THE MOTOR CONTROL IN HUMANS

THE MOTOR SYSTEM

- The contraction of skeletal muscle produces movement by acting on the skeleton.
- Motor neurons activate the skeletal muscles.
- Sensory feedback from muscles is important for precise control of contraction.
- The output of sensory receptors like the muscle spindle can be adjusted.
- The spinal cord is the source of reflexes that are important in the initiation and control of movement.
- Spinal cord function is influenced by higher centers in the brainstem.
- The highest level of motor control comes from the cerebral cortex.
- The basal ganglia and the cerebellum provide feedback to the motor control areas of the cerebral cortex and brainstem.

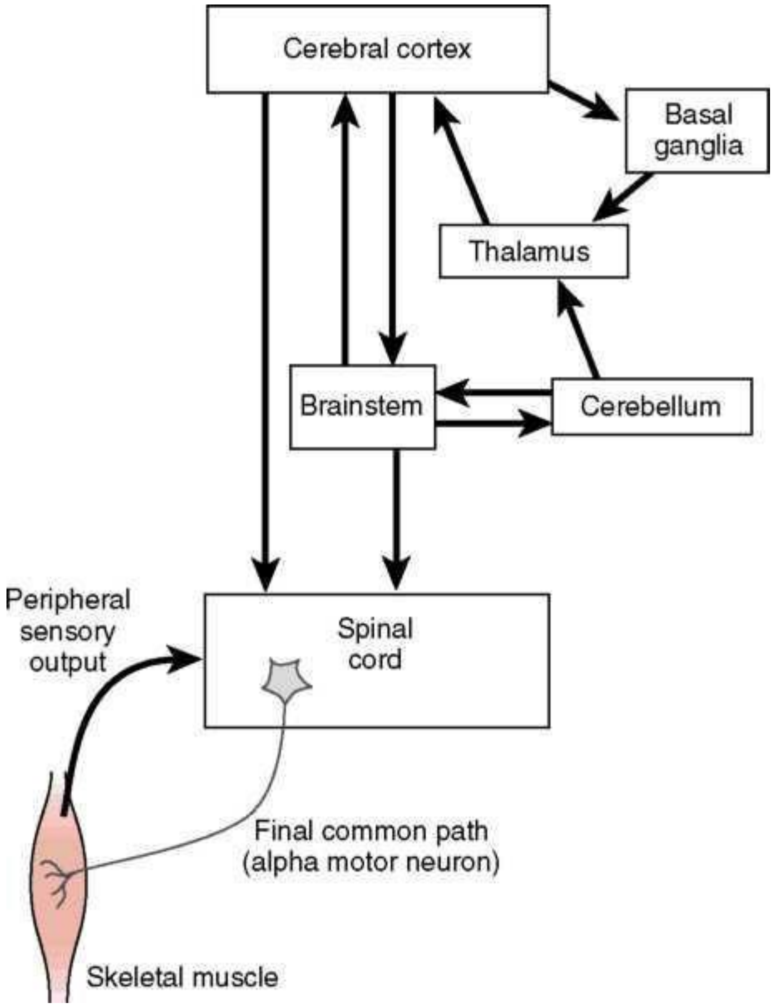
- ***Muscles*** span joints and are attached at two or more points to the bony levers of the skeleton.

- The muscles provide the power that moves the body's levers. Muscles are described in terms of their ***origin*** and ***insertion*** attachment sites. The ***origin*** tends to be the more fixed, less mobile location, while the ***insertion*** refers to the skeletal site that is more mobile.

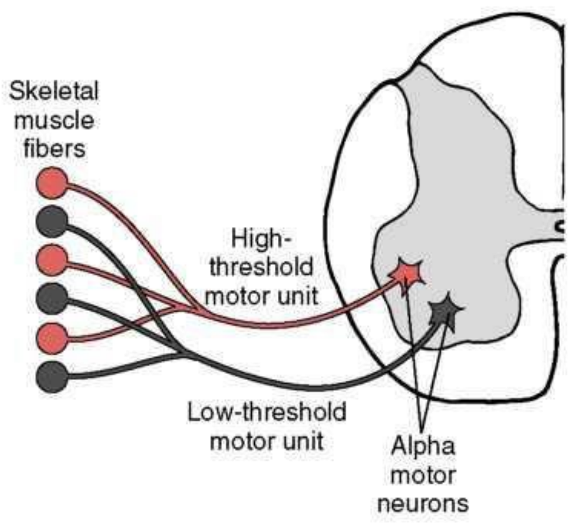
- ***Movement*** occurs when a muscle generates force on its attachment sites and undergoes shortening. This type of action is termed an ***isotonic*** or ***concentric*** contraction. Another form of muscular action is a controlled lengthening while still generating force. This is an ***eccentric*** contraction. A muscle may also generate force but hold its attachment sites static, as in ***isometric*** contraction.

