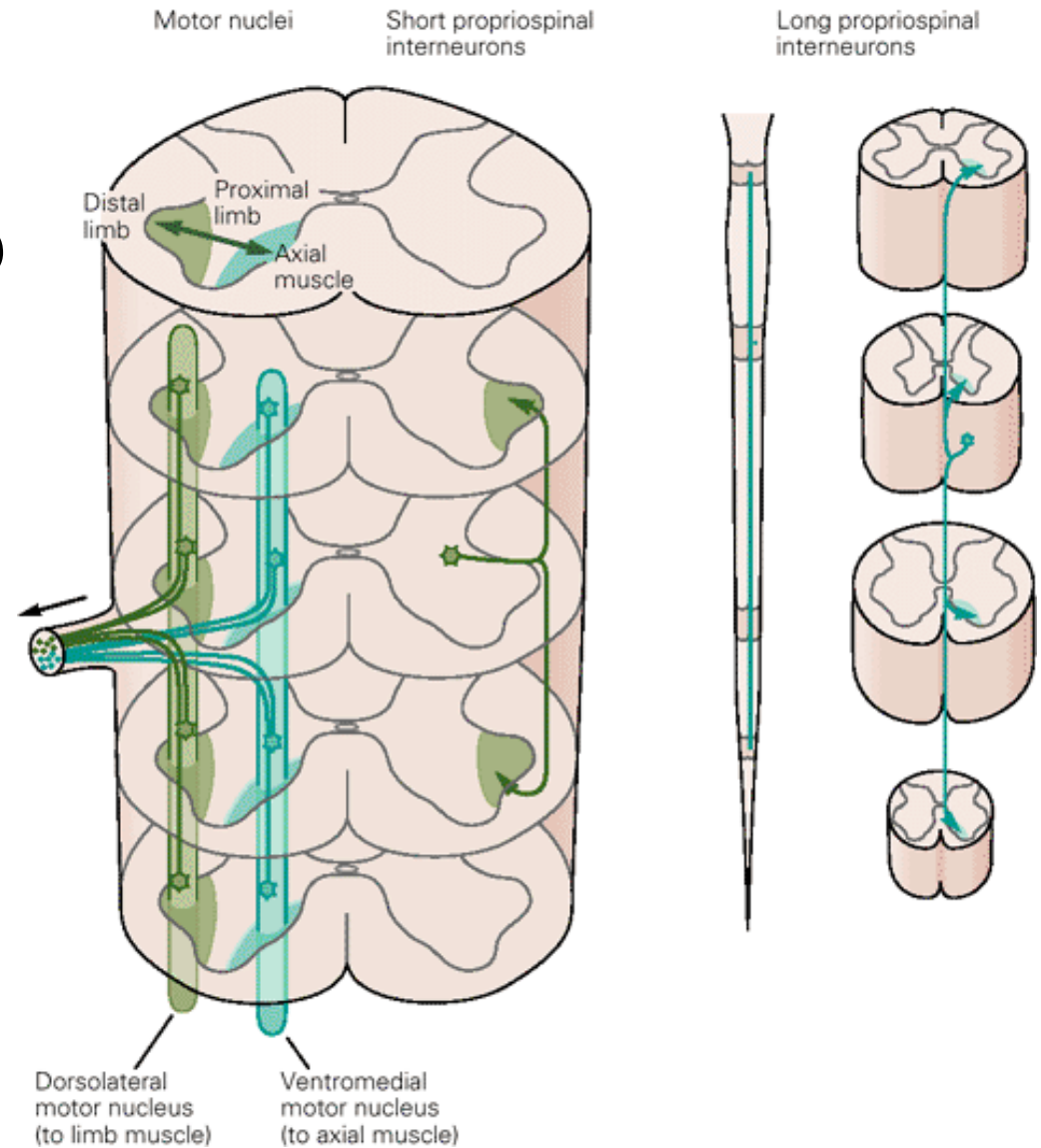
Spinal cord, Brain stem and spinal tracts

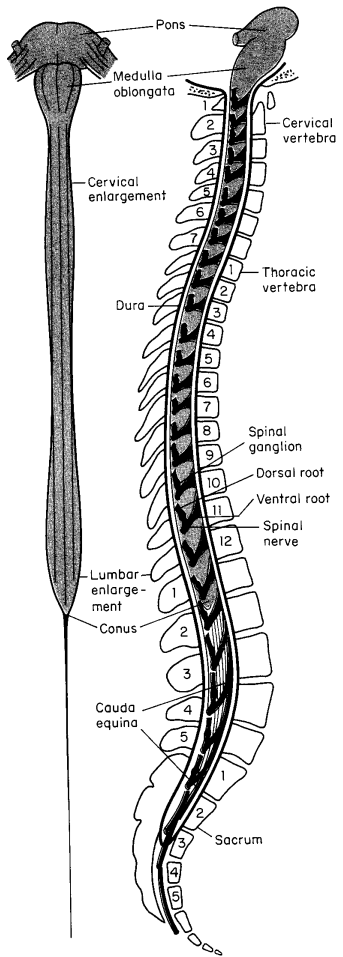
Spinal cord

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.

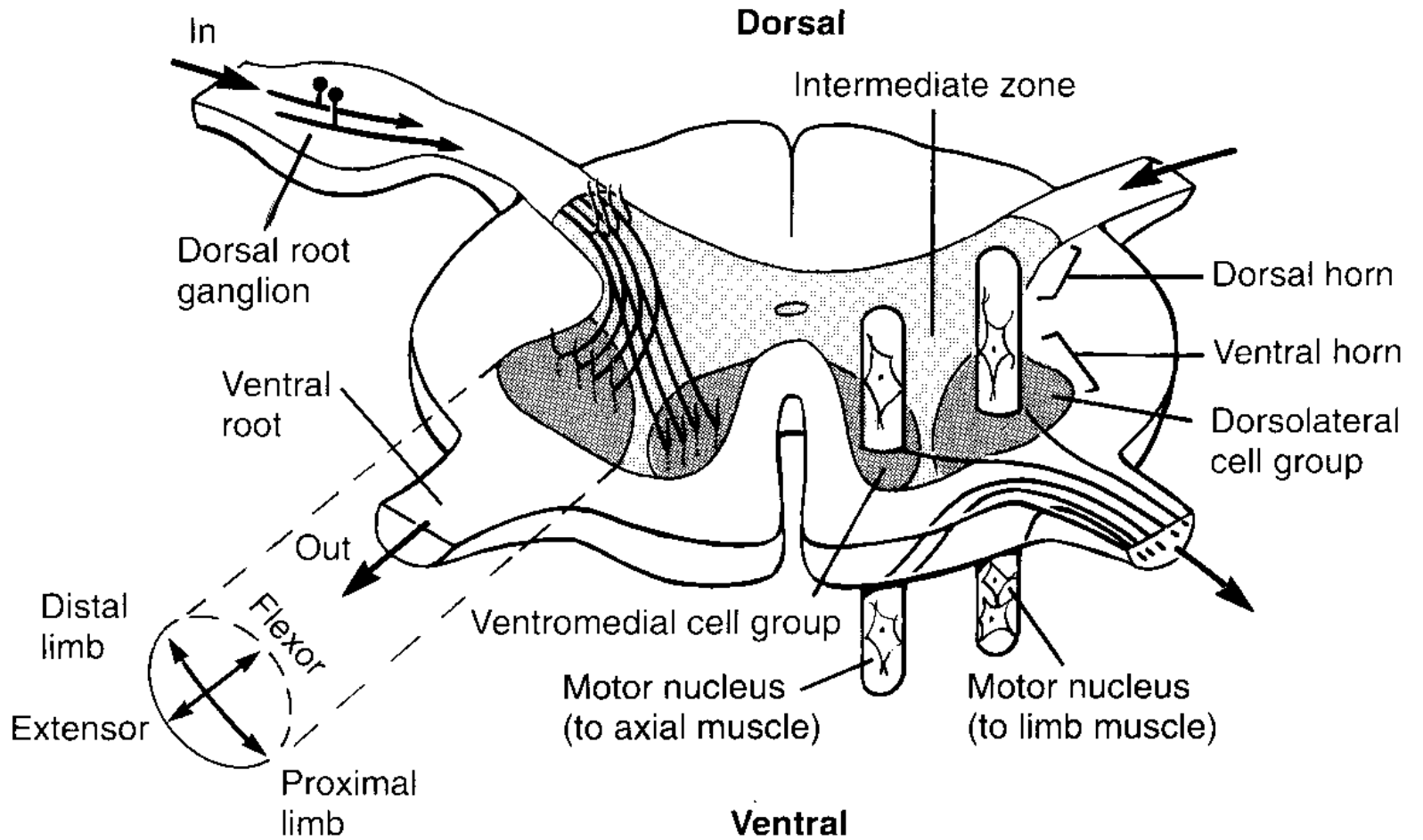
Medial nuclei are long across segments
Lateral are shorter





