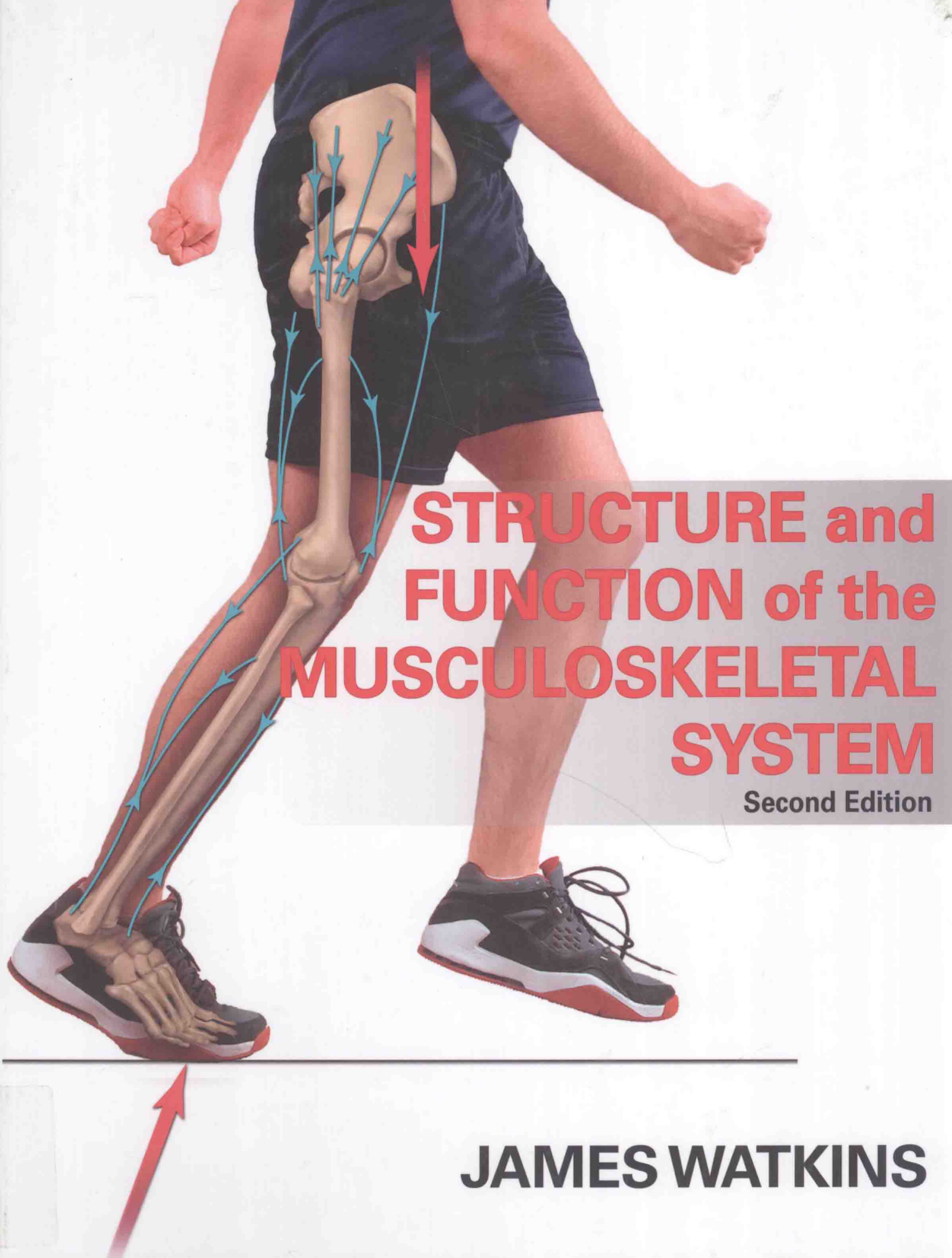


STRUCTURE and FUNCTION of the MUSCULOSKELETAL SYSTEM

Second Edition

JAMES WATKINS

Structure and Function of the Musculoskeletal System

SECOND EDITION

James Watkins, PhD
Swansea University, Wales

Human Kinetics

Library of Congress Cataloging-in-Publication Data

Watkins, James, 1946-
Structure and function of the musculoskeletal system / James Watkins. -- 2nd ed.
p. ; cm.
Includes bibliographical references and index.
ISBN-13: 978-0-7360-7890-0 (hard cover)
ISBN-10: 0-7360-7890-8 (hard cover)
1. Musculoskeletal system--Physiology. 2. Musculoskeletal system--Anatomy. 3. Human mechanics. I. Title.
[DNLM: 1. Musculoskeletal Physiological Phenomena. 2. Biomechanics. 3. Musculoskeletal System--anatomy & histology. WE 102 W335s 2010]
QP301.W34 2010
612.7--dc22

