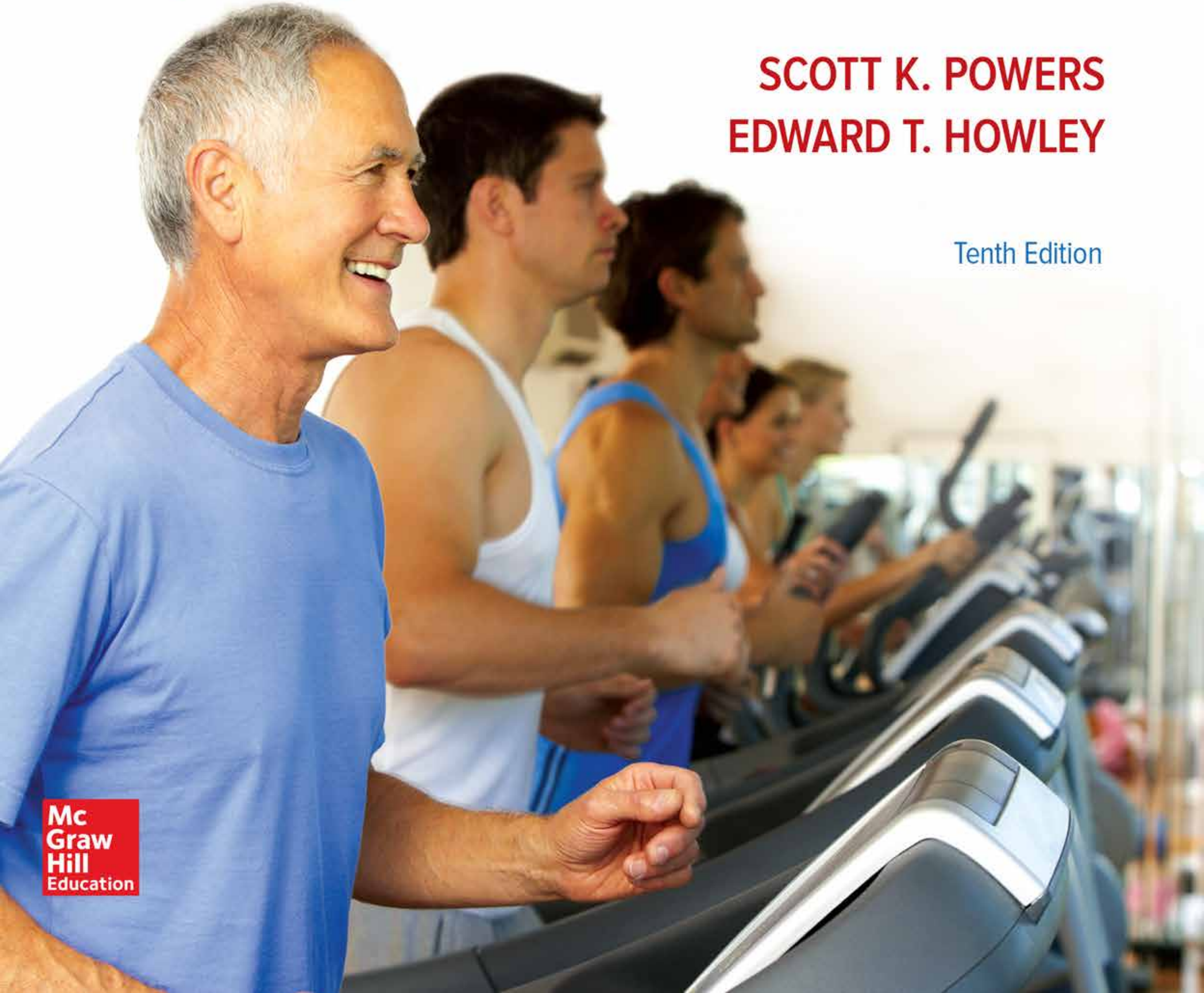
EXERCISE PHYSIOLOGY

Theory and Application to Fitness and Performance



SCOTT K. POWERS
EDWARD T. HOWLEY

Tenth Edition

Mc Graw Hill Education

EXERCISE PHYSIOLOGY

Theory and Application to Fitness and Performance

TENTH EDITION

Scott K. Powers
University of Florida

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University of Tennessee, Knoxville

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Education

EXERCISE PHYSIOLOGY: THEORY AND APPLICATION TO FITNESS AND PERFORMANCE,
TENTH EDITION

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Dedicated to Lou and Ann
for their love, patience, and support.

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Preface

As with all previous editions, the tenth edition of *Exercise Physiology: Theory and Application to Fitness and Performance* is intended for students interested in exercise physiology, clinical exercise physiology, human performance, kinesiology/exercise science, physical therapy, and physical education. The overall objective of this text is to provide the student with an up-to-date understanding of the physiology of exercise. Moreover, the book contains numerous clinical applications including exercise tests to evaluate cardiorespiratory fitness and information on exercise training for improvements in health-related physical fitness and sports performance.

This book is intended for a one-semester, upper-level undergraduate or beginning graduate exercise physiology course. Clearly, the text contains more material than can be covered in a single 15-week semester. This is by design. The book was written to be comprehensive and afford instructors the freedom to select the material that they consider to be the most important for the composition of their class. Furthermore, if desired, the book could be used in a two-semester sequence of exercise physiology courses (e.g., Exercise Physiology I and II) to cover the entire 25 chapters contained in the text.

NEW TO THIS EDITION

The tenth edition of our book has undergone *major* revisions and highlights the latest research in exercise physiology. Indeed, every chapter contains new and expanded discussions, new text boxes, new figures, updated references, and contemporary suggested readings.

New Topics and Updated Content

The content of this new edition has been markedly updated. Specifically, each chapter has been revised and updated to include new and amended box features, new illustrations, new research findings, and the inclusion of up-to-date references and suggested readings. The following list describes some of the significant changes that have made the tenth edition more complete and up-to-date:

- **Chapter 0:** Two new "A Look Back" features were added to highlight the careers of Elsworth Buskirk and Frances Hellebrandt.
- **Chapter 1:** New suggested readings and updated references were added.
- **Chapter 2:** Updated discussion on the role that heat shock proteins play in the cellular adaptation to stress.
- **Chapter 3:** New illustration and box feature added to highlight the structure and function of the two subpopulations of mitochondria found in skeletal muscle.
- **Chapter 4:** Several figures were upgraded along with the addition of a new section on measurement of $\dot{V}O_2$ max.
- **Chapter 5:** Numerous new and improved figures were added along with a new table highlighting hormonal changes during exercise. New information added on the impact of both growth hormone and anabolic steroids on skeletal muscle size and function.
- **Chapter 6:** Update on the latest research findings on the impact of exercise on the immune system added.
- **Chapter 7:** Expanded discussion on muscle sense organs (i.e., Golgi tendon organ and muscle spindles). New information added about the exceptions to the size principle. Further, a new section was added discussing how central pattern generators control movement during exercise. Additionally, Clinical Applications 7.2 was expanded

to discuss the risk of chronic traumatic encephalopathy (CTE) in contact sports.

- **Chapter 8:** Updated information on the role that satellite cells play in exercise-induced skeletal muscle hypertrophy was added. Further, new information on how exercise training alters the structure and function of the neuromuscular junction was included in this chapter. Lastly, new research on the cause of exercise-related skeletal muscle cramps was added along with a new box feature discussing new pharmacological approaches to prevent muscle cramps.
- **Chapter 9:** Updated information on the prediction of maximal heart rates in older individuals. Expanded discussion highlighting new research on the regulation of muscle blood flow during exercise. Added a new A Closer Look 9.3 to discuss the impact of body position on stroke volume during exercise.
- **Chapter 10:** Updated with the newest research findings on control of breathing during exercise. Also, new research on sex differences in breathing during exercise was also added.
- **Chapter 11:** Several new and improved illustrations were added along with an expanded discussion on intracellular acid-base buffer systems. New section added about how buffering capacity differs between muscle fiber types and how exercise training impacts muscle buffer systems. Further, the chapter was improved by the addition of the latest information on nutritional supplements used to improve acid-base balance during exercise.
- **Chapter 12:** Several new illustrations were added along with a discussion on the impact of a hot environment on exercise performance. Further, a box feature was added to discuss the influence of precooling on exercise performance. Lastly, the discussion of exercise in a cold environment was expanded to discuss the latest research findings.
- **Chapter 13:** Numerous new illustrations were included in this greatly revised chapter along with the addition of two new box features that discuss (1) the impact of genetics on $\dot{V}O_2$ max and (2) the influence of endurance exercise training on skeletal muscle mitochondrial volume and turnover. Moreover, a new section was also added to discuss muscle adaptations to anaerobic exercise. Finally, new and expanded information on the signaling events that lead to resistance training-induced muscle growth was included.
- **Chapter 14:** Major revision to this chapter provides more focus on the importance of physical activity in the prevention of chronic diseases. Section on metabolic syndrome was extensively revised to include an expanded discussion of how physical activity and diet impacts the inflammation that is linked to chronic disease.
- **Chapter 15:** Wide revision of the screening process for individuals entering a physical activity program along with new figures. Latest information regarding the new national standards for $\dot{V}O_2$ max.
- **Chapter 16:** Updated references and suggested readings.
- **Chapter 17:** New information on ACSM's physical activity recommendations for all special populations. New figure added on effect of age on $\dot{V}O_2$ max along with a new Clinical Application box discussing physical activity and risk of cancer.
- **Chapter 18:** Extensive revision to include new information on vitamins and minerals along with the new dietary guidelines for Americans. Widespread revision of the discussion on how to determine body composition along with a focused analysis of the causes and treatment for obesity.
- **Chapter 19:** New "A Look Back" on Brenda Bigland-Ritchie along with an expanded discussion on the linkages between central and peripheral fatigue. Update on the role that free radicals play in exercise-induced muscle fatigue and new information on why Kenyan runners are often successful in long distance races.
- **Chapter 20:** Chapter updated with latest research findings plus the addition of new suggested readings.
- **Chapter 21:** Three new box features added to address the following: (1) What are the physiological limits to the enhancement of endurance performance?; (2) Do compression garments benefit athletes during competition and recovery from training?; and (3) Treatment of delayed onset muscle soreness.
- **Chapter 22:** New illustration was added along with the latest research findings on the female athlete triad coupled with a discussion of the recent proposal to replace the term *female athlete triad* with new terminology.
- **Chapter 23:** Updated information from the 2016 ACSM position stand on nutrition and performance along with an expanded

