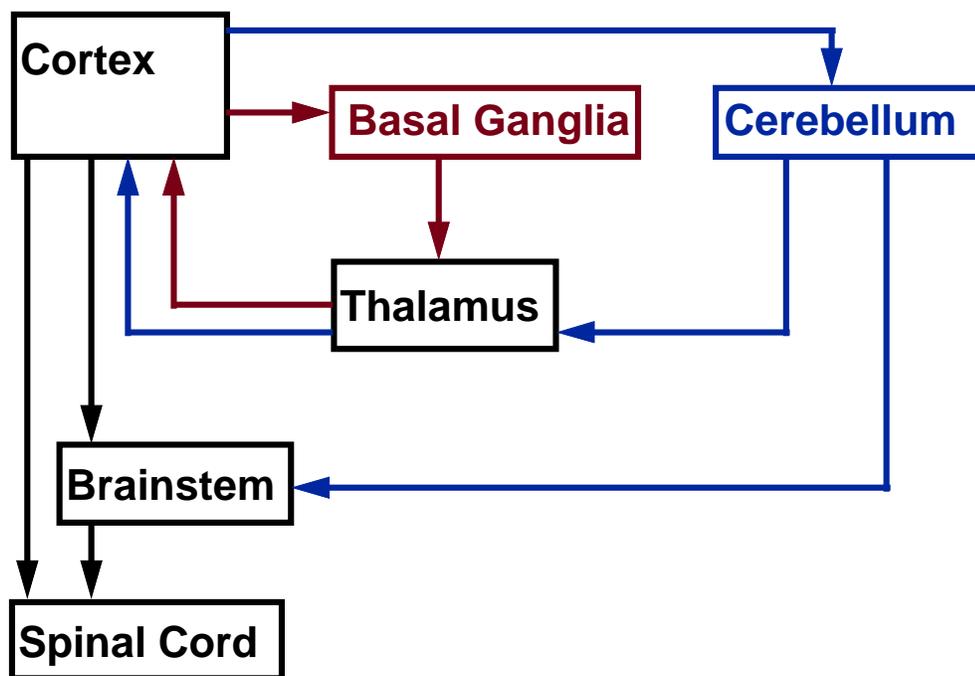


Motor Systems I - Muscles & Spinal Cord

Introduction

Normal motor function requires the coordination of multiple inter-related areas of the CNS. Understanding the contributions of these areas to generating movements and the disturbances that arise from their pathology are important challenges for the clinician and the scientist. Despite the importance of diseases that cause disorders of movement, the precise function of many of these areas is not completely clear. The main constituents of the motor system are the **cortex, basal ganglia, cerebellum, brainstem, and spinal cord.**



In very broad terms, cortical motor areas initiate voluntary movements. The cortex projects to the spinal cord directly, through the corticospinal tract - also known as the pyramidal tract, or indirectly through relay areas in the brain stem. The cortical output is modified by two parallel but separate re-entrant side loops. One loop involves the basal ganglia while the other loop involves the cerebellum. The final outputs for the entire system are the alpha motor neurons of the spinal cord, also called the **Lower Motor Neurons.**

Cortex: Planning and initiation of voluntary movements and integration of inputs from other brain areas.

Basal Ganglia: Enforcement of desired movements and suppression of undesired movements.

Cerebellum: Timing and precision of fine movements, adjusting ongoing movements, motor learning of skilled tasks

Brain Stem: Control of balance and posture, coordination of head, neck and eye movements, motor outflow of cranial nerves

Spinal Cord: Spontaneous reflexes, rhythmic movements, motor outflow to body.

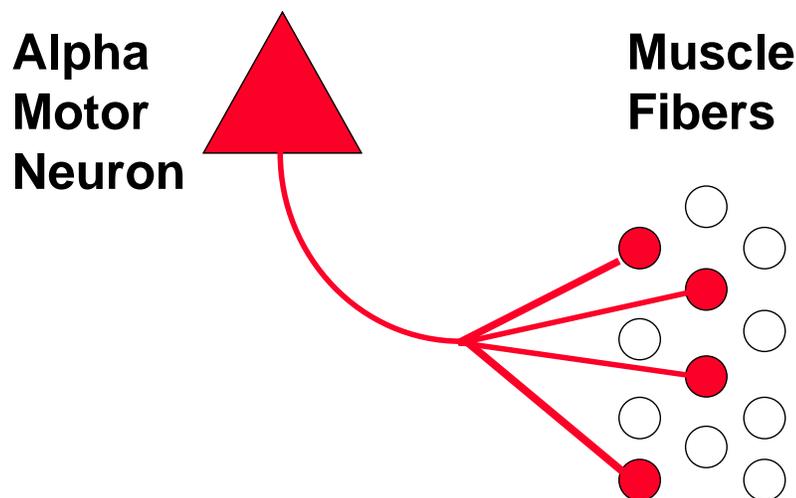
Muscles: Movement of body, sensory organs - muscle spindle and Golgi tendon organs.

