INTRODUCTION

The purpose of this chapter is to provide the student with a review of neuroanatomy. Basic structures within the nervous system are described and their functions discussed. This information is important to physical therapists and physical therapist assistants who treat patients with neurologic dysfunction because it assists clinicians with identifying clinical signs and symptoms. In addition, it allows the physical therapist assistant to develop an appreciation of the patient’s prognosis and potential functional outcome. It is, however, outside the scope of this text to provide a comprehensive discussion of neuroanatomy. The reader is encouraged to review the works of Cohen (1999), Curtis (1990), Farber (1982), FitzGerald (1996), Gilman and Newman (2003), Littell (1990), Lundy-Ekman (2002), and others for a more in-depth review of these concepts.

MAJOR COMPONENTS OF THE NERVOUS SYSTEM

The nervous system is divided into two parts, the central nervous system (CNS) and the peripheral nervous system (PNS). The CNS is composed of the brain, the cerebellum, the brain stem, and the spinal cord, whereas the PNS comprises all the components outside the cranium and spinal cord. Physiologically, the PNS is divided into the somatic nervous system and the autonomic nervous system (ANS). Figure 2-1 illustrates the major components of the CNS.

The nervous system is a highly organized communication system that serves the body. Nerve cells within the nervous system receive, transmit, analyze, and communicate information to other areas throughout the body. For example, sensations such as touch, proprioception, pain, and temperature are transmitted from the periphery as electrochemical impulses to the CNS through sensory tracts. Once information is processed within the brain, it is relayed as new electrochemical impulses to peripheral structures through motor tracts. This transmission process is responsible for an individual’s ability to interact with the environment. Individuals are able to perceive sensory experiences, to initiate movement, and to perform cognitive tasks as a result of a functioning nervous system.

Types of Nerve Cells

The brain, brain stem, and spinal cord are composed of two basic types of nerve cells called neurons and neuroglia. Three different subtypes of neurons have been identified based on their function: (1) afferent neurons, (2) interneurons, and (3) efferent neurons. Afferent or sensory neurons are responsible for receiving sensory input from the periphery of the body and transporting it into the CNS. Interneurons connect neurons to other neurons. Their primary function is to organize information received from many different sources for later interpretation. Efferent or motor neurons transmit information to the extremities to signal muscles to produce movement.

Neuroglia are non-neuronal supporting cells that provide critical services for neurons. Three different types of neuroglia (astrocytes, oligodendrocytes, and microglia) have been identified. Astrocytes are responsible for maintaining the capillary endothelium and as such provide a vascular link to neurons. Additionally, astrocytes contribute to the metabolism of the CNS and regulate extracellular concentrations of neurotransmitters (Gilman and Newman, 2003). Oligodendrocytes wrap myelin sheaths around axons in the white matter and produce satellite cells in the gray matter that participate in ion exchange between neurons. Microglia cells are known as the phagocytes of the CNS. They engulf and digest pathogens and assist with nervous system repair after injury.

Neuron Structures

As depicted in Figure 2-2, a neuron consists of a cell body, dendrites, and an axon. The dendrite is responsible for

OBJECTIVES

After reading this chapter, the student will be able to

1. Differentiate between the central and peripheral nervous systems.
2. Identify significant structures within the nervous system.
3. Understand primary functions of structures within the nervous system.
4. Describe the vascular supply to the brain.
5. Discuss components of the cervical, brachial, and lumbosacral plexuses.
receiving information and transferring it to the cell body, where it is processed. Dendrites bring impulses into the cell body from other neurons. The number and arrangement of dendrites present in a neuron vary. The cell body or soma is composed of a nucleus and a number of different cellular organelles. The cell body is responsible for synthesizing proteins and supporting functional activities of the neuron, such as transmitting electrochemical impulses and repairing cells. Cell bodies that are grouped together in the CNS appear gray and thus are called gray matter. Groups of cell bodies with similar functions are assembled together to form nuclei. The axon is the message-sending component of the nerve cell. It extends from the cell body and is responsible for transmitting impulses from the cell body to target cells that can include muscle cells, glands, or other neurons.

**Synapses**

The space between the axon of one neuron and the dendrite of the next neuron is called the **synapse**. Synapses are the connections between neurons that allow different parts of the nervous system to communicate with and influence each other. An axon transports electrical impulses or chemicals called neurotransmitters to and across synapses. The relaying of information from one neuron to the next takes place at the synapse.

**Neurotransmitters**

Neurotransmitters are chemicals that transmit information across the synapse. An in-depth discussion of neurotransmitters is beyond the scope of this text. We will, however, discuss some common neurotransmitters because of their relationship to CNS disease. Furthermore, many of the pharmacologic interventions available to patients with CNS pathology act by facilitating or inhibiting neurotransmitter activity. Common neurotransmitters include acetylcholine, glutamate, γ-aminobutyric acid (GABA), dopamine, and norepinephrine. "Acetylcholine is the neurotransmitter used by all neurons that synapse with muscle..."
fibers (lower motor neurons)” (Lundy-Ekman, 2002). Acetylcholine also plays a role in regulating heart rate and other autonomic functions. Glutamate is an excitatory neurotransmitter and facilitates neuronal change during development. Glutamate is also thought to contribute to neuron destruction after an injury to the CNS. GABA is an inhibitory neurotransmitter and exerts its influence over interneurons within the spinal cord. Dopamine influences motor activity, motivation, and cognition. Norepinephrine is used by the ANS and produces the “fight-or-flight response” to stress (Lundy-Ekman, 2002).

