
BIOMECHANICS AND BIOLOGY OF MOVEMENT

BENNO M. NIGG
BRIAN R. MACINTOSH
JOACHIM MESTER

EDITORS

Biomechanics and Biology of Movement

Benno M. Nigg, PhD

Director, Human Performance Laboratory
University of Calgary

Brian R. MacIntosh, PhD

Professor, Faculty of Kinesiology
University of Calgary

Joachim Mester, PhD

Director, Institute of Training and Movement
German Sport University

Editors



Human Kinetics

Library of Congress Cataloging-in-Publication Data

Biomechanics and biology of movement / [edited by] Benno M. Nigg, Brian R. MacIntosh, Joachim Mester.

p. cm.

Includes bibliographical references and index.

ISBN 0-7360-0331-2

1. Human mechanics. 2. Human locomotion. 3. Exercise--Physiological aspects. 4. Energy metabolism. I. Nigg, Benno Maurus. II. MacIntosh, Brian R., 1952- III. Mester, J. (Joachim)

QP303 .B56836 2000

612.7'6--dc21

99-059795

ISBN-10: 0-7360-0331-2

ISBN-13: 978-0-7360-0331-5

Copyright © 2000 by Benno M. Nigg, Brian R. MacIntosh, and Joachim Mester

All rights reserved. Except for use in a review, the reproduction or utilization of this work in any form or by any electronic, mechanical, or other means, now known or hereafter invented, including xerography, photocopying, and recording, and in any information storage and retrieval system, is forbidden without the written permission of the publisher.

Acquisitions Editor: Loarn D. Robertson, PhD; **Managing Editor:** Cynthia McEntire; **Assistant Editor:** John Wentworth; **Copyeditor:** Judy Peterson; **Proofreader:** Pamela S. Johnson; **Indexer:** Marie Rizzo; **Permission Manager:** Cheri Banks; **Graphic Designer:** Nancy Rasmus; **Graphic Artist:** Kathleen Boudreau-Fuoss; **Cover Designer:** Jack W. Davis; **Printer:** Sheridan Books

Printed in the United States of America

10 9 8 7 6 5 4 3 2

Human Kinetics

Web site: www.HumanKinetics.com

United States: Human Kinetics

P.O. Box 5076

Champaign, IL 61825-5076

800-747-4457

e-mail: humank@hkusa.com

Canada: Human Kinetics

475 Devonshire Road Unit 100

Windsor, ON N8Y 2L5

800-465-7301 (in Canada only)

e-mail: orders@hkcanada.com

Europe: Human Kinetics

107 Bradford Road

Stanningley

Leeds LS28 6AT, United Kingdom

+44 (0) 113 255 5665

e-mail: hk@hkeurope.com

Australia: Human Kinetics

57A Price Avenue

Lower Mitcham, South Australia 5062

08 8372 0999

e-mail: liaw@hkaustralia.com

New Zealand: Human Kinetics

Division of Sports Distributors NZ Ltd.

P.O. Box 300 226 Albany

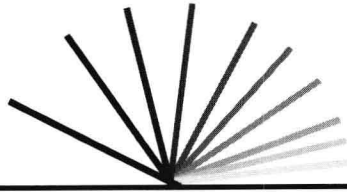
North Shore City

Auckland

0064 9 448 1207

e-mail: info@humankinetics.co.nz

Biomechanics and Biology of Movement



Contributors

Adams, Douglas J.

Department of Orthopaedic Surgery
University of Connecticut Health Center
Farmington, CT

Alexander, R. McNeill

University of Leeds
Department of Pure and Applied Biology
Leeds, England

Allen, David G.

Department of Physiology
University of Sydney
Sydney, New South Wales, Australia

Alt, Wilfried

Sportmedizinisches Institut
Frankfurt am Main, Germany

Anderson, Donald D.

Biomechanics Laboratory
Minneapolis Sports Medicine Center
Minneapolis, MN

Bobet, Jacques

Assistant Professor, Physical Therapy
University of Alberta
Edmonton, AB, Canada

Denoth, Jachen

Laboratorium für Biomechanik
ETH Zurich
Schlieren, Switzerland

Fischer, Kenneth J.

