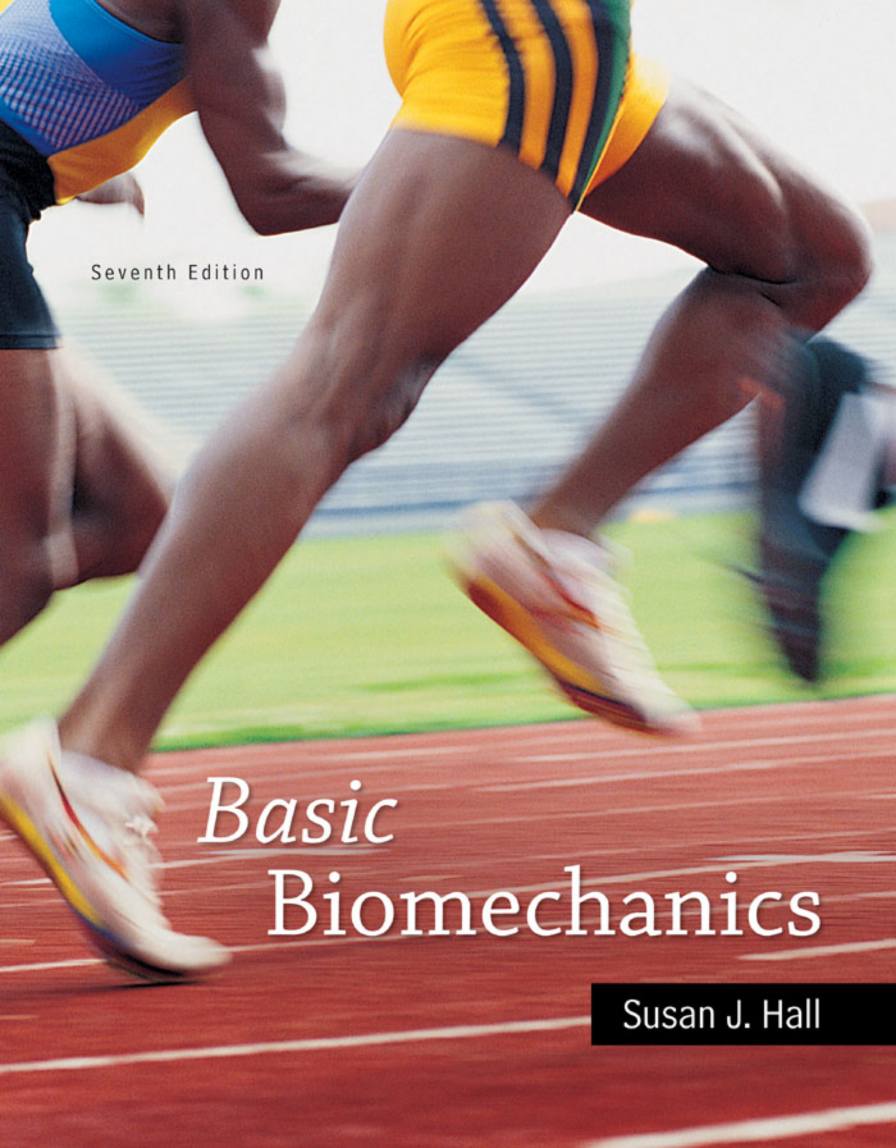

Seventh Edition

Basic Biomechanics

Susan J. Hall

BASIC BIOMECHANICS

SEVENTH EDITION

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McGraw Hill Education

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BRIEF CONTENTS

CONTENTS

PREFACE

The seventh edition of *Basic Biomechanics* has been significantly updated and redesigned from the previous edition. As the interdisciplinary field of biomechanics grows in both breadth and depth, it is important that even introductory textbooks reflect the nature of the science. Accordingly, the text has been revised, expanded, and updated, with the objectives being to present relevant information from recent research findings and to prepare students to *analyze* human biomechanics.

The approach taken remains an integrated balance of qualitative and quantitative examples, applications, and problems designed to illustrate the principles discussed. The seventh edition also retains the important sensitivity to the fact that some beginning students of biomechanics possess weak backgrounds in mathematics. For this reason, it includes numerous sample problems and applications, along with practical advice on approaching quantitative problems.

