The Structure and Functions of the Human Skeletal System

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Abstract
The human skeletal system is a dynamic and highly integrated organ system that provides structural support, protects vital organs, facilitates movement, maintains mineral homeostasis, and supports hematopoiesis. This review examines the structure and functions of the human skeletal system by synthesizing evidence from contemporary anatomical, physiological, radiological, and educational literature. The review discusses the organization of bone tissue, including cortical and trabecular bone, bone marrow, vascular networks, and the mechanisms of bone remodeling regulated by osteoblasts, osteoclasts, and hormonal signaling pathways. It further explores the essential physiological roles of the skeleton in locomotion, mineral storage, endocrine regulation, immune function, and systemic health. Recent advances in medical imaging have enhanced the understanding of skeletal development, metabolism, and pathology, while animal models have contributed valuable insights into bone biology despite recognized translational limitations. In addition, emerging educational innovations, particularly three-dimensional (3D) printing and active learning approaches, have improved the teaching and clinical application of skeletal anatomy. Contemporary perspectives also emphasize the skeleton as part of an interconnected musculoskeletal and connective tissue network, encouraging a more holistic understanding of human anatomy. Overall, this review highlights the multifaceted nature of the skeletal system and underscores the importance of integrating anatomy, physiology, imaging, biomechanics, and educational innovations to advance research, clinical practice, and anatomy education.
Keywords: Skeletal system; Bone anatomy; Bone physiology; Bone remodeling; Mineral homeostasis; Hematopoiesis; Medical imaging; 3D printing; Musculoskeletal system.

1. Introduction

The skeletal system comprises a connected assembly of bones, cartilage, and supporting connective tissues that together form the musculoskeletal framework of the human body. It functions not only as passive scaffolding but as an active organ system involved in mineral homeostasis, hematopoiesis, protection of vital organs, and locomotion through muscular attachments and joint mechanics. This review integrates evidence from anatomical, physiological, radiological, and educational literature to present a cohesive picture of the structure and functions of the human skeleton and its clinical and educational implications Kushdilian et al., 2016; , Ritchlin & Adamopoulos, 2019; , , Musumeci, 2015), Ogaili & Almanseekanaa, 2022).

2. Structural Organization of the Human Skeleton

The human skeletal system consists of 206 bones that together form a continuous framework supporting the body, protecting vital organs, and providing attachment sites for muscles and connective tissues. In addition to its structural role, the skeleton houses bone marrow, where hematopoiesis occurs through the production of red blood cells, white blood cells, and other immune cells. Bone also serves as the body's primary reservoir for essential minerals, particularly calcium and phosphate, which are continuously regulated to maintain normal physiological functions such as muscle contraction, nerve transmission, and metabolic balance (Bafaraj et al., 2014; Kushdilian et al., 2016; Ritchlin & Adamopoulos, 2019; Roosen et al., 2011; Park et al., 2011).

Bone tissue is composed of two major structural types: cortical (compact) bone and trabecular (spongy) bone. Cortical bone forms the dense outer layer of bones, accounting for most of the skeletal mass and containing Haversian systems that accommodate blood vessels and nerves. In contrast, trabecular bone forms a porous internal network that provides mechanical support while reducing skeletal weight. Together, these components determine the strength, flexibility, and mechanical properties of bones and allow continuous adaptation through the process of bone remodeling (Bafaraj et al., 2014; Al-Agele et al., 2019; Ritchlin & Adamopoulos, 2019).

The skeletal system is also highly vascularized, with an extensive network of blood vessels supplying nutrients, oxygen, and signaling molecules required for bone maintenance and repair. The periosteum and nutrient canals provide the principal neurovascular supply to bone tissue, while bone remodeling is maintained through the coordinated activities of osteoclasts, which resorb old bone, and osteoblasts, which synthesize new bone. This tightly regulated process is controlled by signaling pathways, including the receptor activator of nuclear factor kappa-B ligand (RANKL) and osteoprotegerin (OPG) system, ensuring skeletal integrity throughout growth, adulthood, and aging (Ritchlin & Adamopoulos, 2019; Roosen et al., 2011).

