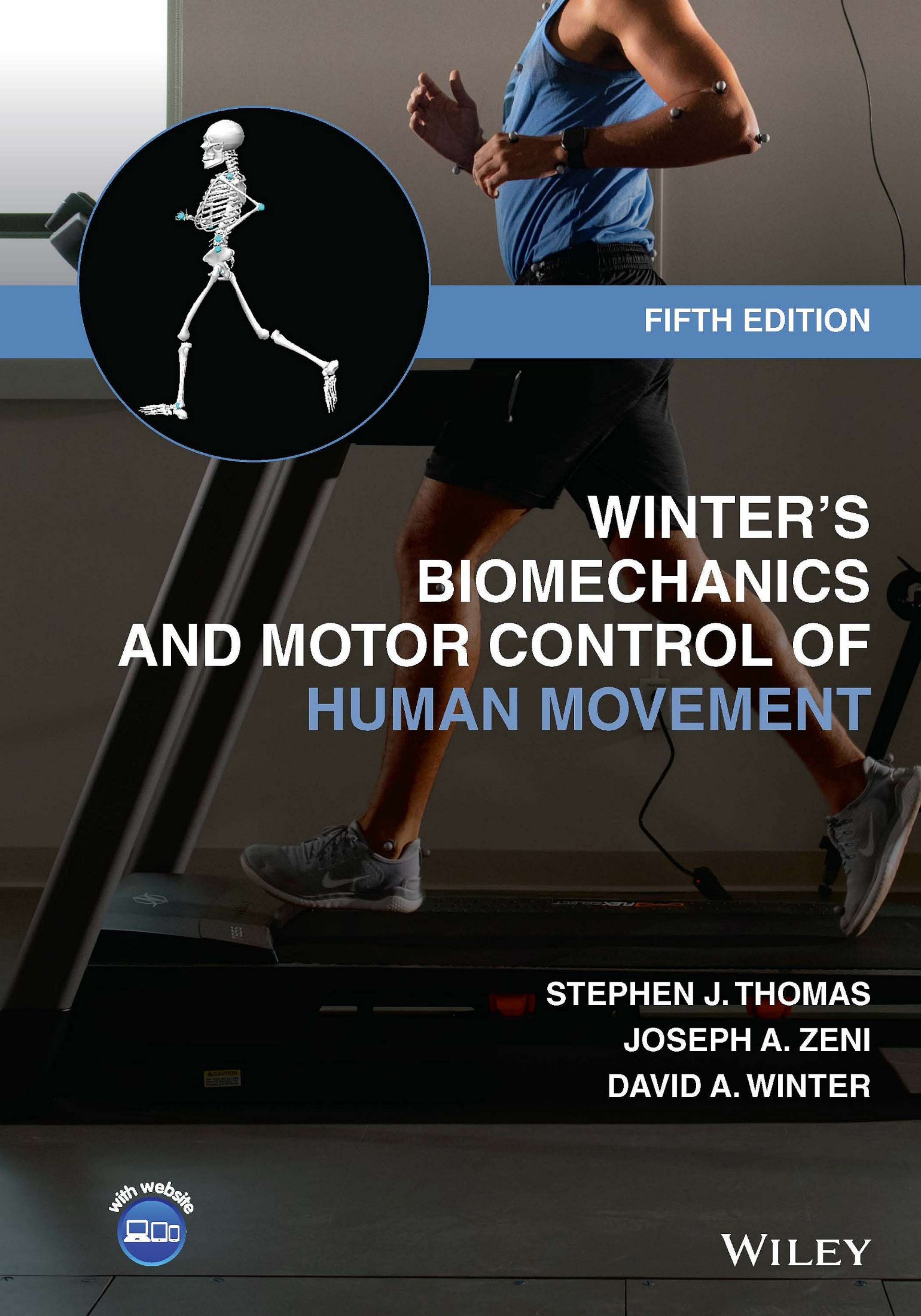

FIFTH EDITION

WINTER'S BIOMECHANICS AND MOTOR CONTROL OF HUMAN MOVEMENT

STEPHEN J. THOMAS
JOSEPH A. ZENI
DAVID A. WINTER

with website

WILEY

WINTER'S BIOMECHANICS AND MOTOR CONTROL OF HUMAN MOVEMENT

WINTER'S BIOMECHANICS AND MOTOR CONTROL OF HUMAN MOVEMENT

Fifth Edition

STEPHEN J. THOMAS
Thomas Jefferson University, Philadelphia, PA, USA

JOSEPH A. ZENI
Rutgers University, Newark, NJ, USA

DAVID A. WINTER (DECEASED)
University of Waterloo, Waterloo, Ontario, Canada

WILEY

This fifth edition first published 2023

Edition History
John Wiley & Sons (1e, 1980, 2e, 1990, 3e, 2004, 4e, 2009)

