Descending information flow in motor systems

Afferent (sensory) systems

High-level cortex	Objects, places, etc.
Primary sensory cortex	Local features
Sensory thalamus	Relay and gating
Retina, olf. bulb, brainstem, etc.	Initial processing
Primary afferent	Transduction

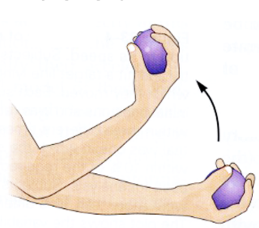
Efferent (motor output) systems

Premotor cortex	Planning
Primary motor cortex (M1)	Motor commands for limbs
Spinal cord motor circuits	Motor commands for muscle groups
Alpha motor neurons (sp. cord)	Motor commands for single muscles
Muscle	Movement

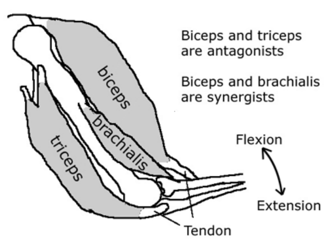
The motor control problem is complex

Multiple muscles control movement at a single joint. Multiple joints must be coordinated. Different types of movement co-exist that are controlled by different brain systems. These all share output in a final common path-way to muscle.

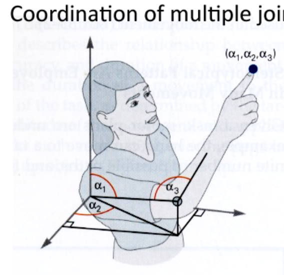
Movement



Motor plant



Coordination of multiple joints

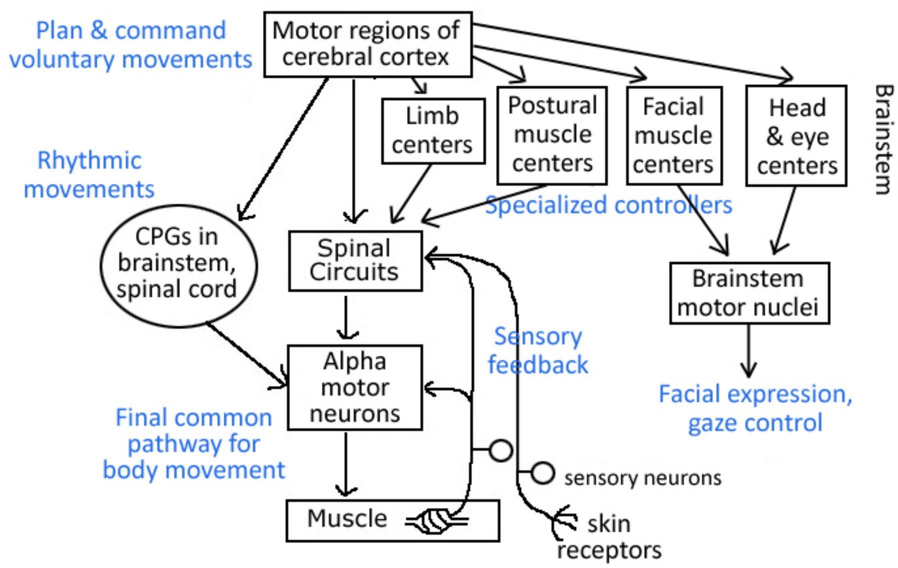


Voluntary movement
Reflex movement
Rhythmic patterns
(breathing, swallowing, walking)

Different types of movement require specialized control systems. These can co-occur and must be coordinated.

The motor system is organized to deal with this complexity

Specialized components handle these challenges.