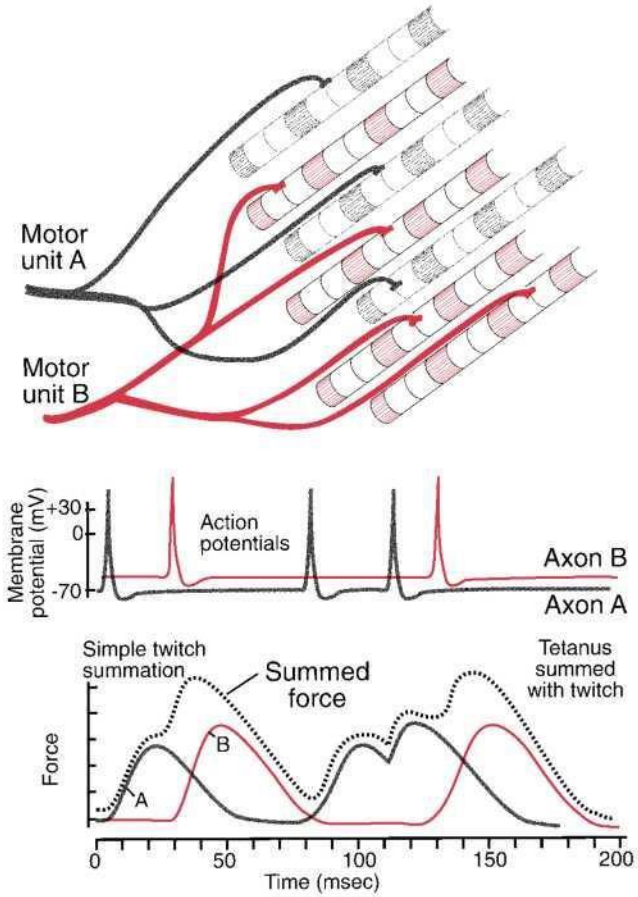
THE MOTOR CONTROL SYSTEM

Alpha motor neurons are **the final common path** for motor control. Peripheral sensory input and spinal cord tract signals that descend from the brainstem and cerebral cortex influence the motor neurons. The cerebellum and basal ganglia contribute to motor control by modifying brainstem and cortical activity.



THE MOTOR UNITS

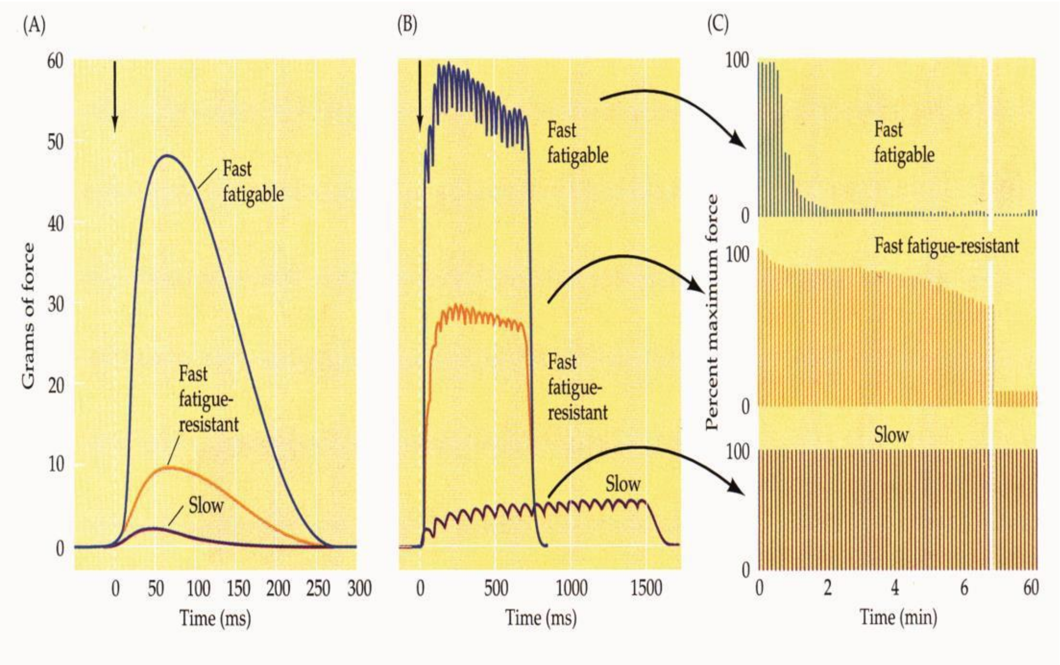




A motor unit consists of an alpha motor neuron and the group of extrafusal muscle fibers it innervates. Functional characteristics, such as activation threshold, twitch speed, twitch force, and resistance to fatigue, are determined by the motor neuron.

