Modèles de l'apprentissage et du contrôle sensori-moteur

Anatomo-physiological organization of motor control

3rd course

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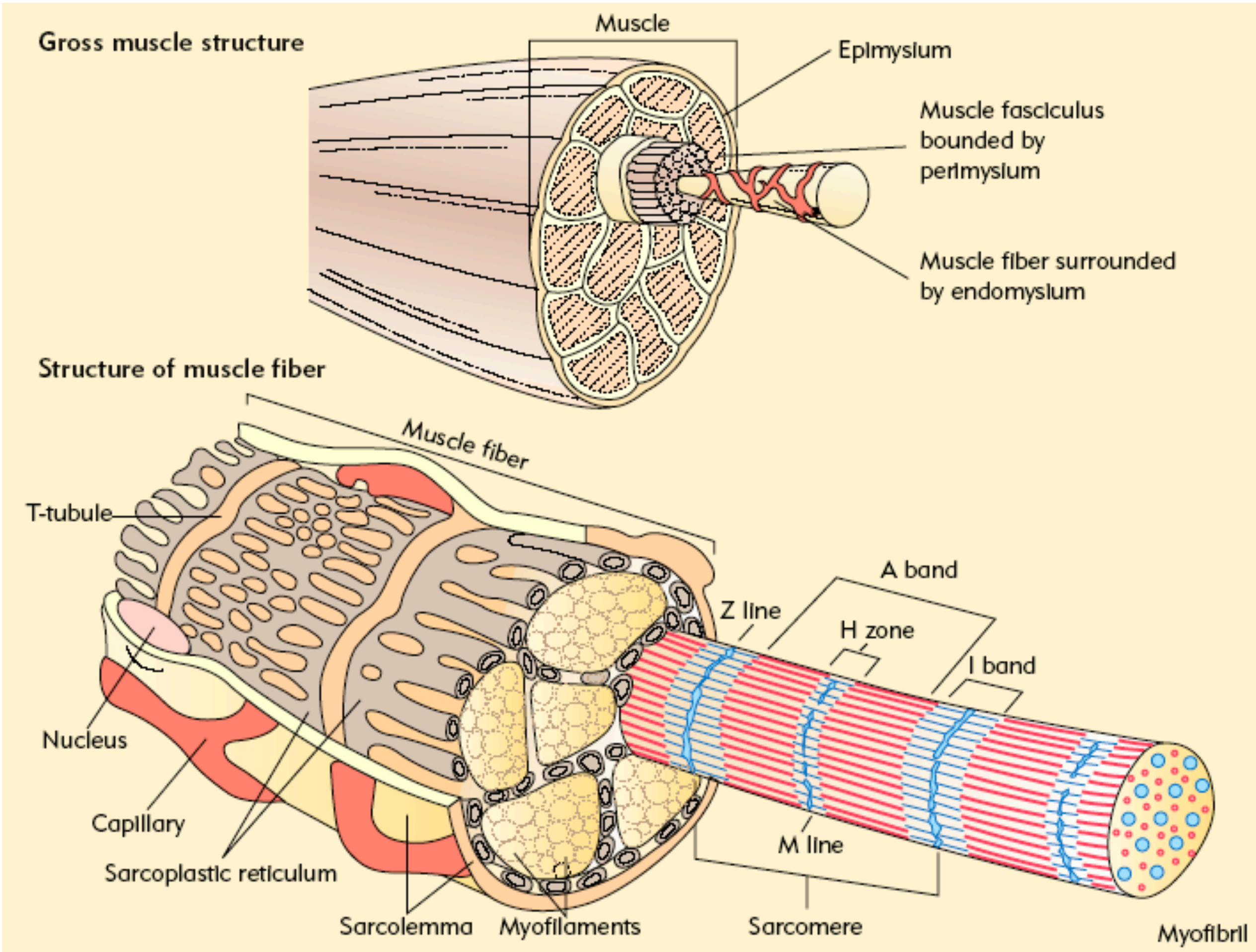
The muscle

Muscle = ensemble of *muscle fibers*
Muscle fiber = ensemble of *myofibrils*
Myofibril = ensemble of *sarcomeres*

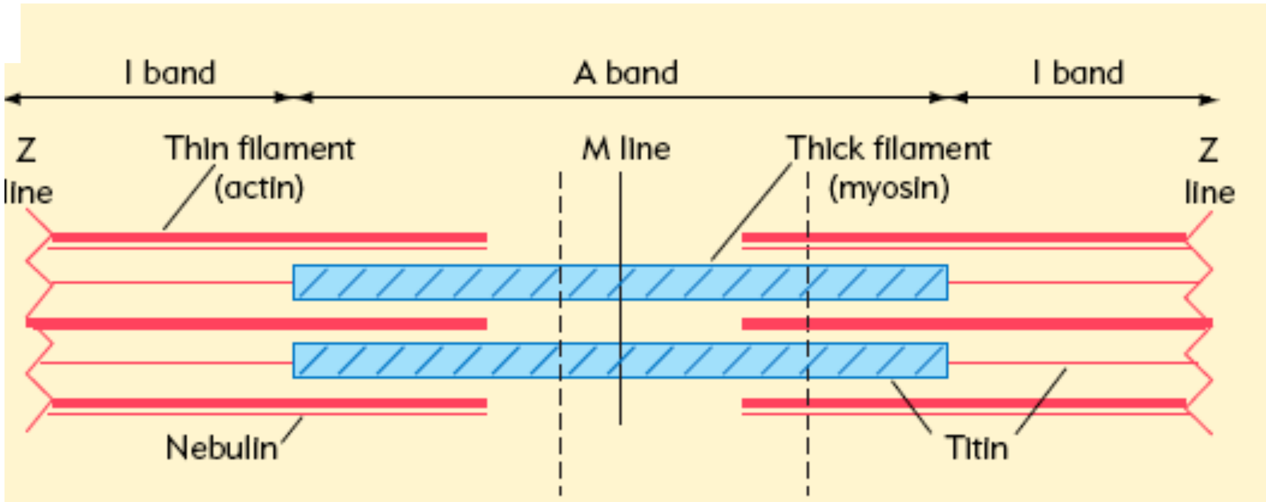
Sarcomere = smallest contractile part = thin filaments (*actin*) + thick filaments (*myosin*)

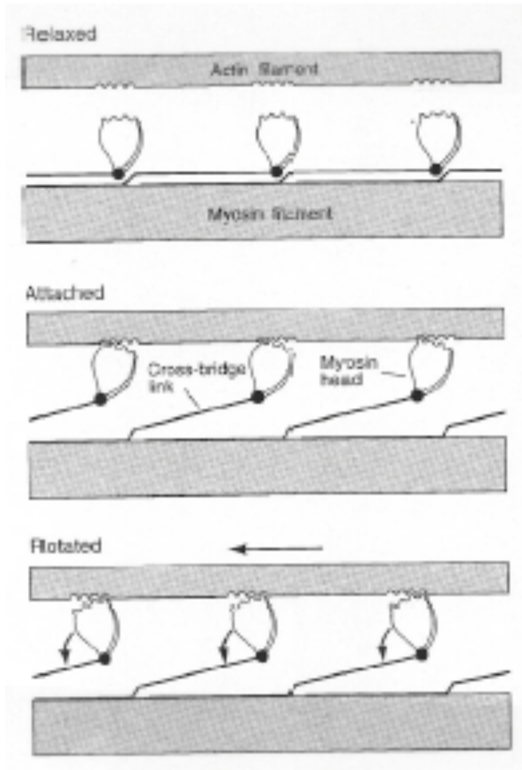


Muscular contraction

Depolarization of a muscle fiber → increase in intracellular calcium → mechanical contraction (excitation-contraction coupling)

Sliding-filament theory (cyclical interactions between filaments): **myosin heads bind on actin molecules to form a cross-bridge; myosin heads undergo a transformation that result in a force exerted on the thin filaments.**

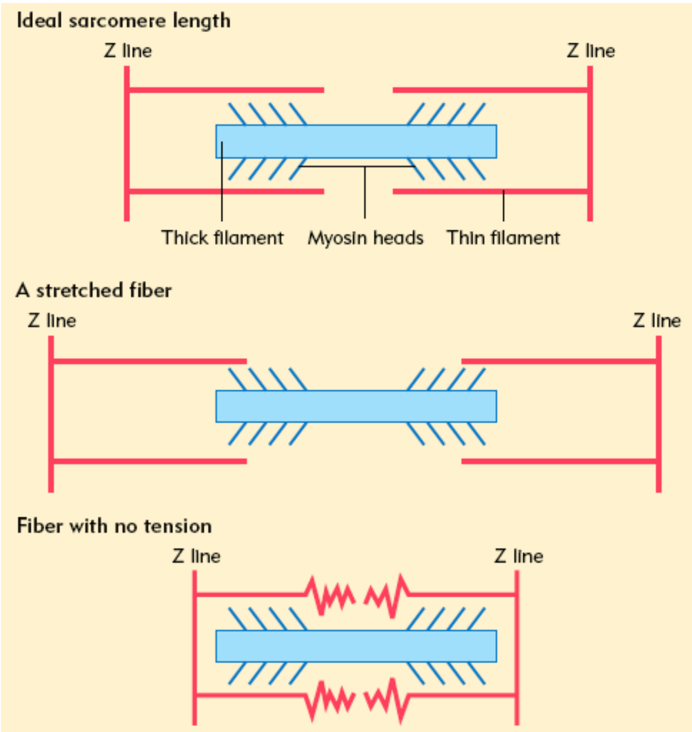


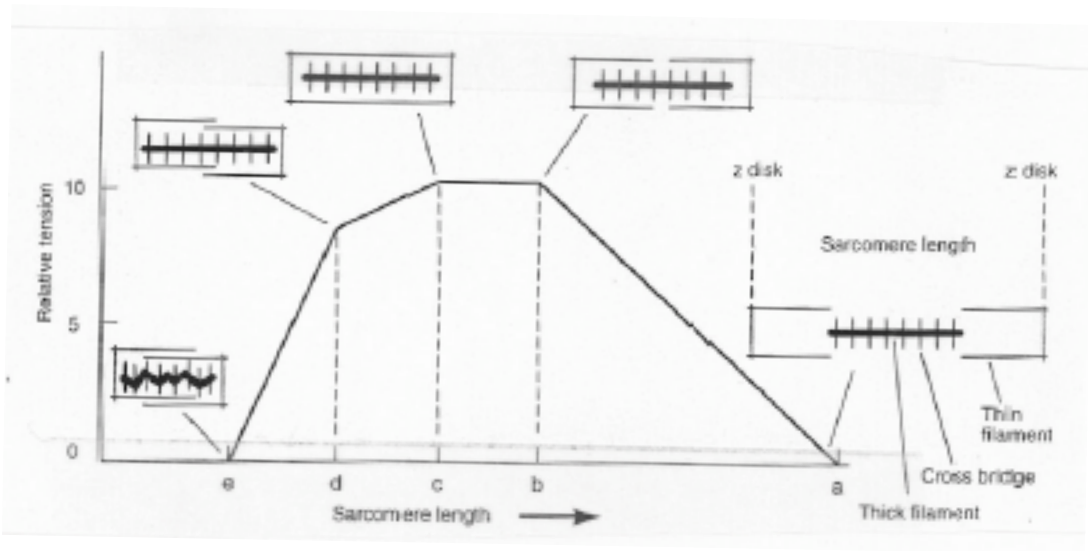


Huxley (1969)

Sarcomere force

Sarcomere tension depends on the degree of overlap between thin and thick filaments.

