

Eleventh Edition

# EXERCISE PHYSIOLOGY

Theory and Application to Fitness and Performance



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



Mc  
Graw  
Hill



# EXERCISE PHYSIOLOGY

---

Theory and Application to  
Fitness and Performance

ELEVENTH EDITION

**Scott K. Powers**

*University of Florida*

**Edward T. Howley**

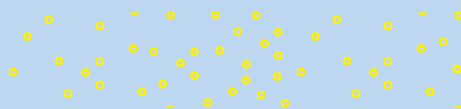
*University of Tennessee, Knoxville*

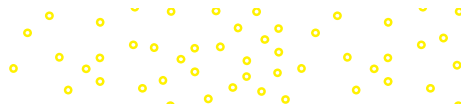
**John Quindry**

*University of Montana*



**Mc  
Graw  
Hill**





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

Published by McGraw Hill LLC, 1325 Avenue of the Americas, New York, NY 10121. Copyright ©2021 by McGraw Hill LLC. All rights reserved. Printed in the United States of America. Previous editions ©2018, 2015, and 2012. No part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written consent of McGraw Hill LLC, including, but not limited to, in any network or other electronic storage or transmission, or broadcast for distance learning.

Some ancillaries, including electronic and print components, may not be available to customers outside the United States.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI 24 23 22 21 20

ISBN 978-1-260-23776-4 (bound edition)  
MHID 1-260-23776-1 (bound edition)  
ISBN 978-1-260-81349-4 (loose-leaf edition)  
MHID 1-260-81349-5 (loose-leaf edition)

Product Developer: *Francesca King*  
Marketing Manager: *Meredith Leo Digiano*  
Content Project Manager: *Lisa Brufodt*  
Buyer: *Sandy Ludovissy*  
Design: *Beth Blech*  
Content Licensing Specialist: *Jacob Sullivan*  
Cover Image: (*exercise class*): *Denkou Images/age fotostock*; (*woman lifting weights*): *vitapix/Getty Images*;  
(*track runners*): *IMAGEMORE Co Ltd./Getty Images*; (*fitness bike*): *wavebreakmedia/Shutterstock*  
Compositor: *MPS Limited*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

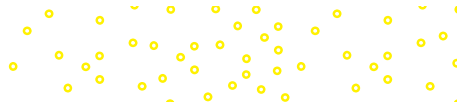
#### Library of Congress Cataloging-in-Publication Data

Names: Powers, Scott K. (Scott Kline), 1950- author. | Howley, Edward T., 1943- author. | Quindry, John, 1971- author.  
Title: Exercise physiology: theory and application to fitness and performance / Scott K Powers, University of Florida, Edward T Howley, University of Tennessee, Knoxville, John Quindry, University of Montana.  
Description: Eleventh edition. | New York, NY : McGraw Hill LLC, 2021. | Includes bibliographical references and index.  
Identifiers: LCCN 2020003042 (print) | LCCN 2020003043 (ebook) | ISBN 9781260237764 (hardcover) | ISBN 9781260813562 (ebook)  
Subjects: LCSH: Exercise—Physiological aspects.  
Classification: LCC QP301 .P64 2020 (print) | LCC QP301 (ebook) | DDC 612/.044—dc23  
LC record available at <https://lccn.loc.gov/2020003042>  
LC ebook record available at <https://lccn.loc.gov/2020003043>

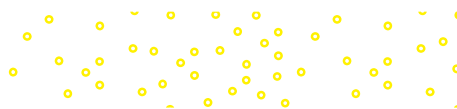
The Internet addresses listed in the text were accurate at the time of publication. The inclusion of a website does not indicate an endorsement by the authors or McGraw Hill LLC, and McGraw Hill LLC does not guarantee the accuracy of the information presented at these sites.

[mheducation.com/highered](http://mheducation.com/highered)





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



# Brief Contents

## SECTION 1

### Physiology of Exercise 1

- 0 Introduction to Exercise Physiology 2
- 1 Common Measurements in Exercise Physiology 22
- 2 Control of the Internal Environment 37
- 3 Bioenergetics 47
- 4 Exercise Metabolism 77
- 5 Cell Signaling and the Hormonal Responses to Exercise 101
- 6 Exercise and the Immune System 137
- 7 The Nervous System: Structure and Control of Movement 152
- 8 Skeletal Muscle: Structure and Function 179
- 9 Circulatory Responses to Exercise 207
- 10 Respiration during Exercise 240
- 11 Acid-Base Balance during Exercise 275
- 12 Temperature Regulation 289
- 13 The Physiology of Training: Effects of Aerobic and Anaerobic Training 314
- 14 The Physiology of Resistance Training 340

## SECTION 2

### Physiology of Health and Fitness 363

- 15 Preventing Chronic Disease: Physical Activity and Healthy Eating 364
- 16 Exercise Prescriptions for Health and Fitness 391

- 17 Exercise for Special Populations 416
- 18 Nutrition, Body Composition, and Weight Management 445

## SECTION 3

### Physiology of Performance 487

- 19 Factors Affecting Performance 488
- 20 Training for Performance 507
- 21 Training for the Female Athlete, Children, Special Populations, and the Masters Athlete 539
- 22 Nutrition, Body Composition, and Performance 561
- 23 Exercise and the Environment 585
- 24 Ergogenic Aids 612

#### Appendices can be found in the Instructor's Resources within Connect

- Appendix A: Calculation of Oxygen Uptake and Carbon Dioxide Production A-1
- Appendix B: Dietary Reference Intakes: Estimated Energy Requirements A-5
- Appendix C: Dietary Reference Intakes: Vitamins A-6
- Appendix D: Dietary Reference Intakes: Minerals and Elements A-8
- Appendix E: Percent Fat Estimate for Men: Sum of Triceps, Chest, and Subscapula Skinfolts A-10
- Appendix F: Percent Fat Estimate for Women: Sum of Triceps, Abdomen, and Suprailium Skinfolts A-11
- Appendix G: MET Equivalents for Exercise, Activities of Daily Living, and Household Chores A-12

