

# Exercise Science: A Systems Approach

***After completing this chapter you will be able to:***

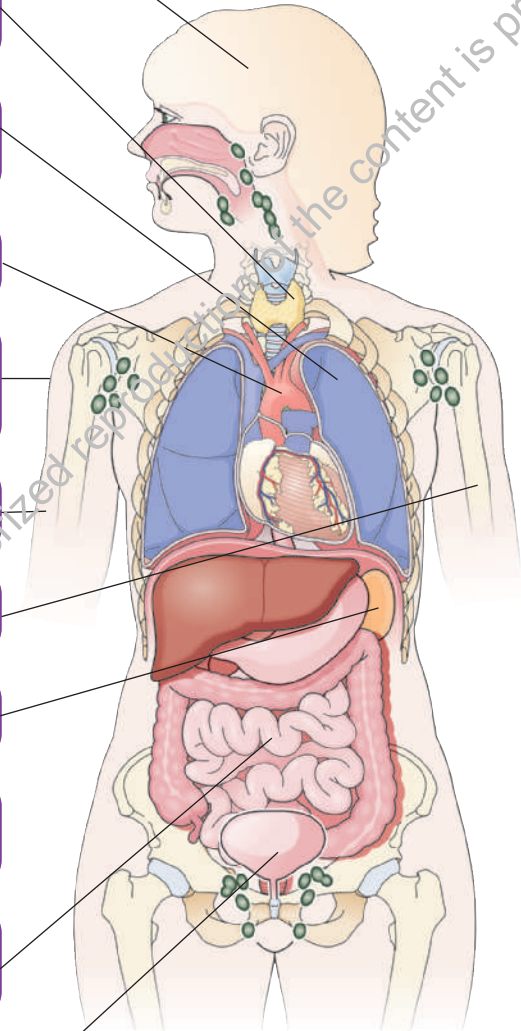
1. Describe the meaning and context of a systems approach to the study of exercise science.
2. Articulate the primary functions of each system of the body.
3. Provide examples of how each system of the body can influence physical activity and exercise.
4. Provide examples of how each system of the body can influence sport and athletic performance.

**As discussed in Chapter 1**, several interrelated disciplines, subdisciplines, and specialty areas constitute exercise science. Collectively, the study of each component of exercise science is based on a core understanding of the structure (anatomy) and function (physiology) of the human body. It is expected that beginning exercise science students enroll in courses in human anatomy and physiology, often in the first year of study in college. The knowledge acquired in these courses provides the necessary foundation for advanced study in exercise science at both the undergraduate and graduate levels.

A systems approach to the study of exercise science allows students to understand how the various systems of the body respond in an integrated fashion to acute and chronic stimuli and conditions. Each system has specific functions that cannot be performed in the expected manner in isolation and without interaction with other systems of the body. This system integration provides for the coordinated control of the body environment and allows the body to respond to the challenges encountered every day. Appropriate responses to challenges, such as physical activity, regular exercise, stress, changes in nutritional intake, and extreme environmental conditions, allow us to be healthy and perform at optimal levels during sport and athletic competition.

This chapter presents a systems approach to the study of exercise science. To maintain a current and accurate knowledge base with today's rapid generation of information, exercise science students must be able to draw on their conceptual understanding of how systems work together to participate in physical activity, exercise, sport, and athletic performance. Athletic trainers, clinical exercise physiologists, sport biomechanists, and other exercise science professionals are better prepared to perform their job by having a solid understanding of how the various structures and systems of the body interrelate and function together. For example, a clinical exercise physiologist designing a rehabilitation program for an individual recovering from a heart attack must understand how the nervous, cardiovascular, pulmonary, endocrine, and muscular systems work together to create movement and respond appropriately to physical activity and exercise. Only with a sound understanding of the structure and functioning of the body's integrated systems, can the clinical exercise physiologist design a rehabilitation program that is safe and effective in preparing the individual to return to activities of daily living and occupational activities without an elevated level of risk for an adverse medical event. Figure 3.1 illustrates the various systems of the body. This chapter provides a short description of the systems of the body and examples of how each system is affected by or responds to (a) physical activity and exercise and (b) sport and athletic performance. This information should provide a foundation for which exercise science students begin to understand the importance of an integrated systems approach to the study of exercise science.

- Nervous system**  
Acts through electrical signals to manage rapid responses of the body. Also responsible for higher functions including consciousness, memory, and creativity.
- Endocrine system**  
Acts by means of hormones secreted into the blood to manage processes that require duration rather than speed (e.g., metabolic activities and water and electrolyte balance).
- Respiratory system**  
Obtains oxygen from and eliminates carbon dioxide to the external environment. Helps regulate body pH by adjusting the rate of removal of acid-forming carbon dioxide.
- Circulatory system**  
Transports nutrients, oxygen, carbon dioxide, waste products, electrolytes, and hormones throughout the body.
- Integumentary system**  
Serves as protective barrier between external environment and remainder of body, also includes sweat glands. Makes adjustments in skin blood flow important to body temperature regulation.
- Muscular system**  
Allows body movement and heat-generation through muscle contractions which is important in body temperature regulation.
- Skeletal system**  
Supports and protects body parts and provides calcium storage in bone.
- Immune system**  
Protects the body against foreign invaders and tumor cells, assists with tissue repair.
- Energy system**  
Not a physically defined system but important to all life requiring processes. Provides energy through aerobic and anaerobic pathways in all cells.
- Digestive system**  
Obtains nutrients, water, and electrolytes from the external environment and transfers them into the plasma. Eliminates undigested food residues to the external environment.
- Urinary system**  
Important in regulating the volume, electrolyte composition, and pH of the internal environment. Removes wastes and excess water, sodium, acids, bases, and electrolytes from the plasma and excretes them in the urine.
- Reproductive system**  
Not essential for homeostasis but essential for perpetuation of the species.



**FIGURE 3.1** Systems of the body. (Adapted from Sherwood L. *Fundamentals of Physiology: A Human Perspective*. Belmont (CA): Thompson Publishing; 2006.)

## NERVOUS SYSTEM

The nervous system is one of the two primary control systems of the body (the other primary control system is the endocrine system). One advantage of the nervous system for controlling the body is that responses can occur very rapidly, typically within a fraction of a second. The nervous system controls the voluntary and involuntary

actions and functions of the body and works with other systems to regulate and respond to challenges, such as exercise or disease conditions. For ease of study, we generally divide the nervous system into the central and peripheral components, but, in reality, the two components function together very closely. The brain and the spinal cord form the primary components of the central nervous system. The peripheral nervous system includes the **afferent neurons** and **efferent neurons**, the motor end plates connecting efferent neurons to muscle fibers, and the sensory receptors on sensory

organs. The efferent neurons are further divided into the **somatic** neurons and the **autonomic** neurons. Figure 3.2 depicts the organization of the nervous system (118).

Each component of the nervous system is responsible for several important functions related to the study of exercise science, with two primary interest areas being the control of body movement by skeletal muscles and the role of the higher brain centers in performing voluntary physical activity and movement. Chapter 9 (Motor Behavior) provides information on the neural control of movement, whereas Chapter 8 (Exercise and Sport Psychology) addresses issues related to exercise behavior and sport performance.

The autonomic nervous system has two divisions: **sympathetic** and **parasympathetic**. These systems work in conjunction to regulate the various functions of the body. The sympathetic nervous system's level of activity is increased when the body is required to respond to higher levels of stress. Because physical activity and exercise act as stressors to the body, there is an increased level of sympathetic nervous system activity during increased body movement. The parasympathetic nervous system is more active during resting conditions and after food consumption. The coordinated interaction of these two systems allows for both subtle and significant changes in body function to occur. A good example



### Thinking Critically

*Why would an understanding of how the systems of the body interact contribute to a greater understanding of how physical activity and exercise influence health and how regular exercise training affects sport and athletic performance?*



**Afferent neurons** Nerves that carry electric impulses toward the brain and spinal cord.

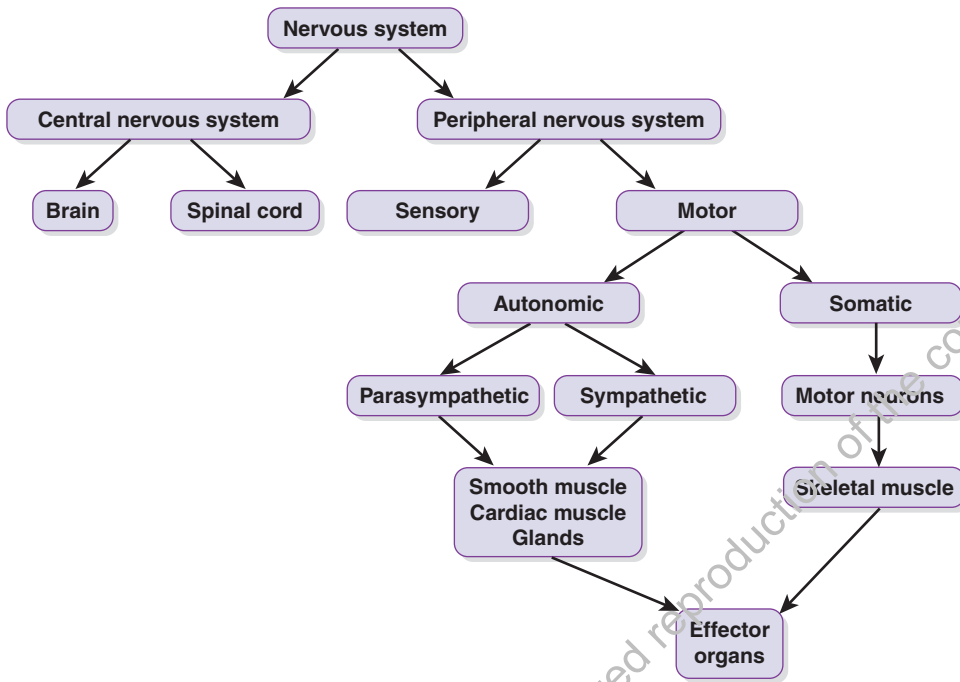
**Efferent neurons** Nerves that carry electric impulses away from the brain and spinal cord.

**Somatic** Part of the nervous system that controls voluntary action.

**Autonomic** Part of the nervous system that regulates involuntary action.

**Sympathetic** Part of the autonomic nervous system that tends to act in opposition to the parasympathetic nervous system, especially under conditions of stress.

**Parasympathetic** Part of the autonomic nervous system that tends to act in opposition to the sympathetic nervous system.



**FIGURE 3.2** Organizational structure of the nervous system.

of this interaction would be during the start of exercise. The increased sympathetic activity and the decreased parasympathetic activity result in an increase in heart rate, force of cardiac muscle contraction, and blood pressure, as well as a redistribution of blood flow from inactive tissues (e.g., stomach and kidneys) to active tissues (e.g., heart and skeletal muscle). These changes allow the body to coordinate an appropriate response to meet the demands of exercise.

