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Biomechanics of Joints and Implants

Concepts to Applications

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Preface

Biomechanics is a field of science that helps to gain insight into the mechanics of living systems. This interdisciplinary subject helps to understand the relationship between the structure and function of human joints, predict changes in the bone tissue due to alterations in the mechanical and biochemical environment, and propose methods of artificial interventions. The fundamental concepts of biomechanics encompass joint kinematics and kinetics, gait analysis and motion capture, tissue mechanics, implant design and analysis, bone remodelling, and bone fracture healing, as well as state-of-the-art techniques of modelling and simulation of biomechanical systems.

This book is derived from materials and lecture notes developed for the course "Mechanics of the Human Body", taught at the Indian Institute of Technology Kharagpur. It has been further enriched by the NPTEL online course *Biomechanics of Joints and Orthopaedic Implants*. Although primarily aimed at undergraduate and postgraduate engineering students, the course has also attracted medical practitioners with a keen interest in biomedical engineering. This book aims to be a valuable resource for students in biomedical and biomechanical engineering, highlighting recent advancements in the biomechanics of joints and orthopaedic implants.

The authors wish that the book accomplishes five goals. The first goal is to introduce the anatomy, physiology, and movements of the human body and its mechanical analogy to the students in order to evoke interest in the relationship between the structure and functions of the musculoskeletal system, in particular the main joints of the upper and lower limbs, as well as the spine. The second goal is to gain an insight into the structure, functions, movements, and forces acting on the joints during daily activities. The biomechanical concepts of the specific joints, the hip, knee, shoulder, elbow, and spine using the concept of static equilibrium have been presented.

The third goal is to quantitatively analyse the human gait cycle as a complex biomechanical system. Herein, focus on the details of gait analysis, measurement techniques, gait abnormalities, and motion capture system. Moreover, insights into the applications of mechanics of rigid bodies in the field of biomechanics have been provided. The estimation of musculoskeletal forces (joint forces and moments, muscle forces) using the fundamental concepts of joint dynamics (kinematics and kinetics) has been presented with relevant solved examples and exercises to impart basic understanding. The quantitative study of the skeletal system is envisaged to provide a comprehensive understanding of the applications of rigid body dynamics.

The fourth goal is to revisit the basic concepts of mechanics of deformable bodies relevant to bone tissue as well as implanted bone structure. The efficacies of joint replacement (hip, knee, shoulder) and spinal surgery have been explored in detail. The concepts of composite beams in the bone-implant structure have been presented to enhance the understanding of stress/strain shielding. Common failure mechanisms of implanted bone structures and biomaterials used in orthopaedic implants have been discussed. Moreover, state-of-the-art modelling techniques of biomechanical systems and experimental validation have been presented. The students/instructors are expected to be benefitted from the extensive discussions on state-of-the-art finite element modelling techniques using CT/MRI scan data.

The fifth goal is to gain insight into the theory and concepts of bone remodelling and fracture healing. The theory, mathematical formulations, and computational framework of bone adaptation have been explored. Different mathematical models of tissue differentiation algorithms, such as mechanoregulatory, bioregulatory, and mechanobioregulatory algorithms have been presented. A brief overview of artificial intelligence and its application in orthopaedic biomechanics research has been discussed.

The contributions of several people have culminated in the development of this manuscript. We sincerely thank Dr. Rahul Gautam Talukdar for his feedback on spine-related content, Dr. Nirmal Kumar Som for his insights into human anatomy, and Mr. Gowtham Reddy for his review on artificial intelligence content. We also thank Mr. Pedada Jagdish for reviewing the manuscript, Mr. Rounak Bhattacharya for his feedback on motion analysis, Mr. Saranjit Sarkar and Ms. Rupa Mukherjee for their contributions to figures and artworks. Lastly, we express our heartfelt gratitude to our families and friends for their unwavering support and encouragement throughout this project.

We welcome corrections and suggestions for improving this textbook, by email to sangupta@mech.iitkgp.ac.in.