**Axons**

Once information is processed, it is conducted to other neurons, muscle cells, or glands by the axon. Axons can be myelinated or unmyelinated. Myelin is a lipid/protein that encases and insulates the axon. The presence of a myelin sheath increases the speed of impulse conduction, thus allowing for increased responsiveness of the nervous system. The myelin sheath surrounding the neuron is not continuous; it contains interruptions or spaces within the myelin called the nodes of Ranvier. Saltatory conduction is the process whereby electrical impulses are conducted along an axon by jumping from one node to the next (Fig. 2-3). This process increases the velocity of nervous system impulse conduction. Unmyelinated axons send messages more slowly than myelinated ones.

**White Matter**

Areas of the nervous system with a high concentration of myelin appear white because of the fat present within the myelin. Consequently, white matter is composed of axons that carry information away from cell bodies. White matter is found in the brain and spinal cord. Myelinated axons are bundled together within the CNS to form fiber tracts.

**Gray Matter**

Gray matter refers to areas that contain large numbers of nerve cell bodies and dendrites. Collectively, these cell bodies give the region its grayish coloration. Gray matter covers the entire surface of the cerebrum and is called the cerebral cortex. The cortex is estimated to contain 14 billion neurons (Gilman and Newman, 2003). Gray matter is also present deep within the spinal cord and is discussed in more detail later in this chapter.

**Fibers and Pathways**

Major sensory or afferent tracts carry information to the brain, and major motor or efferent tracts relay transmissions from the brain to smooth and skeletal muscles. Sensory information enters the CNS through the spinal cord or by the cranial nerves as the senses of smell, sight, hearing, touch, taste, heat, cold, pressure, pain, and movement. Information travels in fiber tracts composed of axons that ascend in a particular path from the sensory receptor to the cortex for interpretation. Motor signals descend from the cortex to the spinal cord through efferent fiber tracts for muscle activation. Fiber tracts are designated by their point of origin and by the area in which they terminate. Thus, the corticospinal tract, the primary motor tract, originates in the cortex and terminates in the spinal cord. The lateral spinothalamic tract, a sensory tract, begins in the lateral white matter of the spinal cord and terminates in the thalamus. A more thorough discussion of motor and sensory tracts is presented later in this chapter.

**Brain**

The brain consists of the cerebrum, which is divided into two cerebral hemispheres (the right and the left), the cerebellum, and the brain stem. The surface of the cerebrum or cerebral cortex is composed of depressions (sulci) and ridges (gyri). These convolutions increase the surface area of the cerebrum without requiring an increase in the size of the brain. The outer surface of the cerebrum is composed of gray matter and is estimated to be 1.3 to 4.5 mm thick, whereas the inner surface is composed of white matter fiber tracts (Gilman and Newman, 2003). Therefore, information is conveyed by the white matter and is processed and integrated within the gray matter.

**Supportive and Protective Structures**

The brain is protected by a number of different structures and substances to minimize the possibility of injury. First, the brain is surrounded by a bony structure called the skull or cranium. The brain is also covered by three layers of membranes called meninges, which provide additional protection. The outermost layer is the dura mater. The dura is a thick, fibrous connective tissue membrane that adheres to the cranium. The area between the dura mater and the skull is known as the epidural space. The next or middle layer is the arachnoid. The space between the dura and the arachnoid is called the subdural space. The third protective layer is the pia mater. This is the innermost layer and adheres to the brain.
itself. The pia mater also contains the cerebral circulation. The cranial meninges are continuous with the membranes that cover and protect the spinal cord. Cerebrospinal fluid bathes the brain and circulates within the subarachnoid space. Figure 2-4 shows the relationship of the skull with the cerebral meninges.

**Lobes of the Cerebrum**

The cerebrum is divided into four lobes—frontal, parietal, temporal, and occipital—each having unique functions, as shown in Figure 2-5, A. The hemispheres of the brain, although apparent mirror images of one another, have specialized functions as well. This sidedness of brain function is called hemispheric specialization or lateralization.

**Frontal Lobe.** The frontal lobe is frequently referred to as the primary motor cortex. The frontal lobe is responsible for voluntary control of complex motor activities. In addition to its motor responsibilities, the frontal lobe also exhibits a strong influence over cognitive functions, including judgment, attention, awareness, abstract thinking, mood, and aggression. The principal motor region responsible for speech (Broca’s area) is located within the frontal lobe. In the left hemisphere, Broca’s area plans movements of the mouth to produce speech. In the opposite hemisphere, this same area is responsible for nonverbal communication, including gestures and adjustments of the individual’s tone of voice.

**Parietal Lobe.** The parietal lobe is the primary sensory cortex. Incoming sensory information is processed and meaning is provided to stimuli within this lobe. Perception is the process of attaching meaning to sensory information. Much of our perceptual learning requires a functioning parietal lobe. Specific body regions are assigned locations within the parietal lobe for this interpretation. This mapping is known as the sensory homunculus (Fig. 2-5, B). The parietal lobe also plays a role in short-term memory functions.

**Temporal Lobe.** The temporal lobe is the primary auditory cortex. Wernicke’s area of the temporal lobe allows an individual to hear and comprehend spoken language. Visual perception, musical discrimination, and long-term memory capabilities are all functions of the temporal lobe.

**Occipital Lobe.** The occipital lobe is the primary visual cortex providing for the organization, integration, and interpretation of visual information. The eyes take in visual information and then send it to the occipital cortex for interpretation.

**Association Cortex**

Association areas are regions within the parietal, temporal, and occipital lobes that horizontally link different parts of the cortex. For example, the sensory association cortex integrates and interprets information from all the lobes receiving sensory input and allows individuals to perceive and attach meaning to sensory experiences. Additional functions of the association areas include personality, memory, intelligence (problem solving and comprehension of spatial relationships), and the generation of emotions (Lundy-Ekman, 2002). Figure 2-5, C, depicts association areas within the cerebral hemispheres.