- Glossary G-1
- Index I-1

# Contents

Preface xiii

## SECTION 1

### Physiology of Exercise 1

#### Chapter 0 Introduction to Exercise

Physiology 2

##### Milestones in the Evolution of Exercise

###### Physiology 3

Milestones in Exercise Physiology—the Early Years (1900–1950) 3

Milestones in Exercise Physiology—Second Half of the Twentieth Century (1951–2000) 5

Milestones in Exercise Physiology Research—2001 to Present 7

##### Exercise Physiology Research: The Path to New Knowledge 10

The Scientific Method 10

Classes of Research Designs 11

Field and Laboratory Research 12

Basic and Applied Research 12

##### Reading and Understanding Scientific Journals 13

Searching the Scientific Literature 14

Components of a Scientific Research Report 16

How to Critically Evaluate the Quality of a Research Study 17

##### Exercise Physiology/Sports Science

Professional Organizations 19

##### Certification by Professional Organizations 19

##### Careers in Exercise Physiology and Related Fields 20

#### Chapter 1 Common Measurements in Exercise Physiology 22

##### Units of Measure 23

Metric System 23

SI Units 23

##### Work and Power Defined 23

Work 23

Power 24

##### Types of Ergometers 24

Bench Step 24

Cycle Ergometer 25

Arm Ergometer 25

Treadmill 26

##### Measurement of Work and Power 26

Bench Step 26

Cycle Ergometer 27

Treadmill 27

##### Measurement of Energy Expenditure 28

Direct Calorimetry 28

Indirect Calorimetry 28

##### Common Expressions of Oxygen Consumption and Energy Expenditure 29

##### Estimation of Energy Expenditure 30

##### Calculation of Exercise Efficiency 31

Factors That Influence Exercise Efficiency 33

##### Running Economy 34

#### Chapter 2 Control of the Internal

Environment 37

##### Homeostasis: Dynamic Constancy 38

##### Control Systems of the Body 39

##### Nature of the Control Systems 39

Negative Feedback 40

Positive Feedback 40

Gain of a Control System 40

##### Examples of Homeostatic Control 41

Regulation of Body Temperature 41

Regulation of Blood Glucose 41

##### Exercise: A Test of Homeostatic Control 41

##### Exercise Improves Homeostatic Control Via Cellular Adaptation 42

##### Stress Proteins Assist in the Regulation of Cellular Homeostasis 44

#### Chapter 3 Bioenergetics 47

##### Cell Structure 48

##### Biological Energy Transformation 48

Cellular Chemical Reactions 49

Oxidation-Reduction Reactions 51

Enzymes 52

##### Fuels for Exercise 55

Carbohydrates 55

Fats 56

Proteins 56

##### High-Energy Phosphates 57

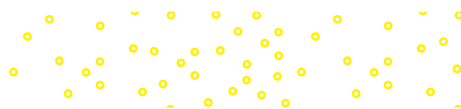
##### Bioenergetics 57

Anaerobic ATP Production 58

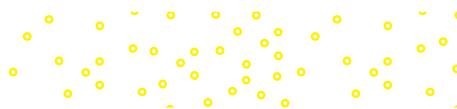
Aerobic ATP Production 61

##### Aerobic ATP Tally 68

Efficiency of Oxidative Phosphorylation	69
<b>Control of Bioenergetics</b>	<b>69</b>
Control of ATP-PC System	70
Control of Glycolysis	70
Control of Citric Acid Cycle and Electron Transport Chain	71
<b>Interaction Between Aerobic/Anaerobic ATP Production</b>	<b>71</b>
<b>Chapter 4 Exercise Metabolism</b>	<b>77</b>
<b>Energy Requirements at Rest</b>	<b>78</b>
<b>Rest-to-Exercise Transitions</b>	<b>78</b>
<b>Recovery from Exercise: Metabolic Responses</b>	<b>80</b>
<b>Metabolic Responses to Exercise: Influence of Duration and Intensity</b>	<b>84</b>
Short-Term, Intense Exercise	84
Prolonged Exercise	84
Incremental Exercise	85
<b>Estimation of Fuel Utilization During Exercise</b>	<b>89</b>
<b>Factors Governing Fuel Selection</b>	<b>90</b>
Exercise Intensity and Fuel Selection	90
Exercise Duration and Fuel Selection	91
Interaction of Fat/Carbohydrate Metabolism	92
Body Fuel Sources	93
<b>Chapter 5 Cell Signaling and the Hormonal Responses to Exercise</b>	<b>101</b>
<b>Neuroendocrinology</b>	<b>102</b>
Blood Hormone Concentration	103
Hormone-Receptor Interaction	104
<b>Hormones: Regulation and Action</b>	<b>107</b>
Hypothalamus and the Pituitary Gland	107
Thyroid Gland	110
Parathyroid Gland	111
Adrenal Gland	111
Pancreas	115
Testes and Ovaries	115
<b>Hormonal Control of Substrate Mobilization During Exercise</b>	<b>120</b>
Muscle-Glycogen Utilization	120
Blood Glucose Homeostasis During Exercise	123
Hormone-Substrate Interaction	130
<b>Chapter 6 Exercise and the Immune System</b>	<b>137</b>
<b>Overview of the Immune System</b>	<b>138</b>
Innate Immune System	138
Acquired Immune System	142
<b>Exercise and the Immune System</b>	<b>144</b>
Exercise and Resistance to Infection	144
Exercise, Circulating Immune Cell Counts, and Activity	145
High-Intensity/Long-Duration Aerobic Exercise Increases the Risk of Infection	146
<b>Exercising in Environmental Extremes: Increased Risk for Infection?</b>	<b>148</b>
<b>Should You Exercise When You Have a Cold?</b>	<b>149</b>
<b>Chapter 7 The Nervous System: Structure and Control of Movement</b>	<b>152</b>
<b>General Nervous System Functions</b>	<b>153</b>
<b>Organization of the Nervous System</b>	<b>153</b>
Structure of the Neuron	154
Electrical Activity in Neurons	154
<b>Sensory Information and Reflexes</b>	<b>161</b>
Joint Proprioceptors	161
Muscle Proprioceptors	161
<b>Muscle Chemoreceptors</b>	<b>164</b>
<b>Somatic Motor Function and Motor Neurons</b>	<b>164</b>
<b>Vestibular Apparatus and Equilibrium</b>	<b>167</b>
<b>Motor Control Functions of the Brain</b>	<b>168</b>
Cerebrum	168
Cerebellum	169
Brain Stem	169
<b>Motor Functions of the Spinal Cord</b>	<b>171</b>
Control of Motor Functions	171
Autonomic Nervous System	173
<b>Exercise Enhances Brain Health</b>	<b>174</b>
<b>Chapter 8 Skeletal Muscle: Structure and Function</b>	<b>179</b>
<b>Structure of Skeletal Muscle</b>	<b>180</b>
<b>Neuromuscular Junction</b>	<b>182</b>
<b>Muscular Contraction</b>	<b>184</b>
Overview of the Sliding Filament/Swinging Lever-Arm Model	184
Energy for Contraction	184
Regulation of Excitation-Contraction Coupling	184
<b>Exercise and Muscle Fatigue</b>	<b>190</b>
<b>Exercise-Associated Muscle Cramps</b>	<b>191</b>
Exercise-Associated Muscle Cramps Are Not Caused by Dehydration or Electrolyte Imbalance	191
Exercise-Associated Muscle Cramps Are Likely Due to Changes in the Central Nervous System	192
Exercise-Associated Muscle Cramps: Conclusions	192
<b>Muscle Fiber Types</b>	<b>193</b>
Overview of Biochemical and Contractile Characteristics of Skeletal Muscle	194
Functional Characteristics of Muscle Fiber Types	195
Fiber Types and Performance	197
<b>Muscle Actions</b>	<b>198</b>
<b>Speed of Muscle Action and Relaxation</b>	<b>198</b>
<b>Force Regulation in Muscle</b>	<b>199</b>
<b>Force-Velocity/Power-Velocity Relationships</b>	<b>201</b>