Kharagpur, India
September 2024

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Contents

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Sanjay Gupta is a Professor in the Department of Mechanical Engineering at the Indian Institute of Technology Kharagpur and is leading the Biomechanics Research Group. He earned his Ph.D. from the Delft University of Technology, The Netherlands. Subsequently, he worked as a senior research fellow at the University of Southampton, UK, and as a research associate at the Imperial College London, UK. He completed his bachelor's degree in mechanical engineering from Bengal Engineering College, University of Calcutta, in 1989 and master's degree in mechanical engineering from Jadavpur University, Calcutta, in 1992. He has 26 years of teaching and research experience. His major areas of research include bone and joint mechanics, pre-clinical analysis of implant design, bone remodelling, and mechanobiology. He has 50 international journal publications in this domain of research. He was awarded the INSA Teachers Award 2022 by the Indian National Science Academy, New Delhi.

Ceby Mullakkara Saviour is pursuing his doctoral study in the field of Biomechanics at the Indian Institute of Technology Kharagpur. He completed his bachelor's degree in mechanical engineering at Cochin University of Science and Technology in 2016 and master's degree in mechanical engineering from the Indian Institute of Technology Guwahati in 2019. During his master's degree, he secured the DAAD-IIT sandwich fellowship and conducted his thesis work at Leibniz University Hannover, Germany, from September 2018 to March 2019. His major areas of research include tissue mechanics, orthopaedic implant design, bone remodelling, and mechanobiology.

Bidyut Pal is an Assistant Professor in the Department of Mechanical Engineering at the Indian Institute of Engineering Science and Technology (IIEST), Shibpur. He obtained his Ph.D. from Indian Institute of Technology Kharagpur in 2010. Subsequently, he worked as a postdoctoral research associate in the Biomechanics Research Group (Mechanical Engineering Department) at Imperial College London, UK, and as a postdoctoral research fellow in the Medical Engineering Research Group at Anglia Ruskin University, UK. Dr. Pal also served as a senior lecturer and lecturer in Mechanical Engineering at the University of Portsmouth, UK. He earned his master's degree in biomedical engineering from Jadavpur University, Kolkata, and his bachelor's degree in mechanical engineering from Kalyani Government Engineering College (Kalyani University), West Bengal, India. His broad research area is computational and experimental orthopaedic biomechanics.

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Kaushik Mukherjee is an Assistant Professor in the Department of Mechanical Engineering at the Indian Institute of Technology Delhi. He is leading the orthopaedic biomechanics and implant design research group as well as the Sports Biomechanics research lab. His research lies across orthopaedic biomechanics, implant design, musculoskeletal modelling, and mechanics of human movement. Dr. Mukherjee earned his doctoral and master's degrees from the Indian Institute of Technology Kharagpur, whereas his undergraduate degree was from West Bengal University of Technology (Kalyani Government Engineering College). Dr. Mukherjee pursued his postdoctoral research in the Department of Bioengineering, Imperial College London, UK, where he was also a recipient of the Marie Skłodowska-Curie Research Fellowship.

Chapter 1
Musculoskeletal System: Structure and Function

In this chapter, our focus will be directed towards the fundamental aspects of the human musculoskeletal system. A detailed understanding of the musculoskeletal system, particularly the intricate relationship between the structure and its function, is necessary prior to discussions on the biomechanics of the human body. Musculoskeletal elements, e.g. bone, muscle, ligament, and tendon, are discussed in the following articles.

1.1 Skeletal System

The skeletal system is a basic framework of bones and connective tissues that provides the human body with essential structure, support, and protection. Additionally, this intricate network of bones and joints allows us to perform a range of movements and activities essential for daily living. The skeletal system is classified into the appendicular skeleton and the axial skeleton, as presented in Fig. 1.1. The group of bones or the skeleton marked in yellow corresponds to the axial skeleton, encompassing the skull, thoracic cage (rib cage), and vertebral column (Fig. 1.1a). The skeletal segment marked in blue colour is knowns as the appendicular skeleton, which includes the upper limbs, lower limbs, shoulder girdle, and pelvic girdle (Fig. 1.1b).