discussion of the benefits and problems associated for athletes training with low levels of muscle glycogen. Expanded discussion of protein requirements for athletes along with a new discussion of the importance of consuming carbohydrates during long distance endurance events.

- **Chapter 24:** Updated discussion on the "Live High Train Low" training strategy. New recommendations for prevention and treatment of heat illnesses coupled with new information on how the WBGT Index fits into planning workouts in hot/humid environments.
- **Chapter 25:** Latest data on the prevalence and use of ergogenic aids. New information of dietary supplements for improving endurance performance along with additional information on the impact of stretching on performance.

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The tenth edition of *Exercise Physiology: Theory and Application to Fitness and Performance* is now available online with Connect, McGraw-Hill Education's integrated assignment and assessment platform. Connect also offers SmartBook™ for the new edition, which is the first adaptive reading experience proven to improve grades and help students study more effectively. All of the title's website and ancillary content is also available through Connect, including:

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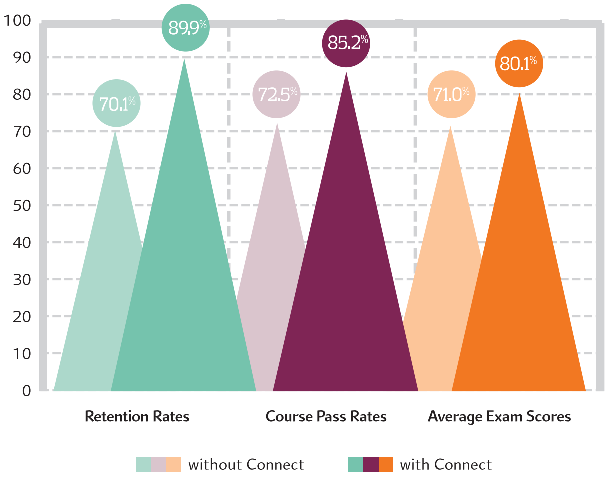

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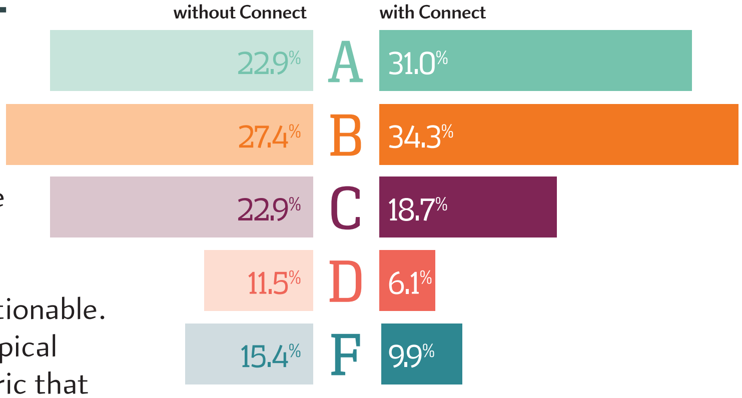

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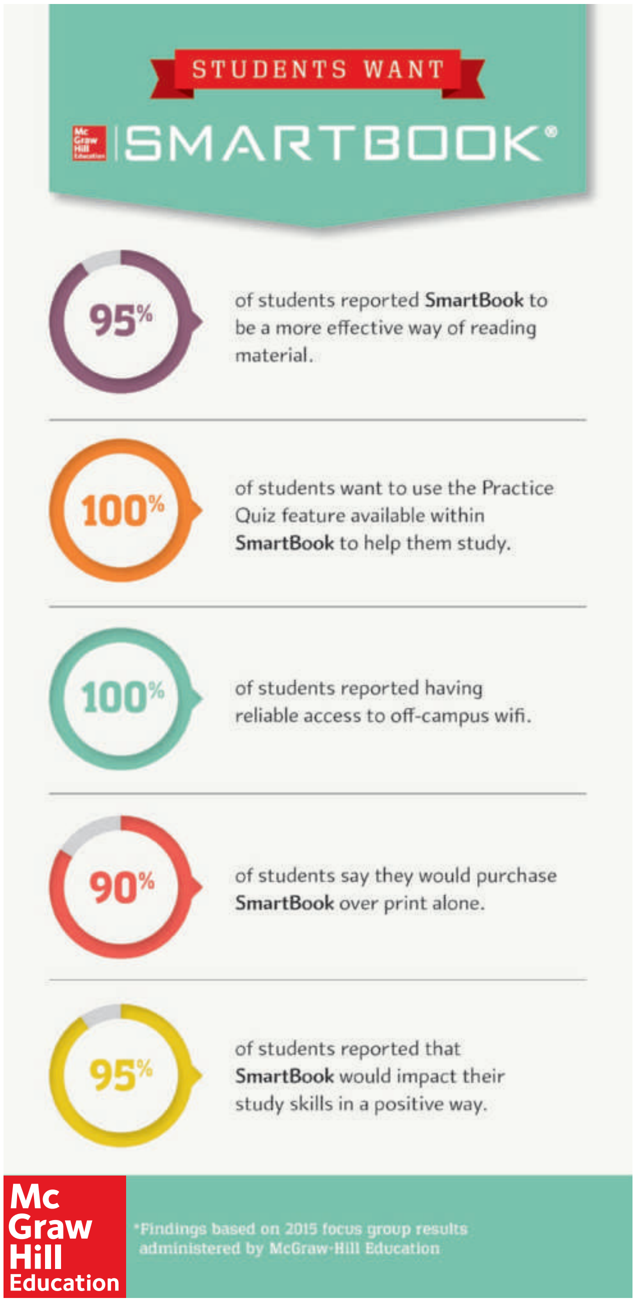

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ACKNOWLEDGEMENTS

This text *Exercise Physiology: Theory and Application to Fitness and Performance* is not the effort of only two authors but represents the contributions of hundreds of scientists from around the world. Although it is not possible to acknowledge every contributor to this work, we would like to recognize the following scientists who have greatly influenced our thinking, careers, and lives in general: Drs. Bruno Balke, Ronald Byrd, Jerome Dempsey, Stephen Dodd, H. V. Forster, B. D. Franks, Steven Horvath, Henry Montoye, Francis Nagle, and Hugh G. Welch.

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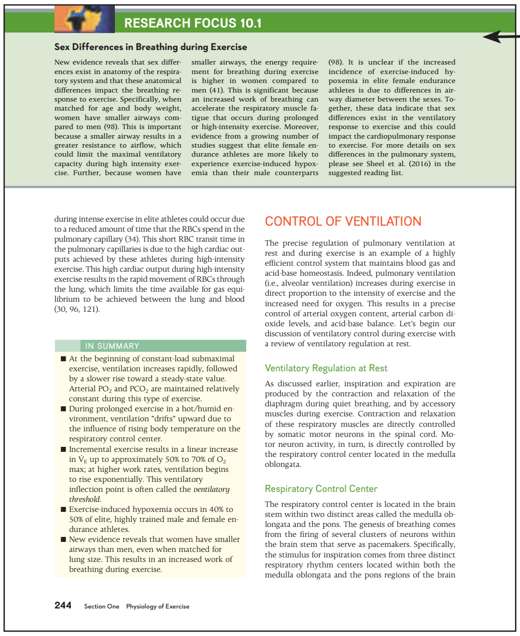
Engaging Presentation of Key Concepts Supported by the Latest Research



RESEARCH FOCUS 10.1

Sex Differences in Breathing during Exercise

New evidence reveals that sex differences exist in anatomy of the respiratory system and that these anatomical differences impact the breathing response to exercise. Specifically, when matched for age and body weight, women have smaller airways compared to men (98). This is important because a smaller airway results in a greater resistance to airflow, which could limit the maximal ventilatory capacity during high intensity exercise. Further, because women have smaller airways, the energy requirement for breathing during exercise is higher in women compared to men (41). This is significant because an increased work of breathing can accelerate the respiratory muscle fatigue that occurs during prolonged or high-intensity exercise. Moreover, evidence from a growing number of studies suggest that elite female endurance athletes are more likely to experience exercise-induced hypoxemia than their male counterparts (98). It is unclear if the increased incidence of exercise-induced hypoxemia in elite female endurance athletes is due to differences in airway diameter between the sexes. Together, these data indicate that sex differences exist in the ventilatory response to exercise and this could impact the cardiopulmonary response to exercise. For more details on sex differences in the pulmonary system, please see Sheel et al. (2016) in the suggested reading list.

during intense exercise in elite athletes could occur due to a reduced amount of time that the RBCs spend in the pulmonary capillary (34). This short RBC transit time in the pulmonary capillaries is due to the high cardiac outputs achieved by these athletes during high-intensity exercise. This high cardiac output during high-intensity exercise results in the rapid movement of RBCs through the lung, which limits the time available for gas equilibrium to be achieved between the lung and blood (30, 96, 121).