I. Muscle Anatomy and Physiology

Motor Units

We will begin our discussion from the bottom up starting with the physiology of the muscles and the spinal cord. An important concept to grasp is that of the **motor unit**. The following points should be kept in mind.

- A whole muscle is made up of many muscle fibers
- A muscle fiber is a single multinucleated cell
- Each muscle fiber is innervated by only one alpha motor neuron
- Each alpha motor neuron innervates numerous muscle fibers within a muscle
- A single neuron and all the muscle fibers it innervates are a **motor unit**
- The motor unit is the smallest division that the system can control individually



The innervation ratio or the number of muscle fibers per neuron varies from 10 to 2000 depending on the muscle. Muscles that require precise fractionated control, such as eye muscles, have a low ratio while muscle involved in coarse movements, such the quadriceps of the leg, have a high ratio.

Types of motor units

There are two main types of motor units - slow and fast. A given motor unit including its muscle fibers is of only one type. Whole muscles are made up of a combination of slow and fast twitch fibers which are randomly interdigitated although different muscles have different ratios of the two muscle types. Motor units are differentiated on basis of several parameters including, histochemical staining, biochemical profile, and physiologic properties.

Slow twitch - Type I fibers are grossly darker than fast twitch fibers. They rely on aerobic metabolism and therefore tend to have more of the oxygen-storing pigment myoglobin and more mitochondria. Slow twitch fibers contract more slowly and generate less force. They are, however, resistant to fatigue. Postural muscles such as those of the back or the soleus muscle of the leg are predominantly made up of slow twitch fibers.

Fast twitch - Type II fibers are grossly paler than slow twitch fibers. They rely primarily on anaerobic metabolism and have a correspondingly higher concentration of glycolytic enzymes. Fast twitch fibers contract more quickly and with greater force than slow twitch fibers but they also fatigue much more quickly than slow twitch fibers. Muscles that have predominantly fast twitch fibers are used when rapid powerful movements are required. Weight training and the use of androgenic steroids causes hypertrophy of the fast twitch fibers.

Fast fatigue-resistant fibers have properties that are intermediate between the other two types.

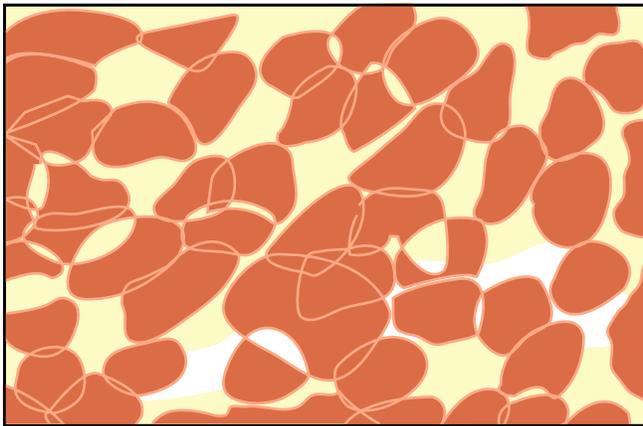


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[Various time intervals for slow, fast fatigue-resistant, and fast fatigable muscle fibers]

The type of the muscle fiber is determined by its innervation. Fibers that have been de-innervated and then re-innervated will take on the type of the nerve that has reinnervated them. This fact is important in the diagnosis of neuromuscular diseases as will be explained further on.

