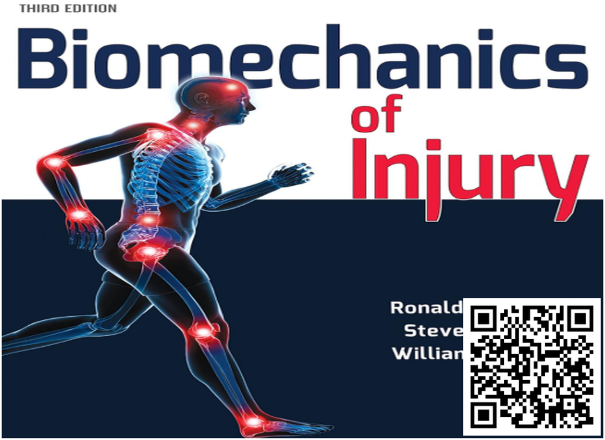
THIRD EDITION
Biomechanics
of
Injury
Ronald

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Ronald F. Zernicke

Steven P. Broglio

William C. Whiting

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In loving memory of my parents, Martha and Clarence; and to Kathy, Kristin, and Eric.
—Ronald F. Zernicke

For Lily.
—Steven P. Broglio

In loving memory of my parents, Richard and Charlotte; and to Marji, Trevor, Emmi, and Tad.
—William C. Whiting

Contents

Preface

The purpose of the first and second editions of *Biomechanics of Musculoskeletal Injury* was to explore the mechanical bases of musculoskeletal injury to better understand the mechanisms involved in causing injury, the effect of injury on musculoskeletal tissues, and, ultimately, how injury might be prevented. That fundamental purpose remains unchanged in this third edition as injury continues to be a pervasive and inevitable part of our lives. However, the title of this third edition has been updated to *Biomechanics of Injury* to reflect the expanded discussion of injury beyond those of the musculoskeletal system.

Biomechanics of Injury was written primarily for undergraduate students in the fields of exercise science, kinesiology, human movement studies, physical education, biomechanics, physical therapy, occupational therapy, and athletic training. The book may also serve as a supplemental reference for practitioners in the fields of orthopedics, sports medicine, sport performance sciences, rheumatology, physical medicine and rehabilitation, physical therapy, occupational therapy, chiropractic medicine, ergonomics, public health, and health and safety sciences.

In this third edition, the format of the inaugural two volumes is fundamentally preserved as the subject matter is enhanced by new research and updated statistics, greater emphasis on lifestyle issues and a life-span approach, new topics and technologies, updated figures, and more photographs.

We are very fortunate to have Dr. Steven Broglio collaborate with us in generating this third edition of the book. His expertise and professional experience significantly expanded key content in chapter 5 (Concepts of Injury and Healing) and chapter 8 (Head, Neck, and Trunk Injuries). At the University of Michigan, Dr. Broglio is a professor of athletic training and the director of the Michigan Concussion Center and the NeuroTrauma Research Laboratory, where he oversees clinical care, educational outreach, and multidisciplinary research aimed at answering fundamental questions about concussion prevention, identification, diagnosis, management, and outcomes.

How This Book Is Organized

In this expanded third edition, we begin chapter 1 with an introduction to the interdisciplinary study of biomechanics and explore the mechanical aspects of injury, briefly assessing the prevalence of injury in our society and the physical, monetary, and emotional costs that result.

Chapter 2 establishes the structural foundation to both appreciate the normal functions of the human musculoskeletal and neuromotor systems and understand how injury may affect these functions. The key roles of embryology and tissue development in determining the morphology and mechanical behavior of the mature human structure are explained, and we highlight the details of tissues that are most often involved in injuries (e.g., bone, cartilage, tendon, ligament, and neural structures). Because many functionally disabling injuries affect joints, chapter 2 concludes with an examination of arthrology, or joint mechanics.

Chapter 3 presents biomechanical concepts essential for understanding injury. These mechanical parameters, such as force, stress and strain, stiffness, and elasticity are explained in the context of tissue injuries. This third edition is expanded to include more in-depth discussions on the application of mechanical principles to tissue mechanics and injury. Although mathematics is inextricably intertwined with biomechanics, we keep mathematical calculations to a minimum, instead emphasizing mechanical concepts.

Chapter 4 includes an introduction to the principle of overload and how this principle applies to tissue adaptation. The chapter builds on information from earlier chapters to explain how tissues respond to mechanical loading in both normal and abnormal environments and how these tissues are tested experimentally to quantify their mechanical behavior. Because a multitude of factors affect the musculoskeletal and neural systems' responses to various forces, we discuss several of these factors, such as age, gender, nutrition, and exercise, with an emphasis on how a person's lifestyle choices might lessen the chance or severity of injury.

With a foundation in the scientific bases of tissue structure and function in place, we progress, in chapter 5, to the exploration of injury mechanisms. This third edition expands the link between basic mechanical properties of tissues and their clinical application and explores in greater depth applied topics such as ergonomics, osteoporosis, and nervous tissue injuries.

The final three chapters delve into the essentials of regional injuries. We begin with the lower extremity in chapter 6, looking in detail at injuries such as ankle sprains, stress fractures, compartment syndromes, and meniscal tears. Chapter 7 examines injuries of the upper extremity, including rotator cuff tears, impingement syndrome, and carpal tunnel syndrome. Finally, chapter 8 discusses injuries of the head, neck, and trunk, including concussion and intervertebral disc injury. With each of these three chapters, our goal is provide a deeper understanding of the mechanisms responsible for specific regional injuries in order to assist with more effective diagnosis, treatment, and prevention.

Special Features of This Book

This text includes the following features to help you understand and retain the information:

- *Objectives* at the start of each chapter highlight the main concepts.
- *Key terms* appear in **bold** in the text and are defined in the glossary.
- *Sidebars* cover special topics of interest, ranging from famous cases to closer examination of specific injuries.
- *Key Points* at the end of each chapter summarize central concepts.
- *Questions to Consider* appear at the end of each chapter to test your understanding and your ability to synthesize and apply the information presented.
- Updated *Suggested Readings* are included at the end of each chapter for students who wish to dive deeper into selected topics.

In each of the final three chapters we present a detailed exploration of a select injury in *A Closer Look.* These include new or expanded sections highlighting topics of current concern such as anterior cruciate ligament (ACL) injury, rotator cuff pathologies, and concussion.

Instructor Resources

In addition to these textbook features, we also provide ancillary products via HK*Propel*.

- ***Presentation package*.** The presentation package includes more than 300 slides based on the material in the book that you may use directly or modify for your lecture outlines.
- ***Image bank*.** The image bank includes most of the figures and tables from the book, separated by chapter, which you may use for lecture materials.
- ***Test package*.** The test package includes more than 190 questions in various formats: multiple-choice, true-false, fill-in-the-blank, and short answer or essay.
- ***Instructor guide*.** The instructor guide provides instructors with a sample syllabus and a sample course outline for organizing lectures and chapters. It also includes supplemental lecture aids, notes, and guidance. The instructor guide also presents outlines for suggested student answers to the review questions found at the end of each chapter.

