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Eleventh Edition

EXERCISE PHYSIOLOGY

Theory and Application to Fitness and Performance

Scott K. Powers | Edward T. Howley | John Quindry

McGraw Hill

ELEVENTH EDITION

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EXERCISE PHYSIOLOGY

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

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Preface

The eleventh edition of this book has undergone major revisions. Identical to all previous editions, this edition of *Exercise Physiology: Theory and Application to Fitness and Performance* is intended for students interested in exercise physiology, medicine, clinical exercise physiology, exercise science, human performance, physical therapy, and physical education. The 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 a discussion of the benefits of exercise for multiple sclerosis patients and the latest information on sports-related brain injuries.

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 their course. 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 eleventh edition of this book has undergone *major* revisions to include the latest research in exercise physiology. Importantly, Dr. John Quindry was recruited to join the author team to provide additional expertise in several chapters of the text. To improve the book, 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 edition has undergone significant revision to provide up-to-date information across all three sections of the book. Specifically, each chapter has been revised and updated to include new and improved 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 been made to make the eleventh edition more complete and up-to-date:

- **Chapter 0:** This chapter underwent a major revision to provide numerous new elements including a discussion of the research process in exercise physiology, an overview of the scientific method, and a summary of the types of research performed in exercise physiology. A new segment also explains how to read and understand scientific journals articles. Further, a fresh section was added to explain how to search the scientific literature. The chapter closes with an up-to-date discussion on careers in exercise physiology and related fields.
- **Chapter 1:** A new section was added to introduce the major types of ergometers used in exercise physiology laboratories. A new figure was inserted to illustrate the differences in running economy between runners varying in experience and ability.
- **Chapter 2:** The chapter was revised to include an expanded discussion of the gain of a biological control system. A New Research Focus box was provided to introduce the concept of exercise-induced hormesis.

- **Chapter 3:** New material has been included to explain the biological wisdom behind why skeletal muscle stores carbohydrate in the form of glycogen. New Research Focus box added to discuss the formation of free radicals in skeletal muscle fibers. New “Ask the Expert” box with Dr. Wayne Willis introduces a simple hydraulic model to assist students in better understanding oxidative phosphorylation.
- **Chapter 4:** Addition of new “A Closer Look” box to discuss $\dot{V}O_2$

max and its verification. New information provided to discuss the role that excess postexercise oxygen consumption plays in exercise-induced weight loss. New figure added to illustrate the Cori cycle.

- **Chapter 5:** This chapter underwent significant revision to include numerous new and improved figures along with an expanded introduction to the basics of endocrine and neuroendocrine physiology. Moreover, updated information was added on both glucagon and cortisol responses to exercise. New information was provided on skeletal muscle as an endocrine organ.
- **Chapter 6:** Update on the latest research findings about the impact of exercise on the immune system. A new illustration was also provided to facilitate student learning.
- **Chapter 7:** Numerous new figures were added to illustrate key concepts. New discussion on exceptions to the size principle were provided in A Closer Look box. New information provided on the central governor theory of exercise-induced fatigue. Finally, the latest research about exercise and brain health was included.
- **Chapter 8:** Expanded discussion of the steps involved in excitation contraction coupling. New information on the causes of exercise-induced muscle fatigue is presented. Numerous new figures added to improve student learning. New information added to define the four domains of exercise intensity.
- **Chapter 9:** New and improved figures added throughout the chapter. Updated information on exercise-induced cardioprotection was also added. Latest information provided about autonomic control of heart rate and cardiac afterload during exercise. Updated information included to describe exercise-induced changes in blood flow to organs throughout the body. Latest information about the blood pressure responses to high-intensity intermittent exercise was also provided.
- **Chapter 10:** Numerous new figures added to chapter to better illustrate concepts related to respiratory system function during exercise. New information provided to explain the changes in breathing patterns that occur during exercise. Latest research

provided about the control of breathing during exercise.

- **Chapter 11:** Several new and improved figures provided to illustrate concepts related to acid-base balance during exercise.
- **Chapter 12:** New box feature added to illustrate the conversion of degrees Fahrenheit to degrees Celsius. Latest information provided on thermoreceptors and their role in temperature regulation during exercise.
- **Chapter 13:** This chapter underwent major revision to focus exclusively on the physiology of aerobic and anaerobic exercise training. Latest research provided about the impact of genetics on $\dot{V}O_2$ max and individual responses to exercise training. New box feature added to discuss microRNA's and the adaptive response to exercise training.
- **Chapter 14:** This is a new chapter in the 11th edition of the book that focuses entirely on the physiological effects of strength training. Specifically, this chapter provides the latest research on resistance training–induced changes to the motor control system and within skeletal muscle fibers. Moreover, the chapter contains a thorough discussion of resistance training–induced changes in muscle biochemistry along with the influence of resistance training on bone and ligament strength. The chapter also discusses detraining following strength training along with the impact that concurrent strength and endurance training has on strength gains.
- **Chapter 15:** This chapter appeared as Chap. 14 in the last edition. The new chapter 15 underwent a major revision to focus on the role of exercise in preventing chronic disease. Major changes include updated information on the risk factors for chronic disease (e.g., hypertension, dyslipidemia, obesity) and a state-of-the-art review of the metabolic syndrome. Further, a new section was added on the impact that regular physical activity has on both diabetes and cancer.

- **Chapter 16:** This chapter was Chap. 15 in the previous edition.

The chapter was revised to provide new information linking $\dot{V}O_2$ max to health outcomes, updated research about the health impact of different exercise intensities (e.g., vigorous vs. moderate-intensity exercise) on achieving health-related outcomes. Moreover, new information on the latest physical activity recommendations is provided along with a new appendix for determining the energy cost of common exercises.

- **Chapter 17:** This chapter was updated to provide new information about exercise prescriptions in diabetic, asthmatic, hypertension, cardiac rehabilitation, chronic obstructive pulmonary disease, aged, and pregnant populations. A new section detailing exercise prescription recommendations and special considerations for cancer patients was also added. Finally, a new Ask the Expert box featuring Dr. Kathryn Schmitz was added to discuss exercise rehabilitation for cancer patients.
- **Chapter 18:** This chapter underwent extensive revision to provide a state-of-the-art introduction to the science of nutrition. This includes an up-to-date discussion of both macronutrients and micronutrients in the diet along with the current nutritional guidelines and requirements. The discussion on body composition underwent extensive revision to provide a contemporary introduction to the major methods used to determine body composition. The chapter closes with a detailed discussion about body energy balance, popular diet plans, and research related to weight loss and management. Further the impact of exercise combined with diet on weight loss is discussed in detail.
- **Chapter 19:** Updated information was included on radical production and muscular fatigue during exercise. Numerous new figures along with new information about the factors affecting short-term performance and the possible sites of central and peripheral fatigue were added.
- **Chapter 20:** (Chap. 21 in 10th edition) Note that key information from Chap. 20 (10th edition) was updated and included in this revised chapter. For example, new information and figures on laboratory tests to determine endurance exercise potential were provided. Also, fresh information on the measurement of peak

running velocity as a predictor of performance was included. Further, several new figures added to illustrate overtraining, individual responses to training, and exercise metabolism during competition. Information was updated about the impact of high-intensity interval training on physiological adaptation.

- **Chapter 21:** (Chap. 22 in 10th edition) New figures added along with a new section discussing the impact of the menstrual cycle influence on performance and training. Latest information on eating disorders in female athletes.
- **Chapter 22:** (Chap. 23 in 10th edition) A new discussion was added to debate the role that antioxidant vitamin supplementation plays in blunting the training adaptation in skeletal muscles.
- **Chapter 23:** (Chapter 24 in 10th edition) A new figure was included along with new information about exercise at altitude, erythropoietin, and red blood cell production.
- **Chapter 24:** (Chap. 25 in 10th edition) Updated information added throughout the chapter. New section provided to discuss the athlete biological passport as a technique to monitor performance enhancing drug use in competitive athletics.

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The eleventh 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® 2.0 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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Bloom's taxonomy.

- Lecture Slides for instructor use in class.
- Instructors manual includes lecture outlines, suggested laboratory experiences, group problem solving activities for use the classroom, and homework assignments for students. Selection of homework assignments (linked to textbook chapters) for instructor use. Homework assignments are designed to increase student understanding of exercise physiology and promote problem-solving skills.

