ECE 331 – INTRODUCTION TO BIOMEDICAL ENGINEERING

STUDY GUIDE: SKELETAL SYSTEM FOR BIOMEDICAL ENGINEERING

CONTENTS

1.0 OBJECTIVE

The objective of this study guide is to enable the student to understand the structure, function, and mechanical properties of the skeletal system, and to apply the knowledge to biomedical engineering problems such as implant design, biomechanics and tissue engineering.

2. CORE CONCEPTS: ANATOMY & PHYSIOLOGY

2.1. Macroscopic Structure

1. The macroscopic skeleton is divided into two types, i.e

    a) **Axial Skeleton:** Skull, vertebral column, rib cage. Primary function: protection of vital organs.

    b) **Appendicular Skeleton:** Limbs, pectoral and pelvic girdles. Primary function: movement and manipulation.

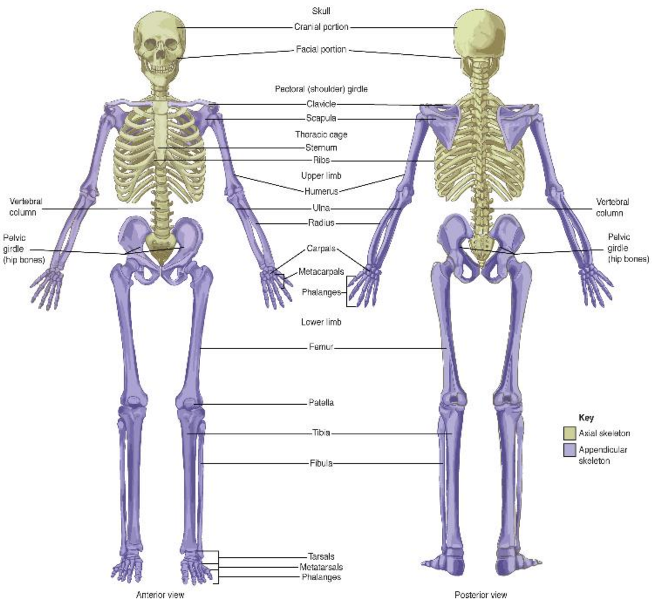

Figure 1. Axial and appendicular skeleton

2. **Bone Classification by Shape:**

    - **Long Bones** (e.g., femur, humerus): Levers for movement. Understand the anatomy: *Diaphysis* (shaft), *Epiphyses* (ends), *Metaphysis*, *Articular Cartilage*, *Medullary Cavity*.
    - **Short Bones** (e.g., carpals, tarsals): Shock absorption.
    - **Flat Bones** (e.g., skull, scapula): Protection and muscle attachment.

- **Irregular Bones** (e.g., vertebrae, pelvis): Specialized functions.

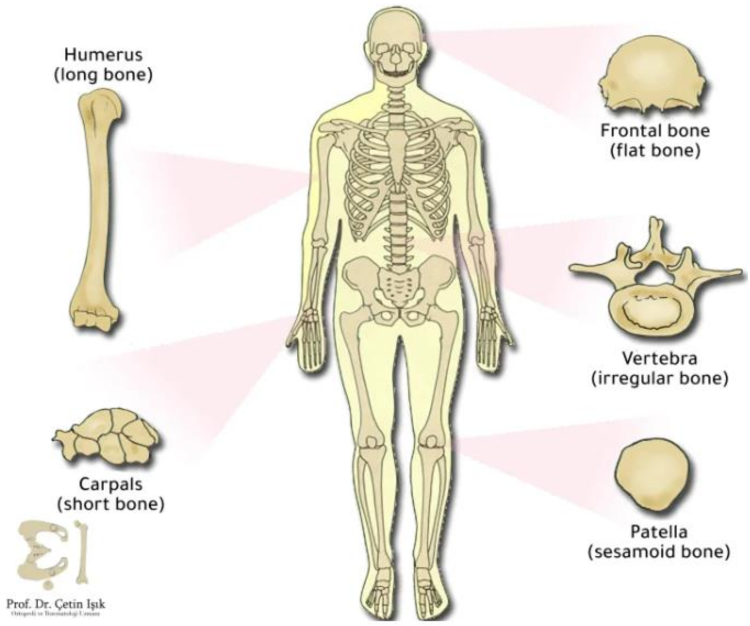

Figure 2. Classification of bones by shape

2.2. Microscopic Structure & Tissue Types

1. **Bone as a Composite Material:**

    a) **Organic Matrix (~35%):** Mostly **Type I Collagen** fibres. Provides tensile strength and flexibility.