<b>Chapter 9</b> Circulatory Responses	
to Exercise	207
<b>Organization of the Circulatory System</b>	208
Structure of the Heart	209
Pulmonary and Systemic Circuits	210
<b>Heart: Myocardium and Cardiac Cycle</b>	210
Myocardium	210
Cardiac Cycle	212
Arterial Blood Pressure	214
Factors That Influence Arterial Blood Pressure	216
Electrical Activity of the Heart	216
<b>Cardiac Output</b>	220
Regulation of Heart Rate	220
Heart Rate Variability	222
Regulation of Stroke Volume	223
<b>Hemodynamics</b>	225
Physical Characteristics of Blood	225
Relationships among Pressure, Resistance, and Flow	226
Sources of Vascular Resistance	226
<b>Changes in Oxygen Delivery to Muscle During Exercise</b>	227
Changes in Cardiac Output During Exercise	227
Changes in Arterial-Mixed Venous O <sub>2</sub> Content during Exercise	229
Redistribution of Blood Flow during Exercise	229
Regulation of Local Blood Flow during Exercise	231
<b>Circulatory Responses to Exercise</b>	232
Emotional Influence	232
Transition from Rest to Exercise	232
Recovery from Exercise	232
Incremental Exercise	232
Arm Versus Leg Exercise	233
Intermittent Exercise	234
Prolonged Exercise	234
<b>Regulation of Cardiovascular Adjustments to Exercise</b>	236
<b>Chapter 10</b> Respiration during Exercise	240
<b>Function of the Respiratory System—The Big Picture</b>	241
<b>Structure of the Respiratory System</b>	241
Conducting Zone	243
Respiratory Zone	244
<b>Mechanics of Breathing</b>	245
Inspiration	245
Expiration	246
Airway Resistance	246
<b>Pulmonary Ventilation</b>	247
<b>Pulmonary Volumes and Capacities</b>	248
<b>Diffusion of Gases</b>	250
<b>Blood Flow to the Lung</b>	251
<b>Ventilation-Perfusion Relationships</b>	253
<b>O<sub>2</sub> and CO<sub>2</sub> Transport in Blood</b>	254
Hemoglobin and O <sub>2</sub> Transport	255
Oxygen-Hemoglobin Dissociation Curve	255
O <sub>2</sub> Transport in Muscle	257
CO <sub>2</sub> Transport in Blood	257
<b>Ventilation and Acid-Base Balance</b>	259
<b>Ventilatory and Blood-Gas Responses to Exercise</b>	259
Rest-to-Work Transitions	259
Prolonged Exercise in a Hot Environment	259
Incremental Exercise	260
Changes in Breathing Pattern during Exercise	261
<b>Control of Ventilation</b>	262
Ventilatory Regulation at Rest	262
Respiratory Control Center	262
Input to the Respiratory Control Center	263
Ventilatory Control during Moderate-Intensity Exercise	265
Ventilatory Control during Heavy and Very Heavy Exercise	265
<b>Do the Lungs Adapt to Exercise Training?</b>	267
<b>Does the Pulmonary System Limit Maximal Exercise Performance?</b>	268
<b>Chapter 11</b> Acid-Base Balance during Exercise	275
<b>Acids, Bases, and pH</b>	276
<b>Hydrogen Ion Production During Exercise</b>	278
<b>Importance of Acid-Base Regulation During Exercise</b>	279
<b>Acid-Base Buffer Systems</b>	280
Intracellular Buffers	280
Influence of Muscle Fiber Type and Exercise Training on Intracellular Buffer Capacity	281
Extracellular Buffers	281
<b>Respiratory Influence on Acid-Base Balance</b>	283
<b>Regulation of Acid-Base Balance Via the Kidneys</b>	284
<b>Regulation of Acid-Base Balance during Exercise</b>	285
<b>Chapter 12</b> Temperature Regulation	289
<b>Overview of Heat Balance During Exercise</b>	290
<b>Temperature Measurement During Exercise</b>	291
<b>Overview of Heat Production/Heat Loss</b>	292
Heat Production	293
Heat Loss	293
Heat Storage in the Body during Exercise	294
<b>Body's Thermostat—Preoptic-Anterior Hypothalamus</b>	296
Shift in the Hypothalamic Thermostat Set Point Due to Fever	297
<b>Thermal Events during Exercise</b>	298
<b>Heat Index—A Measure of How Hot It Feels</b>	300





