Introduction to Motor Control

UNIT TWO

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CHAPTER 4

Neuromotor Basis for Motor Control

Concept: The neuromotor system forms the foundation for the control of movement.

After completing this chapter you will be able to

- Describe the general structure of a neuron and the types and functions of neurons
- Identify and describe the structural components of the brain that are most directly involved in control of movement and describe their primary functions
- Identify and describe the neural pathways that make up the ascending and descending tracts
- Describe a motor unit, the recruitment of motor units, and their relationship to the control of movement
- Describe the basic components of a conceptual hierarchical model that describes the CNS structures and their functions in the control of movement

APPLICATION

When you are reading at your desk and want to write a few notes about what you are reading, you must undertake a sequence of coordinated movements to accomplish your goal. You must first pick up your pen and then position your head, body, arm, hand, and fingers so that you can use the pen. Then you must initiate the movements required to write the words you want to put on the paper. Although this example may seem to describe a relatively simple task that you can do very easily and quickly, have you ever thought about what is happening in your nervous system to allow you to carry out this sequence of events? As simple as the individual movements may be, a rather complex array of neural activity is associated with planning and performing the task. For example, your decision to pick up the pen was a cognitive activity, but what happened in the nervous system to change this cognitive act into a motor act? To answer this question, we need to consider two important issues in the study of motor control. One concerns the neurophysiologic basis of the neural activity associated with this sequence of events. The other is the more theoretical issue of how the cognitive intention to perform an action becomes a sequence of movements that enables a person to achieve the intended action goal. We will consider the first of these issues in this chapter by looking at the central nervous system in terms of its structure and function as related to the performance of motor skills. We will briefly consider the second issue from a neurological perspective but then address it in more detail in chapter 5, where we discuss theories of motor control.

You may be asking why understanding this process is necessary for someone who wants to pursue a professional career that essentially entails helping people learn or relearn motor skills or improve their performance of skills. The answer is that a basic understanding of the physiology underlying the control of voluntary movement establishes a more comprehensive appreciation and awareness of the capabilities and limitations of the people with whom a practitioner works. The person who plans to enter a profession where physical rehabilitation is the focus needs this knowledge for the assessment of physical dysfunctions and limitations as well as for the development of appropriate rehabilitation interventions.

Application Problem to Solve Describe a motor skill that you perform or might help people learn. Describe the parts of the central nervous system involved in the performance of this skill.

DISCUSSION

Our study of the structure and function of the neuromotor system will focus on the parts of the central nervous system (CNS) that are involved in the control of voluntary, coordinated movement. It is important to note that the peripheral nervous system's sensory components are not included here but will be considered in chapter 6 in discussions concerning the role of the tactile, proprioception, and visual sensory systems in motor control. In addition, it is important to point out that the study of the neuromotor system in this chapter and in chapter 6 is intended to provide a basic introduction, or review (for some students), rather than an in-depth discussion.

THE NEURON

The basic component of the nervous system is the nerve cell, which is called a **neuron**. Neurons in the nervous system number in the billions. These functional units, which vary in size from 4 to 100 microns,

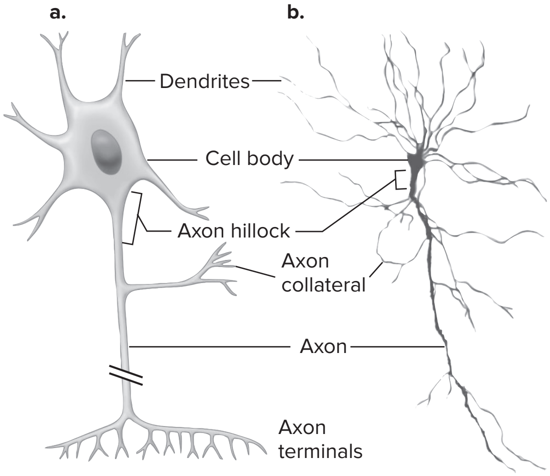

FIGURE 4.1 (a) An illustration of a neuron (the break in the axon indicates that axons may extend for long distances). (b) A neuron as observed through a microscope. *Source:* From Widmaier, E. P., Raff, H., & Strang, K. T. (2019). *Vander's human physiology: The mechanisms of body function* (15th ed.), p. 137. New York, NY: McGraw-Hill.

provide the means for receiving and sending information through the entire nervous system. Although there are several types of neurons, most share a similar general three-part structure: the cell body and two processes, which are called dendrites, and the axon (see figure 4.1).

General Structure of Neurons

The *cell body* contains the all-important nucleus, which regulates the homeostasis of the neuron. **Dendrites** are extensions from the cell body and are primarily responsible for receiving information from other neurons. A neuron may have none

neuron a nerve cell; the basic component of the nervous system.

dendrites extensions from a neuron's cell body that receive neural impulses from other neurons; a neuron may have none or as many as thousands of dendrites.

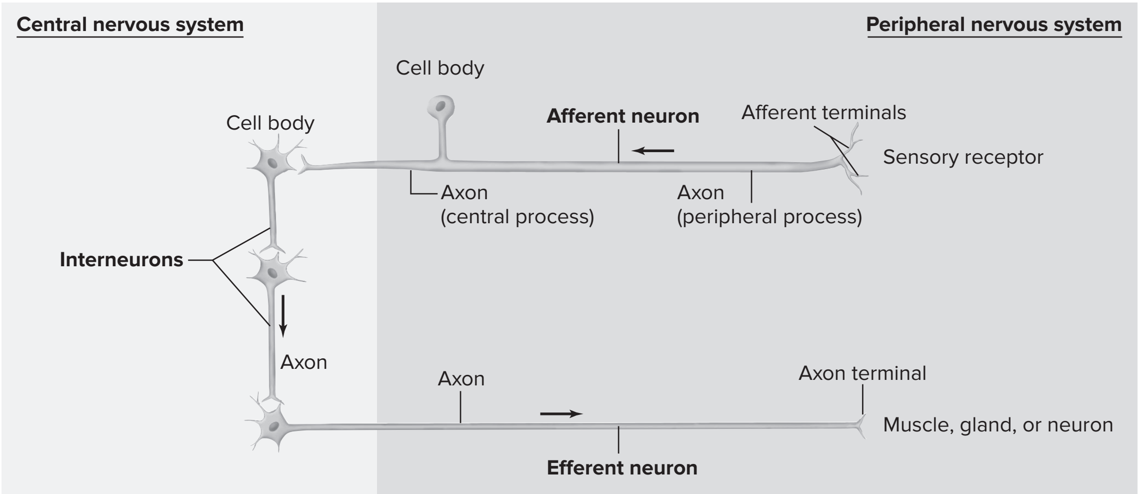

FIGURE 4.2 Three types of neurons. The arrows indicate the direction of transmission of neural activity. *Source:* From Widmaier, E. P., Raff, H., & Strang, K. T. (2019). *Vander's human physiology: The mechanisms of body function* (15th ed.), p. 140. New York, NY: McGraw-Hill.

