Chapter 12 – Motor Neuron Organization, Reflexes and Movement

Objectives

Given the synopsis in this chapter, competence in each objective will be demonstrated by writing short essays, drawing diagrams, and responding to multiple choices or matching questions, at the level of 85% or greater proficiency for each student.

A. To describe the anatomical organization of motor neurons and motor units.
B. To explain the function of and the circuitry for stretch reflexes.
C. To explain the function of and the circuitry for withdrawal reflexes.
D. To explain the function of and the circuitry for tendon reflexes.
E. To explain the function of and the circuitry for vestibuloocular reflexes.
F. To compare and contrast the general function and circuitry of the medial and lateral motor pathways.
G. To explain the specific functions and circuitry of the vestibulospinal tract, the tectospinal tract, and the reticulospinal tracts.
H. To explain the specific functions and circuitry of the corticospinal tract, and the rubrospinal tract.
I. To explain the control of voluntary movement by the cerebral cortex.
J. To explain the role of the basal nuclei and cerebellum in the control of movement.

Motor Neurons and Motor Units

Motor neurons are multipolar neurons. Please refer to Chapter 7, especially Figure 7.2 for a review of the organization of multipolar neurons. The cell bodies of the motor neurons are in the central nervous system, the dendrites receive signals from other neurons, and the axons send signals to muscle cells. Motor neurons that connect to skeletal muscle cells (also known as extrafusal muscle cells) are called **alpha motor neurons**, and their cell bodies are located either in the **ventral horn** of the spinal cord or in cranial nerve motor nuclei of the brain stem. The photomicrographs in Figure 12.1 show axons of motor neurons forming synapses with skeletal muscle cells. For review the organization of the spinal cord is shown in Figure 12.2.

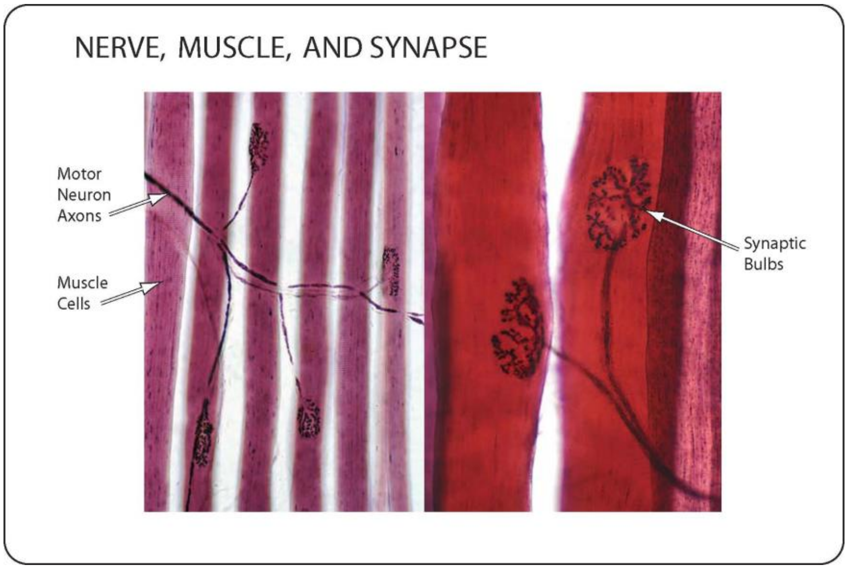


Figure 12.1 © 2007 David G. Ward, Ph.D.

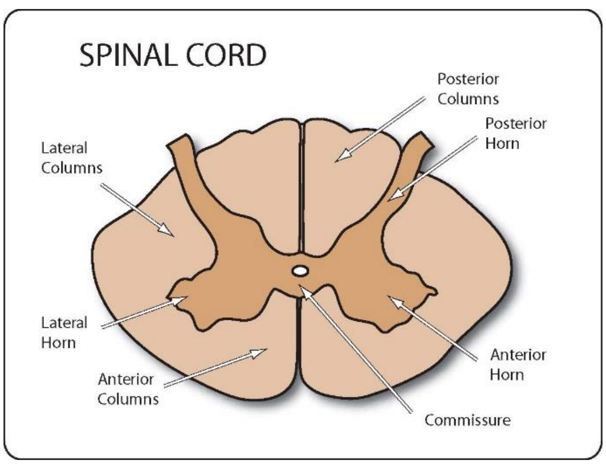


Figure 12.2 © 2007 David G. Ward, Ph.D.

The motor unit is the basic element for motor control, as shown in Figure 12.3. All movement depends on neural circuits that synapse onto alpha motor neurons.

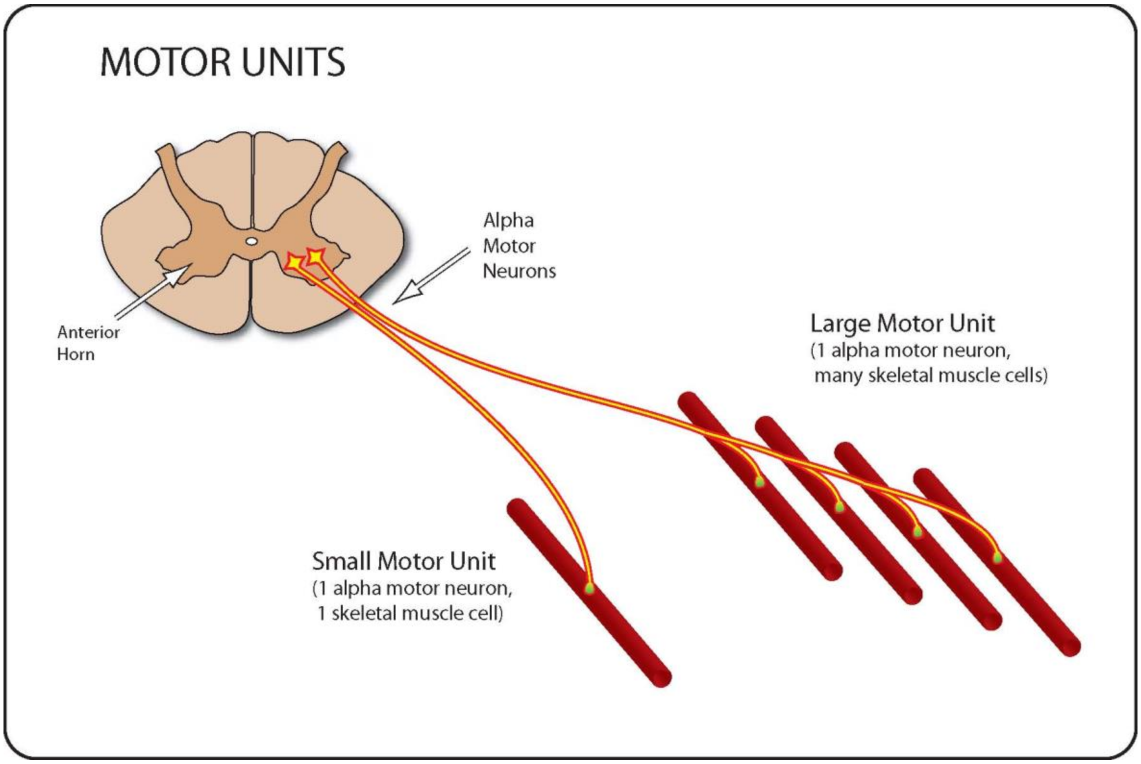


Figure 12.3 © 2007 David G. Ward, Ph.D.