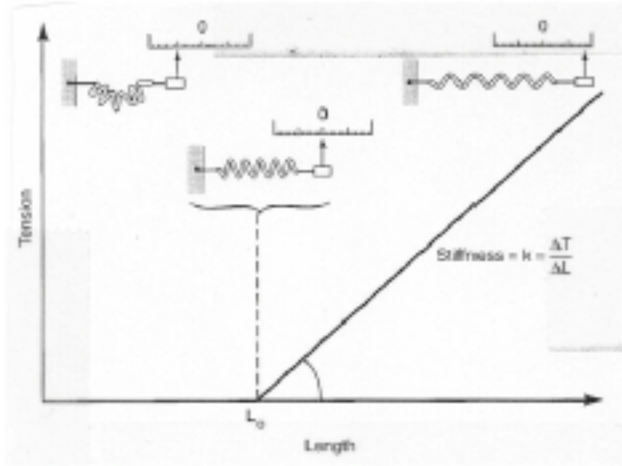


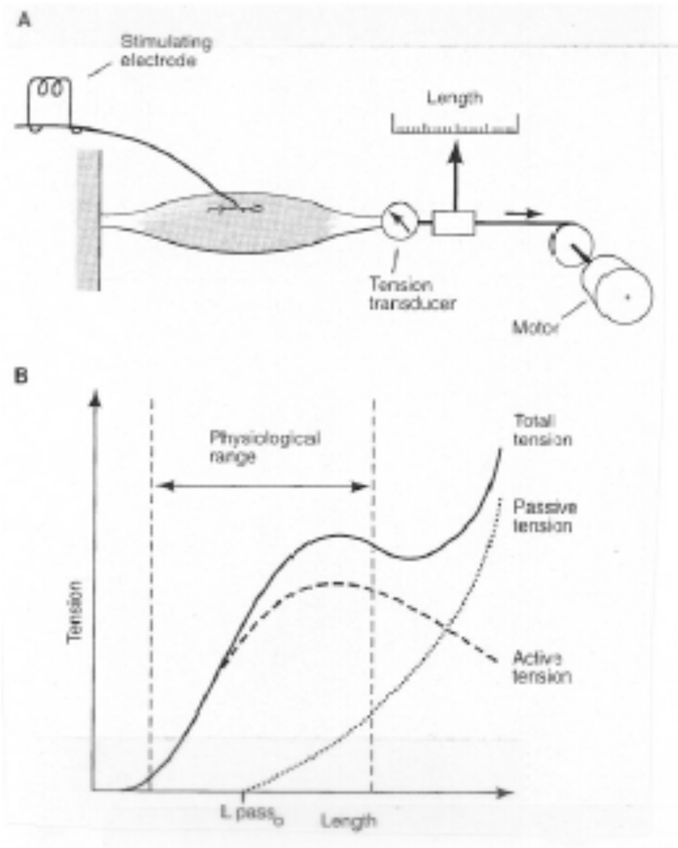


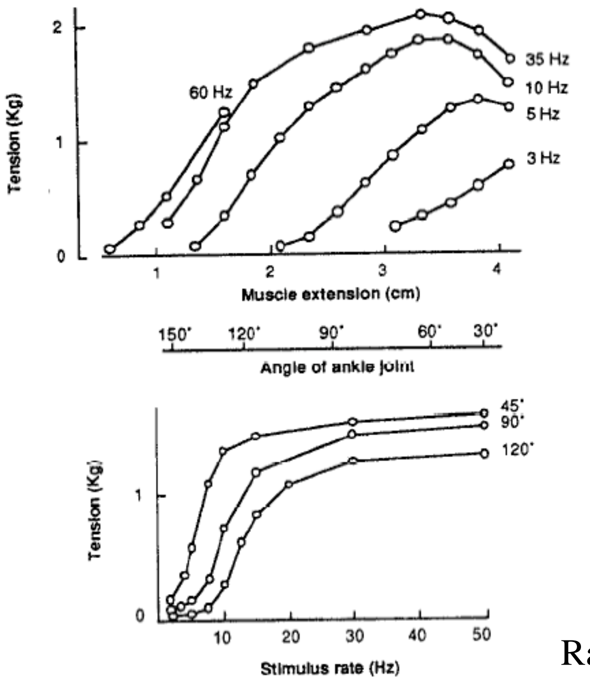
Gordon et al. (1966)

Muscular force

A muscle behaves as a spring: it generates force when it is stretched beyond a threshold length; the force increases with length; the threshold changes with the stimulation level.







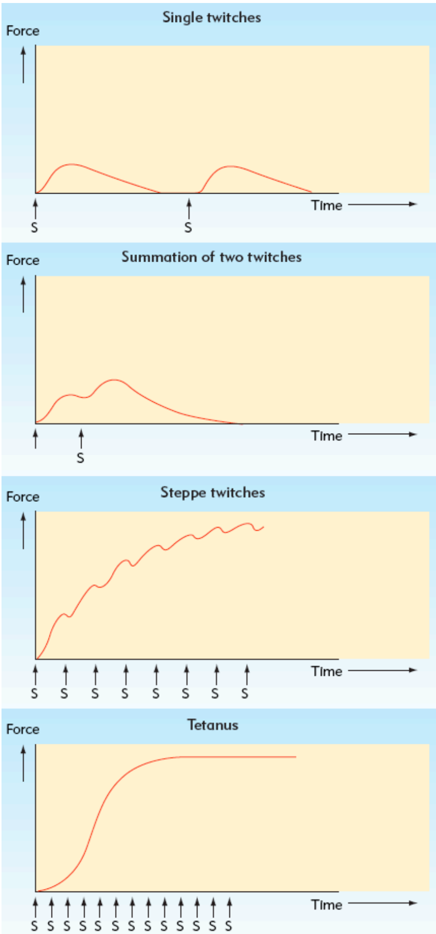
Stiffness: slope of force/length relationship

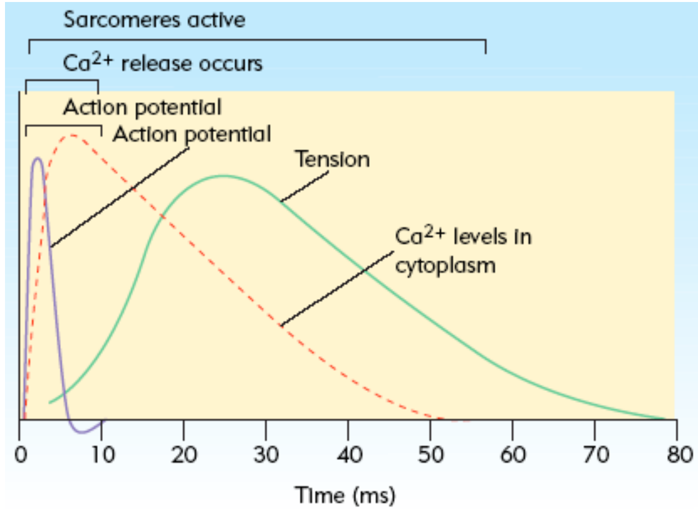
$$F = K(L - L_0)$$

Rack & Westbury (1969)

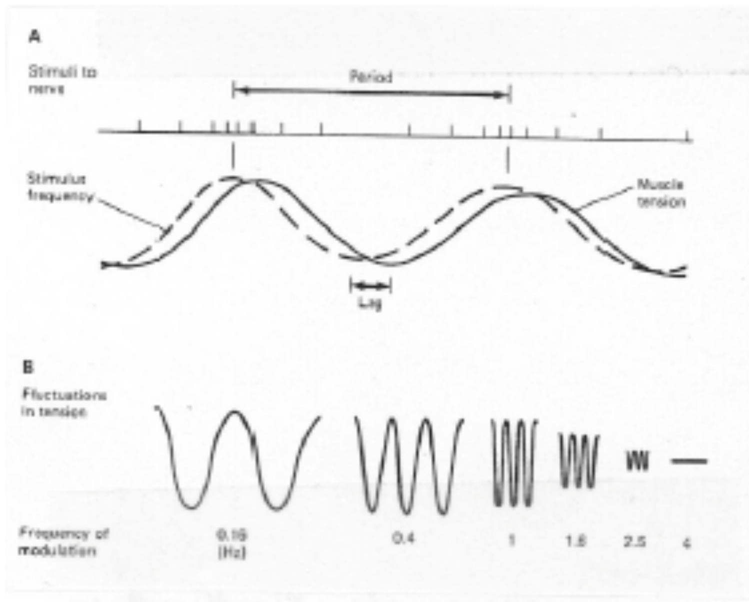
Muscular force (...)

Muscular force depends on the frequency of action potentials in the motor nerve.





The muscle behaves as a low-pass filter. At low frequency, muscular tension varies with input frequency. When frequency increases, fluctuations disappear.

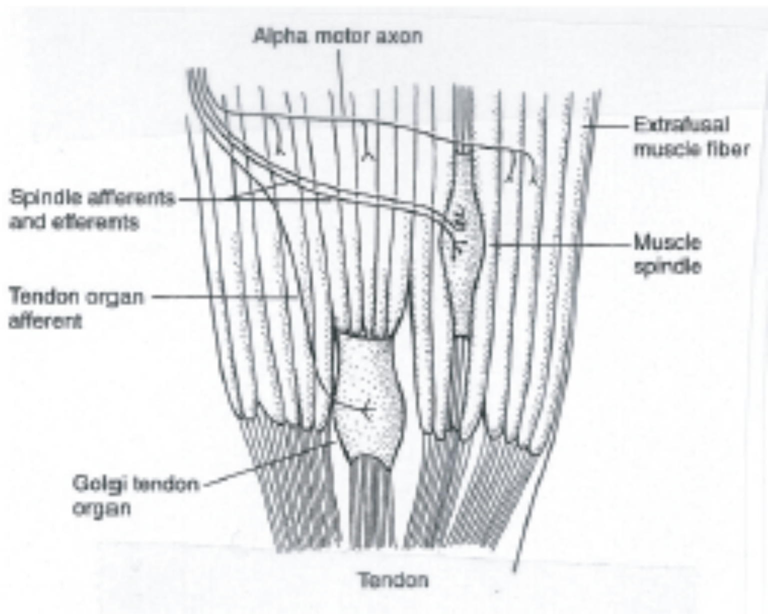


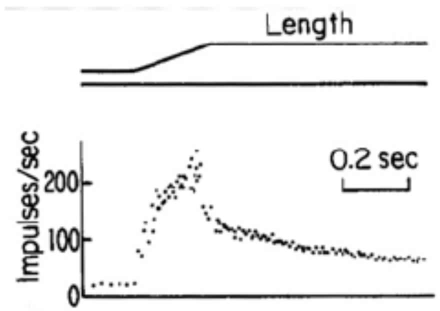
Partridge (1966)

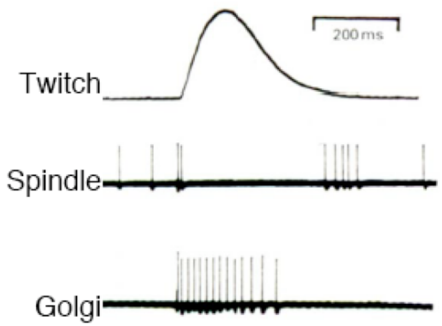
Sensory receptors

• Spindles are structures arranged in parallel with the muscle. They transmit information on the length and changes of length of the muscle.

• Golgi tendon organs are structured in series with the muscle, at the junction bewteen the muscle and the tendon. They transmit information on muscular tension.