IN SUMMARY

- At the beginning of constant-load submaximal exercise, ventilation increases rapidly, followed by a slower rise toward a steady-state value. Arterial PO_2 and PCO_2 are maintained relatively constant during this type of exercise.
- During prolonged exercise in a hot/humid environment, ventilation "drifts" upward due to the influence of rising body temperature on the respiratory control center.
- Incremental exercise results in a linear increase in $\dot{V}_E$ up to approximately 50% to 70% of O_2 max; at higher work rates, ventilation begins to rise exponentially. This ventilatory inflection point is often called the *ventilatory threshold.*
- Exercise-induced hypoxemia occurs in 40% to 50% of elite, highly trained male and female endurance athletes.
- New evidence reveals that women have smaller airways than men, even when matched for lung size. This results in an increased work of breathing during exercise.

CONTROL OF VENTILATION

The precise regulation of pulmonary ventilation at rest and during exercise is an example of a highly efficient control system that maintains blood gas and acid-base homeostasis. Indeed, pulmonary ventilation (i.e., alveolar ventilation) increases during exercise in direct proportion to the intensity of exercise and the increased need for oxygen. This results in a precise control of arterial oxygen content, arterial carbon dioxide levels, and acid-base balance. Let's begin our discussion of ventilatory control during exercise with a review of ventilatory regulation at rest.

Ventilatory Regulation at Rest

As discussed earlier, inspiration and expiration are produced by the contraction and relaxation of the diaphragm during quiet breathing, and by accessory muscles during exercise. Contraction and relaxation of these respiratory muscles are directly controlled by somatic motor neurons in the spinal cord. Motor neuron activity, in turn, is directly controlled by the respiratory control center located in the medulla oblongata.

Respiratory Control Center

The respiratory control center is located in the brain stem within two distinct areas called the medulla oblongata and the pons. The genesis of breathing comes from the firing of several clusters of neurons within the brain stem that serve as pacemakers. Specifically, the stimulus for inspiration comes from three distinct respiratory rhythm centers located within both the medulla oblongata and the pons regions of the brain

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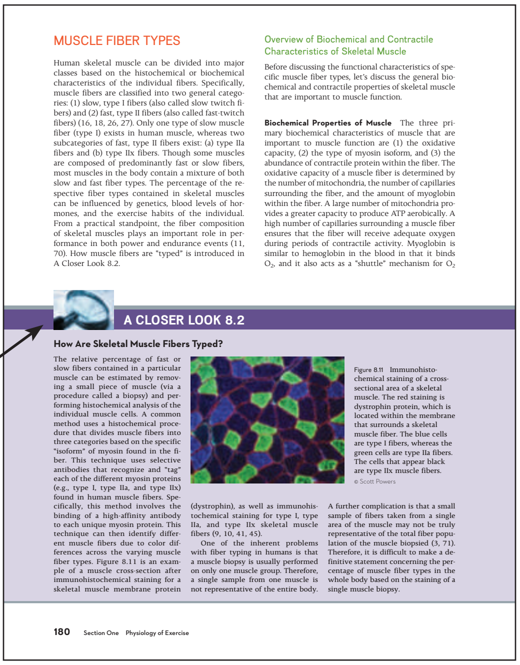
Research Focus

No matter what their career direction, students must learn how to read and think about the latest research. Research Focus presents new research and explains why it's relevant.



MUSCLE FIBER TYPES

Human skeletal muscle can be divided into major classes based on the histochemical or biochemical characteristics of the individual fibers. Specifically, muscle fibers are classified into two general categories: (1) slow, type I fibers (also called slow twitch fibers) and (2) fast, type II fibers (also called fast-twitch fibers) (16, 18, 26, 27). Only one type of slow muscle fiber (type I) exists in human muscle, whereas two subcategories of fast, type II fibers exist: (a) type IIa fibers and (b) type IIx fibers. Though some muscles are composed of predominantly fast or slow fibers, most muscles in the body contain a mixture of both slow and fast fiber types. The percentage of the respective fiber types contained in skeletal muscles can be influenced by genetics, blood levels of hormones, and the exercise habits of the individual. From a practical standpoint, the fiber composition of skeletal muscles plays an important role in performance in both power and endurance events (11, 70). How muscle fibers are "typed" is introduced in A Closer Look 8.2.

Overview of Biochemical and Contractile Characteristics of Skeletal Muscle

Before discussing the functional characteristics of specific muscle fiber types, let's discuss the general biochemical and contractile properties of skeletal muscle that are important to muscle function.

Biochemical Properties of Muscle The three primary biochemical characteristics of muscle that are important to muscle function are (1) the oxidative capacity, (2) the type of myosin isoform, and (3) the abundance of contractile protein within the fiber. The oxidative capacity of a muscle fiber is determined by the number of mitochondria, the number of capillaries surrounding the fiber, and the amount of myoglobin within the fiber. A large number of mitochondria provides a greater capacity to produce ATP aerobically. A high number of capillaries surrounding a muscle fiber ensures that the fiber will receive adequate oxygen during periods of contractile activity. Myoglobin is similar to hemoglobin in the blood in that it binds O_2, and it also acts as a "shuttle" mechanism for O_2

A CLOSER LOOK 8.2

How Are Skeletal Muscle Fibers Typed?

The relative percentage of fast or slow fibers contained in a particular muscle can be estimated by removing a small piece of muscle (via a procedure called a biopsy) and performing histochemical analysis of the individual muscle cells. A common method uses a histochemical procedure that divides muscle fibers into three categories based on the specific "isoform" of myosin found in the fiber. This technique uses selective antibodies that recognize and "tag" each of the different myosin proteins (e.g., type I, type IIa, and type IIx) found in human muscle fibers. Specifically, this method involves the binding of a high-affinity antibody to each unique myosin protein. This technique can then identify different muscle fibers due to color differences across the varying muscle fiber types. Figure 8.11 is an example of a muscle cross-section after immunohistochemical staining for a skeletal muscle membrane protein (dystrophin), as well as immunohistochemical staining for type I, type IIa, and type IIx skeletal muscle fibers (9, 10, 41, 45).

One of the inherent problems with fiber typing in humans is that a muscle biopsy is usually performed on only one muscle group. Therefore, a single sample from one muscle is not representative of the entire body. A further complication is that a small sample of fibers taken from a single area of the muscle may not be truly representative of the total fiber population of the muscle biopsied (3, 71). Therefore, it is difficult to make a definitive statement concerning the percentage of muscle fiber types in the whole body based on the staining of a single muscle biopsy.

Figure 8.11 Immunohistochemical staining of a cross-sectional area of a skeletal muscle. The red staining is dystrophin protein, which is located within the membrane that surrounds a skeletal muscle fiber. The blue cells are type I fibers, whereas the green cells are type IIa fibers. The cells that appear black are type IIx muscle fibers.

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A Closer Look

A Closer Look offers an in-depth view of topics that are of special interest to students. This feature encourages students to dig deeper into key concepts.

ASK THE EXPERT 12.1

Exercise Performance in a Hot Environment
Questions and Answers with Dr. Michael Sawka

Courtesy of Dr. Michael Sawka

Michael Sawka, Ph.D., *is Professor of Applied Physiology at the Georgia Institute of Technology.*

Dr. Sawka is an internationally recognized expert in both exercise physiology and environmental stress. Indeed, Dr. Sawka has authored more than 200 highly regarded research studies related to both exercise and environmental physiology. In particular, Dr. Sawka and his team have performed many studies investigating the impact of a hot environment on exercise performance.

In this box feature, Dr. Sawka addresses three important questions related to exercise performance in the heat.

QUESTION: Your work has established that environmental heat stress has a negative impact on aerobic exercise performance. However, how does heat stress impact performance in team sports, such as soccer or American football?