A motor unit is an alpha motor neuron and the skeletal muscle cells it innervates.

- All of the skeletal muscle cells in a motor unit are of the same type; slow, fast fatigue resistant or fast fatigable (see Table 11.1).
  - Alpha motor neurons associated with slow muscle cells are relatively smaller and have smaller, more slowly conducting axons.
  - Alpha motor neurons associated with fast muscle cells are relatively larger and have larger, more rapidly conducting axons.

- Motor units vary in the number of muscle cells the alpha motor neuron innervates.
  - In small motor units an alpha motor neuron may innervate as few as one skeletal muscle cell.
  - In larger motor units an alpha motor neuron innervates many skeletal muscle cells, up to a hundred or more.

There are only three major sources of synaptic input to an alpha motor neuron:

- Sensory neurons that originate from muscle spindles (see below). These neurons provide information about muscle length.
- Neurons (pyramidal cells) in the cerebral cortex and brainstem. These neurons are important for the initiation and control of voluntary movement.
- Interneurons in the spinal cord provide the largest input to alpha motor neurons. Interneurons may be either excitatory or inhibitory and are part of the circuitry that determines the pattern of activity of spinal motor neurons.

Spinal Control of Motor Neurons

Muscle Spindles and Spinal Circuits for Stretch Reflexes

Muscle Spindles are composed of nerve endings of sensory neurons that wrap around intrafusal muscle cells as shown in Figure 12.4.

- The intrafusal muscle cell attaches in parallel to extrafusal muscle cells (skeletal muscle cells) in a motor unit.
- Changes in the length of the extrafusal muscle cells will cause a parallel change in the length of the intrafusal muscle cell and produce a signal in the sensory neuron.

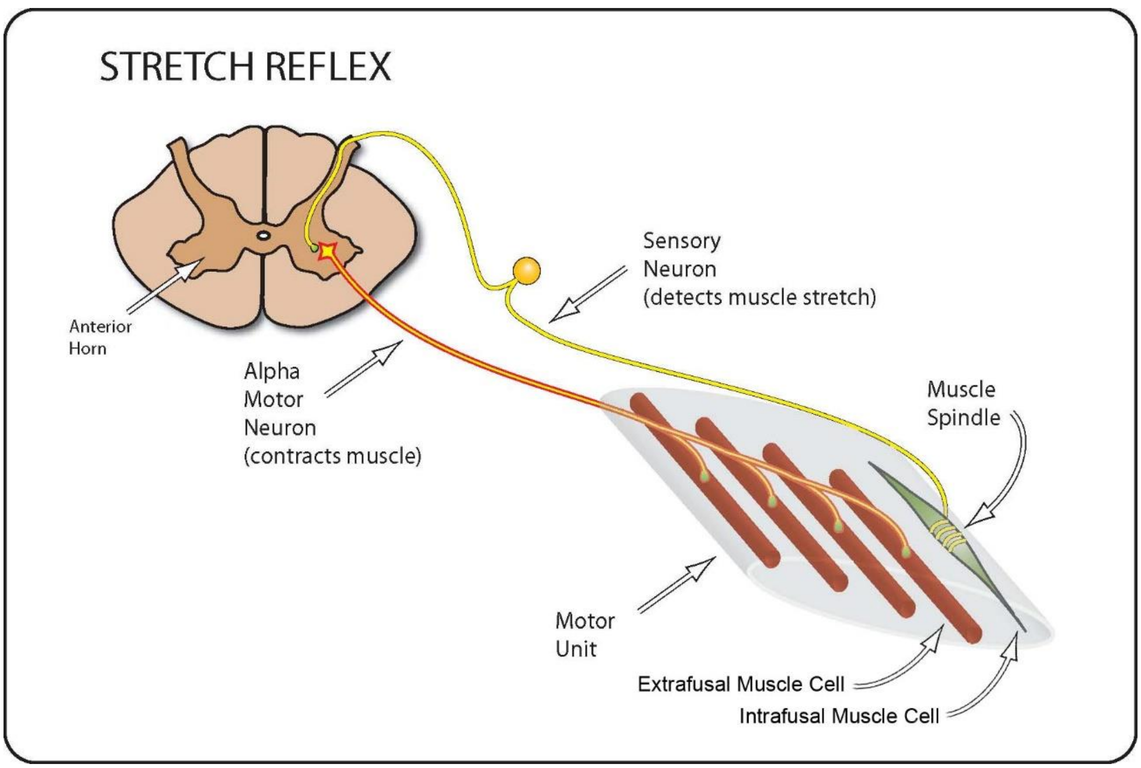


Figure 12.4 © 2007 David G. Ward, Ph.D.

Stretch reflexes are fundamental to motor responses through negative feedback control of muscle length and tension. The basic circuit for a stretch reflex is also shown in Figure 12.4.

- The axon from the sensory neuron (first order neuron) of the muscle spindle travels through the posterior horn, and into the anterior horn, ipsilateral.
- The axon of the first order neuron synapses in the anterior horn on the alpha motor neuron of the motor unit that contains the muscle spindle.
- The axon of the alpha motor neuron travels out of the spinal cord and synapses on the skeletal muscle cells of its motor unit.
- The sensitivity of the muscle spindles is controlled by gamma motor neurons (not shown) that change the degree of contraction of the intrafusal muscle.

The patellar stretch reflex is a classic example of a stretch reflex and is shown in Figure 12.5.