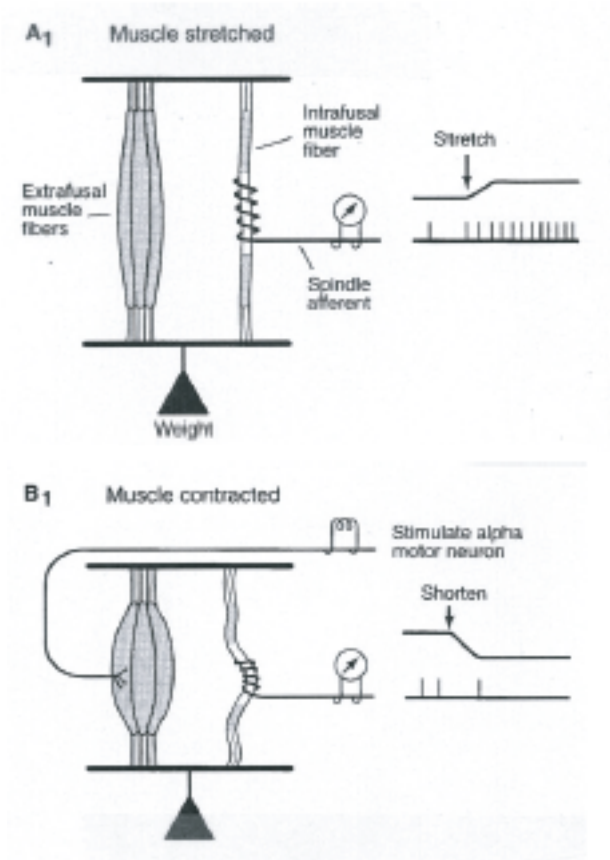


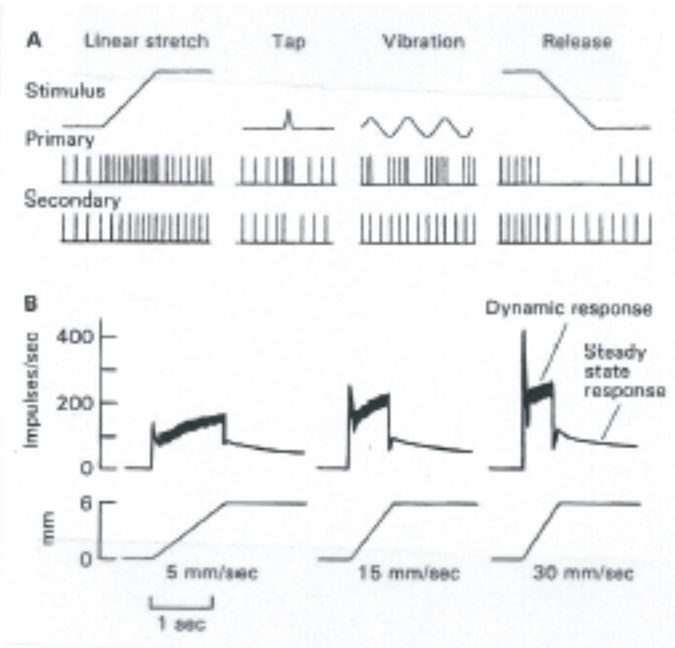




Muscle spindles

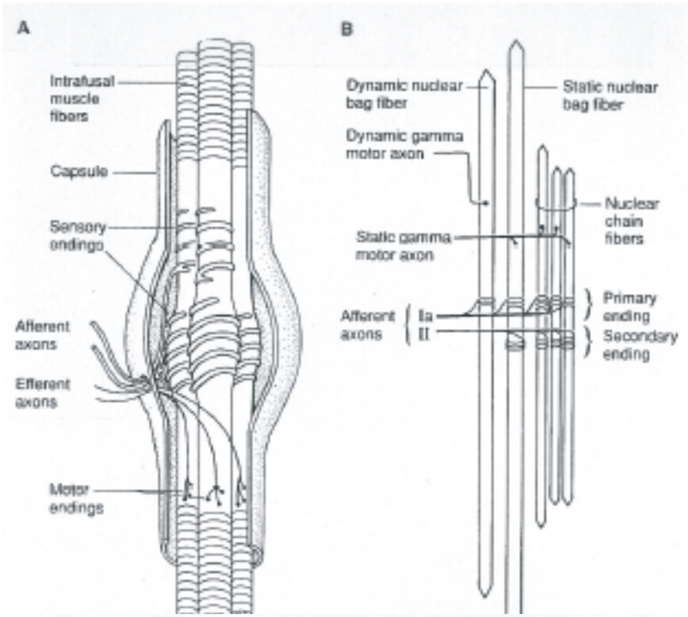
- They transmit information on the length and changes in the length of the muscle.
- Primary spindles: sensitive to length and velocity; secondary spindles: sensitive only to length.

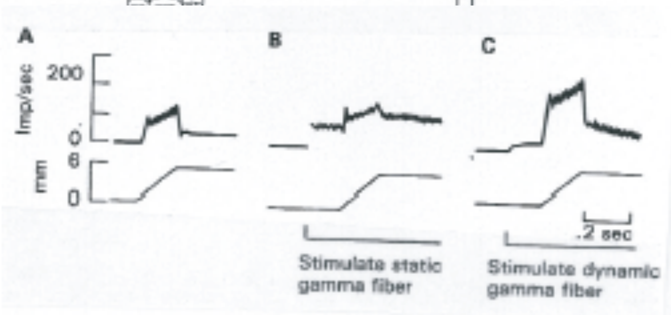


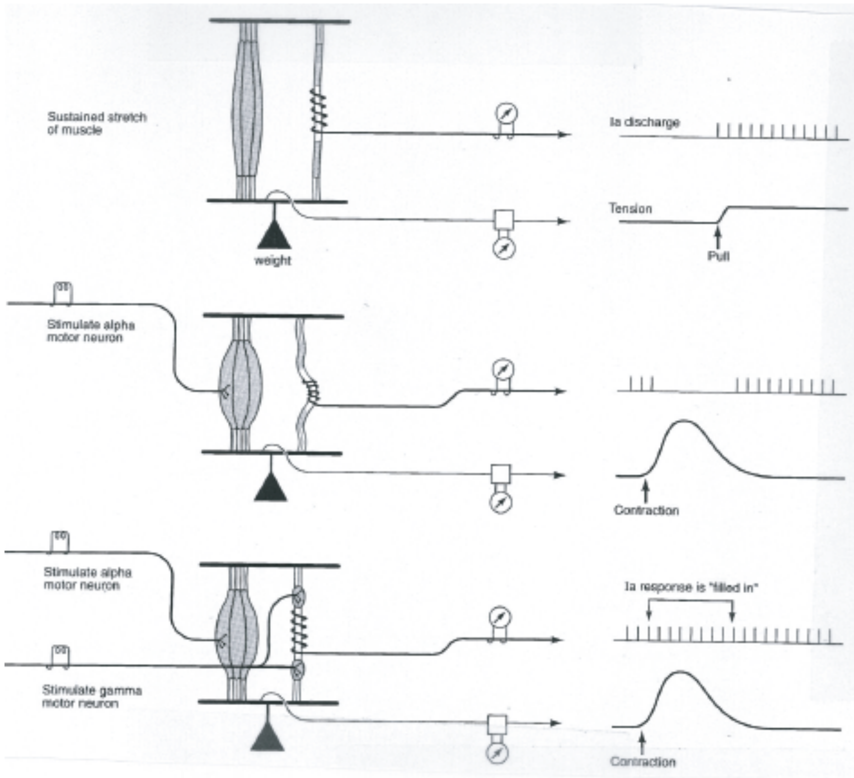


Muscle spindle (...)

• The spindles innervate alpha motoneurons (MNs) through Ia (primary) and II (secondary) fibers. The spindles are innervated by gamma MNs, which modulate their sensitivity. Gamma modulation allows the sensitivity of spindles to be modulated during muscular contraction.

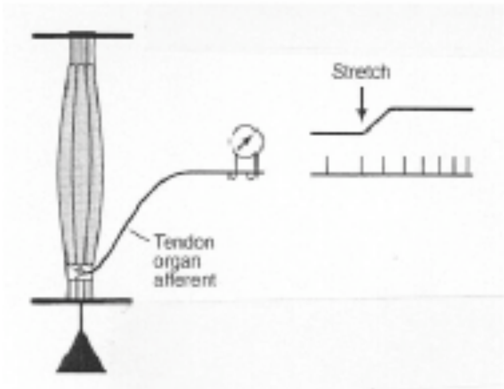


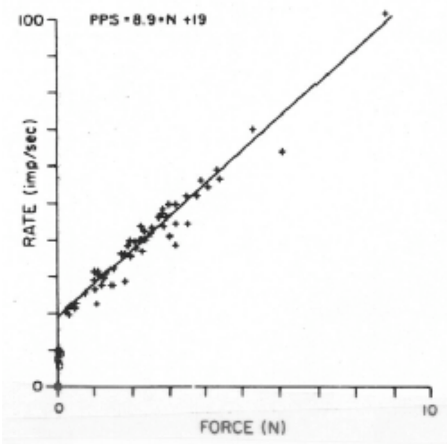




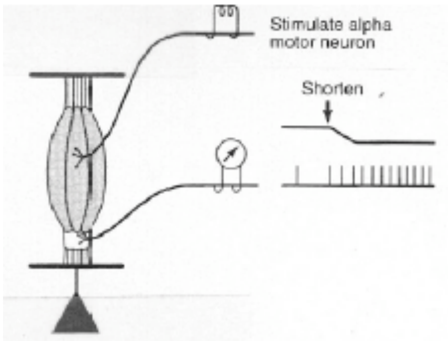
Golgi tendon organs

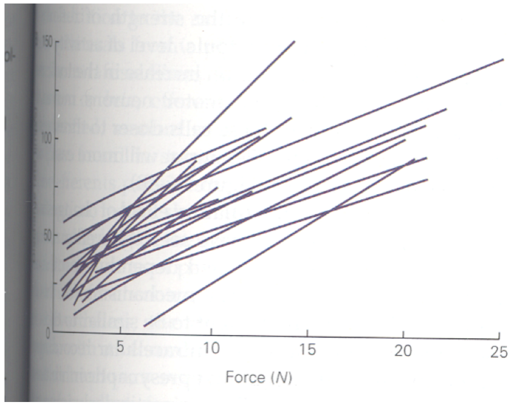
Their discharge closely reflects the tension developed by the muscle.

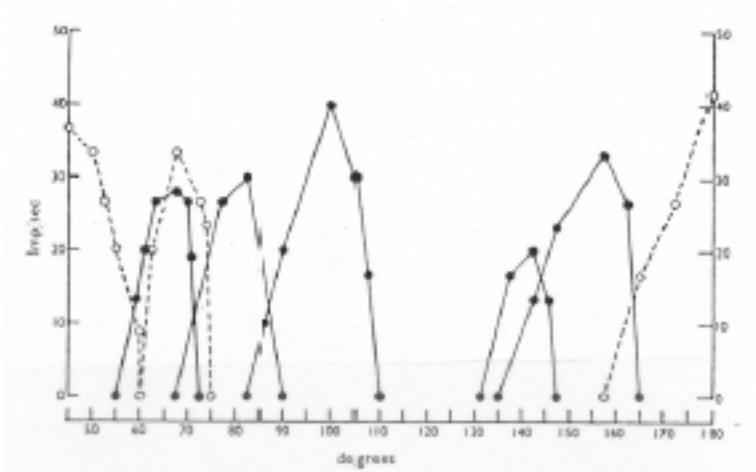




Note: Articular receptors are active only in a restricted range of articular positions. However, the majority of receptors are active only at extreme articular positions. They are not appropriate to transmit a precise postural information.







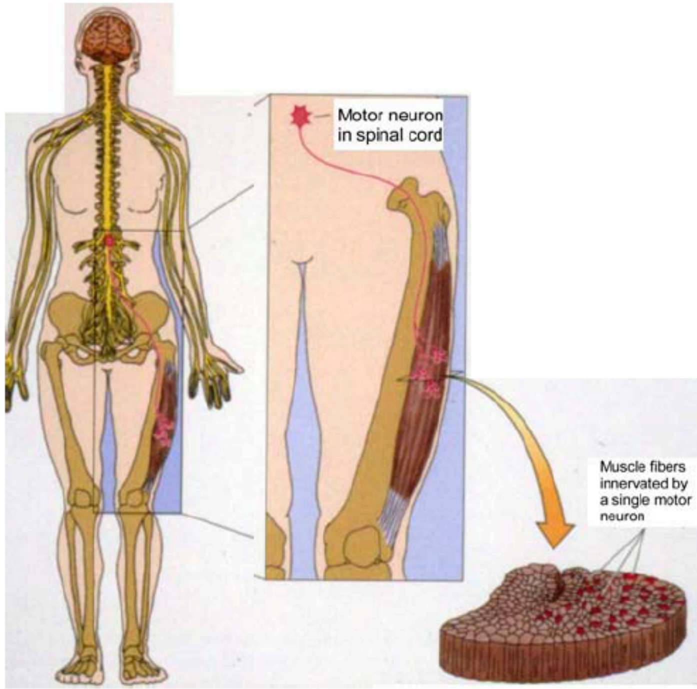
Motor unit

- Each muscle fiber is innervated by a single MN.

- A MN innervates an ensemble of muscle fibers.

