Sensory-Motor Integration in the Spinal Cord

Required Reading: These notes and PowerPoint presentation

Learning Objectives: After this lecture, students will be able to:

1. Describe the functional sets of neurons found in the spinal cord.
2. Explain the concept of lower motor neurons, interneurons, and central pattern generators and their role in motor function.
3. Explain the concept of the motor unit and describe the 3 different types of motor units in skeletal muscles.
4. Tell the 3 main inputs that help regulate lower motor neuro function.
5. Describe the structure and function of the muscle spindle.
6. Define gamma motor neurons, explain their function, describe the interrelation of alpha and gamma motor neurons and the importance of the alpha-gamma co-activation.
7. Describe the structure and function of the Golgi tendon organ.
8. Describe the components of the muscle stretch reflex and indicate its clinical significance.
9. Explain the function of the reverse myotatic reflex and explain its contribution to the regulation of muscle tension.
10. Describe reciprocal inhibition, flexor reflex and cross- extensor reflex.
11. Explain how spinal reflexes are modifiable.

Overview

The spinal cord is the main conduit through which motor information is relayed to the body. The primary neurons responsible for movement in the spinal cord and brainstem are called α-motor neurons or lower motor neurons. In this section we will learn about how these neurons innervate skeletal muscle fibers and how they are influenced by sensory inputs to modify their activity. The most recognizable examples of this sensory-motor integration are the spinal reflexes.

In clinical practice reflexes are a quick bedside assessment tool to evaluate the integrity of the sensory and motor components that participate in the reflex loop. The reflex examination can be vital to localizing the site of neurologic damage.

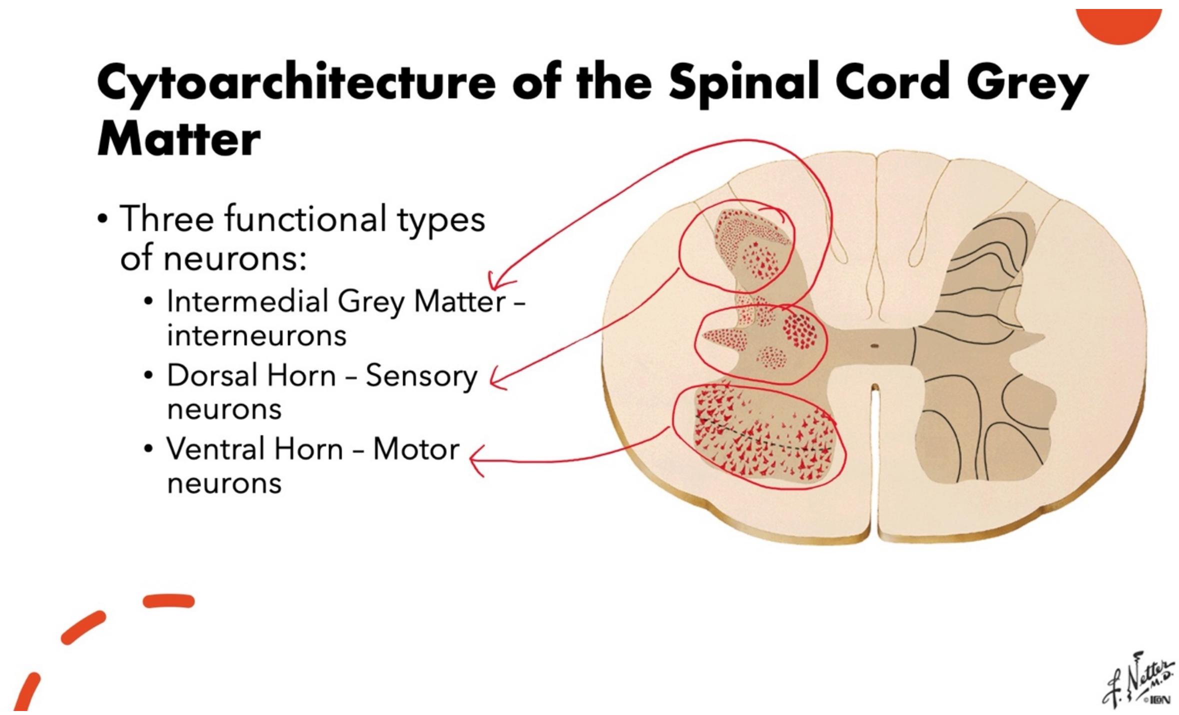
These notes, along with the PowerPoint presentation will be your main source of information for the first Medical Neurosciences section. Further information can be found in your Guyton and Hall Medical Physiology, Chapter 54: Motor functions of the spinal cord; the cord reflexes.

Presentation Notes

What is a reflex? According to the definition proposed by Charles Sherrington in 1906, reflexes are “stereotyped motor behaviors that follow a sensory stimulation”. Reflexes are modifiable and can adapt to motor task. Reflexes are coordinated in the spinal cord; the sensory stimulus that triggers a reflex starts from a receptor located in the muscles, the joints or the skin. The circuitry underlining the motor response resides entirely in the spinal cord, even if the response can be modulated by higher motor centers through the descending motor pathways.

Objective # 1; Slide 3

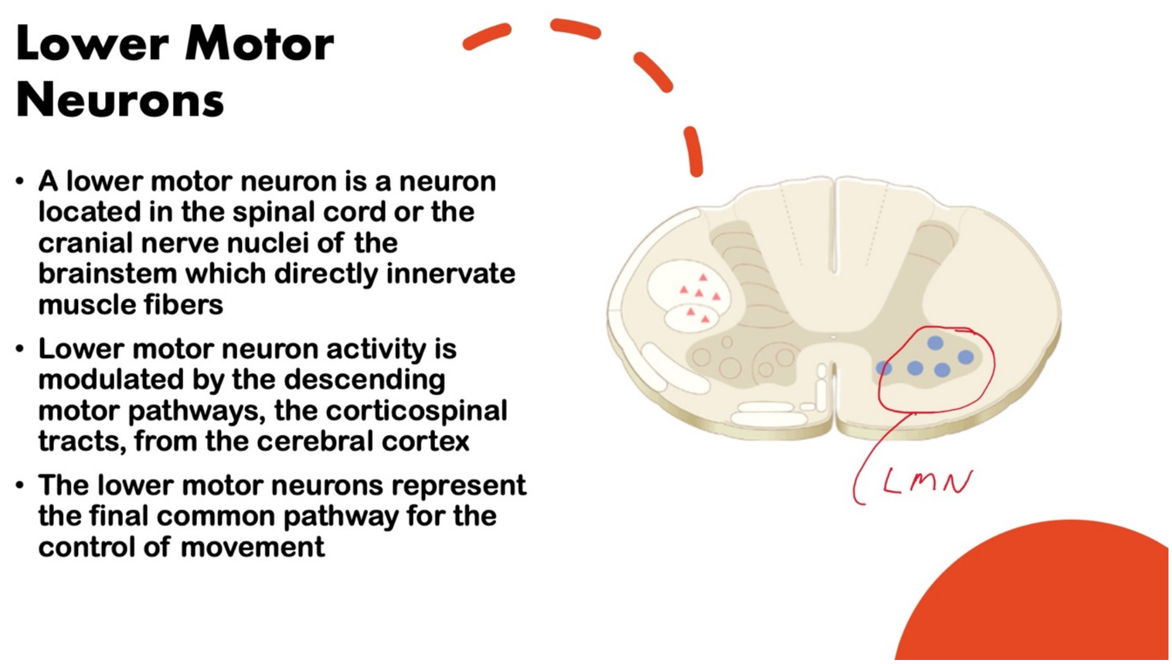
Diagram of the spinal cord showing the location of the main 3 functional neuronal groups.