In order to accurately describe the position and orientation of the anatomical structures in space, it is necessary to define anatomical reference planes and anatomical directions. In Fig. 1.2, three mutually perpendicular planes, i.e. the coronal plane, the sagittal plane, and the axial plane, are presented. These planes are referred to as anatomical planes of reference, and they are essential for precisely determining the position of structures in space. The sagittal plane is a vertical plane that passes through the body longitudinally, dividing the body into a left section and a right section. The coronal plane is another vertical plane, perpendicular to the sagittal plane, that divides the body into a front section and a back section. The transverse

S. Gupta et al., *Biomechanics of Joints and Implants*,
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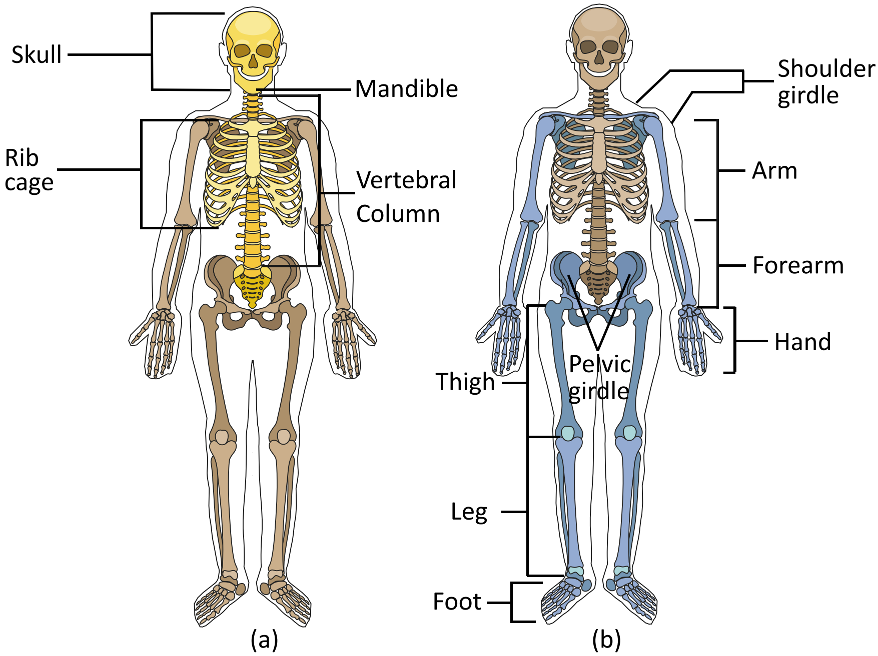

Fig. 1.1 The skeletal system; **a** axial skeleton, **b** appendicular skeleton

plane, also known as the axial plane, is an anatomical plane perpendicular to the above two planes that divides the body into top and bottom sections. Additionally, anatomical directions describe the position of a structure relative to another structure. Specific directions have been designated, including superior, inferior, anterior, posterior, proximal, distal, medial, and lateral, as illustrated in Fig. 1.3. For instance, the anterior and posterior directions are employed to describe structures located toward the front (anterior side) or toward the back (posterior side) of the body. An example is the toe being described as anterior to the heel. Part 'A' is said to be superior to part 'B', if part 'A' lies above part 'B'. Whereas, if part 'A' lies below the reference part 'B', we can say that part 'A' is inferior to part 'B'. For example, the pelvis is inferior to the abdomen. In addition to superior and inferior, anatomical terms such as proximal and distal are commonly used to denote relative positions. As the name suggests, while distal refers to a position far or at a certain distance, proximal indicates proximity. In precise terms, proximal indicates a position closer to the trunk or the point of attachment or origin of a structure, while distal refers to a location further away from it. For example, the foot is distal to the knee joint, whereas the knee is proximal to the foot. The knee joint is located closer to the trunk, while the foot is located farther away from it, making it distal to the knee joint. The femoral head is proximally located in the femur, whereas the femoral condyles are distally located.