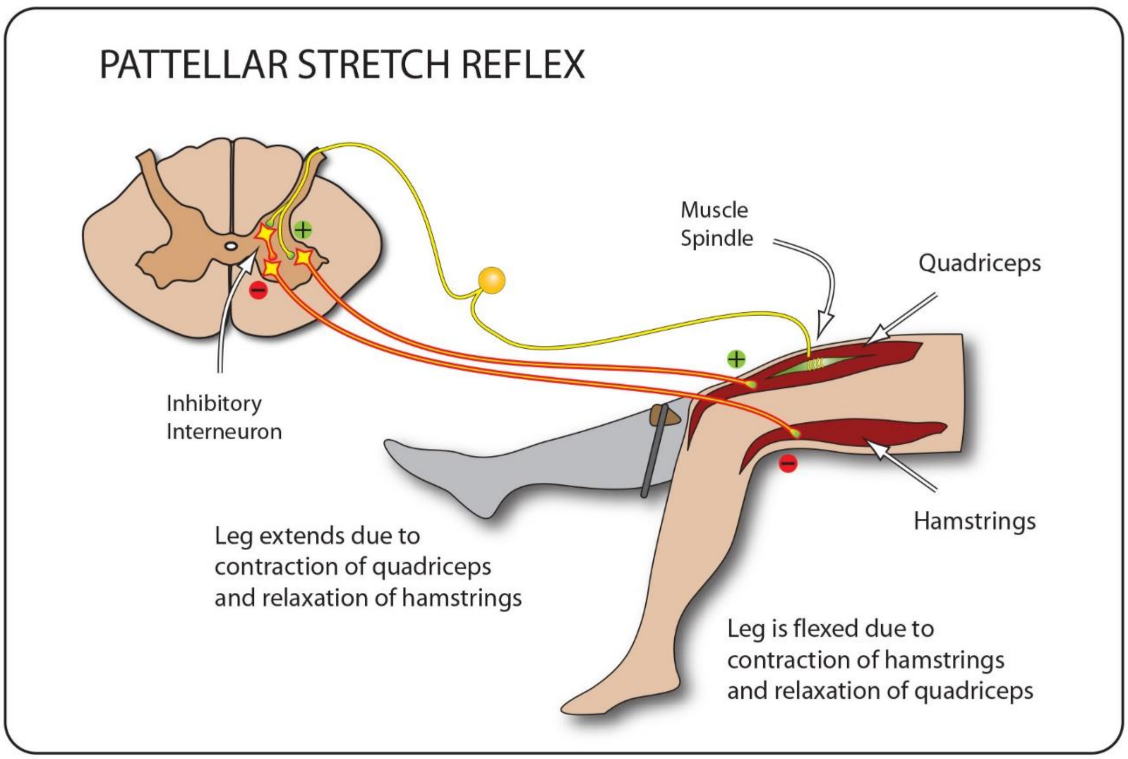


Figure 12.5 © 2014 David G. Ward, Ph.D.

- A tap of the patellar tendon pulls on the quadriceps muscles and stretches the muscle spindles.
- The axon from the sensory neuron of the muscle spindles travels into the posterior horn. One branch continues into the anterior horn, ipsilateral. Another branch excites an **inhibitory interneuron**.
- The sensory neuron excites the alpha motor neuron in the anterior horn innervating the quadriceps muscle and causes contraction.
- The inhibitory interneuron inhibits the alpha motor neuron in the anterior horn innervating the hamstrings and causes relaxation.
- The leg extends (shown in gray shading).

More generally, stretch of a skeletal muscle leads to a compensatory contraction of the affected skeletal muscle which maintains a desired length of the muscle. The desired length of the skeletal muscle is determined by the length of the muscle spindle which is controlled by gamma motor neurons. Gamma motor neurons are stimulated by neurons in the brainstem and cerebral and cerebellar cortex.

Nociceptors and Spinal Circuits for Withdrawal Reflexes

Stimulation of nociceptors or high threshold muscle and cutaneous receptors triggers the withdrawal of a limb from a noxious stimulus. The withdrawal of the leg from painful stimulation is shown in Figure 12.6.

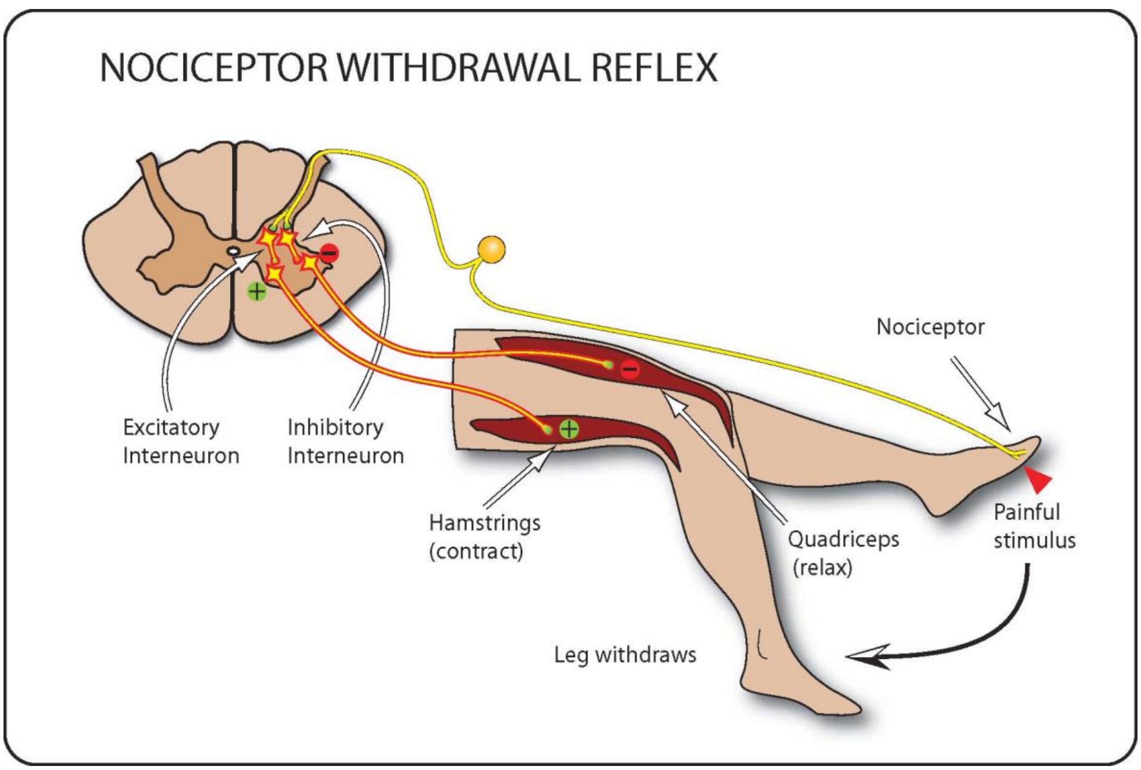


Figure 12.6 © 2007 David G. Ward, Ph.D.

- Painful stimulation is detected by nociceptors in the plantar surface of the foot.
- The axon from a sensory neuron travels into the posterior horn and branches. One branch excites an **excitatory interneuron**. Another branch excites an **inhibitory interneuron**.
- The excitatory interneuron excites the alpha motor neuron in the anterior horn innervating the hamstrings muscle and causes contraction.
- The inhibitory interneuron inhibits the alpha motor neuron in the anterior horn innervating the quadriceps muscle and causes relaxation.
- The leg flexes (withdraws).

More generally, noxious stimulation of a limb leads to contraction of the flexor muscles and relaxation of the opposing extensor muscles and causes flexion (withdrawal) of the affected limb. Sometimes this type of stimulation also leads to contraction of the extensor muscles and relaxation of the opposing flexor muscle and causes extension in the contralateral limb.

Golgi Tendon Organs and Spinal Circuits for Tendon (Myotatic) reflexes

Golgi tendon organs are composed of nerve endings of sensory neurons that wrap around the tendons of skeletal muscle and detect stretch of the tendons. Tendon (Myotatic) reflexes prevent unusually high tension in a muscle by negative feedback control of muscle tension in response to high tension in a tendon.