ANSWER: The performance of a team is dependent upon the performance of the individual athletes. If the individual athlete's performance is impaired, then it is likely the team's performance will also be suboptimal. In addition, team sports are greatly dependent upon both cohesion and decision making, and there is evidence that heat stress and dehydration can degrade cognitive function, which will have a negative impact on decision making and team cohesion.

QUESTION: Your group has extensively studied the mechanism(s) to explain why environmental heat stress impairs aerobic exercise performance. What are the primary explanations as to why a hot environment impairs aerobic performance?

ANSWER: Heat stress impairs aerobic exercise performance because of two primary reasons: (1) cardiovascular strain needed to support high skin blood flow, and (2) dehydration, which reduces plasma volume and thus increases cardiovascular strain. During exercise in a hot environment, the high skin blood flow and reduced plasma volume both act to reduce venous pressure and thus reduce cardiac filling. Despite a compensatory increase in heart rate and contractility, stroke volume will usually decline and thus make it difficult to maintain blood pressure and to sustain adequate blood flow to skeletal muscle and the brain. In addition, thermal discomfort and perceived exertion are elevated. The net effect is that heat stress degrades maximal aerobic power and that any submaximal work rate is performed at a greater relative work rate (i.e., percent of maximal aerobic power), which also increases perception of effort. Further, heat stress alters skeletal muscle metabolism (increased glycogen use and lactate accumulation) and may modify central nervous system function, which can contribute to impaired exercise performance.

QUESTION: Strong evidence indicates that heat acclimation improves exercise tolerance in hot environments. However, are there other strategies (e.g., precooling or hyperhydration) that athletes can utilize to improve aerobic performance in a hot environment?

ANSWER: By far the most effective strategies to sustain performance during heat stress are to achieve heat acclimation and maintain adequate hydration. In addition, heat acclimation has recently been demonstrated to confer benefits to improve aerobic exercise performance in temperate environments. There is some evidence that precooling and hyperhydration can improve performance in a hot environment, but in my opinion their benefits are marginal and if improperly used might be counterproductive.

Hyperhydration can result in a small increase in blood volume and slightly delay developing dehydration; together, these changes help to support the cardiovascular system during exercise in a hot environment. Nonetheless, these benefits are marginal and, depending upon the methods employed, hyperhydration could increase the likelihood of hyponatremia (i.e., low blood sodium levels), discomfort associated with increased urine output, or elevated risk of headache.

Precooling allows body temperature (skin and core) to be lower at the beginning of exercise, but the small benefits demonstrated in laboratory studies may be lost in real-life competition when athletes are exposed to the hot environment for a significant period before initiating competition. In addition, overcooling the skeletal muscles might initially impair muscle performance.

after the first exposure (51, 70) (Fig. 12.13). A brief discussion of each of these physiological adaptations follows.

Heat acclimation results in a 10% to 12% increase in plasma volume (17, 67). This increased plasma volume maintains central blood volume, stroke volume, and sweating capacity, and allows the body to store more heat with a smaller temperature gain.

A key aspect of heat acclimation is an earlier onset of sweating and an increase in the sweat rate. An earlier onset of sweating simply means that sweating begins rapidly after the commencement of exercise; this translates into less heat storage at the beginning of exercise and a lower core temperature. In addition, heat acclimation can increase the sweating capacity almost threefold above the rate achievable prior to

Chapter Twelve Temperature Regulation 285

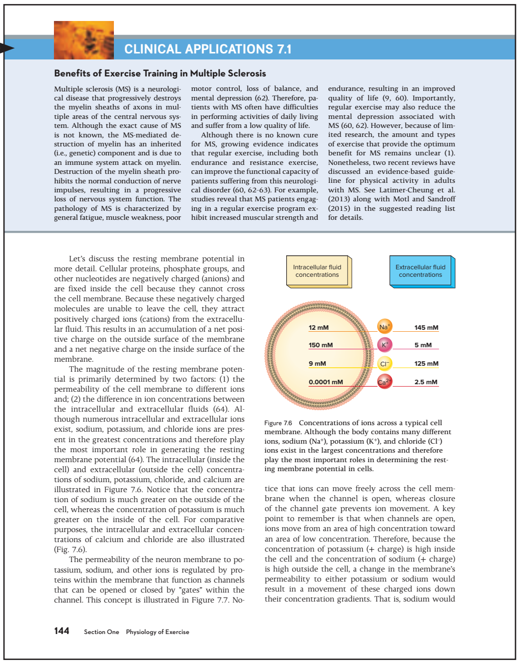
Ask the Expert

This question-and-answer feature lets you find out what leading scientists have to say about topics such as the effect of space flight on skeletal muscle and the effect of exercise on bone health.

Practical Applications of Exercise Physiology

Clinical Applications

Learn how exercise physiology is used in the clinical setting.



CLINICAL APPLICATIONS 7.1

Benefits of Exercise Training in Multiple Sclerosis

Multiple sclerosis (MS) is a neurological disease that progressively destroys the myelin sheaths of axons in multiple areas of the central nervous system. Although the exact cause of MS is not known, the MS-mediated destruction of myelin has an inherited (i.e., genetic) component and is due to an immune system attack on myelin. Destruction of the myelin sheath prohibits the normal conduction of nerve impulses, resulting in a progressive loss of nervous system function. The pathology of MS is characterized by general fatigue, muscle weakness, poor motor control, loss of balance, and mental depression (62). Therefore, patients with MS often have difficulties in performing activities of daily living and suffer from a low quality of life.

Although there is no known cure for MS, growing evidence indicates that regular exercise, including both endurance and resistance exercise, can improve the functional capacity of patients suffering from this neurological disorder (60, 62–63). For example, studies reveal that MS patients engaging in a regular exercise program exhibit increased muscular strength and endurance, resulting in an improved quality of life (9, 60). Importantly, regular exercise may also reduce the mental depression associated with MS (60, 62). However, because of limited research, the amount and types of exercise that provide the optimum benefit for MS remains unclear (1). Nonetheless, two recent reviews have discussed an evidence-based guideline for physical activity in adults with MS. See Latimer-Cheung et al. (2013) along with Motl and Sandroff (2015) in the suggested reading list for details.

Let's discuss the resting membrane potential in more detail. Cellular proteins, phosphate groups, and other nucleotides are negatively charged (anions) and are fixed inside the cell because they cannot cross the cell membrane. Because these negatively charged molecules are unable to leave the cell, they attract positively charged ions (cations) from the extracellular fluid. This results in an accumulation of a net positive charge on the outside surface of the membrane and a net negative charge on the inside surface of the membrane.

The magnitude of the resting membrane potential is primarily determined by two factors: (1) the permeability of the cell membrane to different ions and; (2) the difference in ion concentrations between the intracellular and extracellular fluids (64). Although numerous intracellular and extracellular ions exist, sodium, potassium, and chloride ions are present in the greatest concentrations and therefore play the most important role in generating the resting membrane potential (64). The intracellular (inside the cell) and extracellular (outside the cell) concentrations of sodium, potassium, chloride, and calcium are illustrated in Figure 7.6. Notice that the concentration of sodium is much greater on the outside of the cell, whereas the concentration of potassium is much greater on the inside of the cell. For comparative purposes, the intracellular and extracellular concentrations of calcium and chloride are also illustrated (Fig. 7.6).

The permeability of the neuron membrane to potassium, sodium, and other ions is regulated by proteins within the membrane that function as channels that can be opened or closed by "gates" within the channel. This concept is illustrated in Figure 7.7. Notice that ions can move freely across the cell membrane when the channel is open, whereas closure of the channel gate prevents ion movement. A key point to remember is that when channels are open, ions move from an area of high concentration toward an area of low concentration. Therefore, because the concentration of potassium (+ charge) is high inside the cell and the concentration of sodium (+ charge) is high outside the cell, a change in the membrane's permeability to either potassium or sodium would result in a movement of these charged ions down their concentration gradients. That is, sodium would

Figure 7.6 Concentrations of ions across a typical cell membrane. Although the body contains many different ions, sodium (Na^+), potassium (K^+), and chloride (Cl^-) ions exist in the largest concentrations and therefore play the most important roles in determining the resting membrane potential in cells.

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The Winning Edge

How do athletes find the "extra edge" that can make the difference between victory and defeat? These features explain the science behind a winning performance.

THE WINNING EDGE 11.1

Exercise Physiology Applied to Sports

Nutritional Supplements to Buffer Exercise-Induced Acid-Base Disturbances and Improve Performance

Because intramuscular acidosis is associated with muscle fatigue, numerous studies have explored nutritional supplements to increase buffering capacity in hopes of improving athletic performance during high-intensity exercise. Indeed, it appears that supplements including sodium bicarbonate, sodium citrate, and beta-alanine have the potential to improve buffering capacity and enhance exercise performance during, high-intensity exercise. Let's discuss these supplement strategies to improve muscle buffering capacity in more detail.