Closing Thoughts

Knowledge of the biological responses of tissues to mechanical loading improves our understanding of injury and its consequences and will enable you, as a health professional, to reduce the likelihood that your clients, patients, or athletes will experience painful and debilitating physical injury.

Acknowledgments

A project of this scope involves the unique contributions of many more people than the three listed on the book's cover. We extend our appreciation to those friends and colleagues. We thank Rainer Martens and the staff at Human Kinetics, in particular the devoted efforts of Loarn Robertson, Elaine Mustain, Melissa Zavala, Jolynn Gower, and Judy Park for sharing our belief in the importance of this project. We acknowledge the hundreds of colleagues and thousands of students who shaped our philosophies, guided our progress, and provided inspiration for our professional work for more than 35 years. In particular, Ron Zernicke acknowledges and thanks two University of Michigan students (undergraduate Ishan Bhalgat and postdoctoral fellow Geoffrey Burns, PhD), who uniquely and creatively provided their perspectives and feedback on chapters 2 and 4. Most importantly, we thank our families for their support, patience, and love while we completed this project. Without them, our work and lives would have little meaning.

PART I

Introduction and Foundations

1

Overview and Perspectives on Injury

We must have perseverance and above all confidence in ourselves. We must believe that we are gifted for something and that this thing must be attained.

Marie Curie (1867-1934; Nobel Laureate 1903 and 1911)

OBJECTIVES

- To define and explain injury, mechanisms of injury, and biomechanics
- To explain the multidisciplinary nature of injury analysis
- To describe perspectives on injury, including historical, epidemiological, health professional, economic, psychosocial, safety professional, and scientific

Injury pervades everyday life. Although people may sustain injuries of varying severity, and some are injured more frequently than others, virtually no one is spared the pain, distraction, and incapacity caused by injury. Along with injury come inevitable physical, emotional, and economic costs, as well as loss of time and normal function.

The worldwide impact of these costs and losses is staggering. The World Health Organization (WHO 2014) reports more than 14,000 fatal injuries *daily*, which projects to more than 5 million injury-related deaths worldwide each year. As tragic as fatal injuries are, they account for only a small percentage of overall injury totals (figure 1.1).

Injury-related deaths are not evenly distributed across the socioeconomic spectrum. Accounting for population size, injury death rates are higher in lower-income countries than in higher-income countries (WHO 2014)—an estimated 90% of fatal injuries occur in low- and middle-income countries. In reporting a systematic analysis of the "global burden" of 369 diseases and injuries in 204 countries and territories, Vos et al. (2020) also pointed to regional differences in health challenges worldwide. Haagsma et al. (2016) concluded that "injuries continue to be an important cause of morbidity and mortality in the developed and developing world. The decline in rates for almost all injuries is so prominent that it warrants a general statement that the world is becoming a safer place to live in. However, the patterns vary widely by cause, age, sex, region and time and there are still large improvements that need to be made" (p. 3).

U.S. National Safety Council (2022) estimates indicate that every 10 minutes, three people from the United States are killed as a result of injury. In the United States, unintentional injury ranks only behind heart disease, cancer, and as of 2020, COVID-19 as a leading cause of death. Prior to 2016, injury-related deaths also ranked behind cerebrovascular disease (stroke) and chronic obstructive pulmonary disease, but vaulted up the rankings based on Centers for Disease Control and Prevention (CDC) estimates from those years.

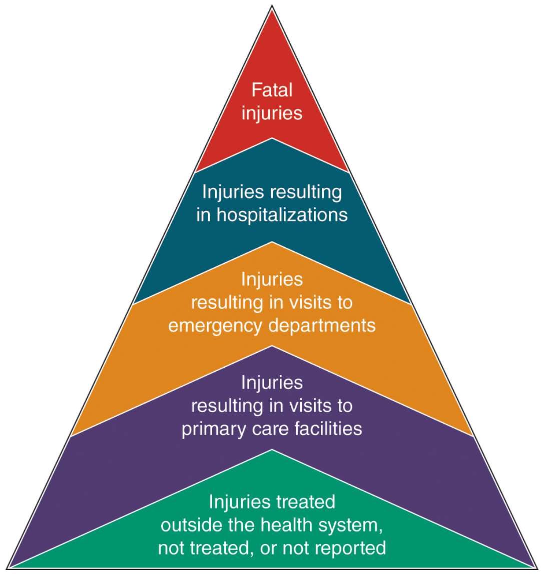


FIGURE 1.1 Injury pyramid.

Reprinted by permission from *Injuries and Violence: The Facts,* (Geneva, Switzerland: World Health Organization, 2014), 6.

Such fatality statistics paint only a partial picture of the impact of injury. Nonfatal accident statistics are even more astounding. Disabling injuries affect more than 20 million people each year in the United States. Every 10 minutes, 885 people in the United States suffer an injury severe enough to require professional medical attention, adding up to an estimated 40 million injury-related emergency room visits in the United States in 2017 (National Center for Health Statistics 2017). (More extensive injury statistics are available on the CDC's Web-based Injury Statistics Query and Reporting System, or WISQARS.)

From the perspective of potential life span remaining and years of potential life lost, the impact of injury-related death is more significant than the impact of death from other causes. Using years of potential life lost as a measure of impact, in 2013 the NCIPC identified unintentional injuries as the leading cause of death, accounting for more than 2 million years lost, outpacing both cancer and heart disease.

Despite historically high rates of injury and significant negative consequences, all is not dark news. On a positive note, a study by Kegler et al. (2017) concluded that, "Increases in life expectancy of the magnitude considered in this report are arguably attainable based on long-term historical reduction in the US injury death rate, as well as significant continuing reductions seen in other developed countries. Contemporary evidence-based interventions can play an important role in reducing injury-related deaths" (p. 1).

Definition of Injury

As will become clear in the following chapters, many injuries have a mechanical cause. Forces and force-related factors can lead to injury and influence the severity of injury. Before delving into the multiple facets of injury, however, we will establish a working definition: **Injury** is the damage sustained by tissues of the body in response to physical trauma. This definition is less encompassing than other generally accepted notions of injury (which may include thermal, chemical, electrical, or radiation causes), but is useful in the context of the biomechanics of injury.

The term *injury* usually is associated with negative outcomes. In some situations, however, injury may be involved in events with positive consequences. In the bone remodeling process, for example, bone must first be "injured" to prepare it for subsequent positive adaptive changes.

Biomechanics is the area of science related to the application of mechanical principles to biological organisms and systems. The number of potential areas of study in biomechanics is immense. Topics as diverse as blood flow dynamics, human and animal locomotion, artificial limbs and prosthetic design, sports, and biomaterials fall under the rubric of biomechanics. The mechanical causes and effects of forces applied to the human musculoskeletal and nervous systems are the primary focal points of our text, within the broader area of biomechanics.