The skeletal system functions in close coordination with muscles, joints, ligaments, tendons, and connective tissues to facilitate movement and maintain posture. Rather than viewing bones as isolated structures, recent anatomical perspectives emphasize the musculoskeletal system as an integrated three-dimensional network in which connective tissues, including fascia, contribute to force transmission and functional coordination. These emerging concepts support a more holistic understanding of musculoskeletal anatomy and biomechanics (Sharkey, 2021; Musumeci, 2015).

Functionally, the skeletal system provides mechanical support and serves as the body's primary framework for movement. Bones act as rigid levers that interact with skeletal muscles and joints to generate motion while maintaining posture and transmitting mechanical loads efficiently. The combined architecture of cortical and trabecular bone enables the skeleton to withstand compression, tension, and torsional forces encountered during daily activities (Bafaraj et al., 2014; Musumeci, 2015).

Another essential function of the skeletal system is the protection of vital organs. The skull safeguards the brain, the vertebral column protects the spinal cord, and the rib cage shields the heart and lungs. Bones also provide stable attachment sites for tendons and ligaments, allowing coordinated muscle action and efficient locomotion. Increasingly, these protective and mechanical roles are being interpreted within broader connective tissue frameworks that emphasize the integration of bones with surrounding soft tissues (Sharkey, 2021; Musumeci, 2015).

Beyond mechanical functions, the skeleton plays a critical role in mineral storage and endocrine regulation. Bone tissue continuously stores and releases calcium and phosphorus to maintain mineral homeostasis, a process essential for normal neuromuscular activity and cellular function. Bone remodeling is closely regulated by hormones such as parathyroid hormone, vitamin D, calcitonin, and estrogen, which coordinate skeletal growth, maintenance, and metabolic balance. Variations in hormonal regulation throughout life also contribute to sex-specific patterns of skeletal development and aging (Bafaraj et al., 2014; Kushdilian et al., 2016; Ritchlin & Adamopoulos, 2019; Dunsworth, 2020).

Bone marrow further contributes to systemic health through hematopoiesis and immune function. Red marrow produces erythrocytes responsible for oxygen transport, while leukocytes and lymphocytes generated within the marrow support innate and adaptive immune responses. Consequently, the skeletal system functions not only as a structural organ but also as a vital component of the immune and circulatory systems (Bafaraj et al., 2014; Ritchlin & Adamopoulos, 2019; Park et al., 2011).

Advances in medical imaging have significantly improved the understanding of skeletal anatomy and physiology. Radiological techniques provide detailed visualization of bone growth, remodeling, mineral metabolism, and pathological changes, making them indispensable for both anatomy education and clinical diagnosis. Imaging studies also demonstrate developmental changes in the skeleton, particularly in pediatric populations, where growth plate maturation and skeletal development can be accurately assessed to guide diagnosis and treatment (Kushdilian et al., 2016; Colucci & Sofka, 2024).

Experimental research on skeletal biology relies extensively on animal models to investigate bone development, remodeling, and disease mechanisms. Zebrafish serve as valuable models for studying osteogenesis and bone metabolism due to their genetic tractability and regenerative capabilities, whereas larger animals such as sheep, goats, and pigs possess skeletal characteristics that more closely resemble those of humans. These large-animal models are especially useful for orthopedic research, imaging studies, biomarker validation, and the evaluation of new therapeutic interventions. Nevertheless, researchers must carefully consider species-specific differences when translating findings to human skeletal biology (Mariotti, 2015; Ogaili & Almanseekanaa, 2022).

Technological advances such as three-dimensional (3D) printing have further enhanced both anatomy education and clinical practice. Anatomically accurate 3D-printed bone models provide students with hands-on learning experiences that improve spatial understanding of skeletal structures while offering cost-effective, reusable teaching tools. In clinical settings, these models facilitate surgical planning, preoperative simulation, and the development of patient-specific implants, ultimately improving reconstructive procedures by allowing surgeons to better understand complex bone geometry and biomechanics before surgery (Ogaili & Almanseekanaa, 2022; Goldsmith, 2022).