- Exercise in a Hot Environment** 300
  - Sweat Rates during Exercise 300
  - Exercise Performance Is Impaired in a Hot Environment 300
  - Gender and Age Differences in Thermoregulation 304
  - Heat Acclimation 305
  - Loss of Acclimation 307
- Exercise in a Cold Environment** 308
  - Physiological Responses to Exercise in the Cold 309
  - Cold Acclimation 310

## Chapter 13 The Physiology of Training: Effects of

- Aerobic and Anaerobic Training 314
- Principles of Training** 315
  - Overload and Reversibility 315
  - Specificity 316
- Endurance Training and  $\dot{V}O_2$  Max** 316
  - Training Programs and Changes in  $\dot{V}O_2$  Max 316
- Why Does Exercise Training Improve  $\dot{V}O_2$  Max?** 318
  - Stroke Volume 318
  - Arteriovenous  $O_2$  Difference 319
- Endurance Training: Effects on Performance and Homeostasis** 320
  - Endurance Training-Induced Changes in Fiber Type and Capillarity 321
  - Endurance Training Increases Mitochondrial Content in Skeletal Muscle Fibers 321
  - Training-Induced Changes in Muscle Fuel Utilization 323
  - Endurance Training Improves Muscle Antioxidant Capacity 325
  - Exercise Training Improves Acid-Base Balance during Exercise 325
- Molecular Bases of Exercise Training Adaptation** 326
  - Training Adaptation—Big Picture 326
  - Specificity of Exercise Training Responses 327
  - Primary Signal Transduction Pathways in Skeletal Muscle 328
  - Secondary Messengers in Skeletal Muscle 329
- Signaling Events Leading to Endurance Training-Induced Muscle Adaptation** 330
- Endurance Training: Links Between Muscle and Systemic Physiology** 332
  - Peripheral Feedback 332
  - Central Command 334
- Detraining Following Endurance Training** 335
- Muscle Adaptations to Anaerobic Exercise Training** 336
  - Anaerobic Training-Induced Increases in Performance 336
  - Anaerobic Training-Induced Changes in Skeletal Muscles 336

## Chapter 14 The Physiology of Resistance

- Training 340
- Physiological Effects of Resistance Exercise Training** 341
  - Resistance Training Promotes Changes in the Nervous System 342
  - Resistance Training-Induced Changes in Muscle Fiber Type 346
  - Does Resistance Training Improve Muscle Oxidative Capacity and Increase Capillary Number? 346
  - Resistance Training Improves Muscle Antioxidant Enzyme Activity 347
  - Resistance Training Increases Tendon and Ligament Strength 347
  - Resistance Training Improves Bone Mineral Content 347
- Time Course and Signaling Events Leading to Resistance Training-Induced Muscle Growth** 347
  - Time Course of Muscle Protein Synthesis 348
  - Signaling Events Leading to Resistance Training-Induced Muscle Growth 349
  - Do Hormones Contribute to Resistance Training-Induced Hypertrophy? 351
  - Do Anti-inflammatory Drugs Impact Training-induced Hypertrophy? 351
  - Role of Satellite Cells in Resistance Training-Induced Hypertrophy 351
  - Genetic Influence on the Magnitude of Resistance Training-Induced Hypertrophy 352
- Detraining Following Strength Training** 353
- Prolonged Inactivity of Skeletal Muscles Leads to Rapid Atrophy** 355
- Concurrent Strength and Endurance Training** 356
  - Mechanisms Responsible for the Impairment of Strength Development during Concurrent Strength and Endurance Training 357

## SECTION 2

## Physiology of Health and Fitness 363

- Chapter 15 Preventing Chronic Disease: Physical Activity and Healthy Eating** 364
- Physical Activity and Health** 366
  - The Dose-Response Relationship between Physical Activity and Health 366
- Risk Factors for Chronic Diseases** 368
  - Inherited/Biological 368
  - Environmental 368
  - Behavioral 369
- Risk Factors for Coronary Heart Disease** 371
  - Sedentary Behavior and All-Cause Mortality 372
  - The Risk of Physical Inactivity Versus the Benefits of Being Active 373

Physical Activity and Hypertension 373  
 Physical Activity and Obesity 374  
 Physical Activity and Dyslipidemia 375

**Inflammation and Coronary Heart Disease 376**  
 Obesity, Inflammation, and Chronic Disease 378  
 Healthy Eating and Physical Activity to Combat Inflammation 378

**The Metabolic Syndrome 379**  
 Risk Factors and the Metabolic Syndrome 379  
 Comorbidities and the Metabolic Syndrome 380  
 Inflammation and Oxidative Stress as Causes of the Metabolic Syndrome 380

**Diabetes 381**  
 The Prevalence and Diagnosis of Diabetes 381  
 Type 1 Diabetes 382  
 Type 2 Diabetes 382  
 The Clinical Progression of Type 2 Diabetes 383  
 Type 2 Diabetes and the Benefits of Physical Activity 383

**Cancer 384**  
 The Link Between Physical Activity, Cancer Prevention, and Disease Occurrence 384  
 Cancer Treatment and Survival 385  
 Muscle and Bone Mineral Density Loss in Cancer Patients Undergoing Treatment 385  
 Physical Activity and Cancer Survival 386  
 Physical Activity and Exercise During Chemotherapy 386  
 The Role of Physical Activity in Terminally Ill Cancer Patients 386

**Chapter 16** Exercise Prescriptions for Health and Fitness 391

**Prescription of Exercise 392**  
 Dose-Response 393  
 Physical Activity and Health 394  
 Physical Activity Guidelines to Improve Health 394  
 Physical Activity Volume 394  
 Physical Activity Intensity Thresholds 395  
 Light-intensity Physical Activity, Step Counts, and Health 396

**General Guidelines for Improving Fitness 397**  
 $\dot{V}O_2$  max and Health 397  
 Assessing  $\dot{V}O_2$  max 398  
 Estimating  $\dot{V}O_2$  max 399  
 Screening 401  
 Progression 401  
 Warm-Up, Stretch, and Cool-Down, Stretch 402

**Exercise Prescription for CRF 402**  
 Frequency 402  
 Intensity 403  
 Time (Duration) 406  
 Monitoring Heart Rate 407