- Axons from sensory neurons (first order neurons) of the Golgi tendon organs travel into the posterior horn ipsilateral.
- The axons of the first order neurons synapse on inhibitory interneurons in the posterior horn.
- The inhibitory interneurons synapse on alpha motor neurons in the anterior horn that control the affected skeletal muscle.
- Axons of the alpha motor neurons travel out of the spinal cord to synapse on skeletal muscle cells.

Stretch of the tendon leads to relaxation of the affected skeletal muscle through inhibition of the alpha motor neurons by the inhibitory interneurons.

Brainstem and Cortical Control of Motor Neurons

Vestibular Receptors and Neural Circuits for the Vestibuloocular Reflex

The semicircular canals detect rotation of the head. Vestibuloocular reflexes keep the eyes pointed toward their target as the head moves. If the head turns to the left, the eyes rotate right to turn the eyes toward their original target. If head rotation exceeds the range of eye movement, the eyes quickly reflect left and a new target is found (Nystagmus). The brainstem circuit for signals coming from the left lateral semicircular canal as the head turns left and causing a vestibuloocular reflex is shown in Figure 12.7.

For sake of clarity, the connections from the right lateral semicircular canal are not shown.

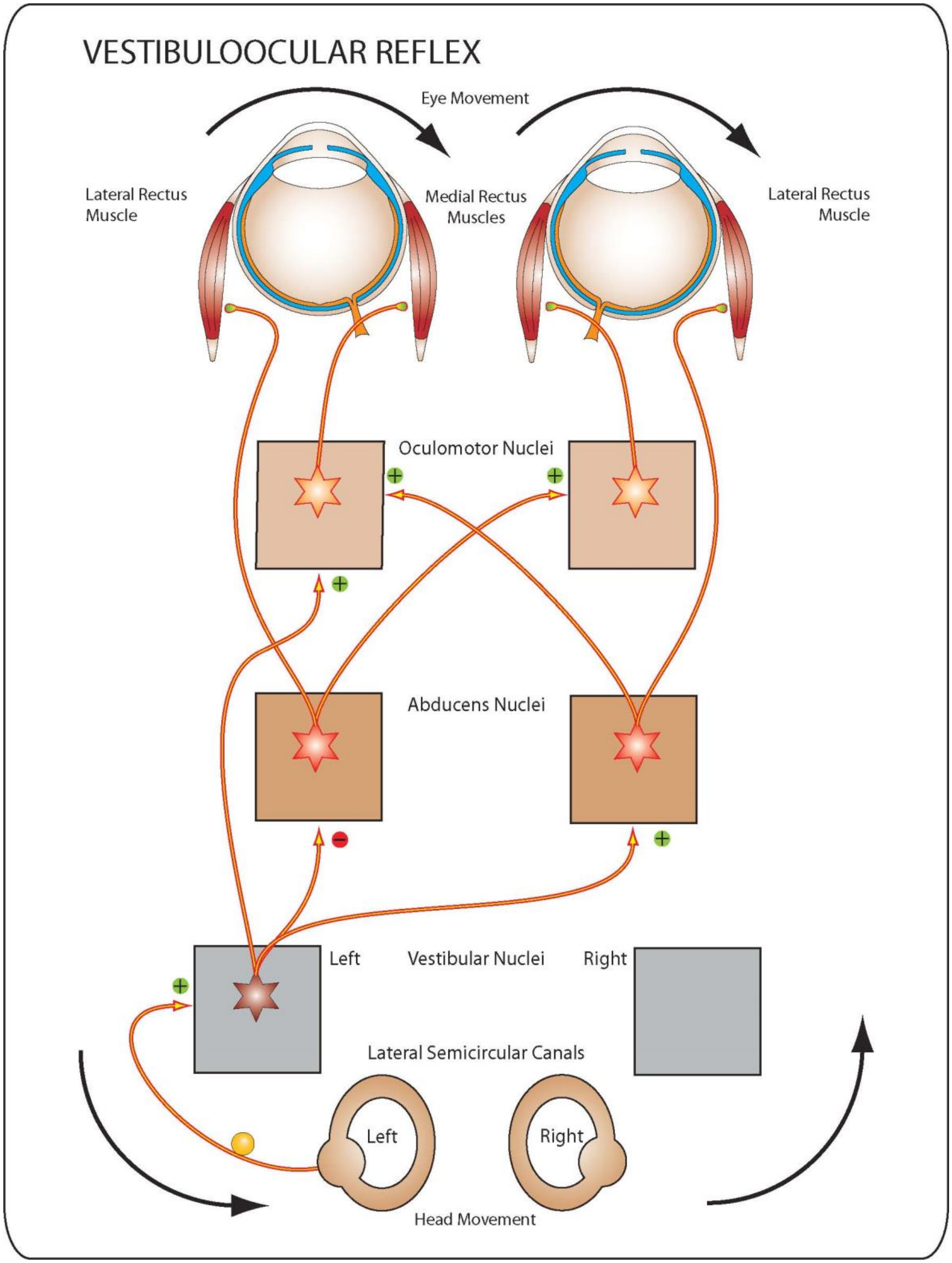


Figure 12.7 © 2007 David G. Ward, Ph.D.

- Axons from sensory neurons of the vestibular ganglion, travel through the vestibular nerve and into the vestibular nuclei of the medulla, ipsilateral.
- The first order neurons synapse on the cell bodies of the neurons in the vestibular nuclei of the Medulla.
- Neurons of the left vestibular nuclei send axons ipsilateral (through the medial longitudinal fasciculus) to excite neurons in the left oculomotor nucleus and to inhibit neurons in the left abducens nucleus.
- Neurons of the left vestibular nuclei send axons contralateral (through the medial longitudinal fasciculus) to excite neurons in the right abducens nucleus.
- Neurons in the abducens nuclei excite the lateral rectus muscle ipsilateral and the oculomotor nuclei contralateral.
- Neurons in the oculomotor nuclei excite the medial rectus muscle ipsilateral.

Medial Motor Pathways

The medial motor pathways originate from the cerebral cortex and brainstem and mediate voluntary and involuntary control of the head and trunk; especially in the control of posture. The medial motor pathways include the

- Vestibulospinal tract
- Tectospinal tract
- Reticulospinal tracts

Vestibulospinal Tract

Signals from the vestibular apparatus, including the semicircular canals, are involved in the control of head movement and posture as well as in the control of eye movement. The basic organization of the vestibulospinal tract, which is involved in the control of head movement and posture, is shown in Figure 12.8.