Musculoskeletal Research Center
University of Pittsburgh
Pittsburgh, PA

Gollhofer, Albert

Universität Stuttgart
Institut für Sport und Sportwissenschaft
Stuttgart, Germany

Hale, Joseph E.

Biomechanics Laboratory
Minneapolis Sports Medicine Center
Minneapolis, MN

Hay, James G.

Department of Sport and Exercise Science
University of Auckland
Auckland, New Zealand

Herzog, Walter

Faculty of Kinesiology
University of Calgary
Calgary, AB, Canada

Holash, R. John

Faculty of Kinesiology
University of Calgary
Calgary, AB, Canada

Hoppeler, Hans

University of Bern
Bern, Switzerland

Komi, Paavo V.

Kinesiology Laboratory
Department of Biology of Physical Activities
University of Jyväskylä
Jyväskylä, Finland

Lemon, Peter W.R.

3M Centre
University of Western Ontario
London, ON, Canada

Lohrer, H.

Orthopädische Abteilung im Sportmedizinischen Institut
Frankfurt am Main, Germany

MacIntosh, Brian R.

Faculty of Kinesiology
University of Calgary
Calgary, AB, Canada

Mester, Joachim

Institute of Training and Movement
German Sport University
Cologne, Germany

Mikulcik, Edwin C.

Department of Mechanical Engineering
University of Calgary
Calgary, AB, Canada

Minetti, Alberto E.
Biomechanics Research Group
Department of Exercise and Sport Science
Crewe + Alsager Faculty
Manchester Metropolitan University
Hassall Road, Alsager, United Kingdom

Neptune, Richard R.
Rehabilitation R & D Center (153)
VA Palo Alto Health Care System
Palo Alto, CA

Nicol, Caroline A.
Université Aix-Marseille II
Marseille Cedex, France

Nigg, Benno M.
Faculty of Kinesiology
University of Calgary
Calgary, AB, Canada

Orizio, Claudio
Department of Biomedical Sciences and Biotechnologies
Institute of Human Physiology
University of Brescia
Brescia, Italy

Stefanyshyn, Darren J.
Faculty of Kinesiology
University of Calgary
Calgary, AB, Canada

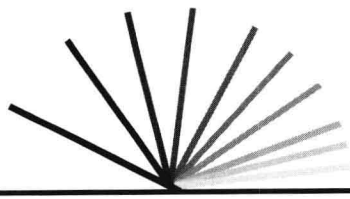
Stein, Richard
Department of Physiology
University of Alberta
Edmonton, AB, Canada

van den Bogert, Anthony J.
Department of Biomedical Engineering
Lerner Research Institute
Cleveland Clinic Foundation
Cleveland, OH

Weibel, Ewald R.
Anatomisches Institut der Universität Bern
Bern, Switzerland

Yeadon, Maurice R.
Department of Sports Science
Loughborough University
Loughborough, United Kingdom

Zehr, E. Paul
Faculty of Physical Education and Recreation
University of Alberta
Edmonton, AB, Canada



Introduction

B.M. Nigg, B.R. MacIntosh, and J. Mester

The life of an average member of civilized society has changed substantially over the last two centuries. About 100 to 200 years ago, most daily activities were associated with movement and physical activity. Today, at the beginning of the third millennium, most professional occupations are sedentary. Most people in the developed countries have minimal daily physical activity, and computers and television dominate the lives of many members of today's society. Most people have a substantial amount of leisure time available. Some use it for physical activities. They enjoy the outdoors or are engaged in daily workout routines. However, the majority of people in the developed countries are not physically fit. Many people are overweight and have only limited mobility. With the increasing life expectancy afforded by health care, mobility and longevity have become some of the most precious aspects of life. Thus, human movement, exercise, and sport have developed in the 20th century into important lifestyle options.