- A MN and its associated muscle fibers define a **motor unit** (MU).

- The number of muscle fibers innervated by a MN is called the innervation ratio. This ratio is roughly proportional to the size of the muscle (10 for extraocular muscles, 100 for hand muscles). A small ratio correspond to a finer control of muscular force.

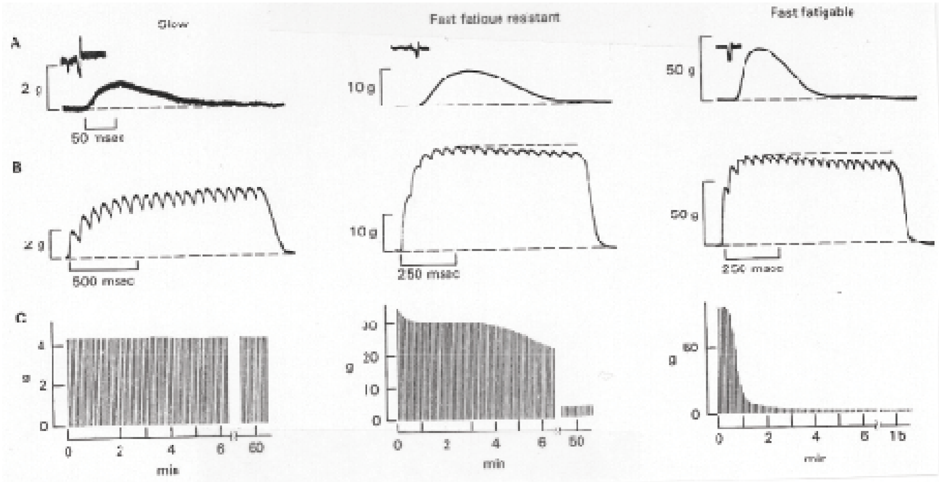


Motor unit (...)

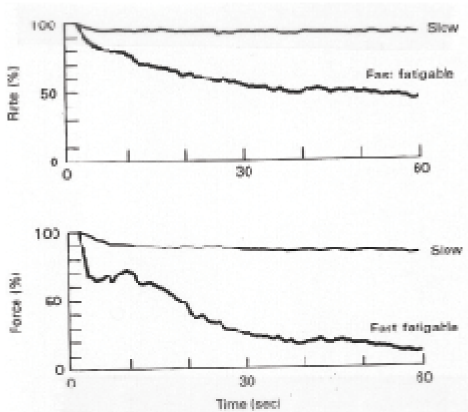
- Three types of MU: **slow** (low force, resistent to fatigue), **fast and fatigue-resistant** (intermediate), **fast and fatiguable** (large force, fast contraction and relaxation, fast fatigue for repeated stimulation).

- Each muscle contains a specific proportions of the different types of MU.

- In a MU, the properties of the MN and fibers are related. The diameter and conduction velocity of axons that innervate fast fatiguable fibers are larger that those for axons that innervate slow fibers.



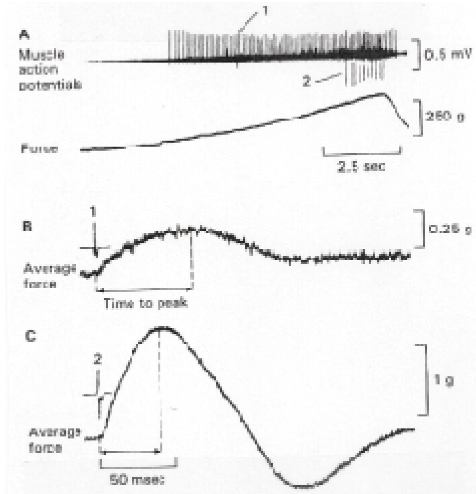
Burke et al. (1974)



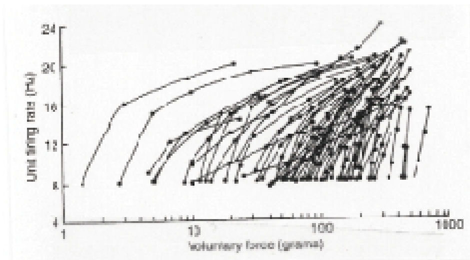
Kernell & Monster (1982)

Motor unit (end)

- Size principe: MNs are recruited by synaptic input according to a fixed order determined by their size. Smaller MN are recruited first, by the smallest inputs. As the size of inputs increases, the number of recruited MNs increases.
- Slow units are the most numerous and most used units. They require the larger metabolic input. Fast units are used more occasionally.
- Force can also be modulated by changes in the discharge frequency of MNs.



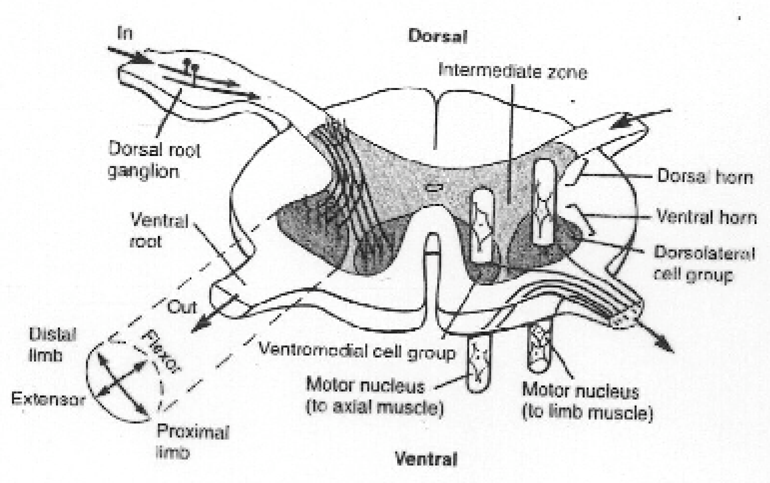
Desmedt & Godaux (1977)

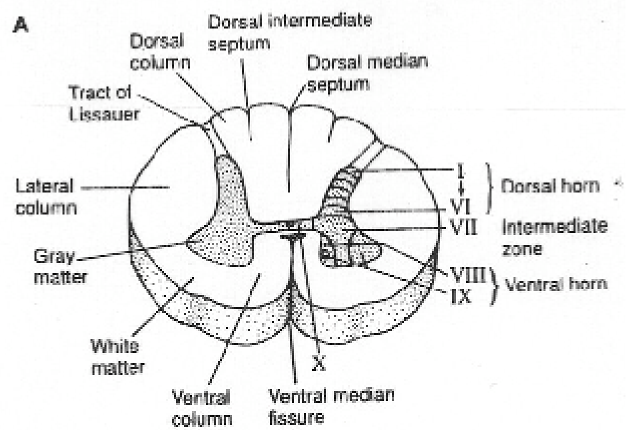


Monster & Chan (1977)

Spinal cord

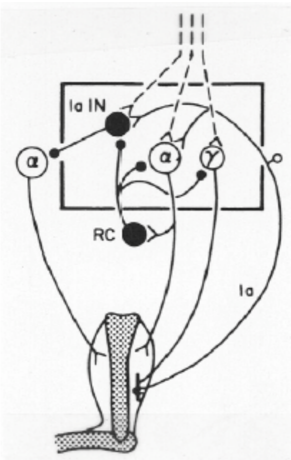
- Motoneurons are located in the **spinal cord**.
- Afferent information enters through the dorsal roots. Efferent information is transmitted through ventral roots.
- Spinal cord is the first relay for somatic sensory information.
- Gray matter contains the cell body of MNs. White matter contains the axons.
- MNs are group into pools that can extend over several segments.

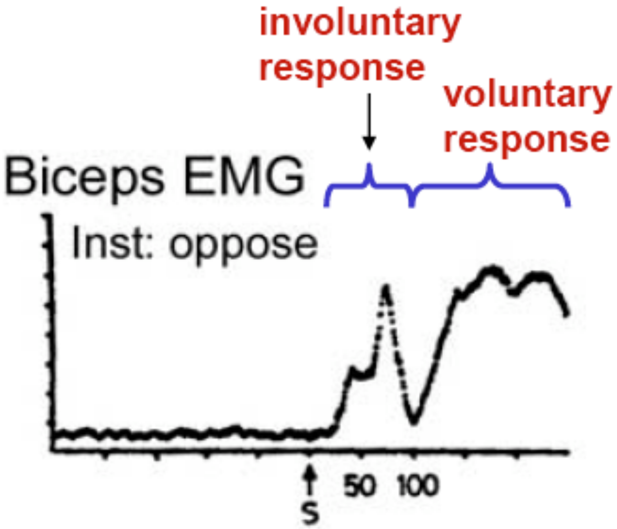


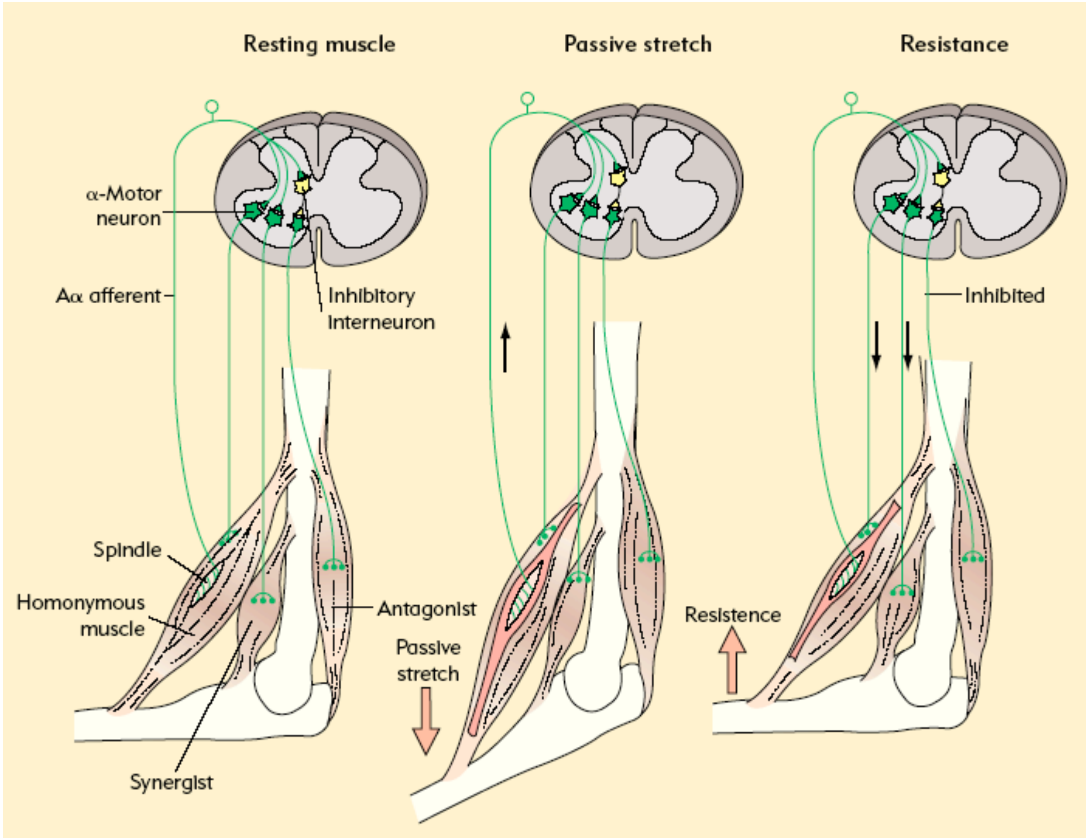


Stretch reflex

• Regulates the output of a MN through a negative feedback process. The feedback gain can be modulated by the nervous system (e.g. gamma MNs). Minimum delay ≈ 30 ms.