2009025659

ISBN-10: 0-7360-7890-8 (print) ISBN-10: 0-7360-8557-2 (Adobe PDF)
ISBN-13: 978-0-7360-7890-0 (print) ISBN-13: 978-0-7360-8557-1 (Adobe PDF)

Acquisitions Editor: John Dickinson, PhD; **Developmental Editor:** Christine M. Drews; **Assistant Editors:** Katherine Maurer and Dena P. Mumm; **Copyeditor:** Julie Anderson; **Proofreader:** Maggie Schwarzentraub; **Indexer:** Michael Ferreira; **Permission Manager:** Dalene Reeder; **Graphic Designer:** Nancy Rasmus; **Graphic Artist:** Dawn Sills; **Cover Designer:** Keith Blomberg; **Illustrator (cover):** Jennifer Gibas; **Photographer (cover):** Jason Allen; **Art Manager:** Kelly Hendren; **Associate Art Manager:** Alan L. Wilborn; **Art Style Development:** Joanne Brummett; **Illustrators:** Katherine Auble, Tim Brummett, Mike Meyer, Andrew Recker, Rachel Rogge; **Printer:** Premier Print Group; **Binder:** Dekker Bookbinding

Printed in the United States of America 10 9 8 7 6 5 4 3 2 1

Human Kinetics
Web site: www.HumanKinetics.com

United States: Human Kinetics
P.O. Box 5076
Champaign, IL 61825-5076
800-747-4457
e-mail: humank@hkusa.com

Canada: Human Kinetics
475 Devonshire Road Unit 100
Windsor, ON N8Y 2L5
800-465-7301 (in Canada only)
e-mail: info@hkcanada.com

Europe: Human Kinetics
107 Bradford Road
Stanningley
Leeds LS28 6AT, United Kingdom
+44 (0) 113 255 5665
e-mail: hk@hkeurope.com

Australia: Human Kinetics
57A Price Avenue
Lower Mitcham, South Australia 5062
08 8372 0999
e-mail: info@hkaustralia.com

New Zealand: Human Kinetics
Division of Sports Distributors NZ Ltd.
P.O. Box 300 226 Albany
North Shore City
Auckland
0064 9 448 1207
e-mail: info@humankinetics.co.nz

E4672

To my mother and father

Mary Watkins 1914-2006
William Watkins 1909-1985

Preface

Human movement is brought about by the musculoskeletal system—the skeletal muscles, bones, and joints—under the control of the nervous system. The bones of the skeleton are linked together at joints in a way that allows them to move relative to each other. The skeletal muscles pull on the bones to control the movements of the joints and, in doing so, control the movement of the body as a whole. Through coordinated activity of the various muscle groups, the forces generated by our muscles are transmitted by our bones and joints to enable us to maintain an upright or partially upright posture, move from one place to another, and manipulate objects, often simultaneously.

The open-chain arrangement of the bones of the skeleton—two arms and two legs attached independently to the vertebral column—allows us to adopt a wide range of body postures and perform a wide range of movements. However, this movement capability is only possible at the expense of low mechanical advantage of skeletal muscles. Most muscles are attached to bones very close to joints, such that in most postures and movements other than lying down, the muscles have to exert very large forces which, in turn, result in very large forces in joints.

In response to the forces exerted on them, the musculoskeletal components experience strain—they are deformed. Under normal circumstances, the musculoskeletal components adapt their size, shape, and structure, a process referred to as structural adaptation, to more readily withstand the time-averaged strain of everyday physical activity. However, excessive strain will result in injury. Structural adaptation is continuous throughout life, but the capacity for structural adaptation decreases markedly with increase in age after maturity; strain that would normally result in structural adaptation in a young person may result in tissue degeneration and dysfunction in an older person. Consequently, there is an intimate relationship between the structure and function of the musculoskeletal system. The purpose of *Structure and Function of the Musculoskeletal System* is to develop knowledge and understanding of this relationship. The book is primarily a course text for undergraduate students of kinesiology, exercise science, sport science, and physical education, but it also has a great deal to offer health care professionals, in particular, physiotherapists and occupational therapists, who deal with the acute and chronic effects of musculoskeletal pathology.