or as many as thousands of dendrites. The **axon**, which is also called a nerve fiber, is responsible for sending information from the neuron. Unlike dendrites, there is only one axon per neuron, although most axons have many branches, which are known as *collaterals.* The ends of the axons, called axon terminals, provide a signal transmission relay station for neurotransmitters, which are the chemical signals passed on to other neurons or to muscles, in the specific case of movement control. Many axons are covered by layers of *myelin,* which is a cellular membrane that speeds up the transmission of neural signals along the axon. The passing on of neural signals from one neuron to another occurs at a *synapse,* which is the junction between the axon of a neuron and another neuron.

Types and Functions of Neurons

The most convenient way to classify neurons is according to their function in terms of sending and receiving information (i.e., neural impulses) to, from, and within the central nervous system (CNS), which consists of the brain and spinal cord. There are three functional classes (see figure 4.2 for illustrations of examples of types of neurons). **Sensory neurons** (also called *afferent neurons*) send neural impulses to the CNS, while **motor neurons** (also called *efferent neurons*) send neural impulses from the CNS to skeletal muscle fibers. A convenient way to remember the distinction between these neurons is to note that afferent neurons arrive at the CNS and efferent neurons exit the CNS. **Interneurons** function within the CNS. Estimates of the quantity of each type of neuron in the body indicate that for each sensory neuron, there are ten motor neurons and 200,000 interneurons (Widmaier, Raff, & Strang, 2019).

Sensory neurons. In their role of receiving information from various sensory receptors in the body, sensory neurons function much like transducers in electronics in that they receive a neural signal and then convert it to an electrical signal that can be transmitted along the neural pathways and received by the CNS. The unique structural characteristic of sensory neurons is that they are unipolar; that is, they have only one axon and no dendrites. The cell body and most of the axon of sensory neurons are in the peripheral nervous system, with only the central process of the axon entering the CNS.

Motor neurons. Two types of motor neurons influence the control of movement. *Alpha motor neurons* are found predominantly in the spinal cord. Sometimes referred to as *motor horn cells,* they emanate from the horn of the spinal cord and have many branching dendrites and long branching axons that connect directly with the skeletal muscle fibers. *Gamma motor neurons* supply a portion of the skeletal muscle called intrafusal fibers, which will be discussed in more detail in chapter 6.

Interneurons. These specialized neurons originate and terminate in the brain or spinal cord. They function as connections between axons descending from the brain, and they synapse on motor neurons and axons from sensory nerves and the spinal nerves ascending to the brain.

THE CENTRAL NERVOUS SYSTEM

The central nervous system (CNS) functions as the "command center" for human behavior, although there are varying views about the precise nature of the commands it issues (in chapter 5 we will discuss two of these views as they relate to motor control). This incredibly complex system, which comprises the brain and spinal cord, forms the center of activity for the integration and organization of the sensory and motor information in the control of movement. Rather than present a complete anatomical and physiological picture of the components of the CNS, we will concentrate on those portions most directly related to the motor control associated with learning and performing the types of motor skills that are the focus of this book, as discussed in chapter 1.

The Brain

The structural components of the brain that are most directly involved in control of movement are the cerebrum, diencephalon, cerebellum, and brainstem. The cerebrum and diencephalon are sometimes referred to as the forebrain. The locations of these components, their subcomponents, and other notable components are illustrated in figure 4.3.

The cerebrum. The **cerebrum** consists of two halves, known as the right and left *cerebral hemispheres,* which are connected by a sheet of nerve fibers known as the *corpus callosum*. Both hemispheres are covered by what is commonly pictured in photographs as an undulating, wrinkly, gray-colored surface called the **cerebral cortex**. This covering is a thin tissue of nerve cell bodies called *gray matter.* The gray matter is about 2–5 mm thick and, if unfolded, would cover about 20 sq ft. The folding results in ridges (each ridge is called a *gyrus*) and grooves (each groove is called a *sulcus*). Cortical neurons are either *pyramidal cells* (based on the

axons (also called nerve fibers) extensions from a neuron's cell body that transmit neural impulses to other neurons, structures in the CNS, or muscles; a neuron has only one axon, although most axons branch into many branches.

sensory neurons (also called afferent neurons) nerve cells that send neural impulses to the CNS.

motor neurons (also called efferent neurons) nerve cells that send neural impulses from the CNS to skeletal muscle fibers.

interneurons specialized nerve cells that originate and terminate in the brain or spinal cord; they function between axons descending from the brain and synapse on motor neurons, and between the axons from sensory nerves and the spinal nerves ascending to the brain.

cerebrum a brain structure in the forebrain that consists of two halves, known as the right and left cerebral hemispheres.

cerebral cortex the undulating, wrinkly, gray-colored surface of the cerebrum; it is a thin tissue of nerve cell bodies (about 2–5 mm thick) called gray matter.