Recruitment

Recruitment of muscle fibers proceeds in an orderly fashion. Smaller neurons are recruited first, then larger neurons. Smaller neurons are connected to the slow fatigue resistant fibers and hence slow fibers are activated first. The fast-fatigue resistant fibers are recruited next and finally the fast fibers are recruited. This arrangement makes sense for several reasons: 1) Simplified modulation by higher centers since only the overall level of synaptic drive needs to be determined and not specific combinations of muscle fibers 2) proportionately constant increase in force with increased synaptic drive 3) fast twitch fibers are used infrequently and have appropriately low metabolic demands at rest.

In addition to orderly recruitment the motor system can increase force by increasing the rate of firing of the alpha motor neurons. Increases in force occur because successive twitches can summate.

Muscle Receptors

There are two types of receptors in muscles, the **muscle spindle** and the **Golgi tendon organ**. The muscle spindles primarily signal the **length** or **stretch** of the muscle while the tendon organs primarily signal the **tension**.

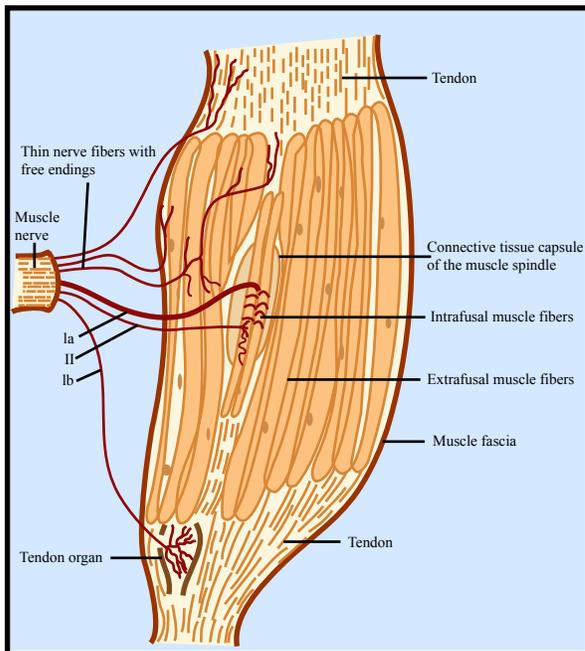


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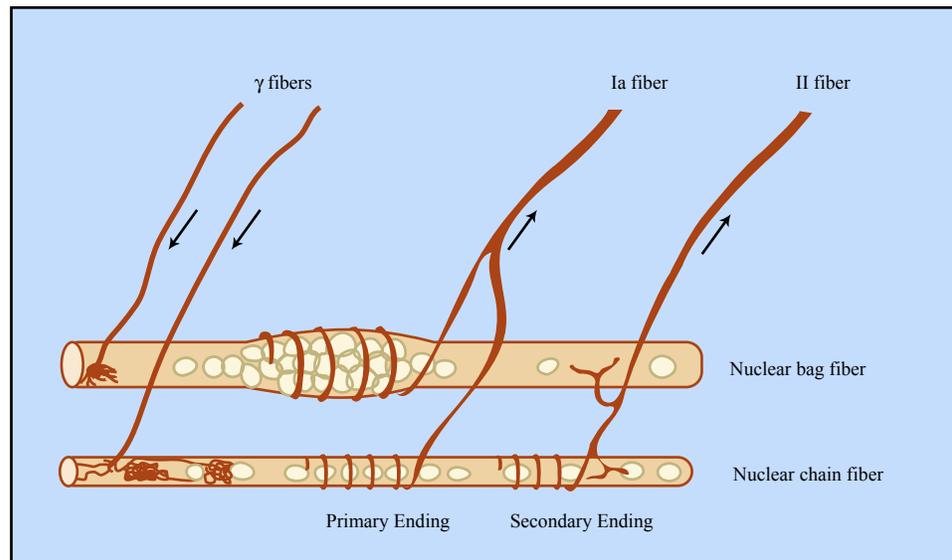


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Muscle Spindles are encapsulated structures that are mechanically connected in **parallel** with the muscle fibers. Each muscle spindle has three main components: a group of specialized muscle fibers (intrafusal fibers), afferent sensory neurons, and efferent motor neurons (gamma neurons).

The intrafusal fibers have a central noncontractile portion around which the sensory fibers terminate. In addition, the polar regions of the intrafusal fibers are contractile and are innervated by the gamma motor neurons. The intrafusal fibers are divided based on their morphology and physiology

into three types: dynamic bag fibers, static bag fibers, and nuclear chain fibers. The bag versus chain nomenclature refers to the arrangement of nuclei within the fibers. The dynamic bag fibers respond primarily during changes in the length of the muscle while the static bag and chain fibers primarily signal the length of muscle without the phasic changes.