**Motor Areas of the Cerebral Cortex**

The primary motor cortex, located in the frontal lobe, is primarily responsible for contralateral voluntary control of upper extremity and facial movements. Thus, a greater proportion of the total surface area of this region is devoted to neurons that control these body parts. Other motor areas include the premotor area, which controls muscles of the trunk and anticipatory postural adjustments, and the supplementary motor area, which controls initiation of movement, orientation of the eyes and head, and bilateral, sequential movements (Lundy-Ekman, 2002).

**Hemispheric Specialization**

The cerebrum can be further divided into the right and left cerebral hemispheres. Gross anatomic differences have been demonstrated within the hemispheres. The hemisphere that is responsible for language is considered the dominant hemisphere. Approximately 95 percent of the population, including all right-handed individuals, are left hemisphere dominant. Even in individuals who are left-hand dominant, the left hemisphere is the primary speech center in about 50 percent of
these people (Geschwind and Levitsky, 1968; Gilman and Newman, 2003; Guyton, 1991; Lundy-Ekman, 2002). Table 2-1 lists primary functions of both the left and right cerebral hemispheres.

**Left Hemisphere Functions.** The left hemisphere has been described as the verbal or analytic side of the brain. The left hemisphere allows for the processing of information in a sequential, organized, logical, and linear manner.
The processing of information in a step-by-step or detailed fashion allows for thorough analysis. For the majority of people, language is produced and processed in the left hemisphere, specifically the frontal and temporal lobes. The left parietal lobe allows an individual to recognize words and to comprehend what has been read. In addition, mathematical calculations are performed in the left parietal lobe. An individual is able to sequence and perform movements and gestures as a result of a functioning left frontal lobe. A final behavior assigned to the left cerebral hemisphere is the expression of positive emotions such as happiness and love.

Common impairments seen in patients with left hemispheric injury include an inability to plan motor tasks (apraxia); difficulty in initiating, sequencing, and processing a task; difficulty in producing or comprehending speech; perseveration of speech or motor behaviors; and anxiousness (O’Sullivan, 2001).

**Right Hemisphere Functions.** The right cerebral hemisphere is responsible for an individual’s nonverbal and artistic abilities. The right side of the brain allows individuals to process information in a complete or holistic fashion without specifically reviewing all the details. The individual is able to grasp or comprehend general concepts. Visual-perceptual functions including eye-hand coordination, spatial relationships, and perception of one’s position in space are carried out in the right hemisphere. The ability to communicate nonverbally and to comprehend what is being expressed is also assigned to the right parietal lobe. Nonverbal skills including understanding facial gestures, recognizing visual-spatial relationships, and being aware of body image are processed in the right side of the brain. Other functions include mathematical reasoning and judgment, sustaining a movement or posture, and perceiving negative emotions such as anger and unhappiness (O’Sullivan, 2001). Specific deficits that can be observed in patients with right hemisphere damage include poor judgment, unrealistic expectations, denial of disability or deficits, disturbances in body image, irritability, and lethargy.

**Hemispheric Connections**

Even though the two hemispheres of the brain have discrete functional capabilities, they perform many of the same actions. Communication between the two hemispheres is constant, so individuals can be analytic and yet still grasp broad general concepts. It is possible for the right hand to know what the left hand is doing and vice versa. The corpus callosum is a large group of axons that connect the right and left cerebral hemispheres and allow communication between the two cortices.

**Deeper Brain Structures**

Subcortical structures lie deep within the brain and include the internal capsule, the diencephalon, and the basal ganglia. These structures are briefly discussed because of their functional significance to motor function.

**Internal Capsule.** All descending fibers leaving the motor areas of the frontal lobe travel through the internal capsule, a deep structure within the cerebral hemisphere. The internal capsule is made up of axons that project from the cortex to the white matter fibers (subcortical structures) located below and from subcortical structures to the cerebral cortex. The capsule is shaped like a less-than sign (<), with an anterior and a posterior limb. The corticospinal tract travels in the posterior part of the capsule and allows information to be transmitted from the cortex to the brain stem and spinal cord. A lesion within this area can cause contralateral loss of voluntary movement and conscious somatosensation, which is the ability to perceive tactile and proprioceptive input. The internal capsule is pictured in Figure 2-6.

**Diencephalon.** The diencephalon is situated deep within the cerebrum and is composed of the thalamus and...
hypothalamus. The diencephalon is the area where the major sensory tracts (dorsal columns and lateral spinothalamic) and the visual and auditory pathways synapse. The thalamus consists of a large collection of nuclei and synapses. In this way, the thalamus serves as a central relay station for sensory impulses traveling upward from other parts of the body and brain to the cerebrum. It receives all sensory impulses except those associated with the sense of smell and channels them to appropriate regions of the cortex for interpretation. Moreover, the thalamus relays sensory information to the appropriate association areas within the cortex. Motor information received from the basal ganglia and cerebellum is transmitted to the correct motor region through the thalamus. Sensations of pain and peripheral numbness can also be identified at the level of the thalamus.

Hypothalamus. The hypothalamus is a group of nuclei that lie at the base of the brain, underneath the thalamus. The hypothalamus regulates homeostasis, which is the maintenance of a balanced internal environment. This structure is primarily involved in automatic functions, including the regulation of hunger, thirst, digestion, body temperature, blood pressure, sexual activity, and sleep-wake cycles. The hypothalamus is responsible for integrating the functions of both the endocrine system and the ANS through its regulation of the pituitary gland and its release of hormones.