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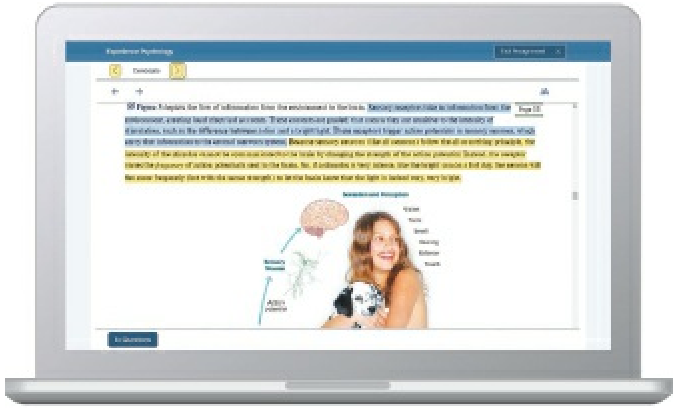

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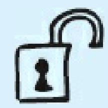

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ACKNOWLEDGEMENTS

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University of Kentucky

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University of the Incarnate Word

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Engaging Presentation Of Key Concepts Supported By The Latest Research

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.


RESEARCH FOCUS 10.1

Sex Differences in Breathing during Exercise

Changes in Breathing Pattern during Exercise

Chapter Ten Respiration during Exercise 261

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.


A CLOSER LOOK 8.2

How Are Skeletal Muscle Fibers Typed?

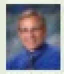
Overview of Biochemical and Contractile Characteristics of Skeletal Muscle

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.

ASK THE EXPERT 12.1

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



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.

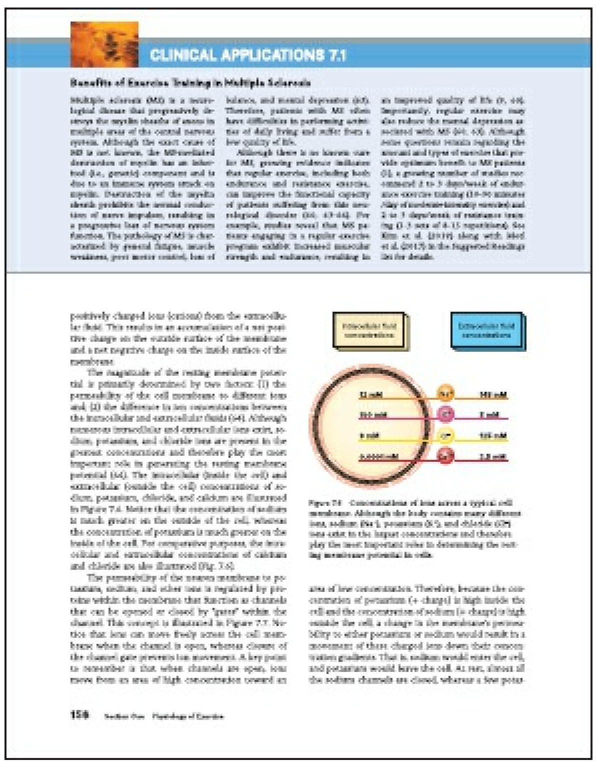
Hyperhydration can result in a small increase in blood volume and slightly delay developing dehydration; together, these changes help to support the cardiovascular system during exercise in a hot environment. Nonetheless, these benefits are marginal and, depending upon the methods employed, hyperhydration 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. For more information about exercise performance in hot environments, see Sawka, Cheuvront, and Kenefick (2014) in the Suggested Readings.

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

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. Although diets that are low in acids can increase plasma pH, these diets do not improve exercise performance during heavy, very heavy, or severe exercise intensities (2). In contrast, supplements including sodium bicarbonate, sodium citrate, and beta-alanine have the potential to improve buffering capacity and enhance exercise performance during very heavy and severe 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). Many studies conclude that performance during high-intensity exercise is improved when athletes ingest sodium bicarbonate prior to exercise (4, 7, 11, 24, 30–32, 34, 37). 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%–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% (7). 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% (28). 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 (28). 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, 24). 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 g/kg 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 (19, 40). Beta-alanine is a non-essential 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.

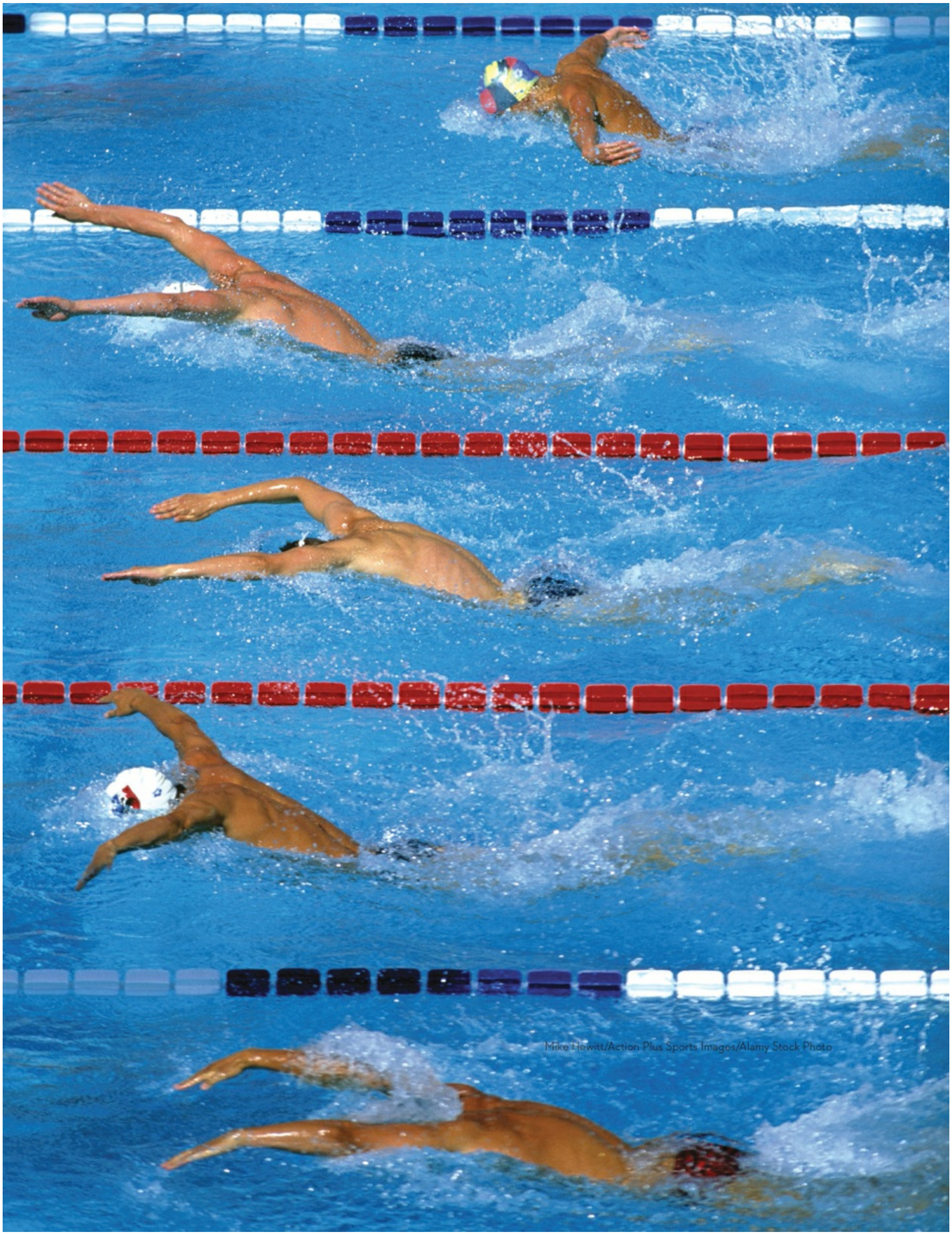
The link between beta-alanine and protection against acidosis is linked to the fact that beta-alanine is an important precursor for the synthesis of carnosine in skeletal muscle. As discussed in the text, carnosine is a small molecule (dipeptide) found in the cytoplasm of excitable cells (i.e., neurons, skeletal, and cardiac muscle fibers) (19). Carnosine has several important physiological functions including the ability to buffer hydrogen ions and protect against exercise-induced decreases in cellular pH (19).