As we explore injury biomechanics, key terms will recur, so we define them at the outset. The first, **mechanics**, is the branch of science that deals with the effects of forces and energy on bodies, materials, and structures. Second, a **mechanism** is defined as the fundamental physical process responsible for a given action, reaction, or result. Chapters 6 through 8 examine in detail the mechanisms of many musculoskeletal and neural injuries.

Perspectives on Injury

The problem of musculoskeletal injuries cannot be addressed effectively by any single discipline examining injury in isolation. Exploration of the biomechanics of injury is an interdisciplinary endeavor that includes anatomy, physiology, mechanics, kinesiology, medicine, engineering, and psychology. In 1996, Caine et al. stated that extensive research on injury supported the notion that "we know many facts—but we lack integrated answers" (p. 1). Although progress has been made in recent decades, further meaningful progress in addressing the problems of injury biomechanics will require an interdisciplinary approach.

Those with an interest in studying injury include physicians, physical therapists, kinesiologists, prosthetists, orthotists, nurses, occupational therapists, chiropractors, osteopaths, ergonomists, safety engineers, strength trainers, athletic trainers, coaches, and athletes, each with their own perspective on injury.

Historical Perspective

As we know from lesions in vertebrate fossils and pathologies in prehistoric bones, injury is as old as life. Skeletal remains of the earliest humans reveal arthritis and fractures, suggesting that at no time have we been invulnerable to injury. The nature of injuries can provide insight into the history of an era. Some ancient Egyptian skeletons, for example, show a fracture of the left ulna, perhaps a result of self-defense from an overhead blow by a club. Today, these types of fractures are sometimes called *nightstick fractures*. Evidence of musculoskeletal disorders is commonly seen in the art of ancient civilizations (figure 1.2).

What's in a Word: Accident or Injury?

Hear the word **accident** and most people envision an event that is unexpected, by chance, unintentional, or—as insurance companies like to say—an "act of God." *Accident* sometimes is used synonymously with *injury* in practical situations. However, this can be an ambiguous and misleading descriptor. *Accident* implies a degree of human error or involvement, but that is not always the case—not all accidents involve injuries and not all injuries are accidental in nature.

Robertson (2018) proffered an interesting take on the issue. He wrote:

> "Accidents" refer to a very large and fuzzily defined set of events, only a small proportion of which are injurious. Any unintended, incidental event that interferes in one's daily pursuits is an accident. In writing these few paragraphs, I had several accidents in typing, but hopefully they will be corrected enough so as not to irritate the reader, and thus become irrelevant to my exposure to risk of injury. (p. 14)

Some years ago, Suchman (1961) provided a list of still-relevant indicators that increase the likelihood that an event is accidental. These indicators are the degree of expectedness, avoidability, and intention. If an event is unexpected, unavoidable, and unintentional, it likely is accidental.

No single definition of *accident* will satisfy everyone. So what should be done? Some organizations no longer officially include the word *accident* in their professional vocabularies at all. In some scientific circles, the word *accident* has been replaced with more specific terminology: What were formerly accidental injuries are now referred to as *unintentional injuries*, and car accidents are now commonly termed *motor vehicle crashes*.

In any case, as Eeyore mused in A.A. Milne's *The House at Pooh Corner*, "They're funny things, Accidents. You never have them till you're having them."

Attempts to treat the injured are nearly as old as injury itself. Archeologists have uncovered evidence of splints and primitive surgical implements (e.g., obsidian knives). Indian surgeons circa

1000 to 600 B.C., predating Hippocrates by several centuries, used instruments such as forceps, scissors, and knives. The Indian surgeon Sushruta documented diseases and drug treatments, as well as 300 or so surgical procedures and treatments for various injuries.

In Western cultures the evolution of medicine into a specialized profession with rational tenets of practice is generally acknowledged to have begun with Hippocrates. Although their knowledge of anatomy was scant and their procedures were often crude by modern standards, Hippocrates and other Greek physicians established the foundations that form the basis for the study and treatment of injury today. Similar advances are documented in Eastern cultures. In China, for example, the *Huangdi Neijing*, a two-text set (*Suwen* and *Lingshu*), covered the theoretical bases of Chinese medicine, diagnostic methods, and acupuncture therapies.

a *b*

FIGURE 1.2 Ancient *(a)* Greek and *(b)* Indian depictions of injury and treatment.

Besides the physicians of the day who studied and treated injury, some of history's great names, often heralded for other pursuits and accomplishments, highlighted injury in some form and accorded it recognition in their work. The Greek poet Homer, in his classic *Iliad*, wrote often of trauma and treatment, describing more than 100 specific wounds and injuries (Apostolakis et al. 2010; Kayhanian and Machado 2020; Koutserimpas et al. 2017; Galanakos et al. 2015; Hutchison and Hirthler 2013; Mylonas et al. 2008; Swinney 2016).

With the decline and eventual fall (146 BC) of the Greek Empire, much of the accumulated Greek knowledge shifted to Byzantium (Asia Minor), Alexandria, and then Rome. Notable among practitioners of this era was Galen (AD 129-199). Galen's work has been credited with defining, for better or worse, the direction of medical treatment for the next 1,500 years. Among his contributions were an appreciation of the nature of muscle contraction; a fundamental understanding of anatomy (although human dissection was still centuries away); the treatment of spinal deformities such as kyphosis, scoliosis, and lordosis; and the use of pressure bandages to control limb hemorrhage (Rang 2000). Soon after Galen's death the Roman Empire declined, and with its abrupt fall in AD 476, western civilization entered the Dark Ages, virtually halting progress in medical science.

The entire world, however, did not suffer the ravages of Europe's Dark Ages. In China during the Tang dynasty (AD 619-901), for example, surgery (e.g., orthopedic treatment of fractures and dislocations) was recognized as a special branch of medicine (LeVay 1990). During the Islamic Golden Age, Inb Sina (known in the West as Avicenna [AD 980-1037]) wrote extensively across many disciplines, including psychology, logic, theology, mathematics, physics, and medicine. His most notable works, *The Canon of Medicine* (1025) and *The Book of Healing* (1027), were used as the foundation of science and medicine in many medieval civilizations and universities for centuries.

Later, as Europe emerged from the Dark Ages, renewed creative energies were applied to medical problems. Anatomical investigation flourished, most notably by Vesalius (1514-1564), whose anatomical drawings still inspire wonder (figure 1.3). As knowledge of human anatomy advanced, so too did understanding of how the body functions.

Leonardo da Vinci (1452-1519), perhaps the best-known figure of the Renaissance, was intrigued by the nature of pain and trauma. In his art we find exquisite depictions of physical pain and agony. In his scientific writing we also find many references to trauma, especially that caused by what he termed *percussion* (impact). From his deep interest in human anatomy, da Vinci was aware that joints in the body serve as shock absorbers. Noticing that the pain produced by landing from a jump on the heels is much greater than when landing on the toes, he deduced "that which gives more resistance to a blow suffers most damage."