Parallel to this development, science that deals with human movement, exercise, and sport has become increasingly important. The number of scientists from many different disciplines concentrating on researching movement, exercise, and sport is still increasing. These scientists attempt to understand (a) the functioning of the human body as it relates to movement, exercise, and sport, (b) biological responses to force stimuli, (c) how to prolong mobility for all age groups, and (d) how to improve performance, whether in sport, in the work place, or during a walk. They work together to solve these important questions, which are relevant for the well-being of humankind.

Scientific disciplines dealing with human movement, exercise, and sport include anatomy, biochemistry, biomechanics, neurosciences, and physiology. Textbooks dealing with aspects of movement, exercise, and sport typically discuss discipline-related aspects. Titles such as *The Biomechanics of Sports Techniques* (Hay 1978), *The Physiology of Joints* (Kapandji 1970), *Functional Anatomy in Sports* (Weineck 1986), or *Biomechanics of Sports* (Vaughan 1989) are typical examples of such publications.

They are discipline driven and lack approaches where the multidisciplinary question of interest drives the method(s) of inquiry. However, human life is not discipline oriented. Human life is exposed daily to practical questions, which ask for an answer. Topics that are important for movement, exercise, and sport include work and energy, balance and control of human movement, load and excessive load during movement and exercise, and fatigue during exercise.

Work and energy aspects are important for an athlete running a marathon, a soccer player participating in a three-week tournament, a mountaineer who wants to climb Mount Everest, or a speed skater attempting to break a world record. Additionally, work and energy questions are important for nonathletes interested in healthy nutrition as well as for people who want to maintain their health and achieve an adequate body weight. Furthermore, work and energy are equally important for a person with an artificial leg (e.g., a below-the-knee amputee) or an elderly person who wants to play her or his daily round of golf or to walk to maintain physical fitness. Work and energy questions are relevant to all sectors of the human population.

Balance and control of movement are important for many sport activities such as balance beam exercises in gymnastics, shooting, somersaulting and twisting in trampolining, and activities on the trapeze. However, balance and control are equally important for children as they learn to move correctly and control their movements and for elderly people who may experience impaired control. Impaired mobility can result in exclusion from a large segment of life activities and people so affected will experience a decrease in the quality of life.

Excessive load during sport and exercise is specifically important for competitive sport activities. Injuries resulting from excessive repetitive forces are speculated to be the cause of early arthritis and disability. Therefore, it is important to understand the factors contributing to excessive loading and the strategies that can be used to avoid inappropriate

loading situations. Furthermore, it is important to understand when a load on the musculoskeletal system is beneficial and contributes to the development of strong and healthy biological structures.

Fatigue is a consequence of repeated use of muscles or other tissues and limits the duration a given activity can be performed. Fatigue may be the limiting factor, which when minimized permits winning or when evident results in losing a competition. Fatigue may impair mobility or general physical capability during daily activities. Furthermore, fatigue may be a contributing factor to the development of acute or chronic injuries. The ability to assess the presence and magnitude of fatigue becomes an important objective in the quest to understand the circumstances and consequences associated with muscle fatigue. Fatigue is also important in the work place and in daily leisure activities. If fatigue can be reduced, work performance may improve or leisure activities may become more enjoyable.

These questions and problems cannot be solved with the methods and approaches of only one scientific discipline. To understand the effects of excessive load, for instance, one needs contributions from biomechanics, biochemistry, and neuroscience. Answering questions related to fatigue requires contributions from physiology, biochemistry, neuroscience, and muscle mechanics. Balance and control questions can be answered only with contributions from neuroscience, biomechanics, anatomy, and physiology. Work and energy questions require contributions from physiology, biochemistry, biomechanics, and thermomechanics. Consequently, when studying movement, exercise, and sport-related questions one should attempt to understand the many facets contributing to the question and synthesize them into a comprehensive analysis.

The editors of this book identified the primary biological and physical knowledge associated with work and energy, balance and motor control, load and excessive load, and fatigue. The editors defined the important components for each topic and invited world-renowned experts in these areas to contribute from their viewpoint and wealth of understanding to the identified topic. Thus, the different sections of this book attempt to discuss important questions using input from the many disciplines of movement, exercise, and sport sciences that belong to the physical and biological sciences. The authors of the various chapters are experts in their fields. To integrate the presented knowledge, the editors added a synthesis to each

topic. The contributions were organized in the form of a concise and comprehensive textbook in the hope that this text may provide a new approach to the exciting field of movement, exercise, and sport sciences.