There are two kinds of sensory fibers innervating the muscle spindle: primary and secondary. The primary sensory fibers (Type Ia neurons) terminate on all three types of fibers. The secondary fibers (Type II neurons) terminate only on the static bag and nuclear chain fibers.

Hence, when a muscle is stretched, the primary fibers have a phasic response during the stretch and then a higher firing rate reflecting the new length of the muscle. In contrast the secondary endings, do not have a phasic response during the stretch but gradually increase their firing to reflect the new length.

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[Stimulus, primary, secondary firing for linear stretch, tap, vibration, and release]

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[Gamma motor neuron innervation (impulses/sec)]

The gamma motor neurons cause the polar ends of the intrafusal fibers to contract. This maintains the sensitivity of the spindle even when the muscle is shortening which would otherwise cause the spindle to become unloaded and hence unresponsive. The gamma motor neuron innervation is also of two types, dynamic and static, but reflects the same basic organization. Dynamic gamma fibers innervate the dynamic bag fibers while static gamma fibers innervate the static bag and nuclear chain fibers. In normal movements, both alpha and gamma motor neurons are activated which allows for continuous monitoring of the length and the rate of change of the length of muscles.

Golgi Tendon Organs are slender encapsulated structures which are located at the junction of muscle and tendon and hence are **in series** with the muscle fibers. Each tendon organ is innervated by a single

afferent (Type Ib). In contrast to the spindles there is no efferent innervation. The firing rate of the tendon organs is very sensitive to changes in muscle **tension**. Tendon organs are stretched more effectively when the muscle actively contracts.

The cell bodies of the sensory afferents from the muscles are in the dorsal root ganglia. They enter the spinal cord and then have multiple collaterals. Some of the collaterals are involved in mediating spinal cord reflexes such as the stretch reflex. Other collaterals travel in the posterior column system and ultimately reaches the cortex. Still other collaterals travel in the posterior and anterior spinocerebellar tracts to reach the cerebellum. So these afferents keep many parts of the CNS informed about the length, tension, and dynamic changes occurring in the muscles.

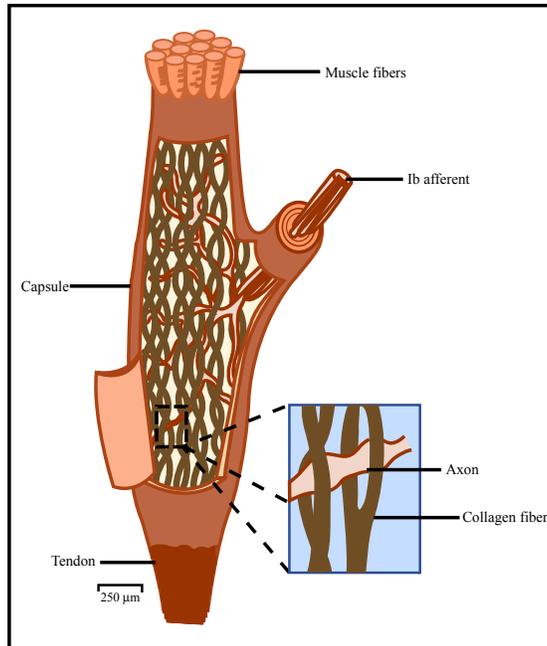


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II. Spinal Cord

The ventral gray matter of the spinal cord contains the cell bodies of the alpha and gamma motor neurons. The alpha motor neurons constitute the final common pathway through which the CNS controls movement. Alpha motor neurons are modulated by descending control, both directly and indirectly, and by afferent sensory input directly and through interneurons. In this next section we will discuss some of the organization of the spinal cord and some of the local circuitry present in the spinal cord.