The availability of beta-alanine is the rate limiting factor for carnosine synthesis in muscle fibers. However, supplementation (2–5 g/day) with beta-alanine for >2 weeks results in a 40% 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 (19). 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 (19). Interestingly, some of these studies have recorded performance improvements of 12% to 14% in untrained subjects supplemented with beta-alanine (19, 40). Note that while numerous studies conclude that beta-alanine supplementation improves athletic performance in high-intensity exercise lasting 1 to 10 minutes in untrained subjects, controversy exists about the efficacy of beta-alanine supplementation in well-trained individuals (reviewed in 40). The failure of beta-alanine supplementation to improve performance

(Continued)

SECTION 1

Physiology Of Exercise



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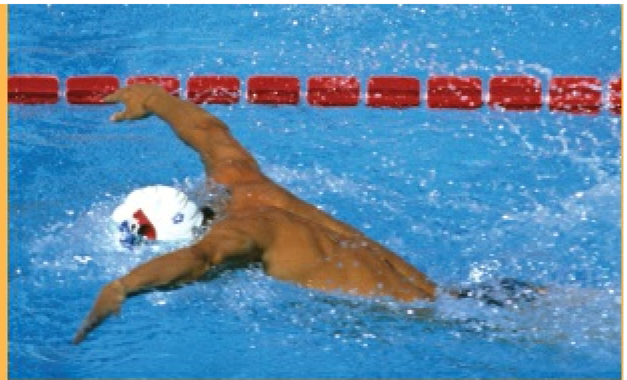

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Introduction To Exercise Physiology

■ Objectives

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

1. Define physiology and exercise physiology.
2. Identify the key milestones in the evolution of exercise physiology from 1900 to the present.
3. List the steps involved in the scientific method.
4. Describe the two major categories of research designs.
5. Identify the two primary venues where research in exercise physiology is performed.
6. Define basic and applied research.
7. Explain evidence-based practice in medicine and exercise science.
8. Outline the process of using a search engine to explore the literature and retrieve peer-reviewed research studies on topics

related to exercise physiology.

9. Identify and discuss the purpose of the individual sections that comprise a scientific research report.
10. Describe five key steps that can be used to evaluate the quality of a research study.
11. Identify six important professional organizations linked to exercise physiology and sports science.
12. Explain the benefits associated with achieving fitness/clinical certifications offered by professional organizations.
13. List five career opportunities for students with a bachelor's degree in exercise physiology and kinesiology.

■ Outline

Key Terms

applied research
basic research
case study
dependent variable
evidence-based practice
experimental research
independent variable
nonexperimental research
placebo
translational research

Physiology is the study of living organisms. Physiologists study questions related to how cells, tissues, and organ systems function in humans and other animals. Exercise physiology is a branch of physiology that investigates how a single bout of exercise (acute exercise) and repeated bouts of exercise (i.e., training programs) impact cells, tissues, and organ systems of the body. Moreover, exercise physiology explores the responses to acute exercise and exercise training at environmental extremes (e.g., high altitudes or high ambient temperatures) to determine the impact of these influences on our ability to perform and adapt to exercise training. Exercise physiology studies are also performed on young and old individuals, both healthy and those with disease. This important research helps to understand the role that regular exercise plays in the prevention of disease or rehabilitation from chronic illnesses. Finally, exercise physiology also explores many sports performance-related questions such as “Does an individual require a genetic gift to become an outstanding distance runner, or can anyone become an exceptional endurance athlete with sufficient training?” “What adaptations occur in your skeletal muscles when you engage in regular resistance training?” “What changes occur in your cardiovascular system and skeletal muscles as a result of an endurance-training program?” The answers to these and many other questions related to human performance, nutrition, and the health-related benefits of exercise are provided throughout this book.

Our knowledge about exercise physiology has expanded over the years because of the quantity and quality of research in this field. This chapter provides an introduction into exercise physiology research, professional organizations, and careers available to individuals with training in exercise physiology and kinesiology. More specifically, we begin with a brief history of research advances in exercise physiology and then describe the research process. We will also discuss how to read and understand research studies published in scientific journals. This chapter ends with an overview of exercise physiology professional organizations, exercise/fitness certifications, and careers in exercise physiology and related fields.

MILESTONES IN THE EVOLUTION OF EXERCISE PHYSIOLOGY

A brief overview of some of the milestones in the growth of exercise physiology will help you understand where the field of exercise physiology has been and where its future lies. Note that throughout the text, a variety of eminent exercise physiology scientists are highlighted in various chapters as physiology subject matter is presented. We hope that by linking a particular scientist to a major accomplishment in exercise physiology, the history of exercise physiology will come alive and will stimulate you to learn more about this exciting field.

This section provides a brief history of the evolution of exercise physiology research. Because a detailed history of exercise physiology is beyond the scope of this chapter, we will limit our discussion to highlights of the field during the past 120 years. Further, although numerous organizations and hundreds of scientists have contributed to the advancement of exercise physiology, space limitations will permit the discussion of only a few milestone events during the evolution of this field.

Milestones in Exercise Physiology—the Early Years (1900–1950)

Figure 0.1 provides a graphical timeline for selected milestones in exercise physiology research during the first half of the twentieth century. During this early period of exercise physiology, almost all of the research was descriptive. That is, most published reports during this time period merely described the physiological responses (i.e., heart rate, blood pressure, etc.) to a bout of acute exercise. Nonetheless, work performed by the Danish scientists August Krogh and Johannes Linhard was an exception to this practice. These investigators often collaborated on research that explored how the body regulates major organ systems during exercise. For example, one of their important studies investigated the control of both the respiratory and circulatory system during exercise (11).

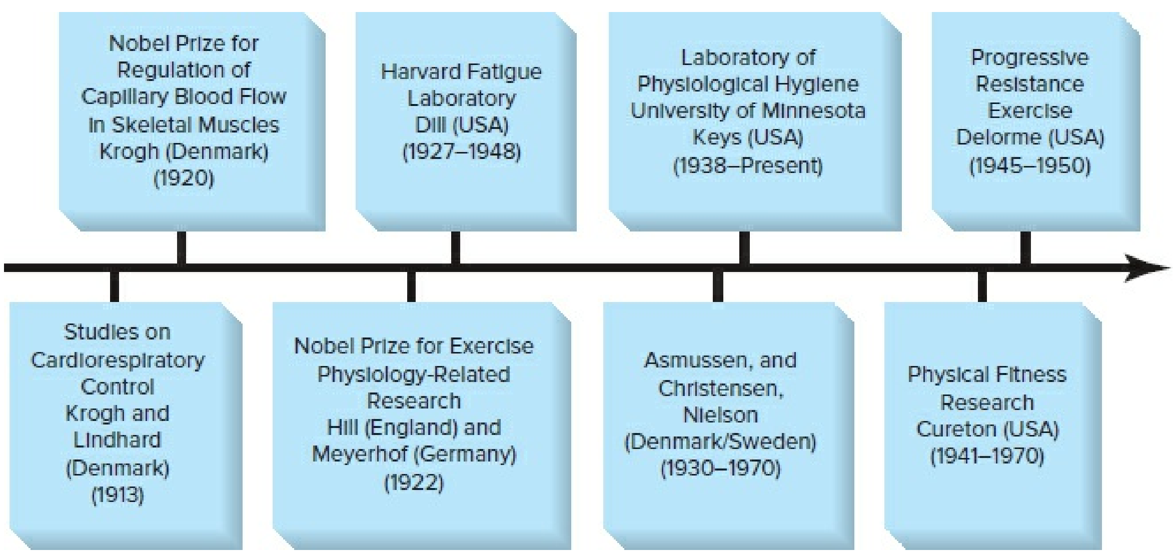

Figure 0.1 Selected historical milestones in exercise physiology that occurred during 1900–1950. See text for details.

The Nobel Prize in Physiology or Medicine is awarded yearly for outstanding discoveries in the fields of life sciences or medicine that benefit mankind. This prize is one of the five Nobel Prizes established in 1895 by the Swedish chemist Alfred Nobel, the inventor of dynamite. In the long history of the Nobel Prize in Physiology or Medicine, only three researchers have been honored with this award for research focused on skeletal muscles or exercise physiology. The first of these Nobel winners was August Krogh. Krogh was awarded the Nobel Prize in Physiology or Medicine in 1920 for his work on the mechanisms responsible for the regulation of capillary blood flow to skeletal muscles. Further, the British scientist A.V. Hill and the German scientist Otto Meyerhof shared the 1922 Nobel Prize in Physiology or Medicine for their research in two separate areas of exercise physiology. Hill was recognized for his discovery that skeletal muscle produces heat during exercise whereas Meyerhof's recognition originated from his contributions to our understanding of the relationship between exercise intensity, oxygen consumption, and lactate metabolism.

The establishment of the Harvard Fatigue Laboratory in 1927 was an important event in exercise physiology research in the United States. Interestingly, this exercise physiology research laboratory was established by the Harvard Business School. While a business school seems like an unlikely home for human physiology research, this lab was created during a time in history when human fatigue in industrial factories was of major interest. The Harvard Fatigue Laboratory was founded by Lawrence Henderson and directed by David Bruce Dill. Without question, the Harvard Fatigue Lab played a major role in stimulating research in exercise physiology worldwide. Indeed, this laboratory was the research home for not only outstanding American physiologists, but also was regularly visited by renowned exercise physiologists from around the world. During the lab's existence (1927–1948), researchers in the Harvard Fatigue Laboratory published over 350 research studies on a variety of exercise physiology topics along with many investigations on the influence of the environment on exercise tolerance. The Harvard Fatigue Laboratory also played a key role in training young exercise physiologists. For instance, after earning their PhD's from Harvard University, both Sid Robinson and Steven Horvath became internationally renowned exercise and environmental physiologists. Sid Robinson performed research throughout his career at Indiana University whereas Steven Horvath directed the Institute for Environmental Stress at the University of California, Santa Barbara. More details about the Institute of Environmental Stress will be provided later.