3. Synthesis of Key Thematic Insights

The skeletal system is increasingly recognized as a dynamic, integrated organ system rather than merely a collection of individual bones. Its structural components—including cortical bone, trabecular bone, and bone marrow—work together to provide mechanical support, maintain mineral homeostasis, and facilitate hematopoiesis. These functions are closely interconnected with endocrine regulation, immune cell production, and overall systemic physiology, highlighting the skeleton's central role in maintaining health (Bafaraj et al., 2014; Ritchlin & Adamopoulos, 2019; Park et al., 2011).

Advances in medical imaging have further strengthened the connection between anatomical structure and physiological function. Radiological techniques enable detailed visualization of bone growth, remodeling, and mineral metabolism while also serving as essential tools for diagnosing skeletal disorders. As a result, imaging has become a valuable resource in both anatomy education and clinical practice, enhancing the understanding of normal bone physiology and pathological changes (Kushdilian et al., 2016; Ritchlin & Adamopoulos, 2019; Colucci & Sofka, 2024).

Experimental research on bone biology also relies heavily on animal models, each offering distinct advantages and limitations. Zebrafish are widely used to investigate osteogenesis and bone metabolism because of their genetic accessibility and regenerative capabilities, whereas larger animals such as sheep, goats, and pigs provide skeletal characteristics that more closely resemble those of humans, making them particularly valuable for orthopedic and imaging research. Nevertheless, differences between species require careful consideration when translating experimental findings to human biology (Mariotti, 2015; Ogaili & Almanseekanaa, 2022).

In anatomy education, innovative teaching strategies have significantly improved students' understanding of skeletal anatomy and physiology. The incorporation of three-dimensional (3D) printed bone models, updated laboratory curricula, and active learning approaches has enhanced spatial visualization and practical comprehension, reflecting modern perspectives on bone biology and improving educational outcomes (McDaniel & Daday, 2017; Musumeci, 2015; Ogaili & Almanseekanaa, 2022).

At the same time, contemporary research continues to refine the conceptual understanding of the musculoskeletal system. Emerging discussions surrounding fascia-inspired frameworks and the integrative role of bone within the broader connective tissue network have challenged traditional anatomical classifications. These evolving perspectives have important implications for future research, clinical practice, and anatomy education by encouraging a more holistic view of musculoskeletal structure and function (Sharkey, 2021; Musumeci, 2015).

4. Practical Implications and Gaps for Future Research

The following points represent the practical implications of the research work as well as the gaps for future research:

- Given the interconnected roles of bone structure, physiology, and systemic health, curricula should emphasize cross-disciplinary integration (anatomy, physiology, imaging, and clinical implications) to prepare learners for clinical decision-making and research translation (Davis & Pinedo, 2021; , Kushdilian et al., 2016; , McDaniel & Daday, 2017).
- Researchers should select skeletal models that best approximate the specific mechanistic aspects under study (e.g., remodeling dynamics, mineral homeostasis, or marrow biology)

and clearly articulate translational limitations when extrapolating to humans (Mariotti, 2015; , Ogaili & Almanseekanaa, 2022).

- The continued integration of 3D-printed bone models into education and preoperative planning holds promise for improving comprehension of complex skeletal anatomy and for developing patient-specific surgical solutions Ogaili & Almanseekanaa, 2022), Ogaili & Almanseekanaa, 2022).
- The debate on bone as fascia invites further empirical work to clarify the functional and developmental implications of connective tissue networks for bone biology and musculoskeletal mechanics (Sharkey, 2021; , Musumeci, 2015).

5. Conclusion

The structure and functions of the human skeletal system are best understood as an integrated system wherein bone morphology, marrow activity, mineral homeostasis, and mechanical function co-evolve within hormonal and immunological contexts. Radiology and modern imaging provide crucial windows into these processes, while animal and large-animal models enable deeper mechanistic understanding and translational progress, albeit with limitations. Educational innovations, including 3D printing and revised laboratory pedagogy, enhance comprehension of skeletal biology and its clinical relevance. Future work should continue to harmonize anatomy, physiology, imaging, and biomechanics within a cohesive educational and research framework, while acknowledging ongoing debates about connective tissue taxonomy and the broader relational anatomy of the musculoskeletal system.

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