**Sequence of Physical Activity 407**  
 Walking 407  
 Jogging 408  
 Games and Sports 409

**Strength and Flexibility Training 409**  
**Environmental Concerns 411**

**Chapter 17** Exercise for Special Populations 416

**Diabetes 417**  
 Exercise and Diabetes 417

**Asthma 421**  
 Diagnosis and Causes 421  
 Prevention/Relief of Asthma 422  
 Exercise-Induced Asthma 422

**Chronic Obstructive Pulmonary Disease 425**  
 Testing and Training 426

**Hypertension 427**

**Cardiac Rehabilitation 428**  
 Population 428  
 Testing 429  
 Exercise Programs 429

**Exercise for Older Adults 430**  
 Maximal Aerobic Power 431  
 Response to Training 432  
 Bone Health and Osteoporosis 433  
 Strength 436

**Exercise During Pregnancy 436**

**Exercise and Cancer 438**  
 Individualized Exercise Prescriptions 438  
 Managing Functional Limitations 438  
 Supervised and Independent Exercise 438  
 Exercise Recommendations for Cancer Patients 439

**Chapter 18** Nutrition, Body Composition, and Weight Management 445

**Nutrition—the Science of Food 446**  
**Classes and Functions of Nutrients 447**  
**Macronutrients 448**  
 Carbohydrates 448  
 Proteins 448  
 Lipids (fats) 449  
 Water 450

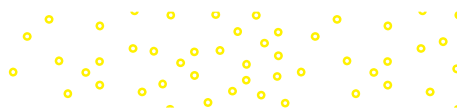
**Micronutrients 451**  
 Vitamins 451  
 Minerals 454

**Nutritional Requirements and Dietary Guidelines 456**  
 Estimated Average Requirements 456  
 Recommended Dietary Allowance 457  
 Adequate Intakes 457  
 Tolerable Upper Intake Levels 457  
 Estimated Energy Requirement 457  
 Acceptable Macronutrient Distribution Ranges 457

**Nutrition Facts Panel on Food 457**

**Nutritional Recommendations for Intake of Macro- and Micronutrients 459**  
 Acceptable Macronutrient Distribution Ranges 459  
 Recommendations for Micronutrient Intake 462

**Dietary Guidelines for Americans 465**  
**Body Composition 465**



Methods of Assessing Overweight and Obesity 466  
 Methods of Measuring Body Composition 467  
**What is a Healthy Percent Body Fat?** 471  
**Weight Loss: Role of Diet and Exercise** 471  
 Body Energy Balance 472  
 Popular Diet Plans 475  
 Does the Macronutrient Composition of Diets Influence Weight Loss? 476  
 Factors that Influence Adherence to a Diet 477  
 Low-Energy Diets Result in a Loss of Both Fat and Fat Free Mass 478  
 Combining Exercise and Diet Promotes Weight Loss and Maintains Fat Free Mass 479  
 Steps to Achieving a Healthy Percent Body Fat 480

## SECTION 3

### Physiology of Performance 487

#### Chapter 19 Factors Affecting Performance 488

**Sites of Fatigue** 489  
 Central Fatigue 490  
 Peripheral Fatigue 492  
 Both Central and Peripheral Fatigue 495  
**Factors Limiting All-Out Anaerobic Performances** 496  
 Ultra Short-Term Performances (Ten Seconds or Less) 496  
 Short-Term Performances (10-180 Seconds) 497  
**Factors Limiting All-Out Aerobic Performances** 499  
 Moderate-Length Performances (3-20 Minutes) 499  
 Intermediate-Length Performances (21-60 Minutes) 499  
 Long-Term Performances (1-4 Hours) 501  
**Athlete as Machine** 503

#### Chapter 20 Training for Performance 507

**Training Principles** 508  
 Overload, Specificity, and Reversibility 508  
 Influence of Gender and Initial Fitness Level 510  
 Influence of Genetics 510  
**Components of a Training Session: Warm-Up, Workout, and Cool Down** 512  
**Training to Improve Aerobic Power** 513  
 Interval Training 513  
 Long, Slow-Distance Exercise 517  
 High-Intensity, Continuous Exercise 517  
 Altitude Training Improves Exercise Performance at Sea Level 518  
**Injuries and Endurance Training** 519  
**Training to Improve Anaerobic Power** 519  
 Training to Improve the ATP-PC System 520  
 Training to Improve the Glycolytic System 520

**Training to Improve Muscular Strength** 520  
 Progressive Resistance Exercise 522  
 General Strength-Training Principles 522  
 Free Weights Versus Machines 524  
 Gender Differences in Response to Strength Training 524  
**Concurrent Strength and Endurance Training Programs** 525  
**Nutritional Influence on Training-Induced Skeletal Muscle Adaptations** 526  
 Carbohydrate Availability in Skeletal Muscle Influences Endurance Training Adaptation 526  
 Protein Availability in Skeletal Muscle Influences Muscle Protein Synthesis Following Exercise 527  
 Supplementation with Mega Doses of Antioxidants 527  
**Muscle Soreness** 528  
**Training to Improve Flexibility** 530  
**Year-Round Conditioning for Athletes** 532  
 Off-Season Conditioning 532  
 Preseason Conditioning 532  
 In-Season Conditioning 533  
**Common Training Mistakes** 533

#### Chapter 21 Training for the Female Athlete, Children, Special Populations, and the Masters Athlete 539

**Factors Important to Women Involved in Vigorous Training** 540  
 Exercise and Menstrual Disorders 540  
 Training and Menstruation 541  
 The Female Athlete and Eating Disorders 541  
 Eating Disorders: Final Comments 544  
 Bone Mineral Disorders and the Female Athlete 545  
 Exercise During Pregnancy 545  
 Risk of Knee Injury in Female Athletes 545  
**Sports Conditioning for Children** 548  
 Training and the Cardiopulmonary System 549  
 Training and the Musculoskeletal System 549  
 Progress in Pediatric Exercise Science 550

#### Competitive Training for People with Diabetes 550

#### Training for People with Asthma 552

#### Epilepsy and Physical Training 552

Does Exercise Promote Seizures? 552  
 Risk of Injury Due to Seizures 553

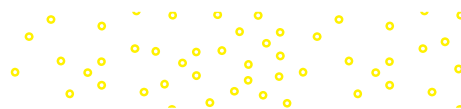
#### Exercise Performance and Training for Masters Athletes 553