Registered Office
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data
Names: Thomas, Stephen J., 1980- author. | Zeni, Joseph A., 1979– author. | Winter, David A., 1930-2012, author. | Winter, David A., 1930-2012. Biomechanics and motor control of human movement.
Title: Winter's biomechanics and motor control of human movement / Stephen J. Thomas (Thomas Jefferson University), Joseph A. Zeni (Rutgers University), David A. Winter (Waterloo, Ontario, Canada).
Other titles: Biomechanics and motor control of human movement
Description: Fifth edition. | Hoboken, NJ : Wiley, 2023. | Includes bibliographical references and index.
Identifiers: LCCN 2022019974 (print) | LCCN 2022019975 (ebook) | ISBN 9781119827023 (cloth) | ISBN 9781119827030 (pdf) | ISBN 9781119827047 (epub)
Subjects: LCSH: Human mechanics. | Motor ability. | Kinesiology.
Classification: LCC QP303 .T46 2023 (print) | LCC QP303 (ebook) | DDC 612.7/6–dc23/eng/20220720
LC record available at https://lccn.loc.gov/2022019974
LC ebook record available at https://lccn.loc.gov/2022019975

Cover Image: © John Emerson
Cover Design: Wiley

Set in 10.75/12pt Times by Straive, Pondicherry, India.

DEDICATION

We would like to dedicate this edition to David A. Winter and his family. To those inside the field of biomechanics, David Winter needs no introduction. He is often described as the founding father of modern biomechanics and rightfully so. His education was in the field of electrical engineering and he went on to become a Fellow of the Institute of Electrical and Electronics Engineers. However, his education, training, and service were not constrained to electrical engineering. He served in professorship roles in biomedical engineering, surgery, and kinesiology. He was a founding member of the Canadian Society for Biomechanics and later, became the first recipient of the Career Investigators Award by the same society. He received the Lifetime Achievement Award by the Gait and Clinical Movement Analysis Society, as well as the Muybridge Medal by the International Society of Biomechanics, which is the society's most prestigious honor. He solely authored four previous editions of this textbook, which is considered the seminal technical biomechanics textbook and is still readily used by professionals in biomechanics, engineering, kinesiology, rehabilitation sciences, and many other related fields. He also authored three additional textbooks and over 100 peer-reviewed research publications. He finished his career as a Distinguished Professor Emeritus in Kinesiology at the University of Waterloo.

His accomplishments in the field of biomechanics demonstrate his drive and passion for his profession. However, his passion and love for his family never took a backseat to his career. We were very fortunate to meet and speak with his three children Merriam, Andrew, and Bruce. The stories they shared about their father made clear that he was a constant and loving presence in their lives. The Winter family always ate dinner together, which served as a roundtable for insightful and thought-provoking conversations about the things the children were currently involved in at school and life. His children revealed that their father never missed an event or activity in their busy lives. His daughter Merriam shared a memory of her father from when she was six years old. When she happened upon her father working in the basement, she asked "What are you doing, dad?" He responded "Making wood!" What he really was doing was building a life-size playhouse for the backyard that included a porch, flower boxes in the windows, benches, a table, and all painted green and pink. She also shared her memories about how David Winter built the family a cottage on the outskirts of Halifax from scratch. His son Bruce shared stories of visiting his father in his gait lab when he was attending college and being able to see David Winter's passion for teaching students and working with patients. David Winter poured his devotion to teaching his students, and Bruce shared that these students became part of the family and would often join the family dinner at their house. These heartwarming stories demonstrate that it is possible to achieve so much in your career, while still putting your family in the forefront. This is an important lesson to anyone in academia or industry, vocations which continually compete for our precious time.

In speaking with David Winter's family, a key lesson became clear; the foundation for a successful life and career is to do what you love, while supporting those around you; whether that be your patients, students, colleagues, or most importantly, your family and friends. We would like to thank his children and grandchildren for sharing their dad and grandfather with all of us, in the field of biomechanics, as we are all better because of him.

