



MECHANICAL PROPERTIES OF SOLID MATERIALS AND BIOLOGICAL TISSUES: A COMPREHENSIVE MEDICAL PERSPECTIVE

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ABSTRACT

The mechanical behavior of solid materials and biological tissues represents a fundamental area of study bridging physics, biology, and clinical medicine. This article provides an in-depth analysis of stress–strain relationships, elasticity, plasticity, and viscoelasticity, with a particular focus on how these principles apply to living tissues such as bone, muscle, tendon, and cartilage. Unlike conventional solid materials, biological tissues exhibit nonlinear, anisotropic, and time-dependent mechanical properties due to their complex microstructure and biochemical composition. Understanding these characteristics is essential for clinical applications, including trauma management, orthopedic surgery, prosthetic design, and rehabilitation medicine.

Keywords: biomechanics, stress, strain, elasticity, viscoelasticity, bone, tendon, cartilage

INTRODUCTION

Mechanical principles govern the behavior of all materials subjected to external forces. In classical physics, solid materials are characterized by predictable and often linear relationships between applied force and resulting deformation. However, biological tissues present a far more complex scenario. They are living, adaptive systems composed of hierarchical structures, including cells, extracellular matrix, and fibrous proteins such as collagen and elastin.

From a medical standpoint, the human body constantly experiences mechanical forces—during movement, weight-bearing, and even at rest. Bones support structural loads, muscles generate force, tendons transmit mechanical energy, and cartilage distributes pressure within joints. The integrity and function of these tissues depend on their mechanical properties. Consequently, understanding their behavior is critical for diagnosing injuries, predicting disease progression, and designing effective therapeutic interventions.

MATERIALS AND METHODS

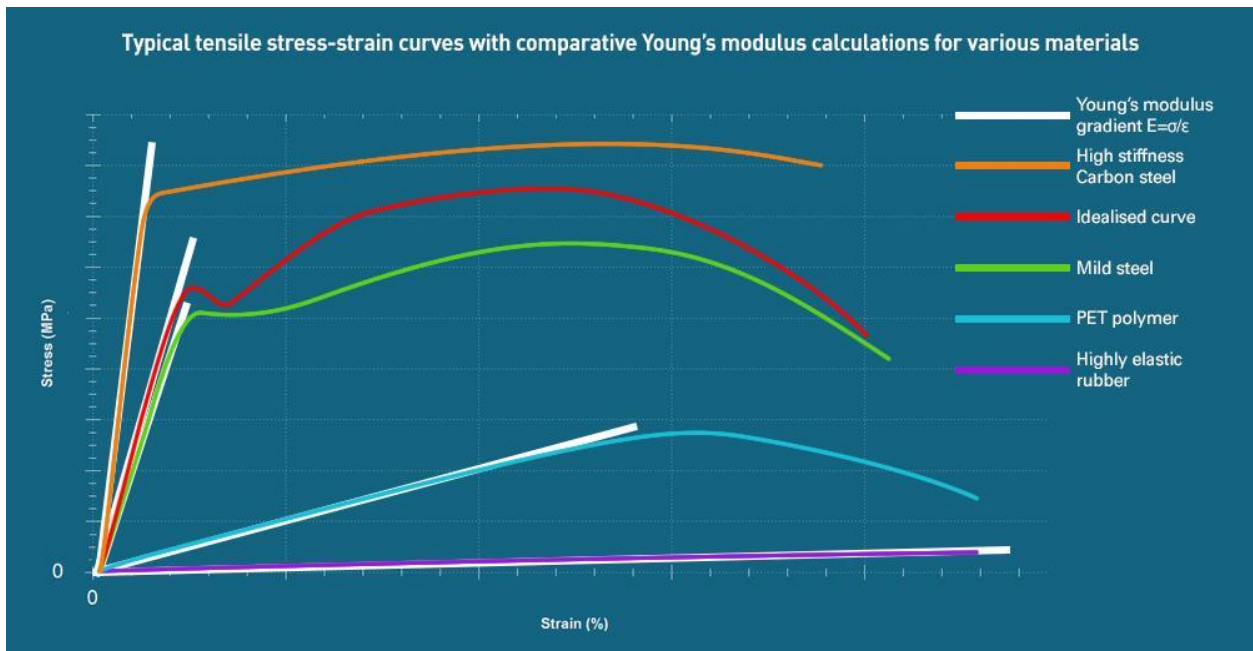
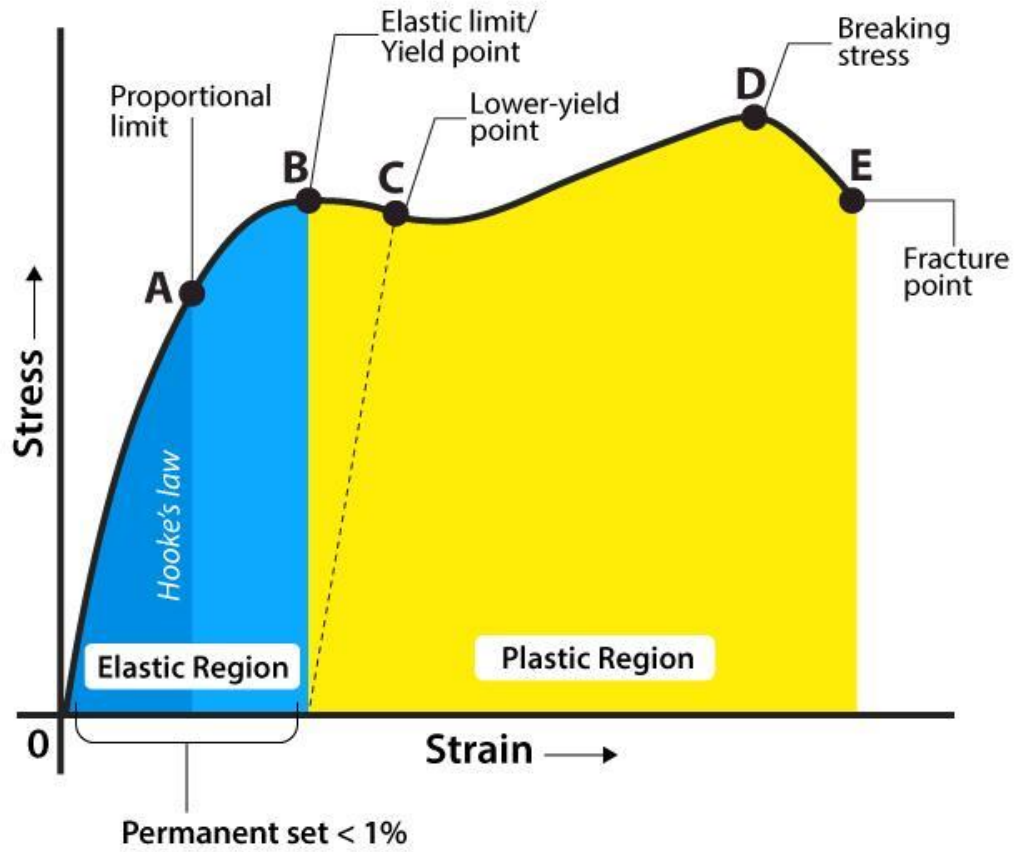
This article is based on an extensive review of established medical and biomechanical literature. Classical mechanical theories were integrated with modern findings in tissue biomechanics. Key parameters such as stress, strain, Young's modulus, and viscoelastic behavior were analyzed and compared between non-living solid materials and biological tissues. Experimental observations from musculoskeletal biomechanics studies were incorporated to provide clinically relevant insights.