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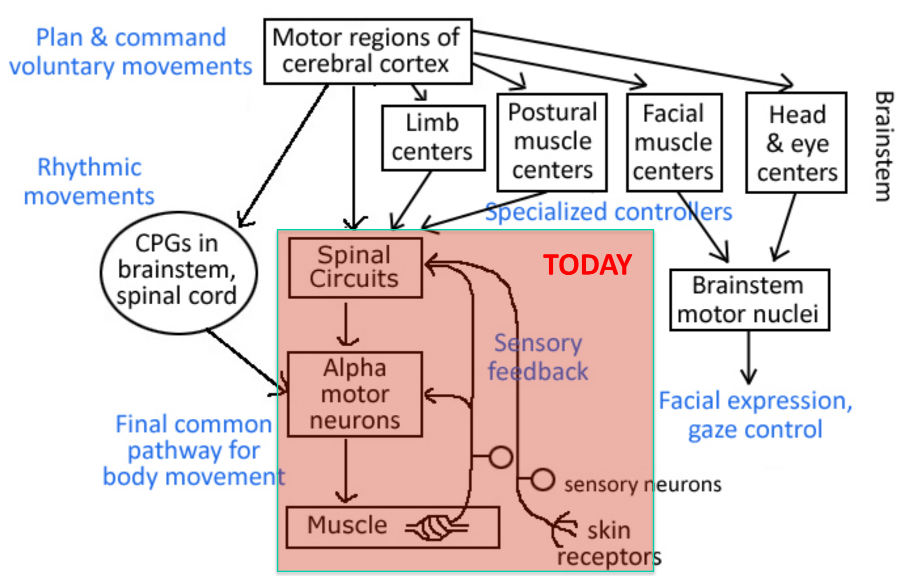
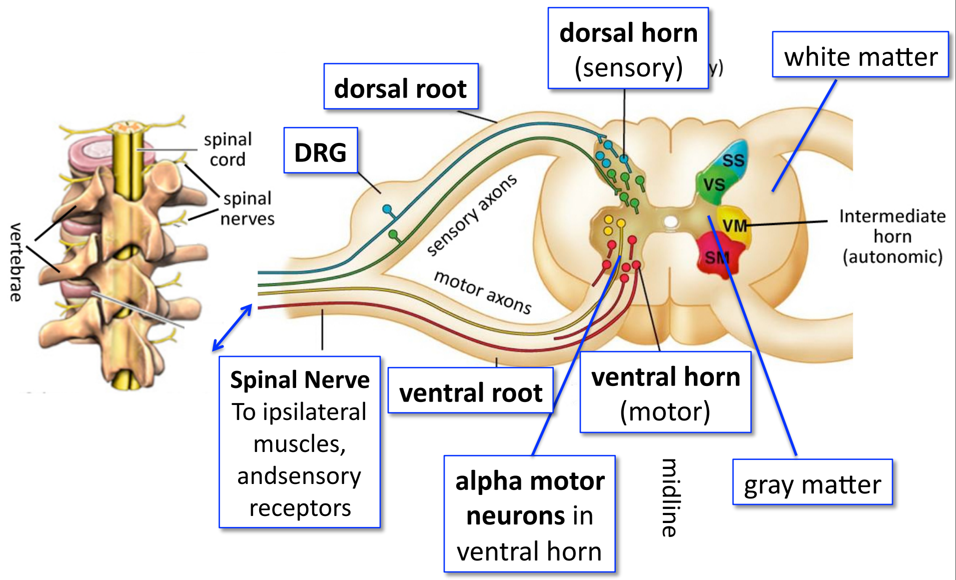
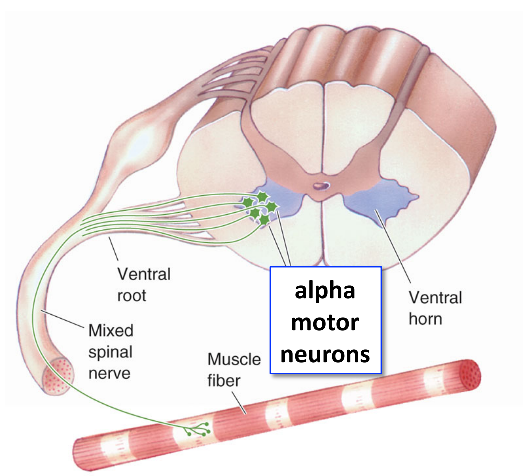
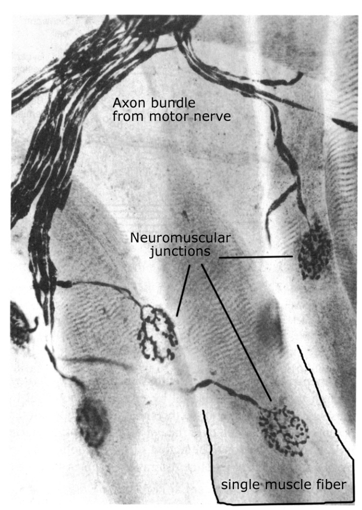


Spinal cord anatomy



Alpha motor neurons in ventral horn of spinal cord





muscle fiber = single muscle cell
each muscle contains hundreds or thousands of fibers

Each α motor neuron spike drives muscle contraction

If you don't know this, read Kandel Chap 34.