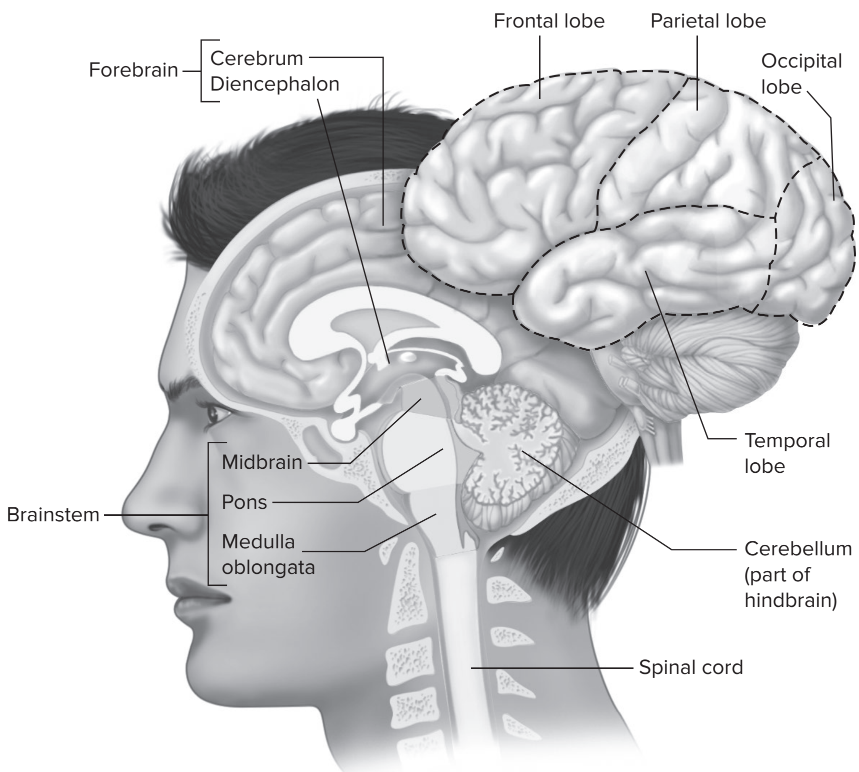

FIGURE 4.3 The major divisions of the brain and the surface of the cerebral cortex with its four lobes. *Source:* From Widmaier, E. P., Raff, H., & Strang, K. T. (2019). *Vander's human physiology: The mechanisms of body function* (15th ed.), p. 173. New York, NY: McGraw-Hill.

shape of the cell body), which are the primary cells for sending neural signals from the cortex to other parts of the CNS, or *nonpyramidal cells.* Underneath the cortex is an inner layer of myelinated nerve fibers called the *white matter.*

The cortex of each hemisphere consists of four lobes that are named according to the skull bones nearest to them. The *frontal lobe,* which is the area anterior to the central sulcus and the lateral fissure, contains brain areas that are vital to the control of voluntary movement. The *parietal lobe,* which is the area just posterior to the central fissure and superior to the lateral fissure, is a key brain center for the control of perception and the integration of sensory information. The most posterior lobe of the cortex is the *occipital lobe,* which contains areas important in visual perception. Finally, the *temporal lobe,* which is located just below the lateral fissure, plays important roles in memory, abstract thought, and judgment.

Several cortex areas are involved in sensory functions. As you can see in figure 4.4, the **sensory cortex** areas are located posterior to the central sulcus. Specific types of sensory information are transmitted via the sensory nerves to the area of the cortex that receives that type of information. Note in figure 4.4 that sensory-specific areas exist for vision, taste, speech, and body (for example, the somatic sensory area receives pain, temperature, and pressure sensory information). Also note in

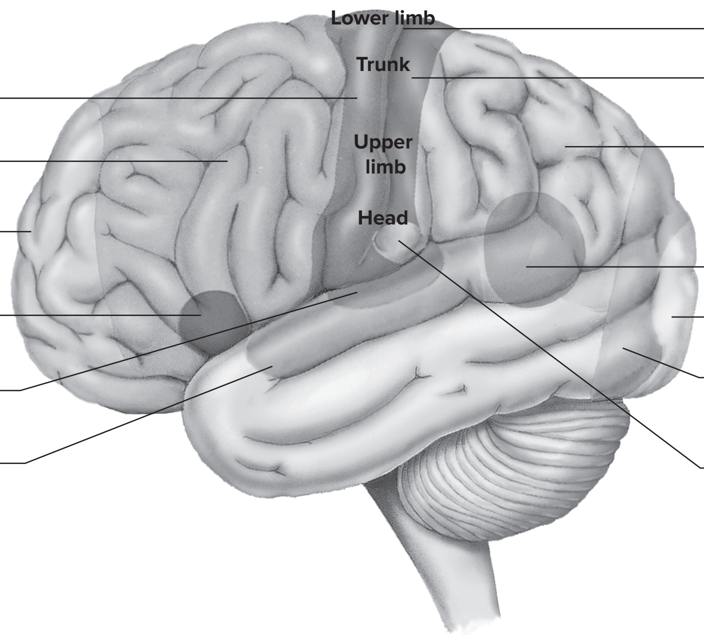

FIGURE 4.4 Functional regions of the cerebral cortex. *Source:* From Seeley, R. R., Stephens, T. D., & Tate, P. (2019). *Essentials of anatomy and physiology* (10th ed.), p. 215. New York, NY: McGraw-Hill.

figure 4.4 the proximity of the sensory and motor areas of the cortex. This proximity is the basis for these areas sometimes being referred to as the *sensorimotor cortex.*

Additional areas of the cortex that are important to note are the *association areas,* which lie adjacent to each specific sensory area in the parietal, temporal, and occipital lobes. The term *association* is used to describe these areas because it is there where the brain "associates," or connects together, information from the several different sensory cortex areas. This connecting together involves the integration of various types of sensory information as well as the sensory information from various parts of the body. In addition, the association areas connect with other cortex areas in ways that allow for the interaction between perceptual and higher-order cognitive functions, such as would occur in a choice reaction time situation where each choice alternative has a different probability of being the correct choice (see Platt & Glimcher, 1999, for an example of research showing parietal cortex involvement in this type of choice situation). Because of the activity that occurs in the association areas of the cortex, some neuroscientists consider these areas as the location for the transition between perception and the resulting action.

Four cortex areas are especially involved in the control of movement (figure 4.4 shows these and other areas related to the control of movement as well as specific sensory functions). One area, the **primary motor cortex**, which is located in the

sensory cortex cerebral cortex area located posterior to the central sulcus; it includes several specific regions that receive sensory information transmitted via the sensory nerves specific to that type of information.

primary motor cortex a cerebral cortex area located in the frontal lobe just anterior to the central sulcus; it contains motor neurons that send axons to specific skeletal muscles throughout the body.

A CLOSER LOOK

Brain-Computer Interfaces: Movement by Imagining Moving

A technological advancement called brain-computer interfaces (BCI) has shown exciting potential for helping people whose neurological disorders prevent them from physical movement to regain the capability to move. This computer-based technology takes advantage of the electrical activity in the brain that results from actively imagining the act of moving (recall the discussion in chapter 2 about the use of EEG to record brain electrical activity). As described in a "News Focus" article in *Science* (Wickelgren, 2003), BCIs read brain waves as a person imagines moving a body part. In some cases, the BCI is part of an EEG skull cap. More recent advances have developed BCIs that can be implanted inside the brain. With training the BCI can provide a means of performing in certain functional activities.*

The *Science* article reports several examples of success stories in which patients with various paralysis problems were trained with a BCI to carry out a variety of movement activities, including typing, manipulating a small wheeled robot through a model house, and moving a cursor on a computer monitor to hit icons that communicated statements such as "I'm hungry."

