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Medical physics

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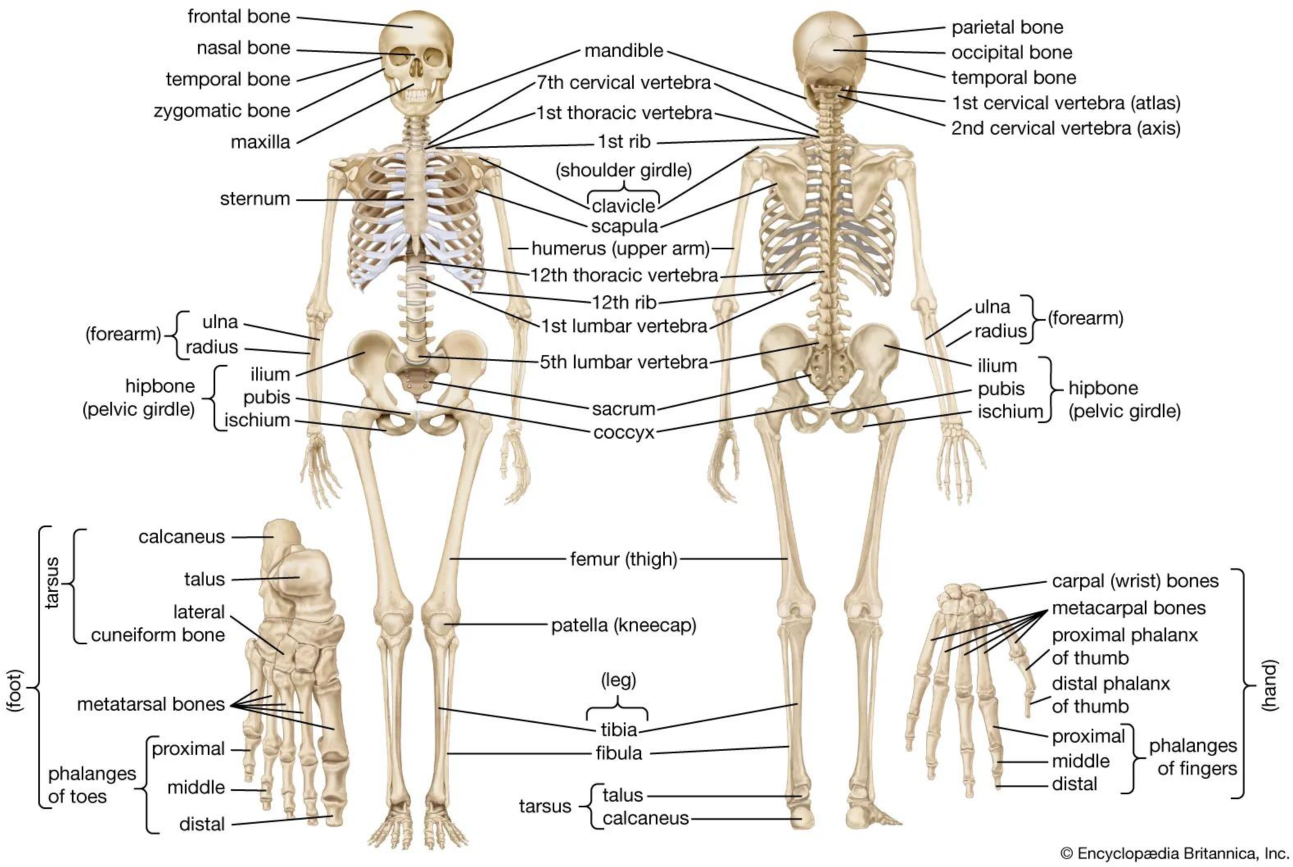
The physics of skeleton



1. Introduction: Why Study Bone Physics?

Understanding the physics of bones is essential for:

- **Medical specialists**: Orthopedic surgeons, dentists, rheumatologists
- **Radiologists**: Interpreting x-ray images and bone density measurements
- **Biomedical engineers**: Designing prosthetic joints and bone replacement materials
- **Physical scientists**: Understanding biological materials and biomechanics

2. The Four Functions of Bone

- The skeleton provides structural support for the body
- Support and protect the soft organs of the body
- Protects the soft body parts. The fused bones of the cranium surround the brain to make it less vulnerable to injury.