    b) **Inorganic Matrix (~65%):** Primarily **Hydroxyapatite** crystals ($Ca_{10}(PO_4)_6(OH)_2$). Provides compressive strength and rigidity.

    Engineering Perspective: This combination makes bone strong yet light, resistant to both fracture (tough) and deformation (stiff).

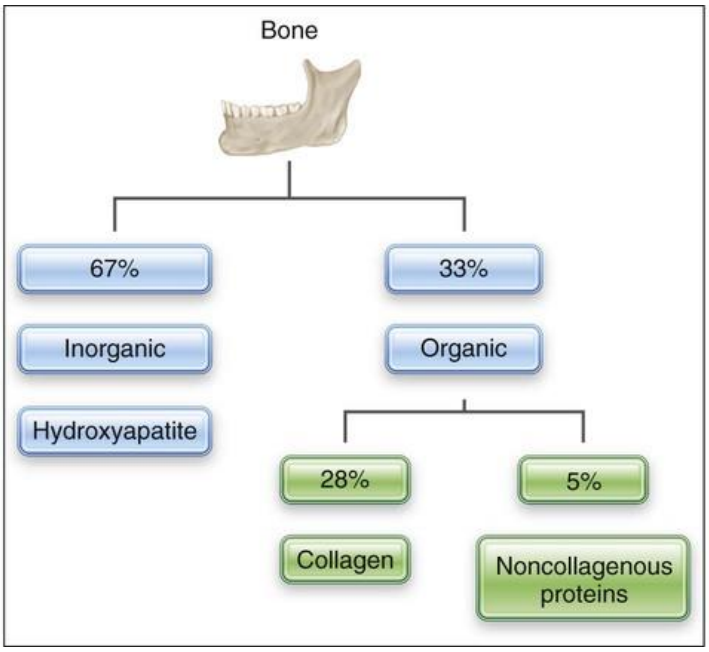

Figure 3. Chemical composition of dry bone

2. **Types of Bone Tissue:**

   - **Cortical (Compact) Bone:** Dense, solid outer layer. ~80% of the skeleton. High stiffness and strength. Organized into **osteons** (Haversian systems)**—** the fundamental functional unit. Understand the structure of an osteon (central canal, lamellae, lacunae, canaliculi).

   - **Trabecular (Cancellous/Spongy) Bone:** Porous, inner network of trabeculae. Found in epiphyses and vertebrae. Provides shock absorption and houses bone marrow. Its mechanical properties are highly dependent on **bone volume fraction** and **trabecular architecture** (orientation, thickness, spacing).

2.3. Bone Cells: The Maintenance Crew

- **Osteoblasts:** Bone-forming cells. Synthesize the organic osteoid matrix.
- **Osteocytes:** Mature osteoblasts trapped in the matrix. Act as mechanosensors—**critical for understanding bone remodeling.**
- **Osteoclasts:** Bone-resorbing cells. Breakdown bone tissue, releasing minerals.