Course of afferent fibers

Location of motor nuclei

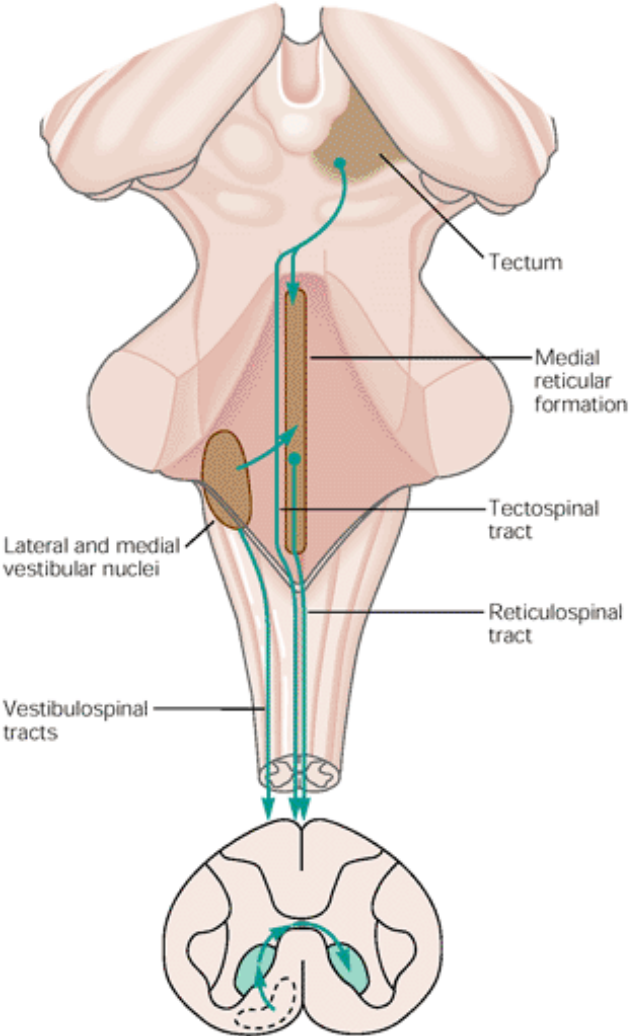


Brain stem pathways

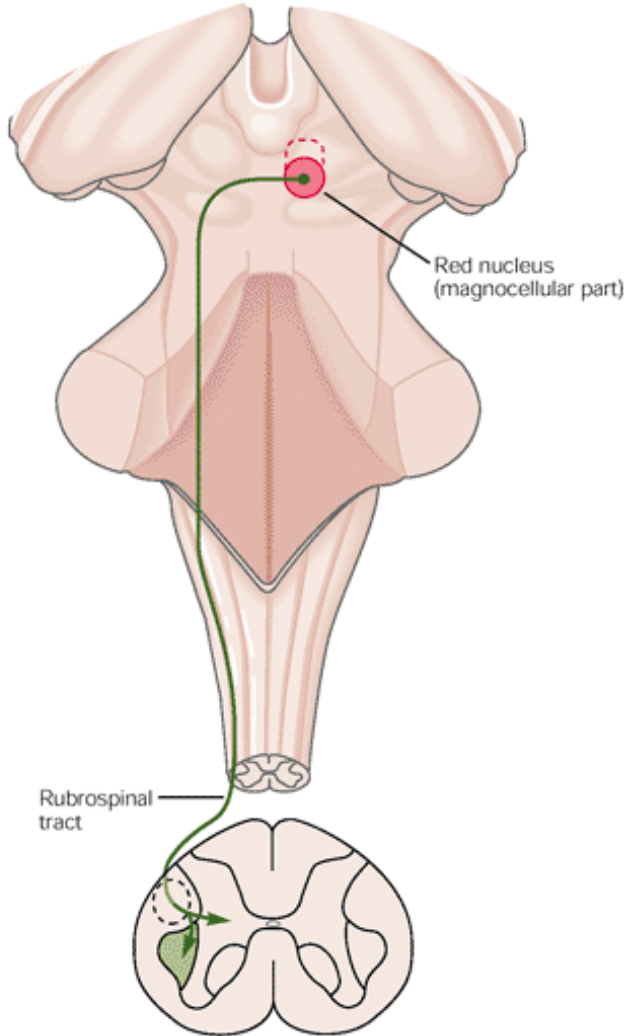
Medial pathways (vestibulospinal, reticulospinal, tectospinal), terminates in ventromedial (axial) for postural control.

Lateral pathways (rubrospinal) terminates in dorsolateral.