Since the publication of the *Science* article, many research reports have been published describing humans using BCI devices to perform functional activities. For example, researchers in Austria (Muller-Putz, Scherer, Pfurtscheller, & Rupp, 2005) reported a case study in which a patient was able to train himself in three days to use an implanted BCI so that his paralyzed hand could maneuver a prosthesis, grasping a small object and moving it from one place to another and then releasing it. Further evidence showing BCI use for grasping was presented by Pistohl and colleagues in Germany (Pistohl, Schulze-Bonhage, Aertsen, Mehring, & Ball, 2012). In addition, researchers from several European countries reported success with two subjects using an EEG-based BCI to drive a real and a simulated wheelchair along a prescribed path (Galán, Nuttin, Lew, Ferrez, Vanacker, Philips, & Milán, 2008). Successful wheelchair control has also been reported by Tsui, Gan, and Hu (2011) in the U.K and Yu et al. (2018) in China.

The continued success of research evidence of the functional use of BCI indicates strong potential for the future benefit of this technique for a wide variety of physical disabilities.

*For an excellent overview of how BCI works, go to http://computer.howstuffworks.com/brain-computer-interface.htm.

frontal lobe just anterior to the central sulcus, contains motor neurons that send axons to specific skeletal muscles throughout the body. This area of the brain is especially critical for movement initiation and the coordination of movements for fine motor skills, such as the finger movements required to type on a keyboard or play a piano. The motor cortex is also involved in the control and learning of postural coordination (see Chiou et al., 2018; Ioffe, Ustinova, Chernikova, & Kulikov, 2006; Petersen, Rosenberg, Petersen, & Nielsen, 2009). The second area, anterior to the primary motor cortex, is the **premotor area**, which controls the organization of movements before they are initiated and rhythmic coordination during movement, thus enabling the transitioning between movements for a skill that involves sequen tial movement, such as keyboard typing or piano playing. Research has also shown the importance of the premotor cortex in the performance benefit derived from the observation of actions performed by another person (Buccino et al., 2001; Holmes & Wright, 2017). In addition, the premotor cortex has been shown to play a key role in the planning of eye movements and orienting visual-spatial attention (Casarotti, Lisi, Umiltà, & Zorzi, 2012). Third, the **supplementary motor area (SMA)**, which is located on the medial surface of the frontal lobe adjacent to portions of the primary motor cortex, plays an essential role in the control of sequential movements (see Parsons, Harrington, & Rao, 2005) and in the preparation and organization of movement, especially in the anterior portion known as the pre-SMA (see Cunnington, Windischberger, & Moser, 2005).

More recently, researchers have shown the SMA to play a role, together with other brain regions, in modifying the continuous, bilateral, multijoint movements associated with variable rate pedaling (Mehta, Verber, Wieser, Schmit, & Schinder-Ivens, 2012). Finally, the **parietal lobe** has been identified in recent years as an important cortical area involved in the control of voluntary movement (Fogassi & Luppino, 2005; Gottlieb, 2007). For example, the parietal lobe plays a significant role in the control of visual and auditory selective attention (Gottlieb, 2007; Sapountzis, Paneri, & Gregoriou, 2018; Shomstein & Yantis, 2007), visually tracking a moving target (Hutton & Weekes, 2007) and grasping (Rice, Tunik, Cross, & Grafton, 2007; Rice, Tunik, & Grafton, 2006). Based on an impressive amount of research demonstrating its role in the control of perceptual and motor activities such as these, there is general agreement that the parietal lobe is especially important in the integration of movement preparation and execution processes by interacting with the premotor cortex, primary motor cortex, and SMA before and during movement (Wheaton, Nolte, Bohlhalter, Fridman, & Hallett, 2005).

An important *subcortical component* for the control of movement is the **basal ganglia** (also known as the *basal nuclei*), which are buried within the cerebral hemispheres and consist of four large nuclei: the *caudate nucleus,* the *putamen,* the *substantia nigra,* and the *globus pallidus.* The basal ganglia receive neural information from the cerebral cortex and the brainstem. Motor neural information from the basal ganglia goes primarily to the brainstem. A loop of information flow, which is important for motor control, involves the nuclei of the basal ganglia, thalamus, and motor cortex.

The basal ganglia play critical roles in the control of movement, especially in the planning and initiation of movement, the control of antagonist muscles during movement, and the control of force (see Pope, Wing, Praamstra, & Miall, 2005). Much of our knowledge of the role of the basal ganglia in motor control comes from research involving people with Parkinson's disease and cerebral palsy, both of which are basal ganglia disorders (see Neumann et al., 2018; Ioffe et al., 2006), and strokes affecting the basal ganglia (see Boyd & Winstein, 2004). For instance, in **Parkinson's disease**, several neural activities associated with the basal ganglia are negatively influenced, with decreased neural information going into the basal ganglia, unbalanced neural facilitation and inhibition interactions, and lower than normal interactions with the motor cortex. Several movement difficulties result from these problems, including bradykinesia (slow movements), akinesia (reduced amount of movement), tremor, and muscular rigidity. People with Parkinson's disease often have difficulty standing from a sitting position, initiating walking, and writing with a pen. The basal ganglia dysfunction associated with this disease results primarily from the lack of dopamine, which is a neurotransmitter important for normal basal

premotor area a cerebral cortex area located in the frontal lobe just anterior to the primary motor cortex.

supplementary motor area (SMA) a cerebral cortex area located on the medial surface of the frontal lobe adjacent to portions of the primary motor cortex.

parietal lobe an area of the cerebral cortex that plays an important role in the control of voluntary movement, such as the integration of movement preparation and execution processes by interacting with the premotor cortex, primary motor cortex, and SMA before and during movement.

basal ganglia (also known as the basal nuclei) a subcortical collection of nuclei (caudate nucleus, putamen, substantia nigra, and globus pallidus) buried within the cerebral hemispheres; they play an important role in the planning and initiation of movement and the control of antagonist muscles during movement.

Parkinson's disease a basal ganglia disorder caused by the lack of production of the neurotransmitter dopamine by the substantia nigra; the disease is characterized by slow movements (bradykinesia), a reduced amount of movement (akinesia), tremor, and muscular rigidity.

ganglia function. Dopamine is produced by neurons of the *substantia nigra;* Parkinson's disease causes these neurons to degenerate, which reduces the production of dopamine.