What's New in the Second Edition?

Changes in the organization and content of the second edition are based largely on feedback from students and teachers over a number of years. The main changes are as follows:

- Revision of all content: Some material was removed and some new material has been added.
- Revision of the content into two parts rather than three: functional anatomy of the musculoskeletal system in part I and response and adaptation of the musculoskeletal system in part II.
- Case studies: A number of case studies are included to illustrate the response and adaptation of the musculoskeletal system to exercise at various ages and to generate discussion of issues pertaining to good practice in the promotion and maintenance of musculoskeletal health.
- Reorganization of elementary biomechanical concepts and principles: In the first edition, all of the fundamental mechanical concepts were contained largely within a single chapter. In the second edition, this chapter has been

deleted and the content incorporated more appropriately into other chapters, including a relatively short, new chapter at the start of part II.

- Highlighted introductory figures: In part I, the sequence of illustrations is such that often one figure introduces several subsequent figures. In these cases, the introductory figure has been highlighted with a light-blue burst. This may help readers gain perspective as they refer across several figures at a time when reading the text.

In addition to the preceding changes, all of the learning features in the first edition have been retained—content overview at the start of each chapter, chapter objectives, key points and additional details on some points highlighted within the text, an extensive running glossary, extensive use of illustrations, review questions, references to guide further reading, and an extensive index.

Instructor Resource

This edition includes a new instructor resource, an Image Bank delivered in Microsoft PowerPoint, which contains all of the figures and tables found in this text. Instructors can customize their own presentations with these figures and tables. The Image Bank also includes a blank PowerPoint template and instructions for creating custom presentations. This instructor resource can be found at www.HumanKinetics.com/StructureandFunctionoftheMusculoskeletalSystem.

Organization of the Second Edition

Part I, Functional Anatomy of the Musculoskeletal System, describes how musculoskeletal function—the generation and transmission of forces to control the movement of the body—is reflected in the structure of the musculoskeletal components. Chapter 1, The Musculoskeletal System, describes the composition and function of the musculoskeletal system. Chapter 2, The Skeleton, describes the open-chain arrangement of the bones of the skeleton. Chapter 3, Connective Tissues, differentiates the ordinary connective tissues, in particular, ligaments, tendons, and fascia, and the special connective tissues of cartilage and bone. Chapter 4, The Articular System, explains the differences in types of joints and, in particular, the way joint design reflects a trade-off between stability and flexibility. Chapter 5, Joints of the Axial Skeleton, describes the joints between the vertebrae and the joints of the pelvis. Chapter 6, Joints of the Appendicular Skeleton, describes the joints and joint complexes of the appendicular skeleton. Chapter 7, The Neuromuscular System, describes the relationship between the nervous and muscular systems in terms of force generation and proprioception.

Part II, Musculoskeletal Response and Adaptation to Loading, describes the immediate and long-term effects of loading on the external form and internal architecture of the musculoskeletal system. Chapter 8, Elementary Biomechanics, develops knowledge and understanding of elementary biomechanical concepts and principles. Chapter 9, Forces in Muscles and Joints, focuses on how the open-chain arrangement of the skeleton affects the forces exerted in muscles and joints. Chapter 10, Mechanical Characteristics of Musculoskeletal Components, describes the musculoskeletal system's response to loading. Chapter 11, Structural Adaptation of the Musculoskeletal System, describes how the structure of the musculoskeletal system adapts to the time-averaged loads exerted on it. Chapter

12, Etiology of Musculoskeletal Disorders and Injuries, describes the main groups of risk factors that influence the level of loading on the musculoskeletal system.

I hope this book will encourage you to learn more about the structure and function of the musculoskeletal system. Adequate musculoskeletal functioning is an important determinant of our quality of life, and the information contained in this book is essential for anyone wishing to maintain, or help others to maintain, a healthy musculoskeletal system.