There are different functional sets of neurons in the spinal cord gray matter: sensory neurons located in the dorsal horns, alpha and gamma motor neurons located in the anterior horns and interneurons mostly concentrated in the central gray matter areas known as the intermediate gray area. Of course, this is a schematic representation because in reality interneurons can be found in almost all grey matter areas.

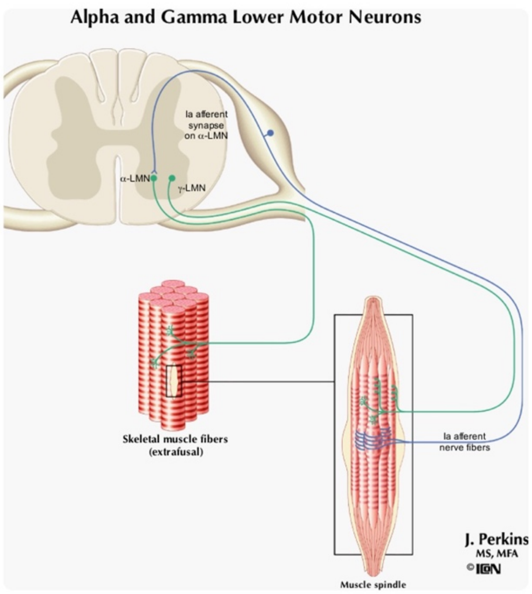
Objective # 2; Slide 4

Lower motor neurons are the neurons that directly innervate muscles fibers. They represent the final common pathway for movement. Their cell bodies are in the anterior or ventral horns and their axons exit through the ventral root to enter a spinal nerve where they travel to their final destinations.



Objective # 2; Slide 5

Lower motor neurons are of 2 types: alpha motor neurons which innervate the regular, skeletal muscle fibers and gamma motor neurons which innervate the specialized muscle fibers inside the muscle spindles. The muscle spindles are sensors of muscle stretch located inside the muscle among the skeletal muscle fibers (more about them later). They are sensory receptors, and they have an important role in modulating the activity of motor neurons.

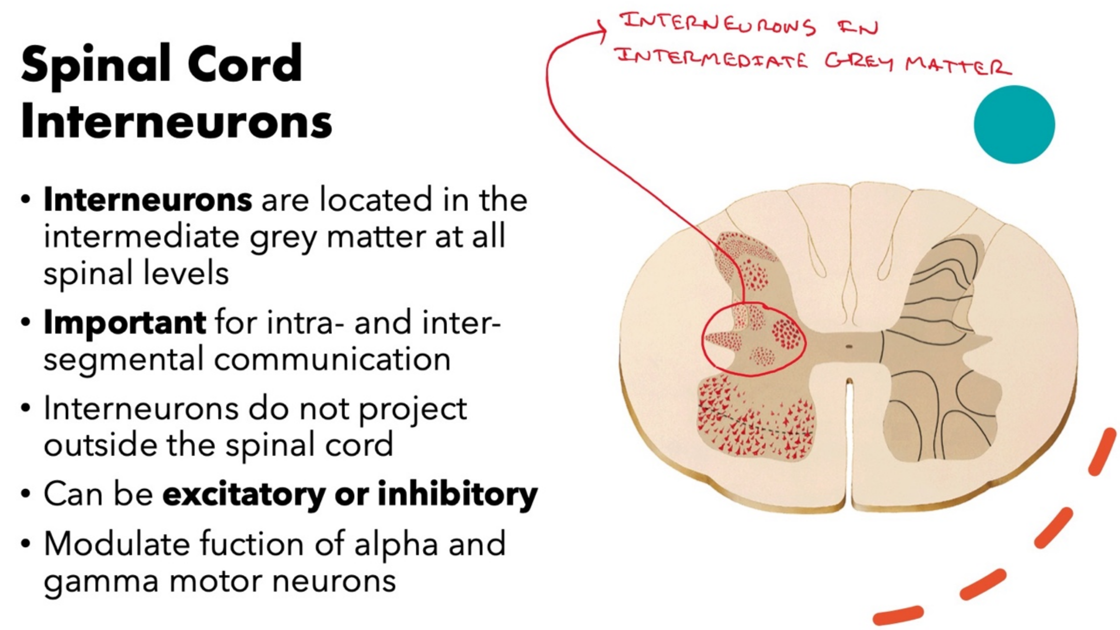


Lower Motor Neurons

- Two main types of anterior horn motor neurons:
  - **Alpha Motor Neurons** – directly innervate skeletal muscle fibers (extrafusal fibers)
  - **Gamma motor neurons** – directly innervate specialized muscle fibers in the muscle spindles

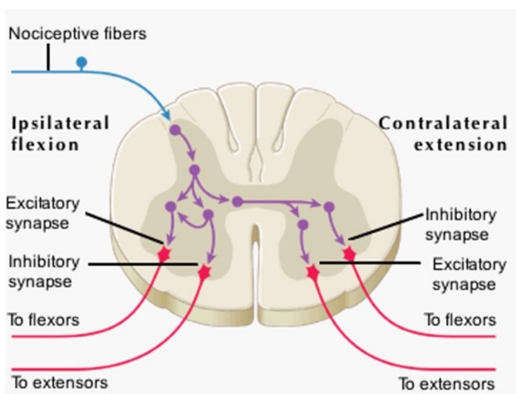
Objective # 2; Slide 6:

Interneurons are mostly but not exclusively located in the central areas of the spinal cord gray matter. They are connected with each other forming extensive networks that receive and coordinate sensory information and motor commands coming from the cortex.



Objective # 2; Slide 7

A particularly interesting group of neurons known as central pattern generators are able to generate rhythmic complex patterns of movements such as locomotion, swimming etc., without requiring sensory inputs from peripheral receptors. These spontaneous patterns can then be modified by proprioceptive and higher-level inputs according to the required task. The diagram in the slide is meant to show the complexity of the interneuron interactions in the spinal cord.



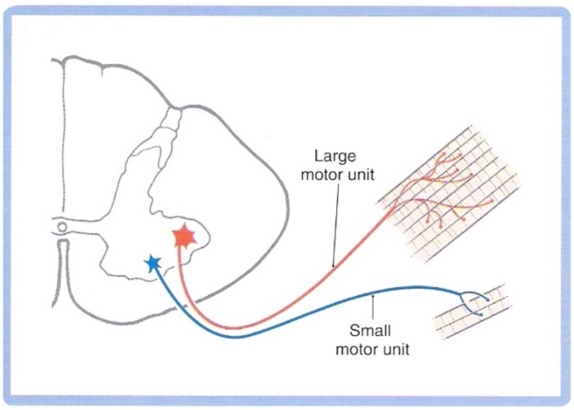
Central Pattern Generators

- The spinal cord contains a significant amount of circuitry for the coordinated control of movement and locomotion
- **Central Pattern Generators** consist of networks of **interneurons** that are able to generate complex rhythmic patterns of movement – locomotion without external sensory input or cerebral input

Objective # 3; Slide 8

The concept of motor unit: A motor unit is composed of an alpha motor neuron and all the muscle fibers innervated by its axon. Because there are much more muscle fibers than motor neurons, each motor neuron axon divides significantly in order to innervate a variable number of muscle fibers. Each muscle fiber receives innervation from only one motor neuron.