The diencephalon. The second component of the forebrain is the **diencephalon**, which lies between the cerebrum and the brainstem. It contains two groups of nuclei, the thalamus and hypothalamus. The *thalamus* serves an important function as a relay station, receiving and integrating most of the sensory neural inputs from the spinal cord and brainstem and then passing them through to the cerebral cortex. The thalamus plays an important role in the control of attention, mood, and the perception of pain. The hypothalamus lies just under the thalamus and is the most critical brain center for the control of the endocrine system and the regulation of body homeostasis, including temperature, hunger, thirst, and physiological responses to stress.

Cerebellum. Located behind the cerebral hemispheres and attached to the brainstem, the **cerebellum** has several distinct parts. The cerebellar cortex covers the cerebellum and, like the cerebral cortex, is divided into two hemispheres. Under the cortex lies white matter in which are embedded the deep cerebellar nuclei: the red nucleus and the oculomotor nucleus.

Sensory neural pathways into the cerebellum arise from three principal regions: the spinal cord, the cerebral cortex, and the brainstem. The motor neural pathways from the cerebellum connect to the spinal cord via the red nucleus and the descending reticular formation. Output also goes to the motor cortex by way of the central lateral nuclei of the thalamus, a neural pathway known as the cerebello-thalamo-cortico (CTC) pathway. Finally, there is output to the oculomotor nuclei, which are involved in the control of eye movements.

The cerebellum plays a key role in the execution of smooth and accurate movements. Damage to the cerebellum typically results in clumsy movement. In its role in the control of movement, the cerebellum functions as a type of movement error detection and correction system as it receives a copy of signals about an intended movement sent from the motor cortex to the muscles (often referred to as an *efference copy*) and compares the motor information with the sensory information it receives from sensory nerves that connect to the cerebellum. This comparison functions in a way that signals to the muscles any needed adjustments to movements already in progress, thus assuring achievement of the intended movement's goal. The cerebellum is also active in the control of other movement activities such as those requiring eye-hand coordination (see Miall & Jenkinson, 2005), movement timing (see Molinari, Leggio, & Thaut, 2007; Spencer, Ivry, & Zelaznik, 2005), force control (see Spraker, Corcos, Kurani, Prodoehl, Swinnen, & Vaillancourt, 2012), and posture control (see Ioffe et al., 2006). In addition, the cerebellum is very much involved in the learning of motor skills as it interacts with areas of the cerebral cortex (see Honda et al., 2018; Ioffe et al., 2006). Researchers are increasingly providing evidence that the cerebellum is also involved in cognition, especially in language, visual-spatial, and working memory processes (Stoodley, 2012), although the specific role played in these processes is only beginning to emerge (see Koziol, Budding, & Chidekel, 2012; Schmahmann, 2019).

Brainstem. Located directly under the cerebral hemispheres and connected to the spinal cord, the **brainstem** contains three main areas that are significantly involved in motor control. The *pons,* which is located at the top of the brainstem, acts as a bridge between the cerebral cortex and cerebellum. Various neural pathways either pass through the pons from the cortex on their way to the spinal cord or terminate as they come from the cortex. The pons appears to be involved in the control of body functions such as chewing, swallowing, salivating, and breathing. It may also play a role in the control of balance.

The second area, the *medulla* (also called the *medulla oblongata*), is like an extension of the spinal cord and serves as a regulatory agent for various internal physiologic processes, such as respiration, in which it interacts with the pons, and heartbeat. In terms of voluntary movement, the medulla functions as a site where the corticospinal tracts of the sensory and motor neural pathways cross over the body midline and merge on their way to the cerebellum and cerebral cortex.

The third area of the brainstem involved in motor control is the *reticular formation.* This composite of nuclei and nerve fibers is a vital link in the chain of neural structures that lie between the sensory receptors throughout the body and the motor control centers of the cerebellum and cerebral cortex. Its primary role in the control of movement is as an integrator of sensory and motor neural impulses. The reticular formation appears to have access to all sensory information and can exert direct influence on the CNS to modify activity of the CNS either by inhibiting or increasing that activity, which in turn influences skeletal muscle activity.

The limbic system. An important group of brain structures form what is known as the **limbic system**. It consists of parts of the frontal and temporal lobes of the cerebral cortex, the thalamus and hypothalamus, and the nerve fibers that interconnect these parts and other CNS structures. This system plays important roles in the learning of motor skills as well as in the control of emotions and several visceral behaviors.

The Spinal Cord

The traditional view of the spinal cord is that it is like a telephone cable that simply relays messages to and from the brain. However, we now know that the spinal cord is much more than that. It is a complex system that interacts with a variety of systems and is critically involved in motor control processes.

Spinal cord composition. The two major portions of the spinal cord are the *gray matter* and the *white matter.* The gray matter is the butterfly- or H-shaped central portion of the cord (note figure 4.5). It consists primarily of cell bodies and axons of neurons that reside in the spinal cord. Two pairs of "horns" protrude from the gray matter, both of which are vital to motor control. The posterior pair of horns, known as the *dorsal horns,* contains cells involved

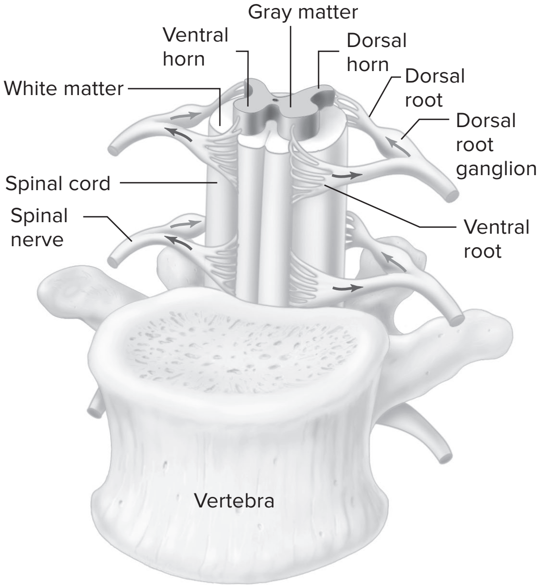

FIGURE 4.5 The structure of the spinal cord and its placement in a vertebra. The arrows indicate the direction of transmission of neural activity. *Source:* From Widmaier, E. P., Raff, H., & Strang, K. T. (2019). *Vander's human physiology: The mechanisms of body function* (15th ed.) p. 176. New York, NY: McGraw-Hill.

diencephalon a component of the forebrain located between the cerebrum and the brainstem; it contains the thalamus and hypothalamus.

cerebellum a brain structure located behind the cerebral hemispheres and attached to the brainstem; it is covered by the cerebellar cortex and is divided into two hemispheres; it plays a key role in the execution of smooth and accurate movements.

brainstem a brain structure located directly under the cerebral hemispheres and connected to the spinal cord; it contains three areas that are significantly involved in motor control: the pons, medulla, and reticular formation.

limbic system a group of brain structures consisting of parts of the frontal and temporal lobes of the cerebral cortex, the thalamus and hypothalamus, and the nerve fibers that interconnect these parts and other CNS structures; it is involved in the learning of motor skills.

in the transmission of sensory information. Sensory neurons from the various sensory receptors in the body synapse on dorsal horn neurons. The anterior pair of horns, known as the *ventral horns,* contains alpha motor neuron cell bodies whose axons terminate on skeletal muscles.