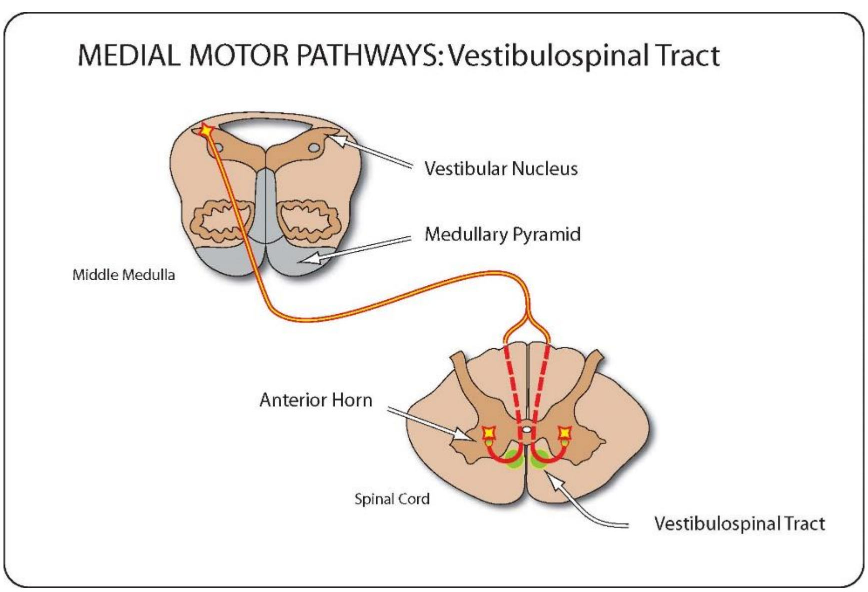


Figure 12.8 © 2007 David G. Ward, Ph.D.

- Axons of neurons in the vestibular nuclei descend through the brainstem.
- One component continues bilaterally down the spinal cord to activate cervical spinal circuits that control neck and back muscles.
- Another component continues ipsilaterally down the spinal cord to activate lumbar spinal circuits that control the legs. Here motor neurons controlling extensor muscles are commonly excited.

Tectospinal Tract

Signals from the retina and the visual cortex are involved in the control of head movement eye movement as well as vision. Each superior colliculus receives signals both from the retina and from the visual cortex, and sends signals to the spinal cord. (The superior colliculus is sometimes referred to as the optic tectum, and thus the connection between the superior colliculus and the spinal cord is called the tectospinal tract.) The basic organization of the tectospinal tract, which is involved in the control of head, neck and trunk movement, is shown in Figure 12.9.

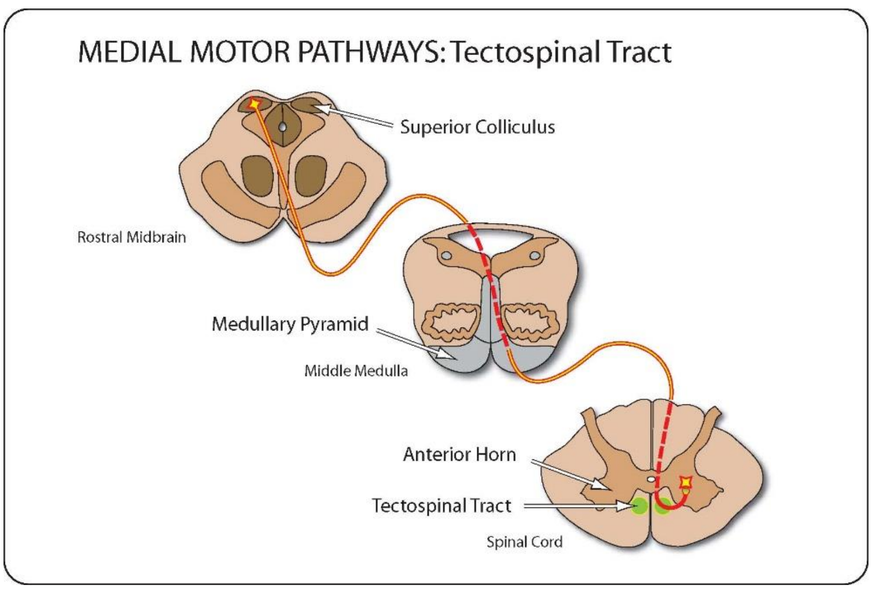


Figure 12.9 © 2007 David G. Ward, Ph.D.

- Axons of neurons in the superior colliculus descend through the brainstem.
- The axons continue contralateral down the spinal cord to activate cervical spinal circuits that control neck and trunk muscles. The head is moved so that the target of interest is imaged on the fovea.

Reticulospinal Tracts

Most of the time, the activity of neurons in the anterior horn of the spinal cord maintains (rather than changes) the length and tension of muscles. Recall that a primary function of the circuitry for the stretch reflex is to maintain muscle length and tension. The sensitivity of these circuits is controlled in part by the reticulospinal tracts. As shown in Figure 12.10, one reticulospinal tract originates in the pons and another originates in the medulla.

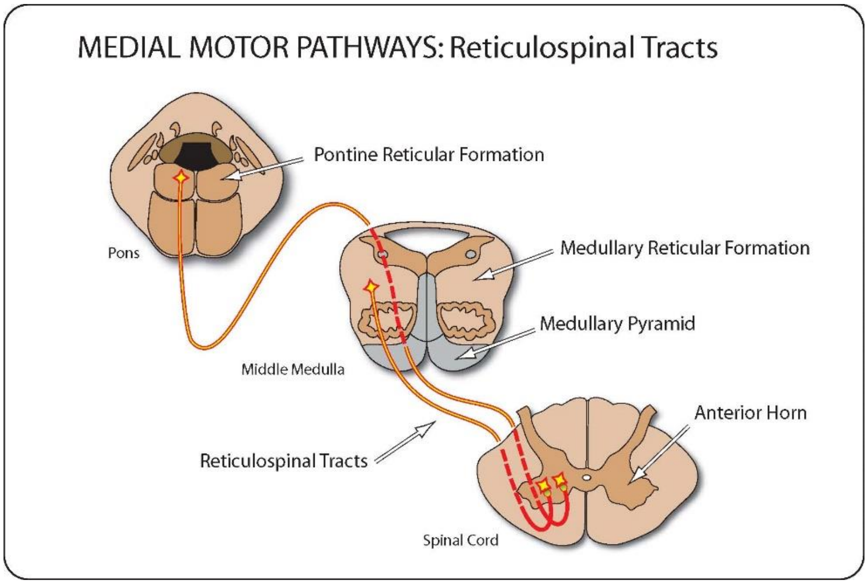


Figure 12.10 © 2007 David G. Ward, Ph.D.

- Axons of neurons in the reticular formation of the pons descend through the brainstem ipsilaterally to synapse on neurons in the ventral horn. Reflex control of extensor muscles of the lower limbs is facilitated.
- Axons of neurons in the reticular formation of the medulla descend through the brainstem ipsilaterally to synapse on neurons in the ventral horn. Reflex control of extensor muscles of the lower limbs is suppressed.

Lateral Motor Pathways

The lateral motor pathways originate from the cerebral cortex or midbrain and mediate voluntary control of distal extremities, especially digits, and mimetic movements of the face and tongue. The lateral motor pathways include the

- Lateral Corticospinal tract
- Rubrospinal tract

Lateral Corticospinal Tract

The lateral corticospinal tract is the most important of the lateral motor pathways and is shown in Figure 12.11. The corticospinal tract originates from pyramidal cells (neurons) in the motor cortex.