Age-Related Changes in Muscular Strength 554  
 Aging and Endurance Performance 554  
 Training Guidelines for Masters Athletes 556

#### Chapter 22 Nutrition, Body Composition, and Performance 561

#### Carbohydrate 562

Carbohydrate Diets and Performance 562



- Carbohydrate Intake Prior to or During a Performance 565
- Carbohydrate Intake Post-Performance 567
- Protein 569**
  - Protein Requirements and Exercise 569
  - Protein Requirements for Athletes 570
- Water and Electrolytes 572**
  - Fluid Replacement—Before Exercise 572
  - Fluid Replacement—During Exercise 572
  - Fluid Replacement—After Exercise 574
  - Salt (NaCl) 576
- Minerals 576**
  - Iron 576
- Vitamins 578**
- Precompetition Meal 578**
  - Nutrients in Precompetition Meal 579
- Body Composition and Performance 579**

**Chapter 23** Exercise and the Environment 585

- Altitude 586**
  - Atmospheric Pressure 586
  - Short-Term Anaerobic Performance 586
  - Long-Term Aerobic Performance 587
  - Maximal Aerobic Power and Altitude 588
  - Acclimatization to High Altitude 590
  - Training for Competition at Altitude 591
  - The Quest for Everest 592
- Heat 595**
  - Hyperthermia 595
- Implications for Fitness 597**
- Implications for Performance 597**
- Cold 599**
  - Environmental Factors 600
  - Insulating Factors 602
  - Heat Production 603
  - Descriptive Characteristics 603
  - Dealing with Hypothermia 604
- Air Pollution 605**
  - Particulate Matter 605
  - Ozone 605
  - Sulfur Dioxide 605
  - Carbon Monoxide 605

- Chapter 24** Ergogenic Aids 612
  - Research Design Concerns 613**
  - Dietary Supplements 614**
  - Aerobic Performance 617**
    - Oxygen 617
    - Blood Doping 618
  - Anaerobic Performance 622**
    - Blood Buffers 622
  - Drugs 623**
    - Amphetamines 623
    - Caffeine 624
  - Mechanical Ergogenic Aids 627**
    - Cycling 627
  - Physical Warm-Up 629**

**Appendices can be found in the Instructor's Resources within Connect**

- Appendix A:** Calculation of Oxygen Uptake and Carbon Dioxide Production A-1
- Appendix B:** Dietary Reference Intakes: Estimated Energy Requirements A-5
- Appendix C:** Dietary Reference Intakes: Vitamins A-6
- Appendix D:** Dietary Reference Intakes: Minerals and Elements A-8
- Appendix E:** Percent Fat Estimate for Men: Sum of Triceps, Chest, and Subscapula Skinfolts A-10
- Appendix F:** Percent Fat Estimate for Women: Sum of Triceps, Abdomen, and Suprailium Skinfolts A-11
- Appendix G:** MET Equivalents for Exercise, Activities of Daily Living, and Household Chores A-12
- Glossary G-1
- Index I-1





# 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.



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<sup>®</sup> 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:

- Quizzes for each chapter.
- A full Test Bank of multiple choice questions that test students on central concepts and ideas in each chapter. Also, new to this edition is the classification of test question difficulty using 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.

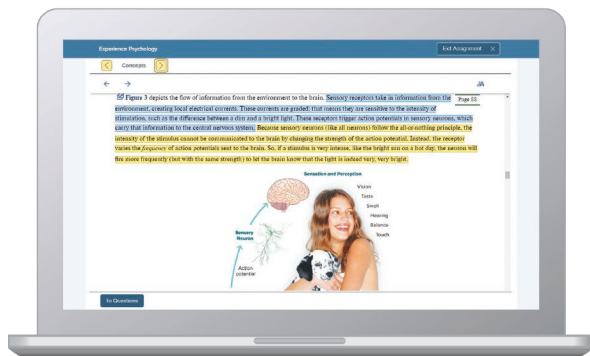


## FOR INSTRUCTORS

### You're in the driver's seat.

Want to build your own course? No problem. Prefer to use our turnkey, prebuilt course? Easy. Want to make changes throughout the semester? Sure. And you'll save time with Connect's auto-grading too.

**65%**  
Less Time  
Grading



Laptop: McGraw-Hill; Woman/dog: George Doyle/Getty Images

### They'll thank you for it.

Adaptive study resources like SmartBook<sup>®</sup> 2.0 help your students be better prepared in less time. You can transform your class time from dull definitions to dynamic debates. Find out more about the powerful personalized learning experience available in SmartBook 2.0 at [www.mheducation.com/highered/connect/smartbook](http://www.mheducation.com/highered/connect/smartbook)

### Make it simple, make it affordable.



Connect makes it easy with seamless integration using any of the major Learning Management Systems—Blackboard<sup>®</sup>, Canvas, and D2L, among others—to let you organize your course in one convenient location. Give your students access to digital materials at a discount with our inclusive access program. Ask your McGraw-Hill representative for more information.

Padlock: Jobalou/Getty Images

### Solutions for your challenges.



A product isn't a solution. Real solutions are affordable, reliable, and come with training and ongoing support when you need it and how you want it. Our Customer Experience Group can also help you troubleshoot tech problems—although Connect's 99% uptime means you might not need to call them. See for yourself at [status.mheducation.com](http://status.mheducation.com)

Checkmark: Jobalou/Getty Images

**SUPPORT** <sup>AT</sup>  
*every step*

## FOR STUDENTS

### Effective, efficient studying.

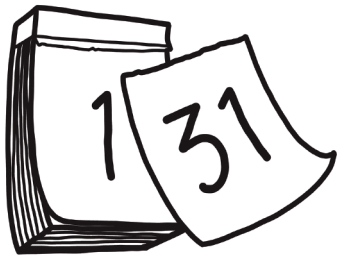
Connect helps you be more productive with your study time and get better grades using tools like SmartBook 2.0, which highlights key concepts and creates a personalized study plan. Connect sets you up for success, so you walk into class with confidence and walk out with better grades.