Stephen J. Thomas, PhD, ATC
Joseph A. Zeni, PhD, PT

CONTENTS

APPENDICES

LIST OF CONTRIBUTORS

Garrett S. Bullock, PT, DPT, DPhil, Instructor, Department of Orthopaedic Surgery, Wake Forest School of Medicine, Winston-Salem, NC, USA

Christopher J. Burcal, PhD, ATC, Assistant Professor, School of Health and Kinesiology, University of Nebraska at Omaha, Omaha, NE, USA

Thomas Hulcher, M.S., Biomechanist, Department of Physical Therapy, Jefferson College of Rehabilitation Science, Thomas Jefferson University, Philadelphia, PA, USA

Namwoong Kim, PhD, Research Associate, Division of Health & Kinesiology, Incheon National University, Incheon, Republic of Korea

Brian A. Knarr, PhD, Associate Professor, Department of Biomechanics, College of Education, Health, and Human Sciences, University of Nebraska at Omaha, Omaha, NE, USA

Amy L. Lenz, PhD, Research Instructor, Department of Orthopaedics, School of Medicine, University of Utah, Salt Lake City, UT, USA

Todd J. Leutzinger, PhD, Instructor, Department of Biomechanics, College of Education, Health, and Human Sciences, University of Nebraska at Omaha, Omaha, NE, USA

Alan R. Needle, PhD, ATC, LAT, CSCS, Associate Professor, Department of Public Health & Exercise Science and Department of Rehabilitation Science, Appalachian State University, Boone, NC, USA.

Kristen F. Nicholson, PhD, Assistant Professor, Department of Orthopaedic Surgery, Wake Forest School of Medicine, Winston-Salem, NC, USA

Ankur Padhye PT, **PhD Student**, Rehabilitation Sciences/Movement Science and Disorders Concentration, Department of Physical Therapy, East Carolina University, Greenville, NC, USA

Stephen J. Thomas, PhD, ATC, Associate Professor and Department Chair, Department of Exercise Science, Jefferson College of Rehabilitation Science, Thomas Jefferson University, Philadelphia, PA, USA

John D. Willson, PhD, PT, Associate Professor, Department of Physical Therapy, East Carolina University, Greenville, NC, USA

David A. Winters (Deceased), University of Waterloo, Waterloo, Ontario, Canada

Joseph A. Zeni, PhD, PT, Associate Professor, Department of Rehabilitation and Movement Sciences, School of Health Professions, Rutgers University, Newark, NJ, USA

PREFACE

The field of biomechanics has experienced a wealth of growth since the printing of the fourth edition. With sweeping technological advancements, biomechanics has become an integral component of robotics, healthcare and medicine, athletic performance, movies and animation, and numerous other fields. With these changes, the discipline of biomechanics has become more tangible, recognizable, and accessible to individuals across the world. This new fifth edition reflects the expanded breadth and depth of biomechanics and includes updated references and research.

The original text, *Biomechanics of Human Movement*, published in 1979, had its title changed to *Biomechanics and Motor Control of Human Movement* when the second edition was published in 1990. This change is to acknowledge the new directions and research of the 1980s. In that second edition, five of eight chapters addressed various aspects of muscles and motor systems. The third edition, published in 2004, added information about three-dimensional (3D) kinematics and kinetics, reflecting the continued emphasis on motor control and the close links between biomechanics and movement analysis. The fourth edition, published in 2009, added updated discussions of anatomy, muscle physiology, and electromyography, with a strong emphasis on dynamic movements and in vivo data and analyses.

In keeping with the past updates, this updated edition integrates the new directions of biomechanics. These new directions include a strong emphasis on the role of the central nervous system in motor control and biomechanical analyses, as well as a focus on practical applications of biomechanics. The fifth edition has two new chapters, Chapter 12, "Central Nervous System's Role in Biomechanics," and Chapter 13, "A Case-Based Approach to Interpreting Biomechanical Data." Chapter 3, "Kinematics," has undergone significant updates to incorporate new technology and approaches to measuring human movement, including, but not limited to markerless technology. Chapter 7, "Understanding 3-D Kinematic and Kinetic Variables," includes new sections on markersets design, event detection, the incorporation of ISB standards, and induced acceleration analysis. Chapter 10, "Modeling of Human Movement" has been completely rewritten to include the current modeling approaches and technologies used in biomechanical research. Chapter 11 has been renamed to "Static and Dynamic Balance" to better reflect the content in this chapter. All chapters have also undergone edits to include updated information in each of the topic areas. The appendices, which underwent major additions in the second edition, remain intact. The extensive numerical tables contained in Appendix A: "Kinematic, Kinetic, and Energy Data" can also be found online in excel format to facilitate learning experiences in the modern classroom.

