

ANISOTROPY AND VISCOELASTICITY

1. Introduction

Bone is a highly specialized connective tissue that provides structural support, protection, and acts as a reservoir for minerals. Its mechanical behavior is influenced by its composite structure (collagen + mineral), hierarchical organization, and loading direction. Two key mechanical properties of bone are **anisotropy** and **viscoelasticity**, which determine how bone responds to different physiological and traumatic loads.

2. ANISOTROPY OF BONE

Definition

Anisotropy refers to the property of a material where its mechanical behavior (strength, stiffness, elasticity) varies depending on the direction of loading.

Why bone is anisotropic?

Bone has a **hierarchical, non-uniform structure**:

Cortical bone has lamellae organized in osteons.

Trabecular bone has lattice-like trabeculae aligned along stress lines.

Collagen fibers and hydroxyapatite crystals are directionally arranged.

Types of Anisotropy

Bone is mainly **orthotropic**, meaning it has three mutually perpendicular directions with different properties:

Longitudinal direction (along osteons)

Radial direction

Circumferential direction

Mechanical Behavior in Different Directions

Property	Longitudinal	Radial	Circumferential
Elastic modulus	Highest	Medium	Lowest
Tensile strength	Highest	Lower	Lowest
Compressive strength	High	Medium	Low

Explanation

Osteons run parallel to the long axis → highest strength and stiffness in that direction.

Perpendicular loading disrupts lamellae and cement lines → weaker mechanical response.

Clinical & Biomechanical Importance

Fracture risk depends on fall direction (e.g., transverse vs longitudinal loads).

Implant design must match directional stiffness.

Helps explain bending and torsional behavior in long bones.

3. VISCOELASTICITY OF BONE

Definition

Viscoelasticity means bone exhibits both:

Elastic behavior (instant recovery when load removed)

Viscous behavior (time-dependent deformation)

Thus, bone response depends on **loading rate**, **duration**, and **speed**.

4. Viscoelastic Characteristics of Bone

4.1 Creep

Constant load → deformation increases with time.

Bone slowly elongates or compresses when continuously loaded.

4.2 Stress Relaxation

Constant deformation → stress gradually decreases.

Example: orthodontic tooth movement (alveolar bone).

4.3 Hysteresis (Energy loss)

Load–unload curve does not overlap.

Represents internal damping of energy.

Important for shock absorption.

4.4 Strain Rate Sensitivity

Bone becomes **stronger and stiffer under higher loading rates**.

At low rates → more ductile.

At high rates (accidents, falls) → more brittle → catastrophic fractures.

5. Factors Influencing Anisotropy & Viscoelasticity

Bone density (cortical vs trabecular)

Age (bone becomes brittle and less viscous)

Disease (osteoporosis alters micro-architecture)

Water content

Rate and mode of loading (tension, compression, torsion)

6. Combined Effect in Bone Mechanics

Bone withstands **compression > tension > shear**.

Direction AND speed of load determine fracture pattern.

Bone design is optimized for **physiological loading** (Wolff's law).

7. Real-World Examples

Hip fracture during sideways fall due to load perpendicular to trabeculae.

Stress fractures from repeated low-rate loading (viscoelastic fatigue).

Long bones stronger in longitudinal compression due to anisotropy.

High-impact sports: rate-dependent stiffness reduces injury until threshold.

8. Conclusion

Anisotropy and viscoelasticity make bone a unique biological composite capable of withstanding complex mechanical environments. Understanding these properties is essential for biomechanics, orthopedics, implant design, injury prediction, and rehabilitation strategies.