### Study anytime, anywhere.

Download the free ReadAnywhere app and access your online eBook or SmartBook 2.0 assignments when it's convenient, even if you're offline. And since the app automatically syncs with your eBook and SmartBook 2.0 assignments in Connect, all of your work is available every time you open it. Find out more at [www.mheducation.com/readanywhere](http://www.mheducation.com/readanywhere)

*"I really liked this app—it made it easy to study when you don't have your textbook in front of you."*

- Jordan Cunningham,  
Eastern Washington University



Calendar: owattaphotos/Getty Images

### No surprises.

The Connect Calendar and Reports tools keep you on track with the work you need to get done and your assignment scores. Life gets busy; Connect tools help you keep learning through it all.

### Learning for everyone.

McGraw-Hill works directly with Accessibility Services Departments and faculty to meet the learning needs of all students. Please contact your Accessibility Services office and ask them to email [accessibility@mheducation.com](mailto:accessibility@mheducation.com), or visit [www.mheducation.com/about/accessibility](http://www.mheducation.com/about/accessibility) for more information.

Top: Jenner Images/Getty Images, Left: Hero Images/Getty Images, Right: Hero Images/Getty Images



## ACKNOWLEDGEMENTS

This text *Exercise Physiology: Theory and Application to Fitness and Performance* is not the effort of only three 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.

Moreover, we would like to thank Luke Alford, Matthew Bomkamp, Kathryn Christison, Shae Gurney, Alfeil A. Felipe, Zoha Irfan, Daniel Khokhar, Yassine Lahlou, Ravinkumar Masheshkumar, Saif A. Memon, Nikhil N. Patel, Francesca Ratovich, Nicholas J. Swartz, Brian C. Tran, and Cassie Williamson-Reisdorph for their assistance in providing suggestions for revisions to this book. Indeed, these individuals provided numerous contributions to the improvement of the eleventh edition of this book. Finally, we would like to thank the following reviewers who provided

helpful comments about the previous editions of *Exercise Physiology: Theory and Application to Fitness and Performance*:

**Brett Bruininks**  
University of St. Thomas

**Dan Carl**  
University of Cincinnati

**Feng He**  
California State University, Chico

**Kathryn Rosie Lanphere**  
University of Kentucky

**Brittanie Lockard**  
University of the Incarnate Word

**Ayanna Lyles**  
California University of Pennsylvania

**Rich Morris**  
Rollins College



# 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 (63). 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, 63-64). 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 (6, 60). Importantly, regular exercise may also reduce the mental depression associated with MS (66, 67). Although some questions remain regarding the amount and types of exercise that provide optimum benefits to MS patients (1), a growing number of studies recommend 2 to 3 days/week of endurance exercise training (10-30 minutes) of moderate intensity exercised and 2 to 3 days/week of resistance training (1-3 sets of 8-15 repetitions). See Kim et al. (2019) along with Mott et al. (2017) in the Suggested Readings list for details.

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 axon 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 almost always 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 enter the cell, and potassium would leave the cell. As you see, almost all the sodium channels are closed, whereas a few potassium channels are open, resulting in a net positive charge on the outside surface of the membrane and a net negative charge on the inside surface of the membrane.

**156** Section One Physiology of Exercise

### 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 (6, 7, 11, 26, 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., 800-1200 VO<sub>2</sub> 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 25 (3). Further, laboratory studies employing repeated bouts of high-intensity exercise (i.e., >100% VO<sub>2</sub> max) have reported that ingestion of sodium bicarbonate prior to exercise can enhance performance by more than 18 (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 also improves physical performance by increasing the extracellular buffering capacity, which, in turn, increases the transport of hydrogen ions out of the muscle fibers (18). 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 inconclusive. 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., 0.35 g/kg body weight) improves performance during high-intensity cycling exercise lasting 120 to 240 seconds (16).

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) (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 (2-3 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 18 to 58 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 reported performance improvements of 12% to 14% in untrained subjects supplemented with beta-alanine (18, 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 future of beta-alanine supplementation to improve performance

(Continued)

**282** Section One Physiology of Exercise

## 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.

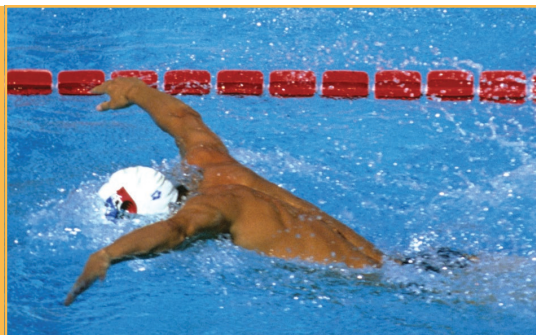
A photograph of four swimmers in a pool, captured in the middle of a butterfly stroke. They are moving from left to right across the frame. The water is a vibrant blue, and there are splashes around each swimmer. Lane lines are visible, with red lines separating the lanes and white and blue lines at the top and bottom. The swimmers are in various stages of their stroke, with arms extended forward and heads above water. The overall scene is dynamic and energetic.

# SECTION 1

## Physiology of Exercise

Mike Hewitt/Action Plus Sports Images/Alamy Stock Photo

# O



Mike Hewitt/Action Plus Sports Images/Alamy Stock Photo

## 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

Milestones in the Evolution of Exercise Physiology	3
Milestones in Exercise Physiology—the Early Years (1900–1950)	3
Milestones in Exercise Physiology—Second Half of the Twentieth Century (1951–2000)	5
Milestones in Exercise Physiology Research—2001 to Present	7
Exercise Physiology Research: The Path to New Knowledge	10
The Scientific Method	10
Classes of Research Designs	11
Field and Laboratory Research	12

Basic and Applied Research	12
Reading and Understanding Scientific Journals	13
Searching the Scientific Literature	14
Components of a Scientific Research Report	16
How to Critically Evaluate the Quality of a Research Study	17
Exercise Physiology/Sports Science Professional Organizations	19
Certification by Professional Organizations	19
Careers in Exercise Physiology and Related Fields	20