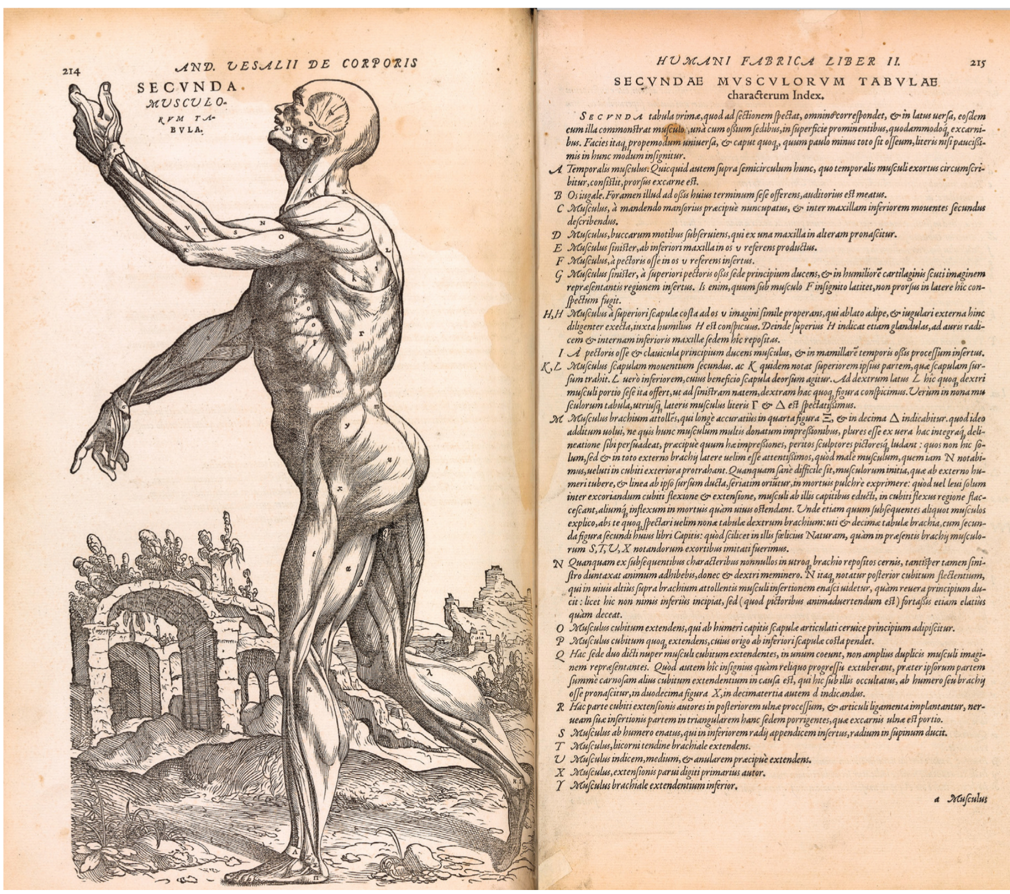


FIGURE 1.3 A "muscle man" from Vesalius's *Fabrica*.

da Vinci had an abiding fascination with the body's senses and in particular with the sense of pain. Although he knew that pain served an important protective function, Leonardo also saw it as the "chief evil" in life, concluding that "the best thing is the wisdom of the soul; the worst thing is pain of the body" (Keele 1983, p. 237). The insights of da Vinci and other great thinkers of the Renaissance era may seem elementary, even naive, compared with current levels of understanding, but compared with the knowledge that was available and accepted for many centuries, their breakthroughs were extraordinary.

With the advent of the Industrial Revolution in the 19th century, medical progress accelerated. Although many new problems arose—notably injuries caused by machinery—the period brought a welcomed prospect for rapid developments in medicine. With the discovery of anesthesia and antiseptics, surgical success improved dramatically. Florence Nightingale (figure 1.4), recognized as the founder of modern nursing, also played a prominent role in introducing hygiene standards and reducing infections during the Crimean War (1853-1856). Furthermore, advances such as clinical arthroscopy, pioneered by Eugen Bircher in the early 1900s, showed the promise of rapidly developing technologies.

Progress continues today, and advancements in the diagnosis and treatment of injury show no sign of slowing. Even a few decades ago the suggestions of routine joint replacement, laser surgery, advanced imaging techniques, microsurgery, and computer- or robot-assisted surgery were viewed as futuristic speculation. Continuing advancements in materials science, computer technology, nanotechnology, robotics, tissue engineering, and genetic engineering promise even more spectacular advances to come. Although technological progress holds great promise, we must not forget that technology can be a double-edged sword. The technological saber swung in one direction has the potential to prevent injury and aid in its diagnosis and treatment, but wielded in the opposite direction has potential to create or exacerbate injury as well. As long as injury remains an unfortunate fact of everyday life, challenges will undoubtedly change but not vanish.

FIGURE 1.4 Florence Nightingale in the Military Hospital at Scutari, 1855.

Epidemiological Perspective

Questions about injuries, such as how many, how often, what kind, and to whom, are central to epidemiology. **Epidemiology** is the study of the distribution and determinants of disease and injury frequency within a given human population. In most cases, the distinction between disease (e.g., measles) and injury (e.g., torn ligament) is clear. In other cases the picture is less clear, and deciding whether a malady is a disease or an injury may not be as obvious. Although we focus on musculoskeletal and neurological injuries, disease can be a contributing factor, because certain diseases may predispose an individual to injury (e.g., osteoporosis can lead to bone fractures).

Hippocrates and Injury

Hippocrates (460–377 BC), generally acknowledged as the "father of medicine," treated numerous injuries in his role as a physician and described in detail many of the orthopedic conditions he encountered. Although some of his descriptions were flawed in light of our current understanding, he successfully treated injuries on a regular basis and related his techniques and results in documentary form. Hippocrates' descriptions of treating shoulder dislocations, for example, gave numerous artists the material to depict the procedures. Hippocrates, with biomechanical insight, noted that even an old dislocated shoulder could be reduced (i.e., bones brought back to their normal position), "for what could not correct leverage move?" (LeVay 1990, p. 24).

Among the many injuries Hippocrates described were acromioclavicular dislocation ("I know many otherwise excellent practitioners who have done much damage in attempting to reduce shoulders of this kind"), spinal deformities (with vertebrae "drawn into a hump by diseases"), and leg fractures ("All bones unite more slowly if not placed in their natural position and immobilized in the same position, and the callus is weaker") (LeVay 1990, pp. 26–37).

Depiction of historical technique of reducing a shoulder dislocation using a large wooden beam.

Reprinted from "Hippocrates," Wikipedia, accessed June 28, 2022, en.wikipedia.org/wiki/Hippocrates#/media/File:GreekReduction.jpg.

Hippocrates exhibited great insight in this summary observation:

> All parts of the body which have a function, if used in moderation and exercised in labours to which each is accustomed, thereby become healthy and well-developed: but if unused and left idle, they become liable to disease, defective in growth, and age quickly. This is especially the case with joints and ligaments, if one does not use them. (LeVay 1990, p. 30)

Epidemiological studies are typically either descriptive or analytical in nature. The first of these, **descriptive epidemiology**, is the most common form of epidemiological research. Types of descriptive epidemiological designs include case reports or case series, cross-sectional surveys, and correlational studies. The purpose of such approaches is to quantify the distribution of disease or injury and address questions pertaining to occurrence (how many injuries occur?), person (who is getting injured?), place (where are the injuries occurring?), and time (when are the injuries happening?).