Founded by Ansel Keys in 1937, the Laboratory of Physiological Hygiene at the University of Minnesota was an important research center for exercise physiology, environmental, and nutrition research. During his long and productive research career (1930–1975), Keys completed many important studies focusing on nutrition. One of Keys' most novel investigations determined the physiological effects of starvation on the body. This important study established nutritional guidelines for treating individuals following starvation and these guidelines have been used many times in developing countries experiencing economic hardship and famine. Keys was also involved in research that developed nutritional strategies for the U.S. military. During World War II, American soldiers were provided food called K-rations. These K-rations (K for Keys) were small portions of high caloric food developed by Keys to provide sufficient energy for solders during combat. Key's research also played an important role in establishing that high blood cholesterol is a risk factor for heart disease. Finally, Keys and his wife Margaret published the first book on the health benefits of a low-fat, Mediterranean diet.

Henry Longstreet Taylor was also an important researcher at the Laboratory of Physiological Hygiene from 1941 until his death in 1983. Taylor's undergraduate education was at Harvard where he worked in the Harvard Fatigue Laboratory. After completing his PhD from the University of Minnesota, he joined forces with Ansel Keys to perform many important research studies including his influential work that helped to establish maximal oxygen uptake (VO_2 max) as the standard measure of cardiorespiratory work capacity. Notably, Taylor was also responsible for training several graduate students in exercise physiology including Ellsworth Buskirk who advanced to an outstanding career in exercise and environmental research at Penn State University.

Outside of the United States, three Danish scientists (Erling Asmussen, Eril Hohwu-Christensen, and Marius Nielson) became important contributors to exercise physiology research during the 1930 to 1940s. These Scandinavian scientists were friends as graduate students, and following graduation they often collaborated on research. Because of their longtime friendship and scientific collaboration, the three were nicknamed the "three musketeers" by August Krogh (17). Together, their studies added significantly to the foundation of our understanding of exercise physiology.

Another key event in the evolution of exercise physiology research in the United States occurred when Thomas Cureton founded the exercise physiology laboratory at the University of Illinois in 1941. During his long career, Dr. Cureton trained numerous exercise physiology graduate students who later achieved distinguished research careers by themselves. Work by Cureton and his students provided some of the early evidence supporting the physiological rationale that regular exercise promotes a healthy body.

Another important exercise physiology milestone during the first half of the twentieth century was the research performed by Dr. Thomas Delorme investigating the therapeutic benefits of resistance training. Delorme was a physician assigned to a U.S. military hospital that treated soldiers injured during World War II. Because of his personal interest in resistance training, Delorme reasoned that resistance exercise training can play an important role in rehabilitative therapy for injured soldiers. To test his prediction, Delorme completed several experiments revealing that progressive resistance exercise accelerated strength gains and recovery in patients suffering from bone and soft tissue injures. Much of Delorme's work was published between1948 and 1950 and this early work provided the scientific basis for the resistance training protocols used in physical therapy today (3–5, 7).

IN SUMMARY

- Numerous Scandinavian scientists contributed to the growth of exercise physiology studies during the first half of the twentieth century.
- August Krogh, A.V. Hill, and Otto Meyerhof won the Nobel Prize for research related to skeletal muscle and exercise physiology.
- The Harvard Fatigue Laboratory played a central role in exercise physiology research in the United States from 1927 to 1948.
- Ansel Keys founded the Laboratory for Physiological Hygiene at the University of Minnesota in 1937; this important research center completed many important exercise and nutritional studies from the 1930s to 1970s.
- Thomas Cureton performed numerous fitness studies and mentored many exercise physiology graduate students at the University of Illinois from 1941 to 1970.
- Thomas DeLorme was a pioneer in research investigating the benefits of progressive resistance exercise on recovery from injury

Milestones in Exercise Physiology—Second Half of the Twentieth Century (1951–2000)

The second half of the twentieth century represented a period of significant achievements in exercise physiology research (Fig. 0.2). A key event that stimulated growth in exercise physiology research and education was the founding of the American College of Sports Medicine (ACSM). This professional organization was created to promote scientific research, education, and the practical applications of exercise science and sports medicine. Since ACSM's formation in 1954, this prominent professional organization has grown to more than 50,000 members and ACSM has become the world's largest professional organization associated with exercise physiology and sports science. Importantly, ACSM has advanced the field of exercise physiology in several important ways. First, in the 1970s, ACSM established certification programs and continuing education for fitness professionals as well as clinicians; these ACSM certifications continue today and are widely accepted around the world as the gold standard for health and fitness qualifications. Further, the ACSM annual meeting has become an important venue for exercise physiology and sports medicine research. Finally, ACSM contributes to educational growth in exercise physiology by publishing two highly regarded peer-reviewed research journals (i.e., (1) *Medicine and Science in Sports and Exercise*; and (2) *Exercise and Sport Sciences Reviews*).

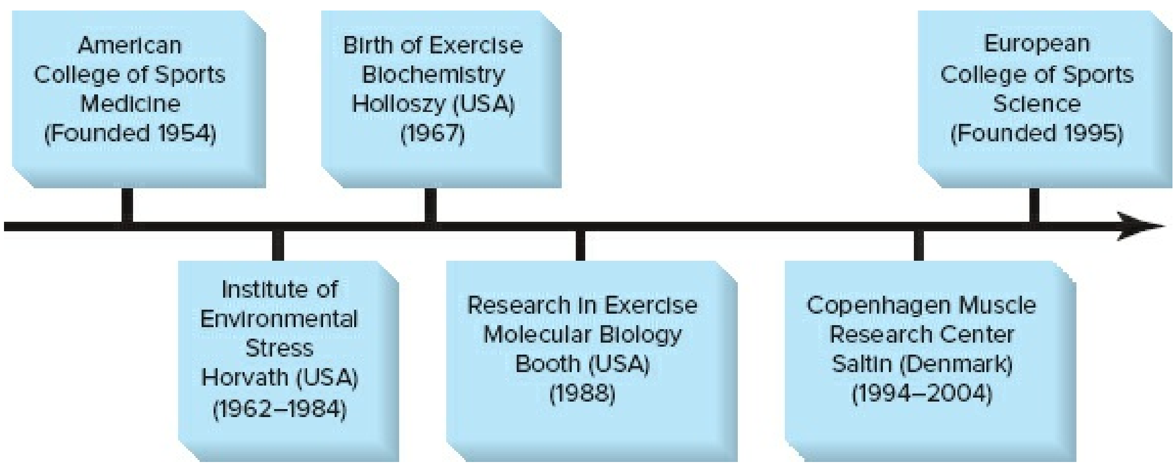

Figure 0.2 Selected historical milestones in exercise physiology that occurred during 1951–2000. See text for details.

The closing of the Harvard Fatigue Laboratory in 1948 created a void in both exercise physiology research and venues for postdoctoral training. Fortunately, this void was filled in 1962 when Steven Horvath founded the Institute of Environmental Stress at the University of California-Santa Barbara (Fig. 0.3). Similar to the Harvard Fatigue Laboratory, this institute conducted exercise physiology/environmental physiology research studies and was a postdoctoral training ground for many exercise/environmental physiologists. Indeed, during its 22-year existence, the Institute of Environmental Stress produced hundreds of important research studies and provided exceptional training for many exercise physiologists who later achieved national and international acclaim for their research.

Figure 0.3 Dr. Steven Horvath standing in front of an environmental chamber designed to simulate high-altitude

conditions. Dr. Horvath was the founder and director of the Institute of Environmental Stress at the University of California-Santa Barbara from 1962 to 1984.
Dr. Peter Horvath

In addition to the outstanding exercise research performed at the Institute of Environment Stress, Dr. John Holloszy also established a robust research program in exercise physiology at Washington University (Saint Louis, Missouri) in the late 1960s. Indeed, many consider John Holloszy to be the "father of exercise biochemistry research" following his 1967 landmark study demonstrating that endurance exercise training increases mitochondrial volume in the trained skeletal muscles. During his 50+ year career, Dr. Holloszy published more than 380 research reports and served as the mentor for approximately 100 postdoctoral research fellows.

Although the first molecular biology study on the effects of exercise on muscle was published by Sandy Williams and colleagues (18), it is widely agreed that the advocacy and research of Dr. Frank Booth launched the field of exercise molecular biology in 1988 (17) (Fig. 0.4). Dr. Booth inspired exercise physiology researchers by his own research and his writings that challenged exercise physiologists to pursue mechanistic questions by using the tools of molecular biology. A review of the exercise physiology literature today reveals that Dr. Booth has achieved his vision as the research literature is now filled with studies using the tools of molecular biology to address important questions related to exercise-induced changes in tissues.