James Watkins

Acknowledgments

I thank my dear wife, Shelagh, for her continuous support throughout the various stages of the writing of the book. I also thank all of the staff at Human Kinetics who contributed to the commissioning and production of the book. I thank my academic colleagues and the large number of undergraduate and graduate students who have helped me, directly and indirectly, over many years, to develop and organize the content of the book.

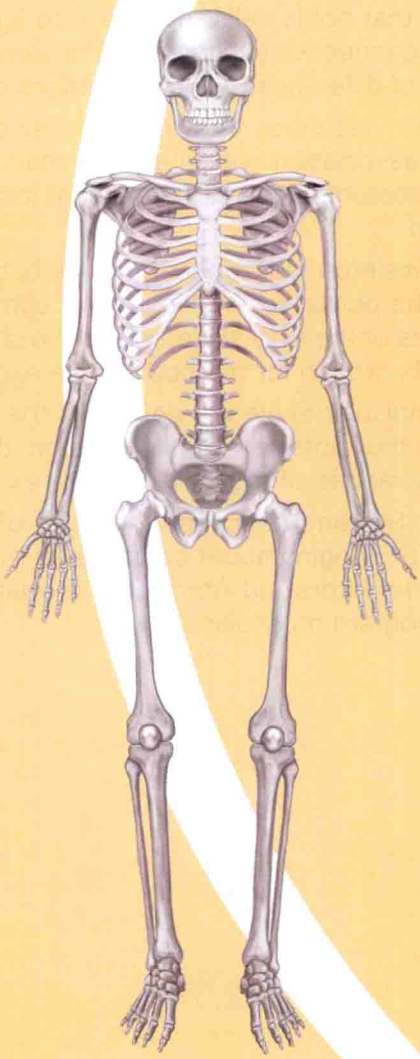
Contents

PART II Musculoskeletal Response and Adaptation to Loading

PART I

Functional Anatomy of the Musculoskeletal System

Your musculoskeletal system—your skeleton and skeletal muscles—account for about half of your total body weight. Your skeleton (12-15% of your total body weight) consists of 206 bones that are linked by more than 200 joints. You have approximately 640 skeletal muscles (30-42% of total body weight), which pull on your bones to control the movement of your joints and enable you to stand up, move around, and manipulate objects. Bone is an ideal support material because it is not only amazingly strong, but also fairly lightweight. Relative to its weight, bone is stronger than concrete and it has a higher strength-to-weight ratio than any other naturally occurring material. Your bones have to be strong to withstand the very large forces that the muscles exert on them during normal everyday movements. If all of your muscles could contract simultaneously in the same direction, they would exert a force in the region of 22 tons.



Human movement is brought about by the musculoskeletal system under the control of the nervous system. The muscles pull on the bones to control the movements of the joints and in doing so control the movement of the body as a whole. Part I describes how musculoskeletal function—the generation and transmission of forces to control the movement of the body—is reflected in the structure of the musculoskeletal components.

- Chapter 1, The Musculoskeletal System, describes the basic structural and functional unit of all living organisms—the cell—and how cells are organized into organs and systems. You will learn how one of these systems, the musculoskeletal system, enables you to move in a controlled manner by generating forces in muscles and transmitting the forces across joints.
- Chapter 2, The Skeleton, describes the bones of the skeleton and the open-chain arrangement of the bones. You will learn how the large differences in size, shape, and surface features of the bones reflect the ability of the bones to transmit muscle forces.
- Chapter 3, Connective Tissues, describes the wide variety of connective tissues, which range from areolar tissue—the glue that holds cells together—to ligaments, tendons, cartilage, and bone. You will learn that all connective tissues have the same basic structure but differ in strength and flexibility because of differences in the proportions of the structural components.
- Chapter 4, The Articular System, describes the various types of joints between the bones of the skeleton. The joints, in association with the open-chain arrangement of the bones, facilitate a wide range of body postures. You will learn that all joints transmit forces and allow a certain amount of movement.
- Chapter 5, Joints of the Axial Skeleton, describes the joints between the vertebrae and the joints between the bones of the pelvis. You will learn that compared with the joints in the appendicular skeleton, the joints of the axial skeleton and the shape of the vertebral column provide a high level of shock absorption for the body at the expense of reduced flexibility.
- Chapter 6, Joints of the Appendicular Skeleton, describes the joints in the arms and legs. You will learn that in contrast to the joints of the axial skeleton, the joints of the appendicular skeleton facilitate relative large ranges of movement at the expense of shock absorption.
- Chapter 7, The Neuromuscular System, describes the parts of the nervous and muscular systems that are responsible for bringing about coordinated movement. You will learn that the nervous system constantly monitors and interprets information from the various senses and uses this information to program muscular activity.