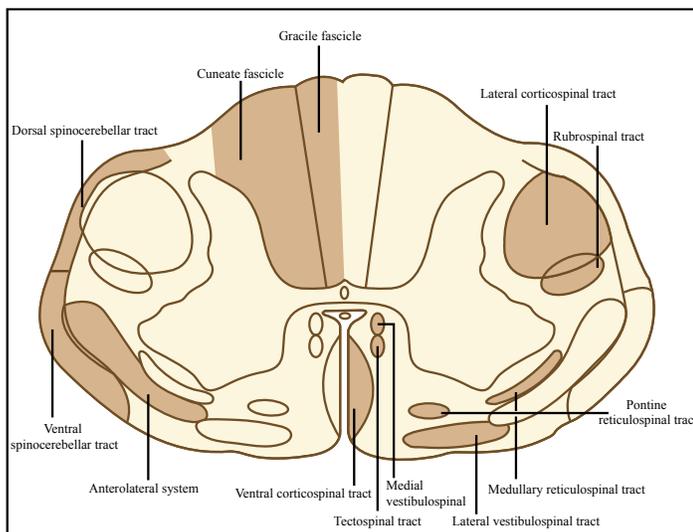


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The motor neurons in the ventral gray matter have a characteristic organization. There is a medial to lateral organization with neurons controlling **distal** musculature being located more **laterally** and neurons controlling **axial** musculature being located more **medially**. There is also a ventral to dorsal organization with neurons controlling flexor muscles being located more dorsally while neurons controlling extensor muscles are found more ventrally. The lateral system is involved in fine control of the limbs while the more medial system is involved in maintaining posture.

There are interneurons connecting the motor neurons called propriospinal neurons. Reflecting the basic organization, propriospinal neurons in the lateral system are confined to the same side and travel for only a few segments up and down. In contrast, propriospinal neurons in the medial system often have bilateral projections and can travel for many segments.

The descending inputs to the spinal cord can also be organized into a lateral and a medial system.

Lateral Tracts:

- Lateral Corticospinal tract
- Rubrospinal tract

Medial Tracts:

- Medial and lateral vestibulospinal
- Medial and lateral reticulospinal
- Ventral corticospinal tract

There is an obvious symmetry between the location of the motor neurons and the descending inputs which influence them. In the lateral funiculi, near the lateral motor neurons, are found the lateral corticospinal and rubrospinal tracts that are known to be involved in fine motor control. In the ventral funiculi near the ventro-medial neurons are the vestibulospinal, reticulospinal and anterior corticospinal tracts. These tracts, as will be elaborated in a following lecture, are important in maintaining posture.

Besides the descending inputs the alpha motor neurons are modulated by a variety of sensory inputs most notably from the muscle spindles and Golgi tendon organs. In addition, the alpha motor neurons are modulated through more complex circuits by cutaneous and nociceptive stimuli.

Interneurons

Many of the functions of the spinal cord are mediated through interneurons.

Renshaw Cells

- Stabilize motor neuron firing rates

Propriospinal Neurons

- Connect different spinal segments
- Lateral neurons are ipsilateral and travel short distances
- Medial neurons are bilateral and travel long distances

Group Ia

- Mediate muscle-spindle inhibition of antagonist muscles in stretch reflex

- Receive input from descending tracts
- Allow for coordination of agonist - antagonist muscles

Group Ib

- Mediate Golgi-tendon inhibition of agonist muscle
- Prevent excessive tension
- Receive multiple muscle, cutaneous, proprioceptive and descending inputs

Reflexes

There are numerous reflexes that are mediated by local spinal cord circuitry. Clinically, the most important of these is the **stretch reflex**. Type Ia afferents from the muscle spindle constitute the afferent limb of the response. Fibers from these neurons synapse directly on motor neurons innervating the same muscle and synergistic muscles. There is also reciprocal inhibition of antagonistic muscles. This inhibition is mediated by inhibitory interneurons which synapse on the motor neurons innervating the antagonist muscles. These inhibitory interneurons are called, cleverly enough, Type Ia interneurons. The stretch reflex functions to maintain muscle tone and muscle length.

The gain on the stretch reflex is normally kept low by descending influences. Lesions which interrupt the influence of the cortical premotor areas on the spinal cord cause an abnormal increase in the gain of the stretch reflex. The result of an overactive stretch reflex is spasticity. Patients with spasticity have hyperactive reflexes, clonus (a rhythmic beating typically of the ankle on brisk dorsiflexion), and increased tone. Neurosurgeons sometimes take advantage of the known circuitry to treat spasticity. In an operation called selective dorsal rhizotomy some dorsal roots are severed thereby eliminating the afferent limb of the reflex.