Basal Ganglia. Another group of nuclei located at the base of the cerebrum comprise the basal ganglia. The basal ganglia form a subcortical structure made up of the caudate, putamen, globus pallidus, substantia nigra, and subthalamic nuclei. The globus pallidus and putamen form the lentiform nucleus, and the caudate and putamen are known as the striatum. The nuclei of the basal ganglia influence the motor planning areas of the cerebral cortex through various motor circuits. Primary responsibilities of the basal ganglia include the regulation of posture and muscle tone and the control of volitional and automatic movement. In addition to their role in motor control, the caudate nucleus is involved in cognitive functions. The most common condition that results from dysfunction within the basal ganglia is Parkinson disease. Patients with Parkinson disease exhibit bradykinesia (slowness initiating movement), akinesia (difficulty in initiating movement), tremors, rigidity, and postural instability. Death of the cells in the substantia nigra, which produces dopamine, has been identified as the cause of this disease.

Limbic System. The limbic system is a group of deep brain structures in the diencephalon and cortex that includes parts of the thalamus and hypothalamus and a portion of the frontal and temporal lobes. The hypothalamus controls primitive emotional reactions, including rage and fear. The limbic system guides the emotions that regulate behavior.
and is involved in learning and memory. More specifically, the limbic system appears to control memory, pain, pleasure, rage, affection, sexual interest, fear, and sorrow.

**Cerebellum**

The cerebellum controls balance and complex muscular movements. It is located below the occipital lobe of the cerebrum and is posterior to the brain stem. It fills the posterior fossa of the cranium. Like the cerebrum, it also consists of two symmetric hemispheres. The cerebellum is responsible for the integration, coordination, and execution of multijoint movements. The cerebellum regulates the initiation, timing, sequencing, and force generation of muscle contractions. It sequences the order of muscle firing when a group of muscles work together to perform a movement such as stepping or reaching. The cerebellum also assists with balance and posture maintenance and has been identified as a comparator of actual motor performance to that which is anticipated. The cerebellum monitors and compares the movement requested, for instance, the step, with the movement actually performed (Horak, 1991).

**Brain Stem**

The brain stem is located between the base of the cerebrum and the spinal cord and is divided into three sections (Fig. 2-7). Moving cephalocaudally, the three areas are the midbrain, pons, and medulla. Each of the different areas is responsible for specific functions. The midbrain connects the diencephalon to the pons and acts as a relay station for tracts passing between the cerebrum and the spinal cord or cerebellum. The midbrain also houses reflex centers for visual, auditory, and tactile responses. The pons contains bundles of axons that travel between the cerebellum and the rest of the CNS and functions with the medulla to regulate the breathing rate. It also contains reflex centers that assist with orientation of the head in response to visual and auditory stimulation. Cranial nerve nuclei can also be found within the pons, specifically, cranial nerves V through VIII, which carry motor and sensory information to and from the face. The medulla is an extension of the spinal cord and contains the fiber tracts that run through the spinal cord. Motor and sensory nuclei for the neck and mouth region are located within the medulla, as well as the control centers for heart and respiration rates. Reflex centers for vomiting, sneezing, and swallowing are also located within the medulla.

The reticular activating system is also situated within the brain stem and extends vertically throughout its length. The system maintains and adjusts an individual’s level of arousal, including sleep-wake cycles. In addition, the reticular activating system facilitates the voluntary and autonomic motor responses necessary for certain self-regulating, homeostatic functions and is involved in the modulation of muscle tone throughout the body.

**Spinal Cord**

The spinal cord has two primary functions: coordination of motor information and movement patterns and communication of sensory information. Subconscious reflexes, including withdrawal and stretch reflexes, are integrated within the spinal cord. Additionally, the spinal cord provides a means of communication between the brain and the peripheral nerves. The spinal cord is a direct continuation of the brain stem, specifically the medulla. The spinal cord is housed within the vertebral column and extends approximately to the level of the first lumbar vertebra. The spinal cord has two enlargements, one that extends from the third cervical segment to the second thoracic segment and another that extends from the first lumbar to the third sacral segment.
segment. These enlargements accommodate the great number of neurons needed to innervate the upper and lower extremities located in these regions. At approximately the L1 level, the spinal cord becomes a cone-shaped structure called the conus medullaris. The conus medullaris is composed of sacral spinal segments. Below this level, the spinal cord becomes a mass of spinal nerve roots called the cauda equina. The cauda equina consists of the nerve roots for spinal nerves L2 through S5. Figure 2-8 depicts the spinal cord and its relation to the brain. A thin filament, the filum terminale, extends from the caudal end of the spinal cord and attaches to the coccyx. In addition to the bony protection offered by the vertebrae, the spinal cord is also covered by the same protective meningeal coverings as in the brain.

**Internal Anatomy**

The internal anatomy of the spinal cord can be visualized in cross-sections and is viewed as two distinct areas. Figure 2-9, A, illustrates the internal anatomy of the spinal cord. Like the brain, the spinal cord is composed of gray and white matter. The center of the spinal cord, the gray matter, is distinguished by its H-shaped or butterfly-shaped pattern. The gray matter contains cell bodies of motor and sensory neurons and synapses. The upper portion is known as the dorsal or posterior horn and is responsible for transmitting sensory stimuli. The lower portion is referred to as the anterior or ventral horn (Fig. 2-9, B). It contains cell bodies of lower motor neurons, and its primary function is to transmit motor impulses. The lateral horn is present at the T1 to L2 levels and contains cell bodies of preganglionic sympathetic neurons. It is responsible for processing autonomic information. The periphery of the spinal cord is composed of white matter. The white matter is composed of sensory (ascending) and motor (descending) fiber tracts. A tract is a group of nerve fibers that are similar in origin, destination, and function. These fiber tracts carry impulses to and from various areas within the nervous system. In addition, these fiber tracts cross over from one side of the body to the other at various points within the spinal cord and brain. Therefore, an injury to the right side of the spinal cord may produce a loss of motor or sensory function on the contralateral side.