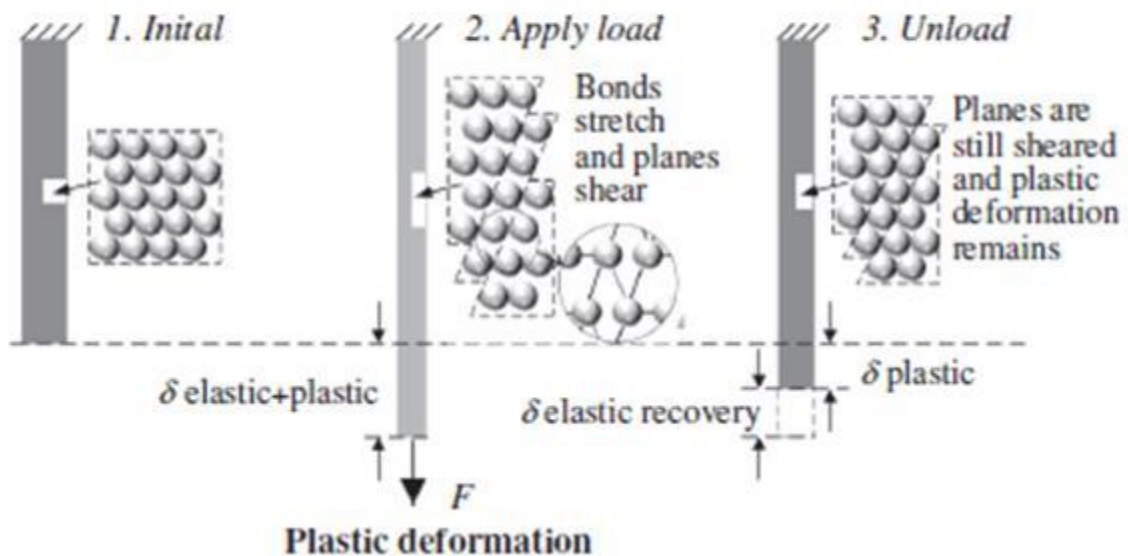
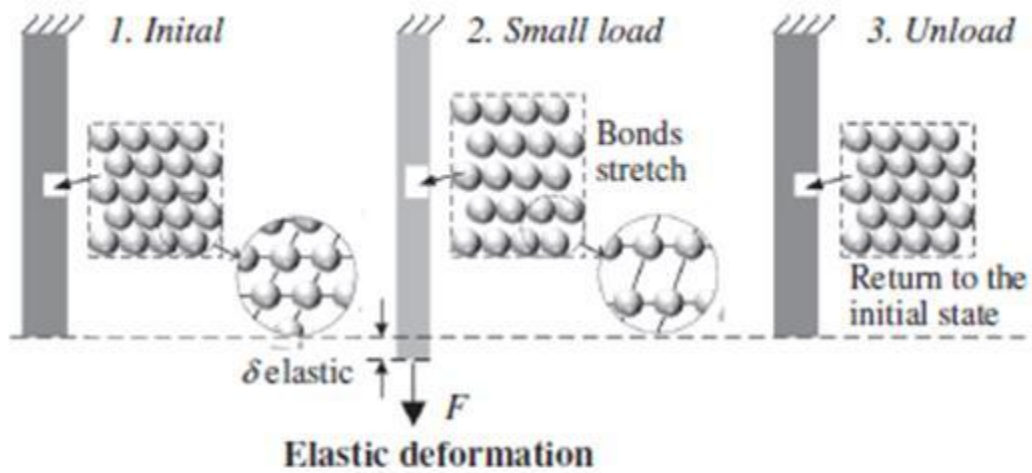
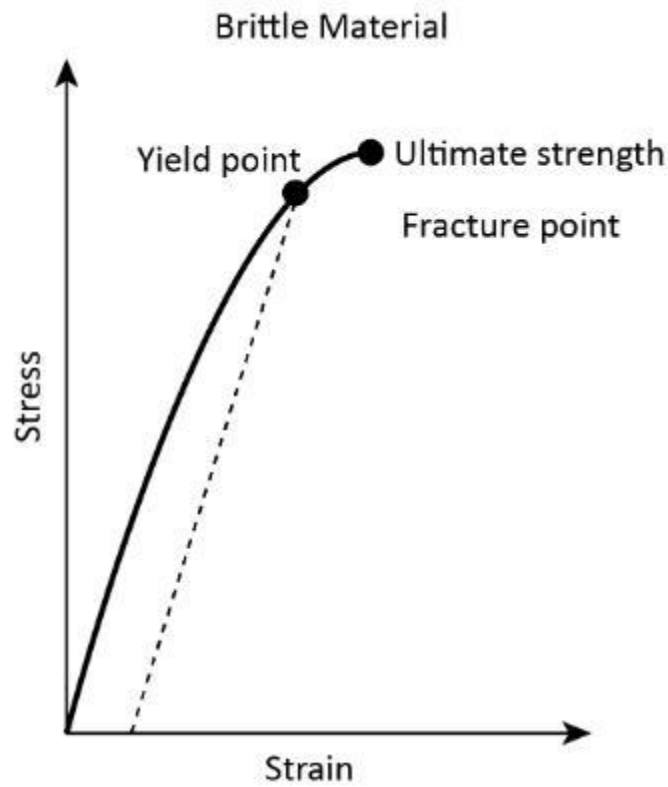
RESULTS