A Medial brain stem pathways

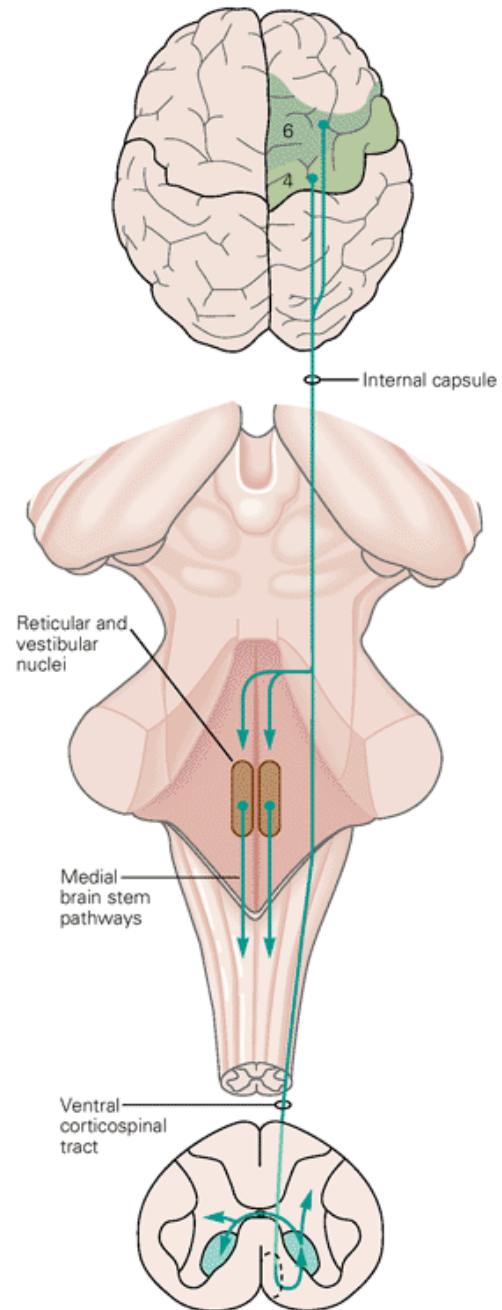


B Lateral brain stem pathways

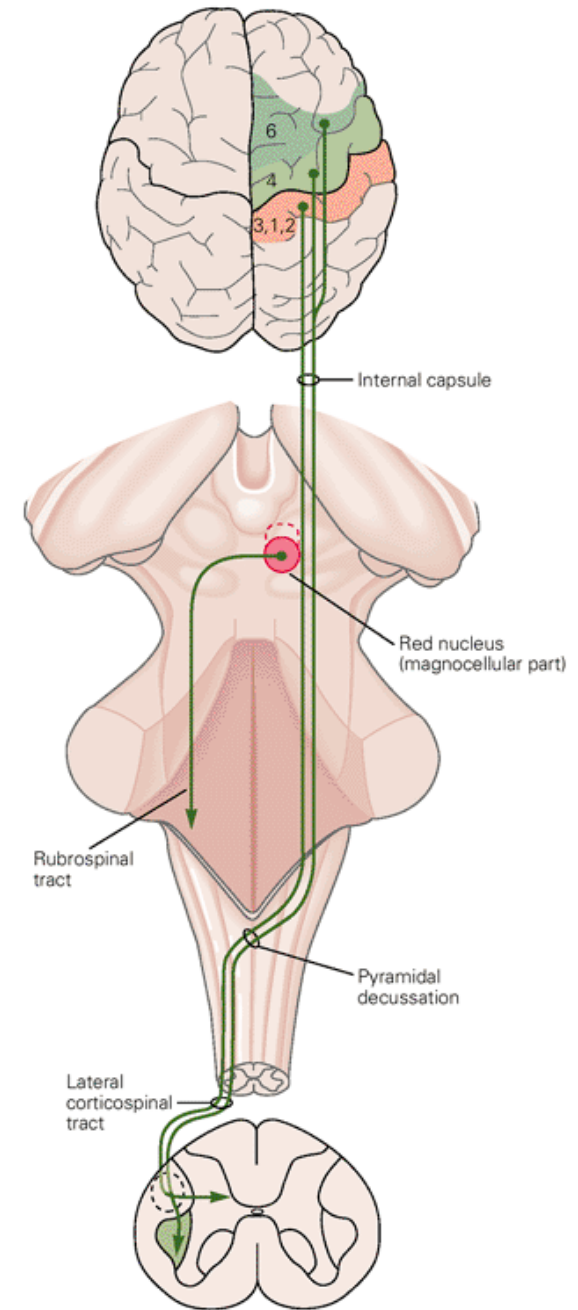


The corticospinal tract

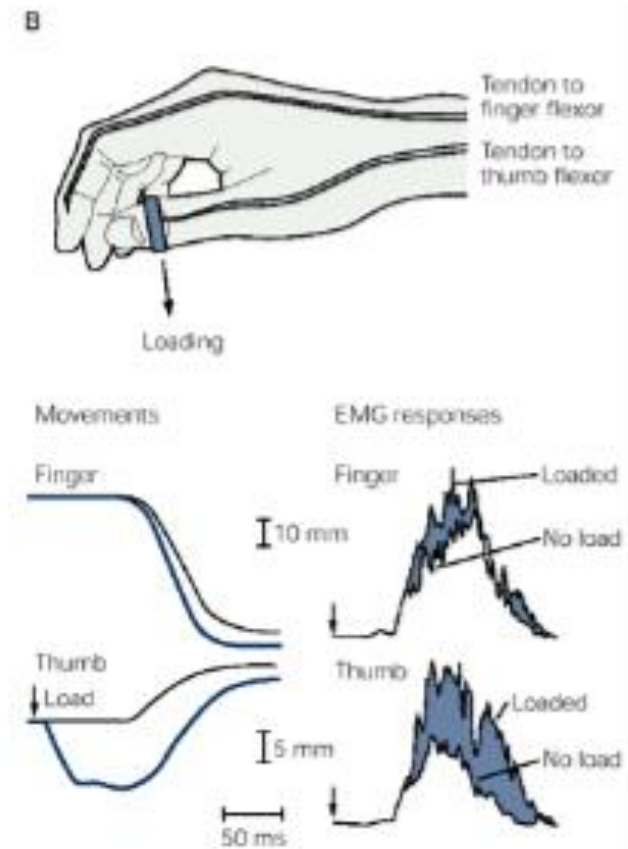
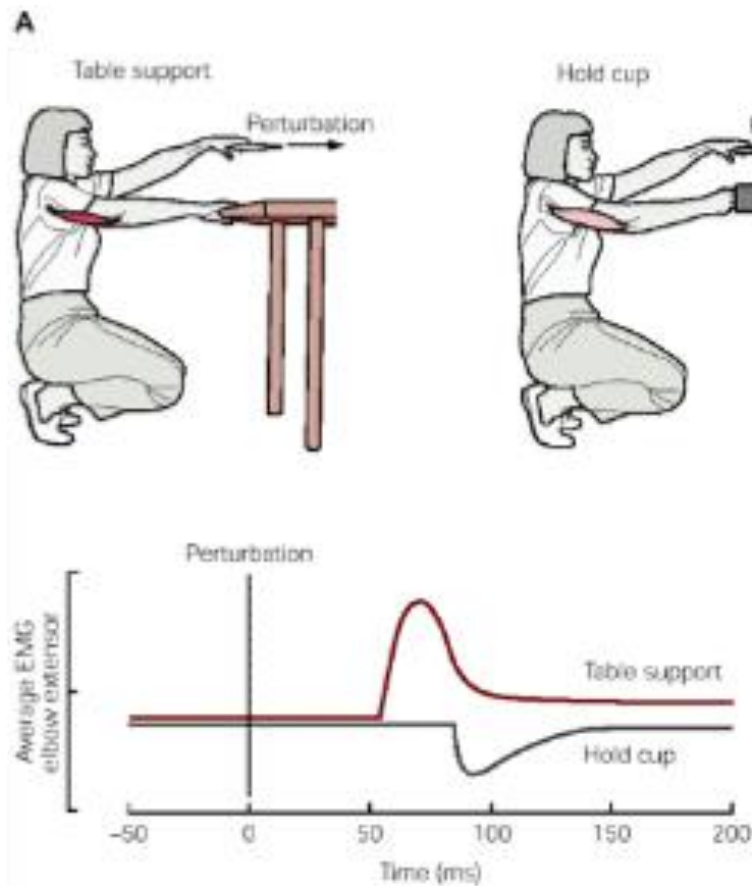
A Ventral corticospinal tract