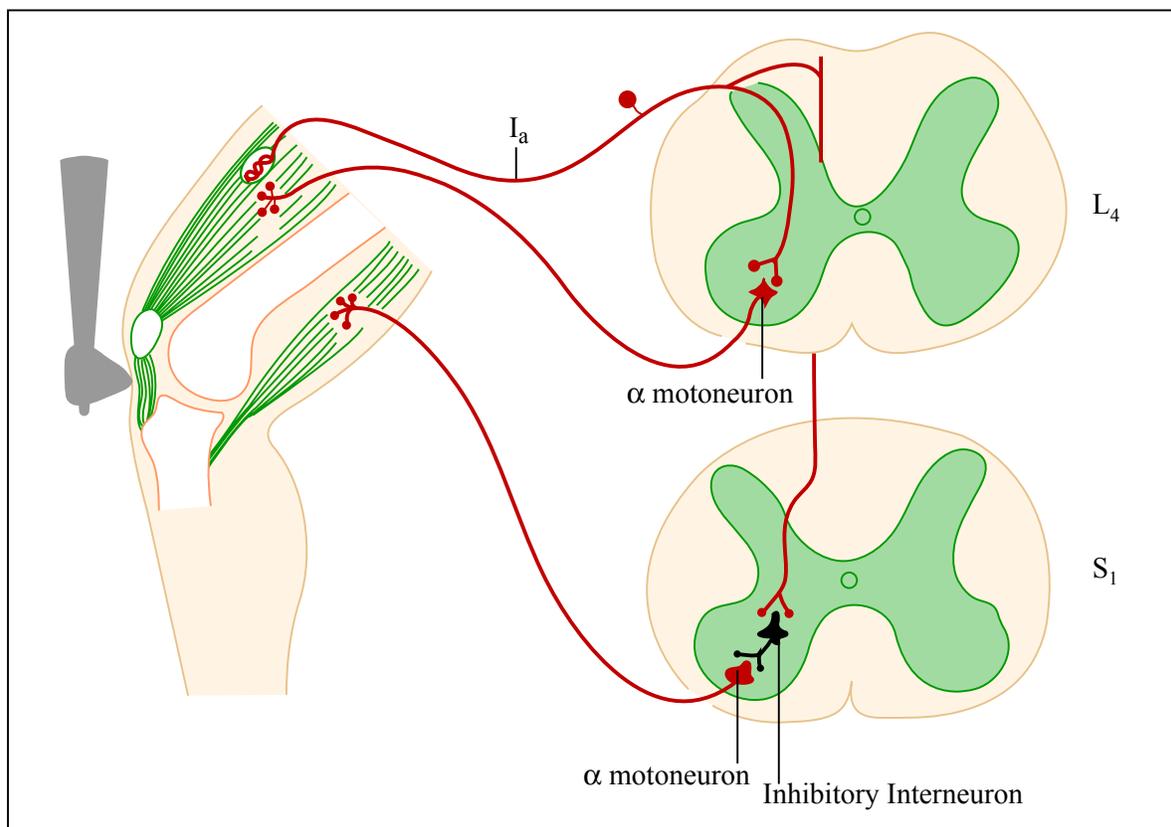


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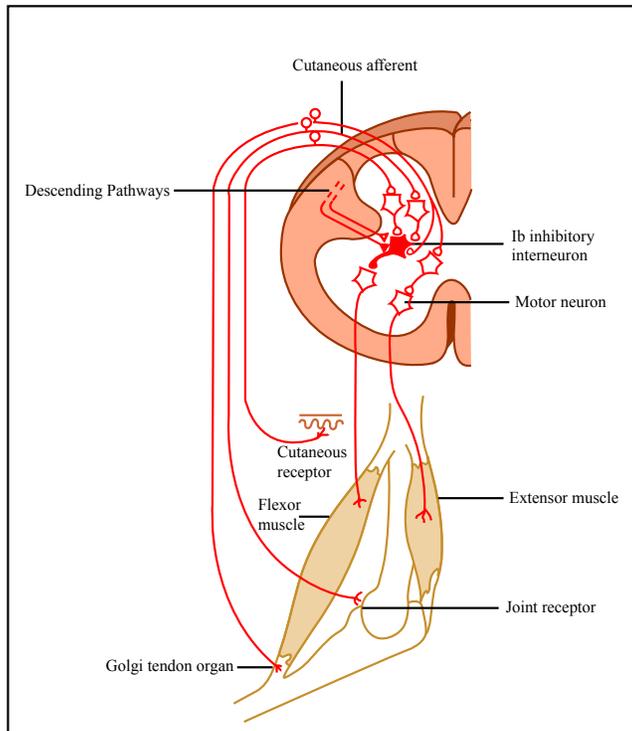