## Nervous System and Exercise Science

Although many neurologic disorders can affect the body's response to physical activity and exercise, many affected individuals can achieve significant health benefits with participation in regular physical activity and exercise programs. For example, the disease condition cerebral palsy interferes with the normal development of areas of the brain that control muscle tone and spinal reflexes. This results in limited ability to move and maintain balance and posture (76). The location and extent of the injury within the brain influences the resulting changes in muscle tone and spinal reflex sequelae that occurs (76). Medical doctors classify individuals based on functional ability, which can be beneficial for helping to identify an appropriate exercise program (76). Individuals with cerebral palsy can benefit from participation in an exercise program focusing on the development of muscular strength, flexibility, and cardiovascular fitness (57, 101, 102, 110). Owing to the nature of the disorder, resistance exercise may be a more suitable type of exercise

**Table 3.1 Neurologic Disorders and the Potential Benefits of Exercise (5)**

NEUROLOGIC DISORDER	BENEFITS OF EXERCISE
Alzheimer disease	Increased fitness, physical function, cognitive function, and positive behavior
Amyotrophic lateral sclerosis	Maintain strength in healthy muscle fibers and range of motion in joints
Cerebral palsy	Improved fitness, work capacity, and sense of wellness
Deaf and hard of hearing	Improved fitness, balance, self-image, and confidence, with enhanced socialization skills
Epilepsy	Improved fitness
Mental illness	Improved fitness, mood, self-concept, and work behavior with decreased depression and anxiety
Multiple sclerosis	Improved fitness and functional performance
Muscular dystrophy	Slow down or possibly reverse the deterioration in muscle function
Parkinson disease	Enhanced functionality and movement
Polio and postpolio syndrome	Improved fitness and lower leg strength
Spinal cord injury	Improved fitness and sense of well-being
Stroke and head injury	Improved fitness and muscular strength
Visual impairment	Improved fitness, balance, self-image, and confidence, with enhanced socialization skills

for individuals with cerebral palsy to perform (110). Exercise science professionals can play a valuable role in helping individuals affected with many neurologic disorders. Table 3.1 lists the various neurologic disorders that can have improved health and fitness outcomes as a result of well-planned and appropriate physical activity and exercise program (5). For additional information about the role of exercise in treatment programs for neurologic disorders, the reader is directed to *American College of Sports Medicine (ACSM) Exercise Management for Persons with Chronic Disease and Disability* (5).

Various components of the nervous system can play an important role in sport and athletic performance. For example, it is believed that as an aerobic endurance athlete becomes better trained, there are changes to the autonomic nervous system that could lead to improvements in performance (30, 46, 47). Following training, increases in parasympathetic nervous activity allow for a reduced heart rate, thereby leading to a longer filling time of the heart during the period of diastole.



**Stroke volume** The volume of blood pumped from the heart with each contraction.

**Cardiac output** The volume of blood pumped by the heart per unit of time, usually 1 minute.

**Table 3.2 Functions of the Nervous System and their Relationship to Physical Activity, Exercise, Sport, and Athletic Performance (118)**

<b>FUNCTION</b>	<b>RELATIONSHIP TO PHYSICAL ACTIVITY, EXERCISE, SPORT, AND ATHLETIC PERFORMANCE</b>
Afferent neurons provide central nervous system (CNS) with sensory and visceral information	Allows for a rapid and coordinated control of body systems in response to movement
Control centers for cardiovascular, respiratory, and digestive systems	Allows for a rapid and coordinated response to movement
Controls activity of smooth muscle, cardiac muscle, and glands through the autonomic nervous system	Allows for a rapid and coordinated response of body systems to movement
Efferent neurons control movement of skeletal muscle through somatic nervous system	Allows for the body to contract skeletal muscle and create movement
Maintenance of balance	Allows for correct positioning of the body during movement
Regulation of temperature control, thirst, urine output, and food intake	Allows for the body to regulate the internal environment, remove waste products, and supply energy to the tissues in response to movement
Voluntary control of movement, thinking, memory, decision-making, creativity, self-consciousness, role in motor control	Allows for control of the body during participation in any type of movement

The increased filling results in a greater **stroke volume** during each contraction of the heart, which in turn causes a higher **cardiac output**, and hence more blood being pumped to working tissues. The changes in autonomic nervous system activity also allow for an increased blood flow to active tissues (e.g., skeletal muscle) during exercise (16). The higher cardiac output and enhanced blood flow to working tissues would result in a greater oxygen delivery to skeletal muscle and most likely an improvement in aerobic endurance performance (16, 108). Table 3.2 provides a summary of the major functions of the nervous system and examples of how those functions relate to physical activity, exercise, sport, and athletic performance.

## MUSCULAR SYSTEM

The muscular system works in conjunction with both the nervous system and the skeletal system to create movement of the human body. In response to nervous system input, the various muscles of the body contract and generate force. The contraction of skeletal muscle causes the bones to which they are attached to move, creating movement of the body parts. Skeletal muscle, because of its ability to generate energy and heat, also helps maintain an appropriate body temperature. Contraction of smooth muscle, found in the walls of the hollow organs and

**Table 3.3 Nomenclature, Specific Contractile, and Metabolic Characteristics of Skeletal Muscle Fibers (48, 69)**

CHARACTERISTIC	TYPE OF FIBER		
	TYPE I—SLOW OXIDATIVE	TYPE IIA—FAST OXIDATIVE	TYPE IIB—FAST GLYCOLYTIC
Speed of contraction	Slow	Fast	Fast
Resistance to fatigue	High	Intermediate	Low
Myosin ATPase activity	Low	High	High
Oxidative energy capacity	High	High	Low
Nonoxidative energy capacity	Low	Intermediate	High
Color of fiber	Red	Red	White

tubes in the body, regulates the movement of blood through the blood vessels, food through the digestive tract, air through the respiratory airways, and urine through the urinary tract. Contraction of cardiac muscle, found in the walls of the heart, generates the force by which the heart delivers blood to the tissues of the body (49, 118).

The primary components of the muscular system are the individual muscle fibers (i.e., muscle cells). Muscle fibers can generate force through the interaction of various contractile and regulatory proteins. This force allows the different types of muscle to perform their specific functions in very unique ways. Muscle fibers have distinct characteristics depending on the type of muscle (e.g., skeletal, smooth, and cardiac). Skeletal muscle fibers are typically named based on certain contractile or metabolic characteristics. Table 3.3 describes the nomenclature, contractile properties, and metabolic characteristics of skeletal muscle (48, 69).

Smooth muscle and cardiac muscle share some basic properties with skeletal muscle, yet each type also displays unique characteristics regarding the force and speed of contraction. In general, the contraction process in all three types of muscle is the same. For example, the initiation of contraction in muscle occurs through a calcium-dependent process, and the generation of force occurs via the sliding protein filament theory. There are some other significant differences among the three muscle types. For example, skeletal muscle is under voluntary control, whereas smooth and cardiac muscles are controlled by the autonomic nervous system. Furthermore, the force of smooth and cardiac muscles contraction can be influenced directly by various hormones from the endocrine system, whereas skeletal muscle cannot (49, 73, 118).

### Muscular System and Exercise Science

Previously sedentary individuals who begin an exercise program for improving their health and fitness are likely to experience delayed-onset muscle soreness



in the active muscles. This muscle soreness generally appears 24 to 48 hours after strenuous exercise and can last for up to 72 to 96 hours. Delayed-onset muscle soreness is believed to result from tissue injury caused by excessive mechanical force exerted upon the muscle fibers and connective tissue (14, 37, 38, 108, 121). Delayed-onset muscle soreness occurs most frequently after unaccustomed exercise, such as high-intensity resistance exercise (108). It is thought that delayed-onset muscle soreness is a result of damage to cellular membranes and proteins in skeletal muscle. This causes the immune system to create an inflammatory response in the muscle, thereby leading to the formation of swelling. Afferent nerves become stimulated in response to the swelling, and the individual feels pain in the muscle. **Eccentric muscle actions** appear to cause greater damage to the tissues and more substantial soreness and pain in the affected muscle (21). The phenomenon of delayed-onset muscle soreness has been studied by exercise science and allied health care professionals in an effort to understand how this soreness develops and to determine whether there are any preventive measures that might eliminate or at least reduce the amount of muscular soreness experienced. A reduction in muscle soreness might improve compliance when starting an exercise program. Gradually increasing the intensity when beginning an exercise program, while simultaneously avoiding strenuous eccentric muscle actions, appears to be the best way to avoid delayed-onset muscle soreness. Whereas some types of treatment therapy have shown promising results for reducing delayed-onset muscle soreness (95, 120), other preventive and treatment measures such as hyperbaric oxygen therapy and prostaglandin-inhibiting drugs seem to provide little protection or relief from delayed-onset muscle soreness (52, 74, 92).

High-intensity resistance exercise training results in significant gains in muscle size and strength that can result in an improvement in sport and athletic performance. The increase in muscle size can occur as a result of either increases in the size of the individual muscle fibers (called **muscle fiber hypertrophy**) or increases in the number of individual muscle fibers (called **muscle fiber hyperplasia**). Muscle fiber hypertrophy has been demonstrated to occur in response to resistance exercise training; however, there is still some question as to whether muscle fiber hyperplasia occurs (79, 86). Growth-promoting agents from the endocrine system help stimulate muscle hypertrophy in conjunction with a training program. Athletes who have engaged in high-intensity and high-volume resistance exercise training for many years appear to have more muscle fibers per motor unit than the average person (75). Additionally, the use of anabolic steroids and other human and synthetic growth-promoting agents may result in an increase in the number of



**Eccentric muscle actions** When the muscle fibers lengthen when generating force.

**Muscle fiber hypertrophy** An increase in the muscle fiber cross-sectional size.

**Muscle fiber hyperplasia** An increase in the number of muscle fibers in a muscle.



**FIGURE 3.3** A resistance-trained athlete who has experienced muscle hypertrophy. (Photo from Blend Images/John Lund/Sam Diephuis/Getty Images.)

individual fibers within a muscle (65). If hyperplasia does occur, it could result from one of two proposed mechanisms (2, 65, 68). First, the fiber number could increase if the existing fibers hypertrophied to the extent that the individual fiber became so large that it split into more than one fiber. A second mechanism for increasing muscle fiber number could occur if existing **undifferentiated satellite cells** in the muscle are stimulated to grow into fully developed muscle fibers. Regardless of the mechanism involved in muscle fiber hyperplasia, the increase in number appears to be small and dependent on a variety of factors, including genetic profile, training history, nutritional intake, and the use of growth-promoting substances (65, 68). Figure 3.3 shows a resistance-trained athlete who has experienced muscle hypertrophy. Table 3.4 provides the functions of the muscular system and examples of how those functions relate to physical activity, exercise, sport, and athletic performance (118).



**Undifferentiated satellite cells** An undeveloped cell that has the potential to convert to a developed cell.

**Table 3.4 Functions of the Muscular System and their Relationship to Physical Activity, Exercise, Sport, and Athletic Performance**

FUNCTION	RELATION TO PHYSICAL ACTIVITY, EXERCISE, SPORT, AND ATHLETIC PERFORMANCE
Cardiac muscle contraction propels blood through the circulatory system	Delivers nutrients and oxygen to the working tissues of the body and removes waste products
Skeletal muscle generates movement, which increases energy expenditure and heat production	Allows for body movement, responsible for the majority of daily energy expenditure
Smooth muscle contraction and dilation regulates diameter of passageways in the cardiovascular and respiratory systems	Allows for coordinated flow of blood to working tissues and air to the lungs for gas exchange

## SKELTAL SYSTEM

The skeletal system serves as a structural framework of the body, protecting the underlying organs and tissues of the body, providing a lever system for movement, and serving as a storage area of minerals important to the body's function. The skeletal system is also involved in blood cell formation. During body movement, the skeletal system works with the muscular system to create movement or to respond to nervous system stimulus. This close interaction of the muscular and skeletal systems often leads to the two systems being discussed together as the musculoskeletal system (93, 118).