ORGANIZATION

Each chapter follows a logical and readable format, with the introduction of new concepts consistently accompanied by practical human movement examples and applications from across the life span and across sport, clinical, and daily living activities.

NEW CONTENT HIGHLIGHTS

New content has been added to provide updated scientific information on relevant topics. All chapters have been revised to incorporate the latest information from the biomechanics research literature, and numerous new sport and clinical applications and examples are included. Topics added or expanded include barefoot running and running economy, stretching and performance, bone health and space flight, the golf swing, ACL injuries, muscle fatigue, and swimming technique.

Balanced Coverage

The former Biomechanics Academy of AAHPERD recommended that undergraduate students in biomechanics devote approximately one-third of study time to anatomical considerations, one-third to mechanical considerations, and the remainder to applications. The integrated approach to coverage of these areas taken in previous editions is continued in this seventh edition.

Applications Oriented

All chapters in this new edition contain discussion of a broad range of updated human movement applications, many of which are taken from the recent biomechanics research literature. Special emphasis has been placed on examples that span all ages and address clinical and daily living issues, as well as sport applications.

Laboratory Experiences

The integrated laboratory manual appears at the end of each chapter with references to simulations on the text's Online Learning Center. The soft-cover design with perforation allows laboratory manual pages to be completed and turned in to instructors.

Integrated Technology

Technology is integrated throughout the text, with an Online Learning Center box appearing on every chapter-opening page and directing students to resources online, while lists of related websites at the end of each chapter offer pertinent sources to students. Problems and laboratory experiences are incorporated throughout the text and updated to reference the Online Learning Center.

The seventh edition of *Basic Biomechanics* can be bundled (for a small additional price) with *MaxTRAQ*™ software. MaxTRAQ is a downloadable motion analysis software that offers an easy-to-use tool to track data and analyze various motion elected by the authors. The MaxTRAQ software includes video clips of motions such as golf swing and gait, 2D manual tracking, coverage of distance and angles—and more!

Visit www.mhhe.com/hall7e for more information about the MaxTRAQ software.

PEDAGOGICAL FEATURES

In addition to the sample problems, problem sets, laboratory experiences, Online Learning Center boxes, end-of-chapter key terms lists, and lists of websites, the book contains other pedagogical features from previous editions. These include **key concepts, marginal definitions, sample problems, chapter summaries, introductory and additional problems, references,** and **appendices.**

ANCILLARIES

Online Learning Center

www.mhhe.com/hall7e
This website offers resources to students and instructors as well as a link to the MaxTRAQ motion analysis software. It includes downloadable ancillaries, student quizzing, additional student exercises and much more.

Resources for the instructor include:

- Downloadable PowerPoint presentations with annotated lecture notes
- Instructor's manual, originally developed by Darla Smith, faculty emerita, University of Texas at El Paso
- Test bank available as downloadable word files and through EZ Test Online, which allows instructors to create and print a test or create and deliver an online and printed (Word or PDF) test.

- Interactive links
- Online laboratory manual with simulations—Image library

Resources for the student include:

- Downloadable PowerPoint presentations
- Self-grading quizzes
- Online laboratory manual with simulations

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I would like to thank developmental editor Andrea Edwards and managing editor Sara Jaeger for their quality work on the new edition of this book. Many thanks also to copy editor Sue Nodine and production editor Heather Ervolino for their very capable and professional work on this revision. I also wish to extend appreciation to the following reviewers:

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Finally, I also very much appreciate the excellent suggestions I have received over the seven editions of this book from numerous students and colleagues.

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This text is available as an eTextbook from CourseSmart, a new way for faculty to find and review eTextbooks. It's also a great option for students who are interested in accessing their course materials digitally and saving money. CourseSmart offers thousands of the most commonly adopted textbooks across hundreds of courses from a wide variety of higher education publishers. It is the only place for faculty to review and compare the full text of a textbook online, providing immediate access without the environmental impact of requesting a print exam copy. At CourseSmart, students can save up to 50% off the cost of a print book, reduce their impact on the environment, and gain access to powerful web tools for learning, including full text search, notes and highlighting, and e-mail tools for sharing notes between classmates. For further details contact your sales representative or go to www.coursesmart.com.