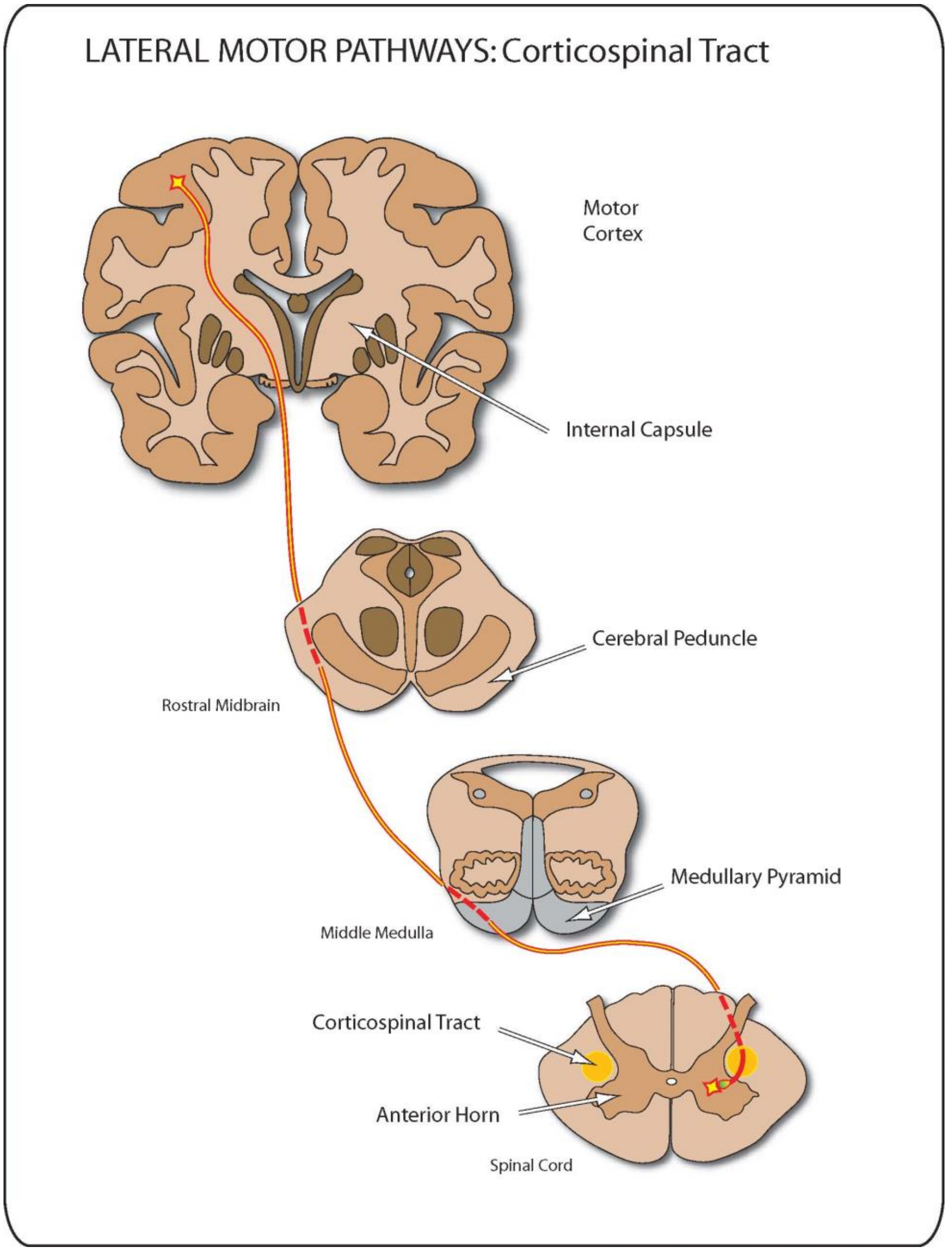


Figure 12.11 © 2007 David G. Ward, Ph.D.

- Axons of pyramidal cells (neurons) in the motor cortex descend ipsilaterally through the internal capsule, the base of the cerebral peduncle and into the medullary pyramid.
- At the junction of the medulla and spinal cord the axons cross over and descend contralateral through the corticospinal tract to synapse on motor neurons in the anterior horn of the spinal cord.

Rubrospinal Tract

The rubrospinal tract is a smaller component of the lateral motor pathways and is shown in Figure 12.12. The rubrospinal tract originates in the red nucleus of the midbrain which in turn receives its major source of input from the primary motor cortex.

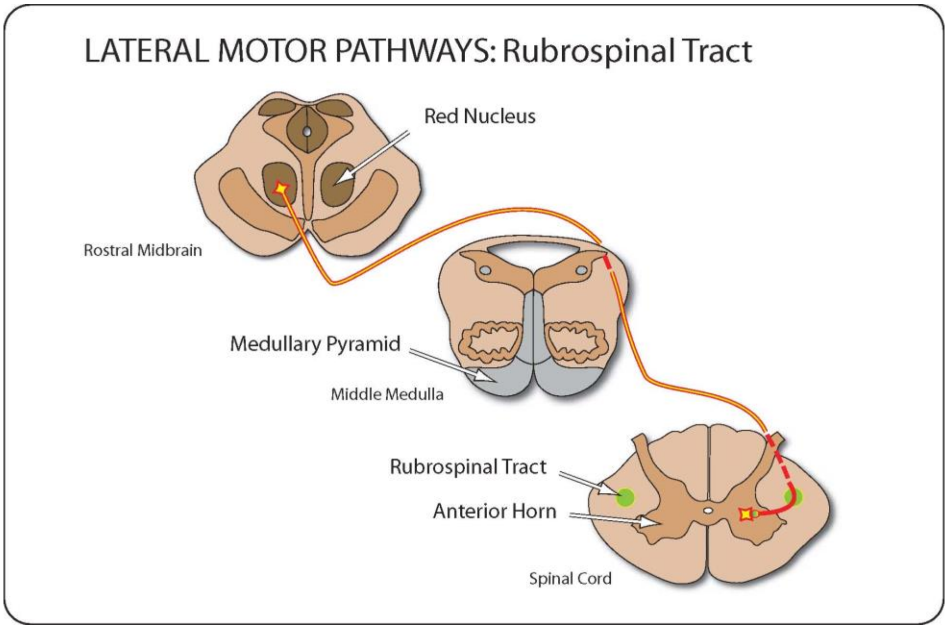


Figure 12.12 © 2007 David G. Ward, Ph.D.

- Axons of neurons in the red nucleus cross over in the pons and descend contralaterally into the medulla.
- The axons run parallel with those of the corticospinal tract to synapse on motor neurons in the anterior horn of the spinal cord.

Cortical control of Voluntary Movement

Much of the cerebral cortex is involved in control of voluntary movement. Critical regions of the cerebral cortex are shown in Figure 12.13. As we saw in Chapter 9, the primary somatosensory cortex is located posterior to the central sulcus in the post-central gyrus. We now see, that the primary motor cortex is located anterior to the central sulcus in the pre-central gyrus. In addition, two other motor areas (or extensions) are located anterior to the primary motor cortex. One, the supplementary motor area, is located medial and superior. The other, the premotor area is located lateral and inferior.