**Major Afferent (Sensory) Tracts**

Two primary ascending sensory tracts are present in the white matter of the spinal cord. The dorsal or posterior columns carry information about position sense (proprioception), vibration, two-point discrimination, and deep touch. Figure 2-10 shows the location of this tract. The fibers of the dorsal columns cross in the brain stem. Pain and temperature sensations are transmitted in the spinothalamic tract located anterolaterally in the spinal cord (see Fig. 2-10). Fibers from this tract enter the spinal cord, synapse, and cross within three segments. Sensory information must be relayed to the thalamus. Touch information has to be processed by the cerebral cortex for discrimination to occur. Light touch and pressure sensations enter the spinal cord, synapse, and are carried in the dorsal and ventral columns.

**Major Efferent (Motor) Tract**

The corticospinal tract is the primary motor pathway and controls skilled movements of the extremities. This tract originates in the frontal lobe from the primary and premotor cortices and continues through interconnections and various synapses, finally to synapse on anterior horn cells in the spinal cord. This tract also crosses from one side to the other in the brain stem. A common indicator of corticospinal tract damage is the Babinski sign. To test for this sign, the clinician takes a blunt object such as the back of a pen and runs it along the lateral border of the patient’s foot (Fig. 2-11). The sign is present when the great toe extends and the other toes splay. The presence of a Babinski sign indicates that damage to the corticospinal tract has occurred.

**Other Descending Tracts**

Other descending motor pathways that affect muscle tone are the rubrospinal, lateral and medial vestibulospinal,
tectospinal, and medial and lateral reticulospinal tracts. The rubrospinal tract originates in the red nucleus of the midbrain and terminates in the anterior horn, where it synapses with lower motor neurons that primarily innervate the upper extremities. Fibers from this tract facilitate flexor motor neurons and inhibit extensor motor neurons. Proximal muscles are primarily affected, although the tract does exhibit some influence over more distal muscle groups. The rubrospinal tract has been said to assist in the correction of movement errors. The lateral vestibulospinal tract assists in postural adjustments through facilitation of proximal extensor muscles. Regulation of muscle tone in the neck and upper back is a function of the medial vestibulospinal tract. The medial reticulospinal tract facilitates limb extensors, whereas the lateral reticulospinal tract facilitates flexors and inhibits extensor muscle activity. The tectospinal tract provides for orientation of the head toward a sound or a moving object.

**Anterior Horn Cell**

An anterior horn cell is a large neuron located in the gray matter of the spinal cord. An anterior horn cell sends out axons
through the ventral or anterior spinal root; these axons eventually become peripheral nerves and innervate muscle fibers. Thus, activation of an anterior horn cell stimulates skeletal muscle contraction. Alpha motor neurons are a type of anterior horn cell that innervates skeletal muscle. Because of axonal branching, several muscle fibers can be innervated by one neuron. A motor unit consists of an alpha motor neuron and the muscle fibers it innervates. Gamma motor neurons are also located within the anterior horn. These motor neurons transmit impulses to the intrafusal fibers of the muscle spindle.

**Muscle Spindle**

The muscle spindle is the sensory organ found in skeletal muscle and is composed of motor and sensory endings and muscle fibers. These fibers respond to stretch and therefore provide feedback to the CNS regarding the muscle’s length.

The easiest way to conceptualize how the muscle spindle functions within the nervous system is to review the stretch reflex mechanism. Stretch or deep tendon reflexes can easily be facilitated in the biceps, triceps, quadriceps, and gastrocnemius muscles. If a sensory stimulus such as a tap on the patellar tendon is applied to the muscle and its spindle, the input will enter through the dorsal root of the spinal cord to synapse on the anterior horn cell (alpha motor neurons). Stimulation of the anterior horn cell elicits a motor response, reflex contraction of the quadriceps (extension of the knee), as information is carried through the anterior root to the skeletal muscle. An important note about stretch or deep tendon reflexes is that their activation and subsequent motor response can occur without higher cortical influence. The sensory input coming into the spinal cord does not have to be transmitted to the

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**FIGURE 2-10.** Cross-section of the spinal cord showing tracts. (From Gould BE. *Pathophysiology for the Health-Related Professions*. Philadelphia, WB Saunders, 1997.)

**FIGURE 2-11.** A. Stroking from the heel to the ball of the foot along the lateral sole, then across the ball of the foot, normally causes the toes to flex. B, Babinski sign in response to the same stimulus. In corticospinal tract lesions, or in infants less than 6 months old, the big toe extends, and the other toes fan outward. (From Lundy-Ekman L. *Neuroscience: Fundamentals for Rehabilitation*, 2nd edition. Philadelphia, WB Saunders, 2002.)
cortex for interpretation. This has clinical implications because it means that a patient with a cervical spinal cord injury can continue to exhibit lower extremity deep tendon reflexes despite lower extremity paralysis.

**Peripheral Nervous System**

The peripheral nervous system (PNS) consists of the nerves leading to and from the CNS, including the cranial nerves exiting the brain stem and the spinal roots exiting the spinal cord, many of which combine to form peripheral nerves. These nerves connect the CNS functionally with the rest of the body through sensory and motor impulses. Figure 2-12 provides a schematic representation of the PNS and its transition to the CNS.

The PNS is divided into two primary components: the somatic (body) nervous system and the ANS. The somatic or voluntary nervous system is concerned with reactions to outside stimulation. This system is under conscious control and is responsible for skeletal muscle contraction by way of the 31 pairs of spinal nerves. By contrast, the ANS is an involuntary system that innervates glands, smooth (visceral) muscle, and the myocardium. The primary function of the ANS is to maintain homeostasis, an optimal internal environment. Specific functions include the regulation of digestion, circulation, and cardiac muscle contraction.