Sodium bicarbonate. Bicarbonate is a buffer that plays an important role in maintaining both extracellular and intracellular pH, despite its inability to freely cross the muscle membrane (i.e., sarcolemma). Although controversy exists (2), many studies conclude that performance during high-intensity exercise is improved when athletes ingest sodium bicarbonate prior to exercise (6, 7, 26, 30–32, 34, 37, 40). Specifically, results from numerous studies reveal that boosting the blood-buffering capacity by ingestion of sodium bicarbonate increases time to exhaustion during high-intensity exercise (e.g., 80% to 120% $\dot{V}O_2$ max). For example, a recent survey of the scientific literature reveals that sodium bicarbonate is effective in improving a 60-second "all out" exercise bout by approximately 2% (5). Further, laboratory studies employing repeated bouts of high-intensity exercise (i.e., >100% $\dot{V}O_2$ max) have reported that ingestion of sodium bicarbonate prior to exercise can enhance performance by more than 8% (18). In addition to these laboratory studies, evidence exists that sodium bicarbonate is also beneficial to sport performance in activities where the metabolic demands are primarily anaerobic, such as judo, swimming, and water polo (18).

It appears that sodium bicarbonate improves physical performance by increasing the extracellular buffering capacity, which, in turn, increases the transport of hydrogen ions out of the muscle fibers (38). This would reduce the interference of hydrogen ions on muscle ATP production and/or the contractile process itself.

In deciding whether to use sodium bicarbonate prior to a sporting event, an athlete should understand the risks associated with this decision. Ingestion of sodium bicarbonate in the doses required to improve blood-buffering capacity can cause gastrointestinal problems, including diarrhea and vomiting (7, 37).

Sodium Citrate. Similar to sodium bicarbonate, sodium citrate is another agent capable of increasing extracellular buffering capacity (18). The question of whether ingestion of sodium citrate can improve exercise performance during high-intensity exercise remains controversial because experimental results are often inconsistent. Nonetheless, a review of the research literature suggests that although low doses of sodium citrate does not improve performance, ingestion of high doses of sodium citrate (i.e., >0.5 grams/kilogram body weight) improves performance during high-intensity cycling exercise lasting 120 to 240 seconds (18).

Unfortunately, similar to sodium bicarbonate, ingestion of high doses of sodium citrate can produce undesired side effects such as nausea, gastrointestinal discomfort, and headaches. Therefore, before deciding whether to use sodium citrate prior to competition, athletes should consider the negative side effects associated with the use of sodium citrate.

Beta-alanine. Recent evidence suggests that supplementation with beta-alanine can play a beneficial role in protecting against exercise-induced acidosis and improve performance during short, high-intensity exercise (39). Beta-alanine is a nonessential amino acid produced in the liver, gut, and kidney. However, fasting blood levels of beta-alanine are low indicating that endogenous synthesis of this amino is limited.

The link between beta-alanine and protection against acidosis is linked to the fact that beta-alanine is an important precursor for the synthesis of carnosine in skeletal muscle. As discussed in the text, carnosine is a small molecule (dipeptide) found in the cytoplasm of excitable cells (i.e., neurons, skeletal and cardiac muscle fibers) (18). Carnosine has several important physiological functions including the ability to buffer hydrogen ions and protect against exercise-induced decreases in cellular pH (18).

The availability of beta-alanine is the rate limiting factor for carnosine synthesis in muscle fibers. However, supplementation (2 to 3 grams/day) with beta-alanine for >2 weeks results in a 60% to 80% increase in muscle carnosine levels. Importantly, this increase in muscle carnosine levels is associated with a 3% to 5% increase in muscle buffering capacity (18). Theoretically, this increase in intracellular buffering capacity could translate into improvements in performance during high-intensity exercise. In this regard, growing evidence suggests that beta-alanine supplementation improves high-intensity exercise performance in both running and cycling events lasting 1 to 4 minutes (18). Interestingly, some of these studies have recorded performance improvements of 12% to 14% (18).

The only known side effect of beta-alanine supplementation is paraesthesia (tingling of the skin); this sensation begins within 20 minutes after ingestion and lasts up to 60 minutes (18). Although harmless, paraesthesia is unpleasant and, several investigations have reported that paraesthesia can be avoided by staggering dosing throughout the day (18).

Final words of caution on use of "supplement buffers" to improve exercise performance. Regardless of the type of buffer ingested, extremely large doses of any buffer can result in severe alkalosis and pose negative health consequences. Another important consideration in the use of any ergogenic aid is the legality of the drug. In regard to the use of acid-base buffers, some sports regulatory agencies have banned the use of sodium buffers during competition. See Sahlin (2014) and Junior et al. (2015) in Suggested Readings for detailed information about the possible ergogenic effects of sodium bicarbonate, sodium citrate, and beta-alanine.

Chapter Eleven Acid-Base Balance during Exercise 263

EXERCISE PHYSIOLOGY

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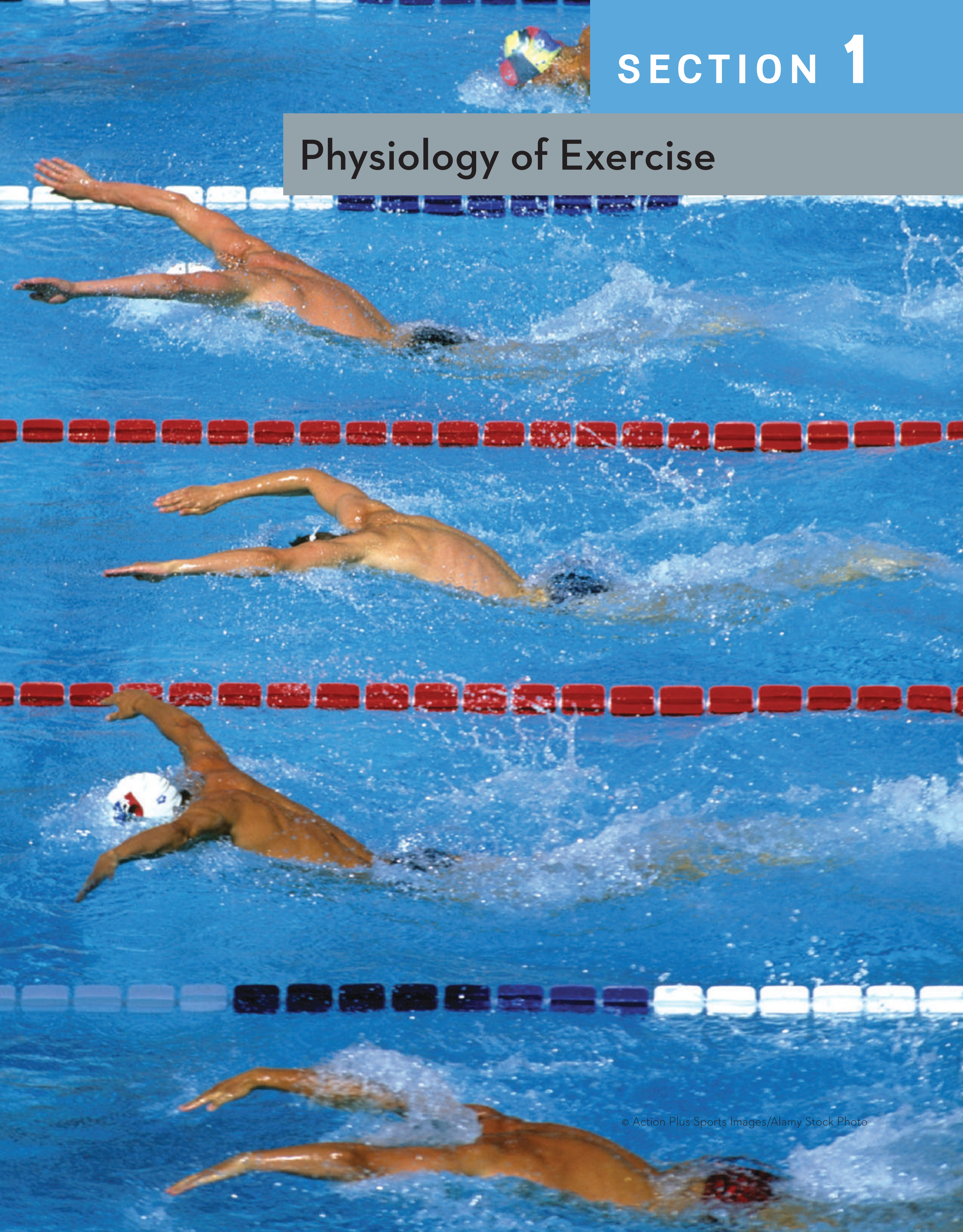

SECTION 1

Physiology of Exercise

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Introduction to Exercise Physiology

Objectives

By studying this chapter, you should be able to do the following:

1. Describe the scope of exercise physiology as a branch of physiology.
2. Describe the influence of European scientists on the development of exercise physiology.
3. Name the three Nobel Prize winners whose research work involved muscle or muscular exercise.
4. Describe the role of the Harvard Fatigue Laboratory in the history of exercise physiology in the United States.
5. Describe factors influencing physical fitness in the United States over the past century.
6. List career options for students majoring in exercise science or kinesiology.