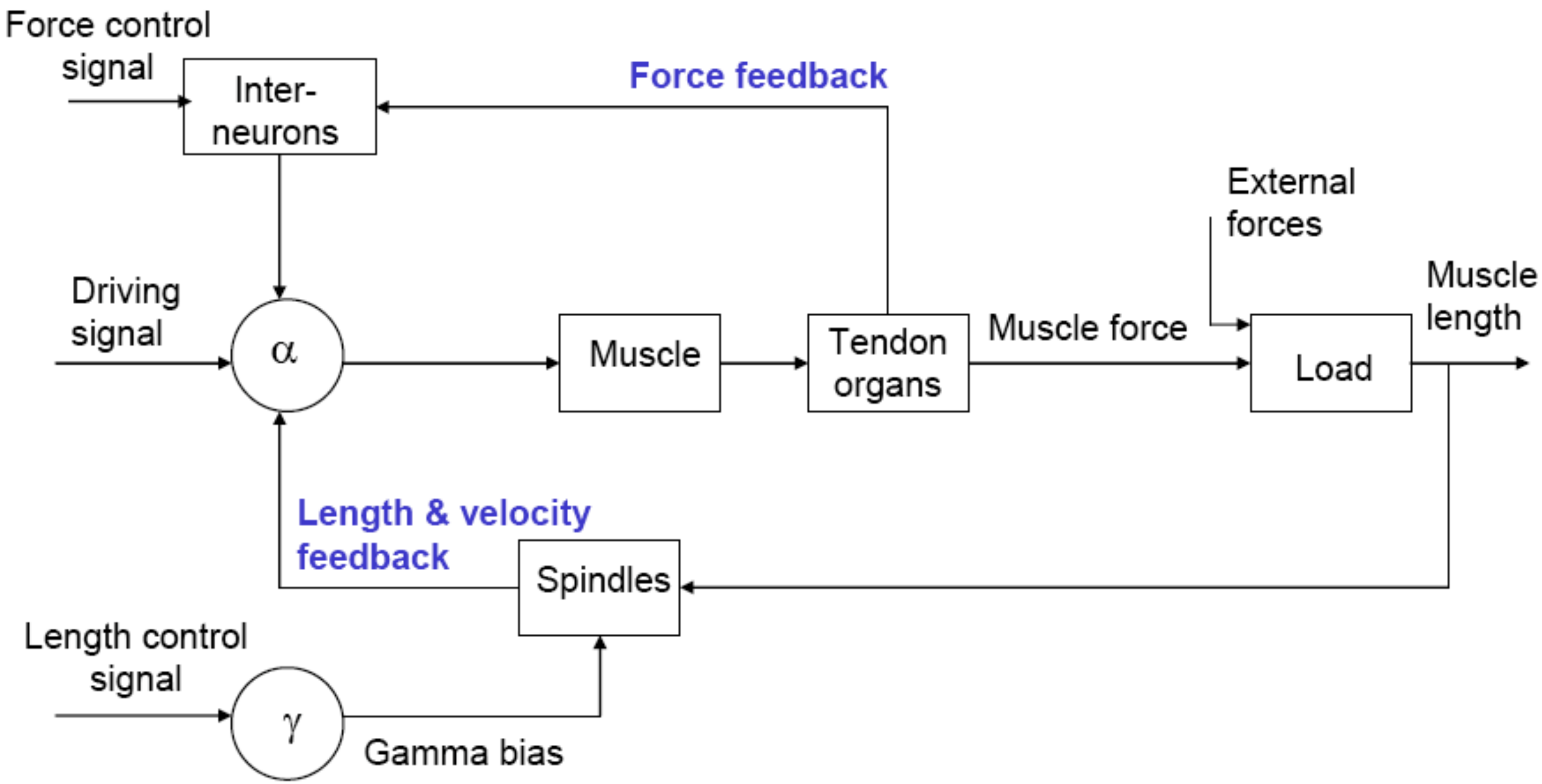






Action of the stretch reflex

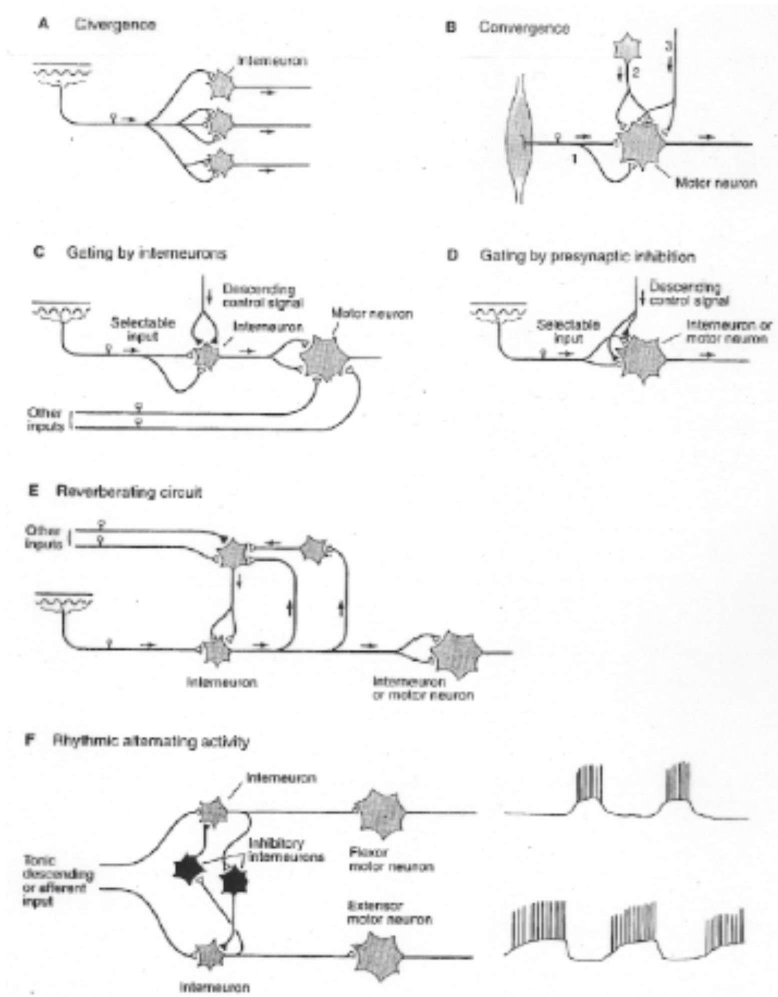
Negative feedback system: reduces deviations around a reference value.



Spinal Mechanisms

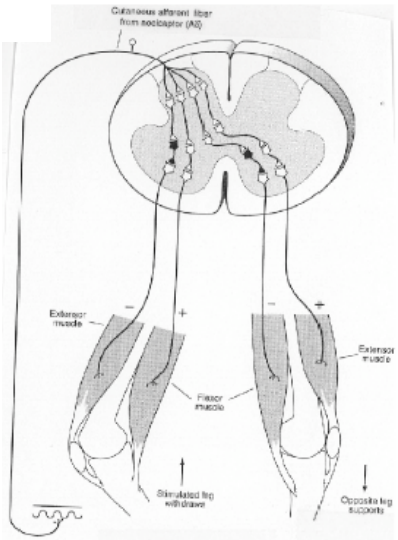
• A motor act generally requires the coordination of a large number of muscles. Spinal circuits play a critical role in this coordination. Spinal reflexes form a set of elementary coordination patterns (e.g. stretch reflex). Most reflexes involve complex circuits that link several muscles or articulations.

• Interneurons (INs) are basic elements of reflexes. Convergence, divergence, gating, reverberation, cyclic interactions, CPG (central pattern generator).

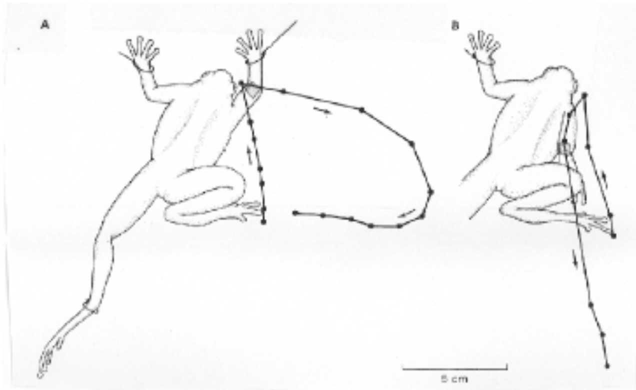


Spiral mechanisms (...)

• A flexion reflex that coordinates a set of segments through a polysynaptic circuit is involved to avoid painful cutaneous stimulation. Flexor muscles of the stimulated limb are activated, and extensor muscles are inhibited. The reflex has an opposite action on the non-stimulated limb.



• Some reflexes are modulated by body posture. Flexion reflex in the frog.

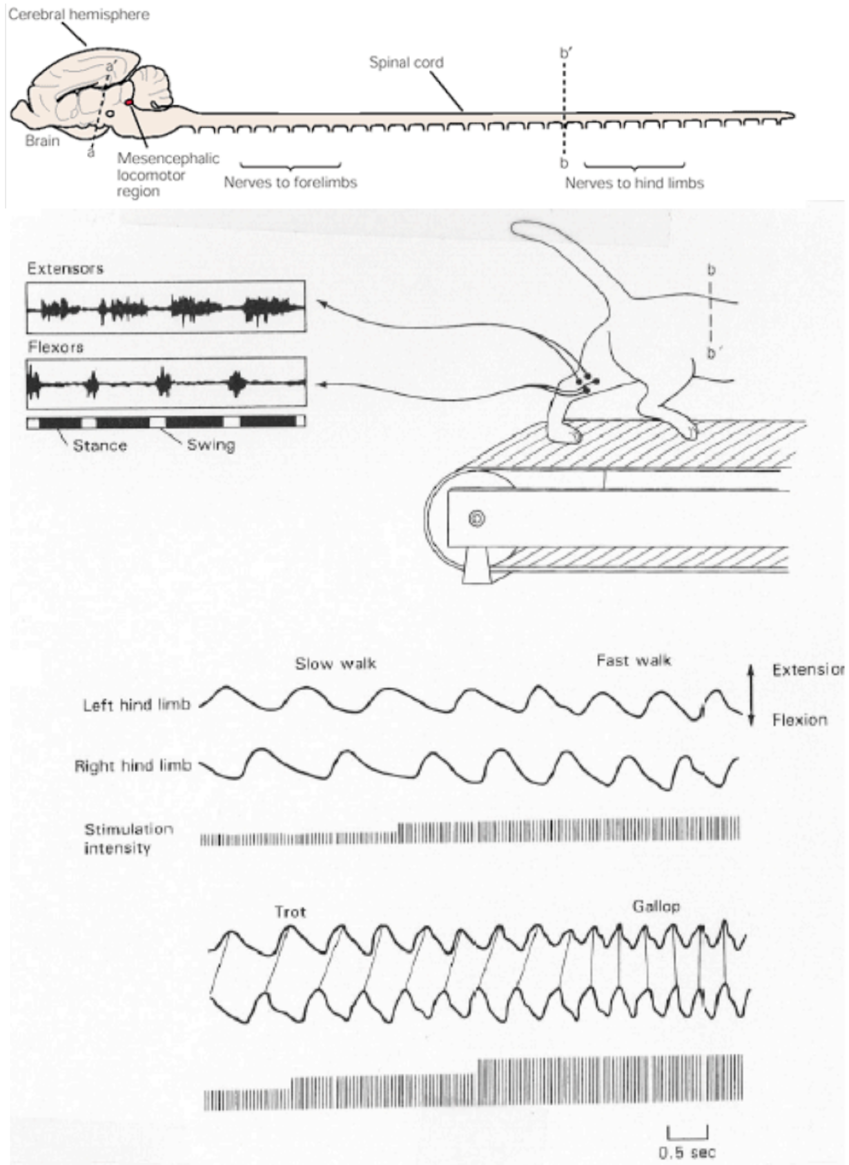


• Some reflexes involve rhythmic movements.

Spinal mechanisms (...)