The Musculoskeletal System

All living organisms are made up of one or more cells. The human body, like most organisms, is made up of billions of cells organized into complex functional groups including, for example, the musculoskeletal system. The first part of this chapter describes the four basic types of cells, called tissues, and the organization of tissues into organs and systems. The second part of the chapter describes the composition and function of the musculoskeletal system.

OBJECTIVES

After reading this chapter, you should be able to do the following:

1. Describe the four types of tissues.
2. Describe cellular organization in multicellular organisms.
3. Describe the composition and function of the musculoskeletal system.

Unicellular and Multicellular Organisms

The basic structural and functional unit of life is the **cell.** All cells have four main components: cytosol, a nucleus, organelles, and a cell membrane (figure 1.1). Cytosol is a semitransparent fluid consisting of a complex solution of proteins, salts, and sugars. The nucleus and organelles are suspended in the cytosol. The nucleus contains genetic material and controls the **life processes** of the cell, which include movement, growth and development, respiration, circulation, digestion, excretion, and reproduction. The organelles, under the direction of the nucleus, carry out the life processes; each organelle carries out a specific function for the cell as a whole. The cytosol and organelles are usually referred to collectively as cytoplasm.

KEY POINT

The basic structural and functional unit of life is the cell, and all living organisms consist of one or more cells.

The cell membrane, also referred to as the plasma membrane or plasmalemma, encloses the cytoplasm and forms the external boundary of the cell. Like cytosol, the cell membrane consists of a viscous fluid, but it is usually much more viscous than the cytosol that it encloses. The viscous nature of the cell membrane and cytosol enables a cell to change its shape without losing its integrity. During normal functioning, all cells continuously change shape to a certain extent. The amount of change varies

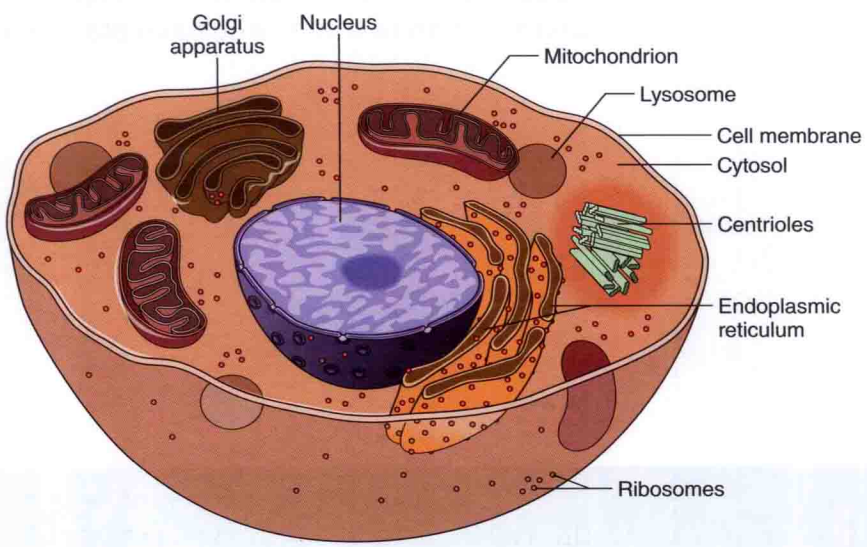


FIGURE 1.1 Cross section of a typical animal cell.

among types of cells. For example, bone cells are likely to experience little change in shape, whereas muscle cells have a highly specialized ability to change shape, which is an essential feature of normal function.

The number of cells that make up an organism reflect its level of evolution. For example, in the lowest forms of animal life such as amoeba and euglena, the entire organism consists of a single cell. These organisms are referred to as **unicellular organisms.** In contrast, most animals consist of many cells and are referred to as **multicellular organisms.** All mammals, birds, and fish are multicellular organisms. The number of cells in multicellular organisms varies considerably. For example, the nematode worm *C. elegans* is 1 mm in length and consists of 959 cells (Kenyon 1988). Most multicellular organisms consist of millions of cells; the human body consists of approximately 10^{14} (one hundred million million) cells (Alberts et al 2002). The size and shape of cells vary considerably among different organisms and within the same organism. Differences in cell size and shape tend to reflect differences in function.