As was stated in the original editions, it is expected that the student has had basic courses in anatomy, mechanics, calculus, and electrical science. The major disciplines to which the book is directed are kinesiology, biomechanics, engineering (bioengineering, mechanical, and rehabilitation engineering), physical education, ergonomics, physical, and occupational therapy, athletic training, neuroscientists, sport scientists, and exercise scientists. The text should also prove valuable to researchers in orthopedics, muscle physiology, and rehabilitation medicine. Lastly, this text can provide valuable information to athletic coaches to help guide them in the appropriate use of biomechanical data to make training and coaching decisions.

Stephen J. Thomas, PhD, ATC
Thomas Jefferson University
Philadelphia, PA, USA
March 2022

Joseph A. Zeni, PhD, PT
Rutgers University
Newark, NJ, USA
March 2022

ACKNOWLEDGMENTS

My first acknowledgment goes to my family. To my parents, Howard and Carol for instilling in me the Scranton, PA grit, and work ethic that has guided me through my career. To my wife Regina, the love of my life, for always supporting our family, and making us laugh. To my son Jaxson and daughter Penelope for always making me proud and putting a smile on my face.

My second acknowledgment goes to my mentors, colleagues, and students who have guided me, inspired me, and helped me tremendously along the way. Although I cannot include everyone I would like to acknowledge a few. Buz and Kathy Swanik who were my mentors from undergrad through my PhD and played a significant role in my career. John Kelly has been a lifelong mentor and big brother not only in my career by also my personal life. Katie Reuther has been a great friend and colleague who taught me many engineering principles starting during my postdoc at the University of Pennsylvania. Tommy Nowakowski, one of my best friends, who is responsible for me becoming an Athletic Trainer. My first cohort of students (Justin Cobb, Ohsana Valle, Morgan Wambold, and Ryan Paul) who I am proud to say I have learned more from then they learned from me. Lastly, all of the professors in the Biomechanics PhD program at the University of Delaware.

Without all of you, this would not be possible!

STEPHEN J. THOMAS, PHD, ATC

This work would not be possible without those who have supported, educated, and nurtured me throughout my life and career. I would like to acknowledge the consistent support of my parents, Kathleen and Joe, who have always worked tirelessly to provide me with opportunities to succeed. My wife, Courtney, has been an unwavering rock in our household, balancing our family, her work, and my endeavors for the past 15 years. I must also acknowledge those who have not only taught me foundational biomechanics, but also passed along a passion for research, education, and the academic world. Foremost, my PhD advisor, Jill Higginson, a biomechanical engineer who took a chance and welcomed me, a clinician with little to no understanding of mechanical systems, into her lab. I learned so much during that time and fell in love with the application of engineering principles to the human body. To Anil Bhave, who introduced me to the clinical world of motion analysis, I am forever grateful for your enthusiasm and patience as my mentor and boss. Numerous professors from the University of Delaware Biomechanics and Movement Science program played a critical role and pushed me to be a better student and enjoy the process of learning: Jim Richards, Bill Rose, Lynn Snyder-Mackler, Thomas Buchanan, Stuart Binder-Macleod, and many others; I thank you for everything. These professors are educators, mentors, and colleagues without equal.

JOSEPH A. ZENI, PHD, PT

ABOUT THE COMPANION WEBSITE

This book is accompanied by a companion website

www.wiley.com/go/Thomas/WintersBiomechanics5e

The website includes:

- Powerpoints which contains the key point for all the individual chapters.
- Appendix contains table regarding the kinematic, kinetic, and energy.

1

BIOMECHANICS AS AN INTERDISCIPLINE

STEPHEN J. THOMAS[1], JOSEPH A. ZENI[2], AND DAVID A. WINTERS[3,†]
[1]*Thomas Jefferson University, Philadelphia, PA, USA*
[2]*Rutgers University, Newark, NJ, USA*
[3]*University of Waterloo, Waterloo, Ontario, Canada*

1.0 INTRODUCTION

Biomechanics of human movement is a field that has grown and advanced significantly in the past decade and includes observing, measuring, analyzing, assessing, and interpreting human movement. A wide variety of physical movements are involved – everything from the gait of the physically handicapped to the lifting of a load by a factory worker to the performance of a superior athlete. The physical and biological principles that apply are the same in all cases. What changes from case to case are the specific movement tasks and the level of detail that is being asked about the assessment and interpretation of each movement.