Motor Neurons and Motor Units



- A motor unit is a single alpha motor neuron and all the muscle fibers that are innervated by its terminal axon branches
- A muscle fiber only receives input from a single alpha motor neuron

Objective # 3; Slide 9

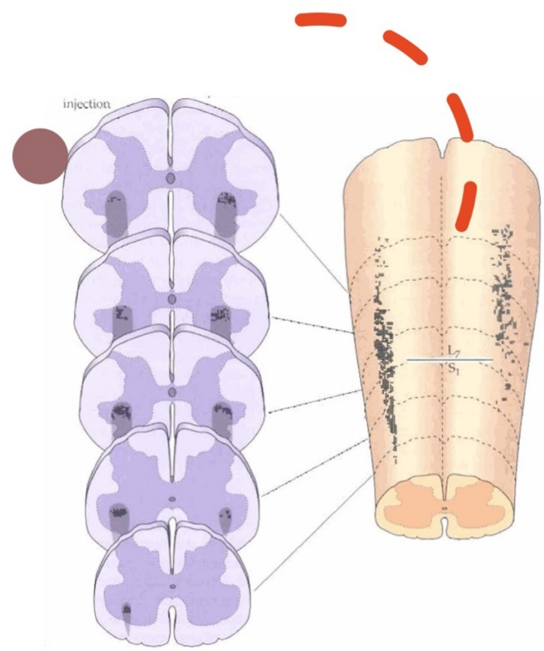
How is the organization of the motor units innervating a single muscle in the spinal cord? One individual muscle or group of muscles performing the same function receives innervation from a variable number of motor units. The motor neuron cell bodies are clustered in a motor nucleus at consecutive spinal cord or brainstem levels. These columnar nuclei in the spinal cord are called motor neuron pools. This arrangement ensures that a lesion affecting a small number of motor neurons produces a partial loss of muscle function and does not affect the entire muscle.

A motor pool is all motor neurons that innervate a single muscle. This includes alpha, gamma, and beta motor neurons. The density of the motor pool correlates with the required level of dexterity for the muscle. The forearm finger flexors for instance would have a high density of motor neurons compared to the abdominal muscles.

Another important concept is the ‘size principal.’ As a motor pool is called on by the CNS to contract a muscle, it starts with the motor neurons that innervated the fewest muscle fibers first. This allows for finer muscle control.

Motor Neuron Pool

- The collection of alpha motor neurons that innervate a single muscle or group of muscles is called a **motor neuron pool**

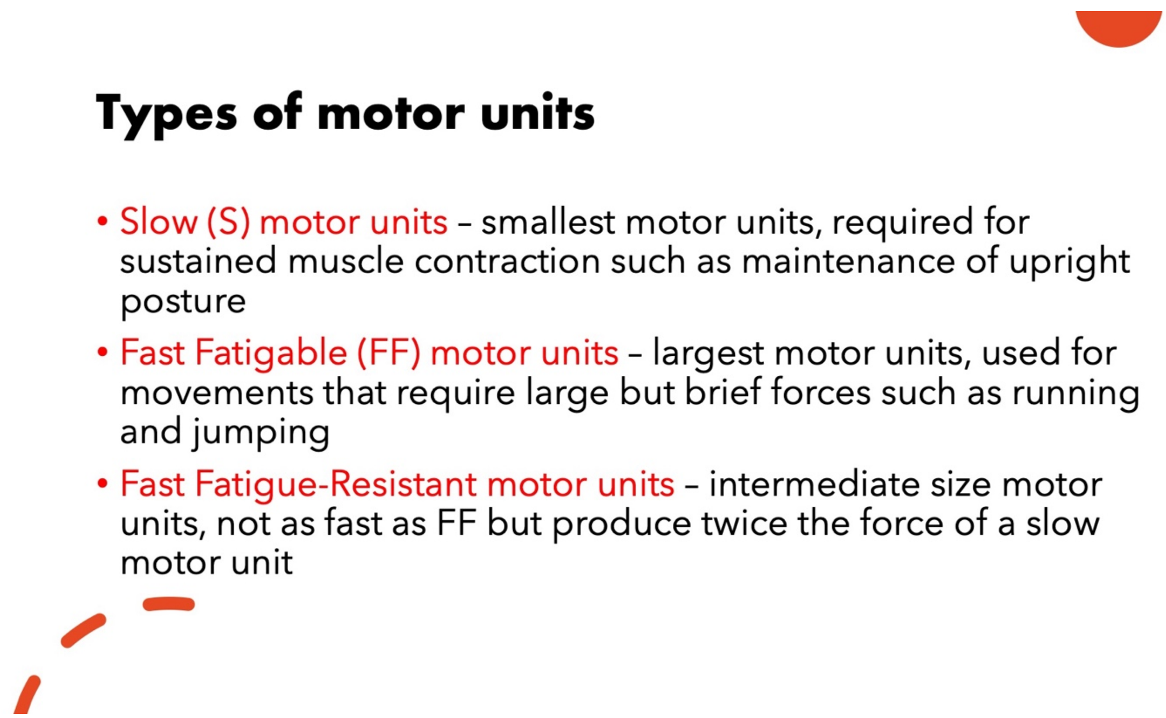


Objective # 3; Slide 10

Alpha motor neurons and motor units are not all equal in size. The smaller alpha motor neurons innervate a small number of muscle fibers and generate small forces; large alpha motor neurons innervate more muscle fibers and generate powerful forces. Motor units vary in size according to the size of the alpha motor neuron and the number of muscles fibers it innervates.

There are 3 different types of motor units:

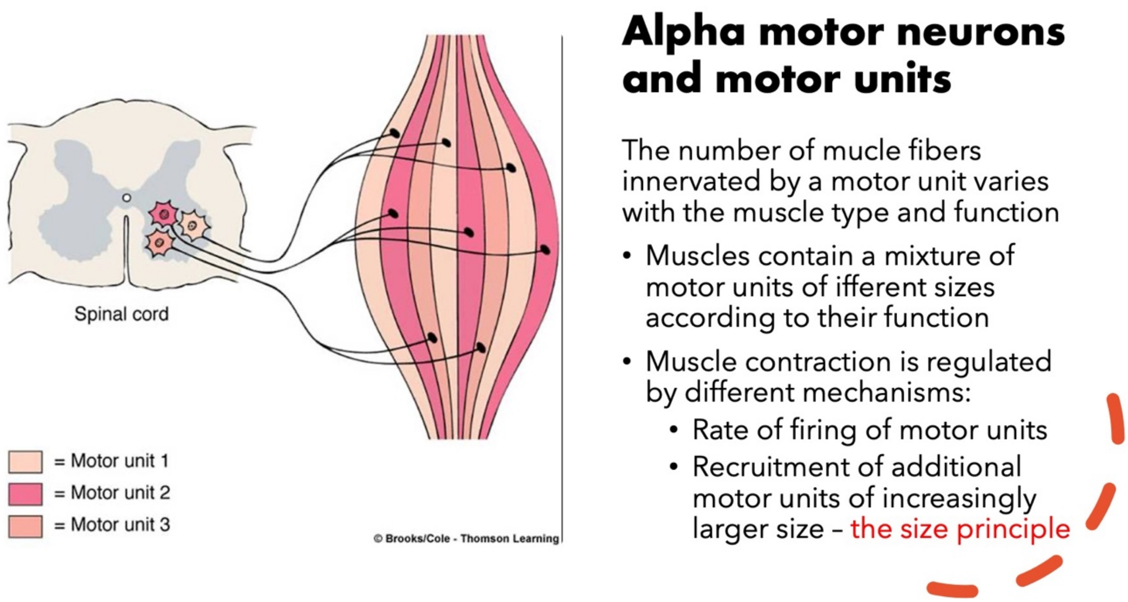
- S (slow) motor units – The smallest motor units, required for sustained muscle contraction such as maintenance of the upright position. These motor units innervate red muscle fibers. They contract slowly and generate relatively small forces, but they are resistant to fatigue due to the high content of myoglobin, numerous mitochondria and rich capillary beds.
- FF (fast fatigable) motor units – The largest motor units, used for movements that require large but brief forces such as running and jumping. They innervate white muscle fibers which generate large forces but fatigue easily because they have less mitochondria.
- FR (fast fatigue-resistant) motor units – Intermediate size motor units, they are not as fast as FF motor units but produce twice the force of a slow motor unit and are resistant to fatigue. They innervate fibers that have properties of both red and white muscle fibers.



Objective # 3; Slide 11

All muscles contain the 3 types of motor units in proportions that depend entirely on the function of the muscle in question. As an example a muscle important for posture such as the soleus contains mostly small motor units, with an average of 180 muscles fibers per motor neuron. On the other side of the spectrum, muscles that require the production of large amounts of force for sudden changes in body position, such as the gastrocnemius contains mostly large motor units. The average of muscle fibers innervated by one alpha motor neuron in these types of muscles is 1000 – 2000.

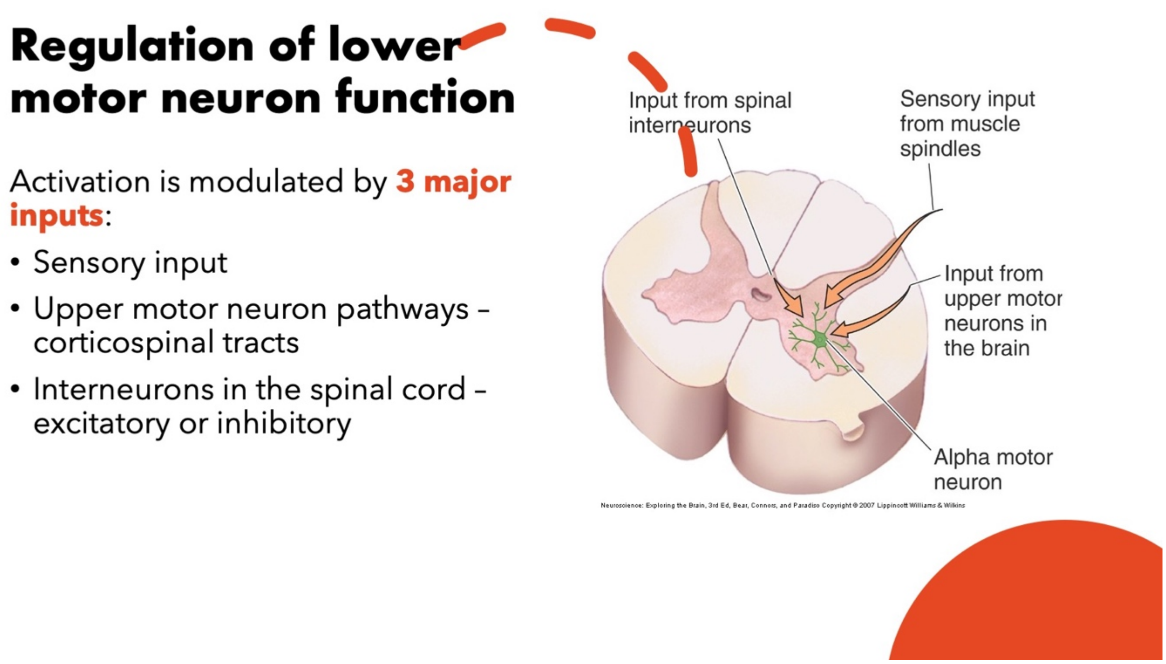
When increased force is needed to perform a task, it can be provided by either increasing the firing of the motor neurons or by recruiting larger motor units. This is known as the size principle.



Objective # 4; Slide 12

Lower motor neuron activation is influenced by three major inputs:

- Somatosensory fibers transmitting proprioceptive information from muscles and joints
- Cortical neurons called UPPER MOTOR NEURONS projecting directly to the lower motor neurons (LMN.) Groups of axons coming from upper levels and terminating in the spinal cord are the corticospinal tracts. Only a few corticospinal fibers are able to directly innervate a LMN. Most of them terminate on interneurons which in turn project to LMNs.
- Excitatory or inhibitory projections from interneuronal networks are the same spinal or other cord levels.