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Whereas the muscle spindle input is used to maintain muscle length, the Golgi tendon organs act to decrease muscle tension. Type Ib afferents from the tendon organs synapse on an inhibitory interneuron, called a Type Ib interneuron, which then inhibits the motor neuron of the same muscle. Type Ib interneurons also receive inputs from multiple other sources including cutaneous, proprioceptive and descending inputs. The overall effect of the connections of the golgi tendon organs is to prevent excessive muscle tension.

The **flexion withdrawal reflex** is a polysynaptic response to noxious stimuli resulting in flexion of the opposite limb away from the offending stimulus. This reflex is accompanied by **the crossed extensor reflex** which is also polysynaptic. The crossed extensor reflex causes extension of the contralateral limb in order to maintain a stable posture. There are also a number of **cutaneous reflexes** which are complex and polysynaptic. Among these are the abdominal reflex (stroking of the skin of the abdomen causes retraction of the umbilicus towards the stimulus) and the Babinski's sign (stroking of the sole of the foot causes dorsiflexion of the big toe in patients with upper motor neuron lesions).

Isolated spinal cord segments can in some cases generate **rhythmic movements**. For example, Sherrington showed that dogs in whom the cervical spinal cord had been transected had an intact scratch reflex in their hind legs. This reflex was maintained even when the dorsal roots from the hind quarter were severed, and stimulation was applied to the spine, indicating that the circuitry was intrinsic to the spinal cord.

Similar experiments have shown that spinal cats are capable of rhythmic stepping on a treadmill even when the dorsal roots are cut. Furthermore, if one of the legs is immobilized the other leg will continue with the stepping movements indicating that the circuitry for each leg can act independently of the other. The relevance of these findings for adult humans is not completely clear. Unfortunately humans with complete spinal cord injuries do not have the rhythmic stepping seen in cats.

III. Clinical Correlates**Upper vs. Lower Motor Neuron Disease**

- Lesions above alpha motor neurons - UMN
- Lesions of alpha motor neurons - LMN

	Upper Motor Neuron	Lower Motor Neuron
Weakness	Yes	Yes
Atrophy	No	Yes
Reflexes	Exaggerated	Diminished
Spasticity	Yes	No
Babinski	Yes	No

Neurogenic vs. Myopathic Diseases

	Neurogenic	Myopathic
Examples	ALS, Polio, Neuropathies Guillain-Barre Syndrome	Muscular Dystrophy, Polymyositis Dermatomyositis
Etiology	Damage to motor neurons	Degeneration of muscle fibers
Atrophy	Yes	Yes
Fasciculations	Yes	No
Loss of Reflexes	Yes	Yes
Creatine Kinase	Normal	Elevated
Muscle Biopsy	Fiber type grouping	Necrosis and regeneration
EMG	Fewer & Larger Potentials	Smaller Potentials

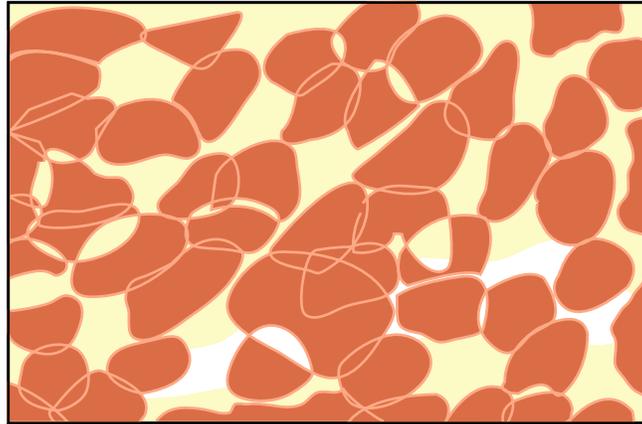


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Fiber type grouping