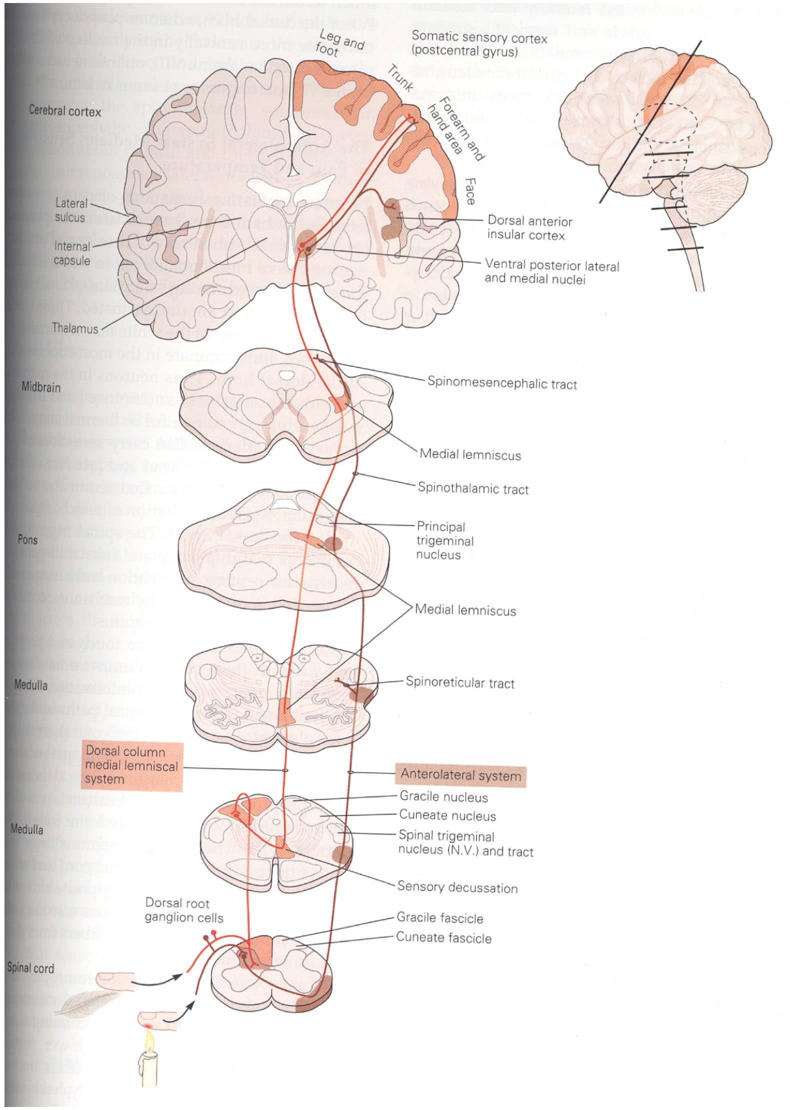
Spinal circuits generate rhythmic patterns for locomotion. After spinal cord transection that isolate segments that control lower limbs, cats walk normally on a treadmill.

When transection isolates the whole spinal cord, electrical stimulation of the mesencephalic locomotor region generates locomotion. As stimulation intensity increases, locomotion becomes faster. Then there is a transition between trot (alterned flexions/extensions) and gallop (simultaneous flexions/extensions).



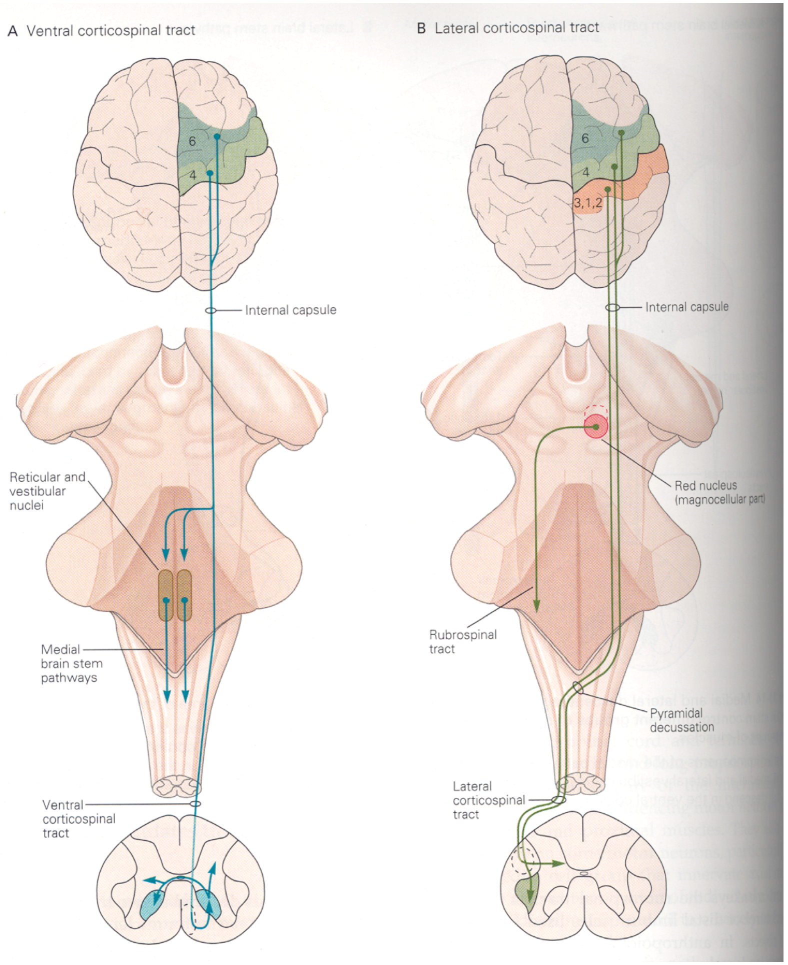
Ascending systems

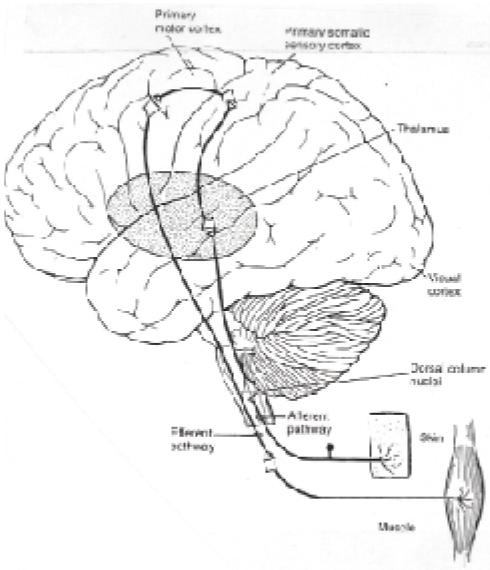
• There exist two main ascending systems:
- dorsal column/median lemniscus system: transmits tactile and proprioceptive information.
- anterolateral system: transmits pain and temperature.



Descending systems

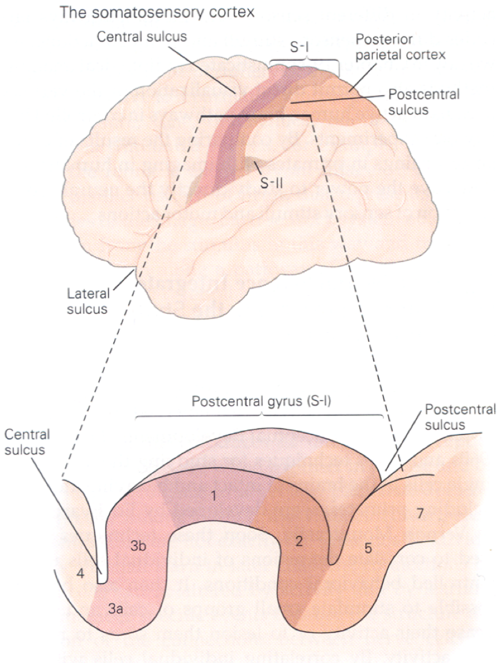
- Motor commands are transmitted through descending pathways. The cortico-spinal tract is the larger pathway (1 million fibers, 30% from primary motor cortex). The lateral pathway controls the distal and proximal muscles. The ventral pathway controls axial muscles.