On the surface, this process should be straightforward, and in most cases it is. However, identification and classification of a specific injury can be problematic, either because clinical manifestations may be similar although the underlying pathology differs, or because there may be multiple injuries resulting from a single incident, which makes classification difficult. Care is essential in classifying injuries so that the resulting categories are mutually exclusive (is an injury suffered in a delivery truck crash a vehicular injury or a work-related injury?), exhaustive (is there a category for every injury?), and useful (does the classification system have practical and meaningful application?).

Clear terminology is essential when we examine the biomechanics of injury. With respect to descriptive epidemiology of injury, results are most commonly reported as either incidence or prevalence rates. Many people use the terms *incidence* and *prevalence* interchangeably. However, incidence and prevalence are in fact distinctly different terms and, when one is analyzing injuries, provide very different estimates.

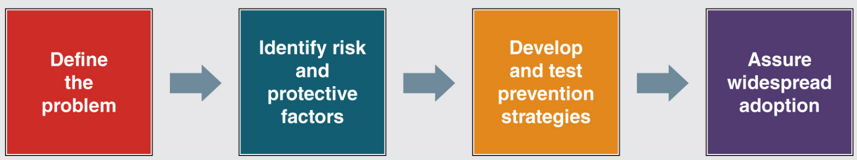
- **Prevalence** describes the number of cases (e.g., injuries), both new and old, that exist in a given population at a specific point in time. For example, the World Health Organization (WHO) reports that more than 200 million people suffer from osteoporosis worldwide (Kanis 2007). This equates to an overall prevalence rate of about 270 in 100,000 persons. However, the prevalence rate is much higher in older populations.
- **Incidence** describes the number of *new* cases that occur within a given population at risk over a specified time period. For example, there are about 340,000 hip fractures in the United States annually (IOF 2020), which equates to an incidence rate of about 103 in 100,000 persons, with higher incidence rates in older groups.

Analytical epidemiology involves complex research strategies to reveal the determinants or underlying causes of disease and injury. Questions such as *how* and *why* injuries happen are addressed by identifying and analyzing factors that may contribute to the occurrence of injury. These contributing factors are known as **risk factors** and are classified as either *intrinsic* or *extrinsic*. Intrinsic risk factors are characteristics of a biological or psychological nature that may predispose an individual to injury. Examples of intrinsic risk factors include physical characteristics such as gender, age, family history of injury or disease, and somatotype or body composition; performance characteristics such as muscular strength, balance, flexibility, or endurance; and cognitive characteristics such as level of anxiety, self-esteem, and self-efficacy.

Public Health Approach to Injury Prevention and Control

One valuable use of descriptive epidemiology in the community is public health surveillance. Surveillance is a systematic and ongoing collection, analysis, interpretation, and dissemination of public health information to assess public health status, define priorities, and evaluate programs set in place to improve the health of a community. Surveillance is carried out by health agencies for a number of reasons, such as estimating the magnitude of a problem, detecting epidemics, generating hypotheses, stimulating further research, evaluating present levels of health care, determining the geographic distribution of a disease, and facilitating planning and resource allocation. *Who*, *what*, *where*, and *when* are addressed, resulting in valuable information that is applicable and accessible to the public.

There are four steps to gathering this information, termed the **public health approach**:



Reprinted from "Injury Prevention and Control: Our Approach," Centers for Disease Control and Prevention, accessed June 28, 2022, www.https://www.cdc.gov/injurEy/about

In contrast, extrinsic risk factors are external or environmental characteristics that influence a person's injury risk, such as the safety conditions, programs, or the use or misuse of protective equipment within a workplace. With respect to sporting events, these factors might include the level of competition, training schedule, or weather conditions during the event. Difficulties arise in the identification of risk factors because in most situations, factors act in concert to result in injury or disease. Before a **causal association** between a risk factor and an injury outcome can be established, the factor under investigation must be examined through a multifactorial model of causation. Intrinsic risk factors are thought to predispose an individual to injury, and once a person is susceptible, extrinsic or "enabling" factors may interact with predisposing factors to increase the likelihood of injury (Meeuwisse et al. 2007) (figure 1.5). Investigators must exercise caution in assigning causal relations to injury by ruling out the possibility of mere correlation or coincidence. Much of the epidemiological information about the biomechanics of injury cannot be used directly because it is described according to circumstance (e.g., injury attributable to automobile collision) rather than by a specific causal agent or mechanism.

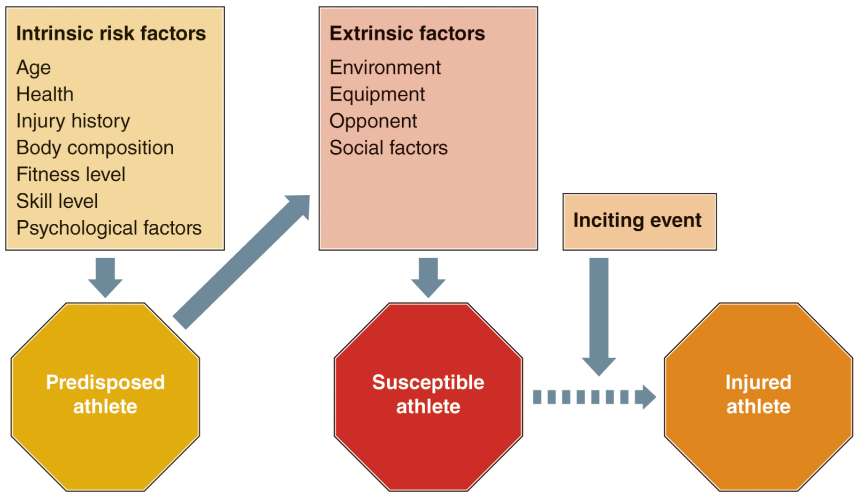


FIGURE 1.5 Sport injury risk assessment and causation: A multifactorial issue.

Adapted from Meeuwisse et al. (2007).

Recently, complex systems modeling has been used to improve our understanding of the relation between risk factors and injury causation patterns (Bittencourt et al. 2016; Fonseca et al. 2020; Hulme et al. 2019). These models seek to explore the interactions of what Philippe and Mansi (1998) termed the "web of determinants," rather than trying to evaluate singular risk factors.

Relative risk is an epidemiological measure used to quantify the likelihood of injury occurrence in one group versus another group. Relative risk is calculated as the injury incidence in group A divided by the injury incidence in group B. For example, you could calculate the relative risk of stress fractures for female long-distance runners as compared to same-age sedentary women with data for these two groups—but not their relative risk compared to other groups (e.g., male runners, sprinters, and older women). When using any statistical measure, investigators must ensure that injury rates are calculated from reliable data and that conclusions based on rates are valid. Caution, care, and clear thinking are warranted before using or accepting any statistical measures, including those for rates of injury.