The list of professionals interested in biomechanics is quite long: orthopedic surgeons, athletic trainers, biomedical and mechanical engineers, occupational and physical therapists, kinesiologists, sport scientists, prosthetists, psychiatrists, orthotists, athletic coaches, sports equipment designers, and so on. At the basic level, the name given to the science dedicated to the area of human movement is kinesiology. It is a broad discipline blending aspects of psychology, sports nutrition, motor development and learning, and exercise physiology as well as biomechanics. Biomechanics, as an outgrowth of both life and physical sciences, is built on the basic body of knowledge of physics, chemistry, mathematics, physiology, and anatomy. It is amazing to note that the first real "biomechanicians" date back to Leonardo da Vinci, Galileo, Lagrange, Bernoulli, Euler, and Young. All these scientists had primary interests in the application of mechanics to biological problems.

1.0.1 Importance of Human Movement Analysis

The first question that one may ask is "What is the benefit of assessing and interpreting human movement." The answer to this can vary depending on the specific movement being studied and the expected outcomes for that specific individual. At the most basic level, it is important to

[†]Deceased.

Winter's Biomechanics and Motor Control of Human Movement, Fifth Edition.
Stephen J. Thomas, Joseph A. Zeni, and David A. Winter.

Companion website: www.wiley.com/go/Thomas/WintersBiomechanics5e

understand the underlying mechanisms responsible for the development of movement and compensation due to injury or pain. These mechanisms will act as a roadmap or equation that clinicians can utilize during rehabilitation to optimize movement, which will result in long-term recovery and injury prevention. When asking this question in reference to athletics, the goal is typically to increase performance and also to prevent overuse injuries. The current conundrum in many sports is that as performance increases the risk of injury also increases. This can result in an exponentially challenging situation for biomechanists to resolve when working with athletes.

1.0.2 The Interprofessional Team

As the field of biomechanics continues to evolve it is becoming much more evident that a team approach needs to be used when working with patients/clients. As mentioned previously, the professions interested in human movement are very broad and span many disciplines that have unique skill sets to help patients/clients. This includes surgery, rehabilitation, exercise, mental health, nutrition, equipment and prosthetic designs, etc. It is unfortunate that often times these professions work in silos, which often result in conflicting advice and direction. This not only confuses the patients/clients but also causes set backs in their progression. The first step in developing an interprofessional team is identifying and respecting the similarities and differences in expertise across the continuum of care for the patient/client. The focus always needs to be directed toward the patient/client. The next step is effective communication between team members and the patient/client. Each team member needs to communicate collectively following assessments so that all of the collected information can be discussed and interpreted. This interpretation will then be used by the team to create an optimal plan to achieve the patient's/client's goals. It is also very important to communicate this plan to the patient/client in a digestible form. Educational programs in biomechanics often focus on the science and technology used to measure and assess human movement very accurately. However, it often falls short on providing training for interpreting and communicating the results of human movement assessments to the patient/client. This is an incredibly important and valuable skill that needs to be taught in educational programs, which will result in the expansion of the field outside the traditional settings of research labs and provide value to patients/clients from all walks of life.

1.1 MEASUREMENT, DESCRIPTION, ANALYSIS, AND ASSESSMENT

The scientific approach as applied to biomechanics has been characterized by a fair amount of confusion. Some descriptions of human movement have been passed off as assessments, some studies involving only measurements have been falsely advertised as analyses, and so on. It is, therefore, important to clarify these terms. Any quantitative assessment of human movement must be preceded by a measurement and description phase, and if more meaningful diagnostics are needed, a biomechanical analysis is usually necessary. Most of the material in this text is aimed at the technology of measurement and description and the modeling process required for analysis. The final interpretation, assessment, or diagnosis is movement specific and is limited to the examples given.

Figure 1.1, which has been prepared for the assessment of the physically handicapped, depicts the relationships between these various phases of assessment. All levels of assessment involve a human being and are based on his or her visual observation of a patient or subject, recorded data, or some resulting biomechanical analysis. The primary assessment level uses direct observation, which places tremendous "overload" even on the most experienced observer. All measures are subjective and are almost impossible to compare with those obtained previously. Observers are then faced with the tasks of documenting (describing) what they see, monitoring changes, analyzing the information, and diagnosing the causes. If measurements can be made during the patient's movement, then data can be presented in a convenient manner to describe the movement quantitatively. Here the assessor's task is considerably simplified. He or she can now quantify