The minerals, such as calcium and phosphorus, and the different cells that constitute the bone marrow are the primary components of the skeletal system. The bones provide structural support, which transfers the weight of the body to the ground through the lower extremities. The bones also provide a site to which muscles can attach, subsequently acting as a lever system for the movement of body parts. Bone tissue is a rigid mass and, therefore, offers protection to underlying structures, such as the brain, spinal cord, heart, and lungs. The skeletal system serves as an active reservoir for calcium, so when calcium levels are insufficient to meet the body's needs, calcium can be taken from bone and then replaced when calcium levels are returned to normal. Several bones of the body contain red bone marrow, which produces all types of blood cells (e.g., red, white, platelets) in a process called **hematopoiesis** (93, 118).



### Thinking Critically

*In what ways has a systems approach to exercise science contributed to a broader understanding of the muscular and skeletal factors that influence successful sport and athletic performance?*



**Hematopoiesis** The formation and development of blood cells.

## Skeletal System and Exercise Science

The interaction of physical activity, exercise, nutrition, and aging has significant implications for the health of the skeletal system. Without appropriate levels of physical activity and adequate mineral intake in the diet, the risk for developing **osteoporosis** can increase in any individual regardless of age. Osteoporosis is a disease condition characterized by low bone mineral density. Figure 3.4 illustrates the differences in bone mineral density between normal bone and osteoporotic bone. An individual is clinically defined as having osteoporosis when the bone mineral density is less than the bone mineral density of the lowest 25% of the population of gender-matched young adults (26, 67). The two primary strategies for decreasing the risk of developing osteoporosis are (a) maximizing peak bone mass by age 30 years and (b) slowing the rate of bone loss over the remaining years of life (70). Maximizing peak bone mass can be best accomplished by performing



**FIGURE 3.4** The differences in bone mineral density between normal bone (top panel) and osteoporotic bone (bottom panel).



**Osteoporosis** A disorder in which the bones become increasingly porous, brittle, and subject to fracture, owing to loss of calcium and other mineral components.

moderately intense exercise that requires some structural support, such as walking or jogging (40, 70, 81, 95). Consuming at least a minimal daily level of calcium also maximizes bone mass. The optimal level of calcium intake varies for each individual and depends on gender and age. Consuming an inadequate amount of calcium will prohibit a younger individual from maximizing bone mineral density and prevent older individuals from maintaining optimal bone mass (26, 54, 55, 70). Exercise science professionals are instrumental in developing effective nutrition and physical activity and exercise programs for reducing the risk of osteoporosis in men and women of all ages.

The skeletal system also plays an important role in determining success in sport and athletic performance. One of the many important factors in determining success in aerobic endurance events is the ability to deliver oxygen to the working tissues of the body. Almost all of the oxygen delivery in the body occurs via red blood cells (49). The red marrow in bone generates red blood cells. The endocrine hormone **erythropoietin** controls this process (49). If the number of red blood cells is increased in the body, oxygen delivery to the tissues increases as well, and we usually see improvements in cardiovascular fitness and endurance exercise performance (16). Aerobic endurance athletes can benefit from an increase in red blood cell count. **Recombinant human erythropoietin** (rEPO) has been demonstrated to increase red blood cell formation and reduce the risk of anemia as part of the therapy for a wide variety of clinically ill patients (42). If rEPO can increase red blood cell formation in well-trained athletes, there exists the potential for improving performance through an increased delivery of oxygen to the working tissues (44). In fact, rEPO has been demonstrated to improve cycling performance (12), and there have been numerous examples of illegal rEPO use by aerobic endurance athletes. Sports-governing associations have routinely expelled athletes from competition because the athletes test positive for rEPO during drug testing (11). Alternatively, high-altitude training may be a legal way to induce bone marrow to produce more red blood cells (77). Living at high altitudes where there is less oxygen and training at lower altitudes may be a way to stimulate bone to increase the red blood cell level, enhance oxygen delivery by the cardiovascular system, and improve aerobic endurance exercise performance (77). In response to the potential for improving aerobic endurance performance with this type of living and training environment, commercial companies have developed altitude tents that allow individuals to rest and sleep at “high altitudes” and train at low altitudes, regardless of an individual’s physical living location. Table 3.5 provides the functions of the skeletal system and examples of how those functions relate to physical activity, exercise, sport, and athletic performance.



**Erythropoietin** A hormone that stimulates the production of red blood cells and hemoglobin.

**Recombinant human erythropoietin** The laboratory production of human erythropoietin.

**Table 3.5 Functions of the Skeletal System and their Relationship to Physical Activity, Exercise, Sport, and Athletic Performance**

<b>FUNCTION</b>	<b>RELATION TO PHYSICAL ACTIVITY, EXERCISE, SPORT, AND ATHLETIC PERFORMANCE</b>
Formation of red blood cells	Carries oxygen to the tissues of the body; a key step in aerobic energy production
Lever system provides movement to the body	Allows for the contraction of the muscles to move body parts
Provides a structural framework to the body	Allows for body position and movement
Storage of minerals such as calcium and phosphorus	Appropriate levels are critical for normal physiologic function and strong bone health

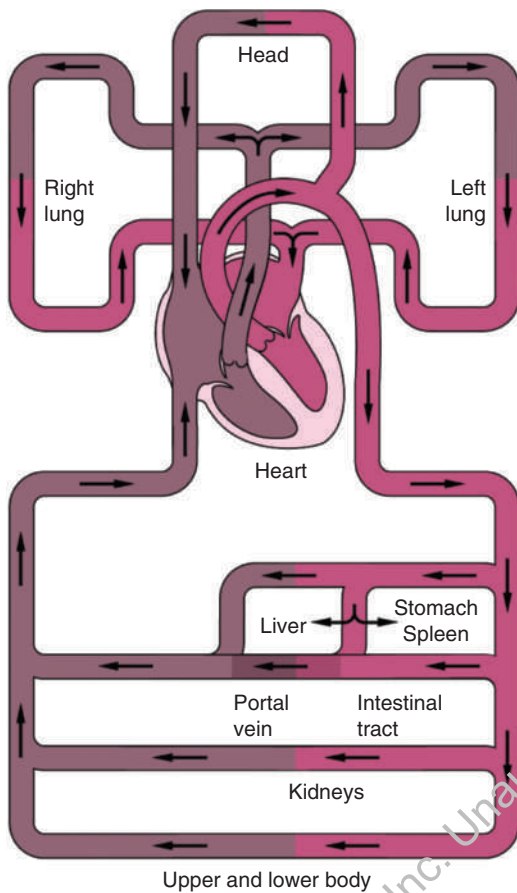
## CARDIOVASCULAR SYSTEM

The cardiovascular system transports blood containing oxygen, nutrients, and other substances (e.g., hormones, electrolytes, and drugs) to the tissues of the body, whereas at the same time facilitating the removal of carbon dioxide and other waste products from the body. The cardiovascular system also assists in body temperature regulation. Owing to the unique interaction of the cardiovascular and respiratory systems, these two systems are often referred to as one system; the cardiorespiratory or the cardiopulmonary system. Although the two systems do work in conjunction with each other, they each have other functions that allow them to be integrated with other systems of the body as well (49, 118).

The primary components of the cardiovascular system include the heart, arteries, capillaries, veins, and blood. The heart is comprised of cardiac muscle and nervous tissue that generates the force that propels the blood through the body. The arteries and some of the veins are comprised of smooth muscle that helps distribute blood through the various tissues of the body. The capillaries are tubes, one cell thick, which facilitate the transfer of gases, nutrients, and waste products to and from the cells of the body. The blood is comprised of red and white blood cells and a watery fluid that carries the various gases, nutrients, and waste products to the body tissues (118). Figure 3.5 illustrates the various components of the cardiovascular system. Both cardiac muscle and smooth muscle respond to input from the nervous and endocrine systems. All of these systems function together to provide a coordinated response to the challenges of physical activity and exercise.

### Cardiovascular System and Exercise Science

A disease-free cardiovascular system with strength sufficient to respond to the demands of daily living, physical activity, and exercise is critical to good health. Cardiovascular disease is one of the leading causes of death in the United States (19).

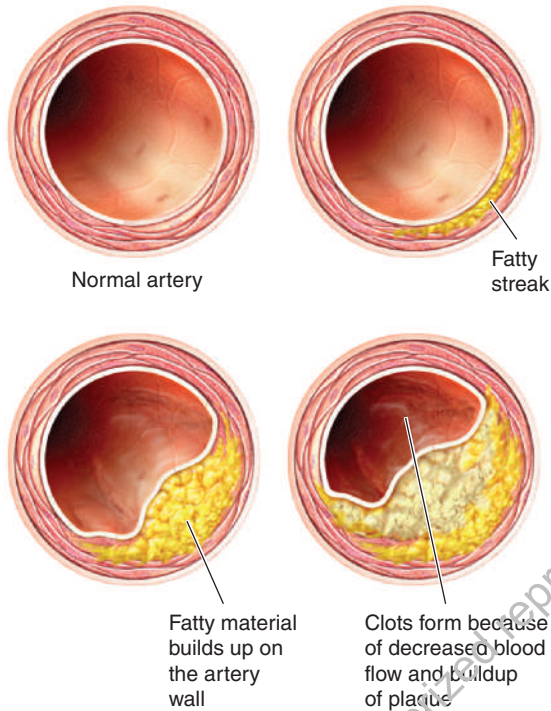


**FIGURE 3.5** Components of the cardiovascular system. (LifeART image copyright © 2010 Lippincott, Williams & Wilkins. All rights reserved.)

Years of research by public health experts and exercise science professionals have provided great insight into factors that lead to the development of cardiovascular disease (13, 25, 88, 89). Coronary artery disease (CAD) is the primary cardiovascular disease in most Americans. **Atherosclerosis**, a disease process whereby cholesterol and blood lipids build up in the arteries supplying blood to the heart, results in a reduction of blood flow to cardiac muscle (49). If blood flow to the heart is reduced to a critical level, a heart attack can result. Figure 3.6 shows how the buildup of plaque can cause a decrease in the lumen of the artery. Increased levels of physical



**Atherosclerosis** A disease process whereby cholesterol and blood lipids build up in the arteries causing a narrowing of the vessel opening.



**FIGURE 3.6** Inset showing how the build-up of plaque can cause a decrease in the lumen of the artery. (Asset provided by Anatomical Chart Co.)

activity and regular exercise are associated with a reduced risk of morbidity and mortality from cardiovascular disease (13, 111, 116). Physical activity and exercise enhance cardiac muscle function and improve blood flow to the heart and other tissues of the body. When an individual has a heart attack, that person is often referred to a cardiac rehabilitation program. In these programs, exercise science and other allied health care professionals work to increase the levels of physical fitness, improve nutritional intake, reduce stress, and change unhealthy behaviors. Cardiac rehabilitation programs use regular exercise as an integral component for helping individuals recover from a cardiac event. For more information on cardiac rehabilitation programs, see Chapter 5 (Clinical Exercise Physiology).

The cardiovascular system also plays an important role in the successful performance of various types of sport and athletic events. The delivery of oxygen and nutrients to working muscles and the removal of metabolic waste products are key in determining success during aerobic endurance events (16, 62). The cardiovascular system works in conjunction with the nervous, pulmonary, and endocrine systems to accomplish this. Athletic events that last longer than approximately 3 to 5 minutes rely heavily on the adequate delivery of oxygen to tissues.