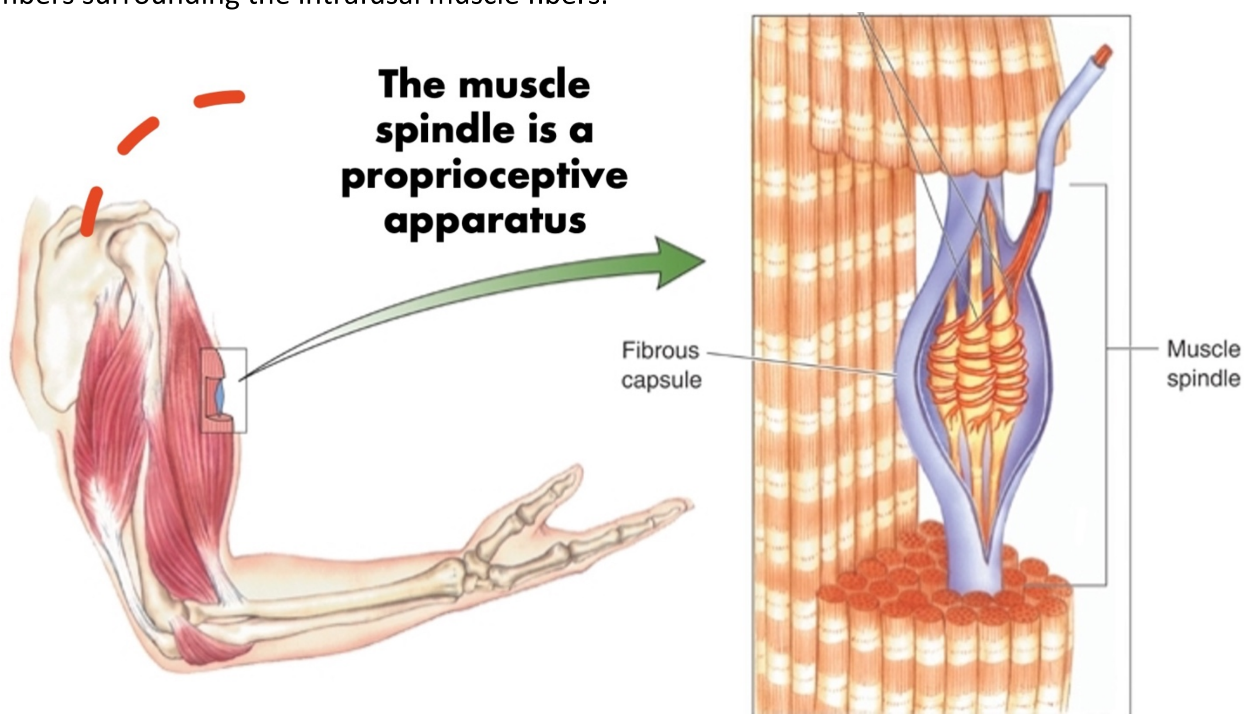


Objective # 5; Slide 13

Sensory information about the state of muscles and joints is what we call proprioception, the sense of where our bodies are in space. Proprioceptive information from muscles and joints is one of the main inputs to the LMNs that make reflexes possible.

Proprioceptive information is transmitted to the spinal cord or the brainstem from specialized encapsulated receptors located in the muscles and tendons named *muscle spindles* and *Golgi tendon organs* respectively. The muscle spindle is an encapsulated proprioceptive receptor embedded within the belly of the muscle. These structures are intermingled with the skeletal or extrafusal muscle fibers. The structure of the spindles consists of 3 to 12 intrafusal fibers which are in parallel with the regular skeletal fibers of the muscle. The poles of these intrafusal fibers are contractile and activated by motor axons of the gamma motor neurons.

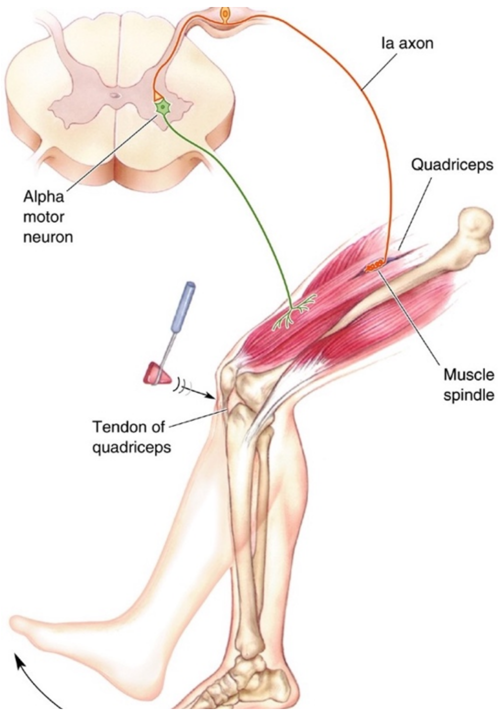
Large-diameter Ia sensory afferents, with cell bodies in the dorsal root ganglion of the appropriate spinal cord segment, wrap around the central part of the intrafusal fibers. Stretch of the intrafusal fibers, which occurs any time the entire muscle stretches, produces activation of the sensory afferents. These proprioceptive Ia fibers transmit information about muscle stretch to the spinal cord. There are also a variable number of type II smaller diameter sensory fibers surrounding the intrafusal muscle fibers.



Objective # 5; Slide 14

The function of the muscle spindles is to inform the CNS about muscle length and rate of change in length of a muscle. When a muscle stretches, the specialized muscle fibers inside the muscle spindle stretch together with the regular skeletal muscle fibers. This change of length information is sent to the spinal cord by the Ia large diameter sensory axon. Once there, the sensory axon divides into multiple terminals to contact different targets. Among these targets are the alpha and gamma motor neurons in the ventral horns. When alpha motor neurons learn that a muscle has been stretched, they will send signals to contract the muscle back to its original length. The appropriate length and tone of a muscle are properties set up by the cortex and cerebellum through the descending motor pathways that help regulate postural tone.

The gamma motor neurons are small motor neurons in the ventral horns of the spinal cord that contact the poles of the muscle spindles and help regulate their function.



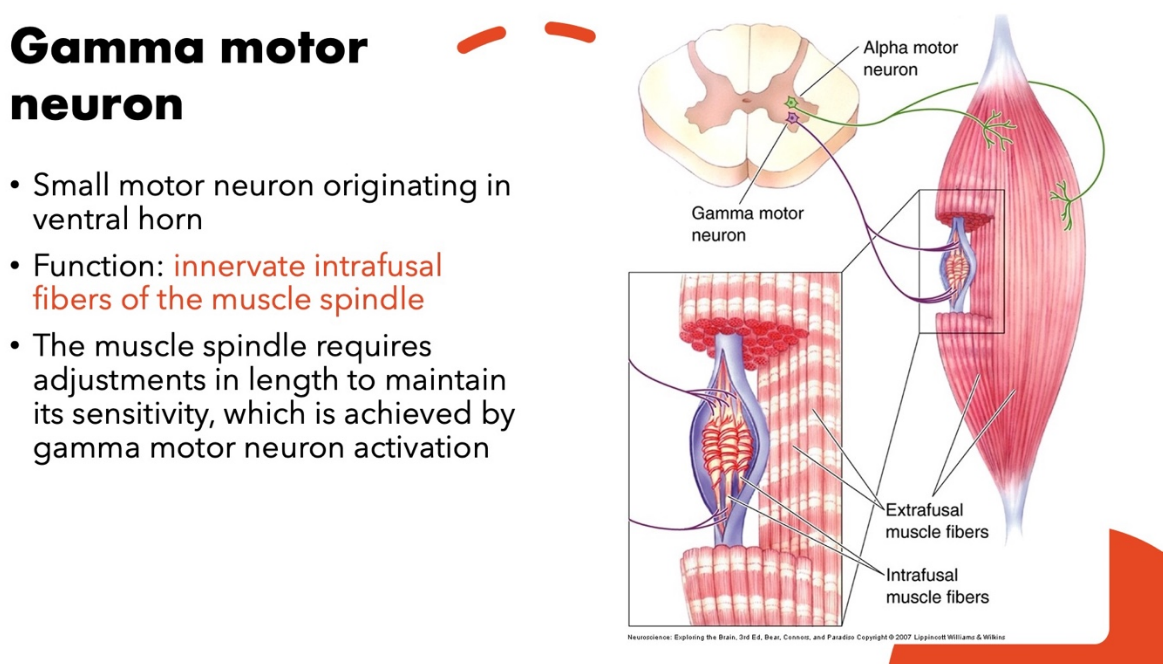
Muscle spindle function

- Informs the CNS about **muscle length and rate of change in length**
- Information transmitted along **1a sensory** axons to the dorsal horn – axon branches make synapses with multiple targets
- These fibers regulate the activity of alpha and gamma motor neurons