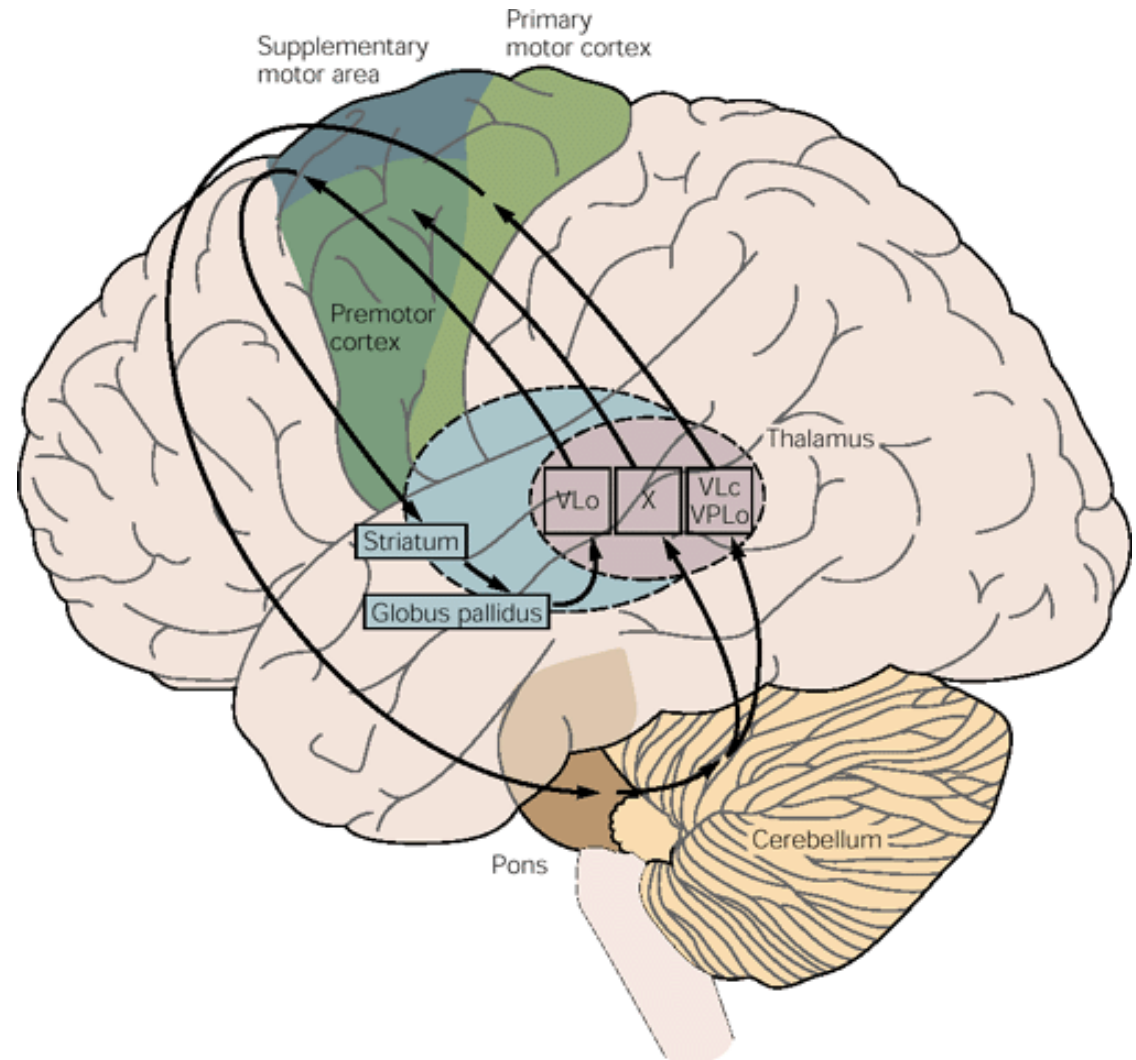
B Lateral corticospinal tract

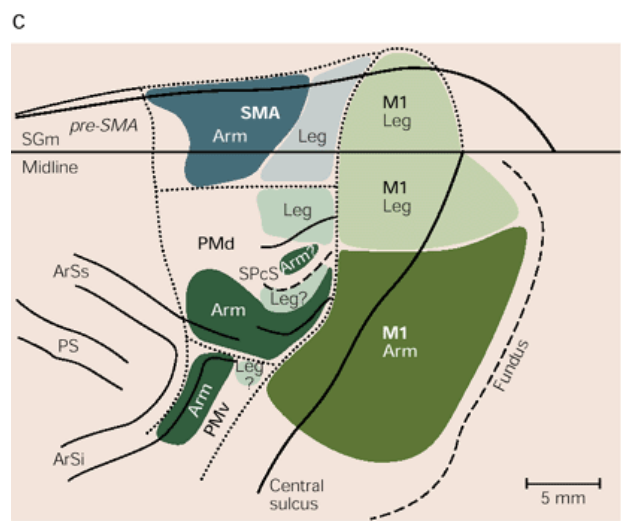
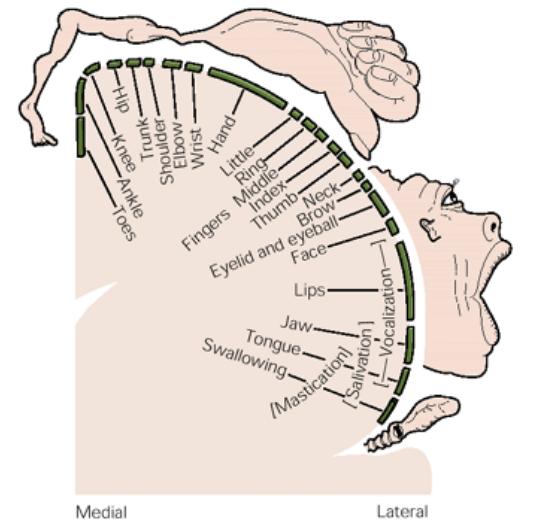
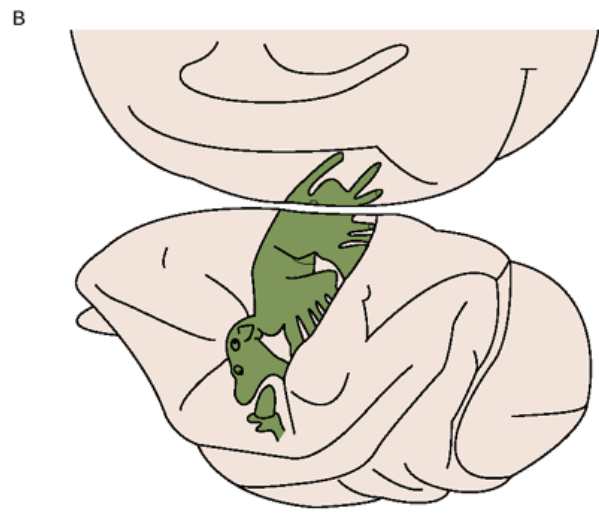
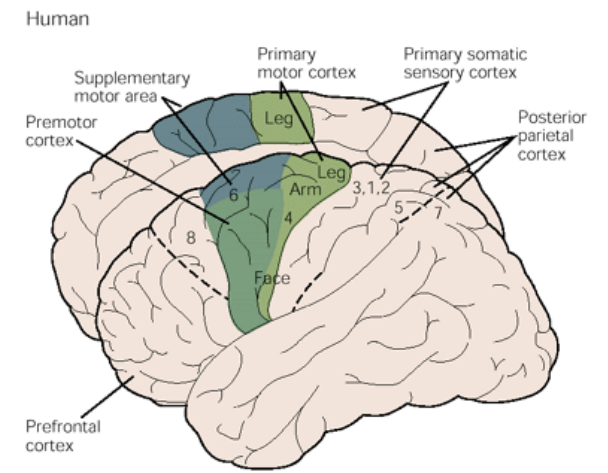
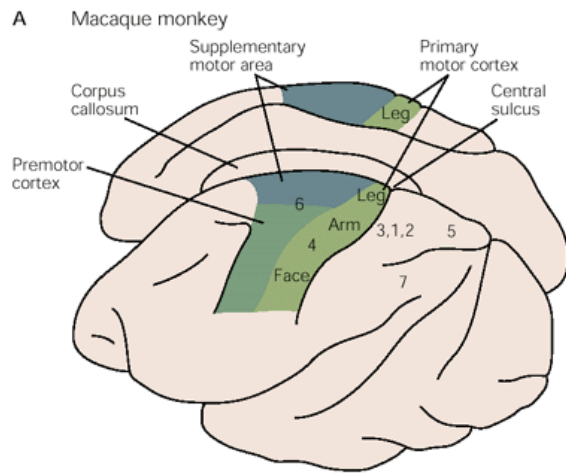


Modulation by task and descending pathways



Cortex and control of voluntary movement





Somato-topical organization

Stimulation in M1

Electrical and magnetic stimulation

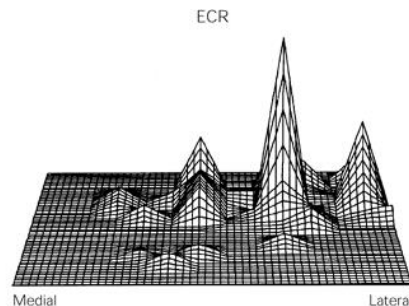
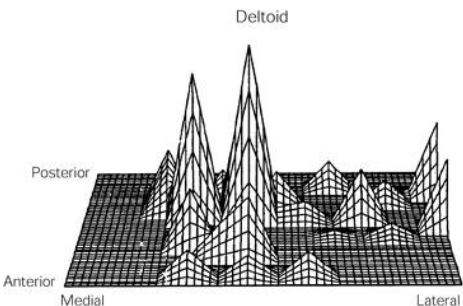
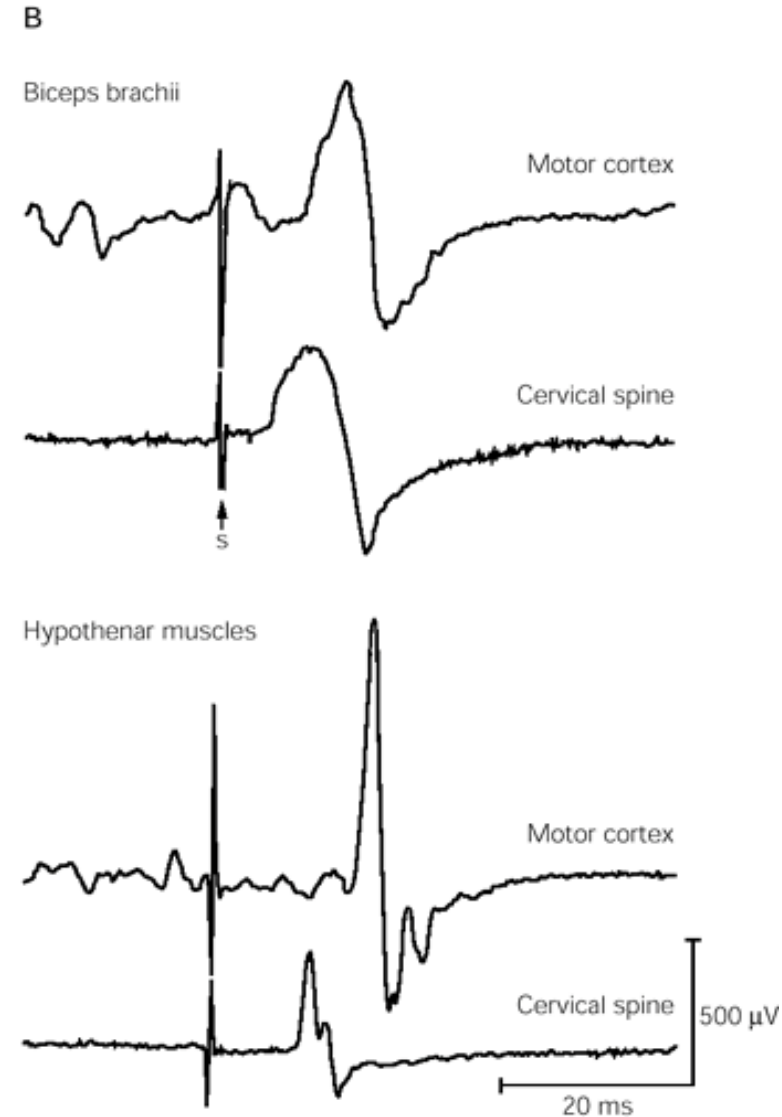
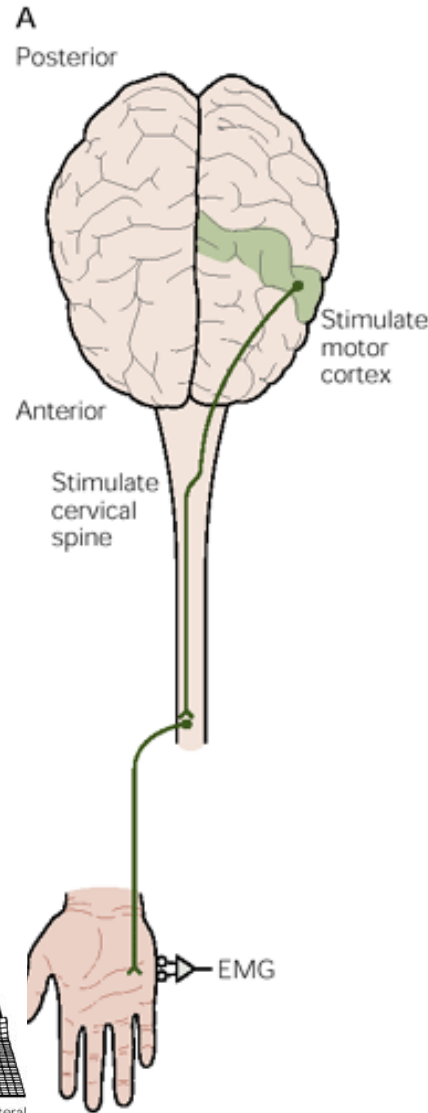
Lowest intensity