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C H A P T E R

1

What Is Biomechanics?

After completing this chapter, you will be able to:

Define the terms *biomechanics, statics, dynamics, kinematics,* and *kinetics,* and explain the ways in which they are related.

Describe the scope of scientific inquiry addressed by biomechanists.

Distinguish between qualitative and quantitative approaches for analyzing human movement.

Explain how to formulate questions for qualitative analysis of human movement.

Use the 11 steps identified in the chapter to solve formal problems.

ONLINE LEARNING CENTER RESOURCES

www.mhhe.com/hall7e

Log on to our Online Learning Center (OLC) for access to these additional resources:

- Online Lab Manual
- Flashcards with definitions of chapter key terms
- Chapter objectives
- Chapter lecture PowerPoint presentation
- Self-scoring chapter quiz
- Additional chapter resources
- Web links for study and exploration of chapter-related topics

Learning to walk is an ambitious task from a biomechanical perspective. Ariel Skelley/Getty Images.

Why do some golfers slice the ball? How can workers avoid developing low back pain? What cues can a physical education teacher provide to help students learn the underhand volleyball serve? Why do some elderly individuals tend to fall? We have all admired the fluid, graceful movements of highly skilled performers in various sports. We have also observed the awkward first steps of a young child, the slow progress of an injured person with a walking cast, and the hesitant, uneven gait of an elderly person using a cane. Virtually every activity class includes a student who seems to acquire new skills with utmost ease and a student who trips when executing a jump or misses the ball when attempting to catch, strike, or serve. What enables some individuals to execute complex movements so easily, while others appear to have difficulty with relatively simple movement skills?

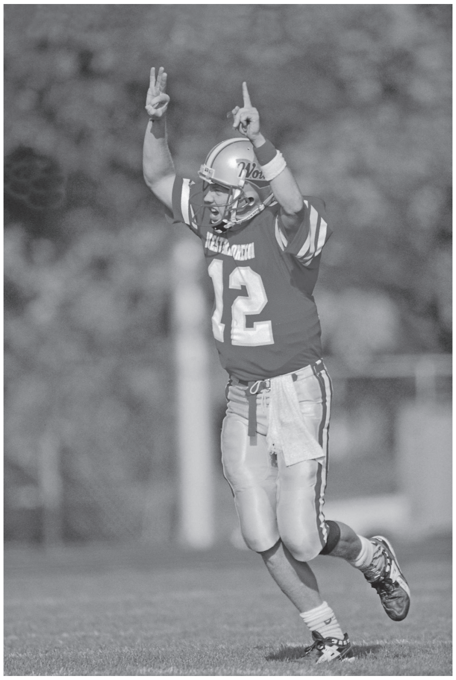
Although the answers to these questions may be rooted in physiological, psychological, or sociological issues, the problems identified are all biomechanical in nature. This book will provide a foundation for identifying, analyzing, and solving problems related to the biomechanics of human movement.

BIOMECHANICS: DEFINITION AND PERSPECTIVE

•*Courses in anatomy, physiology, mathematics, physics, and engineering provide background knowledge for biomechanists.*

biomechanics
application of mechanical principles in the study of living organisms

The term *biomechanics* combines the prefix *bio,* meaning "life," with the field of *mechanics,* which is the study of the actions of forces. The international community of scientists adopted the term *biomechanics* during the early 1970s to describe the science involving the study of the mechanical aspects of living organisms. Within the fields of kinesiology and exercise science, the living organism most commonly of interest is the human body. The forces studied include both the internal forces produced by muscles and the external forces that act on the body.



Anthropometric characteristics may predispose an athlete to success in one sport and yet be disadvantageous for participation in another. (Both photos) Royalty-Free/CORBIS.