Figure 0.4 Dr. Frank Booth played a major role in the evolution of research in exercise molecular biology.
Dr. Frank Booth

Dr. Bengt Saltin provided major contributions to exercise physiology research from the 1960s till his death in 2018. Dr. Saltin was trained in both medicine and physiology at the Karolinska Institute in Sweden where he worked under the tutorage of the esteemed physiologist Per-Olof Astrand. In 1994, Dr. Saltin organized the Copenhagen Muscle Research Center at the University of Cophenhagen, Denmark. Saltin was joined in this venture by other outstanding Scandinavian exercise physiologists including Henrik Galbo, Erik Richer, Bente Kiens, Carsten Juel, Niels Secher, and Bente Pedersen (8). The research focus of this center was on the regulation of muscle metabolism and its coupling to blood flow; these investigations generated numerous significant research reports (8).

Finally, another important milestone in exercise physiology that transpired during the second half of the twentieth century was the formation of the European College of Sport Science in 1995. Similar to ACSM, this important professional organization is dedicated to the promotion of both education and research in exercise science.

Moreover, the European College of Sport Science annual meeting has become an important venue for distribution of the latest research in both exercise physiology and biomechanics.

IN SUMMARY

- The American College of Sports Medicine was founded in 1954 and has played an important role in promoting exercise physiology research during the past 60+ years.
- The Institute of Environmental Stress was founded by Steven Horvath in 1962. This important laboratory was an epicenter for exercise and environmental research in the United States from 1962 to 1984.
- John Holloszy's research at Washington University played a major role in launching the era of exercise biochemistry research.
- Frank Booth was instrumental in promoting research in exercise molecular biology.
- The Copenhagen Muscle Research Center was founded by Bengt Saltin in 1994 and this research laboratory made significant contributions to exercise physiology research.
- The European College of Sport Science was formed in 1995; this important professional organization promotes research in both exercise physiology and biomechanics.

Milestones in Exercise Physiology Research—2001 to Present

Figure 0.5 highlights both the emergence of several important research tools and discoveries in exercise physiology that occurred during the first 20 years of the twenty-first century. Moreover, note the large increase in the number of published research papers during the past 19 years (Fig. 0.6). Indeed, the number of exercise-related research studies published each year increased from 13,968 in 2000 to 52,551 papers published in 2019.

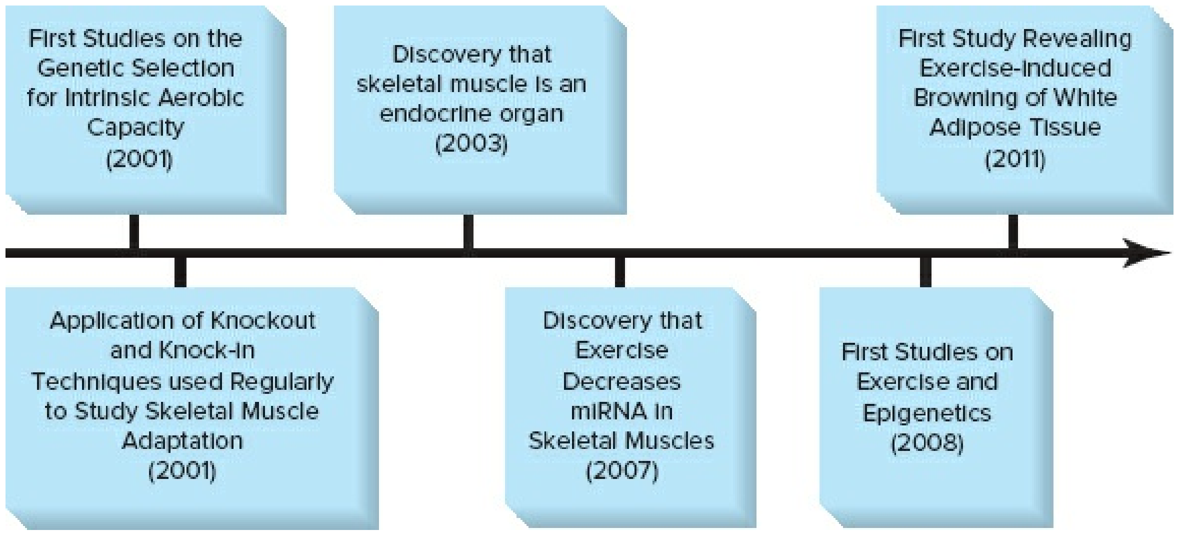

Figure 0.5 Selected historical milestones in exercise physiology that occurred from 2001 to the present time. See text for details.

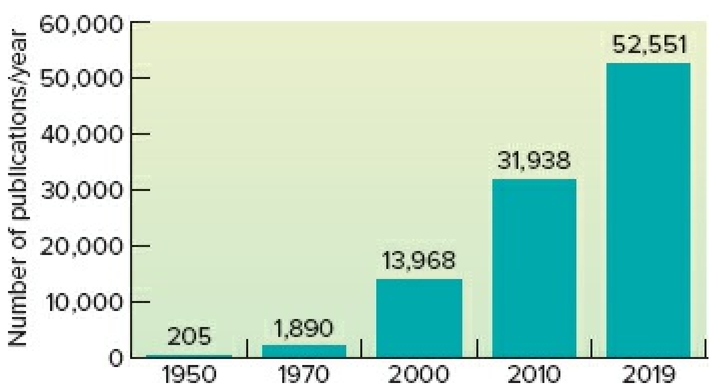

Figure 0.6 Illustration of the growth of scientific publications in exercise physiology from 1950 to 2019.

In the previous sections describing important milestones in the history of exercise physiology, we emphasized both individuals and professional organizations that made significant contributions to the advancement of this field. In this final section describing the historical evolution of exercise physiology, we highlight advancements in research tools and describe several important experimental discoveries in exercise physiology that have ensued during the past two decades. We begin with a discussion of advances in research tools.

Advances in Research Tools in Exercise Physiology

In recent years, our knowledge in exercise physiology has grown significantly, in part, because of advancements in research technology. For example, the technique to manipulate genes within cardiac or skeletal muscle fibers is a powerful experimental tool to study muscle physiology. Although the technology to add or remove genes from cells of laboratory animals evolved during the 1980 to 1990s, these tools were not widely used in exercise physiology research until early in the twenty-first century. Indeed, because of these powerful tools, research progress has been remarkable during the past two decades. A brief overview of how these tools have advanced our understanding of exercise physiology follows.

The development of genetic tools have markedly improved our grasp of cardiac and skeletal muscle function. Indeed, these tools have provided techniques used to study the influence of a single protein on muscle fiber function. As you may recall from a previous course, a gene is a segment of DNA located in the nucleus of cells; each gene directs the synthesis of a specific protein (see Chap. 2 for details). The term "gene knockout" refers to a technique to inactivate a specific gene (i.e., gene is knocked out of the cell). The end result of a gene knockout procedure is that following the "knockout" the affected cells cannot manufacture the specific protein generated by this gene. Therefore, the ability to knockout specific genes in a tissue (e.g., skeletal muscle) has provided researchers with a powerful tool to determine what happens to the function of a skeletal muscle fiber when a specific protein is removed; these types of experimental approaches reveal important information about the function of individual muscle proteins.

A second research tool that has advanced our understanding of the function of a particular protein is gene transfection. In brief, gene transfection results in overexpression of a single protein. The term "gene overexpression" refers to the "switching on" of genes to produce more of a specific protein. One of the ways to promote gene overexpression in cells is to transfect additional copies of the gene into the cells of interest. Transfection is the process of inserting specific genes into cells; this typically results in the increased manufacture of the protein generated by this gene. The ability to transfect genes into skeletal muscle and overexpress specific proteins has provided researchers in exercise physiology with another powerful tool to understand the functions of specific muscle proteins. For example, exercise training increases the production of several different proteins in the trained muscle fibers. Because training increases the abundance of numerous proteins in the trained muscle fibers, it is impossible to determine the unique role that each of these proteins play in the training-induced improvement in muscle performance. However, using the technique of gene transfection, it becomes possible to investigate the unique role that an individual protein plays in muscle function by transfecting and overexpressing a specific gene that increases the abundance of a single protein.

The relative contribution of genes versus environmental factors to define the observed differences in endurance capacity between individuals is difficult to investigate in humans (2). In an effort to overcome this problem, researchers have used selective breeding to produce rats with intrinsically low- and high-endurance capacities (10). The development of these genetically unique animals eliminates the environmental factors that influence a high-endurance capacity and provides researchers with a powerful tool to study the physiological factors that contribute to a high-endurance capacity (2).