Twitch in single muscle/joint

Large (Betz) cells in lamina V

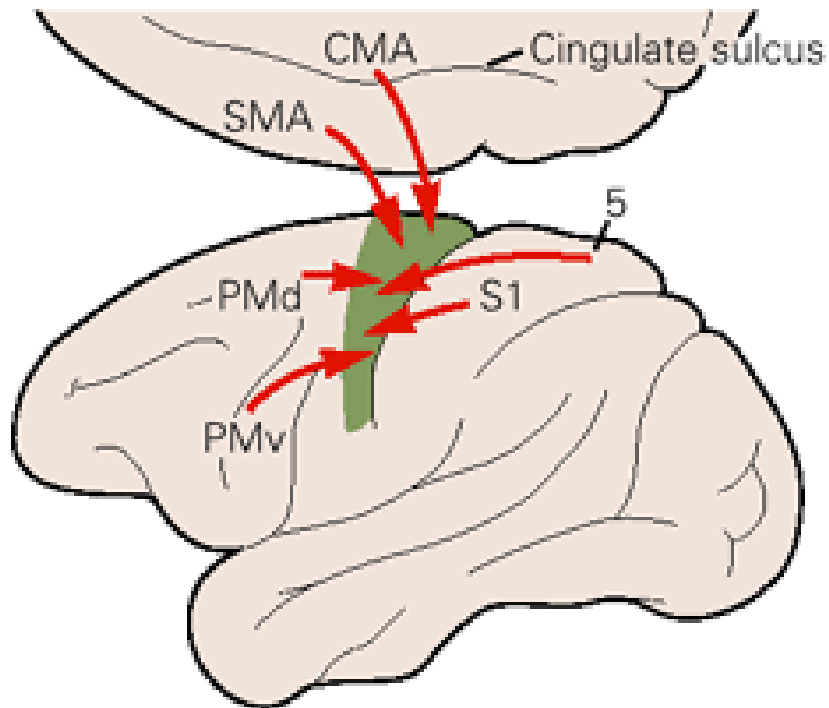
Many locations -> same muscle

Location -> several muscles

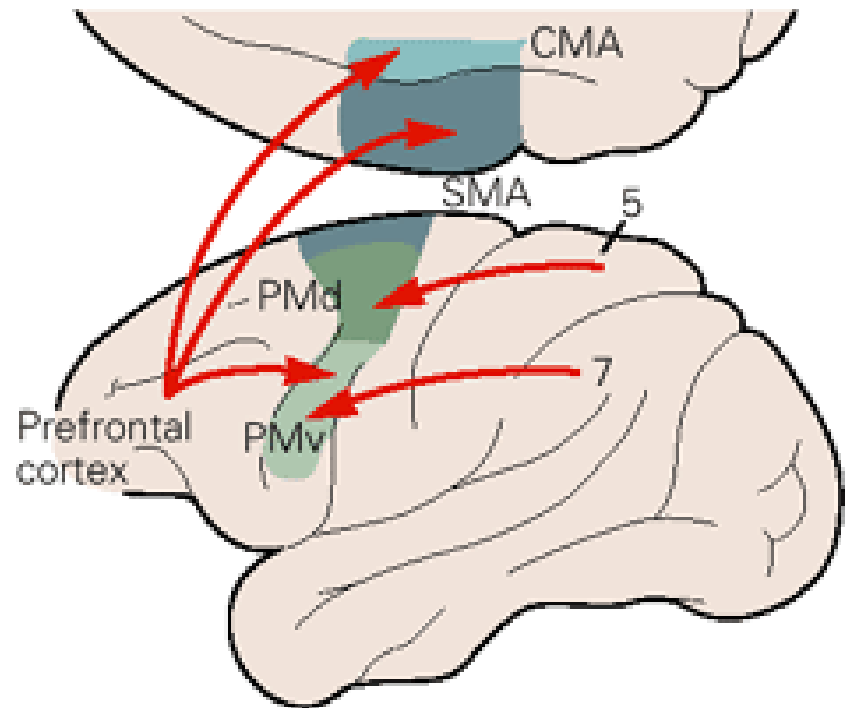


Cortical inputs

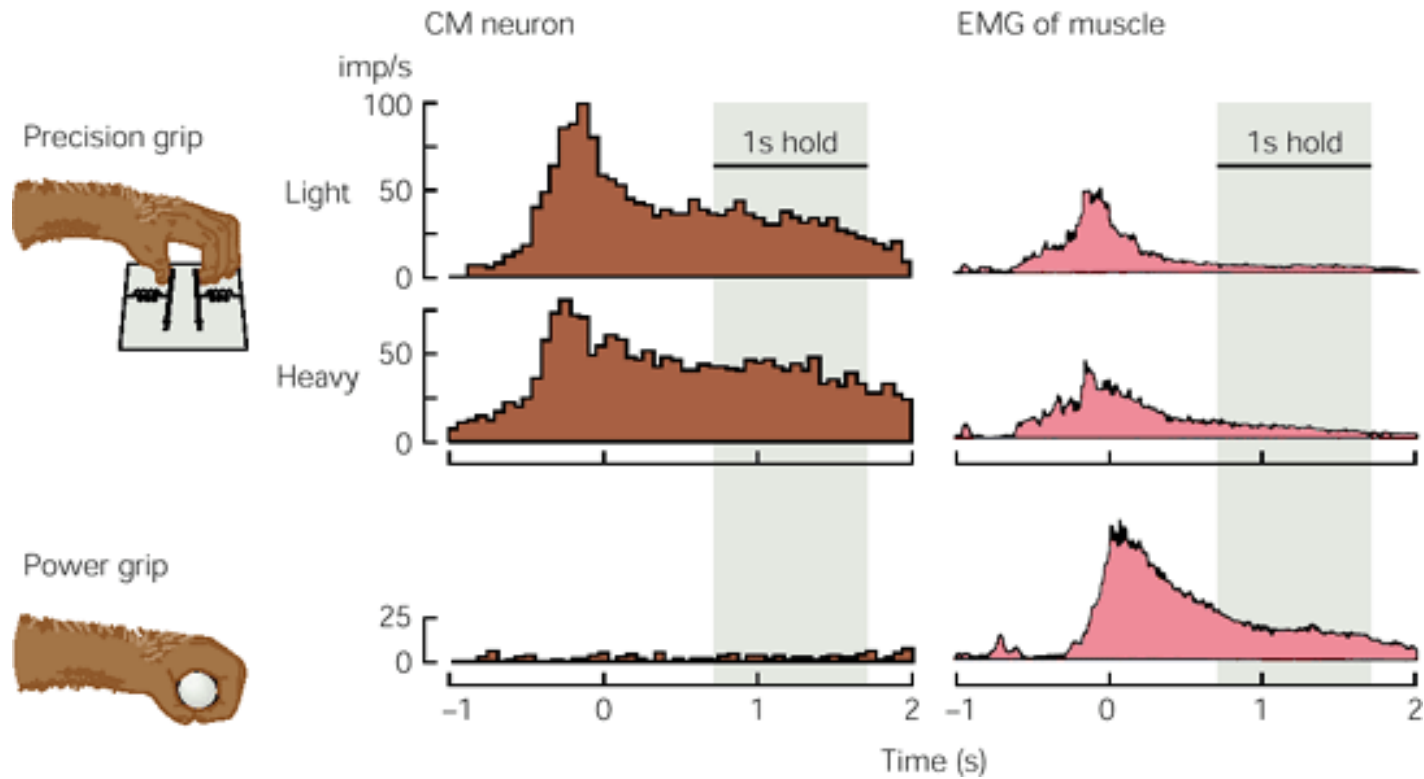
A Inputs to primary motor cortex



B Inputs to premotor areas

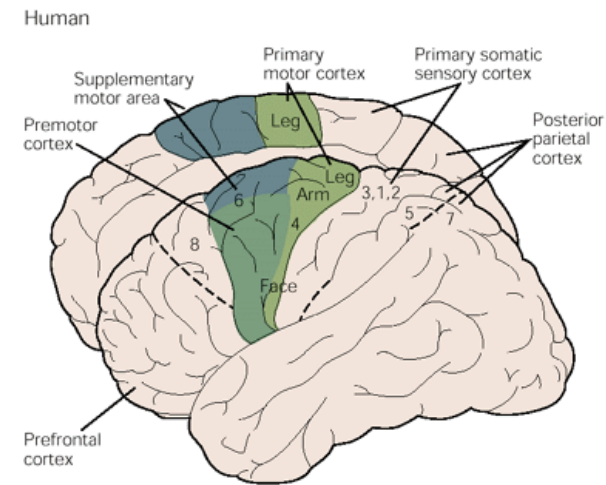
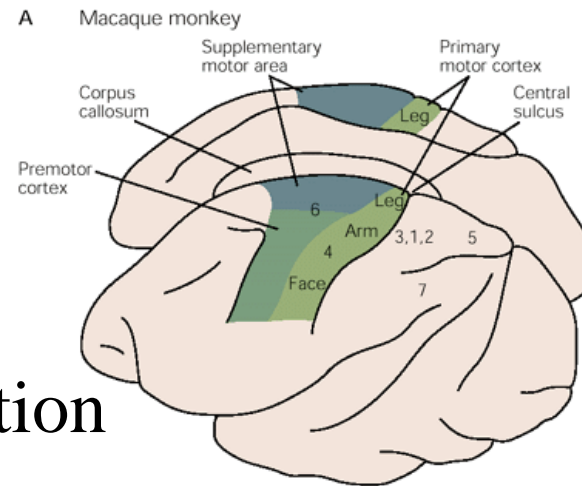