Objective # 6; Slide 15

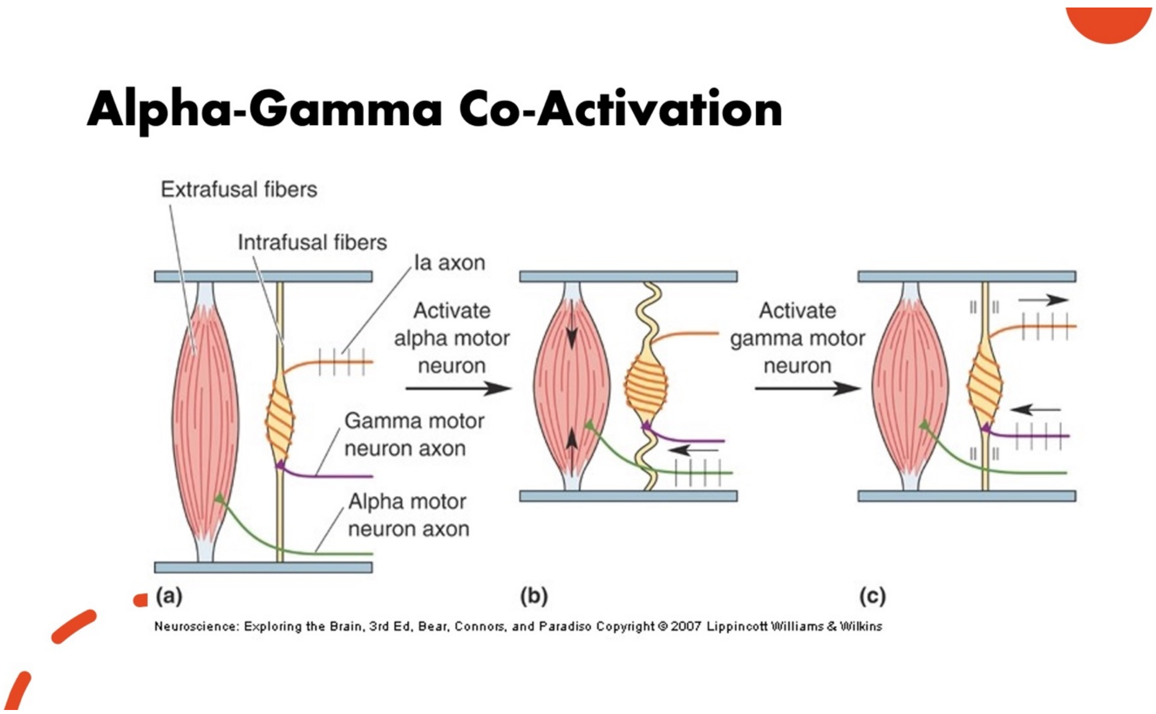
Axons of gamma motor neurons innervate intrafusal fibers at the spindle's poles. Ia sensory fibers bringing information to the spinal cord about muscle stretch terminate simultaneously on both alpha and gamma motor neurons. Activation of alpha motor neurons produces the contraction of the regular, skeletal muscle fibers, while activation of the gamma motor neurons produces the contraction of the intrafusal fibers. This is referred to as the alpha-gamma co-activation. The contraction of the intrafusal fibers shortens the spindle and increases its sensitivity to sense a new stretch of the muscle and send the appropriate information to the spinal cord. The gamma motor neuron/intrafusal muscle fiber system is specialized to set the "gain" of the muscle spindle. Some alpha motor neurons also send axons to intrafusal muscle fibers. These axons are called beta axons and their function is similar to the gamma motor neurons. Beta axons are the only mechanism to contract intrafusal fibers in lower vertebrates and we don't know its real relevance in humans.

Because muscle spindles sense both the state of a muscle's stretch and the *rate* of stretch, they need to be 'tuned' or modulated for maximal sensitivity for a given length of muscle. This is mediated by gamma motor neuron activation.



Objective # 6; Slide 16

Activation of the muscle spindle by muscle stretch is referred to as “loading spindle” (a) in the diagram. If the alpha motor neurons would contract without co-activation of the gamma motor neurons (b) the spindle will remain “unloaded” and thus unable to signal a new stretch of the muscle. Co-activation of alpha and gamma motor neurons prevents that event (c). The gamma motor neurons adjust the sensitivity of the muscle spindle being useful in many voluntary movements.

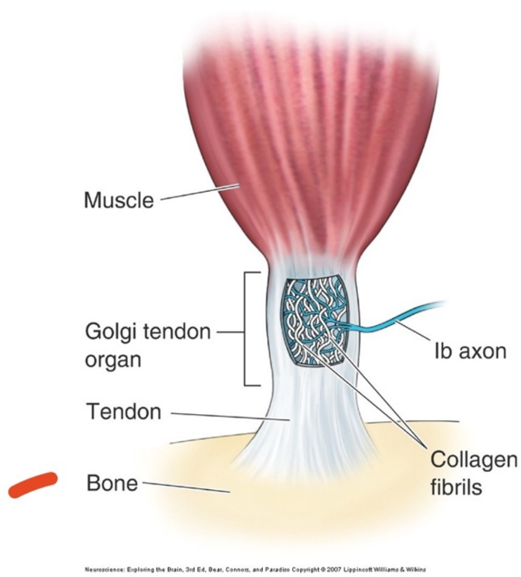


Objective # 7; Slide 17

The golgi tendon organ is an encapsulated receptor located at the junction of the muscle fibers and the tendon. Each receptor consists of a group of collagen fibers connected in series to 10 to 15 muscle fibers. Each tendon organ is innervated by a single axon of the type Ib with the cell body located in a DRG at the appropriate level. The axon branches extensively intermingle with the collagen fibers in the receptor. Stretching the tendon stimulates the sensory fibers, so contraction of the muscle fibers attached to the tendon is a potent stimulus. The function of this proprioceptive receptor is to detect the degree of tension in each small segment of a muscle.

The general concept has always been that the Golgi tendon organ has a protective function to prevent damage to muscles by inhibiting the motor neurons innervating them. But we know now that they signal minute changes in muscle tension providing precise information about the state of a muscle’s contraction. This information would be particularly important to allow for precise spinal control of muscle force in activities such as grasping delicate objects.