**Somatic Nervous System**

Within the PNS are 12 pairs of cranial nerves, 31 pairs of spinal nerves, and the ganglia or cell bodies associated with the cranial and spinal nerves. The cranial nerves are located in the brain stem and can be either sensory or motor nerves. Primary functions of the cranial nerves include eye movement, smell, sensation perceived by the face and tongue, and innervation of the sternocleidomastoid and trapezius muscles. See Table 2-2 for a more detailed list of cranial nerves and their major functions.

**Neuroanatomy**

![Image of neuroanatomy](image-url)
The spinal nerves consist of 8 cervical, 12 thoracic, 5 lumbar, and 5 sacral nerves and 1 coccygeal nerve. Cervical spinal nerves C1 through C7 exit above the corresponding vertebrae. Because there are only 7 cervical vertebrae, the C8 spinal nerve exits above the T1 vertebra. From that point on, each succeeding spinal nerve exits below its respective vertebra. Figure 2-13 shows the distribution and innervation of the peripheral nerves.

Spinal nerves, consisting of sensory (posterior or dorsal root) and motor (anterior or ventral root) components, exit the intervertebral foramen. The region of skin innervated by sensory afferent fibers from an individual spinal nerve is called a dermatome. Myotomes are a group of muscles innervated by a spinal nerve. Once through the foramen, the spinal nerve divides into two primary rami. This division represents the beginning of the PNS. The dorsal or posterior rami innervate the paravertebral muscles, the posterior aspects of the vertebrae, and the overlying skin. The ventral or anterior primary rami innervate the intercostal muscles, the muscles and skin in the extremities, and the anterior and lateral trunk.

The 12 pairs of thoracic nerves do not join with other nerves and maintain their segmental relationship. However, the anterior primary rami of the other spinal nerves join together to form local networks known as the cervical, brachial, and lumbosacral plexuses (Guyton, 1991). The reader is given only a brief description of these nerve plexuses, because a detailed description of these structures is beyond the scope of this text.

**Cervical Plexus.** The cervical plexus is composed of the C1 through C4 spinal nerves. These nerves primarily innervate the deep muscles of the neck, the superficial anterior neck muscles, the levator scapulae, and portions of the trapezius and sternocleidomastoid. The phrenic nerve, one of the specific nerves within the cervical plexus, is formed from branches of C3 through C5. This nerve innervates the diaphragm, the primary muscle of respiration, and is the only motor and main sensory nerve for this muscle (Guyton, 1991). Figure 2-14 identifies components of the cervical plexus.

**Brachial Plexus.** The anterior primary rami of C5 through T1 form the brachial plexus. The plexus divides and comes together several times, providing muscles with motor and sensory innervation from more than one spinal nerve root level. The five primary nerves of the brachial plexus are the musculocutaneous, axillary, radial, median, and ulnar nerves. Figure 2-15 depicts the constituency of the brachial plexus. These five peripheral nerves innervate the majority of the upper extremity musculature, with the exception of the medial pectoral nerve (C8), which innervates the pectoralis muscles; the subscapular nerve (C5 and C6), which innervates the subscapularis; and the thoracodorsal nerve (C7), which supplies the latissimus dorsi muscle (Guyton, 1991).

The musculocutaneous nerve innervates the forearm flexors. The elbow, wrist, and finger extensors are innervated by the radial nerve. The median nerve supplies the forearm pronators and the wrist and finger flexors, and it allows thumb abduction and opposition. The ulnar nerve assists the median nerve with wrist and finger flexion, abducts and adds the fingers, and allows for opposition of the fifth finger (Guyton, 1991).

**Lumbosacral Plexus.** Although some authors discuss the lumbar and sacral plexuses separately, they are discussed here as one unit because together they innervate lower extremity musculature. The anterior primary rami of L1 through S3 form the lumbosacral plexus. This plexus innervates the muscles of the thigh, lower leg, and foot. This plexus does not undergo the same separation and reuniting as does the brachial plexus. The lumbosacral plexus has eight roots, which eventually form six primary peripheral nerves: obturator, femoral, superior gluteal, inferior gluteal, common peroneal, and tibial. The sciatic nerve, which is frequently

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**TABLE 2-2 Cranial Nerves**

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<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Function</th>
<th>Connection to Brain</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Olfactory</td>
<td>Smell</td>
<td>Inferior frontal lobe</td>
</tr>
<tr>
<td>II</td>
<td>Optic</td>
<td>Vision</td>
<td>Diencephalon</td>
</tr>
<tr>
<td>III</td>
<td>Oculomotor</td>
<td>Moves eye up, down, medially; raises upper eyelid; constricts pupil</td>
<td>Midbrain (anterior)</td>
</tr>
<tr>
<td>IV</td>
<td>Trochlear</td>
<td>Moves eye medially and down</td>
<td>Midbrain (posterior)</td>
</tr>
<tr>
<td>V</td>
<td>Trigeminal</td>
<td>Facial sensation, chewing, sensation from temporomandibular joint</td>
<td>Pons (lateral)</td>
</tr>
<tr>
<td>VI</td>
<td>Abduces</td>
<td>Abducts eye</td>
<td>Between pons and medulla</td>
</tr>
<tr>
<td>VII</td>
<td>Facial</td>
<td>Facial expression, closes eye, tears, salivation, taste</td>
<td>Between pons and medulla</td>
</tr>
<tr>
<td>VIII</td>
<td>Vestibulocochlear</td>
<td>Sensation of head position relative to gravity and head movement; hearing</td>
<td>Between pons and medulla</td>
</tr>
<tr>
<td>IX</td>
<td>Glossopharyngeal</td>
<td>Swallowing, salivation, taste</td>
<td>Medulla</td>
</tr>
<tr>
<td>X</td>
<td>Vagus</td>
<td>Regulates viscera, swallowing, speech, taste</td>
<td>Medulla</td>
</tr>
<tr>
<td>XI</td>
<td>Accessory</td>
<td>Elevates shoulders, turns head</td>
<td>Spinal cord and medulla</td>
</tr>
<tr>
<td>XII</td>
<td>Hypoglossal</td>
<td>Moves tongue</td>
<td>Medulla</td>
</tr>
</tbody>
</table>

discussed in physical therapy practice, is actually composed of the common peroneal and tibial nerves encased in a sheath. This nerve innervates the hamstrings and causes hip extension and knee flexion. The sciatic nerve separates into its components just above the knee (Guyton, 1991). The lumbosacral plexus is shown in Figures 2-16 and 2-17.