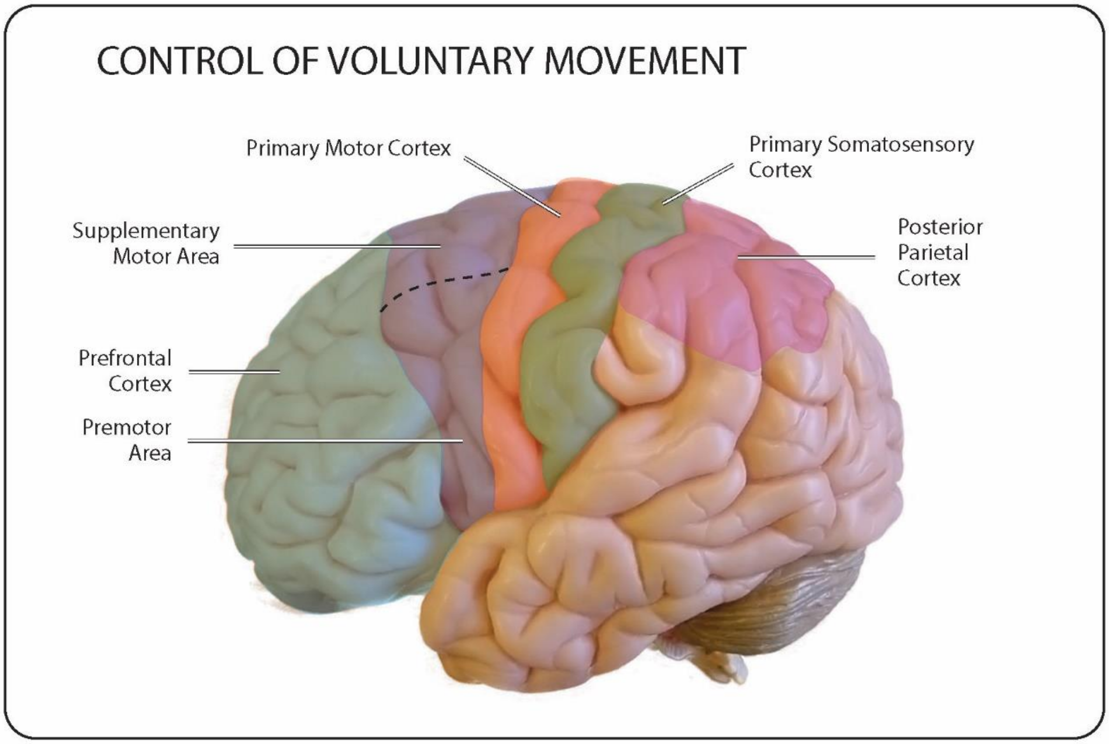


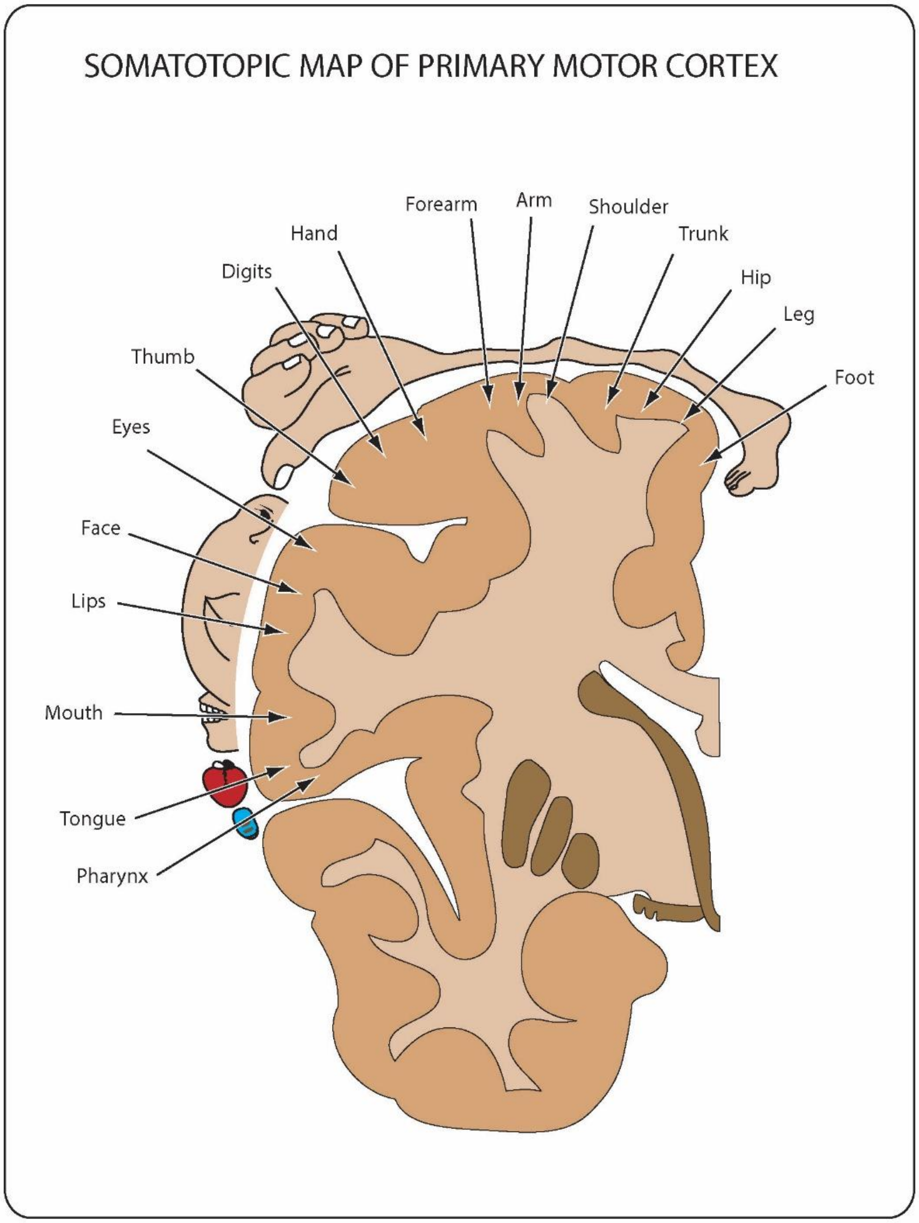
Figure 12.13 © 2018 David G. Ward, Ph.D.

The primary motor cortex is located anterior to the primary somatosensory cortex and is organized somatotopically, as shown in Figure 12.14, much like the somatosensory cortex.

- Axons of neurons in the primary motor cortex synapse directly on motor neurons in spinal cord via the lateral corticospinal tract.
- The primary motor cortex seems to be especially involved in control of distal muscles and precise movements.

Both the supplementary motor area and the premotor area are located anterior to the primary motor cortex, and are organized somatotopically.