*1a fibers -> muscle spindle
*1b fibers -> golgi tendon organ



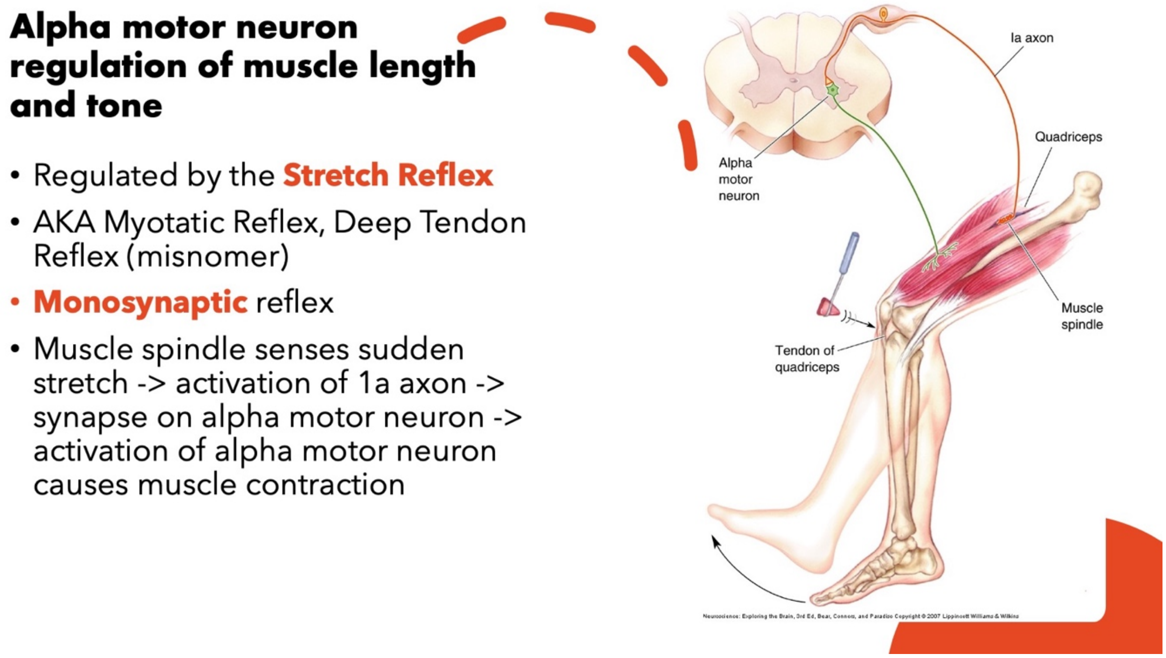
Golgi Tendon Organ

- Another proprioceptive apparatus
- Informs the CNS about **muscle tension and rate of change of tension**
- Transmitted to the dorsal horn of the spinal cord via **1b axons**

Objective # 8; Slide 18

Reflexes in the spinal cord are integrated through sensory-motor interactions. The simplest of all these reflexes is the deep tendon reflex also called stretch reflex or myotatic reflex. The sensory receptor that participates in this reflex is the muscle spindle. Each time a muscle is stretched, actively triggered by our movements or passively trigged by a reflex hammer, information about the length of the muscle is sent to the spinal cord where it directly activates the alpha motor neurons innervating the particular muscle skeletal muscle fibers or extrafusal fibers. Activation of the alpha motor neurons contracts the muscle returning it to its original length and tone. Remember that gamma motor neurons will be simultaneously activated returning the spindle to the original size.

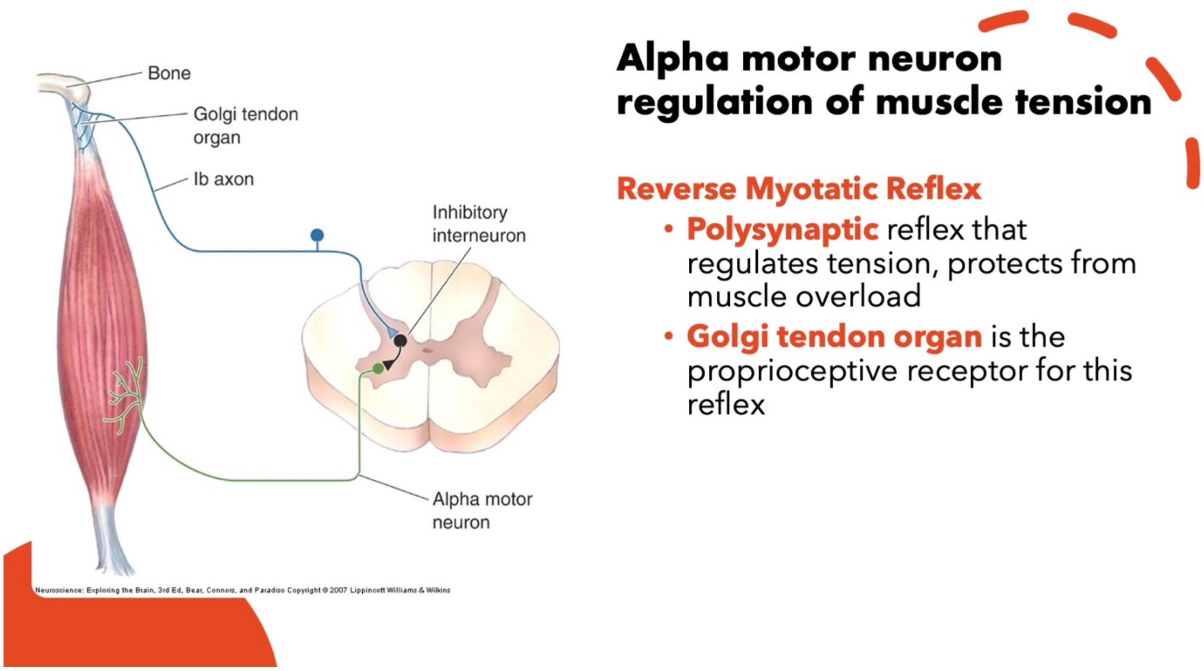
Appropriate muscle length and tone are determined by the cerebral cortex and the brainstem thorough the input of the corticospinal and other descending pathways on lower motor neurons and interneurons. Clinically, we test this reflex when we tap a muscle tendon with the reflex hammer producing passive stretch. However, we are actively stretching our muscles any time we move, so the reflex is working at all times.



Objective # 9; Slide 19

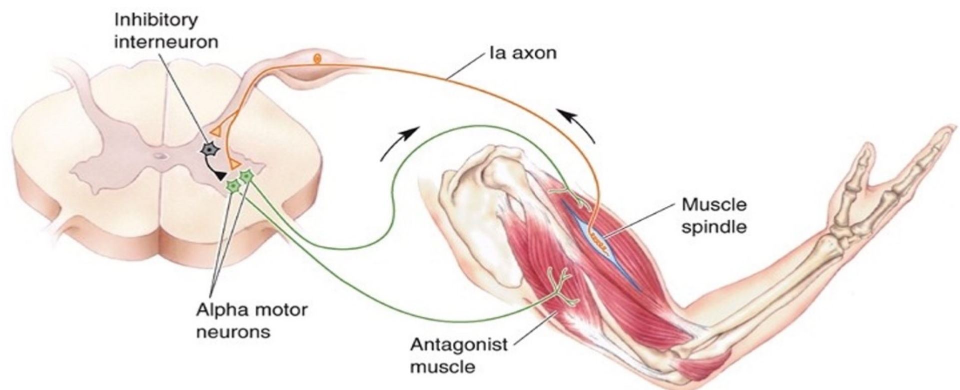
The reverse myotatic reflex is mediated by the Golgi tendon organ. Also called the golgi tendon reflex. Ib proprioceptive sensory afferents, with cell bodies located in the DRGs of appropriate spinal segmental levels, innervate the tendon receptor and transmit information about muscle tension to the spinal cord. This is a polysynaptic reflex where the Ib primary afferent fiber contacts an inhibitory interneuron of the intermediate gray matter which in turn inhibits the activity of the lower motor neurons innervating the involved muscle.

The actions of the Golgi tendon organs when we perform complex movements coordinated by upper pathways is complex due to the fact that the inhibitory interneuron in the spinal cord receives multiple inputs from other sources such as muscle spindles, cutaneous receptors, joints, and excitatory and inhibitory inputs from various descending pathways.