These statistical data can be found from a variety of sources. The World Health Organization (WHO) reports a variety of international injury data, such as its 2014 publication *Injuries and Violence: The Facts*, as well as national reports such as *The High Burden of Injuries in South Africa* (2007). The International Labour Organization, a specialized agency of the United Nations, is another source of data through their efforts to promote safe work environments. Other global-region organizations, such as the European Injury Database (EU-IDB) and the Latin American Association of Safety and Hygiene at Work (ALASEHT), also provide a wide array of injury information.

Many countries have national organizations that gather and report injury-related data. In the United States, the National Safety Council, the Occupational Safety and Health Administration (OSHA), insurance companies, and traffic safety boards routinely collect and publish accident and injury data. Health Canada collects similar data annually for Canada, as does Safe Work Australia, the Japan Industrial Safety and Health Association, the Chinese Center for Disease Control and Prevention, and many others.

For two primary reasons, much of the available injury data are for injury-related deaths. First, the catastrophic nature of fatalities makes them prominent and definitive, and second, death statistics are easy to compile. Less attention is paid to the documentation of nonfatal injuries, especially those of a minor nature that may never be reported at all. This raises a question: What percentage of all injuries are actually reported? The answer to that question is unknown. Certainly many injuries are never officially recorded, and therefore any published statistics undoubtedly underestimate the true injury toll.

In the United States in 2019, unintentional, preventable injury deaths totaled an estimated 173,040 (nearly two-thirds of them men), which translates to a rate of 51.1 injury deaths per 100,000 (National Safety Council 2022). In 2014, the World Health Organization estimated that on average, 9% of all mortality occurring in its member countries was attributable to unintentional injury. That percentage, however, varied substantially between high-income and low- and middle-income countries. Variation in injury-related death rates around the world is attributed to the influence of many economic, social, and cultural factors.

Deaths attributable to injury are also disproportionately higher in the young. According to the U.S. National Safety Council (2020), injury is the number one cause of death among individuals aged 1 to 44. Statistics for nonfatal injuries are equally daunting. In the United States, for example, the National Center for Health Statistics (NCHS 2022) estimated nearly 40 million injury-related emergency department visits in the United States in 2017. Virtually all nonfatal injury statistics are approximations based on hospital or commission records or extrapolations from interview surveys.

Health Professional Perspective

Many health professionals and organizations are involved in strategies to reduce the incidence and severity of injuries. In the United States, groups such as the National Safety Council, the Centers for Disease Control and Prevention, and the Consumer Product Safety Commission perform injury prevention analyses. Both Canada and New Zealand have injury prevention strategy organizations that function in much the same way. In Europe, Asia, Africa, and South America, the World Health Organization (WHO) is actively involved in similar analyses. At an individual level, safety engineers, ergonomists, safety consultants, job supervisors, health professionals, parents, teachers, coaches, and many others are in positions to stress safety and injury prevention.

Severe injuries often require immediate medical attention. Emergency medical personnel, such as paramedics, emergency room physicians, and support staff, provide life-saving emergency diagnosis and treatment. Less severe injuries may require nonemergency treatment. Physicians, athletic trainers, and other allied health professionals perform these less urgent diagnostic and treatment tasks. Many injuries, especially those requiring surgical treatment, require postsurgical rehabilitation to ensure a return to preinjury performance levels. Rehabilitation personnel (e.g., physical and occupational therapists) perform these essential services.

Economic Perspective

In addition to the physical and emotional costs, the financial costs of injury are enormous. Because public policy decisions are often based on fiscal considerations, the economic perspective of injury requires comment.

In comparison to long-recognized public health hazards such as cardiovascular disease and cancer, only in the last several decades has injury been recognized as a true public health hazard. A watershed study, *Injury in America* (Committee on Trauma Research 1985), helped bring injury into the public health spotlight and prompted the U.S. Congress to commission a study on the economic and noneconomic impact of injury. Results of that study showed that injury had a tremendous effect on both individuals and society as a whole (Rice and Max 1996).

The National Safety Council estimated the total cost of unintentional injuries for 2019 at more than $1 trillion (USD). On average, that breaks down to $118 million per hour! This includes estimates of such economic losses as employer costs, vehicle damage, fire losses, wage and productivity losses, medical expenses, and administrative expenses. If to that $1 trillion we add a similar estimated amount for lost quality of life from those injuries, the resulting comprehensive cost of injury for 2019 alone is well more than $2 trillion.

Soon after the landmark 1985 *Injury in America* study, Runge (1993) issued a challenge to health professionals to become more involved as advocates for injury prevention and control, thereby contributing to efforts to limit the present cost of injury. Because we all pay the price that injury exacts, his challenge remains germane today.

Psychosocial Perspective

The most obvious consequence of injury is the direct, physical damage to bodily tissues. However, often overlooked are the psychological and social factors that may be involved before, during, and after an injury. Collectively, consideration of all these areas has been termed a *biopsychosocial approach* to injury (Brewer and Redmond 2017). These factors can influence the likelihood and severity of injury and the course of healing and rehabilitation. Aspects of injury in which psychological factors may be integrally involved include risk behaviors and predisposition to injury, human error and accidents, theories of causation, risk evaluation, and emotional response to injury.

Ivarsson et al. (2017) performed a meta-analysis of psychosocial factors and sport injuries and concluded that psychosocial variables, along with psychological-based interventions, can influence injury risk in athletes. They specifically found that high levels of negative stress and strong stress responsivity were strongly associated with injury risk, and that psychological-based interventions reduced the rate of injuries (compared to control groups).

The likelihood of being injured depends largely on the task in which a person is engaged, the environment in which the injury occurs, and the person's psychological state. Some activities such as playing football or occupations such as oil drilling are inherently riskier than others. Certain environments, such as rugged outdoor terrain or construction sites, are more risk laden than an office environment. In addition, certain psychological states, such as inattention, distraction, fatigue, or stress, may predispose a person to injury.

Key points from a discussion of the role of human error, accident causation, and risk evaluation in injury prevention and control by Sanders and McCormick (1993) highlight the importance of including psychological factors in the overall context of injury analysis:

- Human error (defined as an inappropriate or undesirable human decision or behavior that reduces or has the potential to reduce effectiveness, safety, or system performance) is responsible for many events leading to injury. Human error leading to injury typically results from the direct action of the injured person but also may be an indirect human error, such as a poor decision made by an engineer in designing a particular product or device. Human error may be reduced by (1) selection of people with appropriate skills and capabilities to perform a particular task, (2) proper training, and (3) effective design of equipment, procedures, and environments. With regard to the third point, direct human error may be incorrectly identified as the cause of injury when the real culprit is indirect human error involved in poorly designed equipment or faulty construction.