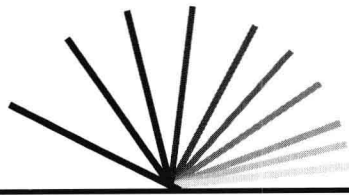
The book is aimed at students and professionals working in kinesiology (e.g., biomechanics, physiology, physiotherapy, athletic therapy, and ergonomics). Readers who already have a basic knowledge of biology, physiology, and biomechanics will obtain the greatest benefits from the use of this text. Thus, the book is expected to be used for advanced undergraduate or early graduate level courses. Furthermore, the book will be a useful resource for research-oriented undergraduate and graduate students.

Each part starts with selected historical highlights for the interested reader. However, the book can be used without reading these historical highlights. This initial section is followed by basic and applied discussions of the topic of interest, followed by a synthesis of the discussed topic. Each part ends with a summary and a list of the most important definitions used. The reader is not expected to read through these definitions. They are collected to provide the reader a place to quickly find definitions if needed. Furthermore, the reader of this book is not required to use all the chapters. It is possible to choose a selection of contributions to a given topic and to make this selection based on the basic knowledge and the specific interest of the reader or student.

Over the last two decades the quality of students in kinesiology and the exercise sciences has improved substantially. Their expertise in biological and mechanical methods has vastly improved. In many universities, students in kinesiology and exercise sciences are among those with the highest entrance averages of all university faculties. The field of kinesiology is expanding and proves to be attractive for many brilliant young students and scientists. A strong indication for this development in kinesiology and the general field of exercise sciences is the establishment of the IOC Olympic Prize, a research award of \$500,000 (U.S.) given for excellence in research on movement, exercise, and sport. It illustrates that intellectual leaders of human society are convinced that science dealing with movement, exercise, and sport is extremely important and should be recognized. This book takes this phenomenon into account. The concepts are presented in a relatively simple way. However, readers will be challenged with the intellectual depth achieved in each section of the text.

References

- Hay, J.G. 1978. *The Biomechanics of Sports Techniques*. Englewood Cliffs, NJ: Prentice Hall.
- Kapandji, I.A. 1970. *The Physiology of the Joints*. Edinburgh: Churchill Livingstone.
- Vaughan, C.L. 1989. *Biomechanics of Sports*. Boca Raton, FL: CRC Press.
- Weineck, J. 1986. *Functional Anatomy in Sports*. Chicago: Year Book Medical.



Contents

Contributors	xiii
Introduction	xv
B.M. Nigg, B.R. MacIntosh, and J. Mester	
Part I Work and Energy	
	Work and Energy Historical Highlights 3
Chapter 1	Mechanical Considerations of Work and Energy 5
B.M. Nigg, D. Stefanyshyn, and J. Denoth	
	The Concept of Mechanical Work and Energy 5
	Mechanical Work 6
	Mechanical Energy 8
	Calculation of Mechanical Energy During Human Movement 8
	The Laws of Conservation of Energy 11
	Conservation of Energy 12
	Summary 17
	References 17
Chapter 2	Storage and Release of Elastic Energy in the Locomotor System and the Stretch-Shortening Cycle 19
R.McN. Alexander	
	Principles of Elasticity 19
	The Properties of Body Parts 20
	Springs Functioning as Catapults 25
	Springs Saving Energy 27
	Springs Cushioning Impacts 28
	Conclusion 28
	References 28
Chapter 3	Length Changes of Muscle-Tendon Units During Athletic Movements 31
J.G. Hay	
	Elaboration of the Concepts 31