Outline

Does one need to have a "genetic gift" of speed to be a world-class runner, or is it all due to training? What happens to your heart rate when you take an exercise test that increases in intensity each minute? What changes occur in your muscles as a result of an endurance-training program that allows you to run at faster speeds over longer distances? What fuel–carbohydrate or fat–is most important when running a marathon? Research in exercise physiology provides answers to these and similar questions.

Physiology is the study of the function of tissues (e.g., muscle, nerve), organs (e.g., heart, lungs), and systems (e.g., cardiovascular). Exercise physiology extends this to evaluate the effect of a single bout of exercise (acute exercise) and repeated bouts of exercise (i.e., training programs) on these tissues, organs, and systems. In addition, the responses to acute exercise and training may be studied at high altitude or in extremes of heat and humidity to determine the impact of these environmental factors on our ability to respond and adapt to exercise. Finally, studies are conducted on young and old individuals, both healthy and those with disease, to understand the role of exercise in the prevention of or rehabilitation from various chronic diseases.

Consistent with this perspective, we go beyond simple statements of fact to show how information about the physiology of exercise is applied to the prevention of and rehabilitation from coronary heart disease, the performances of elite athletes, and the ability of a person to work in adverse environments such as high altitudes. The acceptance of terms such as *sports physiology, sports nutrition,* and *sports medicine* is evidence of the growth of interest in the application of physiology of exercise to real-world problems. Careers in athletic training, personal-fitness training, cardiac rehabilitation, and strength and conditioning, as well as the traditional fields of physical therapy and medicine, are of interest to students studying exercise physiology. We will expand on career opportunities later in the chapter.

In this chapter, we provide a brief history of exercise physiology to help you understand where we have been and where we are going. In addition, throughout the text a variety of scientists and clinicians are highlighted in a historical context as subject matter is presented (i.e., muscle, cardiovascular responses, altitude). We hope that by linking a person to a major accomplishment within the context of a chapter, history will come alive and be of interest to you.

BRIEF HISTORY OF EXERCISE PHYSIOLOGY

The history of exercise physiology represents a global perspective involving scientists from many different countries. In this section, we begin with the impact European scientists have had on the development of exercise physiology. We then describe the role of the Harvard Fatigue Laboratory in the growth of exercise physiology in this country.

European Heritage

A good starting place to discuss the history of exercise physiology in the United States is in Europe. Three scientists, A. V. Hill of Britain, August Krogh of Denmark, and Otto Meyerhof of Germany, received Nobel Prizes for research on muscle or muscular exercise (13). Hill and Meyerhof shared the Nobel Prize in Physiology or Medicine in 1922. Hill was recognized for his precise measurements of heat production during muscle contraction and recovery, and Meyerhof for his discovery of the relationship between the consumption of oxygen and the measurement of lactic acid in muscle. Hill was trained as a mathematician before becoming interested in physiology. In addition to his work cited for the Nobel Prize, his studies on humans led to the development of a framework around which we understand the physiological factors related to distance-running performance (6) (see Chap. 19).

A. Archibald V. Hill, B. August Krogh, C. Otto F. Meyerhof

(A) © Lafayette/Hulton Archive/Getty Images; (B) © Underwood And Underwood/LIFE Images Collection/Getty Images; (C) © Ullstein Bild/Getty Images

Although Krogh received the Nobel Prize for his research on the function of capillary circulation, he had a major impact on numerous areas of investigation. Furthermore, like many productive investigators, his influence was due not only to his own work but to that of his students and colleagues as well. Krogh's collaboration with Johannes Lindhard resulted in classic studies dealing with carbohydrate and fat metabolism during exercise, and how the cardiovascular and respiratory systems' responses are controlled during exercise (4). Three students in Krogh's lab, Erling Asmussen, Erik Hohwü-Christensen, and Marius Nielsen (called "the three musketeers" by Krogh), had a major impact on exercise physiology research throughout the middle of the twentieth century. These investigators, in turn, trained a number of outstanding physiologists, several of whom you will meet throughout this text. The August Krogh Institute in Denmark contains some of the most prominent exercise physiology laboratories in the world. Marie Krogh, his wife, was a noted scientist in her own right and was recognized for her innovative work on measuring the diffusing capacity of the lung. We recommend the biography of the Kroghs written by their daughter, Bodil Schmidt-Nielsen (see Suggested Readings), for those interested in the history of exercise physiology.

Several other European scientists must also be mentioned, not only because of their contributions to the exercise physiology but also because their names are commonly used in a discussion of exercise physiology. J. S. Haldane did some of the original work on the role of CO_2 in the control of breathing. Haldane also developed the respiratory gas analyzer that bears his name (16). C. G. Douglas did pioneering work with Haldane in the role of O_2 and lactic acid in the control of breathing during exercise, including some work conducted at various altitudes. The canvas-and-rubber gas collection bag used for many years in exercise physiology laboratories around the world carries Douglas's name. A contemporary of Douglas, Christian Bohr of Denmark, did the classic work on how O_2 binds to hemoglobin. The "shift" in the oxygen-hemoglobin dissociation curve due to the addition of CO_2 bears his name (see Chap. 10). Interestingly, it was Krogh who did the actual experiments that enabled Bohr to describe his famous "shift" (4, 16).

IN SUMMARY

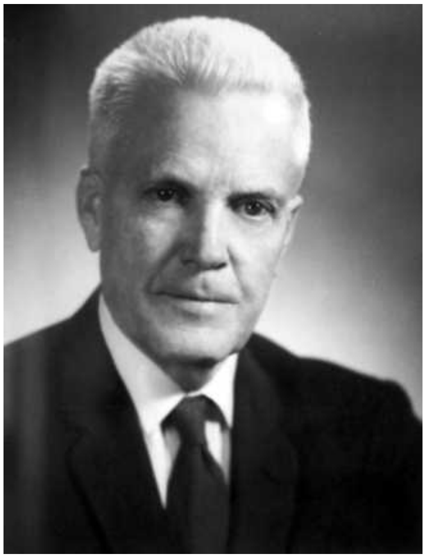
- A. V. Hill, August Krogh, and Otto Meyerhof received the Nobel Prize for work related to muscle or muscular exercise.
- Numerous European scientists have had a major impact on the field of exercise physiology.

Harvard Fatigue Laboratory

A focal point in the history of exercise physiology in the United States is the Harvard Fatigue Laboratory. Professor L. J. Henderson organized the laboratory within the Business School to conduct physiological research on industrial hazards. Dr. David Bruce Dill was the research director from the time the laboratory opened in 1927 until it closed in 1947 (19). Table 0.1 shows that the scientists conducted research in numerous areas, in the laboratory and in the field, and the results of those early studies have been supported over the years. Dill's classic text, *Life, Heat, and Altitude* (15), is a recommended reading for any student of exercise and environmental physiology. Much of the careful and precise work of the laboratory was conducted using the now-classic Haldane analyzer for respiratory gas analysis and the van Slyke apparatus for blood-gas analysis. The advent of computer-controlled equipment in the 1980s has

The "three musketeers": From left to right: Erling Asmussen, Erik Hohwü-Christensen, and Marius Nielsen

Courtesy of The Physiological Society



David Bruce Dill

Courtesy of American College of Sports Medicine

TABLE 0.1 **Active Research Areas in the Harvard Fatigue Laboratory**

- Metabolism
  - Maximal oxygen uptake
  - Oxygen debt
  - Carbohydrate and fat metabolism during long-term work
- Environmental physiology
  - Altitude
  - Dry and moist heat
  - Cold
- Clinical physiology
  - Gout
  - Schizophrenia
  - Diabetes
- Aging
  - Basal metabolic rate
  - Maximal oxygen uptake
  - Maximal heart rate
- Blood
  - Acid–base balance
  - O_2 saturation: role of PO_2, PCO_2, and carbon monoxide
  - Nutrition assessment techniques
  - Vitamins
  - Foods
- Physical fitness
  - Harvard Step Test

made data collection easier but has not improved on the accuracy of measurement (see Fig. 0.1).

The Harvard Fatigue Laboratory attracted doctoral students as well as scientists from other countries. Many of the alumni from the laboratory are recognized in their own right for excellence in research in the physiology of exercise. Two doctoral students, Steven Horvath and Sid Robinson, went on to distinguished careers at the Institute of Environmental Stress in Santa Barbara and Indiana University, respectively.