Motor unit summation. Two units are shown above; their motor nerve action potentials and muscle twitches are shown below. In the first contraction, there is a simple summation of two twitches; in the second, a brief tetanus in one motor unit sums with a twitch in the other.

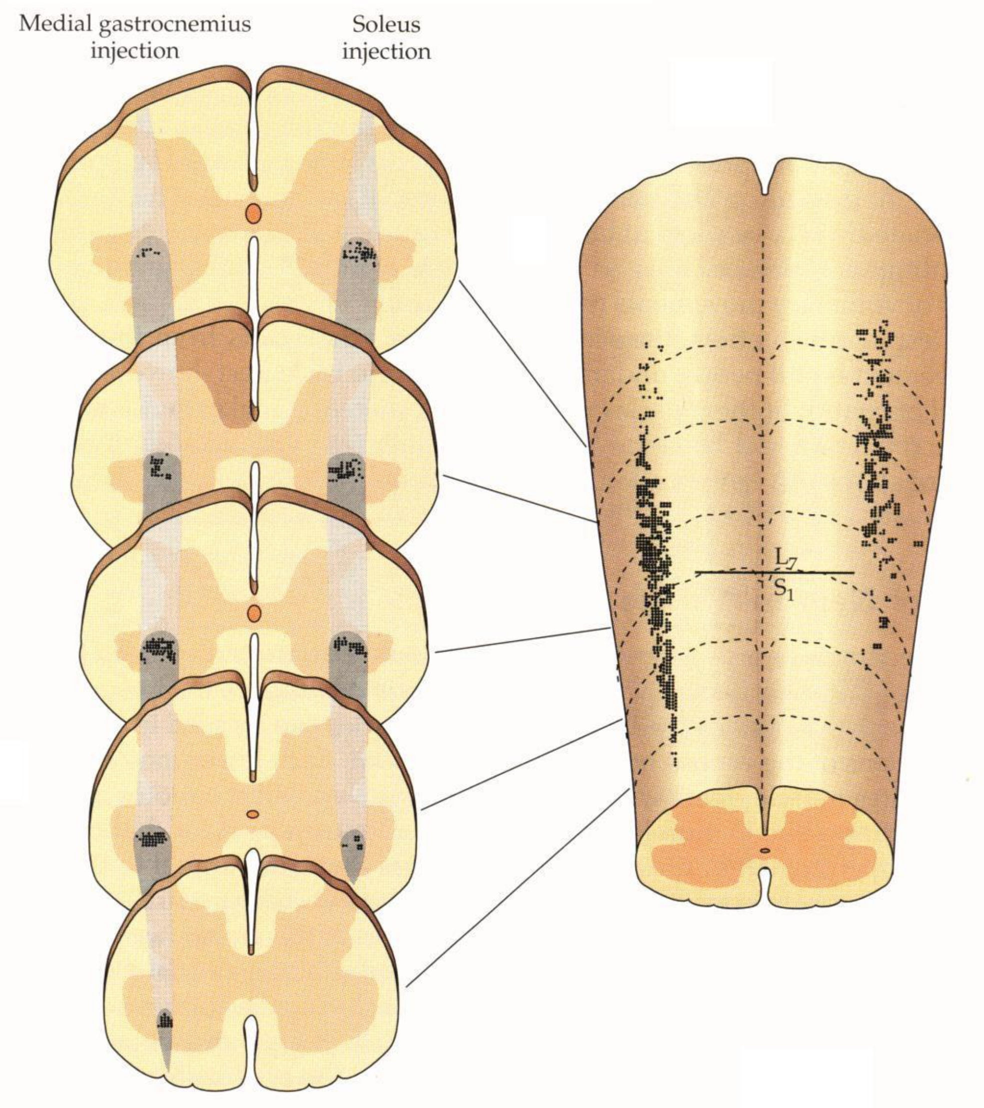
TYPES OF THE MOTOR UNITS



Small a motor neurons innervate relatively few muscle fibers and form motor units that generate small forces, whereas large motor neurons innervate larger, more powerful motor units. Motor units also differ in the types of muscle fibers that they innervate. In most skeletal muscles, the small motor units innervate small "red" muscle fibers that contract slowly and generate relatively small forces; but, because of their rich myoglobin content, plentiful mitochrondria, and rich capillary beds, such small red fibers are resistant to fatigue.

The small units are called slow (S) motor units and are especially important for activities that require sustained muscular contraction, such as the maintenance of an upright posture. Larger a motor neurons innervate larger, pale muscle fibers that generate more force; however, these fibers have sparse mitochrondria and are therefore easily fatigued. These units are called fast fatigable (FF) motor units and are especially important for brief exertions that require large forces, such as running or jumping. A third class of motor units has properties that lie between those of the other two. These fast fatigue-resistant (FR) motor units are of intermediate size and are not quite as fast as FF units.