	Long Jump	32
	Volleyball Block	38
	Sprinting	39
	Cycling	42
	Summary and Potential Applications	44
	References	46
Chapter 4	Work and Energy Influenced by Athletic Equipment	49
	D.J. Stefanyshyn and B.M. Nigg	
	Energy Return	49
	Minimizing the Loss of Energy	54
	Additional Situations With an Unnecessary Loss of Energy	62
	Situations Where a Loss of Energy is Advantageous	63
	Summary	63
	References	63
Chapter 5	The Three Modes of Terrestrial Locomotion	67
	A.E. Minetti	
	Mechanics and Energetics of Locomotion	67
	Slow Speed: Walking and Brachiation	69
	Intermediate Speed: Running, Trotting, and Hopping	72
	High Speed: Galloping and Skipping	73
	Gait Transition	76
	Gradient Locomotion	76
	Different Gravity Conditions	77
	Summary and Potential Applications	77
	References	78
Chapter 6	The Pathways for Oxygen and Substrates	79
	H. Hoppeler and E.R. Weibel	
	The Primary Concepts	79
	Historical Highlights	80
	Model of the Respiratory System	80
	Muscle Mitochondria Set the Demand for Oxygen	85
	Supply of Substrates From Cellular Stores to Mitochondria	89
	Microcirculatory Supply of Oxygen and Substrates	91
	Convective Transport of Oxygen and Substrates by the Heart	94
	Oxygen Diffusion in the Lung	95
	Conclusions	98
	References	98
Chapter 7	Energy and Nutrient Intake for Athletic Performance	103
	P.W.R. Lemon	
	Food Energy	104
	Carbohydrate	105

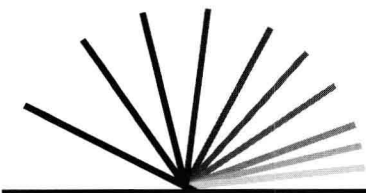
	Fat	108
	Protein	110
	Water	115
	Minerals	117
	Vitamins	121
	Summary and Potential Applications	122
	References	123
Chapter 8	Intensity of Cycling and Cycle Ergometry: Power Output and Energy Cost	129
	B.R. MacIntosh, R.R. Neptune, and A.J. van den Bogert	
	Primary Concepts	129
	Ergometer Cycling	131
	Road Cycling	132
	Kinematic Methods	134
	Kinetic Methods	134
	Indirect Calorimetry	138
	Steady State Energetics	139
	Determinants of Steady State Energy Cost of Cycle Ergometry	140
	Slow Component of Oxygen Uptake	142
	Supramaximal Energy Use, Anaerobic Metabolism	144
	Measurement of the Energy Cost of Cycling	144
	Summary	145
	References	146
	Work and Energy Summary	149
	Work and Energy Definitions	155
Part II	Balance and Control of Movement	
	Balance and Control of Movement Historical Highlights	161
Chapter 9	Basic Concepts of Movement Control	163
	R. Stein, E.P. Zehr, and J. Bobet	
	Review of Control Theory	163
	Feedforward (Muscle) Control	164
	Isometric Contractions	164
	Force-Length Curve	166
	Force-Velocity Curve	167
	Feedback (Reflex) Control	169
	Stretch Reflexes and Servo-Control	170
	Servo-Assistance and Fusimotor Set	171
	Inhibitory Modulation	171
	Golgi Tendon Organs	172
	Cutaneous Receptors	172

	Central Control of Locomotion	174
	References	176
Chapter 10	Muscle Activation and Movement Control	179
	W. Herzog	
	Muscle Activation	179
	Movement Control: Experimental Considerations	181
	Movement Control: Theoretical Considerations	185
	Applications to Sport Science	187
	Final Comments	191
	References	191
Chapter 11	Power Output and Force-Velocity Properties of Muscle	193
	B.R. MacIntosh and R.J. Holash	
	The Primary Concepts	193
	Shape of the Force- and Power-Velocity Relationships	194
	Muscle Architecture and the Force-Velocity Relationship	197
	Ways of Studying Force-Velocity Properties	200
	Factors Affecting the Force- and Power-Velocity Relationships	202
	A Model of Force-Velocity Properties for Mixed Fiber Types	204
	Functional Implications of the Force-Velocity Properties of Muscle	207
	Concluding Remarks	208
	References	208
Chapter 12	Stability and Control of Aerial Movements	211
	M.R. Yeadon and E.C. Mikulcik	
	Statement of the Problem	211
	Primary Concepts	212
	Elaboration of Concepts	212
	Film Analysis	217
	Summary and Potential Applications	220
	References	221
Chapter 13	Movement Control and Balance in Earthbound Movements	223
	J. Mester	
	Statement of the Problem	223
	The Primary Concepts	223
	Elaboration of Concepts	224
	Bottom-Up Regulation: Building Up Posture and Balance Against Gravity	226
	Top-Down Regulation: Central Input and Supervision	228
	Control and Balance of Directional Earthbound Movements	229
	Balance in Standing Upright Under High External Forces	233
	Balance in Sitting Under Low External Forces	235
	Movement Control Under Time Pressure	236