In addition to alpha motor neurons and sensory neurons, the spinal cord also contains *interneurons.* Located primarily in the ventral horn, these interneurons are called *Renshaw cells.* Many of the nerve fibers that descend from the brain terminate on interneurons rather than on motor neurons. These interneurons can influence the neural activity of alpha motor neurons by inhibiting the amount of activity, sometimes turning off the activity so that the neurons can fire again in a short period of time.

Sensory neural pathways. Several sensory neural pathways, called **ascending tracts**, pass through the spinal cord and brainstem to connect with the various sensory areas of the cerebral cortex and cerebellum. These tracts contain sequences of two or three neurons. The first neuron in the chain synapses with a sensory neuron outside the spinal cord. Most of these tracts are specialized to carry neural signals from certain types of sensory receptors, such as those specific to proprioception, touch, pain, and the like. Two ascending tracts to the sensory cortex transmit sensory information important for the control of voluntary movement. The *dorsal column* transmits proprioception, touch, and pressure information, and the *anterolateral system* transmits pain and temperature information as well as some touch and pressure information. These tracts enter the thalamus where they synapse with another sensory neuron to continue to the cerebral cortex. Several ascending tracts, called the *spinocerebellar tracts,* transmit proprioception information to the cerebellum. Two of these tracts originate in the arms and neck, and two originate in the trunk and legs. The ascending tracts cross at the brainstem from one side of the body to the other, which means that sensory information from one side of the body is received in the opposite side of the brain.

Motor neural pathways. The several sets of motor pathways (called **descending tracts**) that descend from the brain through the spinal cord can be collectively classified as *pyramidal tracts* and *extrapyramidal tracts.* Although these tracts are anatomically distinct, they are not functionally independent because both function together in the control of movement (see Beatty, 2001). The *pyramidal tract* (also called the *corticospinal tract*) originates in various parts of the cerebral cortex and projects axons to the spinal cord. This tract's name results from the pyramid shape of the tract's collection of nerve fibers as it travels from the cortex to the spinal cord. Approximately 60 percent of the pyramidal tract fibers originate in the primary motor cortex (Beatty, 2001). Most of the fibers of this tract cross over to the opposite side of the body (referred to as *decussation*) at the medulla in the brainstem and continue down the lateral column of the spinal cord. The pyramidal tract transmits information that is primarily involved in the control of movements associated with the performance of fine motor skills. Because of the pyramidal tract crossover in the brainstem, the muscles on each side of the body are controlled by the opposite cerebral hemisphere.

The *extrapyramidal tracts,* which are sometimes referred to as *brainstem pathways* (Widmaier et al., 2019), have their cell bodies in the brainstem with axons descending into the spinal cord. Unlike the pyramidal tract fibers, most of the extrapyramidal tract fibers do not cross over to the opposite side of the body. The neural pathways of these tracts are involved in postural control as well as in the facilitation and inhibition of muscles involved in the flexion and extension of hands and fingers.

The Motor Unit

The ultimate end of the transmission of motor neural information is the motor unit (figure 4.6). The concept of the motor unit was first introduced at the beginning of the twentieth century by Sherrington (1906). Defined as the alpha motor neuron and all the muscle fibers it innervates, the **motor unit** serves as the functional unit of motor control for the innervation of the muscles involved

A CLOSER LOOK

Playing a Piece of Music on a Piano Activates Different Brain Regions

One of the ways to identify the complex nature of brain activity during the performance of a motor skill, as well as the involvement of specific brain regions to process specific aspects of the performance, is to observe brain activity while a person performs a skill. An excellent demonstration of this complexity and specificity of brain activity was reported by Bengtsson and Ullén (2006), researchers at the Karolinska Institute in Sweden. Their research was based on the premise that the performance of a piece of music on a piano involves two distinct processes:

- The identification of and movement to spatial locations of the piano keys as specified by the notes on the written music (referred to as the ***melodic*** component of the written music).
- The identification and performance of specific timing features of the notes on the written music (referred to as the ***rhythmic*** component of the written music).

Using fMRI, the researchers scanned 11 professional concert pianists while they played visually displayed musical scores with their right hands on a modified keyboard that could be used in the MRI scanner. Each score required 32 key presses. The results showed that during the performances of the scores, the melodic and rhythmic components were processed by the following distinct brain regions (note that some of the brain regions are not specifically identified in the discussion in this chapter):

Melodic Component
- Medial occipital lobe
- Superior temporal lobe
- Rostral cingulated cortex
- Putamen
- Cerebellum

Rhythmic Component
- Lateral occipital lobe
- Inferior temporal lobe
- Left supramarginal gyrus
- Left inferior and ventral frontal gyri
- Caudate nucleus
- Cerebellum

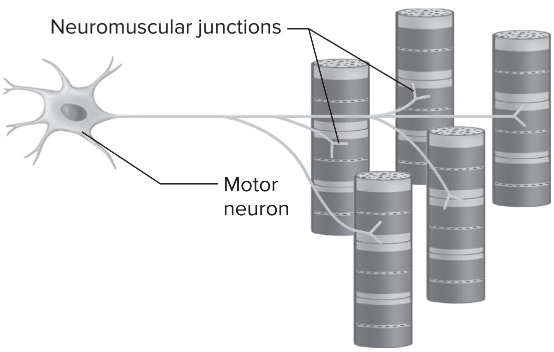

FIGURE 4.6 A single motor unit consisting of one motor neuron and the muscle fibers it innervates. *Source:* From Widmaier, E. P., Raff, H., & Strang, K. T. (2019). *Vander's human physiology: The mechanisms of body function* (15th ed.), p. 263. New York, NY: McGraw-Hill.

in a movement (figure 4.6). Some researchers estimate that in the spinal cord there may be as many as 200,000 motor neurons with their dependent motor units. The connection between an alpha motor neuron and skeletal muscle fibers occurs at the neuromuscular junction, which is located near the middle of muscle fibers. This special type of synapse allows nerve impulses to be transmitted

ascending tracts sensory neural pathways in the spinal cord and brainstem that connect with the various sensory areas of the cerebral cortex and cerebellum.

descending tracts motor neural pathways that descend from the brain through the spinal cord.

motor unit the alpha motor neuron and all the muscle fibers it innervates; it serves as the functional unit of motor control for the innervation of the muscles involved in a movement.

from the nerve fiber to the muscle fibers so that the appropriate muscle contraction can occur.