Neurons can be context-dependent



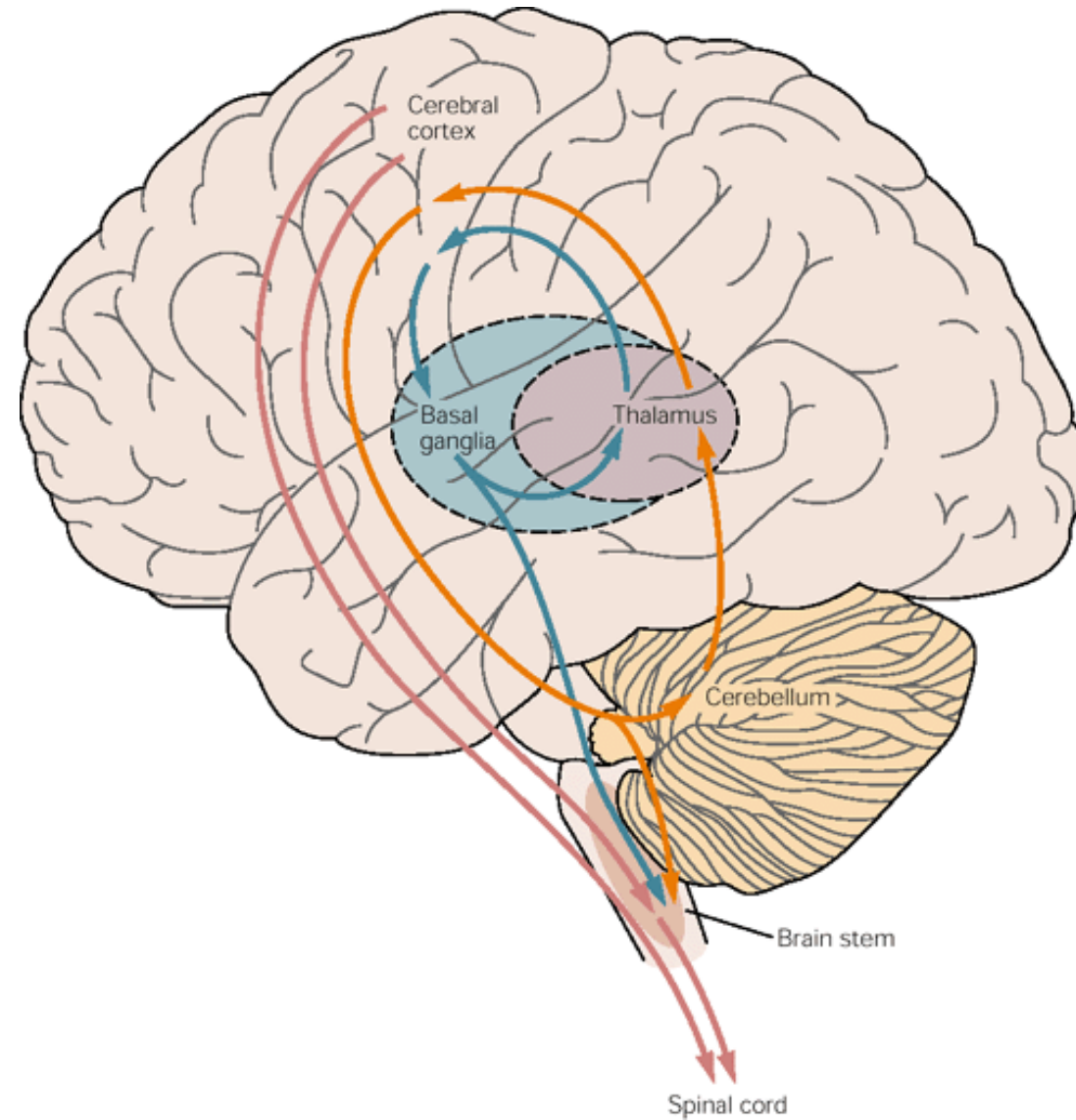
Premotor areas

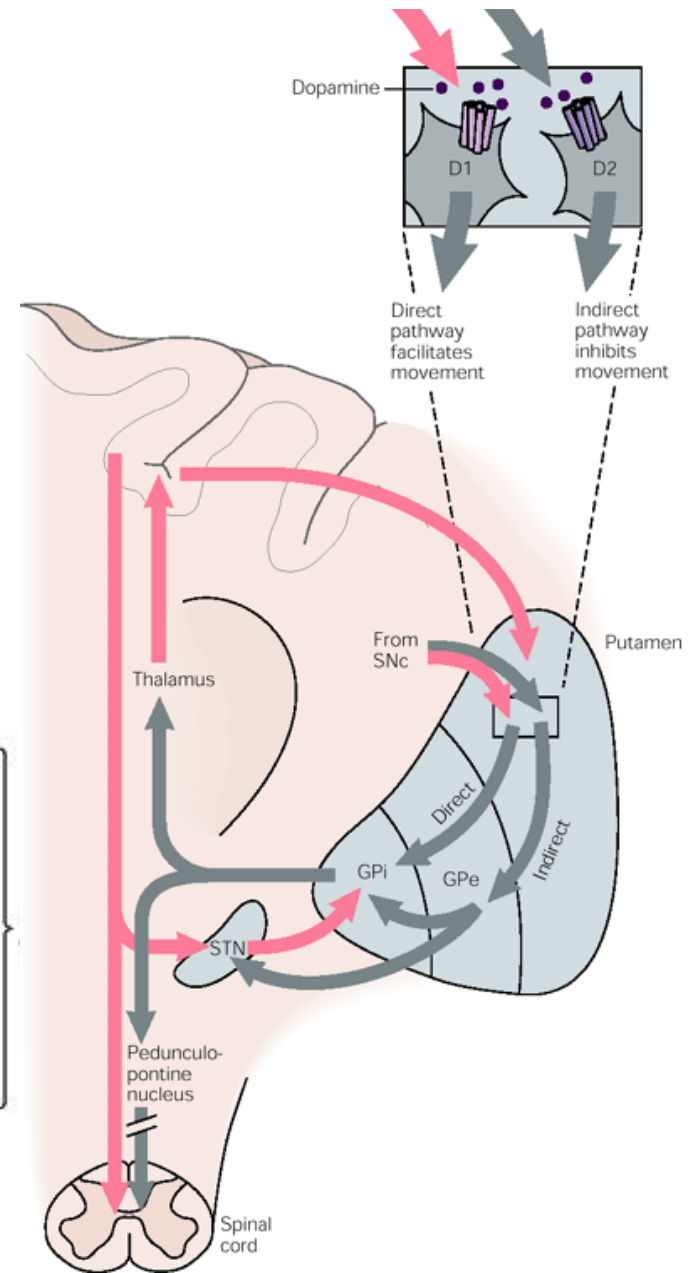
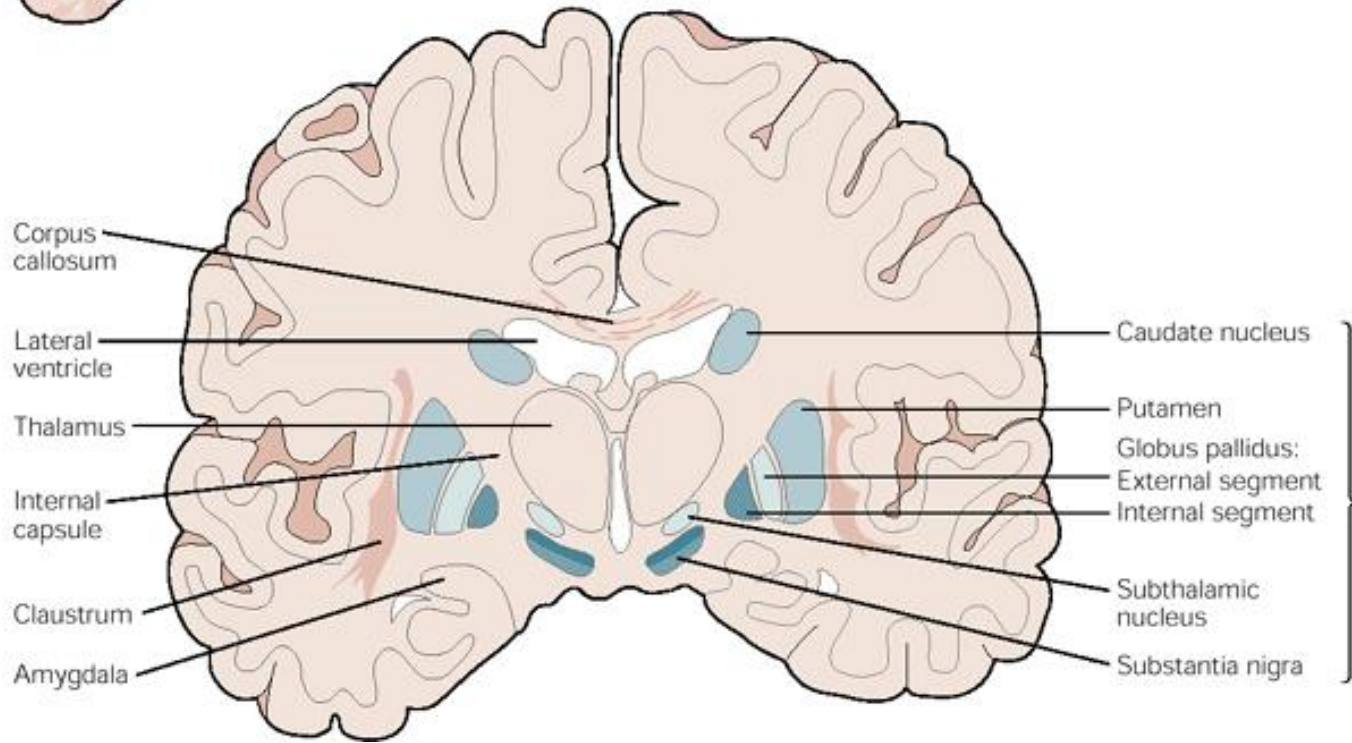
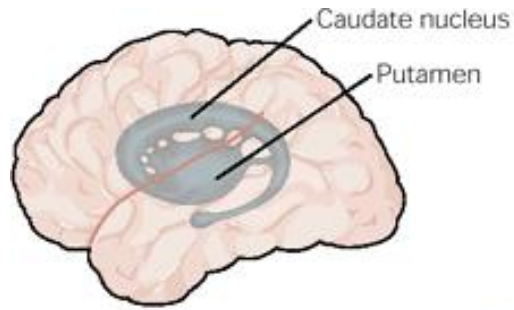
Premotor dorsal (PMd), premotor ventral (PMv), supplementary motor area (SMA), cingulate (CMA)