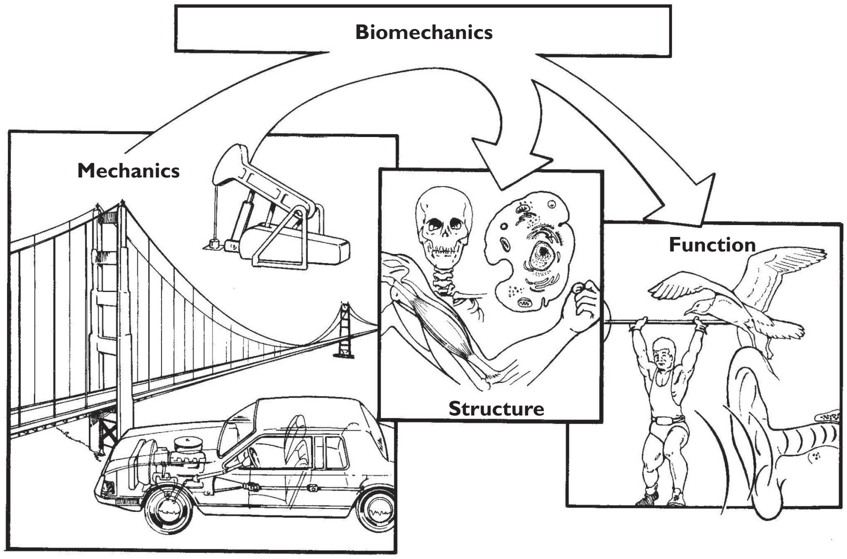


FIGURE 1-1

Biomechanics uses the principles of mechanics for solving problems related to the structure and function of living organisms.

Biomechanists use the tools of mechanics, the branch of physics involving analysis of the actions of forces, to study the anatomical and functional aspects of living organisms (Figure 1-1). Statics and dynamics are two major subbranches of mechanics. Statics is the study of systems that are in a state of constant motion, that is, either at rest (with no motion) or moving with a constant velocity. Dynamics is the study of systems in which acceleration is present.

mechanics
branch of physics that analyzes the actions of forces on particles and mechanical systems

statics
branch of mechanics dealing with systems in a constant state of motion

dynamics
branch of mechanics dealing with systems subject to acceleration

Kinematics and kinetics are further subdivisions of biomechanical study. What we are able to observe visually when watching a body in motion is termed the *kinematics* of the movement. Kinematics involves the study of the size, sequencing, and timing of movement, without reference to the forces that cause or result from the motion. The kinematics of an exercise or a sport skill execution is also known, more commonly, as *form* or *technique*. Whereas kinematics describes the appearance of motion, kinetics is the study of the forces associated with motion. Force can be thought of as a push or pull acting on a body. The study of human biomechanics may include questions such as whether the amount of force the muscles are producing is optimal for the intended purpose of the movement.

kinematics
study of the description of motion, including considerations of space and time

kinetics
study of the action of forces

Although biomechanics is relatively young as a recognized field of scientific inquiry, biomechanical considerations are of interest in several different scientific disciplines and professional fields. Biomechanists may have academic backgrounds in zoology; orthopedic, cardiac, or sports medicine; biomedical or biomechanical engineering; physical therapy; or kinesiology, with the commonality being an interest in the biomechanical aspects of the structure and function of living things.

The biomechanics of human movement is one of the subdisciplines of kinesiology, the study of human movement. Although some biomechanists study topics such as ostrich locomotion, blood flow through constricted arteries, or micromapping of dental cavities, this book focuses primarily on the biomechanics of human movement from the perspective of the movement analyst.

kinesiology
study of human movement

Biomechanics is also a scientific branch of sports medicine. *Sports medicine* is an umbrella term that encompasses both clinical and scientific aspects of exercise and sport. The American College of Sports Medicine is an example of an organization that promotes interaction between scientists and clinicians with interests in sports medicine–related topics.

sports medicine
clinical and scientific aspects of sports and exercise

What Problems Are Studied by Biomechanists?

As expected given the different scientific and professional fields represented, biomechanists study questions or problems that are topically diverse. For example, zoologists have examined the locomotion patterns of dozens of species of animals walking, running, trotting, and galloping at controlled speeds on a treadmill to determine why animals choose a particular stride length and stride rate at a given speed. They have found that running actually consumes less energy than walking in small animals up to the size of dogs, but running is more costly than walking for larger animals such as horses (16). One of the challenges of this type of research is determining how to persuade a cat, a dog, or a turkey to run on a treadmill (Figure 1-2).