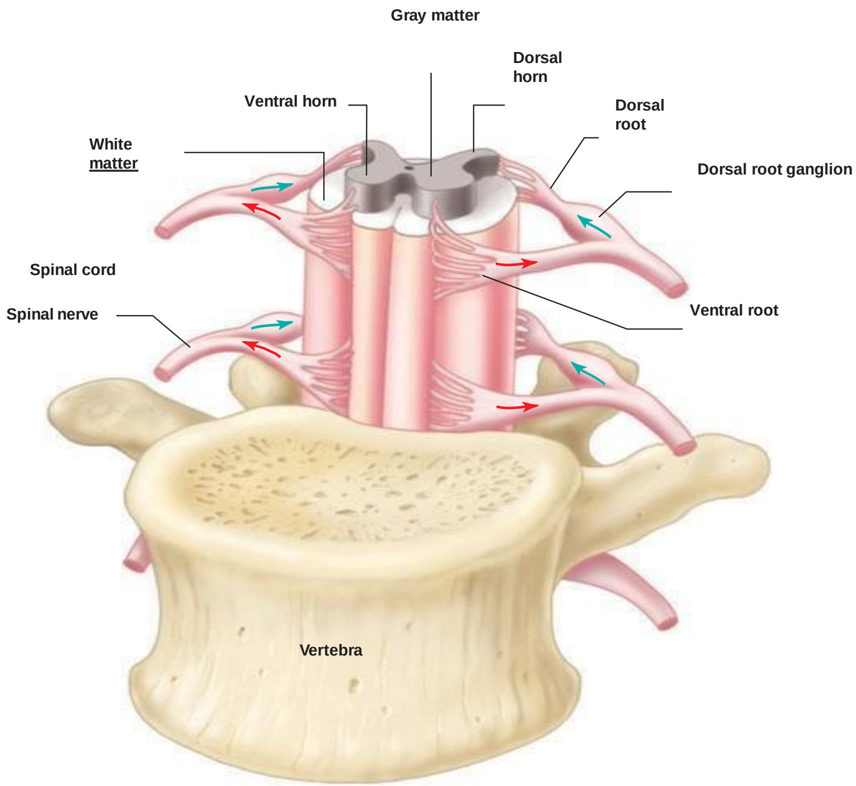
ORGANIZATION OF THE MOTONEURONS IN THE VENTRAL HORN OF THE SPINAL CORD

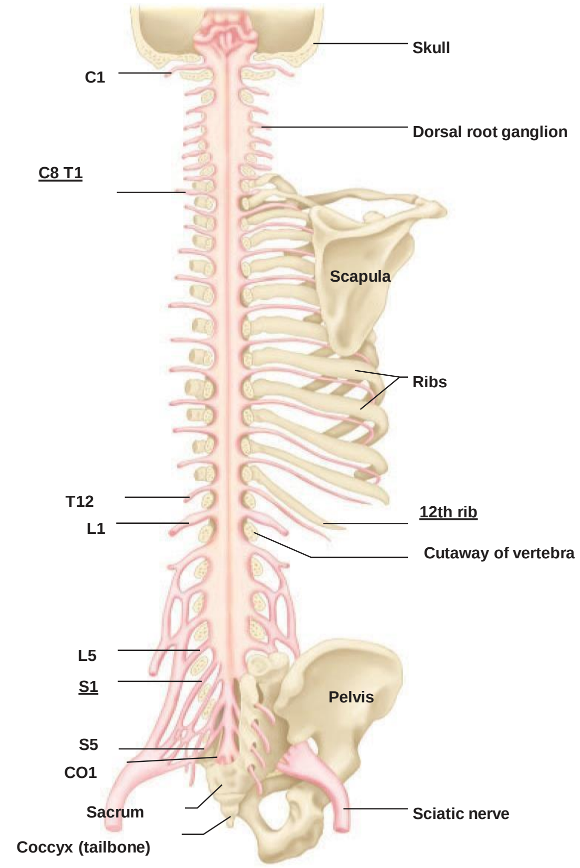


Neurons were identified by placing a retrograde tracer into the medial gastrocnemius or soleus muscle of the cat.

Section through the lumbar level of the spinal cord showing the distribution of labeled cell bodies. Lower motor neurons form distinct clusters (motor pools) in the ventral horn. Spinal cord cross sections and a reconstruction seen from the dorsal surface illustrate the distribution of motor neurons innervating individual skeletal muscles in the long axis of the cord. The cylindrical shape and distinct distribution of different pools are especially evident in the dorsal view of the reconstructed cord.