Summary and Potential Applications	238
References	238
Balance and Control of Movement Summary	241
Balance and Control of Movement Definitions	245
Part III Load During Physical Activity	
Load During Physical Activity Historical Highlights	249
Chapter 14 Forces Acting on and in the Human Body	253
B.M. Nigg	
Definitions and General Comments	253
The Force System Analysis	261
Order of Magnitude of Forces	265
Summary	266
References	266
Chapter 15 Force Production in Human Skeletal Muscle	269
W. Herzog	
Structure and Morphology of Skeletal Muscle	269
Gross Structure of Skeletal Muscle	272
Excitation-Contraction Coupling	272
The Cross-Bridge Theory	273
Muscle Force	275
History Dependence of Force Production	280
Final Comments	280
References	281
Chapter 16 Mechanical Effects of Forces Acting on Bone, Cartilage, Ligaments, and Tendons	283
D.D. Anderson, D.J. Adams, and J.E. Hale	
The Primary Concepts	283
Characterizing Mechanical Properties	284
Hierarchy: A Composite Structural Theme in Musculoskeletal Tissues	288
Summary and Potential Applications	302
References	303
Chapter 17 Biological Response to Forces Acting in the Locomotor System	307
K.J. Fischer	
Statement of the Problem	307
The Primary Concepts	308
Bone Adaptation	308
Articular Cartilage Adaptation	313
Tendon Adaptation	317

	Ligament Adaptation	320
	Summary and Potential Applications	324
	References	324
Chapter 18	Prevention of Excessive Forces With Braces and Orthotics	331
	A. Gollhofer, W. Alt, and H. Lohrer	
	The Primary Concepts	331
	The Ankle Joint	331
	The Knee Joint	339
	Further Bracing Applications	344
	Summary and Potential Application	344
	Conclusions	345
	References	345
	Load During Physical Activity Summary	351
	Load During Physical Activity Definitions	355
Part IV	Fatigue and Exercise	
	Fatigue and Exercise Historical Highlights	363
Chapter 19	Contractile Changes and Mechanisms of Muscle Fatigue	365
	B.R. MacIntosh and D.G. Allen	
	Primary Concepts	365
	Ways of Studying Fatigue	366
	Contractile Consequences Associated With Fatigue	368
	Cellular Mechanisms of Muscle Fatigue	372
	Summary	378
	References	378
Chapter 20	Stretch-Shortening Cycle Fatigue	385
	P.V. Komi and C. Nicol	
	Muscle Fatigue During Isolated Eccentric Actions	386
	Eccentrically Induced Muscle Damage and Soreness	387
	Specific Functional Effects of Fatiguing SSC Exercises	392
	Concluding Hypothesis	403
	References	404
Chapter 21	Muscle Fatigue Monitored by Force, Surface Mechanomyogram, and EMG	409
	C. Orizio	
	Fatigue: Local Muscle Fiber Changes and Muscle Motor Control Alterations	410

Changes in Muscle Mechanical and Electrical Signals	414
Applications	427
Concluding Remarks	428
References	428
Fatigue and Exercise Summary	435
Fatigue and Exercise Definitions	439
Name Index	441
Subject Index	451
About the Editors	467



PART I

Work and Energy