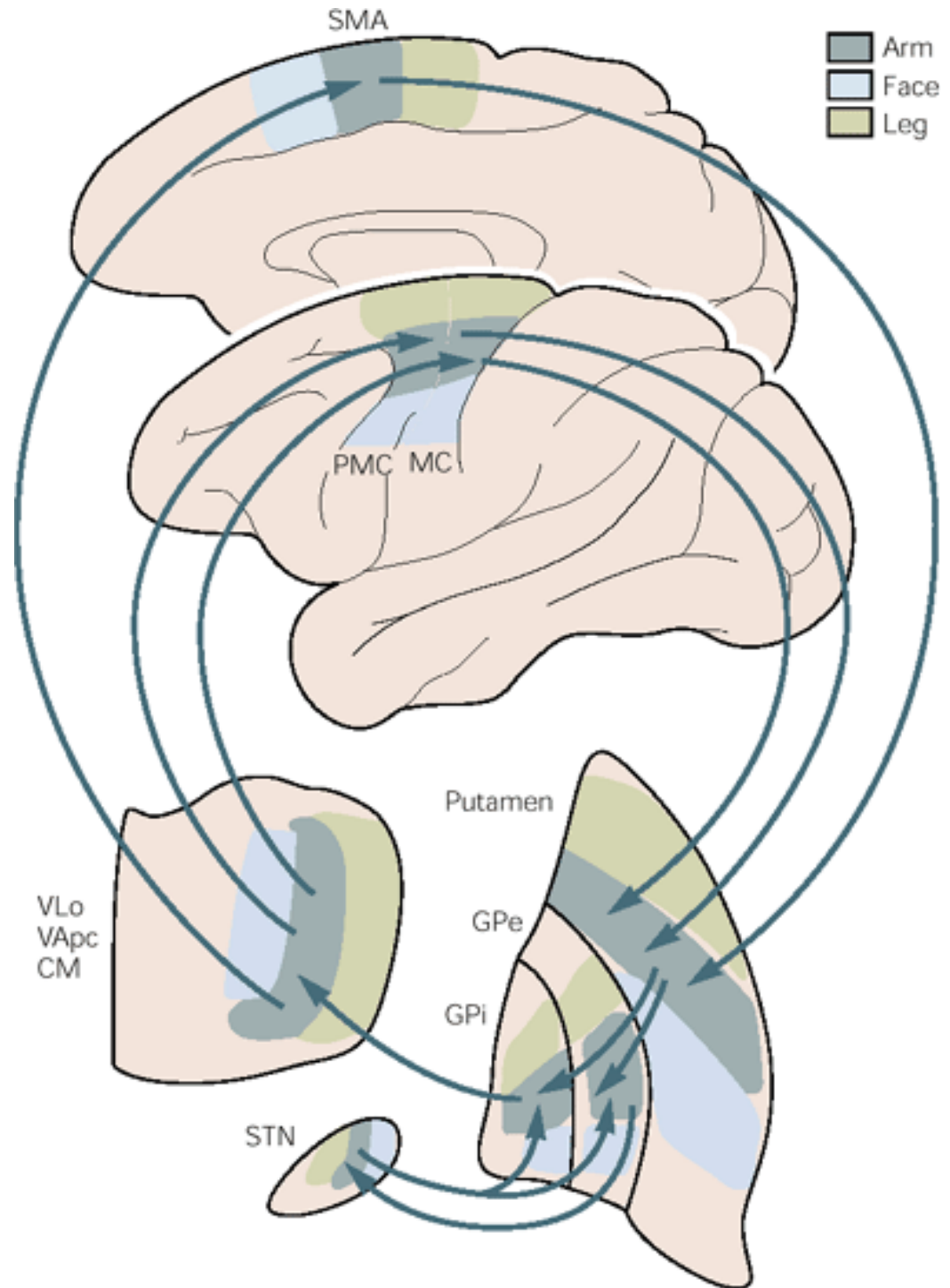
- Multi-joint representation
- Complex, meaningful
- Sensorimotor transformations
- Preparatory (set) activity
- Bimanual coordination (SMA)
- Sequence learning (SMA)
- Self-initiation (PMv, SMA) vs. cue-driven (PMd)
- Language, theory of mind