Novel Research Discoveries in Exercise Physiology (2001 to Present)

Numerous important research breakthroughs have occurred during the past two decades. In this section, we discuss four innovative findings in exercise physiology: (1) Skeletal muscle is an endocrine organ; (2) Exercise stimulates the production of microRNA in skeletal muscle; (3) Exercise training promotes epigenetic changes in skeletal muscle; and (4) Endurance exercise training results in a “browning” of white fat cells. Let’s begin with a brief discussion about the unique finding that skeletal muscle is an endocrine organ.

In 2003, Bente Pedersen and colleagues discovered that skeletal muscle is an endocrine organ (15). This important research revealed that contracting skeletal muscles release peptides (chains of amino acids) into the circulation; these circulating muscle-released “hormones” are called “myokines.” After release from the contracting muscle fiber, myokines move into the circulation and travel throughout the body to exert changes in various tissues. The fact that skeletal muscle produces and releases myokines provides a new understanding of how skeletal muscles communicate with other organs such as adipose tissue (i.e., fat cells), bone, liver, pancreas, and the brain (9). Research in myokines is advancing rapidly and this new knowledge will markedly improve our understanding of how muscular exercise promotes good health.

A microRNA (abbreviated miRNA) is a small RNA molecule that regulates gene expression by binding to messenger RNA and preventing the production of a particular protein. Although miRNA was discovered in 1993, these molecules were not recognized as important biological regulators in skeletal muscle until the early 2000s. Notably, in 2007, it was discovered that overload of skeletal muscles (i.e., resistance exercise training) decreases two specific miRNA in skeletal muscle fibers (14). This key finding suggests that changes in miRNA levels may play a key role in skeletal muscle adaptation in response to exercise training (12, 13). Research in the exciting field of exercise-induced changes in miRNAs continues and there is much more to be learned about this important topic.

Epigenetics is a new and rapidly developing field that investigates the changes in gene function that occur without alterations in the DNA sequence of the gene. An example of a mechanism that can produce an epigenetic change is DNA methylation (i.e., adding a methyl group (CH3) to DNA); this modification of DNA can result in a change in gene expression. The discovery that exercise promotes epigenetic changes in tissues occurred in 2008. Since this original finding, many studies have confirmed that regular muscular exercise results in epigenetic changes within numerous tissues and these changes can be passed along to offspring of trained individuals (6). Importantly, several of the exercise-induced epigenetic changes within body tissues likely contribute to the health benefits of exercise. Future studies in this expanding field will provide additional insight into how different modes and doses of exercise (i.e., intensity, frequency, and duration) promote these epigenetic changes in the body.

Another important discovery is the finding that endurance exercise modifies the structure and function of white fat cells to improve overall health. While it has long been known that regular exercise training promotes adaptations to white adipose tissue including a decrease in fat cell size, growing research reveals that exercise-induced changes in white fat cells plays an important role in the health benefits of exercise. A brief summary of this exciting new area of exercise physiology research follows.

The major fat depots in the body are white fat cells located beneath the skin (subcutaneous fat cells) and in the abdominal cavity (visceral fat cells). Recent animal studies reveal that endurance exercise training results in a "browning" of white fat cells. Much of this research has been guided by the laboratory of Dr. Laurie Goodyear at Harvard University (Fig. 0.7). Investigations by Dr. Goodyear and colleagues reveals that this exercise-induced "browning effect" of white fat cells results from increases in mitochondrial volume (cellular organelles responsible for aerobic production of ATP) and other proteins involved in energy metabolism. This apparent conversion of white fat cells to brown fat cells is important because an increase in the abundance of brown adipose tissue is associated with increased resting energy expenditure and improvements in blood glucose control. Therefore, this exercise-induced browning of white fat cells might be an important mechanism by which endurance exercise training improves health and reduces the risk of developing type II diabetes (16). Research in this new area of exercise physiology remains at an early stage and future studies are required to determine if the exercise-induced changes in white adipose tissue that occur in animals also happen in humans.

Figure 0.7 Dr. Laurie Goodyear is a professor of medicine at Harvard University. Dr. Goodyear is a leader in research investigating the impact of endurance exercise training on fat cells.

Dr. Laurie Goodyear

IN SUMMARY

- Studies on rats using selected breeding has created animals with genetic differences in intrinsic aerobic capacity. This research has provided important insight into those factors that limit endurance exercise performance.

- Research applications using gene transfection and knock-out animals became common in exercise physiology during the first two decades of the twenty-first century; these studies provide key information about the role that specific proteins play in skeletal muscle and other tissues.
- Bente Pedersen and colleagues discovered in 2003 that skeletal muscle is an endocrine organ; this work provides the first clues as to how exercising skeletal muscles communicate with other organ systems of the body.
- The fact that exercise decreases muscle-specific miRNA was uncovered in 2007; this key observation provides important insight into how skeletal muscles adapt in response to exercise training.
- The first studies on exercise and epigenetics were published in 2008; this important work reveals that muscular exercise promotes epigenetic changes within numerous tissues and these changes can be passed along to offspring of exercise trained individuals.
- The first study demonstrating that endurance exercise training promotes browning of white adipose tissue was published in 2011; this valuable research suggests that the exercise-induced changes in white adipose tissue may be part of the mechanism by which exercise improves whole-body metabolic health.

EXERCISE PHYSIOLOGY RESEARCH: THE PATH TO NEW KNOWLEDGE

Research is the systematic investigation of a specific problem; research in exercise physiology involves the scientific study of the effects of acute and/or chronic exercise on the body. The next sections introduce the scientific method, outline several types of research in exercise physiology, and discuss the importance of rigor in research.

The Scientific Method

The scientific method is a systematic approach used by researchers to test hypotheses and, of course, provide new scientific knowledge. In brief, the scientific method involves a six-step process that begins with the conception of a research question and ends with publication of the research findings (Fig. 0.8):

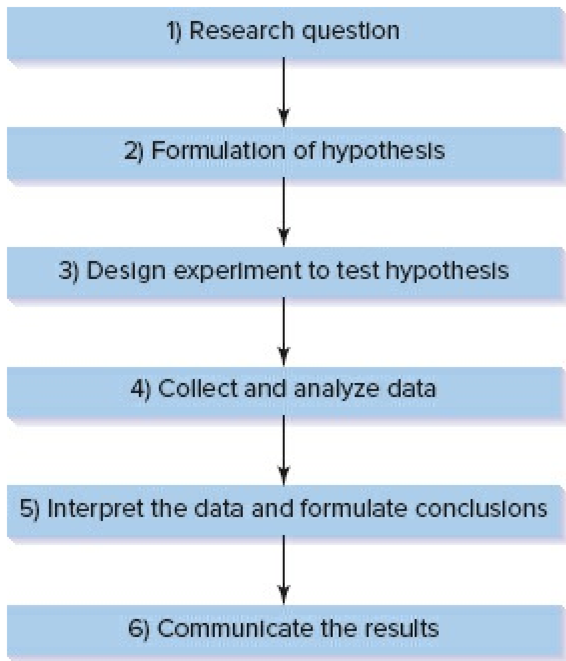

Figure 0.8 Steps involved in the scientific method. See text for details.

1. Establishing the Research Question

Research is designed to answer questions and it follows that all research studies begin with a scientific question. For example, one of the earliest inquiries raised by exercise physiologists was "What happens to a subject's heart rate when the intensity of exercise is increased?"

2. Formation of a Hypothesis

The second key step in the scientific method is the construction of a research hypothesis. A hypothesis is simply the predicted answer to a scientific question. In order to develop an informed research hypothesis, a researcher typically performs a preliminary study to gain knowledge about the research question that he or she desires to answer. This additional knowledge is used to formulate the research hypothesis. Therefore, a hypothesis is an “educated guess” about the answer to a scientific question. For example, let’s consider the process of developing a research hypothesis to address the above question “What happens to a subject’s heart rate when the intensity of exercise is increased?” In this case, the researcher would begin by recording the resting heart rate in a small number of subjects and then measure heart rate in the same subjects during exercise of varying intensities (e.g., low-, moderate-, and high-intensity exercise). After gaining this preliminary insight about the heart rate response to exercise, the researcher then formulates a hypothesis (e.g., “heart rate increases as a function of exercise intensity”).

3. Design an Experiment to Test the Research Hypothesis

A scientific hypothesis can be tested by a well-designed experiment. Experimental designs can be straight-forward or complicated depending upon the complexity of the hypothesis tested. Importantly, a scientific hypothesis can only be rigorously tested by a precise experimental design that incorporates the appropriate experimental groups (e.g., control and experimental groups), an adequate sample size (i.e., number of subjects per group), and the selection of the correct dependent variables (e.g., physiological measurements recorded).

4. Collect and Analyze the Data

After designing the experiment, the next step is to collect and analyze the experimental data. Careful data collection and statistical analysis of the results is an important step that is required to test a scientific hypothesis.

5. Interpret the Results and Formulate Conclusions

A thoughtful interpretation of the scientific data permits the researcher to decide if the results of the study supports or rejects the hypothesis tested.