Key Terms

cell The basic structural and functional unit of all organisms.

life processes The activities a cell carries out to sustain the life of the cell.

unicellular organism An organism that consists of a single cell.

multicellular organism An organism that consists of many cells.

KEY POINT

There are two types of living organisms: unicellular and multicellular.

Cellular Organization in Multicellular Organisms

All living organisms are similar in that they are capable of carrying out all of the essential life processes. In unicellular organisms the life processes are relatively simple. However, in multicellular organisms the cells are organized into complex functional groups that carry out the various life processes for the body as a whole. Multicellular organization can be divided into three structural levels: tissues, organs, and systems.

KEY POINT

All living organisms are capable of carrying out a number of essential life processes. In multicellular organisms the life processes involve a high level of organization and integration between the cells. Cells are organized on three levels: tissues, organs, and systems.

Tissues

In multicellular organisms all of the cells originate from a single cell formed by the fertilization of a female ovum by a male sperm. This cell undergoes rapid cell division to form a ball of cells. Soon after this, the cells begin to differentiate in size, shape, and structure to fulfill different functions in the body of the organism. This process of **cellular differentiation** results in the formation of four types of cells called tissues: epithelia, nerve, muscle, and connective. A **tissue** is a group of cells having the same specialized structure, enabling them to perform a particular function in the body (Freeman and Bracegirdle 1967). The word *tissue* is also used in a general sense to refer to any part of the body: for example, soft tissues, bone tissue, and skin tissue.

Key Terms

cellular differentiation The specialization of cells into tissues.

tissue A group of cells having the same specialized structure, enabling them to perform a particular function in the body.

Epithelial Tissue

There are two types of epithelial tissue: covering and glandular. Covering epithelia form the surface layer or layers of cells of all the internal and external free surfaces of the body except the surfaces inside synovial joints. For example, the surfaces of the skin and the lining of the digestive tract, heart chambers, and blood vessels are covering epithelia.

All cells can secrete fluid to a greater or lesser extent, but glandular epithelial cells are specialized for this purpose and as such form the two types of glands found in the body: exocrine and endocrine. Many of the exocrine glands, such as the gastric glands in the lining of the stomach, secrete fluids containing enzymes necessary for the digestion of food. Endocrine glands, such as the pituitary gland at the base of the brain and the adrenals at the upper end of each kidney, secrete hormones that, in association with the nervous system, regulate and coordinate the various body functions.

Nerve Tissue

Nerve cells (neurons) are specialized to conduct electrochemical impulses throughout the body to regulate and coordinate the various body functions. The structure and function of nerve tissue are covered in detail in chapter 7, which deals with the neuromuscular system.

Muscle Tissue

Muscle cells are specialized to contract (i.e., create pulling forces to bring about movement). There are three types of muscle cells: skeletal, visceral, and cardiac. Skeletal muscle is so-called because it generally is attached to the skeleton. It is also called *voluntary muscle* because it is normally under the conscious control of the person. The structure and functions of skeletal muscle are covered in detail in chapter 7.

Visceral or involuntary muscle is found in parts of the body that involve involuntary movement, that is, in body parts not under our conscious control. Visceral muscle is found, for example, in the walls of the alimentary canal and the larger arteries.

Cardiac muscle is found only in the heart. It has characteristics of both skeletal and visceral muscle but differs from them in that it contracts rhythmically throughout life even though the rate of contractions (heart rate) may alter frequently.

Connective Tissue

As its name suggests, connective tissue supports and binds other tissues together. The bones of the skeleton and the fibrous structures holding the bones together at joints are forms of connective tissue. The structure and functions of connective tissue are covered in detail in chapter 3.

Organs and Systems

An **organ** is a combination of tissues designed to carry out a specific bodily function. For example, the heart pumps blood around the body. The structure of the heart consists of

- cardiac muscle cells;
- connective tissue, which binds the muscle cells together;
- epithelial tissue, which lines the chambers of the heart; and
- nerve tissue, which innervates the muscle cells.

Other examples of organs are the lungs, the stomach, and a skeletal muscle (such as the quadriceps) complete with its tendons, which attach the muscle to the skeletal system.