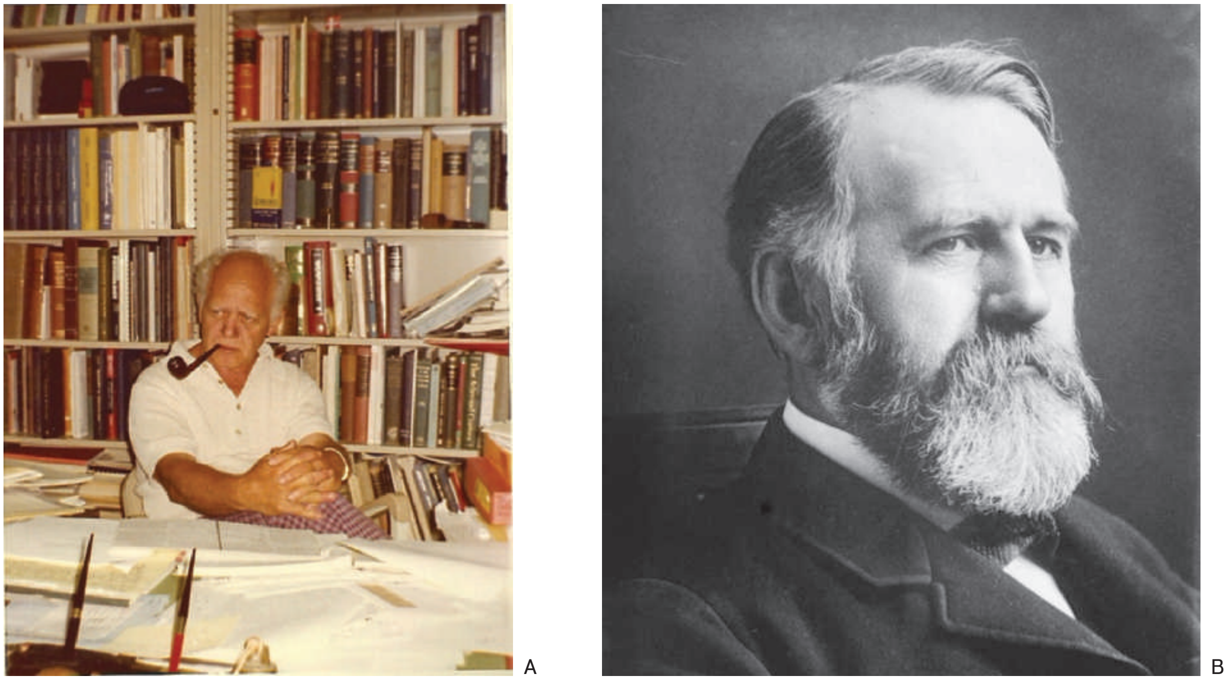
Foreign "Fellows" included the "three musketeers" mentioned in the previous section (E. Asmussen, E. Hohwü-Christensen, and M. Nielsen) and the Nobel Prize winner August Krogh. These scientists brought new ideas and technology to the lab, participated in laboratory and field studies with other staff members, and published some of the most important work in the exercise physiology between 1930 and 1980. Rudolfo Margaria, from Italy, went on to extend his classic work on oxygen debt and described the energetics of locomotion. Peter F. Scholander, from Norway, gave us his chemical gas analyzer that is a primary method of calibrating tank gas used to standardize electronic gas analyzers (19).

In summary, under the leadership of Dr. D. B. Dill, the Harvard Fatigue Laboratory became a model for research investigations into exercise and environmental physiology, especially as it relates to humans. When the laboratory closed and the staff dispersed, the ideas, techniques, and approaches to scientific inquiry were distributed throughout the world, and with them, Dill's influence in the area of environmental and exercise physiology. Dr. Dill continued his research outside Boulder City, Nevada, into the 1980s. He died in 1986 at the age of 93.

Progress toward understanding any issue in exercise physiology transcends time, national origin, and scientific training. Solutions to difficult questions require the interaction of scientists from diverse disciplines and professions such as physiology, biochemistry, molecular biology, and medicine. We recommend *Exercise Physiology–People and Ideas* (see the Suggested Readings) to further your understanding of important historical connections. In this book, internationally known scientists provide a historical treatment of a number of important issues in exercise

Figure 0.1 Comparison of old and new technology used to measure oxygen consumption and carbon dioxide production during exercise. (*Right:* COSMED.)

(LEFT) © Ullstein Bild/Getty Images; (RIGHT) Photo courtesy of www.cosmed.com



A. Steven Horvath, B. Dudley Sargent

(A) Courtesy of Steven Horvath; (B) Library of Congress [LC-B2- 1121-5]

physiology, with an emphasis on the cross-continent flow of energy and ideas. We highlight several scientists and clinicians with our "Ask the Expert" boxes throughout the text, both to introduce them to you and for them to share their current ideas. In addition, A Look Back–Important People in Science is used to recognize well-known scientists who have influenced our understanding of exercise physiology. In this context, you will get to know those who have gone before and those who are currently leading the charge.

IN SUMMARY

- The Harvard Fatigue Laboratory was a focal point in the development of exercise physiology in the United States. Dr. D. B. Dill directed the laboratory from its opening in 1927 until its closing in 1947. The body of research in exercise and environmental physiology produced by the scientists in that laboratory formed the foundation for new ideas and experimental methods that still influence us today.

PHYSIOLOGY, PHYSICAL FITNESS, AND HEALTH

Physical fitness is a popular topic today, and its popularity has been a major factor in motivating college students to pursue careers in physical education, exercise physiology, health education, nutrition, physical therapy, and medicine. In 1980, the Public Health Service listed "physical fitness and exercise" as one of 15 areas of concern related to improving the country's overall health (32). This was far from a new idea. Similar interests and concerns about physical fitness existed in this country more than 100 years ago. Between the Civil War and the First World War (WWI), physical education was primarily concerned with the development and maintenance of fitness, and many of the leaders in physical education were trained in medicine (14) (p. 5). For example, Dr. Dudley Sargent, hired by Harvard University in 1879, set up a physical training program with individual exercise prescriptions to improve a person's structure and function to achieve "that prime physical condition called fitness–fitness for work, fitness for play, fitness for anything a man may be called upon to do" (35) (p. 297).

Sargent, D., *Physical Education.* Boston,
MA: Ginn and Company, 1906.

Dr. Sargent was clearly ahead of his time in promoting health-related fitness. Later, war became a primary force driving this country's interest in physical fitness. Concerns about health and fitness were raised during WWI and WWII when large numbers of draftees failed the induction exams due to mental and physical defects (18) (p. 407). These concerns influenced the type of physical education programs in the schools during these years, making them resemble premilitary training programs (40) (p. 484). Interestingly, whereas stunted growth and being underweight were major reasons for rejecting military recruits in WWII, obesity is the major cause for rejecting recruits today (see "Still Too Fat to Fight" at **http://www.missionreadiness.org/2012/still-too-fat-to-fight/**).

The present interest in physical activity and health was stimulated in the early 1950s by two major findings: (1) autopsies of young soldiers killed during the Korean War showed that significant coronary artery disease had already developed and (2) Hans Kraus showed that American children performed poorly on a minimal muscular fitness test compared to European children (40) (p. 516). Due to the latter finding, President Eisenhower initiated a conference in 1955 that resulted in the formation of the President's Council on Youth Fitness. The American Association for Health, Physical Education, and Recreation (AAHPER) supported these activities and in 1957 developed the AAHPER Youth Fitness Test with national norms to be used in physical education programs throughout the country. Before he was inaugurated, President Kennedy expressed his concerns about the nation's fitness in an article published in *Sports Illustrated*, called "The Soft American" (24):

> For the physical vigor of our citizens is one of America's most precious resources. If we waste and neglect this resource, if we allow it to dwindle and grow soft, then we will destroy much of our ability to meet the great and vital challenges which confront our people. We will be unable to realize our full potential as a nation.
>
> Kennedy, J., "The Soft American," *Sports Illustrated*, 13, pp. 14–17, 1960.

During Kennedy's term, the council's name was changed to the "President's Council on Physical Fitness" to highlight the concern for fitness. The name was changed again in the Nixon administration to the "President's Council on Physical Fitness and Sports," which supported fitness not only in schools but also in business, industry, and for the general public. The name was most recently changed by President Obama to the "President's Council on Fitness, Sports, & Nutrition" to focus more attention on the obesity epidemic (see **www.fitness.gov**). Items in the Youth Fitness Test were changed over the years, and in 1980, the American Alliance for Health, Physical Education, Recreation, and Dance (AAHPERD) published a separate *Health-Related Physical Fitness Test Manual* (1) to distinguish between "performance testing" (e.g., 50-yard dash) and "fitness testing" (e.g., skinfold thickness). This health-related test battery is consistent with the direction of lifetime fitness programs, being concerned with obesity, cardiorespiratory fitness, and low-back function. A parallel fitness test, Fitnessgram, was developed by The Cooper Institute in 1982, including software to support the scoring and printing of reports (see **https://www.cooperinstitute.org/youth/fitnessgram**). The President's Council now recommends that the Fitnessgram be used to evaluate fitness in children. For readers interested in the history of fitness testing in schools, we recommend Morrow et al.'s review in the Suggested Readings.