**Table 3.6 Functions of the Cardiovascular System and their Relationship to Physical Activity, Exercise, Sport, and Athletic Performance**

FUNCTION	RELATION TO PHYSICAL ACTIVITY, EXERCISE, SPORT, AND ATHLETIC PERFORMANCE
Assists with temperature regulation	Controls body temperature during periods of increased movement
Removes carbon dioxide and waste products from active tissues	Allows for elimination of metabolic waste products of metabolism
Transports nutrients and other substances to the tissues of the body	Allows for delivery of macronutrients and substances to working tissues

**Maximal oxygen consumption** ( $VO_{2\max}$ ) is defined as the maximal amount of oxygen consumed by the body during maximal effort exercise. Much of the available research indicates that the delivery of blood and oxygen to the working tissues by the cardiovascular system is one of the limiting factors in determining an individual's  $VO_{2\max}$ . Because successful performance in most aerobic endurance events is determined, in part, by an individual's  $VO_{2\max}$ , this makes the contribution of the cardiovascular system critical to endurance performance success (16, 34, 50, 62). Exercise science professionals are frequently involved in developing training programs, improving biomechanical movement, enhancing nutritional intake, and improving psychological factors in an effort to enhance oxygen delivery to the tissues and improving sport and athletic performance. Table 3.6 provides a summary of the functions of the cardiovascular system and examples of how those functions relate to physical activity, exercise, sport, and athletic performance.

## PULMONARY SYSTEM

The pulmonary system brings air into the lungs, allows for oxygen to be removed from the air, and facilitates the elimination of carbon dioxide into the external environment. By regulating the carbon dioxide levels in the blood, the pulmonary system also helps maintain the acid–base balance of the body. The lungs and associated structures create a large surface area between the blood and the external environment that allows for the fast and efficient exchange of oxygen and carbon dioxide in a healthy individual. The pulmonary system works in close conjunction



**Maximal oxygen consumption** The maximum amount of oxygen the body can use during maximal effort exercise.

with the cardiovascular system, and the two systems are often referred to as the cardiorespiratory or cardiopulmonary system (49, 118).

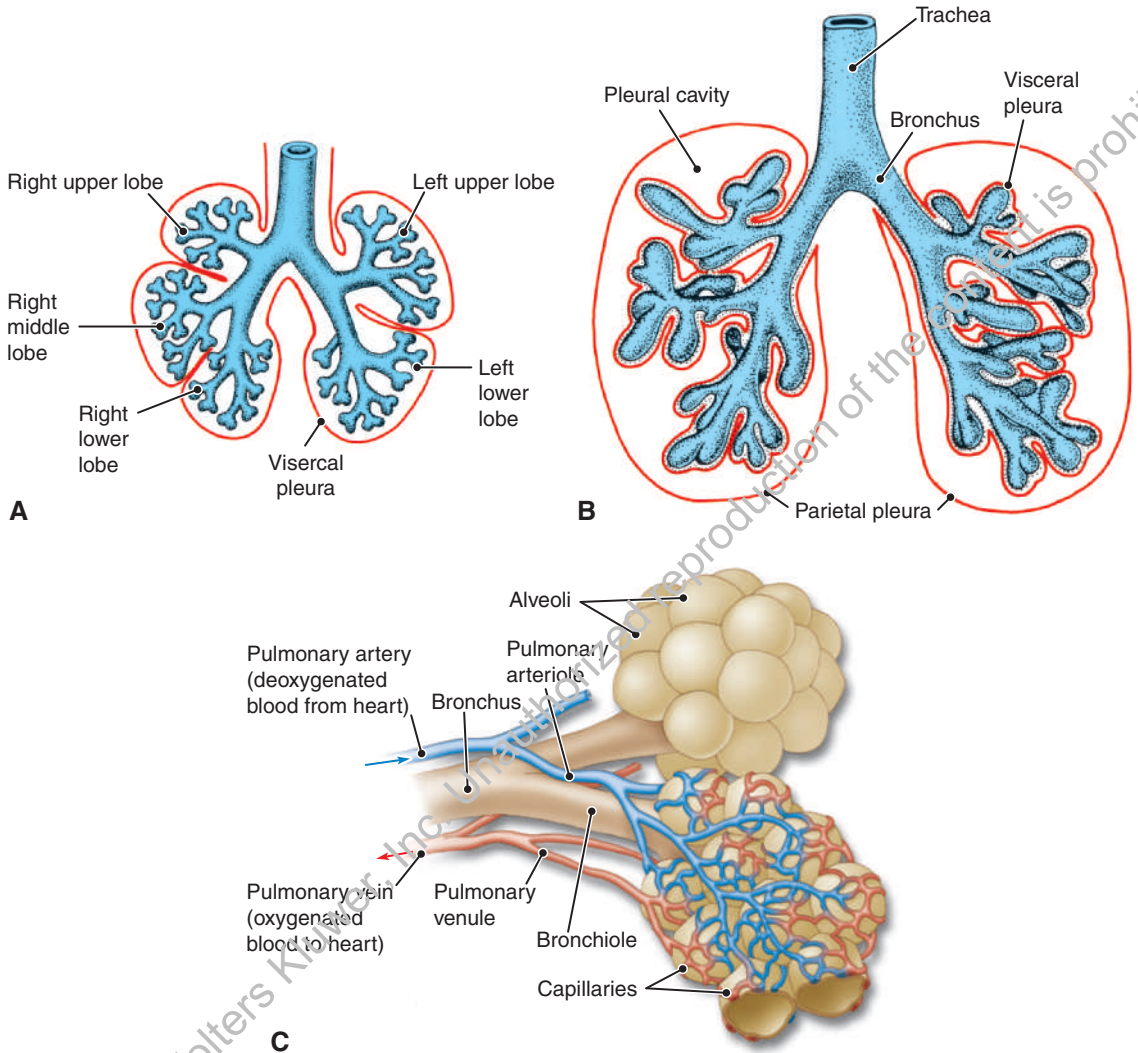
The primary components of the pulmonary system are the respiratory muscles, the respiratory airways, and the respiratory units. The respiratory muscles (internal and external intercostals, diaphragm, and abdominals) create a pressure gradient in the chest and lungs that allow for airflow into and out of the lungs. The respiratory airways, some of which contain smooth muscle, begin with the mouth and nose, continue with the trachea, right and left bronchus, bronchiole, and end with the terminal bronchiole. Those respiratory airways, which contain smooth muscle, are able to dilate and constrict, in response to internal and external stimuli. The bronchodilation and bronchoconstriction of the air passageways allow for increased or decreased airflow into the lungs, respectively. The respiratory unit consists of individual alveoli (where gas exchange occurs) and the pulmonary capillaries, which surround the alveoli. The majority of the exchange of oxygen and carbon dioxide occurs in the respiratory units (49, 118). Figure 3.7 illustrates the primary components of the pulmonary system.

### Pulmonary System and Exercise Science

Disease conditions of the pulmonary system play a significant role in the performance of physical activity and exercise by individuals. For example, chronic obstructive pulmonary disease (COPD) is a health condition that includes chronic bronchitis and emphysema and often results in a reduced ability to perform physical activity and exercise. Often, the health care management team for an individual with COPD will include physical and respiratory therapists, pulmonologists, and clinical exercise physiologists. These individuals work together to improve the functional performance of the pulmonary system and increase the individual's quality of life. Physical activity and exercise can also affect the pulmonary system and result in an asthmatic event triggered by an immune system response (104). This asthmatic event is typically referred to as **exercise-induced asthma**. Exercise-induced asthma can result in airway constriction, shortness of breath, and wheezing similar to those experienced with asthma, but, in exercise-induced asthma, symptoms occur on a transient basis (71). The type, intensity, and duration of exercise can all act to trigger an asthmatic event in susceptible individuals. Other environmental factors, such as tobacco smoke, molds, dust, and cold temperatures, may also play a role in triggering an exercise-induced asthma episode. An attack can result in difficult and labored exercise and reduce exercise compliance (61). The key to minimizing the occurrence of exercise-induced asthma is to avoid any predetermined factors that may trigger an episode (71).



**Exercise-induced asthma** A medical condition characterized by shortness of breath induced by exercise.



**FIGURE 3.7** Primary components of the pulmonary system.

The pulmonary system also plays an important role in successful sport and athletic performance. During very high- to maximal-intensity exercise, skeletal muscle breaks down carbohydrate and increases the production of lactic acid. The accumulation of lactic acid, which dissociates into a lactate ion and a hydrogen ion, can cause the pH (a measure of the hydrogen ion concentration) in tissues of the body to decrease and become more acidic. To maintain pH of the body's fluids and tissues within an acceptable range, chemical reactions in the body occur, and these reactions result in an increased production of carbon dioxide (49). The

**Table 3.7 Functions of the Pulmonary System and their Relationship to Physical Activity, Exercise, Sport, and Athletic Performance**

FUNCTION	RELATION TO PHYSICAL ACTIVITY AND EXERCISE AND SPORT AND ATHLETIC PERFORMANCE
Brings oxygen into the body	Allows for energy production during movement through aerobic metabolism
Eliminates carbon dioxide from the body	Allows for the removal of carbon dioxide, a waste product of macronutrient metabolism
Helps regulate acid–base balance	Controls pH levels in the body during periods of high-intensity movement



### Thinking Critically

*How would participation in a regular program of physical activity and exercise improve the functional ability of the pulmonary system to a disease condition of the lungs?*

primary reaction that results in the formation of carbon dioxide as a result of an increase in hydrogen ion concentration is  $\text{H}^+ + \text{HCO}_3^- \rightarrow \text{H}_2\text{CO}_3 \rightarrow \text{H}_2\text{O} + \text{CO}_2$ . The increased carbon dioxide is ventilated outside the body by the lungs, and this helps keep the tissues of the body from becoming too acidic as it lowers the concentration of hydrogen ions (49).

Table 3.7 provides a summary of the functions of the pulmonary system and examples of how those functions relate to physical activity, exercise, sport, and athletic performance.

## URINARY SYSTEM

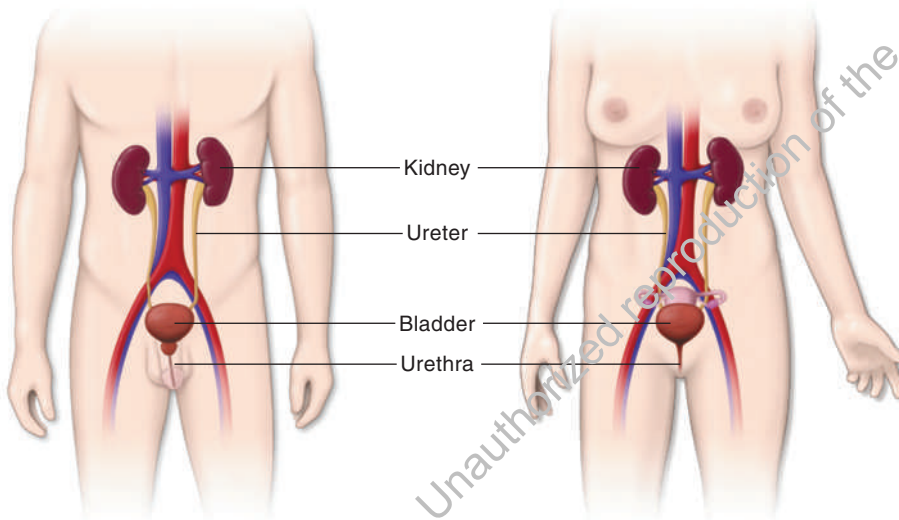
The urinary system eliminates waste products from the body and regulates the volume, electrolyte composition, and pH of the body fluids. All tissues of the body depend on the maintenance of a stable environment of the body fluids and removal of the toxic metabolic wastes produced by the cells as they perform their normal functions. Of special importance is the body's ability to regulate the volume and **osmolarity** (i.e., concentration of all solutes, such as electrolytes, proteins, glucose, urea, and others) of the internal fluid environment by controlling sodium and water balance (49, 118).