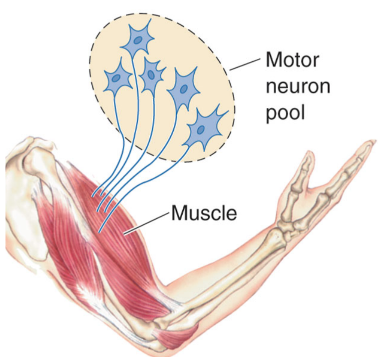
Synaptic transmission at neuromuscular junction (NMJ)
Spike in α motor neuron axon → ACh release at NMJ → nicotinic AChR channel opens → muscle fiber depolarizes

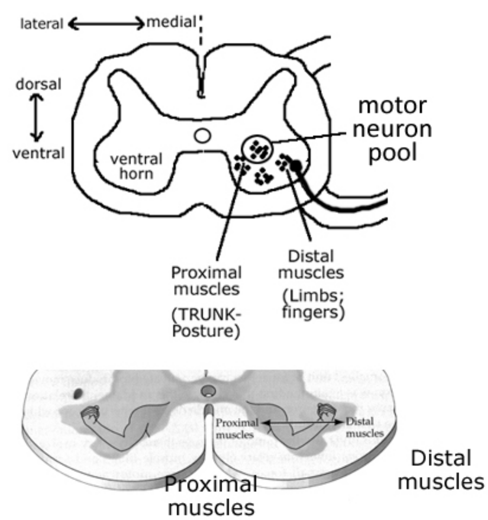
Spike and calcium rise in muscle fiber
Na_V channels open → action potential in muscle fiber → Ca release from sarcoplasmic reticulum

Calcium drives contraction via actin-myosin motor
Ca binds to troponin → displaces troponin/tropomyosin complex → enables movement of myosin along actin filament → muscle contraction (twitch)

Muscle innervation and motor pools

Each motor neuron innervates one muscle. All motor neurons for that muscle are located together in the spinal cord, and are called a **motor neuron pool.**

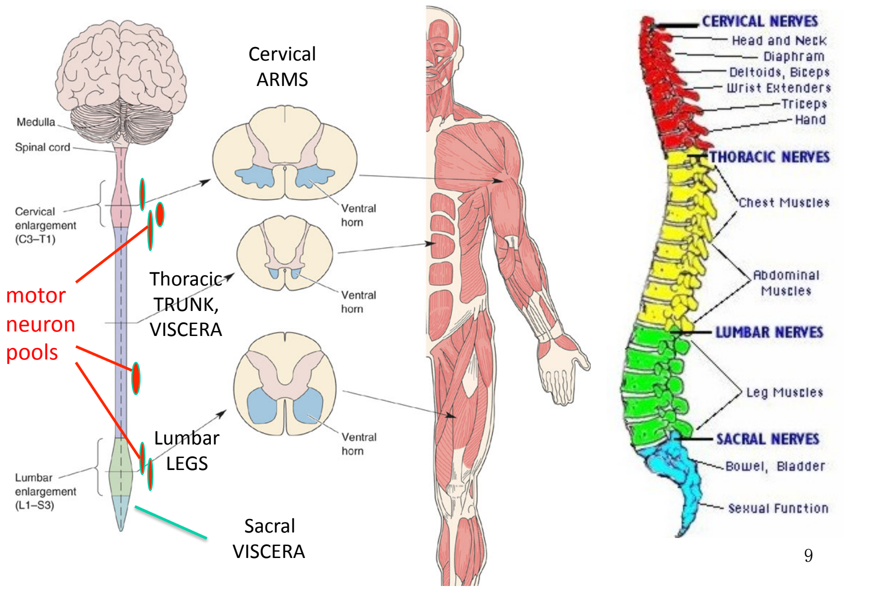




Topography of motor neuron pools
(mediolateral dimension)

Muscle innervation and motor pools

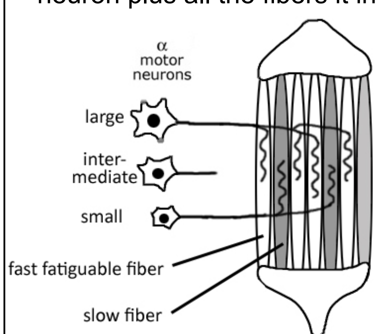
Topography in rostrocaudal dimension (up and down spinal cord)