Objective # 10; Slide 20

Reciprocal inhibition occurs any time a movement is performed. As a group of muscles contract to favor a movement (agonist muscles), the antagonist group relaxes. This is coordinated by the many inhibitory interneurons in the intermediate gray matter of the spinal cord. These interneurons receive information from Ia (proprioceptive) fibers about movement and then inhibit the alpha motor neurons that control the antagonist muscles. These interneurons are also under control of the descending cortical neurons for voluntary movement. However, this arrangement does not work in all voluntary movements because sometimes contraction of agonist and antagonists simultaneously is advantageous for stabilizing a joint if we need to perform very precise movements. To do this, inhibitory interneurons receive both excitatory and inhibitory inputs from cortical and brainstem pathways.

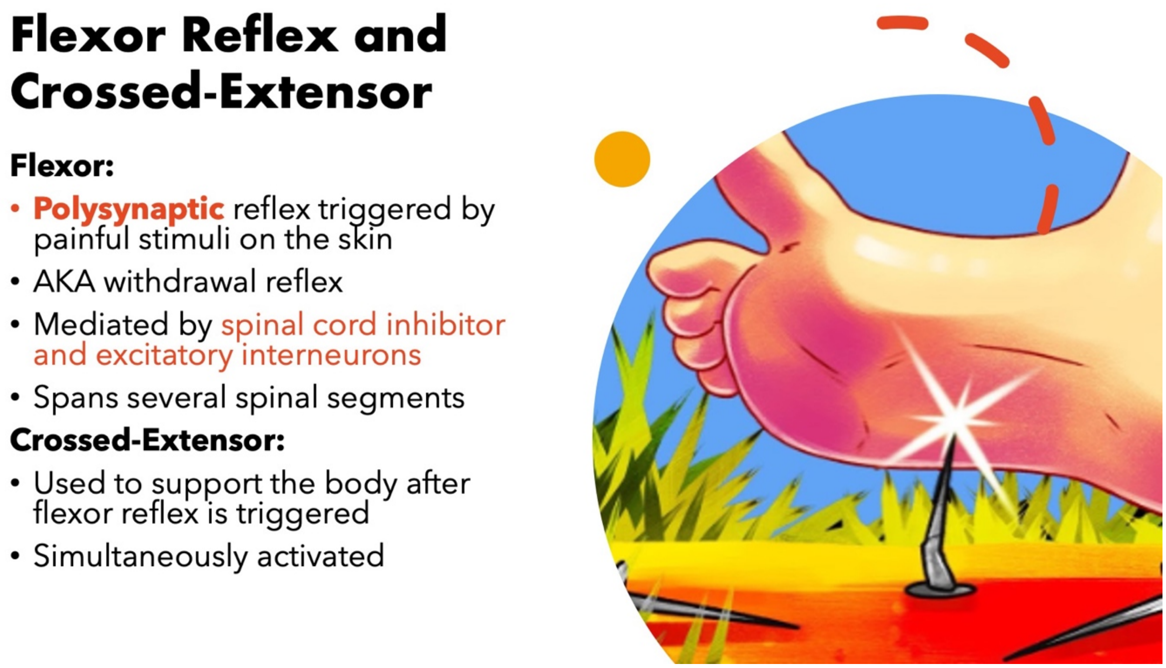


Reciprocal inhibition and interneurons

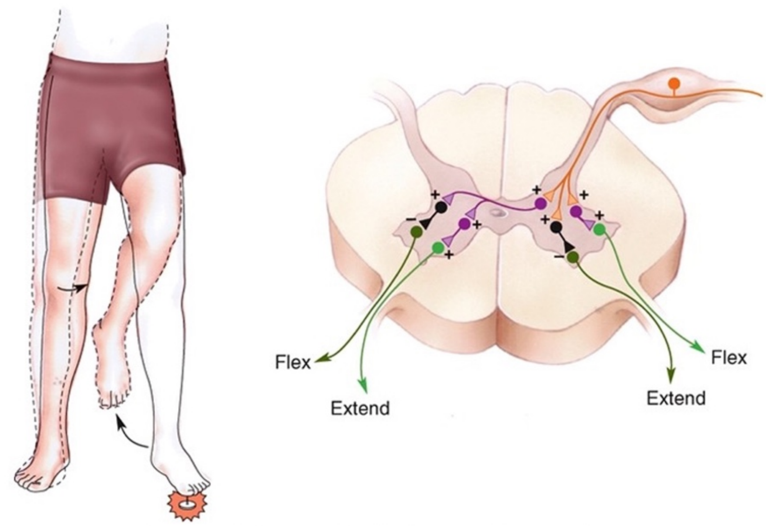
- Any movement will require contraction of one set of muscles (agonist) and relaxation of another set (antagonist.)
- This is called reciprocal inhibition and is coordinated inhibitory interneurons

Objective # 10; Slides 21 – 23

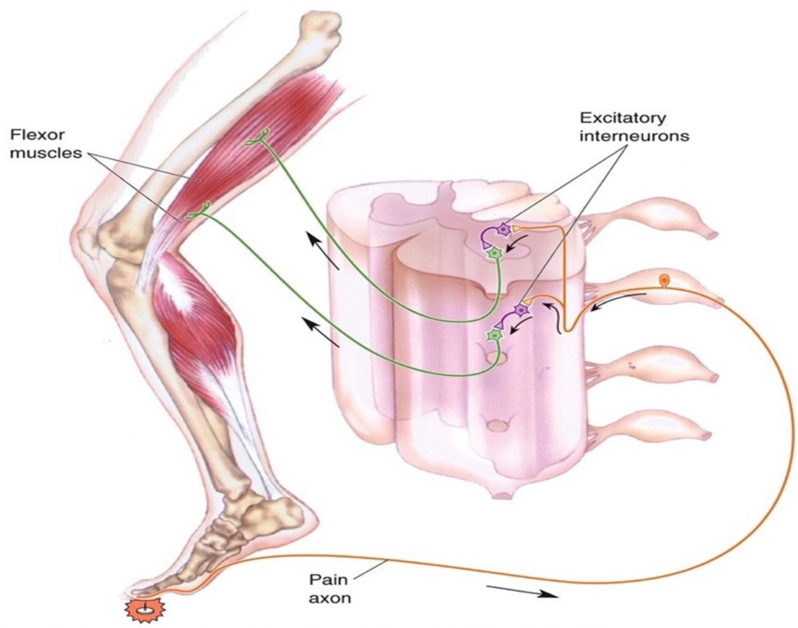
The flexor reflex or withdrawal reflex is mediated by skin nociceptors. It is integrated by interneurons at various spinal cord levels. Its function is to remove, by flexion, a limb that has encountered a noxious stimulus. It implies activation of flexor muscles and inhibition of extensor muscles on the affected limb, for example a leg. At the same time a crossed-extensor reflex will provide postural support for the body as one leg is flexed. The contralateral limb will exhibit the opposite response: activation of extensor muscles and inhibition of flexors. This demands a tremendous amount of coordination between many spinal segments and at both sides of the spinal cord. This coordination is provided by the action of interneurons as can be seeing in the pictures.



Crossed-Extensor Reflex Arc



Flexor Reflex Arc



Objective # 11; Slide 24

As a summary let's remember that movement is generated at spinal cord levels using the basic reflexes we have studied. All these spinal reflexes are constantly modified by hierarchically higher centers through the descending motor pathways. The descending motor pathways provide the lower motor neurons with modulatory input through inhibitory and excitatory interneurons in the intermediate gray matter of the spinal cord.