The basal Ganglia



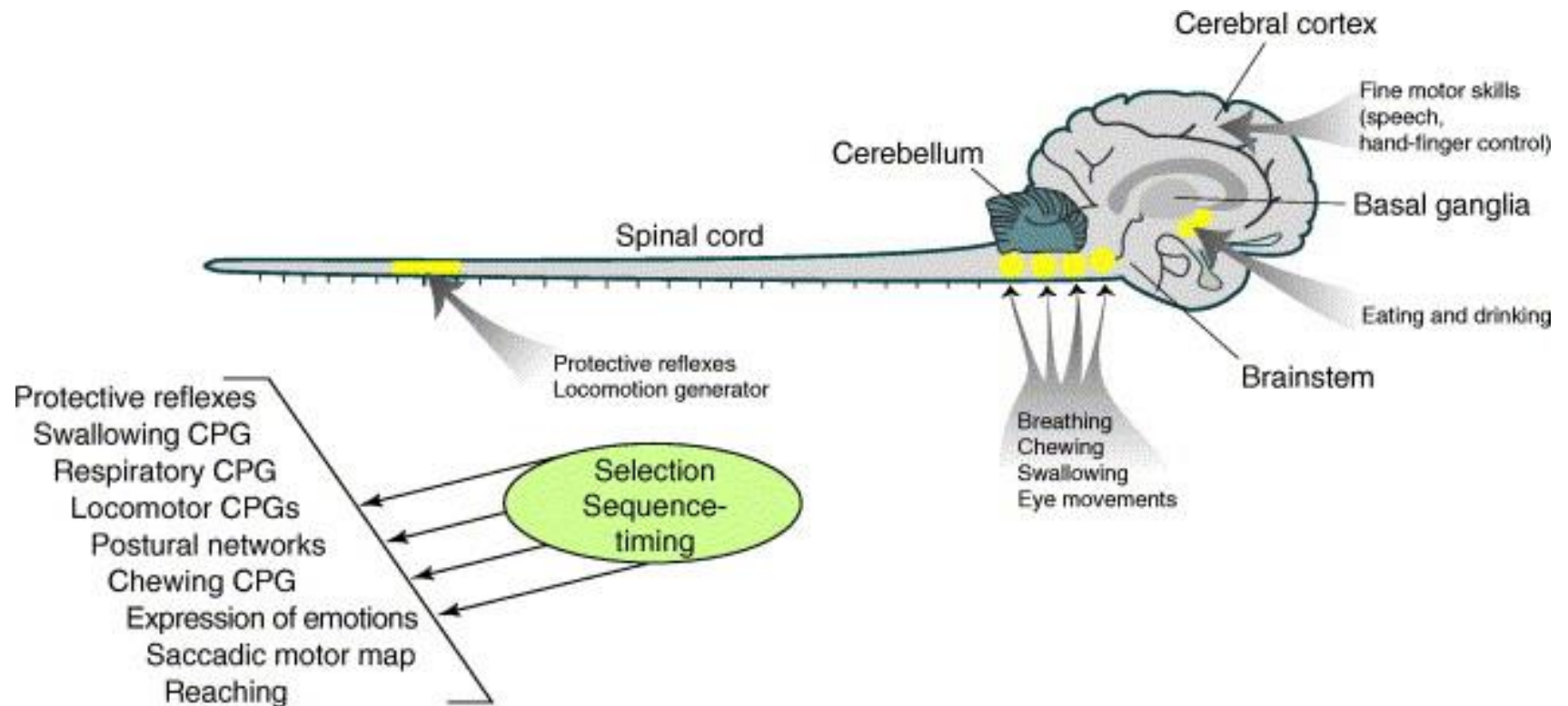


Cortico loops



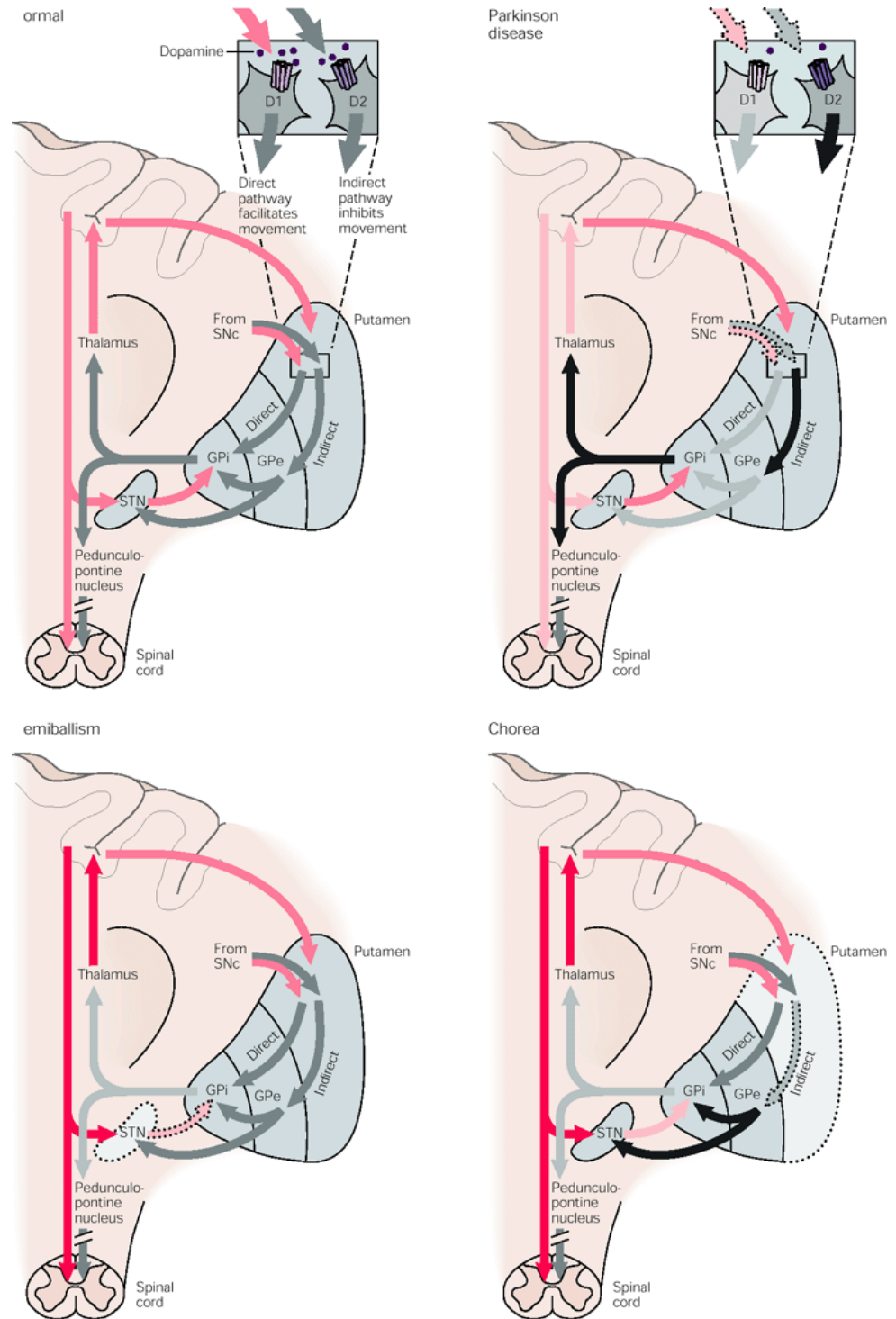
Action - Selection

Direct pathway: facilitates movement.
Indirect pathway: inhibits movement.



Parkinson and Dopamine

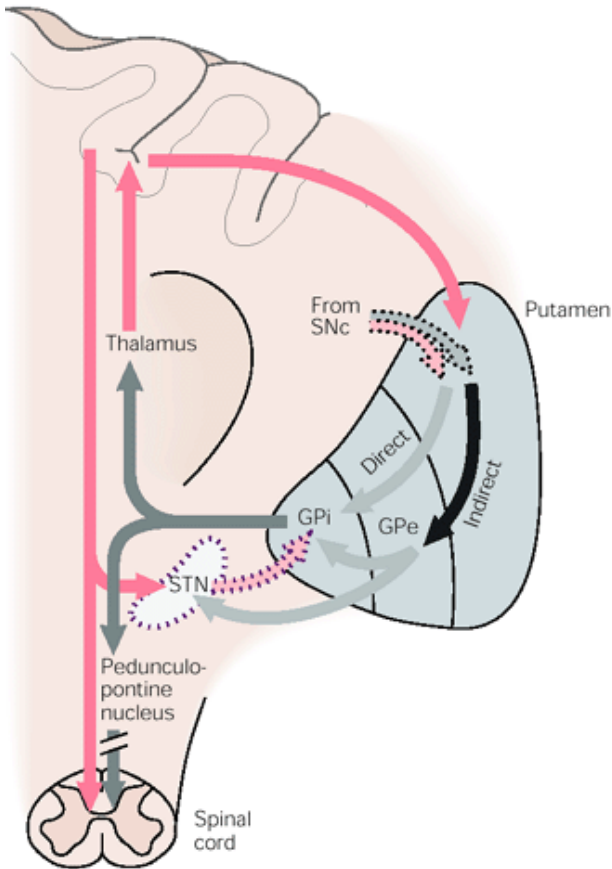
Loss of dopaminergic input leads to increase in the indirect and decrease in the direct pathway => increase GPi => inhibition =? Hypokinesia



Treatment: pallidotomy or DBS

Parkinson disease + surgical therapies

TN lesion



GPI lesion