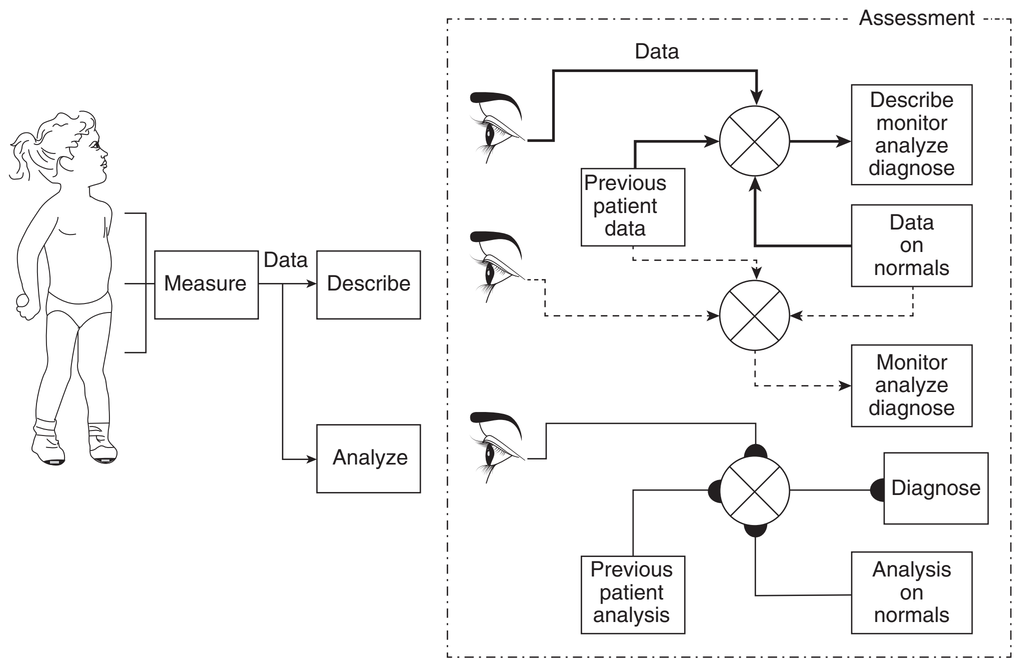

Figure 1.1 Schematic diagram showing the three levels of assessment of human movement.

changes, carry out simple analyses, and try to reach a more objective diagnosis. At the highest level of assessment, the observer can view biomechanical analyses that are extremely powerful in diagnosing the exact cause of the problem, compare these analyses with the normal population, and monitor their detailed changes with time.

The measurement and analysis techniques used in an athletic event could be identical to the techniques used to evaluate an amputee's gait. However, the assessment of the optimization of the energetics of the athlete is quite different from the assessment of the stability of the amputee. Athletes are looking for very detailed but minor changes that will improve their performance by a few percentage points, sufficient to move them from fourth to first place. Their training and exercise programs and reassessment normally continue over an extended period of time. The amputee, on the other hand, is looking for major improvements, probably related to safe walking, but not fine and detailed differences. This person is quite happy to be able to walk at less than maximum capability, although techniques are available to permit training and have the prosthesis readjusted until the amputee reaches some perceived maximum. When working with Para-athletes these approaches and goals are often are blended together. In ergonomic studies, assessors are likely looking for maximum stresses in specific tissues during a given task, to thereby ascertain whether the tissue is working within safe limits. If not, they will analyze possible changes in the workplace or task in order to reduce the stress or fatigue.

1.1.1 Measurement, Description, and Monitoring

It is difficult to separate the two functions of measurement and description. However, for clarity, the student should be aware that a given measurement device can have its data presented in a number of different ways. Conversely, a given description could have come from several different measurement devices.

Earlier biomechanical studies had the sole purpose of describing a given movement, and any assessments that were made resulted from visual inspection of the data. The description of the data can take many forms: plots of body coordinates, stick diagrams, or simple outcome measures such as gait velocity, load lifted, or height of a jump. A video camera, by itself, is a measurement device, and the resulting plots form the description of the event in time and space. The coordinates of key anatomical landmarks can be extracted and plotted at regular intervals in time. Time history plots of one or more coordinates are useful in describing detailed changes in a particular landmark. They also can reveal changes in velocity and acceleration. A total description in the plane of the movement is provided by the stick diagram, in which each body segment is represented by a straight line or stick. Joining the sticks together gives the spatial orientation of all segments at any point in time. Repetition of this plot at equal intervals of time gives a pictorial and anatomical description of the dynamics of the movement. Here, trajectories, velocities, and accelerations can be visualized. To get some idea of the volume of the data present in a stick diagram, the student should note that one full page of coordinate data is required to make the complete plot for the description of the event. The coordinate data can be used directly for any desired analysis: reaction forces, muscle moments, energy changes, efficiency, and so on. Conversely, an assessment can occasionally be made directly from the description. A trained observer, for example, can scan a stick diagram and extract useful information that will give some directions for training or therapy, or give the researcher some insight into basic mechanisms of movement.