The number of muscle fibers served by one alpha motor neuron axon varies greatly. In general, muscles involved in the control of fine movements, such as the muscles of the eye and larynx, have the smallest number of muscle fibers for each motor unit, which in some cases is one per fiber. On the other hand, large skeletal muscles, such as those involved in the control of posture and gross motor skills, have the largest number of muscle fibers per motor unit, with as many as 700 muscle fibers innervated by one motor unit. When an alpha motor neuron activates (i.e., it "fires"), all the muscle fibers to which it connects contract.

Motor unit recruitment. The number of muscle fibers active at any one time influences the amount of force the muscle can exert. This variation of force is controlled by the number of motor units active in the muscle. To increase the amount of force exerted by a muscle, a process known as **motor unit recruitment** occurs in which the number of motor neurons activated increases. The recruitment of motor units follows a specific procedure that involves motor neuron size, which refers to the diameter of the neuron's cell body. The process of recruitment begins with the smallest, and therefore the weakest, motor units and systematically progresses to the largest, which are the most powerful motor units. This recruitment process is commonly referred to as the Henneman size principle (named after the initial reporting of this process by Henneman (1957)). Researchers have demonstrated this process for the performance of various motor skills.[1]

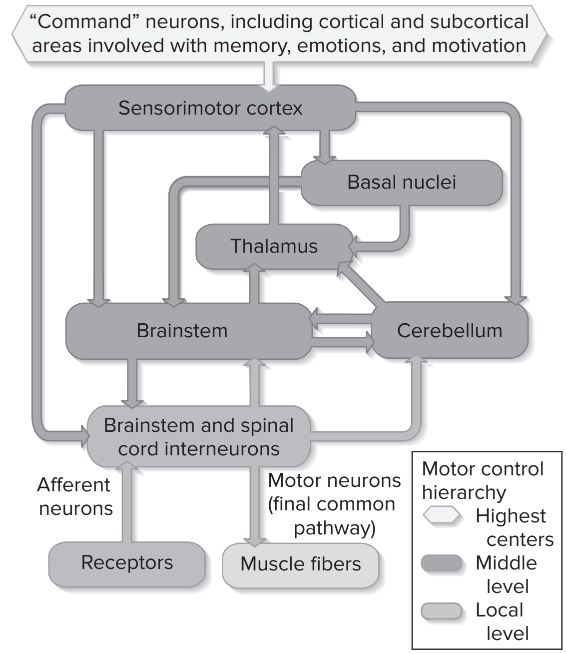

FIGURE 4.7 The diagram shows a conceptual hierarchical organization of the neural systems controlling voluntary movement. Table 4.1 describes the function of each of the three levels of the hierarchy and the specific neural structures in each level. *Source:* From Widmaier, E. P., Raff, H., & Strang, K. T. (2019). *Vander's human physiology: The mechanisms of body function* (15th ed.), p. 302. New York, NY: McGraw-Hill.

THE NEURAL CONTROL OF VOLUNTARY MOVEMENT

Performing a motor skill typically begins with a cognitively derived intent that is based on the dictates of the situation or needs of the person. If the person needs to go to a room that is up a flight of stairs, the situation and personal needs require that the person walk up the stairs. The movement implementation of this intent requires numerous neurophysiologic events that involve the cooperative interaction of many CNS structures in addition to sensory-perceptual system components and the peripheral nervous system. This interaction occurs both hierarchically and in parallel, as conceptually illustrated in figure 4.7 and table 4.1. Although the organizational diagram in the figure presents a

[1]For an excellent review of the study of motor units and associated research, see Duchateau and Enoka (2011).

motor unit recruitment the process of increasing the number of motor units needed to increase the number of muscle fibers active at any one time and thereby increase the amount of force the muscle can exert.

TABLE 4.1 Conceptual Motor Control Hierarchy for Voluntary Movements

I. Higher centers
  a. Function: forms complex plans according to individual's intention and communicates with the middle level via "command neurons."
  b. Structures: areas involved with memory, emotions and motivation, and sensorimotor cortex. All these structures receive and correlate input from many other brain structures.

II. The middle level
  a. Function: converts plans received from higher centers to a number of smaller motor programs that determine the pattern of neural activation required to perform the movement. These programs are broken down into subprograms that determine the movements of individual joints. The programs and subprograms are transmitted through descending pathways to the lowest control level.
  b. Structures: sensorimotor cortex, cerebellum, parts of basal nuclei, some brainstem nuclei.

III. The local level
  a. Function: specifies tension of particular muscles and angle of specific joints at specific times necessary to carry out the programs and subprograms transmitted from the middle control levels.
  b. Structures: brainstem or spinal cord interneurons, afferent neurons, motor neurons.

Source: From Widmaier, E. P., Raff, H., & Strang, K. T. (2019). *Vander's human physiology: The mechanisms of body function* (15th ed.), New York, NY: McGraw-Hill (Table 10.1, p. 303).

hierarchical model of structures, many of the functions of the structures described in the table are carried out in parallel, which means they occur at the same time rather than as a sequence of events. One of the notable features of the figure is its depiction of the wide distribution of brain structures involved from the initial intent to perform a skill until the neural innervation of the muscles associated with producing the movements needed to perform the skill. Clearly, a complex array of neural activities underlies the performance of seemingly simple behavioral activities.

In an essay addressing the issue of the neural correlates of coordinated movement, Carson and Kelso (2004) emphasized the importance of not limiting our understanding of the involvement of brain structures in the control of movement to different types of movements. They argue that we should also understand the interactions between regions of the CNS and the muscles in terms of the cognitive intent of the movement. That is, different CNS patterns of activity can occur when the same movement pattern is used to achieve two different action goals. Their example involves a simple flexion movement of the index finger. The two different action goals are to have the peak amount of flexion coincide with the beat (synchronization) or occur off the beat (syncopation) of an auditory metronome. Carson and Kelso describe research evidence of different neural activity in the cerebral cortex for the synchronization and syncopation tasks. When the participants' intent was to perform the synchronization task, activation of the contralateral sensorimotor cortex, SMA, and ipsilateral cerebellum occurred. In contrast, when their intent was to perform the syncopation task, additional brain areas activated, including the premotor, prefrontal, and temporal association areas, along with the basal ganglia.