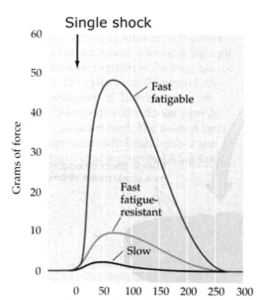


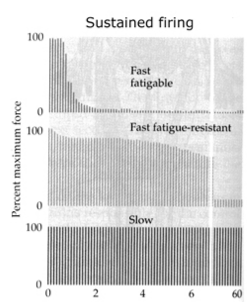
9

Control of muscle force

Each muscle fiber is innervated by a **single** motor neuron, but each motor neuron innervates many muscle fibers (a few to hundreds). One motor neuron plus all the fibers it innervates is called a **motor unit**.







Small motor units innervate few slow fibers (red) that generate small forces but don't fatigue. **Large motor units** innervate many "fast fatiguable" fibers (pale) that generate large forces, but fatigue quickly. **Intermediate motor units** innervate "fast, fatigue-resistant" fibers with intermediate properties.

The brain controls muscle force in two ways

1. By sending progressively stronger synaptic input to the motor neuron pool, the brain first recruits **small motor units** (slow, low force), then **intermediate motor units** (fast, fatigue-resistant, medium force), then **large motor units** (fast-fatiguable, high force).

   This is called the **size principle of recruitment of motor units**.

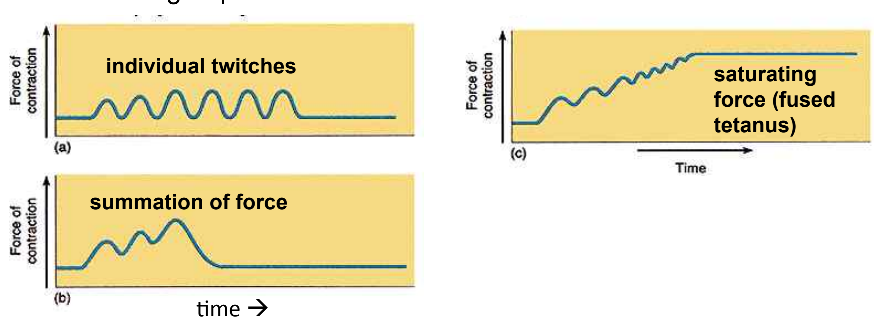
   Example:
   Standing (S, low-force) → walking (FR) → jumping (FF, high-force)

   What do you think is the mechanism for the size principle?

11

The brain controls muscle force in two ways

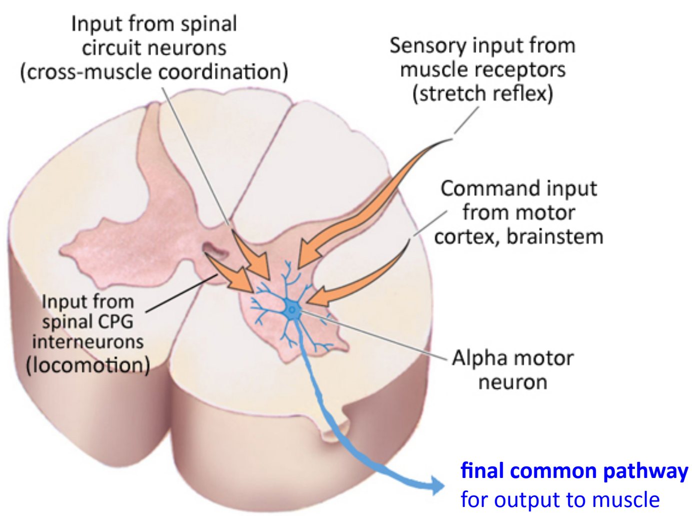
2. More force is also generated by increasing α motor neuron firing rate within each group.



Muscle tone is a low level of average baseline contraction in each muscle, due to spontaneous firing of α motor neurons.