Paralleling this interest in the physical fitness of youth was the rising concern about the death rate from coronary heart disease in the middle-aged American male population. Epidemiological studies of the health status of the population underscored the fact that degenerative diseases related to poor health habits (e.g., high-fat diet, smoking, inactivity) were responsible for more deaths than the classic infectious and contagious diseases. In 1966, a major symposium highlighted the need for more research in the area of physical activity and health (33). In the 1970s, there was an increase in the use of exercise tests to diagnose heart disease and to aid in the prescription of exercise programs to improve cardiovascular health. Large corporations developed "executive" fitness programs to improve the health status of that high-risk group. While most Americans are now familiar with such programs and some students of exercise physiology seek careers in "corporate fitness," such programs are not new. In fact, as early as 1923, *textbooks such as McKenzie's Exercise in Education and Medicine* (27) showed businessmen participating in a dance exercise class. In short, the idea that regular physical activity is an important part of a healthy lifestyle was "rediscovered." If any questions remained about the importance of physical activity to health, the publication of the Surgeon General's Report in 1996 and the appearance of the first U.S. Physical Activity Guidelines in 2008 put them to rest (see "A Closer Look 0.1").

IN SUMMARY

- Fitness has been an issue in this country from the latter part of the nineteenth century until the present. War, or the threat of war, exerted a strong influence on fitness programs in the public schools. In WWII, being underweight and small of stature were major reasons for rejecting military recruits; today, obesity is a major cause for rejection.
- Recent interest in fitness is related to the growing concern over the high death rates from disease processes that are attributable to preventable factors, such as poor diet, lack of exercise, and smoking. Government and professional organizations have responded to this need by educating the public about these problems.
- Schools use health-related fitness tests, such as the Fitnessgram, to evaluate a child's physical fitness.

A CLOSER LOOK 0.1

By the early to mid-1980s, it had become clear that physical inactivity was a major public health concern (32). In 1992, the American Heart Association made physical inactivity a major risk factor for cardiovascular diseases, just like smoking, high blood pressure, and high serum cholesterol (3). In 1995, the Centers for Disease Control and Prevention (CDC) and the American College of Sports Medicine published a public health physical activity recommendation that "Every U.S. adult should accumulate 30 minutes or more of moderate-intensity physical activity on most, preferably all, days of the week" (30). A year later, the *Surgeon General's Report on Physical Activity and Health* was published (39).

This report highlighted the fact that physical inactivity was killing U.S. adults, and the problem was a big one—60% of U.S. adults did not engage in the recommended amount of physical activity, and 25% were not active at all. This report was based on the large body of evidence available from epidemiological studies, small-group training studies, and clinical investigations showing the positive effects of an active lifestyle. For example, physical activity was shown to

- Lower the risk of dying prematurely and from heart disease
- Reduce the risk of developing diabetes and high blood pressure
- Help maintain weight and healthy bones, muscles, and joints
- Help lower blood pressure in those with high blood pressure and promote psychological well-being

In 2008, the first edition of the *U.S. Physical Activity Guidelines* was published (**http://www.health.gov/paguidelines/guidelines/default.aspx**). This document was developed on the basis of an Advisory Committee's comprehensive review of the research since the publication of the Surgeon General's Report in 1996 (for the Advisory Committee Report, see **http://health.gov/paguidelines/report/**). Recently, a Midcourse Report focusing on strategies to increase physical activity among youth was published (**http://www.health.gov/paguidelines/midcourse/**). The *U.S. Physical Activity Guidelines*, along with the *Dietary Guidelines for Americans 2015* (**http://health.gov/dietaryguidelines/2015/guidelines/**), provides important information on how to address our problems of inactivity and obesity. (We discuss this in more detail in Chaps. 16, 17, and 18.)

PHYSICAL EDUCATION TO EXERCISE SCIENCE AND KINESIOLOGY

Undergraduate academic preparation in physical education has changed over the past five decades to reflect the explosion in the knowledge base related to the physiology of exercise, biomechanics, and exercise prescription. This occurred at a time of a *perceived* reduced need for school-based physical education teachers and an increased need for exercise professionals in the preventive and clinical settings. These factors, as well as others, led some college and university departments to change their names from Physical Education to Exercise Science or Kinesiology. This trend is likely to continue as programs move further away from traditional roots in education and become integrated within colleges of arts and sciences or allied health professions (38). There has been an increase in the number of programs requiring undergraduates to take one year of calculus, chemistry, and physics, and courses in organic chemistry, biochemistry, anatomy, physiology, and nutrition. In many colleges and universities, little difference now exists between the first two years of requirements in a pre-physical therapy or pre-medical track and the track associated with physical education/kinesiology professions. The differences among these tracks lie in the "application" courses that follow. Biomechanics, physiology of exercise, fitness assessment, exercise prescription, strength and conditioning, and so on belong to the physical education/kinesiology track. However, it must again be pointed out that this new trend is but another example of a rediscovery of old roots rather than a revolutionary change. Kroll describes two 4-year professional physical education programs in the 1890s, one at Stanford and the other at Harvard, that were the forerunners of today's programs (25) (pp. 51-64). They included the detailed scientific work and application courses with clear prerequisites cited. Finally, considerable time was allotted for laboratory work. No doubt, Lagrange's 1890 text, *Physiology of Bodily Exercise* (26), served as an important reference source for these students. The expectations and goals of those programs were almost identical to those specified for current kinesiology undergraduate tracks. In fact, one of the aims of the Harvard program was to allow a student to pursue the study of medicine after completing two years of study (25) (p. 61).

GRADUATE STUDY AND RESEARCH IN THE PHYSIOLOGY OF EXERCISE

While the Harvard Fatigue Laboratory was closing in 1947, the country was on the verge of a tremendous expansion in the number of universities offering graduate study and research opportunities in exercise physiology. A 1950 survey showed that only 16 colleges or universities had research laboratories in departments of physical education (21). By 1966, 151 institutions had research facilities, 58 of them in exercise physiology (40) (p. 526). This expansion was due to the availability of more scientists trained in the research methodology of exercise physiology, the increased number of students attending college due to the GI Bill and student loans, and the increase in federal dollars to improve the research capabilities of universities (12, 38).

"The scholar's work will be multiplied many fold through the contribution of his students." This quote, taken from Montoye and Washburn (28, 29), expresses a view that has helped attract researchers and scholars to universities. Evidence to support this quote was presented in the form of genealogical charts of contributors to the *Research Quarterly* (29). These charts showed the tremendous influence a few people had through their students in the expansion of research in physical education. Probably the best example of this is Thomas K. Cureton, Jr., of the University of Illinois, a central figure in the training of productive researchers in exercise physiology and fitness. The proceedings from a symposium honoring Dr. Cureton in 1969 listed 68 Ph.D. students who completed their work under his direction (17). Although Dr. Cureton's scholarly record includes hundreds of research articles and dozens of books dealing with physical fitness, the publications of his students in the areas of epidemiology, fitness, cardiac rehabilitation, and exercise physiology represent the "multiplying effect" that students have on a scholar's productivity. For those who would like to read more about Dr. Cureton, see Berryman's article (7).

Montoye, H., and Washburn, R., "Genealogy of Scholarship Among Academy Members," *The Academy Papers*, 13: 94–101, 1980.

An example of a major university program that can trace its lineage to the Harvard Fatigue Laboratory is found at the Laboratory for Human Performance Research (Noll Laboratory) at Pennsylvania State University (see "A Look Back–Important People in Science"). However, it is clear that excellent research in exercise and environmental physiology is conducted in laboratories other than those that have a tie to the Harvard Fatigue Laboratory. Laboratories are found in physical education/kinesiology departments, physiology departments in medical schools, clinical medicine programs at hospitals, and in independent facilities such as the Cooper Institute for Aerobics Research. The proliferation and specialization of research involving exercise is discussed in the next section.

It should be no surprise that the major issues studied by researchers in exercise physiology have changed over the years. Table 0.2, from Tipton's look at the 50 years following the closing of the Harvard Fatigue Laboratory, shows the subject matter areas that were studied in considerable detail between 1954 and 1994 (38). A great number of these topics fit into the broad area of systemic physiology or were truly applied physiology issues. Although research continues to take place in most of these areas, Tipton believes that many of the most important questions to be addressed in the future will be answered by those with special training in molecular biology. Baldwin (5) supported Tipton's viewpoint and provided a summary of important questions dealing with exercise and chronic disease whose answers are linked to functional genomics and proteomics, important new tools for the molecular biologist. However, he also noted the need for increased research to address physical activity and chronic diseases at the lifestyle and behavioral levels. This "integrated" approach, crossing disciplines and technologies, should be reflected in the academic programs educating the next generation of kinesiology students. We recommend the chapters by Tipton (38) and Buskirk and Tipton (12) for those interested in a detailed look at the development of exercise physiology in the United States.

IN SUMMARY

- The increase in research in exercise physiology was a catalyst that propelled the transformation of physical education departments into exercise science and kinesiology departments. The number of exercise physiology laboratories increased dramatically between the 1950s and 1970s, with many dealing with problems in systemic and applied physiology and the biochemistry of exercise.
- In the future, the emphasis will be on molecular biology and its developing technologies as the essential ingredients needed to solve basic science issues related to physical activity and health.
- However, there is no question about the need for additional research to better understand how to permanently change the physical activity and eating behaviors of individuals in order to realize health-related goals.