SUMMARY

- The neuron is the basic component of the nervous system. There are three types of neurons in the nervous system: sensory neurons, which transmit neural information along neural pathways to the CNS; motor neurons, which transmit neural information to the muscles; and interneurons, which interact in the spinal cord with both sensory and motor neurons.

- The structural components of the brain that are most directly involved in control of movement are the cerebrum, diencephalon, cerebellum, and brainstem.
- The cerebrum consists of the right and left cerebral hemispheres, which are covered by the cerebral cortex. The cortex of each hemisphere consists of four lobes: the frontal lobe, parietal lobe, occipital lobe, and temporal lobe.
- The sensory areas of the cerebral cortex receive specific types of sensory information from the sensory nerves. Sensory-specific areas of the cortex exist for vision, taste, speech, and body.
- The association areas of the cerebral cortex integrate various types of sensory information as well as the sensory information from various parts of the body. These areas also interconnect with other cortex areas to enable the interaction between perceptual and higher-order cognitive functions.
- Four cerebral cortex areas are especially involved in the control of movement:
  - ► Primary motor cortex, which is especially critical for movement initiation and the coordination of movements for fine motor skills and posture.
  - ► Premotor area, which is involved in the organization of movements before they are initiated and the control of rhythmic coordination during movement; it plays an important role in the observation of actions performed by another person.
  - ► Supplementary motor area (SMA), which plays an essential role in the control of sequential movements and in the preparation and organization of movement.
  - ► Parietal lobe, which is involved in the integration of movement preparation and execution processes by interacting with the premotor cortex, primary motor cortex, and SMA before and during movement.
- The basal ganglia are an important subcortical component for the control of movement. They consist of the caudate nucleus, the putamen, the substantia nigra, and the globus pallidus. The basal ganglia play critical roles in the planning and initiation of movement, the control of antagonist muscles during movement, and the control of force.
- The diencephalon contains the thalamus and hypothalamus. The thalamus receives and integrates most of the sensory neural inputs from the spinal cord and brainstem and then passes them through to the cerebral cortex. The hypothalamus is the most critical brain center for the control of the endocrine system and the regulation of body homeostasis.
- The cerebellum receives sensory neural pathways and is the beginning location for several motor neural pathways. It plays a key role in the execution of smooth and accurate movements; it also functions as a type of movement error detection and correction system; and it is an important site for the control of movement activities requiring eye-hand coordination, movement timing, force control and posture control.
- The brainstem, which is connected to the spinal cord, contains three main areas that are significantly involved in motor control: the pons, medulla (also called the medulla oblongata), and reticular formation. Each area functions in specific ways that influence the control of voluntary movement.
- The spinal cord is a complex system that interacts with a variety of systems and is critically involved in motor control processes. It consists primarily of cell bodies and axons of neurons that reside in the spinal cord.
- Several sensory neural pathways, called ascending tracts, carry neural signals from the various types of sensory receptors through the spinal

cord and brainstem to connect with the sensory areas of the cerebral cortex and cerebellum. The dorsal column and the anterolateral system are two ascending tracts to the sensory cortex. The spinocerebellar tracts are ascending tracts to the cerebellum.

- Several sets of motor pathways, called descending tracts, transmit motor neural information from the brain through the spinal cord. The pyramidal tract (also called the corticospinal tract) begins in various parts of the cerebral cortex and projects to the spinal cord. The extrapyramidal tracts (also called the brainstem pathways) have their cell bodies in the brainstem with axons descending into the spinal cord.
- The motor unit, which is the ultimate end of the transmission of motor neural information, is made up of the alpha motor neuron and all the muscle fibers it innervates. It serves as the functional unit of motor control for the innervation of the muscles involved in a movement. The amount of force generated by a muscle is controlled by the number of motor units active in the muscle. To increase the amount of force exerted by a muscle, a process known as the recruitment of motor units increases the number of motor neurons activated.
- The neural control underlying the performance of a motor skill is a complex process that begins with a cognitively derived intent to perform the skill. The implementation of the movements required to achieve the goal of the intended action requires numerous neurophysiologic events that involve the cooperative interaction of many CNS structures. The structural interactions can be conceptualized hierarchically with the intent located in the higher centers of the cortex; the planning and organization of the required movements occurring in middle centers of the brain, including the sensorimotor cortex, diencephalon, cerebellum, and brainstem; and finally the execution of the movement plan involving the brainstem, spinal cord, muscle fibers, and sensory receptors.

POINTS FOR THE PRACTITIONER

- Because the intent of an action is a critical part of the planning, organization, and execution of it, be certain that the person or people you are working with have a clear understanding of what they are supposed to do when you give them instructions related to performing a skill.
- If you are working with a person who has a neurological dysfunction, be sure that you know the location of the damage in the nervous system so that you are aware of the person's capabilities and limitations in terms of planning, organizing, and executing movements.
- If you are working with a person who is taking medication to help overcome the limitations imposed by a neurological dysfunction, check with the person to make sure he or she has taken the most recent dose of the medication before beginning a rehabilitation session.

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STUDY QUESTIONS

1. (a) Describe the general structure of a neuron, the function of each component, and the three different types of neurons and their functions. (b) How does the structure of a sensory neuron differ from the structure of the other two types of neurons?
2. Identify by name and location the four parts of the brain that are the most actively involved in the control of voluntary movement.
3. Identify by name and location the areas of the cerebral cortex that are most actively involved in the control of voluntary movement, and describe the role each area plays in motor control.
4. Describe the location of the cerebellum and discuss its roles in motor control.
5. Explain the neurological basis for Parkinson's disease.
6. Describe the structural characteristics of the spinal cord and their functions in the control of voluntary movement.
7. Distinguish between the ascending and descending tracts of the CNS and describe their functions in the control of voluntary movement.
8. Describe a motor unit and its function in the control of voluntary movement. Discuss how the motor unit is involved in the generation of muscular force.
9. Discuss the three-part hierarchical organization that characterizes the neural control of voluntary movement.

Specific Application Problem:
Describe a motor skill that you perform and describe the performance effects that would result from an injury to or neurological dysfunction of one of the parts of the central nervous system.