The term *monitor* needs to be introduced in conjunction with the term *describe*. To monitor means to note changes over time. Thus, a physical therapist will monitor the progress (or the lack of it) for each physically disabled person undergoing therapy. Only through accurate and reliable measurements will the therapist be able to monitor any improvement and thereby make inferences to the validity of the current therapy. What monitoring does not tell us is why an improvement is or is not taking place; it merely documents the change. All too many coaches or therapists document the changes with the inferred assumption that their intervention has been the cause. However, the scientific rationale behind such inferences is missing. Unless a detailed analysis is done, we cannot document the detailed motor-level changes that will reflect the results of therapy or training.

1.1.2 Analysis

The measurement system yields data that are suitable for analysis. This means that data have been calibrated and are as free as possible from noise and artifacts. *Analysis* can be defined as any mathematical operation that is performed on a set of data to present them in another form or to combine the data from several sources to produce a variable that is not directly measurable. From the analyzed data, information may be extracted to assist in the assessment stage. In some cases, the mathematical operation can be very simple, such as the processing of an electromyographic (EMG) signal to yield an *envelope* signal. The mathematical operation performed here can be described in two stages. The first is a full-wave *rectifier* (the electronic term for a circuit that gives the absolute value). The second stage is a low-pass filter (which mathematically has the same transfer function as that between a neural pulse and its resultant muscle twitch). A more complex biomechanical analysis could involve a link-segment model, and with appropriate kinematic, anthropometric, and kinetic output data, we can carry out analyses that could yield a multitude of significant time-course curves. Figure 1.2 depicts the relationships between some of these variables. The output of the movement is what we see. It can be described by a large number of kinematic variables: displacements, joint angles, velocities, and accelerations. If we have an accurate model of the human body in terms of anthropometric variables, we can develop a reliable link-segment model. With this model and accurate kinematic data, we can predict the net forces and muscle moments that caused the movement we just observed. Such an analysis technique is called an *inverse solution*. It is extremely valuable, as it allows us to estimate variables such as joint reaction forces and moments. Such variables are not measurable directly. In a similar manner, individual muscle forces might be predicted through the development of a mathematical model of a muscle, which could have neural drive, length, velocity, and cross-sectional area as inputs.

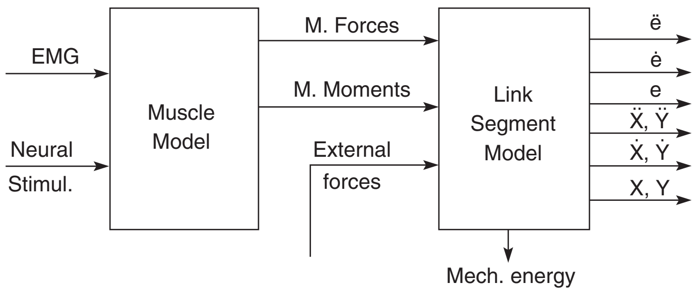

Figure 1.2 Schematic diagram to show the relationship between the neural, kinetic, and kinematic variables required to describe and analyze human movement.

1.1.3 Assessment and Interpretation

The entire purpose of any assessment is to make a positive decision about a physical movement. An athletic coach might ask, "Is the mechanical energy of the movement better or worse than before the new training program was instigated, and why?" Or the orthopedic surgeon may wish to see the improvement in the knee muscle moments of a patient a month after surgery. Or a basic researcher may wish to interpret the motor changes resulting from certain perturbations and thereby verify or negate different theories of neural control. In all cases, if the questions asked yield no answers, it can be said that there was no information present in the analysis. The decision may be positive in that it may confirm that the coaching, surgery, or therapy has been correct and should continue exactly as before. Or, if this is an initial assessment, the decision may be to proceed with a definite plan based on new information from the analysis. The information can also cause a negative decision, for example, to cancel a planned surgical procedure and to prescribe therapy instead.