ANATOMY OF THE SPINAL CORD



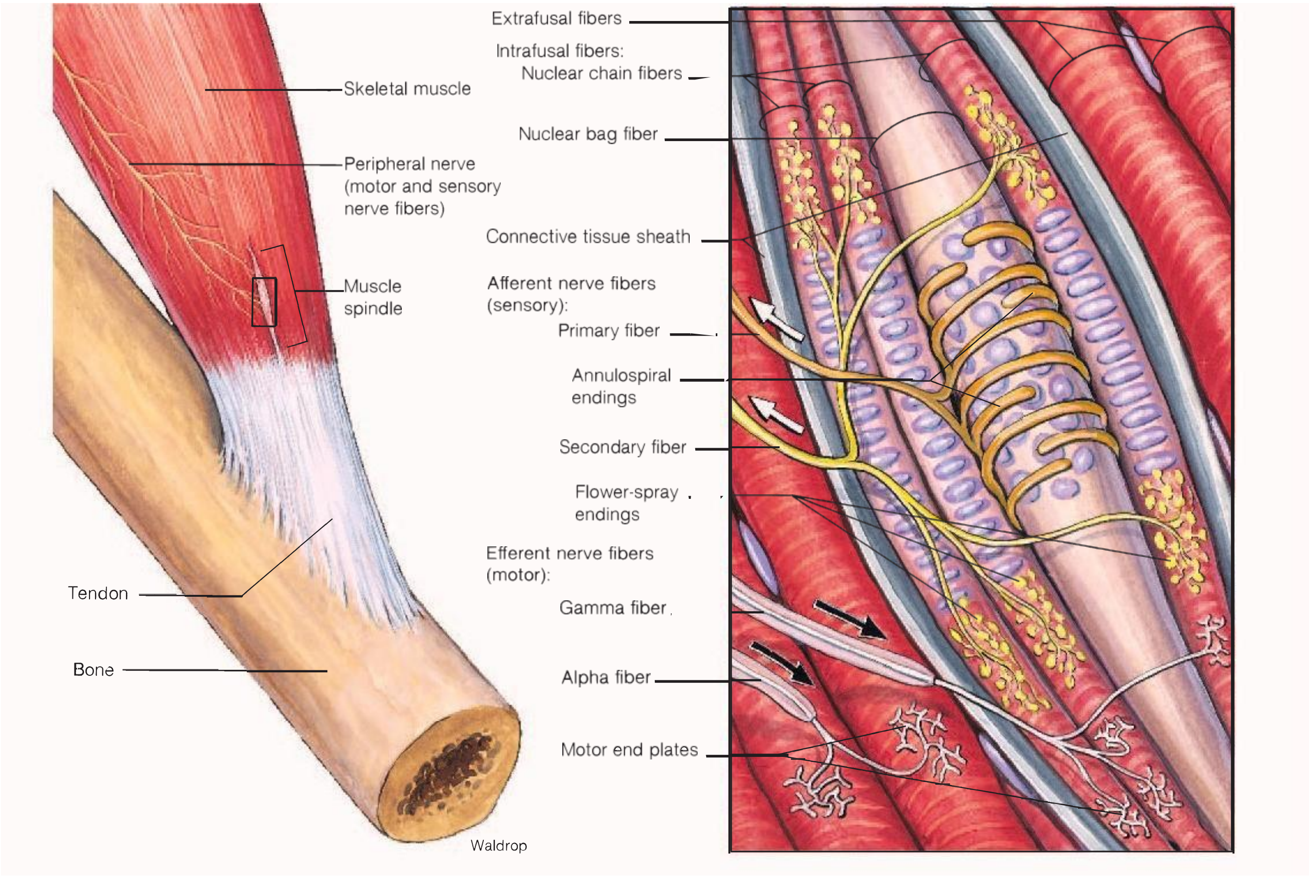


Section of the spinal cord, ventral view. The arrows indicate the direction of transmission of neural activity.