•*In research, each new study, investigation, or experiment is usually designed to address a particular question or problem.*

Among humans, the energy cost of running increases with running speed, as well as with the amount of weight being carried by the runner. Beginning runners have been observed to develop more economical running kinematics over a period of weeks as they become accustomed to training (13). Interestingly, researchers have shown that barefoot or minimally shod running is more economical than running in running shoes, possibly due to storage and return of elastic energy in the foot (14).

The U.S. National Aeronautics and Space Administration (NASA) sponsors another multidisciplinary line of biomechanics research to promote understanding of the effects of microgravity on the human musculoskeletal system. Of concern is the fact that astronauts who have been out of the earth's gravitational field for just a few days have returned with muscle atrophy, cardiovascular and immune system changes, and reduced bone density, mineralization, and strength, especially in the lower extremities (20). The issue of bone loss, in particular, is currently a limiting factor for long-term space flights. Both increased bone resorption and decreased calcium absorption appear to be responsible (see Chapter 4) (19).

Since those early days of space flight, biomechanists have designed and built a number of exercise devices for use in space to take the place of

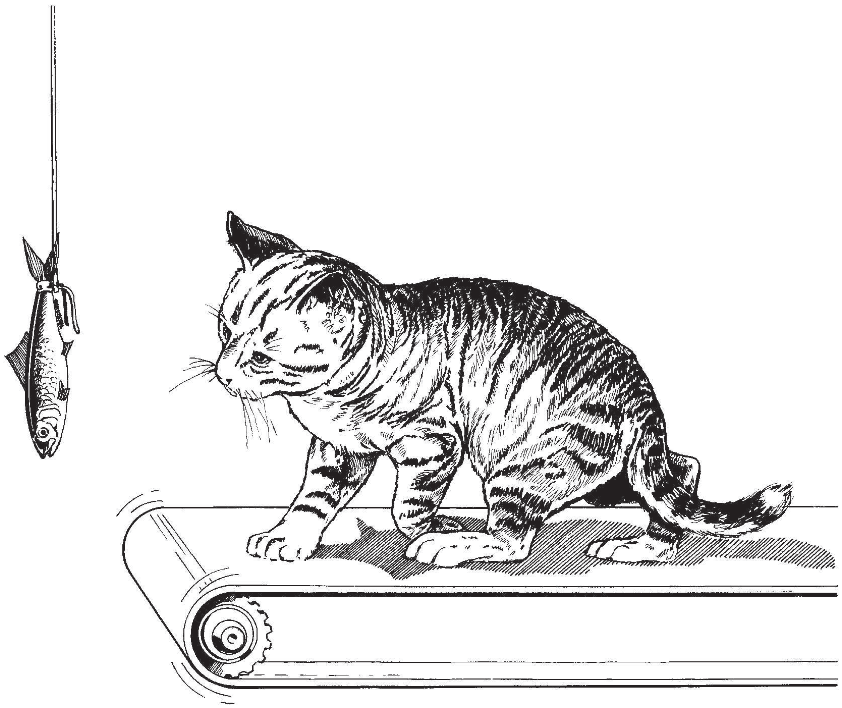


FIGURE 1-2

Research on the biomechanics of animal gaits poses some interesting problems.

normal bone-maintaining activities on Earth. Some of this research has focused on the design of treadmills for use in space that load the bones of the lower extremity with deformations and strain rates that are optimal for stimulating new bone formation. Another approach involves combining voluntary muscle contraction with electrical stimulation of the muscles to maintain muscle mass and tone (25). So far, however, no adequate substitute has been found for weight bearing for the prevention of bone and muscle loss in space.

Maintaining sufficient bone-mineral density is also a topic of concern here on Earth. Osteoporosis is a condition in which bone mineral mass and strength are so severely compromised that daily activities can cause bone pain and fracturing. This condition is found in most elderly individuals, with earlier onset in women, and is becoming increasingly prevalent throughout the world with the increasing mean age of the population. Approximately 40% of women experience one or more osteoporotic fractures after age 50, and after age 60, about 90% of all fractures in both men and women are osteoporosis-related. The most common fracture site is the vertebrae, with the presence of one fracture indicating increased risk for future vertebral and hip fractures (8). This topic is explored in depth in Chapter 4.