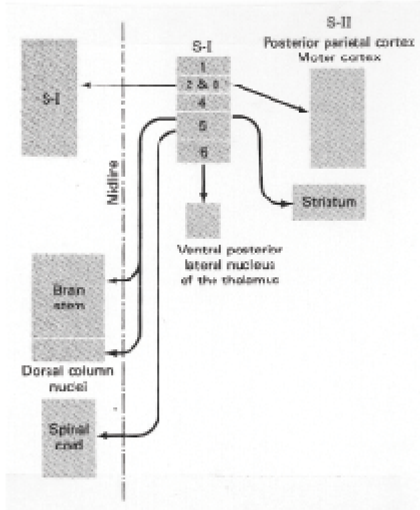




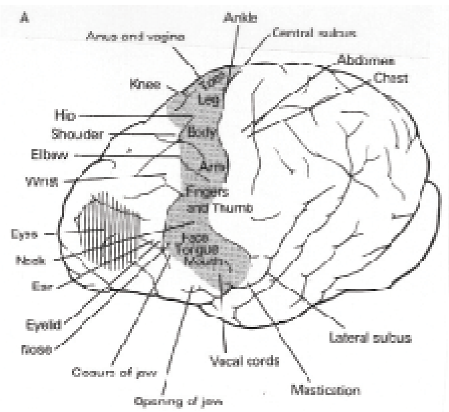
Representations

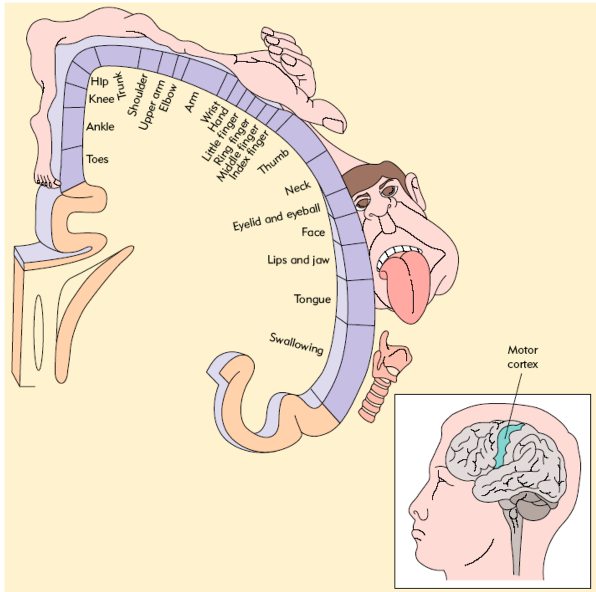
Somatic



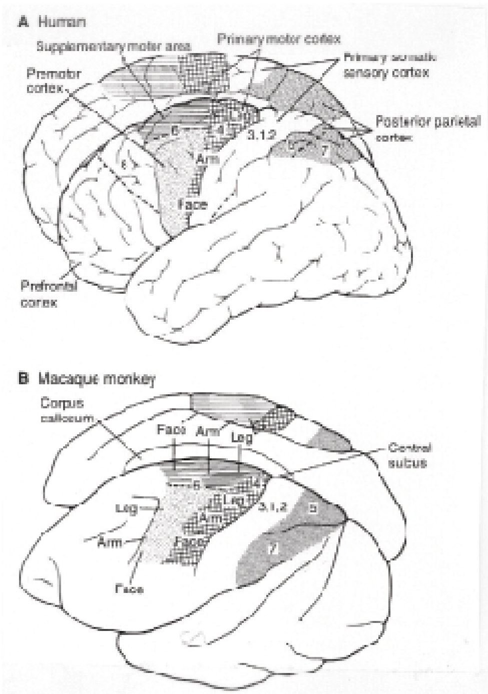


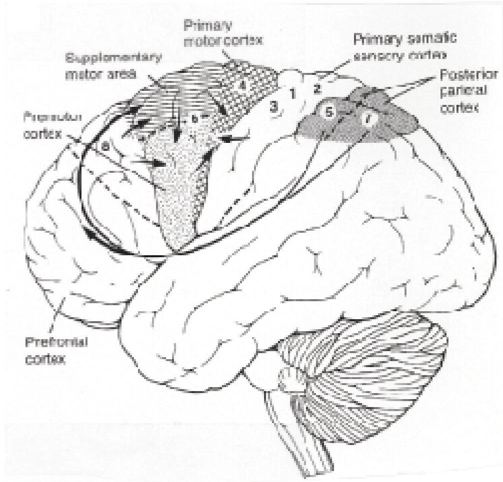
Motor

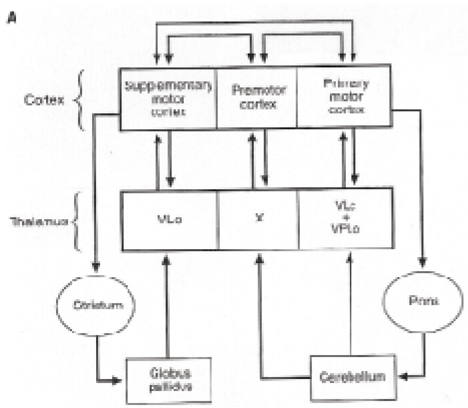




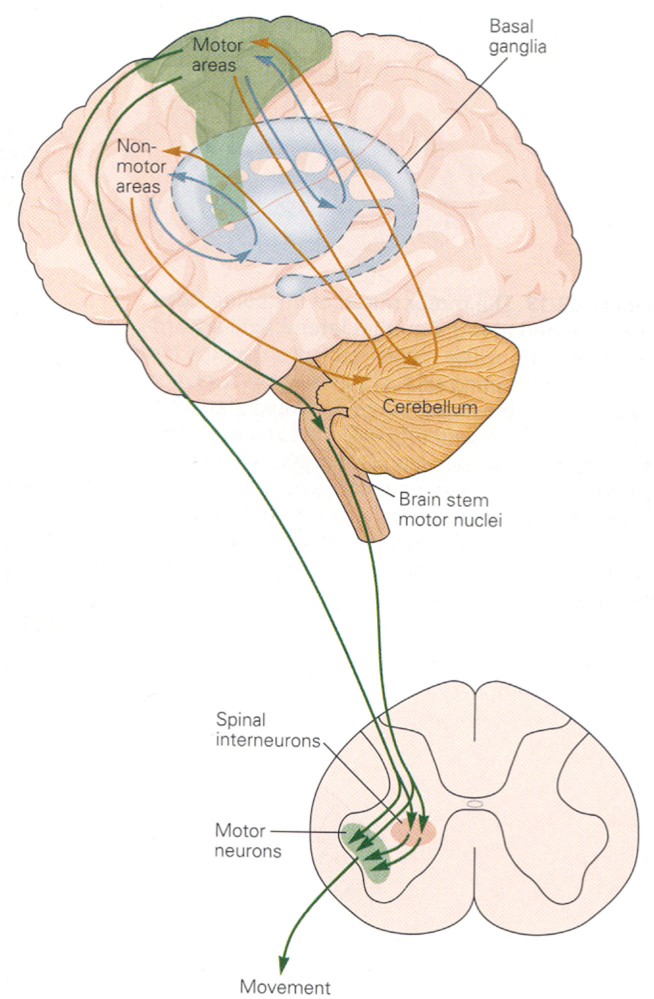
Cortical anatomy

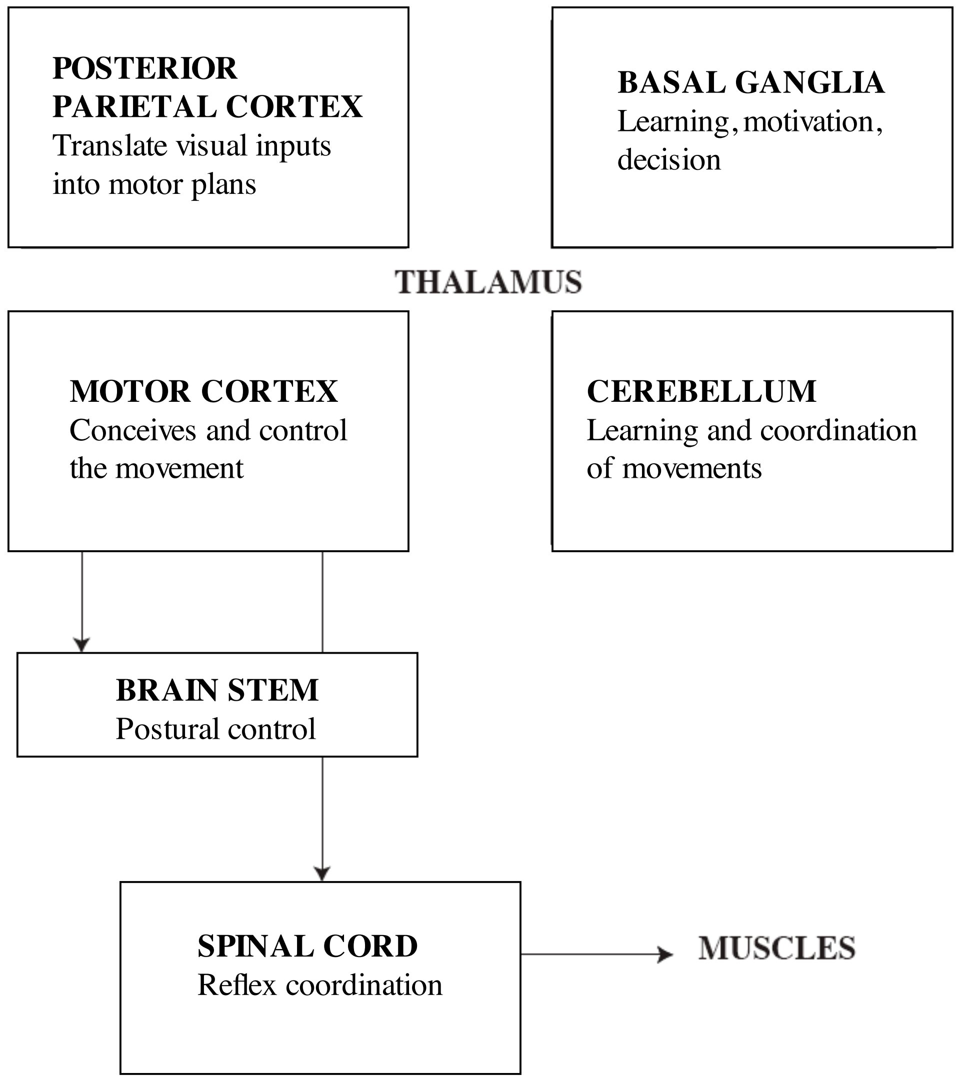




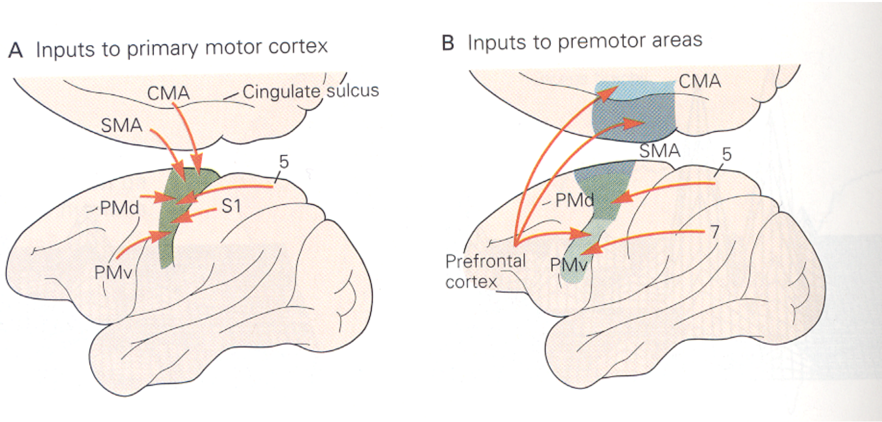


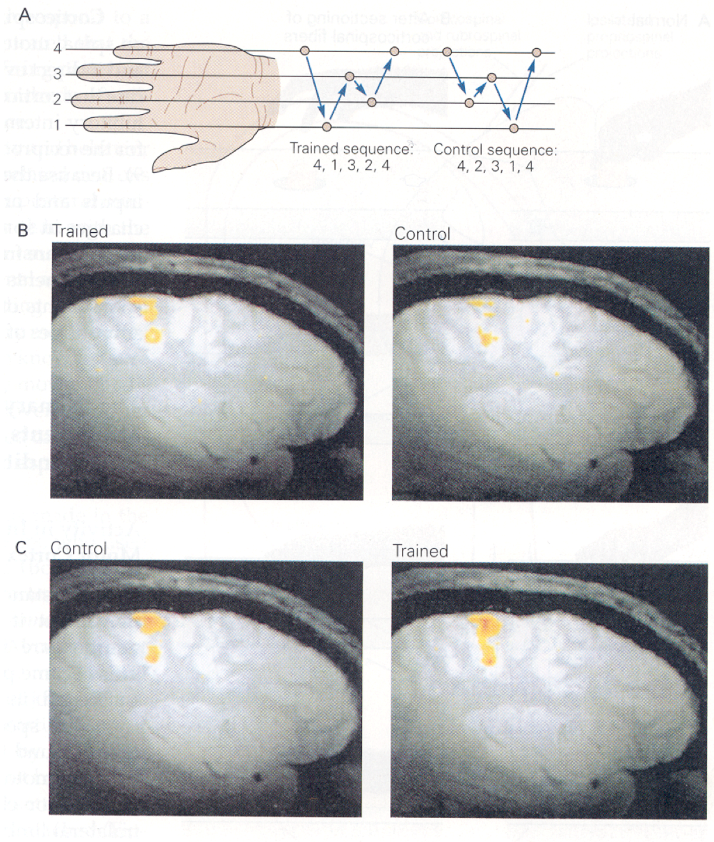
Architecture and functions

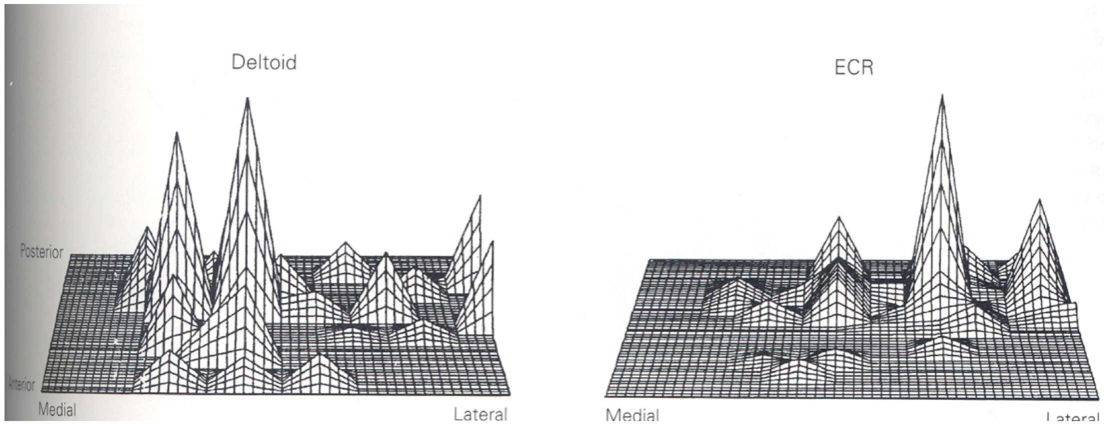




Motor cortex



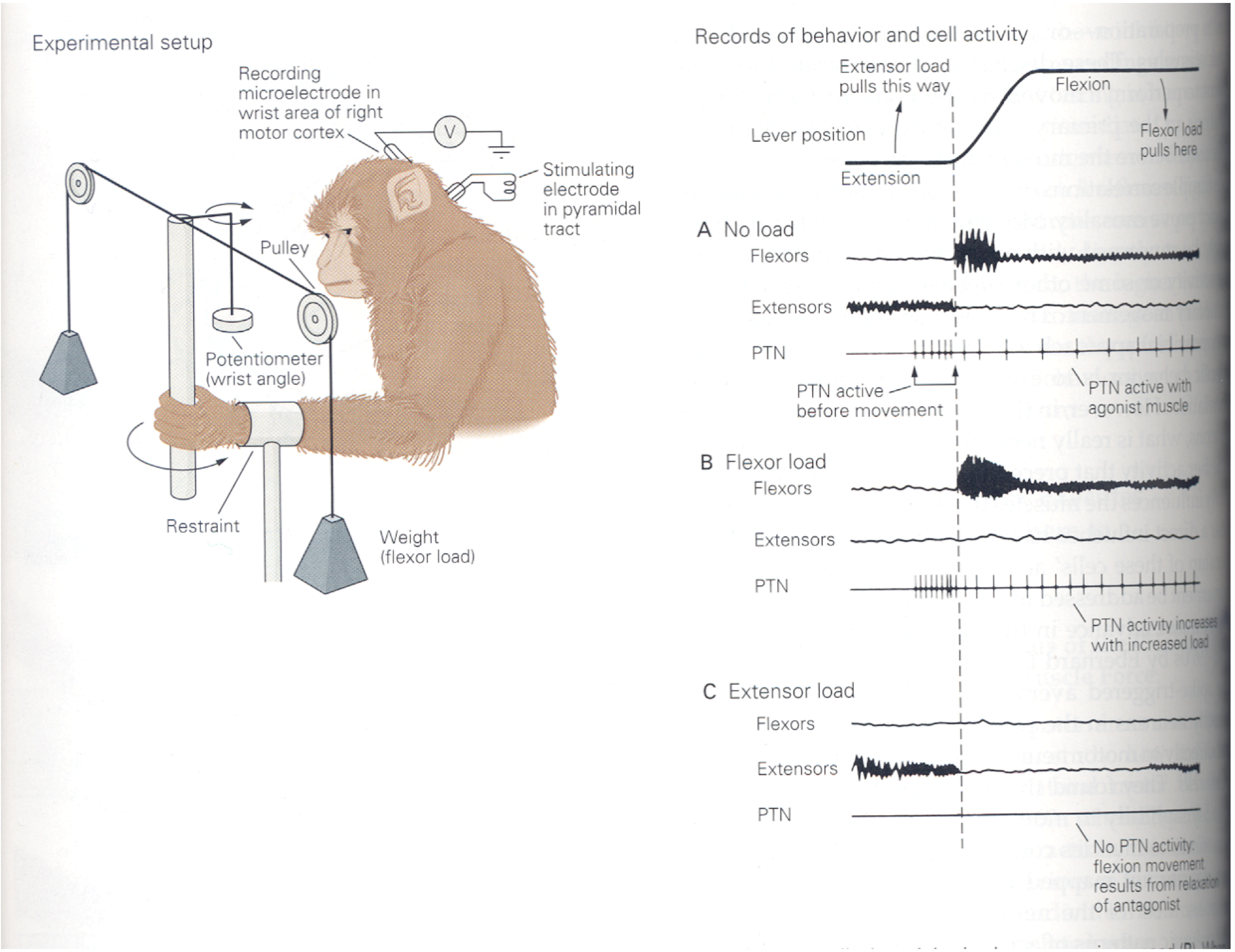




Sites controlling an individual muscle are not located together but are distributed over a wide area of motor cortex