The primary components of the urinary system are the kidneys, renal artery and vein, ureter, urinary bladder, and urethra. The kidneys regulate the concentration of many of the plasma constituents, especially the electrolytes and water, and eliminate all the metabolic waste products (except for carbon dioxide). Plasma, which is the watery portion of the blood, progresses through the renal artery into

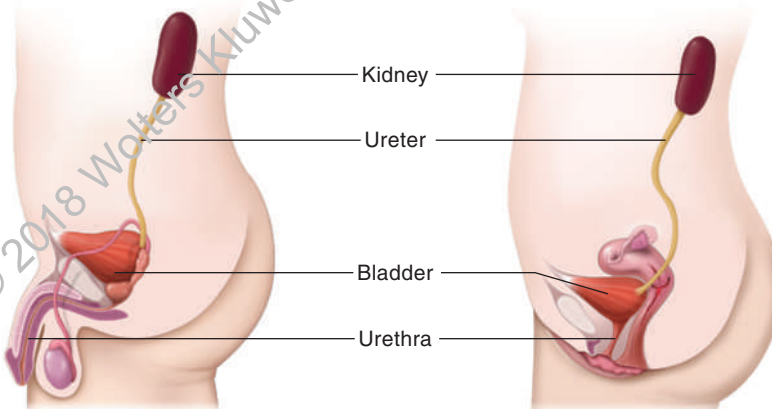


**Osmolarity** A measure of the concentration of a solution.

the kidney, where substances important to the body are retained and the undesirable or excess materials are filtered into the urine for excretion from the body. The plasma then moves back to the central circulation through the renal vein. The ureter is responsible for transporting the fluid and waste products (now called urine) to the urinary bladder for storage until the urine is eliminated from the body through the urethra (49, 118). Figure 3.8 illustrates the primary components of the urinary system.



**A Anterior view**



**B Lateral view**

**FIGURE 3.8** Primary components of the urinary system. (From Premkumar K. *The Massage Connection Anatomy and Physiology*. Baltimore (MD): Lippincott, Williams & Wilkins; 2004.)

## Urinary System and Exercise Science

The urinary system regulates the total fluid volume and electrolyte concentration of the body, and this function can have important implications for reducing the risk for certain diseases. Hypertension affects large numbers of individuals in the United States with approximately 33% of adults older than 20 years of age with measured high blood pressure and/or taking antihypertensive medication (18). Individuals with this condition have an increased risk of developing cardiovascular disease (especially CAD and stroke) and kidney disease (18). Furthermore, all-cause mortality increases progressively with higher levels of both systolic blood pressure and diastolic blood pressure. The primary treatment of individuals with hypertension involves preventing morbidity and mortality associated with the high blood pressure and controlling blood pressure by the least invasive means possible (63). Individuals with a resting blood pressure of 140/90 mm Hg are treated for hypertension (63). Changes in physical activity and exercise habits and modification of nutritional intake are at the center of effective treatment programs for hypertension. The urinary system can play an important role in helping to manage blood pressure in hypertensive individuals by regulating fluid volume in the body. Diuretics are a group of drugs that increase the excretion of sodium and water by the kidneys (72). Diuretics block the absorption of sodium from urine by the kidney, and this in turn increases the volume of fluid excreted as urine. The reduction of sodium concentration in the blood results in a reduction of total blood volume and decreases the resistance provided by the blood vessels of the body. Both of these actions have the effect of reducing blood pressure (49).

The urinary system plays an important role in sport and athletic performance in many ways. Athletes who train and play sports in hot and/or humid conditions regulate body temperature primarily by sweating. As a result of sweating, the total body fluid volume decreases. In response to this decrease, the urinary system reabsorbs sodium and water from the urine in an effort to maintain an acceptable level of body water. The process of sodium and water reabsorption by the kidneys decreases the urine volume and makes the urine more concentrated. Exercise science professionals, including sport nutritionists, athletic trainers, and sports medicine professionals, encourage athletes to carefully examine the color of their urine in order to monitor hydration status. When the urine is a dark concentrated color, and coupled with body weight loss from pre- to postexercise, this usually indicates that the athlete is dehydrated and should consume more fluids (109). Athletes in sports using weight classes for competition may illegally use diuretics to increase the urine volume excreted from the body. This assists those athletes attempting to lose body weight to participate in a lower weight class. Athletes have also used diuretics to decrease the concentration of a drug in the urine by increasing the volume of urine excreted from the body. Increasing the volume of urine excreted will assist in lowering the concentration of the drug



### Thinking Critically

*In what ways has a systems approach to exercise science contributed to a better understanding of the role of the cardiovascular system in promoting good health by reducing the risk for heart disease and enhancing aerobic endurance performance?*

**Table 3.8 Functions of the Urinary System and their Relationship to Physical Activity, Exercise, Sport, and Athletic Performance**

<b>FUNCTION</b>	<b>RELATION TO PHYSICAL ACTIVITY, EXERCISE, SPORT, AND ATHLETIC PERFORMANCE</b>
Eliminate waste products from the body	Removes waste products from increased levels of metabolism experienced during movement
Long-term regulation of acid–base balance	Helps control body pH levels that may be affected by alterations in metabolism
Regulate fluid volume and electrolyte concentrations	Controls levels of body fluids and electrolyte concentrations that are critical for efficient functioning of the body during movement

or its metabolites in the urine (49) and may help the athlete avoid the detection of illegal drug use. Table 3.8 provides a summary of the functions of the urinary system and examples of how those functions relate to physical activity, exercise, sport, and athletic performance.

## DIGESTIVE SYSTEM

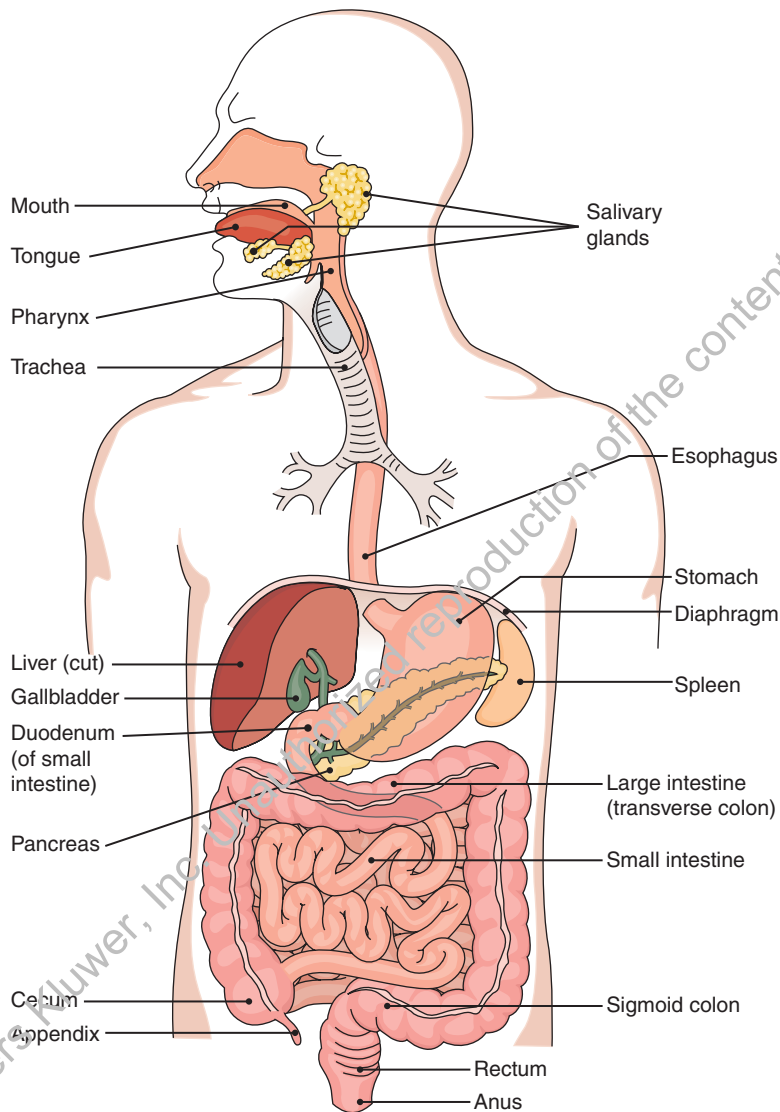
The digestive system works to transfer **macronutrients**, **micronutrients**, **electrolytes**, and water from the food we consume into the body so that normal functions can be performed and proper health can be maintained. The macronutrients are carbohydrates, fats, proteins, and the micronutrients are vitamins and minerals. These macronutrients and micronutrients contained in the food we consume represent essential sources of compounds that form the basic structures of the body and regulate the various processes of cells and tissues. Without a consistent supply of nutrients, the ability to maintain good health, perform physical activity and exercise, and train at levels required for sport and athletic competition becomes severely compromised (49, 118).

The primary components of the digestive system are the mouth, pharynx, esophagus, stomach, pancreas, liver, and small intestine and large intestine. The

**Macronutrients** The foodstuffs needed in large quantities, including carbohydrates, fats, and proteins that are used for numerous processes in the body.

**Micronutrients** The foodstuffs needed in smaller quantities, including vitamins and minerals that are used for numerous processes in the body.

**Electrolytes** The anions and cations that are distributed in the fluid compartments of the body.



**FIGURE 3.9** Primary components of the digestive system. (Reprinted with permission from Cohen BJ, Wood DL. *Memmler's The Human Body in Health and Disease*. 9th Ed. Philadelphia (PA): Lippincott Williams & Wilkins; 2000.)

mouth and pharynx and the esophagus are responsible for chewing and swallowing food, respectively. The stomach mixes and promotes further digestion by using digestive juices that come from the pancreas and liver. The small intestine absorbs nutrients and most of the electrolytes and water. The large intestine is primarily responsible for absorbing salt and water and converting the remaining contents into fecal matter (49, 118). Figure 3.9 illustrates the primary components of the digestive system.



## Digestive System and Exercise Science

Increasing physical activity and exercise and altering nutritional habits may play a role in decreasing the risk of developing certain forms of cancer, one of the leading causes of death in the United States (19). Several lines of research have suggested that increasing dietary fiber intake may reduce the risk of developing colorectal cancer. A protective effect of increased fiber intake may occur as a result of the dilution of fecal **carcinogens** and **procarcinogens**, reduction in the time fecal matter moves through the bowel, production of short-chain fatty acids (which promote **anticarcinogenic** action), and the binding of bile acids that are carcinogenic (78). However, the results of numerous large population studies examining the role of increased fiber intake in reducing cancer risk have been inconsistent (103, 113). Several investigations have demonstrated beneficial effects of increasing dietary fiber intake for reducing colorectal cancer incidence (10, 64, 100). Conversely, most prospective group studies have found little or no association between the dietary fiber intake and the risk of colorectal cancer (41, 82, 90, 114, 123) or adenomas (106), and randomized clinical trials of dietary fiber supplementation have failed to show any decrease in the recurrence of colorectal adenomas (4, 80, 91, 115). One of the biggest contributors to the colorectal cancer-causing process is dietary fat. The consumption of a meal high in fat increases the amount of bile acids that are released into the digestive tract. Bile acids help break down the fats we consume, but when the large amounts of bile acids get into the colon, they may be converted to secondary bile acids, which could promote cancerous tumor growth. This is especially true of the cells that line the area of the colon (78). The incidence of colon cancer is very high in some population groups, including black men, white men, and black women (20).