MUSCLE SPINDLE APPARATUS

- In order for the nervous system to control skeletal movements properly, it must receive continuous sensory feedback information concerning the effects of its actions. This sensory information includes (1) the tension that the muscle exerts on its tendons, provided by the **Golgi tendon organs,** and (2) muscle length, provided by the **muscle spindle apparatus.**
- The **spindle apparatus**, so called because it is wider in the center and tapers toward the ends, functions as a length detector. Muscles that require the finest degree of control, such as the muscles of the hand, have the highest density of spindles.
- Each **spindle apparatus** contains several thin muscle cells, called ***intrafusal*** *fibers*, packaged within a connective tissue sheath. Like the stronger and more numerous "ordinary" muscle fibers outside the spindles—the ***extrafusal*** *fibers*—the spindles insert into tendons on each end of the muscle. Spindles are therefore said to be in parallel with the extrafusal fibers.
- Unlike the extrafusal fibers, which contain myofibrils along their entire length, the contractile apparatus is absent from the central regions of the intrafusal fibers. The central, noncontracting part of an intrafusal fiber contains nuclei. There are two types of intrafusal fibers. One type, the *nuclear bag fibers,* have their nuclei arranged in a loose aggregate in the central regions of the fibers. The other type of intrafusal fibers, called *nuclear chain fibers,* have their nuclei arranged in rows.
- Two types of sensory neurons serve these intrafusal fibers. **Primary,** or **annulospiral, sensory endings** wrap around the central regions of the nuclear bag and chain fibers, and **secondary,** or **flower-spray, endings** are located over the contracting poles of the nuclear chain fibers.

THE LOCATION AND STRUCTURE OF A MUSCLE SPINDLE



(a) A muscle spindle within a skeletal muscle. *(b)* The structure and innervation of a muscle spindle.

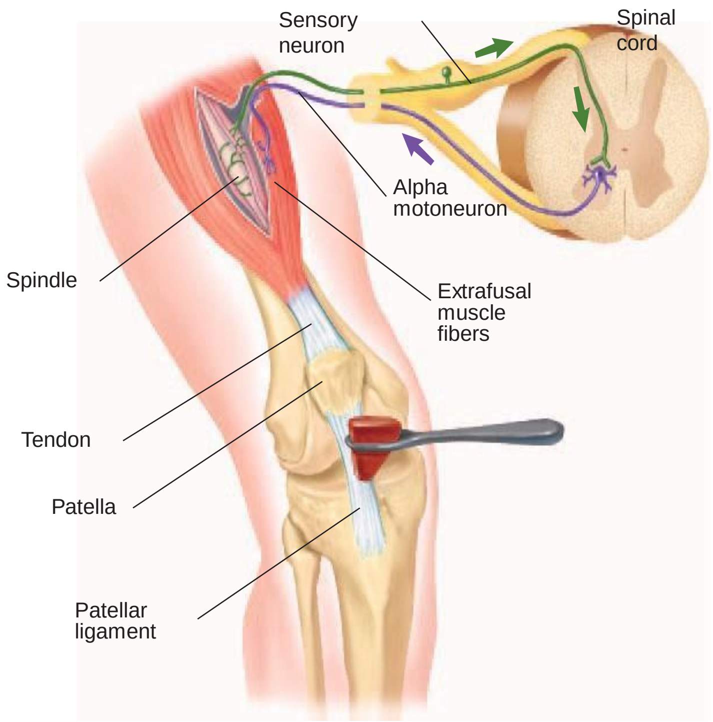
COACTIVATION OF ALPHA AND GAMMA MOTONEURONS

- Most of the fibers in the descending motor tracts synapse with interneurons in the spinal cord; only about 10% of the descending fibers synapse directly with the lower motor neurons. It is likely that very rapid movements are produced by direct synapses with the lower motor neurons, whereas most other movements are produced indirectly via synapses with spinal interneurons, which in turn stimulate the motor neurons.
- ***Upper motor neurons*** — neurons in the brain that contribute fibers to descending motor tracts—usually stimulate alpha and gamma motoneurons simultaneously. Such stimulation is known as **coactivation.**
- Stimulation of alpha motoneurons results in muscle contraction and shortening; stimulation of gamma motoneurons stimulates contraction of the intrafusal fibers, and thus "takes out the slack" that would otherwise be present in the spindles as the muscles shorten. In this way, the spindles remain under tension and provide information about the length of the muscle even while the muscle is shortening.
- Under normal conditions, the activity of gamma motoneurons is maintained at the level needed to keep the muscle spindles under proper tension while the muscles are relaxed. Undue relaxation of the muscles is prevented by stretch and activation of the spindles, which in turn elicits a reflex contraction. This mechanism produces a normal resting muscle length and state of tension, or **muscle tone.**