A **system** is a combination of organs working together to carry out a particular function in the body. For example, the cardiovascular system consists of the heart and blood vessels and is responsible for transporting blood around the body. There are 11 separate systems in the human body (Tortora and Anagnostakos 1984):

integumentary system The external covering of the body, that is, the skin and associated structures such as nails.

skeletal system The bones of the skeleton and the structures that form the joints between the bones.

muscular system The skeletal muscles.

nervous system The nerves, organized into central (brain and spinal cord) and peripheral (spinal nerves) components.

endocrine system The glands that secrete hormones, which regulate and coordinate the various body functions in association with the nervous system.

cardiovascular system The heart and blood vessels.

lymphatic system The system of vessels and associated structures that drains and returns fluid leaked from the blood and protects against disease.

respiratory system The lungs and associated passageways.

digestive system The alimentary canal and associated structures that break down food and eliminate solid waste.

urinary system The kidneys, bladder, and associated structures that eliminate nitrogenous waste as urine.

reproductive system The ovaries and associated structures (female) and testes and associated structures (male), which enable the body to produce offspring.

These systems are responsible for carrying out the body's life processes. Whereas all of the life processes involve a certain degree of integration between systems, some processes involve closer integration among systems than do others. For example, the transport of oxygen from the air to all the cells of the body is carried out by the combined activity of the nervous, respiratory, and cardiovascular systems. Similarly, movement of the body is brought about by the combined activity of the nervous, muscular, and skeletal systems. Consequently, for descriptive purposes it is usual to refer to combinations of systems: for example, the cardiorespiratory system, the musculoskeletal system, and the neuromuscular system. Cellular differentiation and organization in multicellular organisms are illustrated in figure 1.2.

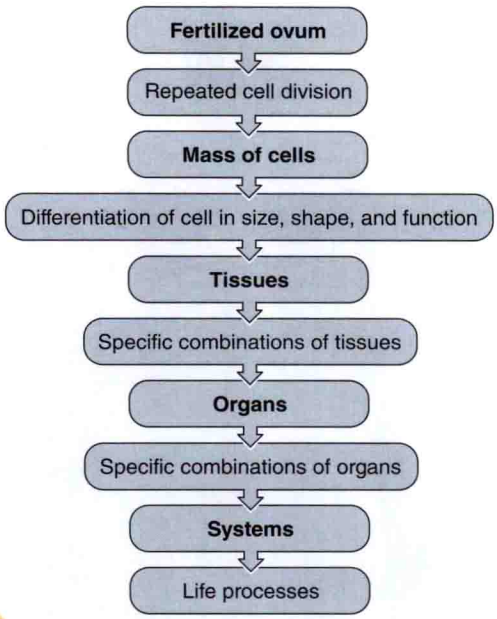


FIGURE 1.2 Cellular differentiation and organization in multicellular organisms.

Key Terms

organ A combination of tissues designed to carry out a specific bodily function.

system A combination of organs working together to carry out a particular bodily function.

KEY POINT

All of the cells of the body originate from a single cell—a fertilized ovum. This cell undergoes rapid cell division and, subsequently, cellular differentiation that results in the formation of different types of tissues that combine to form specialized organs. Organs then work together to form systems to carry out the life processes of multicellular organisms.

Composition and Function of the Musculoskeletal System

Human movement is brought about by the **musculoskeletal system** under the control of the nervous system. The musculoskeletal system consists of the **skeletal system** and the **muscular system** (figure 1.3). The skeletal system consists of the skeleton (the bones) and