**Peripheral Nerves.** Two major types of nerve fibers are contained in peripheral nerves: motor (efferent) and sensory (afferent) fibers. Motor fibers have a large cell body with multiple branched dendrites and a long axon. The cell body and the dendrites are located within the anterior horn of the spinal cord. The axon exits the anterior horn through the white matter and is located with other similar axons in the anterior root, which is located outside the spinal cord in the intervertebral foramen. The axon then eventually becomes part of a peripheral nerve and innervates a motor end plate in a muscle. The sensory neuron, on the other hand, has a dendrite that originates in the skin, muscle tendon, or Golgi tendon organ and travels all the way to its cell body, which is located in the dorsal root ganglion within the intervertebral foramen (Fig. 2-18). Golgi tendon organs are encapsulated nerve endings found at the musculotendinous junction. They are sensitive to tension within muscle tendons and transmit this information to the spinal cord. The axon travels through the dorsal (posterior) root of a spinal nerve and into the spinal cord through the dorsal horn. The axon may terminate at this point, or it may enter the white matter fiber tracts and ascend to a different level in the spinal cord or brain stem. Thus, a sensory neuron sends information from the periphery to the spinal cord.

**Autonomic Nervous System**

Functions of the autonomic nervous system (ANS) include the regulation of circulation, respiration, digestion, metabolism, secretion, body temperature, and reproduction. Control centers for the ANS are located in the hypothalamus and the brain stem. The ANS is composed of motor neurons located within spinal nerves that innervate smooth muscle, cardiac muscle, and glands, which are also called effectors or target organs. The ANS is divided into the sympathetic and parasympathetic divisions. Both the sympathetic and parasympathetic divisions innervate internal organs, use a two-neuron pathway and one-ganglion impulse conduction, and function automatically. Autoregulation is achieved by integrating information from peripheral afferents with information from receptors within the CNS. The two-neuron pathway (preganglionic and postganglionic neurons) provides the connection from the CNS to the autonomic effector organs. Cell bodies of the preganglionic neurons are located within the brain or spinal cord. The myelinated axons exit the CNS and synapse with collections of postganglionic cell bodies. Unmyelinated axons from the postganglionic neurons ultimately innervate the effector organs (Farber, 1982).

**FIGURE 2-16.** The lumbar plexus and its branches, especially the femoral nerve. (From Guyton AC. Basic Neuroscience: Anatomy and Physiology, 2nd edition. Philadelphia, WB Saunders, 1991.)

**FIGURE 2-17.** The sacral plexus and its branches, especially the sciatic nerve. (From Guyton AC. Basic Neuroscience: Anatomy and Physiology, 2nd edition. Philadelphia, WB Saunders, 1991.)
The sympathetic fibers of the ANS arise from the thoracic and lumbar portions of the spinal cord. Axons of preganglionic neurons terminate in either the sympathetic chain or the prevertebral ganglia located in the abdomen. The sympathetic division of the ANS assists the individual in responding to stressful situations and is often referred to as the fight-or-flight response. Sympathetic responses help the individual to prepare to cope with the perceived stimulus by maintaining an optimal blood supply. Activation of the sympathetic system stimulates smooth muscle in the blood vessels to contract, thereby causing vasoconstriction. Norepinephrine, also known as noradrenaline, is the major neurotransmitter responsible for this action. Consequently, heart rate and blood pressure are increased as the body prepares for a fight or to flee a dangerous situation. Blood flow to muscles is increased by being diverted from the gastrointestinal tract.

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The parasympathetic division maintains vital bodily functions or homeostasis. The parasympathetic division receives its information from the brain stem, specifically cranial nerves III (oculomotor), VII (facial), IX (glossopharyngeal), and X (vagus), and from lower sacral segments of the spinal cord. The vagus nerve is a parasympathetic preganglionic nerve. Motor fibers within the vagus nerve innervate the myocardium and the smooth muscles of the lungs and digestive tract. Activation of the vagus nerve can produce the following effects: bradycardia, decreased force of cardiac muscle contraction, bronchoconstriction, increased mucus production, increased peristalsis, and increased glandular secretions. Efferent activation of the sacral components results in emptying of the bowels and bladder and arousal of sexual organs. Acetylcholine is the chemical transmitter responsible for sending nervous system impulses to effector cells in the parasympathetic division. Acetylcholine is used for both divisions at the preganglionic synapse and dilates arterioles. Thus, activation of the parasympathetic division produces vasodilation. When an individual is calm, parasympathetic activity decreases heart rate and blood pressure and signals a return of normal gastrointestinal activity. Figure 2-19 shows the influence of the sympathetic and parasympathetic divisions on effector organs (Farber, 1982; Lundy-Ekman, 2002).