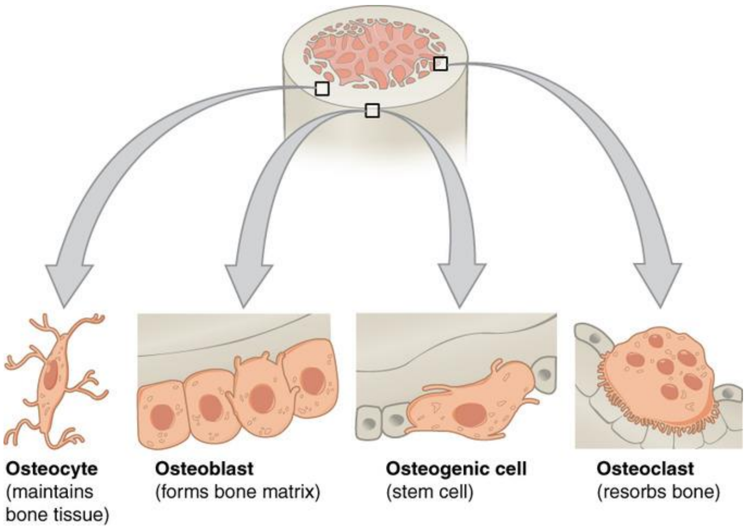

Figure 4. Cell types in bones

2.4. Bone Remodelling: A Continuous Process

Bone remodelling refers to the coupled process of resorption (by osteoclasts) and formation (by osteoblasts). This is how bone repairs micro-damages and adapts to mechanical stress (Wolff's Law).

Engineering Importance: This is the biological basis for stress shielding (bone loss around stiff metal implants) and is a key consideration for designing implants with compatible stiffness.

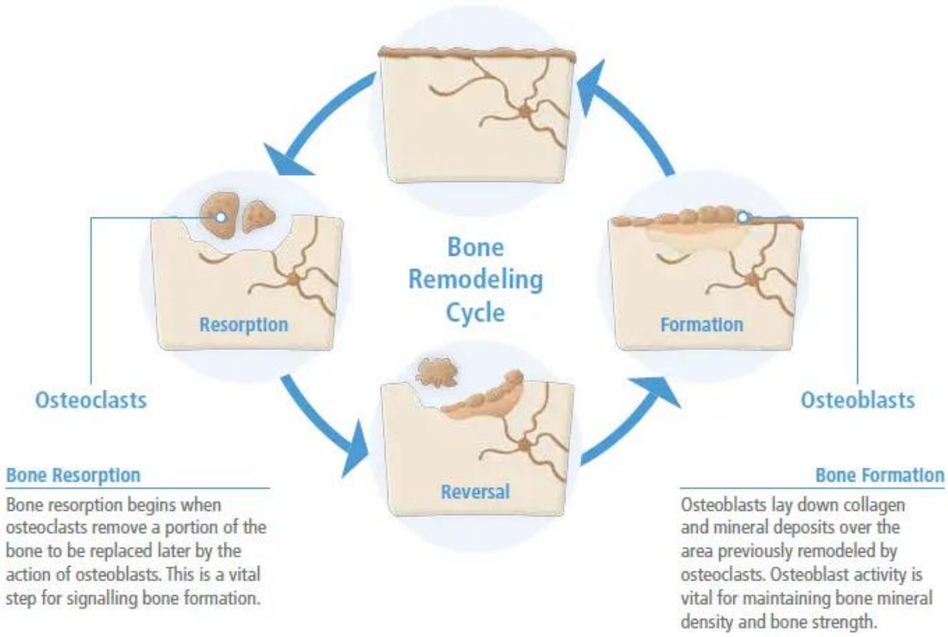

Figure 5. Bone remodelling cycle.

3. ENGINEERING PRINCIPLES: BIOMECHANICS & BIOMATERIALS

3.1. Mechanical Properties of Bone

1. **Anisotropic:** Properties differ based on the direction of load (e.g., stronger along the long axis).
2. **Viscoelastic:** Mechanical response depends on the rate of loading (e.g., bone is stronger under high strain rates).
3. **Key Properties to Quantify:**
   a) **Elastic Modulus (Stiffness):** Slope of the stress-strain curve in the elastic region. Cortical bone: ~15-20 GPa.
   b) **Yield Strength:** Stress at which permanent deformation begins.
   c) **Ultimate Strength:** Maximum stress a material can withstand.
   d) **Toughness:** Area under the stress-strain curve; resistance to fracture.
4. **Compare these properties for Cortical vs. Trabecular Bone.** Trabecular bone is less stiff and strong but more ductile.