- Bones work together with muscles as simple mechanical lever systems to produce body movement.
- **These are the only bones that reach full adult size before birth!**

3. What is Bone Made Of?

3.1 Chemical Composition of Bone

Bone consists of two main materials plus water:

Component	Percentage by Weight	Percentage by Volume	Function
Collagen	40%	60%	Organic protein matrix - provides flexibility
Bone Mineral	60%	40%	Inorganic crystals - provides strength
Water	Variable	Variable	Surrounds components

Large percentage of calcium with heavier nucleus, high x-ray absorption. Collagen; major organic fraction, 40% of the weight of solid bone and 60% of its volume. Collagen remainder; flexible and bends easily, large tensile strength, produced by osteoblast cells. Bone mineral remainder: fragile, can be crushed with fingers, formed on the collagen.

Collagen makes bones flexible (elastic), Mineral makes bones rigid, Water in interstitial spaces stores nutrients.

3.2 Bone Mineral Details

- **Chemical formula**: $Ca_{10}(PO_4)_6(OH)_2$ - **Calcium Hydroxyapatite**
- **Crystal structure**: Rod-shaped crystals
  - Diameter: 20-70 Angstroms (Å)
  - Length: 50-100 Å
  - (1 Å = 10^{-10} m)

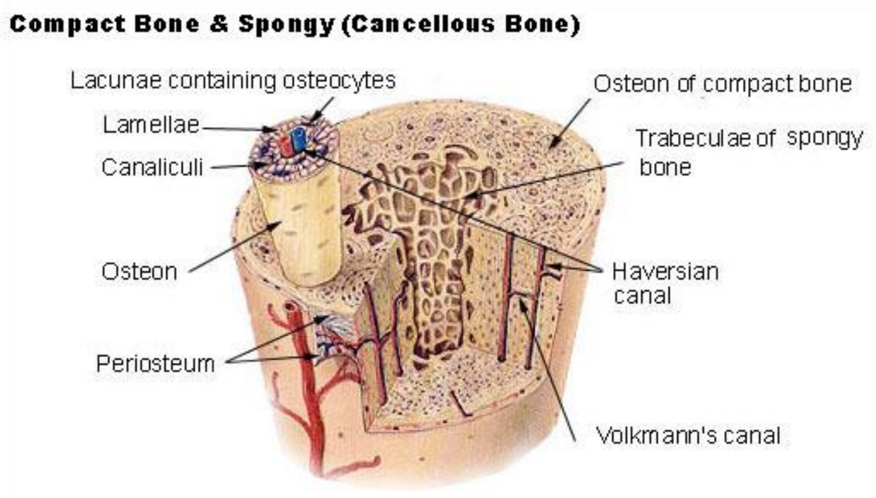
  When blood calcium levels decrease below normal, calcium is released from the bones so that there will be an adequate supply for metabolic needs. When blood calcium levels are increased, the excess calcium is stored in the bone matrix. The dynamic process of releasing and storing calcium goes on almost continuously.

4. Bone Density and Living Tissue

- **Density of compact bone**: ~1.9 g/cm³ (constant throughout life)
- **Comparison**: Water = 1.0 g/cm³.
- Bone is approximately 1.9 times as dense as water.
- Bone is not static - it continuously changes throughout life.
- Complete skeleton renewal: Every 7 years.
- Young & growing (0-35 years): Osteoblasts > Osteoclasts → bone mass increases
- After 35-40 years: Osteoclasts > Osteoblasts → gradual bone mass decrease
- Total bone mass decreases from age 35-40 onward.

5. Types of Bone Structure

1. Compact Bone
2. Spongy (Cancellous) Bone



6. Mechanical Properties of Bone

6.1 Stress and Strain Definitions

Stress (σ): Force per unit area

$$\sigma = \frac{F}{A}$$

Units: N/m² (Pascals, Pa) or N/mm²

Strain (ε): Fractional change in length

$$\varepsilon = \frac{\Delta L}{L}$$

Units: Dimensionless (or expressed as percentage).