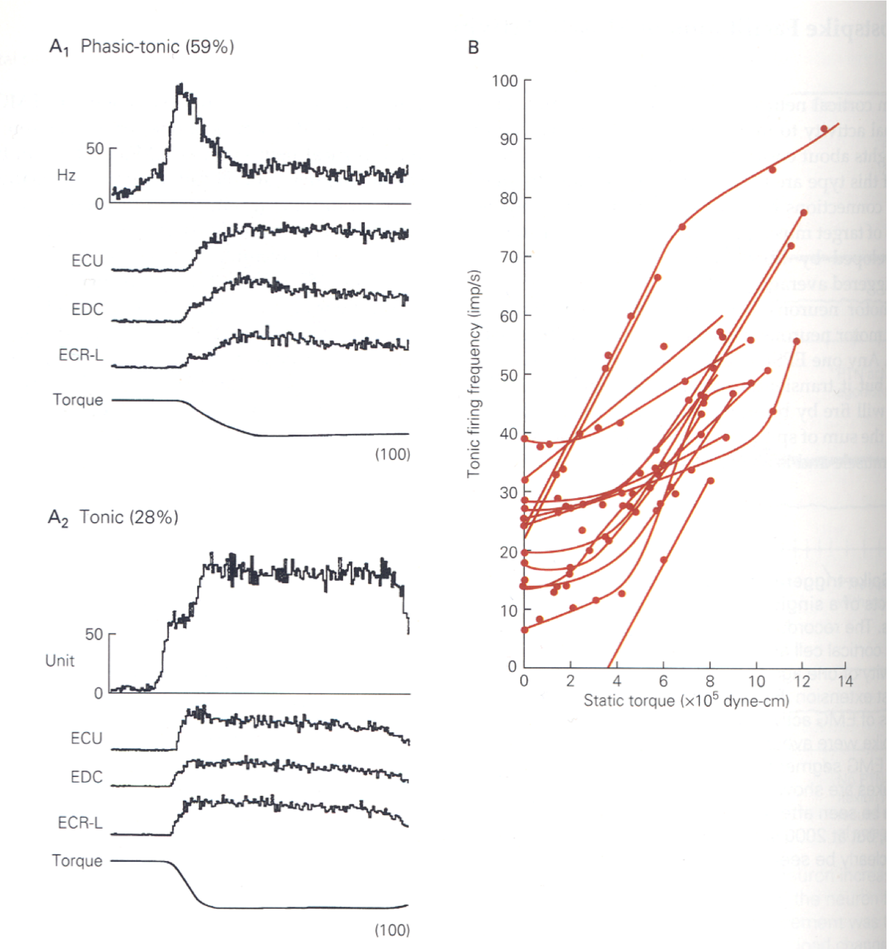
Neural properties

Neural activity is motor cortex is modulated by muscular force.

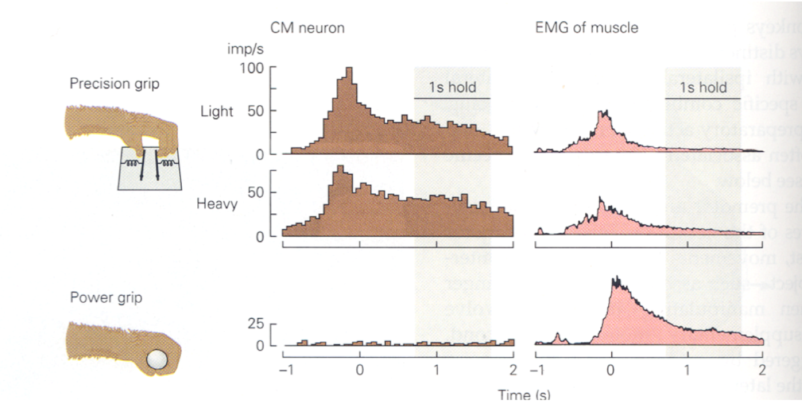


Evarts (1968)

Neural proprerties (...)



Cheney & Fetz (1980)

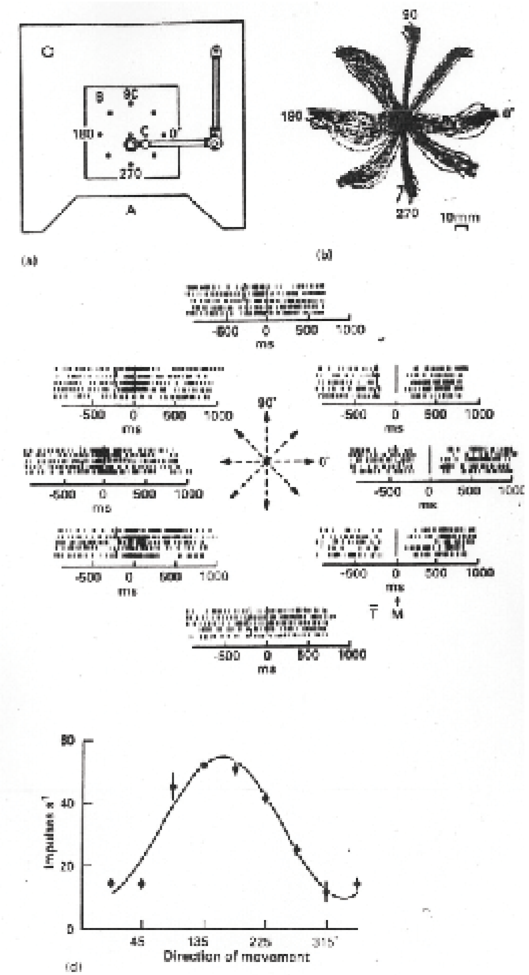


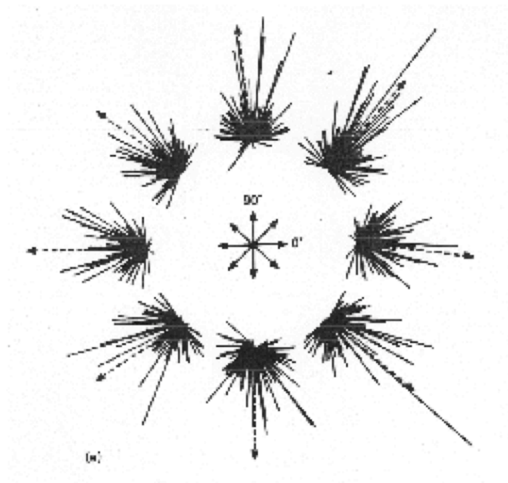
Motor cortical activity is task-dependent.

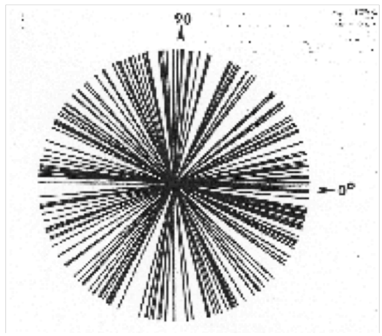
Muir & Lemon (1983)

Neural proprerties (end)

Neural activity in motor cortex is modulated by movement direction.

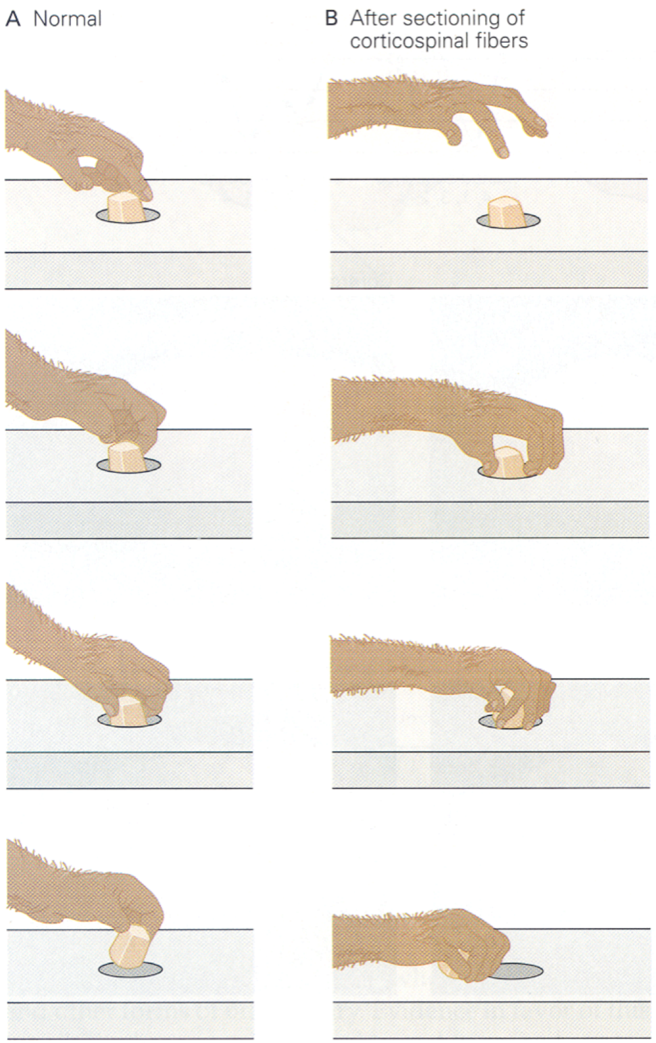






Georgopoulos et al. (1982)

Lesion of motor cortex



The direct corticospinal tract is necessary for fine control of finger movements.

Lawrence & Kuypers (1968)