SKELETAL MUSCLE REFLEXES

- Although skeletal muscles are often called voluntary muscles because they are controlled by descending motor pathways that are under conscious control, they often contract in an unconscious, reflex fashion in response to particular stimuli. In the simplest type of reflex, a skeletal muscle contracts in response to the stimulus of muscle stretch.
- The **reflex arc,** which describes the nerve impulse pathway from sensory to motor endings in such reflexes, involves only a few synapses within the CNS. The simplest of all reflexes — ***the muscle stretch reflex*** — consists of only one synapse within the CNS. The sensory neuron directly synapses with the motor neuron, without involving spinal cord interneurons. The stretch reflex is thus a **monosynaptic reflex** in terms of the individual reflex arcs (although, of course, many sensory neurons are activated at the same time, leading to the activation of many motor neurons). Resting skeletal muscles are maintained at an optimal length, as previously described under the heading "Length-Tension Relationship," by **stretch reflexes**.
- The **stretch reflex** is present in all muscles, but it is most dramatic in the extensor muscles of the limbs. The **knee-jerk reflex** — the most commonly evoked stretch reflex—is initiated by striking the patellar ligament with a rubber mallet. This stretches the entire body of the muscle, and thus passively stretches the spindles within the muscle so that sensory nerves with primary (annulospiral) endings in the spindles are activated. Axons of these sensory neurons synapse within the ventral gray matter of the spinal cord with ***alpha motoneurons***. These large, fast-conducting motor nerve fibers stimulate the extrafusal fibers of the extensor muscle, resulting in isotonic contraction and the knee jerk. This is an example of negative feedback—stretching of the muscles (and spindles) stimulates shortening of the muscles (and spindles).

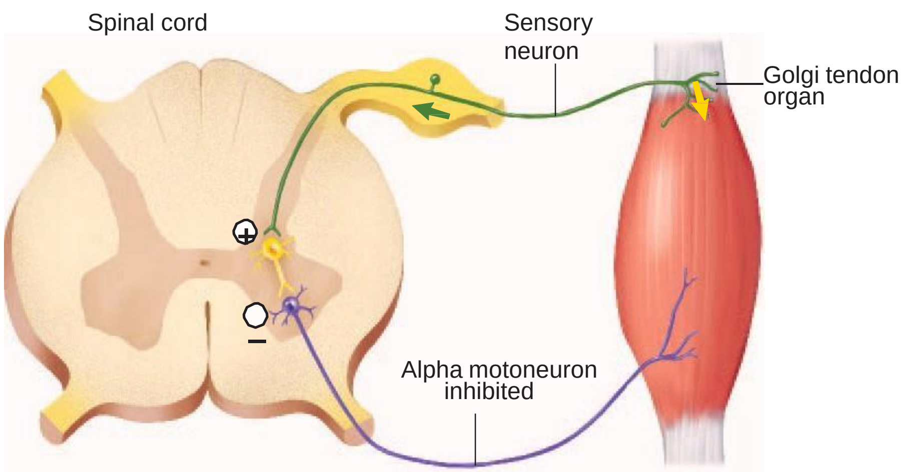
GOLGI TENDON ORGANS



The knee-jerk reflex. This is an example of a monosynaptic stretch reflex.

The Golgi tendon organs continuously monitor tension in the tendons produced by muscle contraction or passive stretching of a muscle. Sensory neurons from these receptors synapse with interneurons in the spinal cord; these interneurons, in turn, have *inhibitory synapses* (via IPSPs and postsynaptic inhibition) with motor neurons that innervate the muscle. This inhibitory Golgi tendon organ reflex is called a disynaptic reflex (because two synapses are crossed in the CNS), and it helps to prevent excessive muscle contractions or excessive passive muscle stretching. Indeed, if a muscle is stretched extensively, it will actually relax as a result of the inhibitory effects produced by the Golgi tendon organs.

THE CENTRAL INHIBITION

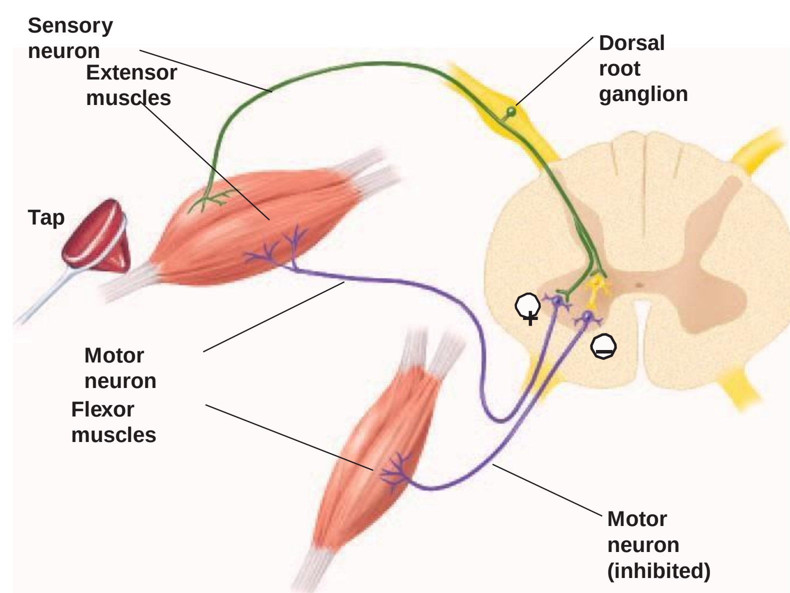


GOLGI TENDON ORGAN INHIBITION.