Another problem area challenging biomechanists who study the elderly is mobility impairment. Age is associated with decreased ability to balance, and older adults both sway more and fall more than young adults, although the reasons for these changes are not well understood. Falls, and particularly fall-related hip fractures, are extremely serious, common, and costly medical problems among the elderly. Each year, falls cause large percentages of the wrist fractures, head injuries, vertebral fractures, and lacerations, as well as over 90% of the hip fractures occurring in the United States (17). Biomechanical research teams are investigating the biomechanical factors that enable individuals to avoid falling, the characteristics of safe landings from falls, the forces sustained by different parts of the body during falls, and the ability of protective clothing and floors to prevent falling injuries (17). Promising work in the development of intervention strategies has shown that the key to preventing falls may be the ability to limit trunk motion (7). Older adults can quickly learn strategies for limiting trunk motion through task-specific training combined with whole-body exercise.

Research by clinical biomechanists has resulted in improved gait among children with cerebral palsy, a condition involving high levels of muscle tension and spasticity. The gait of the cerebral palsy individual is characterized by excessive knee flexion during stance. This problem is treated by surgical lengthening of the hamstring tendons to improve knee extension during stance. In some patients, however, the procedure also diminishes knee flexion during the swing phase of gait, resulting in dragging of the foot. After research showed that patients with this problem exhibited significant co-contraction of the rectus femoris with the hamstrings during the swing phase, orthopedists began treating the problem by surgically attaching the rectus femoris to the sartorius insertion. This creative, biomechanics research–based approach has enabled a major step toward gait normalization for children with cerebral palsy.

Research by biomedical engineers has also resulted in improved gait for children and adults with below-knee amputations. Ambulation with a prosthesis creates an added metabolic demand, which can be particularly significant for elderly amputees and for young active amputees who participate in sports requiring aerobic conditioning. In response to this problem, researchers have developed an array of lower-limb and foot prostheses that store and return mechanical energy during gait, thereby

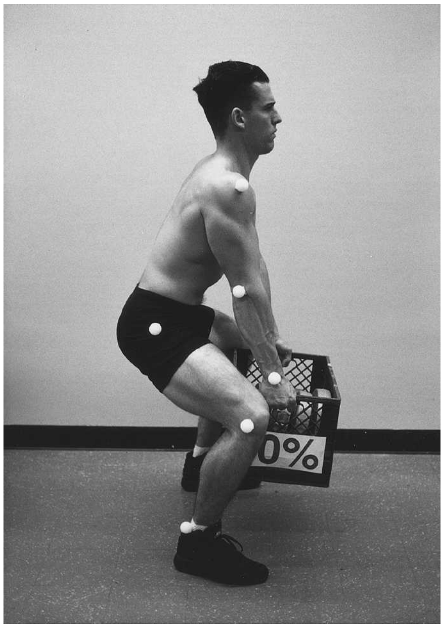
Exercise in space is critically important for preventing loss of bone mass among astronauts. Photo courtesy of NASA.

reducing the metabolic cost of locomotion. Studies have shown that the more compliant prostheses are better suited for active and fast walkers, whereas prostheses that provide a more stable base of support are generally preferred for the elderly population. Microchip-controlled "Intelligent Prostheses" show promise for reducing the energy cost of walking at a range of speeds (3). Researchers are currently developing a new class of "bionic" prosthetic feet that are designed to better imitate normal gait (21).

Occupational biomechanics is a field that focuses on the prevention of work-related injuries and the improvement of working conditions and worker performance. Researchers in this field have learned that work-related low back pain can derive not only from the handling of heavy materials but from unnatural postures, sudden and unexpected motions, and the characteristics of the individual worker (12). Sophisticated biomechanical models of the trunk are now being used in the design of materials-handling tasks in industry to enable minimizing potentially injurious stresses to the low back (1).

carpal tunnel syndrome
overuse condition caused by compression of the median nerve in the carpal tunnel and involving numbness, tingling, and pain in the hand

Biomechanists have also contributed to performance improvements in selected sports through the design of innovative equipment. One excellent example of this is the Klapskate, the speed skate equipped with a hinge near the toes that allows the skater to plantar flex at the ankle during push-off, resulting in up to 5% higher skating velocities than were obtainable with traditional skates (9). The Klapskate was designed by van Ingen Schenau and de Groot, based on study of the gliding push-off technique in speed skating by van Ingen Schenau and Baker, as well as work on the intermuscular coordination of vertical jumping by Bobbert and van Ingen Schenau (4). When the Klapskate was used for the first time by competitors in the 1998 Winter Olympic Games, speed records were shattered in every event.