### ■ 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).

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



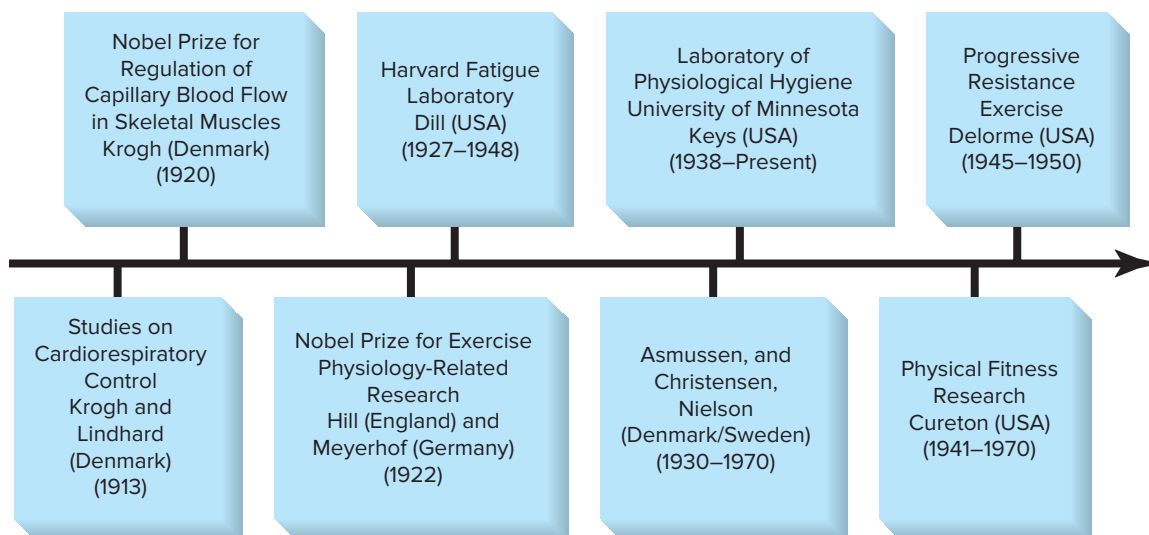


Figure 0.1 Selected historical milestones in exercise physiology that occurred during 1900-1950. See text for details.

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 soldiers 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 long-time 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 injuries. Much of Delorme’s work was published between 1948 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

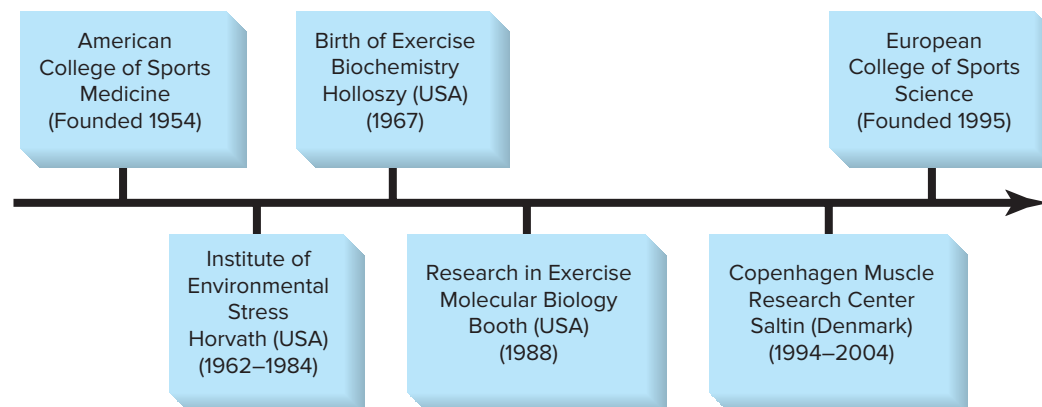


Figure 0.2 Selected historical milestones in exercise physiology that occurred during 1951–2000. See text for details.

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*).

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.

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



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



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

Dr. Frank Booth

tools of molecular biology to address important questions related to exercise-induced changes in tissues.

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 Copenhagen, 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.

- 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.

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.

#### 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.

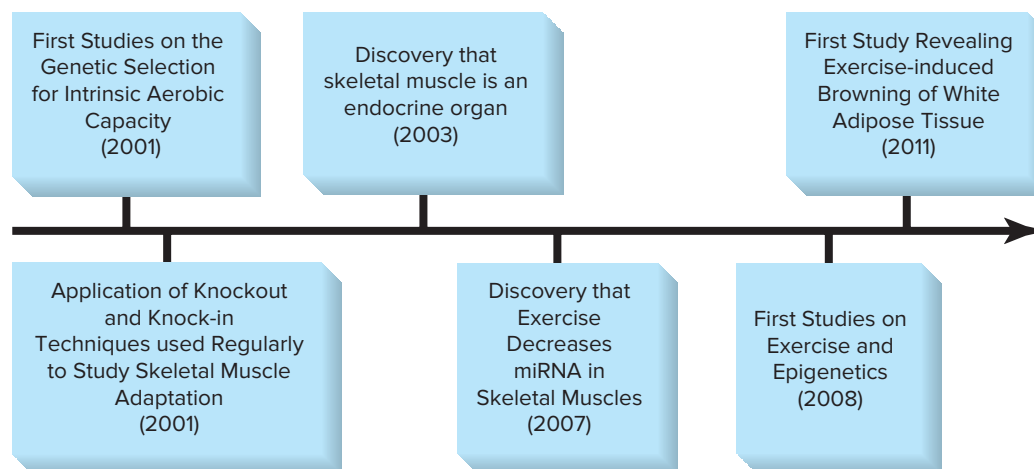


Figure 0.5 Selected historical milestones in exercise physiology that occurred from 2001 to the present time. See text for details.

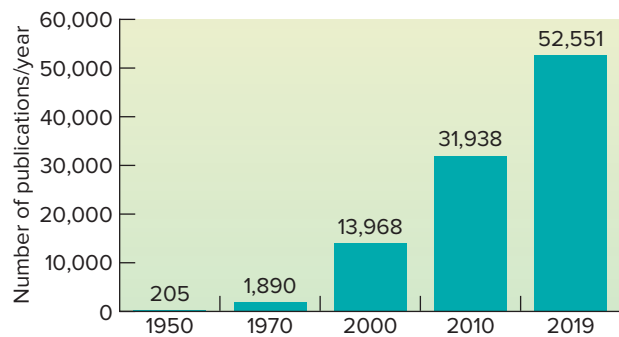


Figure 0.6 Illustration of the growth of scientific publications in exercise physiology from 1950 to 2019.

**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 (CH<sub>3</sub>) 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.



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

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.