The CNS also exerts influence over the ANS. The regions most closely associated with this control are the hypothalamus, which regulates functions such as digestion, and the medulla, which controls heart and respiration rates.
Cerebral Circulation

A final area that must be reviewed when discussing the nervous system is the circulation to the brain. The cells within the brain completely depend on a continuous supply of blood for glucose and oxygen. The neurons within the brain are unable to carry out glycolysis and to store glycogen. It is therefore absolutely essential that these neurons receive a constant supply of blood. Knowledge of cerebrovascular anatomy is the basis for understanding the clinical manifestations, diagnosis, and management of patients who have sustained cerebrovascular accidents and traumatic brain injuries.

Anterior Circulation

All arteries to the brain arise from the aortic arch. The first major arteries ascending anteriorly and laterally within the neck are the common carotid arteries. The carotid arteries are responsible for supplying the bulk of the cerebrum with circulation. The right and left common carotid arteries bifurcate just behind the posterior angle of the jaw to become the external and internal carotids. The external carotid arteries supply the face, whereas the internal carotids enter the cranial and supply the cerebral hemispheres, including the frontal lobe, the parietal lobe, and parts of the temporal lobe. In addition, the internal carotid artery supplies the optic nerves and the retina of the eyes. At the base of the brain, the internal carotid bifurcates into the right and left anterior and middle cerebral arteries. The middle cerebral artery is the largest of the cerebral arteries and is most often occluded. It is responsible for supplying the lateral surface of the brain with blood and also the deep portions of the frontal and parietal lobes. The anterior cerebral artery supplies the superior border of the frontal and parietal lobes. Both the middle cerebral artery and the anterior cerebral artery make up what is called the anterior circulation to the brain. Figures 2-20 and 2-21 depict the cerebral circulation.

Posterior Circulation

The posterior circulation is composed of the two vertebral arteries, which are branches of the subclavian. The vertebral arteries supply blood to the brain stem and cerebellum. The vertebral arteries leave the base of the neck and ascend posteriorly to enter the skull through the foramen magnum. The two vertebral arteries then unite to form the basilar artery. The basilar artery supplies the brain stem and the medial portion of the temporal and occipital lobes with circulation. This artery also bifurcates to form the right and left posterior cerebral arteries. The two posterior cerebral arteries supply blood to the occipital and temporal lobes.

The anterior and posterior communicating arteries, which are branches of the carotid and basilar arteries, are interconnected at the base of the brain and form the circle of Willis. This connection of blood vessels provides a protective mechanism to the structures within the brain.

Because of the circle of Willis, failure or occlusion of one cerebral artery does not critically decrease blood flow to that region. Consequently, the occlusion can be circumvented or bypassed to meet the nutritional and metabolic needs of cerebral tissue.

REACTION TO INJURY

What happens when the CNS or the PNS is injured? The CNS and the PNS are prone to different types of injury, and each system reacts differently. Within the CNS, artery obstruction of sufficient duration produces cell and tissue death within minutes. Neurons that die because they are deprived of oxygen do not possess the capacity to regenerate. Neurons in the vicinity of damage are also at risk of injury secondary to the release of glutamate, an excitatory neurotransmitter. At normal levels, glutamate assists with CNS functions; however, at higher levels glutamate can be toxic to neurons and can promote neuronal death. The presence of excessive glutamate also facilitates calcium release, which ultimately produces a cascade of events including the liberation of calcium-dependent digestive enzymes, cellular edema, cell injury, and death (Lundy-Ekman, 2002).

Changes within the neurons themselves are not evident for 12 to 24 hours. By 24 to 36 hours, the damaged area
becomes soft and edematous. Liquefaction and cavitation begin, and the area of necrotic tissue is eventually converted into a cyst. In time, the infarct will eventually retract, and the cystic cavity will be surrounded by a glial scar. The damaged neurons will not be replaced, and the original function of the area will be lost (Branch, 1987).

Nearby undamaged axons demonstrate collateral sprouting 4 to 5 days after injury. These sprouts replace the damaged synaptic area, thus increasing input to other neurons. Although these collateral sprouts do not replace original circuits, they do develop from systems most closely associated with the injured area.

Conversely, peripheral nerve injuries often result from means other than vascular compromise. Common causes of peripheral nerve injuries include stretching, laceration, compression, traction, disease, chemical toxicity, and nutritional deficiencies. The response of a peripheral nerve to the injury is different from that in the CNS. If the cell body is destroyed, regeneration is not possible. The axon undergoes necrosis distal to the site of injury, the myelin sheath begins to pull away, and the Schwann cells phagocytize the area, producing wallerian degeneration (Fig. 2-22). If the damage to the peripheral nerve is not too significant and occurs only to the axon, regeneration is possible. Axonal sprouting from the proximal end of the damaged axon can occur. The axon regrows at the rate of 1.0 mm per day depending on the size of the nerve fiber (Lundy-Ekman, 2002). To have a return of function, the axon must grow and reinnervate the appropriate muscle. Failure to do so results in degeneration of the axonal sprout. The rate of recovery from a peripheral nerve injury depends on the age of the patient and the distance between the lesion and the destination of the regenerating nerve fibers. A discussion of the physical therapy management of peripheral nerve injuries is beyond the scope of this text.

Injury to a motor neuron can result in variable findings. If an individual experiences damage to the corticospinal tract from its origin in the frontal lobe to its end within the spinal cord, the patient is classified as having an upper motor neuron injury. Clinical signs of an upper motor neuron injury include spasticity (increased resistance to passive stretch), hyperreflexia, the presence of a Babinski sign, and possible clonus. Clonus is a repetitive stretch reflex that is elicited by passive dorsiflexion of the ankle or passive wrist extension. If the injury is to the anterior horn cell, the motor nerve cells of the brain stem, the spinal root, or the spinal nerve, the patient is recognized as having a lower
motor neuron injury. Clinical findings of this type of injury include flaccidity, marked muscle atrophy, muscle fasciculations, and hyporeflexia.

**REFERENCES**