12

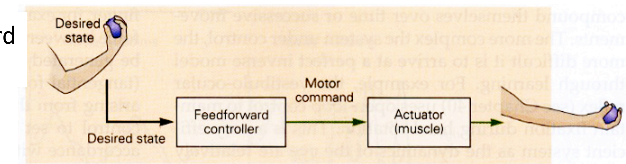
α motor neurons are the final common output from multiple motor control pathways



Local spinal circuits for feedback control of movement

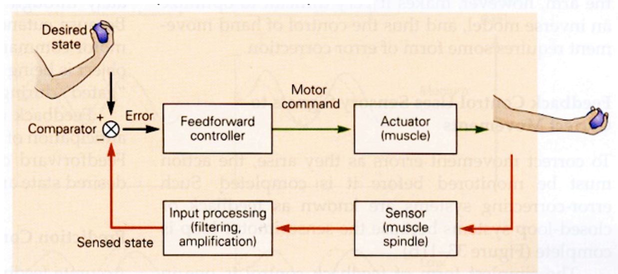
Unexpected loads and tired muscles change performance. To compensate for this, rapid, low-level **sensory feedback** is used to monitor and correct most movements.

Feedforward control



Only used for fast reflexive movements (eye and head saccades, limb withdrawal)

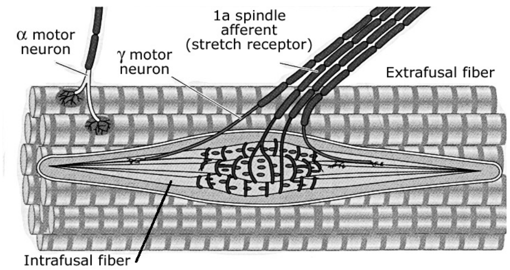
Feedback control



Most movements

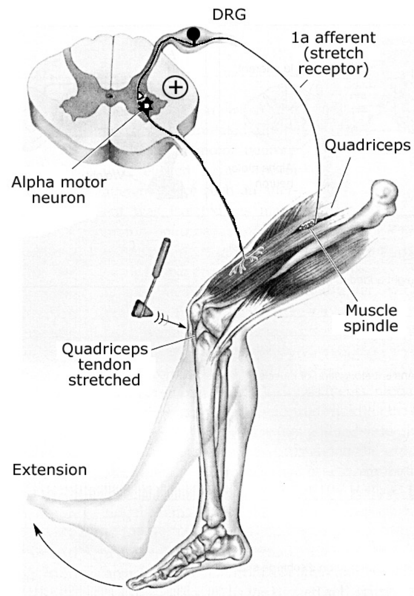
The stretch reflex: a basic mechanism of feedback control

Muscle stretch is sensed by muscle spindle mechanoreceptor, embedded in muscle. Spindles sense muscle **length**.



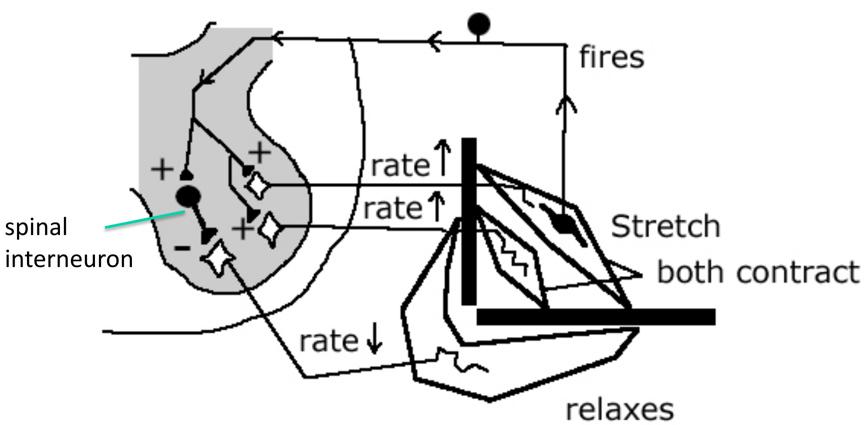
Stretch increases firing rate of 1a afferent (DRG neuron), which synapses directly on alpha motor neurons.

Alpha motor neuron firing rate increases → reflex contraction of the muscle.