The digestive system also plays an important role in sport and athletic performance. Carbohydrates are the preferred fuel of skeletal muscle for most high-intensity sport competitions and athletic events. An inadequate supply of dietary carbohydrate consumed prior to and during competition can lead to poor performance. Carbohydrate ingestion during exercise increases blood glucose availability and maintains the ability of the working tissues to use carbohydrate as an energy source during high-intensity exercise lasting longer than 60 minutes. The ingestion of carbohydrate during prolonged, high-intensity aerobic endurance exercise enhances performance (22, 23) and may also increase performance during high-intensity short-duration exercise (53).

There is a limit to the peak rate of blood glucose utilization during prolonged exercise when carbohydrates are ingested orally (22, 24). The gastrointestinal system plays a key role in the delivery of carbohydrate to the body during exercise. The gastrointestinal tract has several potential sites for limiting carbohydrate use, including

**Carcinogens** A cancer-causing substance or agent.

**Procarcinogens** Compounds or substances that can lead to the formation of cancer cells.

**Anticarcinogenic** Tending to inhibit or prevent the activity of a carcinogen or the development of carcinoma.

**Table 3.9 Functions of the Digestive System and their Relationship to Physical Activity, Exercise, Sport, and Athletic Performance**

FUNCTION	RELATION TO PHYSICAL ACTIVITY AND EXERCISE AND SPORT AND ATHLETIC PERFORMANCE
Delivery of macronutrients to the body	Carbohydrates, fats, and proteins are essential for the optimal function of the body during and after movement
Delivery of micronutrients to the body	Vitamins and minerals are essential for the optimal function of the body during and after movement

gastric emptying and intestinal absorption (50). An examination of how the gastrointestinal, cardiovascular, and muscular systems interact can help demonstrate these limitations. Gastric emptying rates and the intestinal absorption of glucose from a 6% glucose electrolyte solution have been measured at 1.2 and 1.3 g/minute under resting conditions and 1 g/minute during exercise (32). As the concentration of glucose in the beverage rises, the rate at which ingested glucose is supplied to the blood is lower than the rate of carbohydrate used in the muscle. This suggests either a gastrointestinal limitation to using the ingested carbohydrate as a fuel or a failure of the cardiovascular system to deliver glucose from the gastrointestinal tract into the main blood supply (87). The simultaneous consumption of both glucose and fructose, which are absorbed from the gastrointestinal tract by different mechanisms, results in the greater use of the carbohydrates for energy by muscle than the ingestion of similar amounts of glucose or fructose consumed alone (3). Furthermore, if glucose is infused into the blood, rather than consumed orally, the glucose can be used to supply energy at a faster rate (27). Collectively, this information suggests that the delivery of ingested carbohydrate from

the gastrointestinal tract to the cardiovascular system might be a limiting factor in the use of ingested carbohydrate as an energy source for contracting muscle during exercise (51). Table 3.9 provides a summary of the functions of the digestive system and examples of how those functions relate to physical activity, exercise, sport, and athletic performance.



### Thinking Critically

*In what ways could consumption of a carbohydrate beverage improve performance during a competitive marathon or triathlon?*

## ENDOCRINE SYSTEM

The endocrine system is the another primary control system (along with the nervous system) of the body. It helps to regulate physiologic function and influence the function of other systems of the body. One advantage of the endocrine system for controlling functions is that the hormones can circulate and influence tissues throughout the entire body without requiring a hard connection (as in the nervous system). Furthermore, endocrine changes can influence function for a duration lasting from a few seconds to several hours. The endocrine system accomplishes these functions through the use of hormones secreted by the various endocrine glands of the body. Even though the endocrine glands are not connected anatomically, they



**Homeostasis** The maintenance of relatively stable internal physiologic conditions.

function as a system in a practical sense. Many of these hormones are important for influencing both the acute responses and the chronic adaptations of the systems of the body to physical activity and exercise (49, 118).

The primary components of the endocrine system are the glands of the body and the hormones that each gland secretes. Some endocrine glands only specialize in hormonal secretion (e.g., anterior pituitary and thyroid), whereas other components of the endocrine system consist of organs that perform other functions in addition to secreting hormones (e.g., testes secrete testosterone and also produce sperm). The endocrine system, by means of the blood-borne hormones it secretes, generally regulates activities and functions at a much slower pace than the other primary control mechanism of the body, the nervous system. Most of the activities under the control of hormones are directed toward maintaining **homeostasis** (normal conditions of functioning) of the body (49, 118). Table 3.10 illustrates

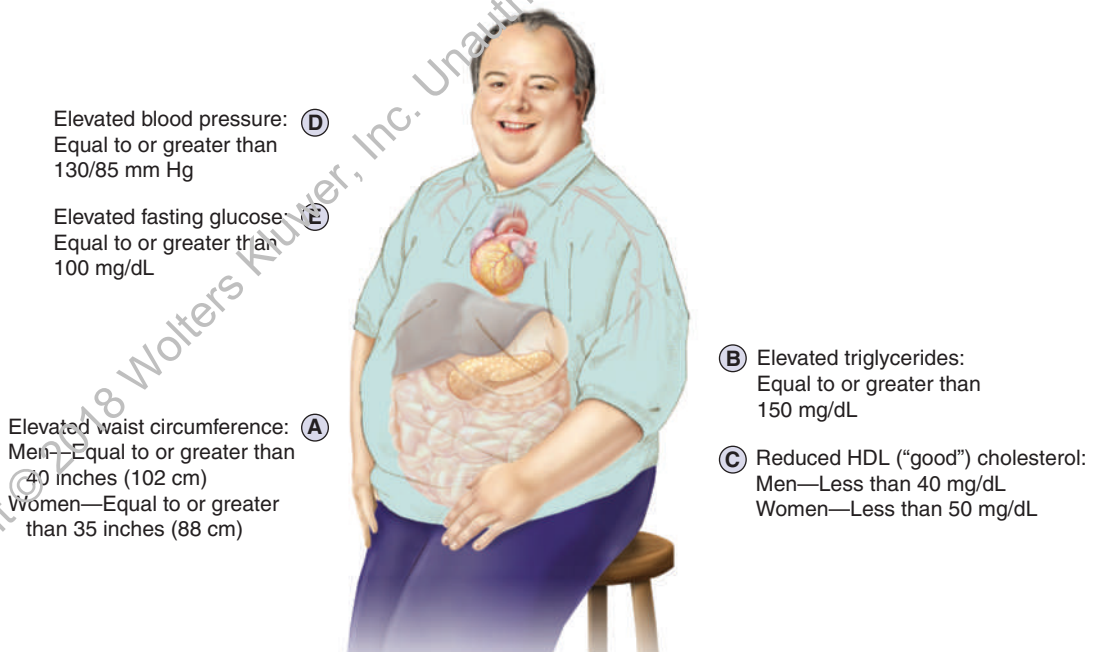
**Table 3.10 Endocrine Glands and Selected Secreted Hormones (118)**

ENDOCRINE GLAND	HORMONES
Hypothalamus	Releasing and inhibiting hormones
Posterior pituitary	Vasopressin
Anterior pituitary	Thyroid-stimulating hormone, adrenocorticotrophic hormone, and growth hormone
Thyroid gland	Thyroxin, triiodothyronine, and calcitonin
Adrenal cortex	Aldosterone, cortisol, and androgens
Adrenal medulla	Epinephrine and norepinephrine
Pancreas	Insulin and glucagon
Parathyroid gland	Parathyroid hormone
Ovaries	Estrogen and progesterone
Testes	Testosterone
Kidneys	Renin and erythropoietin
Stomach	Gastrin
Liver	Somatomedins
Skin	Vitamin D
Heart	Atrial natriuretic peptide
Adipose tissue	Leptin and adiponectin

various endocrine glands of the body of interest to exercise science and the primary hormones each secretes.

## Endocrine System and Exercise Science

Hormones affect the systematic responses of the body in various ways and often work with other systems of the body to regulate normal functions during physical activity and exercise. For example, epinephrine and norepinephrine (also called adrenaline and noradrenaline, respectively) have been shown to increase heart rate and blood pressure in response to stress, including physical activity and exercise (16). Insulin maintains blood glucose concentrations by increasing glucose uptake and utilization as an energy source in tissues of the body. The interaction of epinephrine, norepinephrine, and insulin has been associated with the development of hypertension in a disease condition called metabolic syndrome (129). Metabolic syndrome describes the clustering of several conditions of the body, including obesity, hyperinsulinemia, elevated triglyceride levels, hypertension, and type 2 diabetes. Figure 3.10 shows the relationship among the clustering of metabolic syndrome risk factors. Central to the understanding of metabolic syndrome is the role insulin resistance plays in the development of some of the associated disease conditions. A diet high in fat and refined sugar (6) contributes significantly to the development of insulin resistance. A decreased ability of cells to absorb glucose at



**FIGURE 3.10** The relationship among the clustering of metabolic syndrome risk factors.  
(Asset provided by Anatomical Chart Co.)

a given insulin concentration characterizes the condition of insulin resistance. In response to increasing insulin resistance by the tissues of the body, the pancreas secretes more insulin in an effort to promote blood glucose uptake into cells and return the blood glucose concentration to normal. If the pancreas cannot secrete sufficient amounts of insulin, the blood glucose concentration remains elevated and type 2 diabetes results (49). When the pancreas is forced to secrete additional insulin to address the insulin resistance, the plasma insulin level becomes elevated (called hyperinsulinemia). This condition can elevate blood pressure and contribute to the development of hypertension. Sympathetic nervous system activity increases in response to elevated insulin levels. This response can lead to an elevation of the hormones epinephrine and norepinephrine, which can lead to an increase in heart rate, stroke volume, and blood pressure. The elevated levels of epinephrine and norepinephrine can also interfere with insulin release from the pancreas and glucose uptake at the tissue, causing an aggravation of the problem. In this case, insulin resistance contributes significantly to the hypertension. Alternatively, given the complex interaction of the events, hypertension may in fact cause the insulin resistance. Physical activity and regular exercise can benefit individuals with insulin resistance and hypertension by improving the body's sensitivity to the hormones insulin, epinephrine, and norepinephrine (51, 83, 108).

Coaches and athletes have long been interested in the use of **exogenous** hormone supplementation to improve assorted types of sports and athletic performance. For example, the use of anabolic steroids (e.g., synthetic testosterone) and human growth hormone for improving athletic performance is common among certain groups of athletes (17, 33, 58, 94, 127) although recent evidence indicates that androgen use has decreased in adolescents (58). Anabolic steroids have both **androgenic effects** and **anabolic effects** (128). The anabolic actions cause the body to increase protein synthesis in skeletal muscles and various other tissues, which can then lead to increased nitrogen retention. The increased protein synthesis can result in an increased muscle size and strength as well as increased body weight (49). For those sports that rely on body size or the generation of power and force by the muscle, the increase in muscle mass and strength often result in improvements in sport and athletic performance. When used in high dosages, as often the case with athletes, there are potentially serious side effects that may be irreversible and cause serious health problems (58, 128). Although the use of these types of substances and others like them is illegal and considered unethical, there has been considerable interest in understanding how these substances work and how the illegal use of these substances can be detected (58, 128). Identifying the mechanism by which these hormones work is important for determining how these substances can be detected in saliva, blood, and urine (66) for compliance



**Exogenous** Coming from outside the body.

**Androgenic effects** The development and maintenance of masculine characteristics.

**Anabolic effects** The development and maintenance of tissue, particularly skeletal muscle.

with athletic-governing association rules. Issues surrounding effective drug testing include using equipment that is sensitive enough to detect drug metabolites in the blood or urine, identifying the various metabolites that are associated with synthetic anabolic steroids, and ensuring that effective drug testing is a deterrent to anabolic steroid and other anabolic substance use by athletes (66). Table 3.11 provides the primary hormones of the endocrine system and some examples of how those functions relate to physical activity, exercise, sport, and athletic performance.