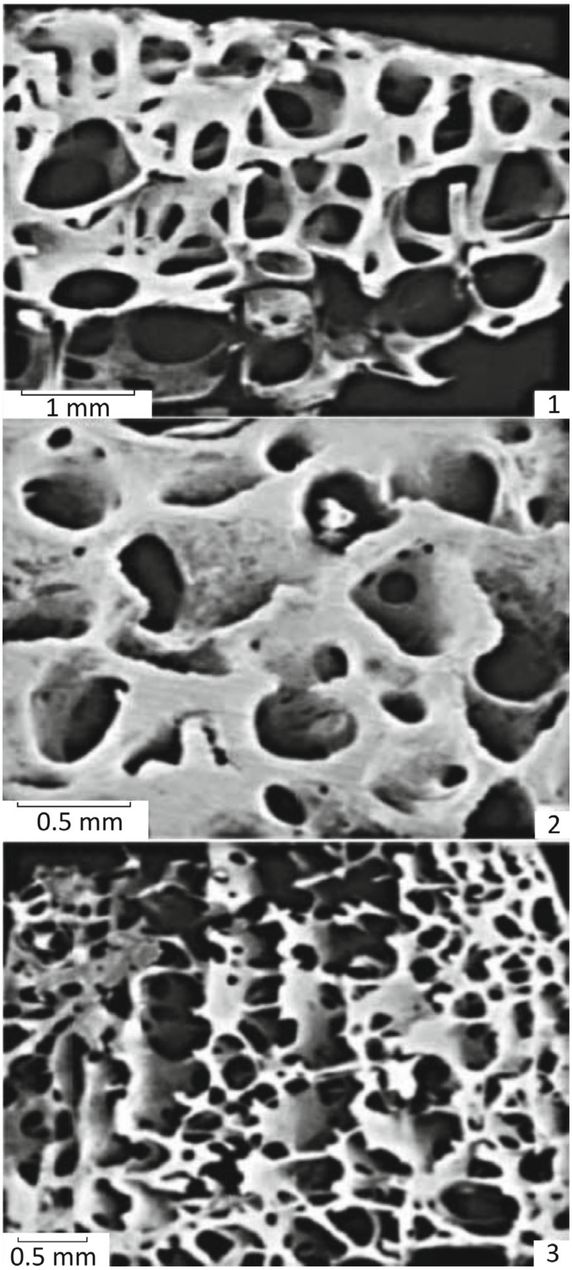

Fig. 5.22 Scanning electron micrographs of cancellous bone structure: **1**. Low density cancellous bone with an asymmetric rod-like structure; specimen taken from femoral head **2**. High density cancellous bone with an asymmetric plate-like structure; specimen taken from femoral head **3**. Plate-like cancellous bone with columnar structure; specimen taken from femoral condyle (Adapted from Gibson L. J. 1985)

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Solution to Practice Problems

Solutions to Practice Problems of Chap. 2

Problem 2.1

Given data:

Reaction force, $R = 80$ kg (subject standing on one foot)

The weight of limb $(W_L) = 13$ kg

Unknown data:

Hip joint reaction force ($\boldsymbol{F_J}$) acting at an angle θ with the horizontal.

Considering the force equilibrium along x- and y-directions (Fig. S2.1),

$$\begin{aligned} &\sum F_X = 0 \\ &F_A \cos 70 = F_J \cos \theta \end{aligned} \tag{S2.1}$$

$$\begin{aligned} &\sum F_Y = 0 \\ &F_A \sin 70 + R = \mathrm{W_L} + F_J \sin \theta \\ &F_A \sin 70 + 80 = 13 + F_J \sin \theta \\ &F_A \sin 70 + 67 = F_J \sin \theta \end{aligned} \tag{S2.2}$$

Taking a moment about centre of pressure,

$$\begin{aligned} &\sum M = 0 \\ &0.082 \times F_A \sin 70 + 0.890 \times F_A \cos 70 - 0.008 \times W_L \\ &-0.014 \times F_J \sin \theta - 0.9 \times F_J \cos \theta = 0 \end{aligned} \tag{S2.3}$$

Substituting Eqs. (S2.1) and (S2.2) in Eq. (S2.3)

S. Gupta et al., *Biomechanics of Joints and Implants*,
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