The stretch reflex: a basic mechanism of feedback control

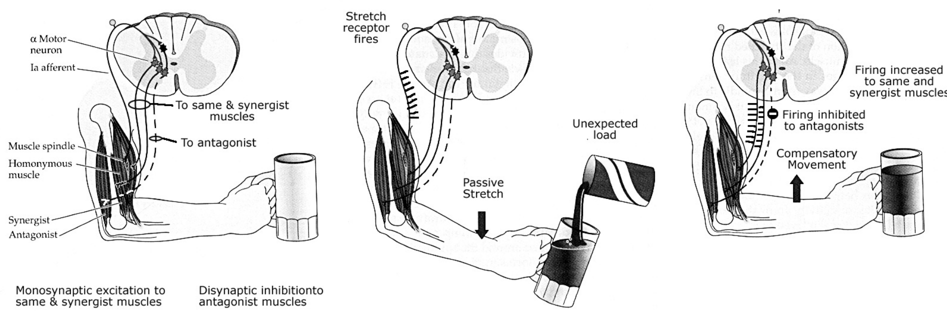
Coordination of stretch reflex across muscles

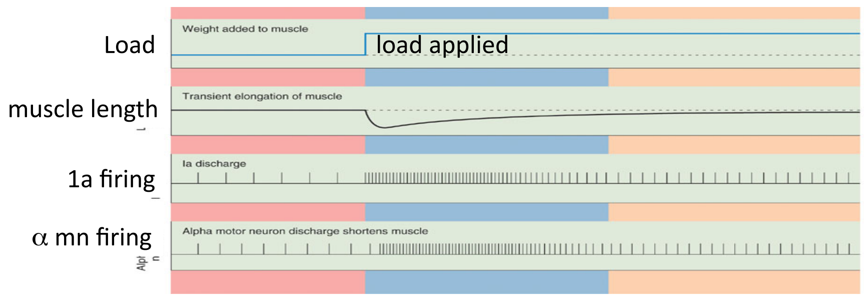


Stretch causes homonymous and agonist muscles contract, and antagonist muscles to relax. This allows the joint to move.

16

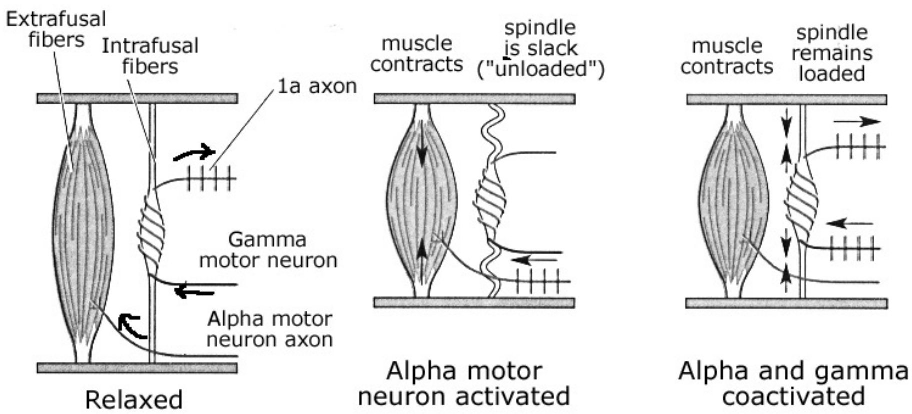
Stretch reflex compensates for unexpected loads





The stretch reflex during dynamic movement

Gain of the stretch reflex can be modulated by gamma motor neurons.



Most voluntary movements cause coactivation of alpha and gamma motor neurons to prevent spindles from becoming unloaded.

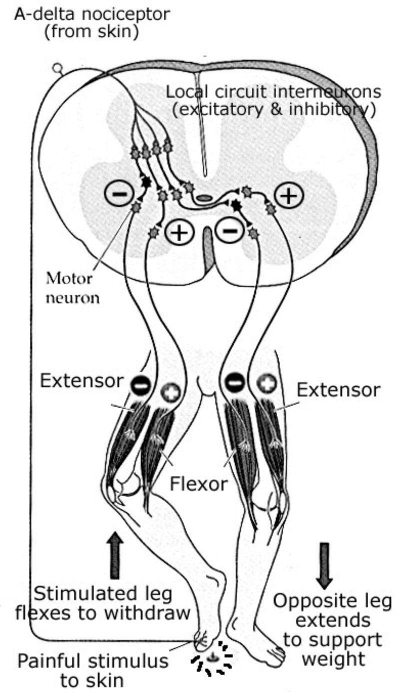
Other low-level spinal reflexes. The flexion and crossed-extensor reflexes

Circuit involves A-delta pain receptors in skin, local spinal interneurons, and α motor neurons.

Pain causes limb flexion on ipsilateral side and limb extension on contralateral side.

Both excitatory and inhibitory interneurons are involved. Flexors are activated on one side, and extensors on the other side.

Sherrington & Adrian, 1920s (Nobel Prize)



Summary