**Table 3.11 Primary Hormones of the Endocrine System and Relationship of Their Functions to Physical Activity, Exercise, Sport, and Athletic Performance**

HORMONE	FUNCTION	RELATION TO PHYSICAL ACTIVITY, EXERCISE, SPORT, AND ATHLETIC PERFORMANCE
Adiponectin	Regulates glucose and fatty acid metabolism	Plays a role in the suppression of metabolic abnormalities
Aldosterone	Increases sodium reabsorption and potassium excretion in the kidneys	Helps regulated fluid balance to prevent dehydration
Calcitonin	Decreases plasma calcium concentration	Increases calcium deposition in bone
Cortisol	Increases blood glucose concentration; contributes to stress adaptation	Helps increase blood glucose concentration to avoid hypoglycemia
Epinephrine and norepinephrine	Reinforces sympathetic nervous system activity	Assists the body when responding to the stress of movement
Erythropoietin	Stimulates red blood cell production in bone marrow	Increases oxygen delivery to working tissues
Estrogen	Responsible for development of secondary sexual characteristics	Helps regulate lean mass and skeletal mass in the body
Glucagon	Promotes maintenance of nutrient levels in blood, especially glucose	Helps regulate blood glucose levels during exercise
Growth hormone	Essential for the growth of bones and soft tissue, protein anabolism, fat mobilization	Promotes the growth of lean and skeletal tissue
Insulin	Promotes uptake of absorbed nutrients, especially insulin	Helps regulate blood glucose levels after food consumption
Leptin	Assists the brain in regulating appetite and metabolism	Helps assist the body in the regulation of an appropriate body weight
Testosterone	Responsible for development of secondary sexual characteristics	Helps regulate lean mass in the body
Vitamin D	Increases absorption of ingested calcium and phosphate in the gastrointestinal tract	Helps regulate levels of calcium in the body, especially bone

## IMMUNE SYSTEM

Overall, the immune system regulates susceptibility to, severity of, and recovery from infection or injury, abnormal tissue growth, and illness. The immune system works with other body systems through a complex arrangement of structures, compounds, and cells. The various components of the immune system are not connected anatomically, yet they do constitute a functional system in the body. The immune system allows the body to make a distinction between its normal components and any foreign elements, with the purpose of protecting itself against those substances foreign to the body (49, 118).

The primary components of the immune system are the physical, mechanical, chemical, blood, and cellular factors of the body. The **innate** (i.e., natural) and **acquired** (i.e., adaptive) components of the immune system function together in a complex interaction to protect the body from outside elements. The innate components of the body offer an immediate and predetermined general protection against any type of foreign challenge to the body. Conversely, the adaptive components of the immune system are extremely specific in the response to a given foreign invader (117). Table 3.12 illustrates the components of innate immunity and acquired immunity.



### Thinking Critically

*How does exercise training for improving health and fitness differ from exercise training for enhancing performance during sport and athletic competitions as they relate to alterations in immune system function?*

### Immune System and Exercise Science

Since the 1980s, there has been steady growth in the study of physical activity, exercise, and immune function and how they all interact to positively and negatively affect health. Exercise may play a role in the prevention and treatment of certain illnesses such as cancer and acquired immune deficiency syndrome (AIDS) (45). Evidence from **epidemiologic** studies indicates an association between regular physical activity and lower rates of certain cancers (35). Animal studies also indicate that exercise training enhances resistance to experimentally induced tumor growth (59). Furthermore, exercise may have a positive effect in stimulating the immune system during times of illness or reduced responsiveness (such as aging or AIDS). Studies over extended periods of 10 to 20 years have reported reduced incidence of cancer in physically active groups (31, 59). There is also evidence that occupational physical activity is associated with a reduced risk of colorectal cancer (119) and that physical inactivity is associated with an increased risk of colorectal cancer (59).

**Innate** Immunity existing from within the body at birth.

**Acquired** Immunity that is derived after birth.

**Epidemiologic** The branch of medicine dealing with the incidence and prevalence of disease in large populations.

**Table 3.12 Components of Innate and Acquired Immunity (117)**

INNATE IMMUNITY	ACQUIRED IMMUNITY
<p><b>Physical barriers</b> (to keep pathogens out) Skin and epithelium Mucus and mucus membrane structures Turbulent air flow</p>	
<p><b>Chemical barriers</b> (to provide a hostile environment or neutralize pathogens inside the system) Complement factors Lysozymes Acute phase proteins Acidic pH in stomach</p>	<p><b>Chemical and soluble defenses</b> (to bind and neutralize pathogens) Immunoglobulins (also known as antibodies)</p>
<p><b>Cellular defenses</b> (to create a toxic environment, kill bacteria or potentially infected cells, or to engulf debris; also play primary role in the inflammation process) Monocytes/macrophages<sup>a</sup> Granulocytes (e.g., neutrophils) Natural killer cells</p>	<p><b>Cellular defenses</b> (to activate immune defenses, kill infected cells, and produce antibodies) T lymphocytes (T cells, multiple types) B lymphocytes (B cells)/plasma cells</p>

<sup>a</sup>They have a role in presenting antigens to cells of the acquired immune arm of the immune system.

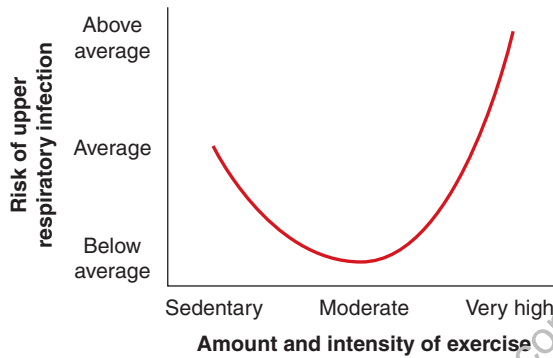
Increased levels of physical activity may also reduce the risk of cancer at other sites such as the breast (9) and reproductive system in women (31, 35). Exercise may positively affect autoimmune diseases such as rheumatoid arthritis, Graves disease, and systemic lupus erythematosus (36). In older adults, increased levels of physical activity and regular exercise may also enhance immune system function (28, 85).

Some competitive athletes may appear to suffer high rates of certain illnesses, such as mononucleosis and upper respiratory illness. The relationship between exercise and upper respiratory illness may be modeled in the form of a “J” curve, as shown in Figure 3.11 (96). This model suggests that although the risk of upper respiratory illness may decrease below that of a sedentary individual when one engages in moderate exercise training, the risk may rise above average during periods of excessive amounts of high-intensity training such as that performed by some athletes (117). Frequent illness has also been observed in athletes experiencing a condition called **overtraining syndrome** (39, 98). Although much of the evidence is anecdotal, the few attempts to quantify rates of illness tend to support a higher incidence of illness among certain groups of athletes (99). In response to this information, prospective studies have examined numerous nutritional aids in an attempt to improve immune function and reduce the incidence of illness in athletes who are training at high intensities. The effects of carbohydrate supplementation



**Overtraining syndrome** A condition whereby too much training results in the maladaptations of body responses.





**FIGURE 3.11** The relationship between exercise and upper respiratory illness may be modeled in the form of a “J” curve (96).

on immune function have received the majority of research work, but there are other nutritional supplements that have potential to modify immune function and reduce the risk of illness in athletes. For example, beta-glucan has demonstrated potential to decrease upper respiratory tract illness and improve immune function in some (7, 29) but not all studies (97). It is likely that training volume and competition exert a combined effect on the susceptibility to illness. Moderate-intensity exercise has been demonstrated to induce a much smaller change in the cellular components of the immune system. Short bouts of high-intensity exercise can cause temporary impairment of the immune response and repeated heavy training, and the stress of top-level competition can have a more serious effect on immune function. Research supports the concept that heavy exertion increases an athlete’s risk of upper respiratory illness because of the changes in immune function and the elevation of the hormones epinephrine and cortisol (105). Table 3.13 provides the functions of the immune system and examples of how those functions relate to physical activity, exercise, sport, and athletic performance.

## ENERGY SYSTEMS

The ability to produce energy is critical for ensuring normal function in all living cells and tissues of the body. The production of energy to support the functions of the body is tightly controlled and regulated so that energy production closely matches energy utilization. Energy exchange in humans occurs when the foods

**Table 3.13** Functions of the Immune System and their Relationship to Physical Activity, Exercise, Sport, and Athletic Performance

FUNCTION	RELATION TO PHYSICAL ACTIVITY, EXERCISE, SPORT, AND ATHLETIC PERFORMANCE
Regulate susceptibility to, severity of, and recovery from infection, abnormal tissue growth, and illness	Provides protective effect from internal and external illness-causing agents

(carbohydrates, fats, proteins) we eat are broken down into a useable form of energy by the body. Although energy exchange in humans is not a system in a structural sense, the various processes by which the body produces energy do constitute a system in the functional sense (49, 118).

The main components of the energy system are the chemical compounds contained in the energy pathways of the cells and the macronutrients carbohydrate, fat and protein. When the cells of the body need energy, they break down a chemical compound called adenosine triphosphate (ATP). Immediately the body begins to resynthesize the ATP from the energy contained in the chemical bonds that hold together the macronutrients. Energy to resynthesize ATP comes from one of the three energy pathways: (a) immediate sources which use stored energy in the form of **creatine phosphate** (often called the ATP-CP energy system); (b) **glycolysis** and **glycogenolysis**, which use blood glucose and stored muscle glycogen, respectively (often called the anaerobic energy system); and (c) **oxidative metabolism**, which use products of carbohydrate, fat, and protein metabolism (often called the aerobic energy system). The immediate stores rapidly resynthesize ATP in the muscle during the initiation of movement and during very high-intensity exercise. Because the immediate energy system is limited in capacity, the body quickly begins to provide energy through other pathways. The processes of glycolysis (using glucose) and glycogenolysis (using glycogen) involve the breakdown of carbohydrates into compounds called pyruvic acid and lactic acid. As the carbohydrate is broken down, energy is formed for use by the body. The need for energy by the body often determines the end product of carbohydrate metabolism. If the energy requirements of the muscle are high, then lactic acid is formed. If the energy requirements of the muscle are lower, then pyruvic acid is formed, which is then used to produce energy in oxidative metabolism. Glucose/glycogen, fats, and proteins can all be used to produce energy. Oxidative metabolism occurs in the mitochondria of cells and is an energy system that is powerful with a large capacity for producing energy (16, 49). Energy production must match utilization during exercise or the exercise intensity must be reduced or exercise must be stopped. The energy pathway that predominates during physical activity or exercise depends on the intensity and duration of the activity. Whether carbohydrates, fats, or proteins are used to produce energy depends on the pathway being used, but can also be influenced by factors such as food consumption, training status, and the use of **ergogenic aids**. Table 3.14 illustrates the pathways for energy production in the body.



**Creatine phosphate** An organic compound found in muscle and cardiac tissue and capable of storing and providing energy for muscular contraction.