- Axons of neurons in the supplementary motor area synapse primarily on motor neurons in the spinal cord, via the lateral corticospinal tract.
- The supplementary motor area seems to be involved in control of distal muscles and in the planning of complex movements.
- Axons of neurons in the premotor area synapse primarily on neurons in the pons and medulla that give rise to the reticulospinal tracts.
- The premotor area seems to be involved in the control of proximal muscles and in the planning of postural and positional movements.



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Other cortical areas are also critically involved in control of voluntary movement.

- The prefrontal cortex is involved, in part, in decision making, planning of actions (movements), and anticipating the outcomes of actions (movements),
- The posterior parietal cortex is involved, in part, in perception of spatial relations.
- Both the prefrontal cortex and the posterior parietal cortex send axons that synapse on neurons of the supplementary motor area and the premotor area.
- Therefore, the supplementary motor area and the premotor area may be junctions where signals encoding *what* actions are desired, are converted into signals that specify *how* the actions will be carried out.

The Basal Ganglia (Nuclei)

One of the functions of the basal nuclei appears to be the selection and initiation of willed movement. The organization of the basal nuclei and some of their critical connections is shown in Figure 12.15.

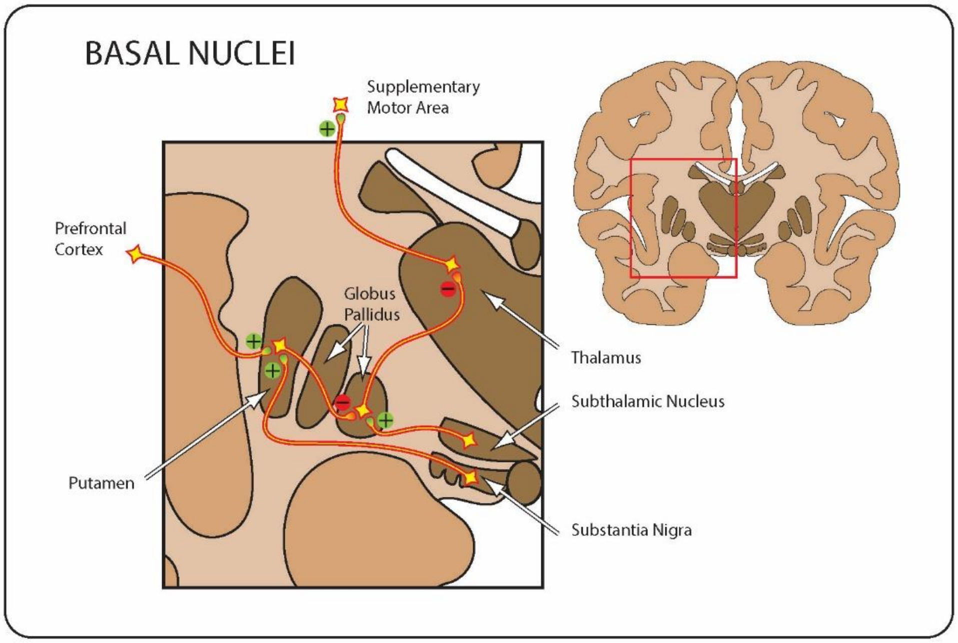

Figure 12.15 © 2007 David G. Ward, Ph.D.

- Neurons in the prefrontal cortex send excitatory signals to the putamen and caudate nucleus.
- The putamen also receives excitatory signals from the substantia nigra.
- Neurons in the putamen send inhibitory signals to the globus pallidus.
- The globus pallidus also receives excitatory signals from the subthalamic nucleus.
- The globus pallidus sends inhibitory signals to the thalamus (ventral lateral nucleus).
- The thalamus sends excitatory signals to the supplementary motor area.
- The signals from the thalamus to the supplementary motor cortex provide a “Go” signal to initiate movement.

Patients with Parkinson’s disease exhibit slowness of movement, difficulty in initiating willed movements, increased muscle tone, and tremors. Loss of dopamine neurons in the substantia nigra, and subsequent loss of excitatory input to the caudate nucleus and putamen, seems to account for the disorders of movement in Parkinson’s patients.

Patients with Huntington’s disease exhibit excess movements, abnormal movements, impaired cognitive abilities, and a disorder of personality. Loss of neurons in the caudate nucleus, putamen, and globus pallidus, and subsequent loss of inhibitory input to the thalamus, seem to account for the disorders of movement in Huntington’s patients.

The Cerebellum

The cerebellum appears to be critically involved with the detailed sequencing and timing of muscle contractions.

- The cerebellum contains more than 50% of the total number of neurons in the CNS.
- The cerebellum is critical for the proper execution of planned voluntary multi-joint movements.
- The cerebellum appears to provide information to the primary motor cortex about the direction, timing, and force of a movement.
- The cerebellum is important for motor learning. For some movements, information provided to the primary motor cortex is based entirely on predictions through experience about the outcome of the movement.

Patients with damage to the cerebellum exhibit uncoordinated and inaccurate movement. Joints are moved sequentially rather than simultaneously. Movements tend to wander and overshoot or undershoot their target.

Quiz Yourself

1-5. Matching (in the context of Motor Neurons)

A)	Synaptic bulbs	generate action potentials	1) _____
B)	Axon Hillock	release neurotransmitters	2) _____
C)	Dendrites	conduct signals from the dendrite	3) _____
D)	Cell body	receive signals from other neurons	4) _____
E)	Axon	conduct signals toward the synaptic bulb	5) _____

6-10. Matching

A)	stretch reflexes	provide for automatic adjustment of skeletal muscle length	6) _____
B)	myotatic reflexes	prevent unusually high tension in a muscle	7) _____
C)	flexor reflexes	withdraw a limb from noxious stimuli	8) _____
		triggered by Golgi tendon organs	9) _____
		triggered by muscle spindles	10) _____

11-15. Place the following events in order following stretch of a muscle.

A)	muscle spindle stretches	11) _____
B)	action potential is initiated in the alpha motor neuron	12) _____
C)	neurotransmitter is released onto alpha motor neuron	13) _____
D)	action potential is initiated in the spindle sensory neuron	14) _____
E)	acetylcholine is released onto skeletal (extrafusal) muscle cell	15) _____

16-20. Matching

A)	medial motor pathway	tectospinal tract	16) _____
B)	lateral motor pathway	corticospinal tract	17) _____
		vestibulospinal tract	18) _____
		involved in control of distal muscles and fine movement	19) _____
		involved in control of proximal, head and trunk muscles and posture	20) _____

Fill in

21. A __________ ____________ is an alpha motor neuron and the skeletal muscle cells it innervates

22. Gamma motor neurons adjust the _______________ of muscle spindles.

23. The _______________ _______________ _______________ is involved in control of body image and perception of spatial relations.

24. The _____________ _____________ ____________ is involved in control of distal muscles.

25. The __________ ____________ are involved in the selection / initiation of willed movement.

Study Questions

1. Describe the organization of motor neurons and motor units.
2. Describe the function of and circuitry for stretch reflexes. Include the role of muscle spindles, alpha motor neurons, and gamma motor neurons.
3. Compare and contrast the organization and function of the medial and lateral motor pathways.
4. Explain the role of the basal nuclei in the control of voluntary movement.