Occupational biomechanics involves study of safety factors in activities such as lifting.
© Susan Hall.

Aerodynamic cycling equipment has contributed to new world records.
Getty Images.

Numerous innovations in sport equipment and apparel have also resulted from findings of experiments conducted in experimental chambers called *wind tunnels* that involved controlled simulation of the air resistance actually encountered during particular sports. Examples include the aerodynamic helmets, clothing, and cycle designs used in competitive cycling, and the ultrasmooth suits worn in other competitive speed-related events, such as swimming, track, skating, and skiing. Wind tunnel experiments have also been conducted to identify optimal body configuration during events such as ski jumping (22). Sport biomechanists have also directed efforts at improving the biomechanical, or technique, components of athletic performance.

One rather dramatic example of performance improvement partially attributable to biomechanical analysis is the case of four-time Olympic discus champion Al Oerter. Mechanical analysis of the discus throw requires precise evaluation of the major mechanical factors affecting the flight of the discus. These factors include the following:

1. The speed of the discus when it is released by the thrower
2. The projection angle at which the discus is released
3. The height above the ground at which the discus is released
4. The angle of attack (the orientation of the discus relative to the prevailing air current)

By using computer simulation techniques, researchers can predict the needed combination of values for these four variables that will result in a throw of maximum distance for a given athlete (10). High-speed cameras can record performances in great detail, and when the film or video is analyzed, the actual projection height, velocity, and angle of attack can be compared to the computer-generated values required for optimal performance. At the age of 43, Oerter bettered his best Olympic performance by 8.2 m. Although it is difficult to determine the contributions of motivation and training to such an improvement, some part of Oerter's success was a result of enhanced technique following biomechanical analysis (18). Most adjustments to skilled athletes' techniques produce relatively modest results because their performances are already characterized by above-average technique.

Some of the research produced by sport biomechanists has been done in conjunction with the Sports Medicine Division of the United States Olympic Committee (USOC). Typically, this work is done in direct cooperation with the national coach of the sport to ensure the practicality of results. USOC-sponsored research has yielded much new information about the mechanical characteristics of elite performance in various sports. Because of continuing advances in scientific analysis equipment, the role of sport biomechanists in contributing to performance improvements is likely to be increasingly important in the future.

• *The USOC began funding sports medicine research in 1981. Other countries began sponsoring research to boost the performance of elite athletes in the early 1970s.*

The influence of biomechanics is also being felt in sports popular with both nonathletes and athletes, such as golf. Computerized video analyses

Biomechanists Develop a Revolutionary New Figure Skate

What do 1996 U.S. figure skating champion Rudy Galindo and 1998 Olympic gold medal winner Tara Lipinski have in common besides figure skating success? They have both had double hip replacements, Galindo at age 32 and Lipinski at age 18.

Overuse injuries among figure skaters are on the rise at an alarming rate, with most involving the lower extremities and lower back (4, 12). With skaters performing more and more technically demanding programs including multirotation jumps, on-ice training time for elite skaters now typically includes over 100 jumps per day, six days per week, year after year.

Yet, unlike most modern sports equipment, the figure skate has undergone only very minor modifications since 1900. The soft-leather, calf-high boots of the nineteenth century are now made of stiffer leather to promote ankle stability and are not quite as high to allow a small amount of ankle motion. However, the basic design of the rigid boot with a screwed-on steel blade has not changed.