• Many psychological theories have been proposed to explain accident causation (with due deference to our earlier comments on use of the word *accident*), including the following:

- *Accident-proneness theory* (some people are more prone to accidents than others)
- *Accident-liability theory* (people are prone to accidents in given situations and this tendency is not permanent)
- *Capability–demand theory* (accidents increase when job demands exceed the capability of workers)
- *Adjustment-to-stress theory* (accidents increase in situations with stress levels that exceed an individual's coping capabilities)
- *Arousal–alertness theory* (accidents are more likely when arousal is too low or too high)
- *Goals–freedom–alertness theory* (freedom of workers to set their own goals results in high-quality performance, which reduces accidents).

No single theory adequately explains all accidents and their resulting injuries; a more likely scenario is that a unique combination of factors is involved in each injury.

• **Risk** refers to the likelihood of injury or death associated with a particular object, task, or environment. The perception and evaluation of risk are important for determining whether an injury will occur and, if it does, the severity of the injury. Interestingly, studies indicate that although most people are quite capable of discerning the relative risk between various activities (e.g., using a computer is less risky than riding a bicycle), their ability to estimate the absolute risk is not nearly as accurate. Perception of risk may be distorted by overestimating the value of one's own expertise and experience, overemphasizing situations receiving media attention, and adopting a philosophy that "it can't happen to me."

Psychological factors are important influences before, during, and immediately following the injury and in the postinjury period, which may last for weeks, months, or even years. Although the psychological factors summarized by Heil (1993) are specific to athletes, many of the factors are applicable to general injury situations as well (table 1.1). Other factors that could be added to the list include family support structures, need to work, and malingering.

TABLE 1.1 Psychological Factors in Injury

Factors preceding injury	Factors associated with injury	Factors following injury
Medical history	Emotional distress	Culpability
Psychological history	Injury site	Compliance with treatment
Somatization	Pain	Perceived effectiveness
Life stress and change	Timeliness	Treatment complications
Sport stress and change	Unexpectedness	Pain
Approach of major competition		Medication use
Marginal player status		Social support
Overtraining		Personality conflicts
Sport-related health risk factors		Fans and the media
		Litigation

Adapted by permission from J. Heil, *Psychology of Sport Injury* (Champaign, IL: Human Kinetics, 1993), 75.

Many injuries, and certainly those that draw the most media attention, occur among athletes. The psychological profiles of highly competitive, elite athletes are in some ways different from those of the general population. These differences can be both beneficial and deleterious when dealing with injury and the recovery process. As noted by Heil (1993), the positive psychological attributes found in many athletes are high levels of motivation, pain tolerance, goal orientation, and good physical training habits. On the negative side, athletes may experience a higher sense of loss, greater threat to their self-image, unrealistic expectations, and desire for a quick recovery, and they may have higher, sport-specific demands to meet than do those in the general population.

Nixon (1992) described a "culture of risk" associated with high-level competitive athletes in which they have been socialized to accept and endure injury and pain as normal components of athletic participation, ignore pain and continue to play while hurt, and conceal their injuries. Nixon (1992) argued that "the willingness of athletes to risk pain and injuries is affected by structural features of their sports networks (called 'sportsnets'), by relations with individual sportsnet members, and by 'the culture of risk' that is deeply embedded in serious athletic subcultures (p. 127).

Whether among athletes or the general public, there is little doubt that psychological factors play an influential role in a comprehensive assessment of injury, and should be neither underestimated nor ignored.

Safety Professional Perspective

The prevention and control of injuries, although not the primary focus of this text, are integral to a broad discussion of injury, and we would be remiss not to mention the role of safety professionals, such as safety consultants, ergonomists, safety engineers, and health and safety educators, in dealing with injury and its prevention.

Injury prevention programs are typically of two types: *injury control programs* and *health and safety education programs*. Collectively, injury prevention programs apply three strategies:

1. Safety education programs seek to persuade (educate) those at risk of injury to alter their behavior to increase self-

protection (e.g., to use helmets while cycling or to use seat belts while driving cars or flying in planes)

2. Injury control programs require changes in individual behavior by law or rules (e.g., enforce laws for mandatory seat belt use in cars, penalize football players who spear-tackle an opponent with the top of the helmet, and require protective eyewear while working with chemicals)
3. Injury control programs provide automatic protection by product or environmental design (e.g., airbags, passive restraints in cars, multidirectional release mechanisms for ski bindings, padding for fixed goalposts, and shock-absorbing heel materials for running shoes).

What injury prevention strategy is likely being applied in the scenario depicted here?

Of these three injury prevention strategies, automatic protection is the most effective, followed by requiring behavioral change. Persuading is the least effective of the three. Although education about injuries is important, many injuries result less from a lack of knowledge than from failure to apply what is known. Most people will acknowledge that it is safer to wear a mask as a baseball catcher or hockey goalie, but sometimes a mask is not available or the player chooses not to wear one. Health behavior research has shown that as the amount of individual effort required to adopt a safer behavior increases, the proportion of the population that will respond by adopting the behavior decreases. For example, the more difficult or cumbersome the protective equipment is to put on, the less likely players are to use it.

Education alone rarely has proven to be an adequate preventive strategy (Committee on Trauma Research 1985). The most successful attempts at changing individual behavior to prevent injuries have involved behaviors that were easily observable and required by law. For example, when laws required helmet use for motorcyclists, almost all complied. In Thailand, for example, after enforcement of a helmet law, the number of helmet wearers increased five-fold (Ichikawa et al. 2003).

Over the past century, safety researchers have developed a wide variety of accident causation models that have sought to clarify the cause, process, and injury consequences of accidents. In a recent comprehensive review of accident causation models, Fu et al. (2020) proposed a classification method specifying linear and nonlinear models, which they divided into human-based, statistics-based, energy-based, and system-based accident models.

A final strategy for preventing musculoskeletal injury worthy of mention in this section is maintenance of personal strength, flexibility, and good physical condition. Whether in the home, in the workplace, or in sports, people with better physical conditioning and flexibility are less likely to be injured, suffer fewer severe injuries, and recover from injury faster than those who are in poor physical condition. Indeed, one of the most important benefits of regular stretching and flexibility training may be the prevention of musculoskeletal injury. Proper flexibility training and pre-exercise stretching can reduce joint stiffness, muscle and tendon tightness, and exercise-related muscle soreness.

WARNING: Hazardous to Your Health

Warning signs, it seems, are everywhere. Their purpose is to inform product users or people in a certain environment of potential dangers posed by the product or place. For any warning to be effective, it must be designed to include the following elements:

1. A clear statement of the danger
2. A pictogram or signal word (e.g., WARNING)
3. A signal to ensure that the person at risk senses the warning (e.g., bright colors or flashing lights) and receives and understands the message (e.g., the message must be short, simple, and unambiguous)
4. A statement of the potential consequences
5. Instructions on what to do to avoid the danger

Effective warnings can go a long way toward reducing the incidence of injury and death in both work and recreational situations.

Considering the enormous numbers and types of injuries that occur, many challenges remain for safety professionals worldwide. The obstacles cross educational, legal, scientific, political, and economic disciplines, suggesting that the most effective solutions will likely be interdisciplinary or multidisciplinary in scope.