3.2. Loading Modes

Understand how bone fails under different loading conditions, crucial for understanding fractures and designing protective equipment:

- **Tension, Compression, Shear, Bending, Torsion.**

3.3. Joints & Articulations

- **Classification:** Synovial (e.g., knee, hip), Fibrous (e.g., skull sutures), Cartilaginous (e.g., intervertebral discs).
- **Synovial Joint Anatomy:** Articular cartilage, synovial fluid, joint capsule, ligaments. Focus on **articular cartilage** as a brilliant tribological material (low friction, wear-resistant).

4. CLINICAL & ENGINEERING APPLICATIONS

4.1. Fracture Fixation

1. **Principles:** Fracture reduction, stability, and load sharing.
2. **Implants:**
   a) **Plates & Screws:** Function in **tension-band plating** and **neutralization**.
   b) **Intramedullary (IM) Nails:** Load-sharing devices that act as an internal splint.
   c) **Engineering Challenge:** The **stiffness mismatch** between metal implants (e.g., Titanium ~110 GPa, Stainless Steel ~200 GPa) and bone (~18 GPa) leads to stress shielding and bone resorption.

4.2. Total Joint Replacements (Arthroplasty)

1. **Hip and Knee Replacements:** Typically a metal (Co-Cr, Ti alloy) component articulating with a polymer (Ultra-High-Molecular-Weight Polyethylene - UHMWPE) component.
2. **Engineering Challenges:**
   a) **Wear Debris:** UHMWPE wear particles can cause osteolysis (bone dissolution) and implant loosening.
   b) **Aseptic Loosening:** The major cause of long-term failure.
   c) **Fixation:** Cemented vs. cementless (press-fit, porous coatings for bone ingrowth).

4.3. Bone Tissue Engineering

- **The Triad:**
  1. **Scaffolds:** Biodegradable polymers (PLA, PLGA), ceramics (Hydroxyapatite, Tricalcium Phosphate), or composites. Must have appropriate porosity, mechanical properties, and surface chemistry.
  2. **Cells:** Mesenchymal stem cells (MSCs), osteoblasts.
  3. **Signals:** Growth factors (e.g., Bone Morphogenetic Proteins - BMPs).
- **Goal:** To create a synthetic graft that guides bone regeneration and is gradually replaced by native bone.

5. STUDY STRATEGIES & RESOURCES

1. **Draw and Label:** Don't just read. Draw a long bone, an osteon, a stress-strain curve. Label everything.
2. **Explain it to a Peer:** Teach the concept of Wolff's Law or stress shielding to someone else. This forces deep understanding.
3. **Connect Biology to Engineering:** For every biological concept, ask "What is the engineering principle?" and vice versa.
    - *Example:* **Osteocytes** (Bio) -> **Mechanotransduction** (Eng) -> **Bone Remodeling** (Bio) -> **Wolff's Law** (Eng) -> **Implant Design** (BME).
4. **Solve Problems:** Work on problems calculating stress on a bone, or comparing the elastic modulus of different biomaterials.

6. SAMPLE STUDY QUESTIONS & APPLICATION PROBLEMS

1. **Compare and contrast** the structure and primary mechanical function of cortical and trabecular bone.
2. A femur with a cross-sectional area of 4 cm^2 experiences a compressive load of 6000 N. What is the stress on the bone? Is this below the yield stress for cortical bone (~150 MPa)?
3. **Explain the phenomenon of stress shielding.** Why is titanium often preferred over stainless steel for orthopaedic implants despite having a lower ultimate strength?
4. Describe the process of bone remodelling. How would a rigid internal fixation plate placed on a bone affect this process in the cortex directly underneath it?
5. What are the primary **wear mechanisms** in a metal-on-polyethylene hip bearing? What engineering strategies are used to reduce wear?
6. List the ideal properties of a scaffold for bone tissue engineering. What materials show promise for this application?