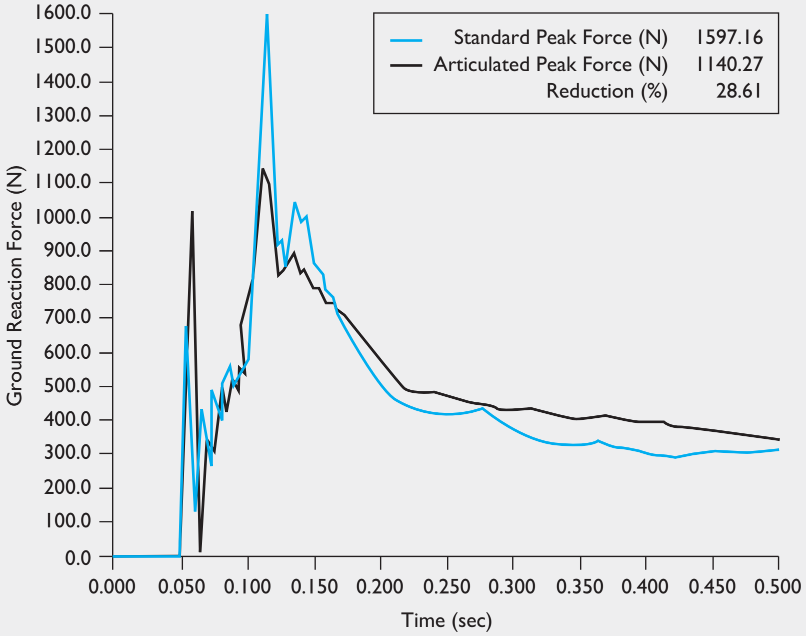
The problem with the traditional figure skate is that when a skater lands after a jump, the rigid boot severely restricts motion at the ankle, forcing the skater to land nearly flat-footed and preventing motion at the ankle that could help attenuate the landing shock that gets translated upward through the musculoskeletal system. Not surprisingly, the incidence of overuse injuries in figure skating is mushrooming due to the increased emphasis on performing jumps, the increase in training time, and the continued use of outdated equipment.

To address this problem, biomechanist Jim Richards and graduate student Dustin Bruening, working at the University of Delaware's Human Performance Lab, have designed and tested a new figure skating boot. Following the design of modern-day Alpine skiing and in-line skating boots, the new boot incorporates an articulation at the ankle that permits flexion movement but restricts potentially injurious sideways movement.

New figure skating boot with an articulation at the ankle designed by biomechanists at the University of Delaware. © Susan Hall.

The boot enables skaters to land toe-first, with the rest of the foot hitting the ice more slowly. This extends the landing time, thereby spreading the impact force over a longer time and dramatically diminishing the peak force translated up through the body. As shown in the graph, the new boot attenuates the peak landing force on the order of 30%.

Although the new figure skating boot design was motivated by a desire to reduce the incidence of stress injuries in skating, it may also promote performance. The ability to move through a larger range of motion at the ankle may well enable higher jump heights and concomitantly more rotations while the skater is in the air.



The new figure skating boot with an articulation at the ankle reduces peak impact forces during landing from a jump on the order of 30%.
Graph courtesy of D. Bruening and J. Richards.

Skaters who adopt the new boot are finding that using it effectively requires a period of acclimatization. Those who have been skating in the traditional boot for many years tend to have reduced strength in the musculature surrounding the ankle. Improving ankle strength is likely to be necessary for optimal use of a boot that now allows ankle motion.

of golf swings designed by biomechanists are commonly available at golf courses and equipment shops. The science of biomechanics can play a role in optimizing the distance and accuracy of all golf shots, including putting, through analysis of body angles, joint forces, and muscle activity patterns (24). A common technique recommendation is to maintain a single fixed center of rotation to impart force to the ball (11).

Other concerns of sport biomechanists relate to minimizing sport injuries through both identifying dangerous practices and designing safe equipment and apparel. In recreational runners, for example, research shows that the most serious risk factors for overuse injuries are training errors such as a sudden increase in running distance or intensity, excess cumulative mileage, and running on cambered surfaces (6). The complexity of safety-related issues increases when the sport is equipment-intensive. Evaluation of protective helmets involves ensuring not only that the impact characteristics offer reliable protection but also that the helmet does not overly restrict wearers' peripheral vision.

• *Impact testing of protective sport helmets is carried out scientifically in engineering laboratories.*

An added complication is that equipment designed to protect one part of the body may actually contribute to the likelihood of injury in another part of the musculoskeletal system. Modern ski boots and bindings, while effective in protecting the ankle and lower leg against injury, unfortunately contribute to severe bending moments at the knee when the skier loses balance.