**Glycolysis** The breakdown of glucose to produce energy.

**Glycogenolysis** The breakdown of glycogen to produce energy.

**Oxidative metabolism** The use of oxygen to break down carbohydrates, fats, and proteins to produce energy.

**Ergogenic aids** Any substance or device that improves physiologic or psychological performance.

**Table 3.14** Energy Production Systems in the Body

ENERGY SYSTEM	SUBSTRATE USED
Immediate sources	ATP and creatine phosphate
Glycolysis and glycogenolysis	Blood glucose and muscle glycogen
Oxidative metabolism	Products of carbohydrate, fat, and protein metabolism

ATP, adenosine triphosphate.

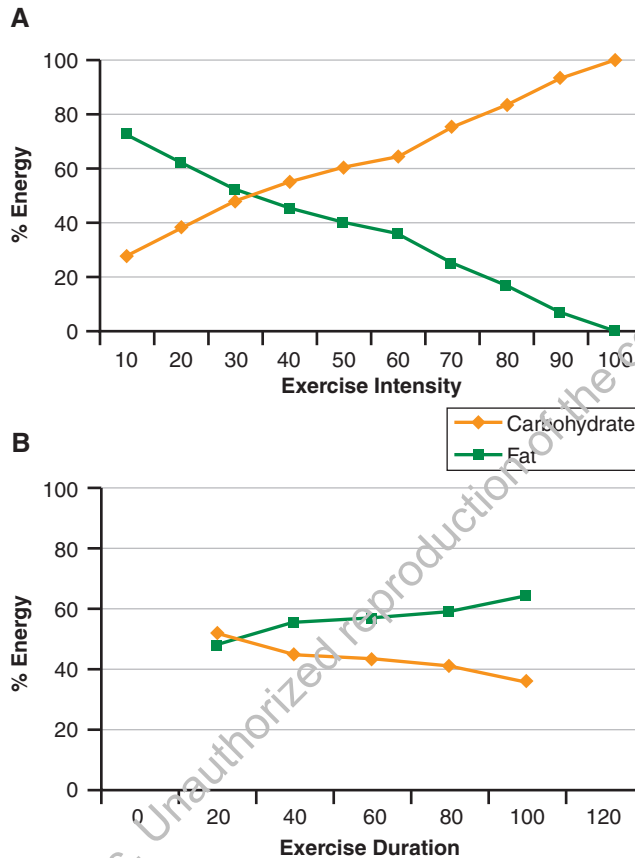
## Energy Systems and Exercise Science

Identifying the appropriate physical activity and exercise intensity to promote the utilization of fat as an energy source is an important issue in the regulation of body weight and body composition. At the beginning of exercise, increases in energy utilization of the body are matched by increases in energy production from the immediate energy sources and the breakdown of glucose and glycogen. As the exercise duration continues, energy production shifts so that, under certain circumstances, more energy is produced from the breakdown of fats. Several factors influence which energy pathway is used to provide energy to the body, including the nutritional status and training level of the individual; the exercise intensity and duration; and various hormonal concentrations in the body. Of those factors, exercise intensity and duration most often have the greatest influence on fat and carbohydrate utilization as energy sources (Fig. 3.12). During physical activity and exercise, the percent contribution of carbohydrate and fat to energy production can be estimated by using the respiratory exchange ratio (RER). RER is calculated as the ratio of the amount of carbon dioxide produced to the amount of oxygen consumed (16). When using the RER to estimate fuel utilization during rest or exercise, the role that protein contributes to energy production is usually ignored because protein generally contributes very little to energy production during physical activity (16). RER can be used to estimate fuel utilization because carbohydrates and fat differ in the amount of oxygen consumed and carbon dioxide produced; fat requires more oxygen than carbohydrate when used for energy production (14, 16).

The understanding of how body weight and **body composition** affect fat utilization is of great interest to understanding the mechanisms behind the obesity epidemic (60). Increases in body weight and body fat, as well as changes in fat utilization as an energy source, have significant implications for the development of several chronic disease conditions, such as insulin resistance, type 2 diabetes, and metabolic syndrome (125). Exercise science professionals are interested in determining



**Body composition** The amount of fat and nonfat tissue in the body.



**FIGURE 3.12** The relationship between exercise intensity (**A**) and duration (**B**) and the use of fat and carbohydrates as energy sources.

the optimal intensity for utilizing fat during physical activity and exercise to better assist those individuals seeking to decrease body fat and lose weight. Recent evidence would indicate that the exercise intensity at which there is maximal fat utilization is approximately 65% of an individual's  $VO_2\text{max}$  (1). Maximizing the rate of fat oxidation during exercise can have beneficial effects on overall health, including improving insulin sensitivity (112) and managing long-term weight control (84).

Determining the optimal exercise intensity during endurance events that are longer than 10 km is critical for maximizing sport and athletic performance. Success in endurance events can be determined by examining several factors. For example, one of the strongest predictors of successful performance in distance running is the running velocity at the **maximal lactate steady state** (124). During moderate- to



**Maximal lactate steady state** The exercise intensity where maximal lactic acid production is matched by maximal lactic acid removal.

**Table 3.15 Components of the Energy System and Their Relationship to Physical Activity, Exercise, Sport, and Athletic Performance**

<b>ENERGY SYSTEM</b>	<b>RELATION TO PHYSICAL ACTIVITY, EXERCISE, SPORT, AND ATHLETIC PERFORMANCE</b>
Immediate sources: ATP and creatine phosphate	Provides energy during the initiation of movement and during high-intensity exercise
Glycolysis and glycogenolysis	Provides energy during moderately high-intensity exercise
Oxidative metabolism	Provides energy during resting and low- to moderately high-intensity physical activity and exercise

ATP, adenosine triphosphate.

high-intensity exercise, the majority of energy produced to power muscular contraction comes from the breakdown of carbohydrates. During the rapid metabolism of glucose and glycogen, there is lactic acid formation, which dissociates into lactate and hydrogen ions. The increase in hydrogen ions can result in a decrease in the intramuscular pH. Unless the pH level is maintained, the increase in hydrogen ion concentration can contribute to fatigue in the contracting muscle (126). The removal of lactic acid occurs through several metabolic processes in the body (8, 15, 43). There is an exercise intensity whereby the maximal formation of lactic acid in the muscle fiber is matched by the maximal clearance of lactic acid from the muscle fiber. This is called the maximal lactate steady state (56). Exercise above the maximal lactate steady state leads to a progressive increase in the lactate and hydrogen ion concentrations in the muscle and ultimately a decrease in exercise performance or a cessation of exercise altogether (56). Endurance coaches and athletes develop and implement training programs with the intent on improving the exercise intensity at the maximal lactate steady state (16, 107, 122). Table 3.15 provides the components of the energy system and examples of how those components relate to physical activity, exercise, sport, and athletic performance.



## INTERVIEW

### J. Timothy Lightfoot, PhD, FACSM,

Registered Clinical Exercise Physiologist, Certified Exercise Specialist (ACSM). Omar Smith Endowed Chair in Kinesiology and Director, Sydney and JL Huffines Institute for Sports Medicine and Human Performance at Texas A&M University.

**Brief Introduction** – I received my bachelors and master's degrees from the University of Louisiana Monroe and my doctorate from the University of Tennessee. I completed a research consultancy with the US National Aeronautics and Space Administration (NASA) at Kennedy Space Center in the Biomedical Laboratory and then a 3-year National Institute of Health postdoctoral research fellowship in the Division of Physiology at Johns Hopkins University. I have been an assistant and associate professor at Florida Atlantic University and a professor at the University of North Carolina Charlotte. I have published over 70 scientific, peer-reviewed articles on the genetics of daily physical activity and exercise endurance, as well as the physiologic response to high-G exposure and hemorrhage. I have received external funding from the National Institutes of Health and Department of Defence to conduct research on the genetics of physical activity. I am a fellow of the American College of Sports Medicine, an ACSM-certified exercise specialist, a registered clinical exercise physiologist, a past president of the Southeast Regional Chapter of the American College of Sports Medicine, and a past member of the Board of Trustees for the American College of Sports Medicine.

**Q: What are your most significant career experiences?**

I have been blessed and honored to have several significant career experiences. My work at Kennedy Space Center at NASA in the mid-1980s was amazing and gave me up-close experiences as to how exercise physiology principles could be applied to a variety of “nonsport” venues—and I’ve followed that path with our work with motorsports athletes and musicians. Taking on an academic administrative role at a fairly young academic age helped me to learn how get individuals to work together to accomplish goals. My years as a department chairperson also taught me many things about how “not” to get people to work together. Taking the leap and switching my primary research interest in the late 1990s to genetics was a significant experience. Suddenly, even though I was an established investigator, I had to start over and rebuild my experience and expertise. It was so worth it because my move into genetics in 1998, gave me the foundation to receive multiple federal grants and gave my research a foundation (the biologic regulation of physical activity) that can impact not only exercise science but also health of our society.

**Q: Why did you choose to become an “exercise scientist”?**

My decision to become an exercise scientist was selfish at first: I wanted to become a better athlete. Thus, I

figured the more I learned, the better I would become. However, I soon realized that I just had a passion for human performance. How humans could perform and adapt in a wide variety of environments and situations stimulated my interest and continuing efforts to understand how it all works mechanistically.

**Q: Why it is important for exercise science students to understand how all of the systems of the body function?**

As scientists, we too often work in “reductionist mode” and try to isolate everything—even down to the molecular level—so we can find “the cause.” However, very few things in physiology work in isolation. So, while reductionism is critically important, the scientist always must ask how their findings work with other pieces to form the system that actually causes the body to function the way it does. Exercise science and exercise physiology is terribly complex, and understanding just one small piece does not allow you to have a general knowledge about how the whole system works together.

**Q: What advice would you have for a student exploring a career in any exercise science profession?**

Find something you are passionate about; a topic that catches your imagination and won’t let you go. The most

successful people I know in exercise science are those who are passionate about the topic or the job that they are doing. So look for a topic or piece of exercise science that makes you stop and say “hey, that’s cool.” That’s the thing you should be doing—it may be research, it may be rehabilitation, it may be coaching—but whatever it is, keep looking. You’ll find it. The second piece

of advice is never be afraid to talk to people. Say “hello” and talk to them about what they are doing. Ask these people about what they are passionate about in exercise science. Chances are you’ll make a great connection for your network, but you’ll also get a sense for why others decide that exercise science is the best career path.

## SUMMARY

- The various systems of the body play important roles in regulating body functions prior to, during, and following physical activity, exercise, sport, and athletic performance.
- Proper control of the body functions require the systems to function together in a coordinated and controlled manner.
- Increased levels of physical activity and regular exercise training usually result in an improved function of the various systems, whereas physical inactivity typically leads to a decrease in functional ability and often diseased conditions in the body.
- Successful performance in sport and athletic competition depends on optimal functioning of the systems of the body.
- Various subject and content areas of exercise science, as well as the professional careers graduates enter into, will rely heavily on a sound knowledge of the systems of the body.

## FOR REVIEW

1. Why should the study of the systems of the body be examined from an integrated approach?
2. What are the primary functional components of the nervous system, and how do those components respond to exercise?
3. What are the three primary types of skeletal muscle fibers?
4. What are the principal functions of the skeletal system?
5. How does the cardiovascular system work to maintain challenges to homeostasis during exercise?
6. Describe the role of the pulmonary system in maintaining normal acid–base balance during rest and exercise.
7. What role does the urinary system play in the treatment of individuals with hypertension?
8. How does the gastrointestinal system influence the delivery of carbohydrate to working skeletal muscle?

9. Describe how insulin resistance influences the development of the disease metabolic syndrome.
10. What is the difference between innate immunity and acquired immunity?
11. Provide a list of the energy sources used in the three primary energy-producing pathways. Which pathways are used during low-, moderate-, and high-intensity exercise?

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