6.2 Young's Modulus (Y)

Young's modulus describes the stiffness of a material:

$$Y = \frac{\text{Stress}}{\text{Strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta L/L}$$

Rearranged for calculations:

$$\Delta L = \frac{LF}{AY}$$

Units: N/m² or N/mm²

Physical meaning:

- High Y = stiff material (small deformation under load)
- Low Y = flexible material (large deformation under load)

7. Mathematical Examples

Example 7.1: Compression of Leg Bone

Problem: A leg bone has a shaft of length L = 1.2 m with an average cross-sectional area A = 3 cm² = 3 × 10^{-4} m². What is the amount of shortening when the full body weight of 700 N is supported on this leg? Young's Modulus equals 1.8 × 10^{10} N/m².

Given:

- L = 1.2 m, A = 3 × 10^{-4} m², F = 700 N, Y = 1.8 × 10^{10} N/m² (for compact bone)

Solution:

$$\Delta L = \frac{LF}{AY} = \frac{(1.2\ \mathrm{m})(700\ \mathrm{N})}{\left(3 \times 10^{-4}\ \mathrm{m}^2\right)\left(1.8 \times 10^{10}\ \mathrm{N/m}^2\right)}$$
$$\Delta L = 1.5 \times 10^{-4}\ \mathrm{m} = 0.15\ \mathrm{mm}$$

Example 7.2: Maximum Load Before Fracture

Problem: Calculate the maximum force of a bone with cross-sectional area of 4 cm² can withstand just prior to fracture, since breaking stress 120 N/mm².

Given:

- A = 4 cm² = 4 × 10^{-4} m²
- Breaking stress (tension) = 120 N/mm² = 120 × 10^{6} N/m²

Solution:

Using: σ = F/A

$$F = \sigma \times A = (120 \times 10^{6}\ \mathrm{N/m}^2)(4 \times 10^{-4}\ \mathrm{m}^2)$$
$$F = 48{,}000\ \mathrm{N} = 48\ \mathrm{kN}$$

Example 7.3: Stress on Femur During Impact

Problem: A parachutist lands with a stiff-legged landing. The force generated is 1.42 × 10^{6} N (32,000 lb). The tibia has a cross-sectional area of about 3.3 cm² at the ankle. What stress does this produce?

Given:

- F = 1.42 × 10^{6} N , A = 3.3 cm² = 3.3 × 10^{-4} m²

Solution:

$$\sigma = \frac{F}{A} = \frac{1.42 \times 10^6 \text{ N}}{3.3 \times 10^{-4} \text{ m}^2}$$
$$\sigma = 4.3 \times 10^9 \text{ N/m}^2 = 430 \text{ N/mm}^2 \approx 215 \text{ N/mm}^2$$

8. Clinical Applications

1. Osteoporosis Detection

Problem: Bone mineral mass decreases slowly (1-2% per year after age 35-40)

- Large change (30-50%) must occur before radiologist can detect on x-ray
- Need more precise technique.

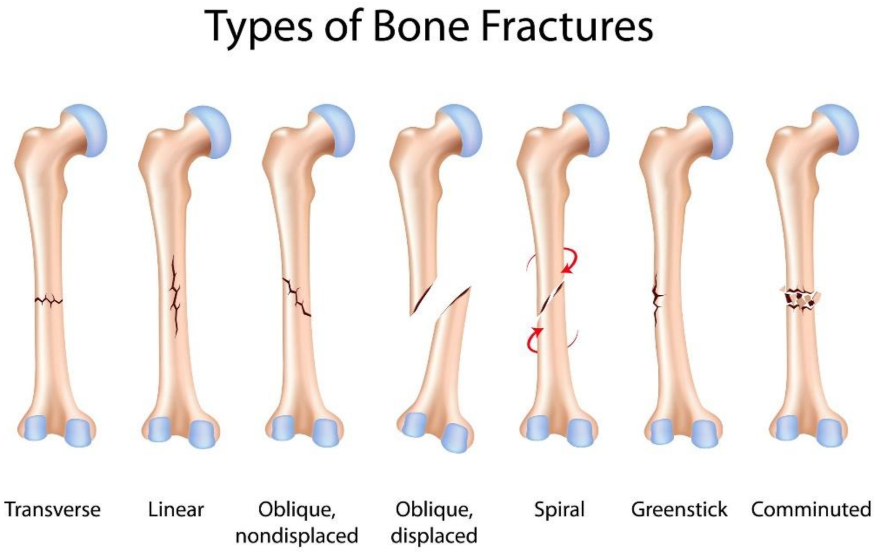
2. Modern solution: **Photon Absorptiometry** (Bone Densitometry)