Scientific Perspective

Among all the perspectives on injury, the one that predominates in the following chapters is a scientific perspective. As stated earlier, many scientific disciplines have a role to play in a comprehensive understanding of injury. Anatomists, for example, study which structures and tissues are actually injured, physiologists examine the biological processes involved in tissue health and repair, psychologists are interested in the behavioral aspects of injury, and engineers design equipment and structures to minimize or prevent injury.

Of all the scientific disciplines, physics and its subdiscipline mechanics are arguably most central to the study of injury. The common denominator of this area of science is energy. Indeed, energy is called the agent of injury. Although thermal, electrical, magnetic, and chemical energy can cause injuries, most injuries involve mechanical energy. The fundamental relation between mechanical energy and injury highlights biomechanics as the logical discipline to study the causes and effects of human musculoskeletal injury.

In *Injury in America,* the Committee on Trauma Research (1985) reinforced the important role of biomechanics research in the prevention of injury with the following conclusions, which remain highly relevant more than three decades later:

- High priority should be given to research that can provide a clearer understanding of injury mechanisms.
- Quantification of the injury-related responses of critical body areas (such as the nervous system, thoracic and abdominal viscera, joints, and muscles) to mechanical forces is needed.

- High priority should be given to defining limits of human tolerance to injury, particularly with regard to segments of the population for whom data are extremely limited, including children, women, and older adults.
- Improvement in injury assessment technology is needed, including the development of methods to assess important debilitating injuries and causes of fatality, improvement of anthropomorphic dummies, and development of valid computer simulation models to predict injury in complex crash conditions.
- Organizations at all levels are needed to conduct research on injury mechanisms and injury biomechanics and ensure a supply of scientists trained in injury biomechanics.

Chapter Review

Key Points

- Statistics emphasize that injury is a serious public health problem that deserves our full attention, should be given greater priority, and should be addressed with combined approaches to prevention and control. Injury is a multifaceted problem, requiring a multidisciplinary approach to find and implement effective solutions.
- An accurate and comprehensive awareness of injury can be developed only by examining it from numerous perspectives. The historical perspective highlights the achievements of many individuals who advanced our knowledge in anatomy, physiology, injury, and trauma, and our current level of knowledge would not exist without the keen investigation, curiosity, and observations of these historical figures.
- An epidemiological perspective offers a chance to answer health questions both observationally (e.g., who, what, where, and when, with respect to injury)

and analytically (how and why). Incidence, prevalence, and risk factors are key measures to consider from an epidemiological perspective.

- Health and safety professionals are involved with injury prevention and treatment. Injury control and safety education programs can reduce the incidence and severity of injury to some degree. Nonetheless, injuries will still occur, and thus health professionals, whether emergency medical personnel, physicians, or athletic trainers, are needed to perform essential services critical to injury diagnosis and treatment.
- The cost of injury is enormous: One must consider not only the direct costs of injury, such as medical expenses and lost wages, but also the indirect costs, such as lost quality of life. Estimated costs of injury exceed trillions of dollars per year worldwide.
- Often overlooked, but nonetheless extremely important to both prevention and recovery from injury, are the psychological factors that may affect a person before, during, or after injury. Many theories have been proposed identifying psychological state as a predisposing risk factor to injury. Additionally, psychological state after injury greatly affects rehabilitation and recovery.
- Many scientific disciplines collaborate to address etiology, affected tissues, and the biological processes underlying injury. Arguably, the scientific discipline of physics, and more specifically the subdiscipline of mechanics, is most pertinent to understanding musculoskeletal and neurological injuries and their prevention.

Questions to Consider

1. Explain why effective consideration of musculoskeletal injury requires a multidisciplinary approach.
2. Our understanding of injury mechanisms, diagnosis, and treatment has increased rapidly in recent decades. Looking into the future, if you were to write a chapter on the history of injury research from the present until the year 2040, what would you cover?
3. What are the limitations of examining injury from a single perspective (e.g., only from a biomechanical viewpoint)?
4. As an injury epidemiologist, you have been hired by a manufacturing company to investigate a recent increase in the rate of work-related injuries. What steps would you take to conduct a comprehensive assessment of the problem?
5. Consider a sport psychologist working with an Olympic-level athlete who has recently suffered a potentially career-ending injury. What factors should the psychologist keep in mind while assisting this athlete?
6. What do you see as the most important future areas of injury-related research?

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2

Classification, Structure, and Function of Biological Tissues

Form follows function.

Louis Henri Sullivan (1856-1924)

OBJECTIVES

- To learn the embryonic origins of the body's tissues, focusing on the connective tissues that form the key elements of the musculoskeletal system
- To understand the common and unique constituents and features of musculoskeletal tissues, including bone, cartilage, tendons, ligaments, skeletal muscle, and joints
- To be able to describe the unique roles that connective tissues and skeletal muscles play during normal function and after injury
- To understand and appreciate how the anatomical structures of joints influence the ranges and planes of motion of the human musculoskeletal system

For centuries, load-bearing connective tissues, such as bone, ligament, tendon, and articular cartilage, were considered nonreactive structures, which reacted uniformly to mechanical stress. In reality, these tissues are dynamic and respond to varying physiological and mechanical stimuli—including injury. This chapter provides background on the formation, structure, and adaptability of musculoskeletal tissues (e.g., bone, cartilage, tendons, ligaments, skeletal muscle, and joints) so we can better understand the underlying mechanisms of their unique responses.

Embryology

To understand normal musculoskeletal system function and injury outcomes, we need to understand the formation and organization of body tissues. Just as woven threads form a fabric, cells, fibers, and other matrix components combine to form tissues. A **tissue** is an aggregation of cells and interstitia that interact to perform specialized functions.

Each tissue in the body has a unique function and a distinctive organization. To better understand how tissues are organized and how they function, it is important to understand where they come from and how they differentiate and form during **gastrulation**—the embryonic process during which a single layer of cells transforms into a gastrula containing multiple cell layers. The following overview of tissue **embryology** highlights common elements of tissues and lays the groundwork for later discussions about the role of cells in the repair and healing processes of tissues of the musculoskeletal and nervous systems.

The following descriptions are arranged in developmental, chronological order following the fusion of sperm and egg nuclei. The **embryonic stage** of human development refers to the time from fertilization to week 8, and the **fetal stage** is the time from week 9 until birth.

Fertilization of the egg (*oocyte)* by a sperm cell (*spermatozoa*) produces a **zygote** following the fusion of haploid nuclei. The zygote begins to mitotically divide in the fallopian tube 1 day after fertilization, and that division continues as the zygote travels toward the uterus (figure 2.1). Between days 1 and 4, the zygote undergoes rapid cell division by a process called embryonic cleavage (i.e., cells “cleave” in half, resulting in no growth in size) to produce a solid ball called the **morula**. This ball hollows out, fills with fluid, and “hatches” from the zona pellucida—the original membrane surrounding the oocyte. By day 5, the morula, now called the *embryo*, consists of a mass of about 64 cells attached to the wall of

Subject Index

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