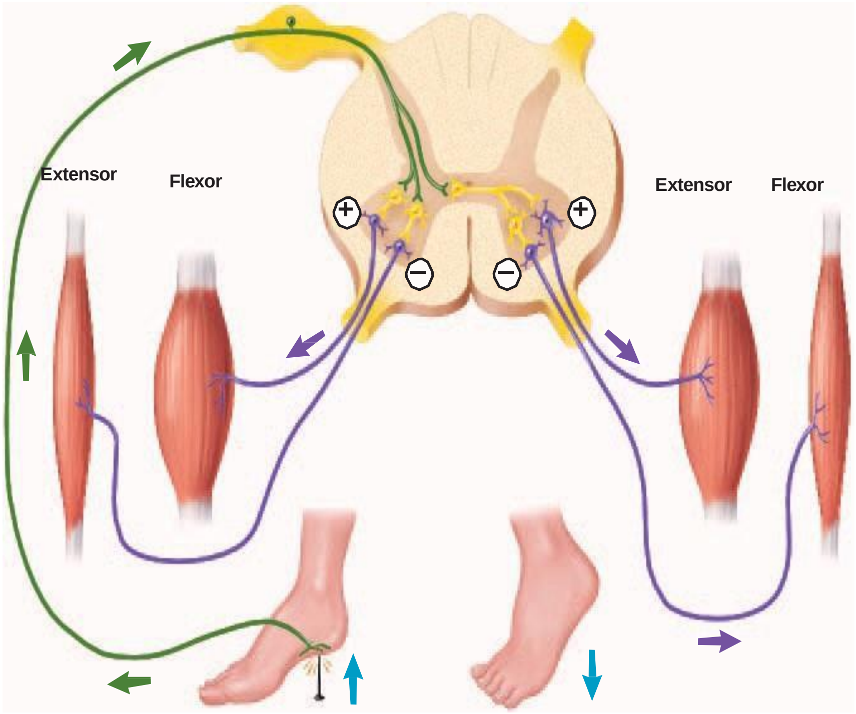
An increase in muscle tension stimulates the activity of sensory nerve endings in the Golgi tendon organ. This sensory input stimulates an interneuron, which in turn inhibits the activity of a motor neuron innervating that muscle. This is therefore a disynaptic reflex.

RECIPROCAL INHIBITION.

Afferent impulses from muscle spindles stimulates alpha motoneurons to the agonists muscle (the extensor) directly, but (via an inhibitory interneuron) they inhibit activity in the alpha motoneuron to the antagonist muscle.



THE CROSSED-EXTENSOR REFLEX



This complex reflex demonstrates double reciprocal innervation. If you step on a tack with your right foot, for example, this foot is withdrawn by contraction of the flexors and relaxation of the extensors of your right leg. The contralateral left leg, by contrast, extends to help support your body during this withdrawal reflex. The extensors of your left leg contract while its flexors relax.

SYMPTOMS OF UPPER MOTOR NEURON DAMAGE

Babinski's reflex—Extension of the great toe when the sole of the foot is stroked along the lateral border	
Spastic paralysis—High muscle tone and hyperactive stretch reflexes; flexion of arms and extension of legs	
Hemiplegia—Paralysis of upper and lower limbs on one side—commonly produced by damage to motor tracts as they pass through internal capsule (such as by cerebrovascular accident—stroke)	
Paraplegia—Paralysis of the lower limbs on both sides as a result of lower spinal cord damage	
Quadriplegia—Paralysis of upper and lower limbs on both sides as a result of damage to the upper region of the spinal cord or brain	
Chorea—Random uncontrolled contractions of different muscle groups (as in Saint Vitus' dance) as a result of damage to basal nuclei	
Resting tremor—Shaking of limbs at rest; disappears during voluntary movements; produced by damage to basal nuclei	
Intention tremor—Oscillations of the arm following voluntary reaching movements; produced by damage to cerebellum	

REVIEW QUESTIONS

1. Draw a muscle spindle surrounded by a few extrafusal fibers. Indicate the location of primary and secondary sensory endings and explain how these endings respond to muscle stretch.
2. Describe all of the events that occur from the time the patellar tendon is struck with a mallet to the time the leg kicks.
3. Explain how a Golgi tendon organ is stimulated and describe the disynaptic reflex that occurs.
4. Explain the significance of reciprocal innervation and double reciprocal innervation in muscle reflexes.
5. Describe the functions of gamma motoneurons and explain why they are stimulated at the same time as alpha motoneurons during voluntary muscle contractions.
6. Explain how a person with spinal cord damage might develop clonus.
7. Explain terms “hemiplegia”, “paraplegia”, and “quadriplegia”.