Some biomechanical assessments involve a look at the description itself rather than some analyzed version of it. Commonly, ground reaction force curves from a force plate are examined. This electromechanical device gives an electrical signal that is proportional to the weight (force) of the body acting on it. Such patterns appear in Figure 1.3. A trained observer can detect pattern changes as a result of pathological gait and may come to some conclusions as to whether the

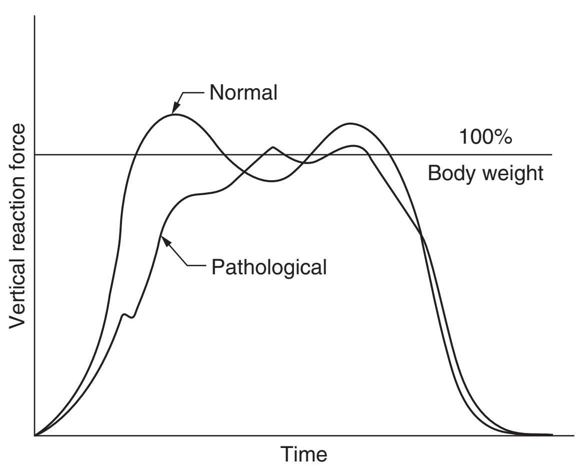

Figure 1.3 Example of a ground reaction force curve that has sometimes been used in the diagnostic assessment of pathological gait.

patient is improving, but he or she will not be able to assess why. At best, this approach is speculative and yields little information regarding the underlying cause of the observed patterns.

1.2 BIOMECHANICS AND ITS RELATIONSHIP WITH PHYSIOLOGY AND ANATOMY

Because biomechanics is still an expanding discipline, it is important to identify its interaction with other areas of movement science: neurophysiology, exercise physiology, and anatomy. The neuromuscular system acts to control the release of metabolic energy for the purpose of generating controlled patterns of tension at the tendon. That tension waveform is a function of the physiological characteristics of the muscle (i.e. fiber type) and of its metabolic state (rested vs. fatigued). The tendon tension is generated in the presence of passive anatomical structures (ligaments, articulating surfaces, and skeletal structures). Figure 1.4 depicts the relationship between the sensory system, the neurological pathways, the muscles, the skeletal system, and the link-segment model that we analyze. The essential characteristic of this total system is that it is converging in nature. The structure of the neural system has many excitatory and inhibitory synaptic junctions, all summing their control on a final synaptic junction in the spinal cord to control individual motor units. The α motoneuron (1), which is often described as the final common pathway, has its synapse on the motor end point of the muscle motor unit. A second level of convergence is the summation of all twitches from all active motor units at the level of the tendon (2). This summation results from the neural recruitment of motor units based on the size principle (DeLuca et al., 1982; Henneman and Olson, 1965). The resultant tension is a temporal superposition of twitches of all active motor units, modulated by the length and velocity characteristics of the muscle. A third level of musculoskeletal integration at each joint center where the moment-of-force (3) is the algebraic summation of the force/moment products of all muscles crossing that joint plus the moments generated by the passive anatomical structures at the joint. The moments

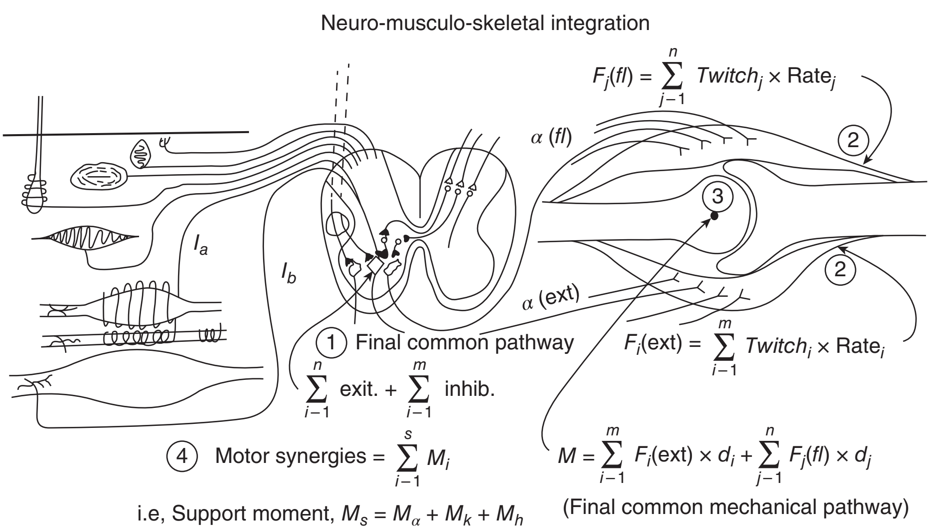

Figure 1.4 Four levels of integration in the neuromusculoskeletal system provide control of human movement. The first is the neural summation of all excitatory/inhibitory inputs to the α motoneuron (1). The second is the summation of all motor twitches from the recruitment of all active motor units within the muscle and is seen as a tendon force (2). The third is the algebraic summation of all agonist and antagonist muscle moments at the joint axis (3). Finally, integrations are evident in combined moments acting synergistically toward a common goal (4).