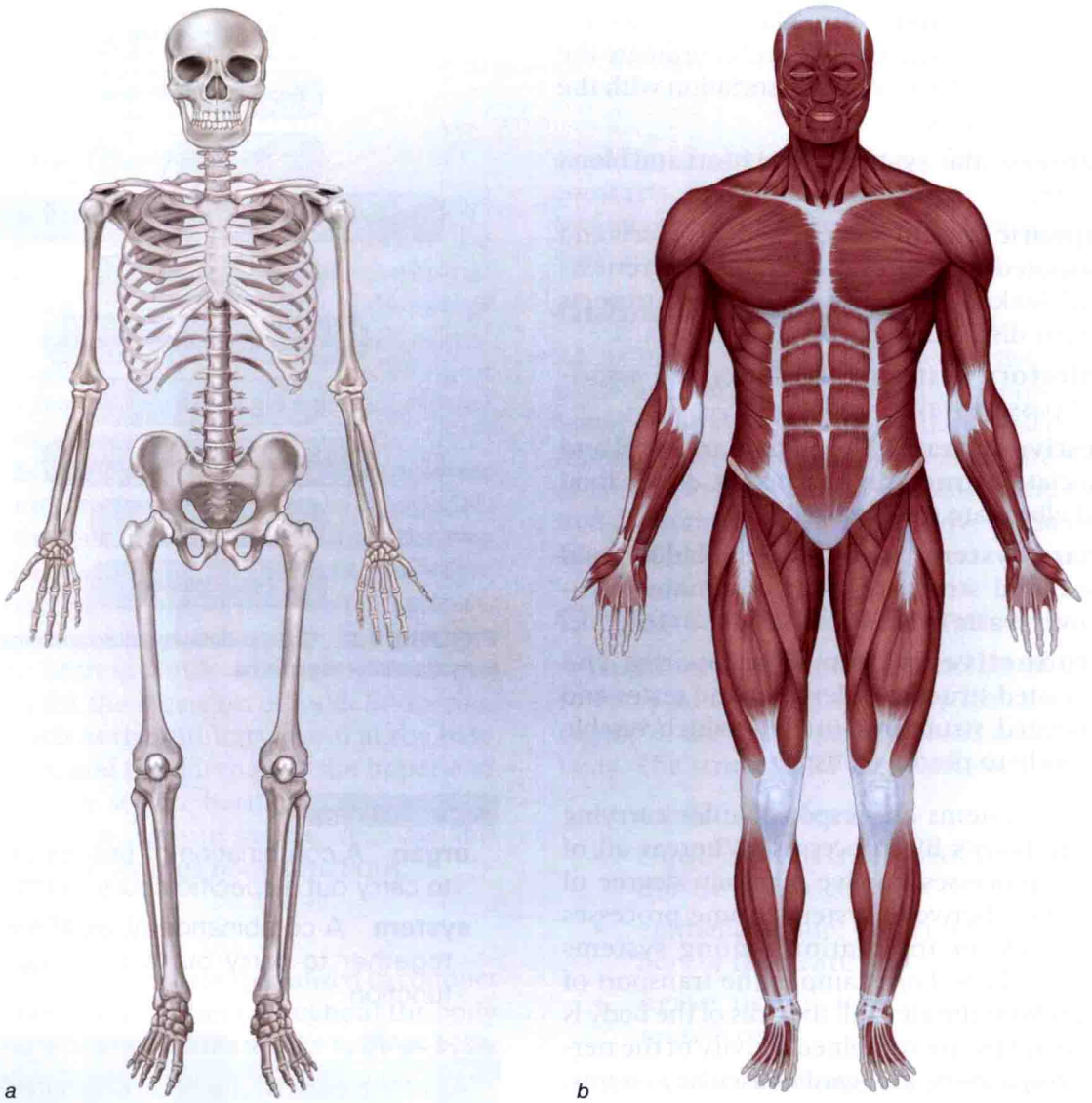


FIGURE 1.3 *(a)* The skeleton. *(b)* The muscular system.

the structures forming the joints between the bones. Similar to the metal framework that supports a building, the skeletal system gives the body its shape and provides a supporting framework for all the other systems. Bone is an ideal support material because it is not only strong but also fairly lightweight. The adult skeletal system normally has 206 bones and more than 200 joints and accounts for between 12% and 15% of total body weight (McArdle et al 1996).

Skeletal, visceral, and cardiac are the three types of muscle tissue. Visceral muscle is usually considered to be part of the digestive system (in the walls of the digestive tract) and cardiovascular system (in the walls of arteries). Cardiac muscle, found only in the heart, is part of the cardiovascular system (Tortora and Anagnostakos 1984). The muscular system refers only to the skeletal muscles. There are approximately 640 skeletal muscles. The skeletal muscles account for an average of approximately 34% and 42% of total body weight in young (18-29 years), healthy, untrained adult females and males, respectively, and an average of approximately 30% and 34% of total body weight in elderly (70-88 years), healthy, untrained adult females and males, respectively (Janssen et al 2000).