6. Communicate the Research Findings

Scientific research is only beneficial when the results are made available to others. The findings of research studies are conveyed to other scientists and the general public by publication in a peer-reviewed scientific journal. The process of scientific peer-review begins with the evaluation of the research study by two or more qualified scientists. Following a careful assessment, these "reviewers" then decide to accept or reject the scientific study for publication based on several criteria including the importance of the hypothesis tested, the rigor of the experimental approach (e.g., strong experimental design, adequate methodology, appropriate analysis, and interpretation of the data) and clarity of the writing.

Scientific journals play an essential role in the advancement of science and numerous journals linked to exercise physiology exist. Later sections in this chapter will provide details about the different types of scientific journals as well as information about how to read and interpret studies reported in these journals.

Classes of Research Designs

Although several types of research designs exist, research strategies generally fall into one of two categories: (1) nonexperimental research and (2) experimental research. The next segments introduce these categories of research design.

Nonexperimental Research

Nonexperimental research does not involve the manipulation of experimental variables and, therefore, these investigations are often descriptive studies, case studies, or correlational investigations. Descriptive research is performed to identify different biological characteristics or physiological events. An example of a descriptive study in exercise physiology is an investigation that examines the change in resting heart rate following a 20-week endurance exercise training program. Another illustration of descriptive research is a study that reports the body composition (i.e., % body fat) of a group of elite distance runners. As the name implies, descriptive research simply reports biological phenomena (or biological characteristics) and does not explain why these biological phenomena occur.

Another example of nonexperimental research is the case study. A **case study** is the intensive study of one individual. For instance, a case study in exercise physiology might report the physiological changes in a champion athlete over the course of several years of exercise training.

Finally, correlational studies are another example of nonexperimental research studies. Correlational studies describe the relationship between two variables; this relationship is often represented by a correlation coefficient. A correlation coefficient is a statistical measure of the extent to which changes in one variable mathematically predict corresponding changes of another. Correlation coefficients are expressed as values between +1 and −1; a correlation coefficient of +1 signifies a perfect positive correlation between two variables whereas a correlation coefficient of −1 indicates a perfect negative correlation. Although a high correlation coefficient suggests that a strong relationship exists between two variables, a numerically high correlation coefficient (e.g., a correlation coefficient of +1) does not prove cause and effect between the two variables. In other words, correlation does not necessarily mean causation.

Experimental Research

Experimental research involves the manipulation of experimental variables. A carefully planned experimental study has the potential to explain cause and effect and, therefore, uncover the mechanism(s) responsible for changes in biological function. A simple experimental research design could involve the comparison of a control group (group that does not receive an experimental treatment) to an experimental group (group that receives an experimental treatment). Control groups are important to experimental research because this group serves as a benchmark to determine the effect of the treatment on the experimental group. Therefore, the control group ensures that changes in the experimental group are due to the treatment and not due to other factors (e.g., aging or the season of the year).

As mentioned previously, experimental research differs from nonexperimental research because experimental research designs involve the manipulation of variables. Specifically, experimental studies contain both independent and dependent variables. An **independent variable** is a variable that is manipulated by the investigator whereas the **dependent variable** is the variable that changes in response to the independent variable. For example, in a study designed to determine the impact of exercise intensity on heart rate, the exercise intensity is the independent variable (i.e., manipulated variable) and heart rate is the dependent variable (i.e., variable that changes as a function of the independent variable).

In addition to dividing research into two general classes determined by the research design, research can also be separated into additional categories based upon: (1) where the study is performed (i.e., field or laboratory); and (2) the objectives of the research (basic and applied).

Field and Laboratory Research

Research can be performed in a variety of venues depending upon the goals and the type of research performed. For example, in medicine, clinical research is often performed in a hospital setting. However, in exercise physiology, much of the research performed is conducted either in the exercise physiology laboratory or a field setting. The next segments provide a brief introduction to both laboratory and field research.

Laboratory Research

As the name implies, laboratory research involves data collection in a laboratory environment. These studies can involve human and/or animal experiments and exercise can be performed using a variety of exercise modalities including treadmill running, stationary cycling, and/or weight lifting. Laboratory experiments offer several advantages that do not exist in field research. For example, laboratory experiments often involve more invasive experimental protocols compared to field research (i.e., blood sampling or a muscle biopsy). Further, compared to field studies, laboratory experiments have the advantage of being conducted in a setting in which environmental conditions such as room temperature and relative humidity are controlled. Moreover, laboratory experiments often involve the performance of biochemical assays using tissue samples and, obviously, these types of measurements can only be performed in the laboratory.

Field Research

Field experiments are conducted in an indoor or outdoor athletic arena. Field research provides the investigator with the opportunity to record physiological measurements (e.g., heart rate and/or body temperature) in a "real" or simulated athletic competition. Compared to laboratory experiments, an obvious advantage of field experiments is that these studies provide the researcher with the opportunity to collect physiological data in the "real world" of athletic competition. As mentioned earlier, disadvantages of field research include the lack of experimental control of environmental conditions and limitations on the types of physiological measurements that can be made.

Basic and Applied Research

Depending upon the goal of the investigation, research studies are often classified as basic or applied research.

Basic Research The goal of **basic research** is to generate new knowledge in a specific field of study; basic research is often performed without the knowledge of how these research findings will be applied in the real world. In the life sciences, **basic research** refers to the systematic study of fundamental topics in biology; these studies provide new information about how cells, tissues, and organ systems function. Basic research in exercise physiology has revealed many of the mechanisms responsible for exercise-induced adaptations in both heart and skeletal muscles. As mentioned earlier, often, the practical application of basic research findings remain unclear for extended periods after the results are published. Nonetheless, basic research studies are vital because these studies provide the foundation for future applied research that leads to improvements in human performance/health and the treatment of disease.

Applied research Studies that are designed to solve practical problems are classified as **applied research**. For example, an applied study in exercise physiology might be an investigation that determines the effectiveness of several different resistance training programs in improving muscular strength. Again, the knowledge generated from basic research discoveries often forms the foundation for applied research that leads to the translation of research findings into practical applications.

The term "translational research" has emerged as a specific subtype of applied research. Specifically, **translational research** refers to a category of applied research that uses basic research findings to create new therapies to treat disease and/or enhance human health. Translational research is sometimes referred to as a "bench-to-bedside" application of research. The term "bench-to-bedside" can be explained as follows. In this context, "bench" denotes basic laboratory research whereas "bedside" refers to the treatment of disease in patients. Hence, the bench-to-bedside expression describes the clinical application of knowledge from basic laboratory research leading to translational research which then leads to new therapies to improve human health. The translational application of research findings to develop therapies for disease is often referred to as "Evidence-Based Practice." Specifically, **evidence-based practice** in medicine is the process of evaluating all of the research evidence available to make an informed decision about how to best treat disease. Evidence-based practice can also be applied in exercise physiology; see Clinical Application 0.1 for a discussion of how basic and translational research in exercise physiology leads to evidence-based practice.

CLINICAL APPLICATION 0.1

Exercise Physiology Research Leads to Evidence-Based

Practice

As discussed earlier, evidence-based practice in medicine describes the process of evaluating the research evidence from well-designed experiments to make informed decisions about the best treatment for patients. More specifically, the application of evidence-based practice in medicine involves the careful review of the scientific literature including both basic and translational research to determine if a particular clinical therapy is an effective treatment for a specific disease.

An illustration of how research in exercise physiology has contributed to evidence-based medical practice is the inclusion of exercise training to cardiac rehabilitation programs. Cardiac rehabilitation is a medical treatment program for patients with many forms of heart disease including people that have suffered a heart attack and/or patients that have undergone heart surgery. The goal of cardiac rehabilitation is to improve cardiovascular health, help patients regain their muscular strength/endurance, reduce the risk of future heart problems, and improve the quality of life. The decision to include exercise training into cardiac rehabilitation programs advanced from years of research demonstrating that an exercise-based cardiac rehabilitation program results in: (1) a reduction in all-cause cardiovascular mortality (i.e., patient death); (2) decreased hospital readmissions; and (3) improved quality of life (1). See Anderson et al. (2016) in the suggested readings for a review of the scientific evidence supporting the benefit of exercise training for cardiac patients.

Note that the concept of evidence-based practice is also widely used in fields outside of medicine. For example, the principle of evidence-based practice is increasingly used in exercise science. For example, evidence-based practice has been used by exercise scientists and strength and conditioning coaches in the design of both diet and exercise programs for athletes. Indeed, in the future, the best trained athletes (in all sports) will be the result of strength and conditioning programs that apply research findings to optimize diet and training programs for athletes.