- The problems with x – ray techniques were eliminated by using;
- Mono-energetics x – ray or gamma ray source, monochromatic light.
- Narrow beam to reduce the scatter.
- Using a Scintillation detector that detects all photons.

The strength of bone depends on the mass of bone mineral present [decreases, 1 to 2% per year]. Osteoporosis: lower bone mineral mass.

I^*o is the intensity of beam before enters the bone.
I is the intensity of beam after enters the beam [transmition beam]
The bone mineral mass MB at any point in the beam is proportional the Log (I^*_o/I)
MB α Log (Io^*/ I)
MB = K Log (Io^*/ I)
Where K = constant.

9. Bone Fractures and Healing

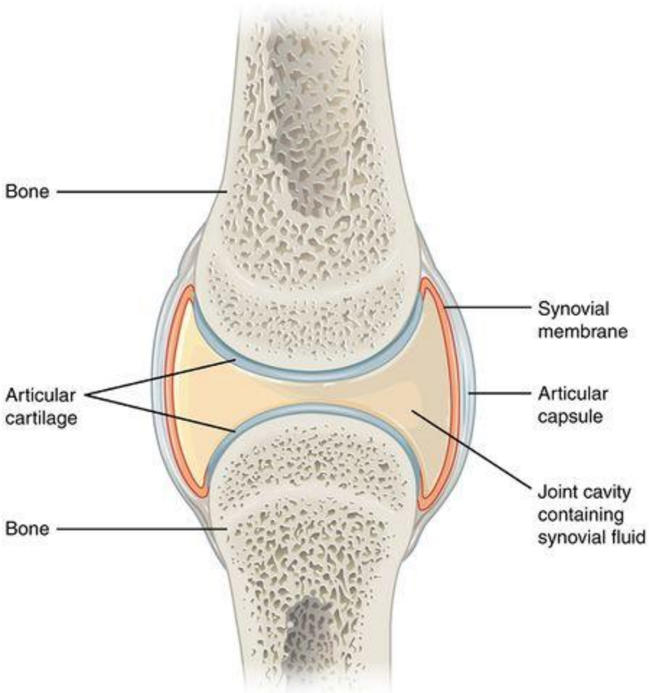


10. Bone joints and synovial fluid play a critical role in enabling smooth, efficient movement while minimizing mechanical wear.

Bone joints (articulations) are the anatomical connections between two or more bones and are classified structurally into **fibrous**, **cartilaginous**, and **synovial joints**. Among these, **synovial joints** are the most mobile and mechanically sophisticated. **They are characterized by opposing articular surfaces covered with hyaline cartilage, enclosed within a joint capsule, and separated by a joint cavity**.

The joint cavity contains **synovial fluid**, a viscous, non-Newtonian fluid rich in hyaluronic acid and lubricin. Synovial fluid serves multiple biomechanical functions: it lubricates the articular surfaces, reduces friction, absorbs shock, and facilitates nutrient transport to the avascular articular cartilage.

From a mechanical perspective, the **coefficient of friction of synovial joints** is exceptionally low, typically in the range of **0.002–0.02**, which is lower than most engineered bearing systems.



11. Practice Problems

Problem 1

A bone 40 cm long with cross-sectional area 2.5 cm^2 is subjected to a tensile force of 3000 N. Calculate: (a) The stress in the bone (b) The strain in the bone (c) The elongation of the bone (Use $Y = 1.65 \times 10^{10}$ N/m^2)

Problem 2

How much force would cause a bone to break if it has a cross-sectional area of 5 cm^2 and the tensile breaking stress is 120 N/mm^2?