IN SUMMARY

- The scientific method involves a six-step process that begins with the establishment of a research question and ends with the publication of the research findings in a peer-reviewed research journal.
- Two categories of research designs exist: (1) Nonexperimental; and (2) Experimental. Nonexperimental research does not involve the manipulation of experimental variables whereas experimental research includes the manipulation of experimental variables.
- Research in exercise physiology is performed in both research laboratories and in the field.
- Basic research in exercise physiology provides fundamental knowledge about how exercise impacts cells, tissues, and organ systems.
- Applied research uses the information provided by basic research to solve practical problems in the real world. It follows that both basic and applied research are required to advance our understanding of the health benefits of regular exercise and how regular exercise training improves human performance.
- Translational research is a subtype of applied research that uses basic research findings to treat disease and/or enhance human health.
- Evidence-based practice in medicine describes the process of evaluating the best research evidence to make informed decisions about the most effective treatment for patients. Evidence-based practice can also be applied in exercise science to design optimal training programs for athletes.

READING AND UNDERSTANDING SCIENTIFIC JOURNALS

When searching for answers to questions related to exercise physiology and health, it is important to look for answers in peer-reviewed research articles. Thousands of peer-reviewed research journals currently exist in the life sciences and more journals are coming online each year. These research journals play a critical role in advancing science by making new research findings available to scientists, coaches, journalists, and the general public. In reference to research journals, the term peer-review refers to the evaluation process that research reports undergo prior to acceptance for publication. The process of peer-review occurs in the following way. After a scientist completes a research study, the results and conclusions of the investigation are crafted into a research report using a standard scientific journal format; the completed research report is then submitted to a journal for publication. When the journal receives the report, the editor of the research journal briefly reviews the work and assigns the research report to two or more scientists for critical review. These reviewers (also called referees) are experts in the field and each referee will independently examine the paper to determine if the study meets the research standards required for publication in the journal. For example, the reviewers will determine if the study suffers from shortcomings such as missing information, flaws in the experimental design, and other issues that diminish the quality of the research. After thorough consideration, the referees will make recommendations to the editor as to whether the research study is suitable for publication. The editor will then consider the reviewers' comments and will make the final decision about whether the paper is of sufficient quality to be published.

Obviously, the goal of scientific peer-review is to prevent flawed studies from being published in the research literature. Although the process of peer-review significantly reduces the risk of unsound studies from being published, the process of peer-review is not perfect and the level of rigor of peer-review differs considerably across scientific journals. For example, the most rigorous scientific journals accept only 1% to 5% of all papers submitted to the journal. In contrast, research journals with much lower publication standards may accept as many as 50% to 70% of the papers submitted to the journal. Therefore, it is important to be an informed consumer of research studies because the quality of published research reports varies widely across research journals.

You are now probably wondering, “How do I evaluate the quality of a research journal?” Unfortunately, there is not a simple answer to this question. Indeed, there is no universal agreement among researchers about how to judge a journal’s quality. Nonetheless, several approaches to rank journals have been proposed and most of these are based on the impact of the journal. Specifically, a widely used method to rank the quality and influence of a journal is the “impact factor.” The journal’s impact factor is a numerical score that reflects the number of times that recently published articles in a journal are cited in the scientific literature. The number of citations of a published article is important because a high number of citations reflects the influence of the research study. While it is clear that the impact factor is an index of the influence of the journal, impact factors may also provide information about the overall quality of a journal. For example, scientific journals with high-impact factors typically receive a large number of research reports for review and accept only a small percentage of the submitted reports. Therefore, because of the high percentage of rejected articles, only the highest quality of the submitted reports are accepted for publication. Although the impact factor is not a perfect tool for measuring journal quality, better approaches to ranking journal quality do not currently exist and until better methods are developed, the journal impact factor remains a widely used benchmark. Nonetheless, even in high-impact factor journals, errors in the evaluation of papers occur resulting in the publication of flawed research. So, it is important that readers critically evaluate the quality of each published report before accepting the study conclusions as fact. Specific suggestions for ways to evaluate the quality of research studies will be provided later in this chapter.

Searching the Scientific Literature

The scientific literature in exercise physiology and sports sciences consists of many journals that publish both original research studies and review articles (see Table 0.1 for examples). An original research study contains the results of an experiment that addresses one or more questions. In contrast, a scientific review article provides a summary of the published research on a specific topic. Because thousands of reports exist on any given topic in exercise physiology, searching the scientific literature to find answers to questions can be challenging. Nonetheless, using some simple guidelines, anyone can become skilled at exploring the research literature. Let's begin with a discussion of selecting a search engine.

TABLE 0.1 Examples of Journals That Publish Exercise Physiology Research. All of Journals Listed Below Are Ranked Within the Top 35% of Journals in the Sports Science or Physiology Category[1].

Journal Title
Acta Physiologica
Applied Physiology Nutrition and Metabolism
European Journal of Applied Physiology
International Journal of Sports Medicine
Journal of Applied Physiology
Journal of Physiology
Journal of Sport and Health Science
Journal of Strength and Conditioning
Medicine and Science in Sports and Exercise
Scandinavian Journal of Medicine and Science in Sports

[1]Relative rank based on 2017 journal impact factors for journals in either the sports science or physiology category. Take note that the above list includes only journals that publish both original research and review articles. Journals are listed in alphabetical order and not ranked by impact factor.

Search Engines

A search of the scientific literature begins with the selection of a search engine. A search engine is a software program that allows users to locate information on the Internet. Several broad topic search engines exist including Google, Yahoo, and Bing; these search tools are useful for exploring almost any topic using key words or phrases. However, several specific search engines exist for examining the scientific literature. For example, three well-established search engines for exploring published research in exercise physiology/sport sciences include PubMed, Google Scholar, and SportDiscus. PubMed is a free and powerful search engine provided by United States National Library of Medicine. Specifically, PubMed is a web-based retrieval system that provides bibliographic information drawn from the life science literature. Similarly, Google Scholar is a free search engine that indexes the scholarly literature across several disciplines. Lastly, SportDiscus is another bibliographic database that covers sport, physical fitness, exercise, sports medicine, sports science, physical education, coaching, training, etc. However, unlike PubMed and Google Scholar which are free to use, SportDiscus requires a paid subscription.

How to Become a Search Wizard

With practice, anyone can become proficient in searching the exercise physiology/sport science literature using the readily available search engines. Here we provide a short tutorial on the use of PubMed to search for published peer-reviewed research related to exercise physiology. Note that PubMed also provides a tutorial on how to build a PubMed search (https://www.nlm.nih.gov/bsd/disted/pubmedtutorial/020_010.html

To use PubMed, you simply enter key words, author names, journal titles, or concepts in the search box. For most searches, it is better to be specific (i.e., use more terms) because with a narrower search, fewer irrelevant results will be retrieved. Consider the following example of a key word search. Let's say you are interested in learning about endurance exercise training-induced adaptations in human skeletal muscle. If you begin the PubMed search with the single key word, "exercise," the search will yield almost 400,000 published papers and many of these reports have nothing to do with endurance exercise and human skeletal muscle. However, if you now enter the words "endurance exercise human skeletal muscle" to the search box, the list of retrieved studies is reduced to approximately 6,400 reports and most of these papers will be relevant to your specific interest.

When you complete your literature search, pay attention to the most recent publication dates as these studies often provide the most up-to-date information.

If you are interested in investigating the research performed by an individual scientist, you can perform a search using the authors' name. Here's an illustration. If you want to know more about the research of the coauthors of this textbook (Scott K. Powers, John C. Quindry, Edward T. Howley), you would enter the authors last name followed by the initials. For example, to search for publications by Edward T. Howley, you simply enter "Howley ET" into the search box; the end result will be a list of the research reports authored by Dr. Howley.

Finally, using connecting words (called Boolean operators), you can divide or combine concepts in your search. In the context of database searching, Boolean operators can assist you in expanding or restricting your search. The Boolean operators OR, NOT, and AND can be used to combine or eliminate search terms in PubMed. Note that in PubMed, these Boolean operators must be entered in uppercase letters (i.e., ALL CAPS). Examples of how to use these Boolean operators follow:

OR (all caps): The connecting term "OR" is used to broaden searches and increase your search findings when synonyms exist for search terms. For instance, several synonyms for resistance training exist including the terms strength training and/or weight training. Using this example, a PubMed search for reports involving "resistance training" yields more than 19,800 results. However, if you now enter "resistance training OR weight training OR strength training" into the PubMed search box, the search engine yields more than 51,800 reports! Therefore, using the connecting term "OR" is valuable to broaden your search and increase your chances of finding important reports on your topic of interest.

NOT (all caps): The use of the Boolean operator "NOT" is helpful in excluding unwanted terms from your search. For example, if you are interested in locating original research about the effects of endurance exercise on skeletal muscle adaptation, you can incorporate the Boolean operator NOT to eliminate the retrieval of reviews. Here's an example of this type of search. In the search box you enter "endurance exercise skeletal muscle NOT review".