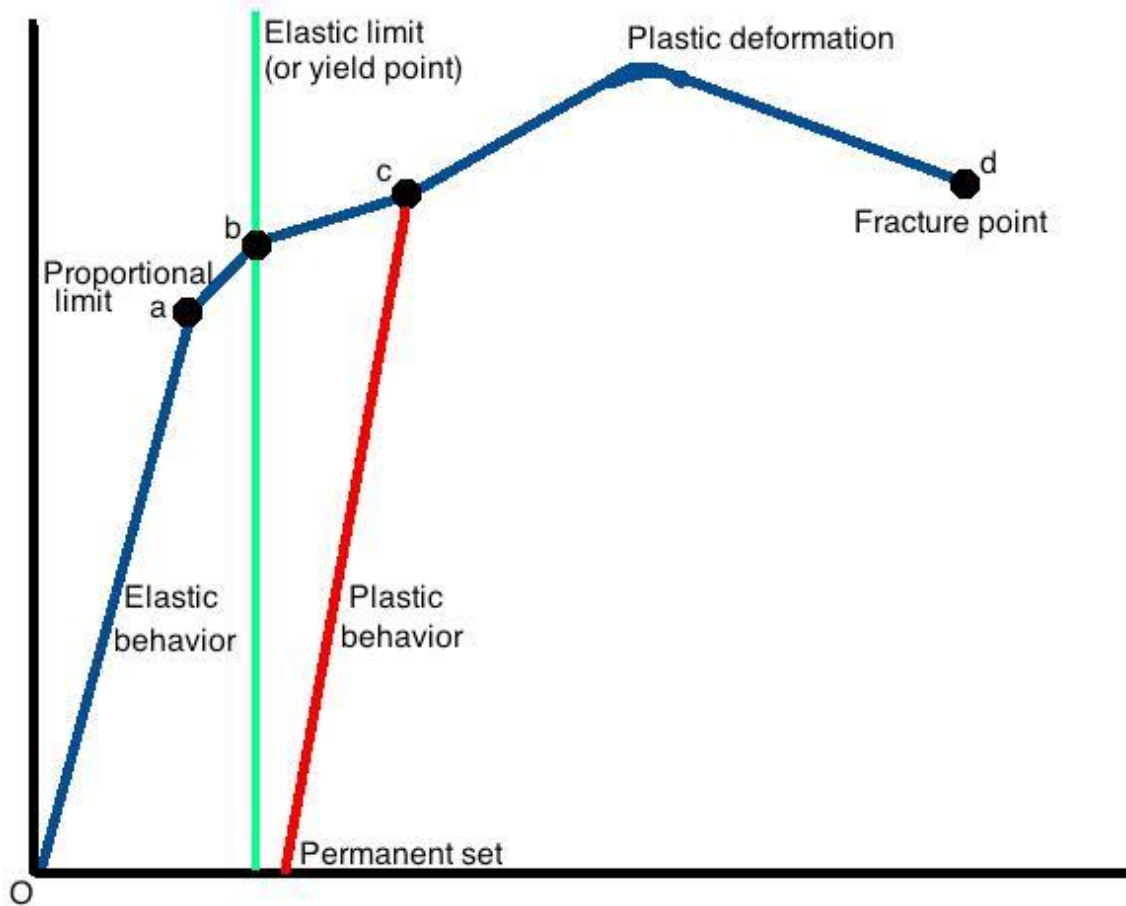
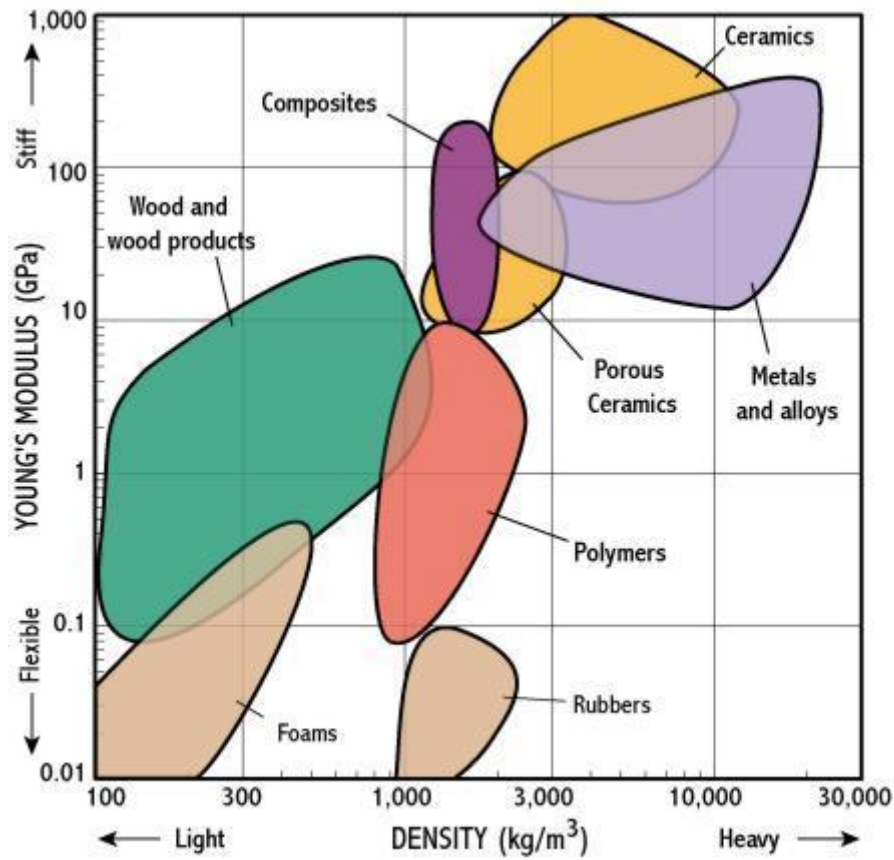
At the core of mechanical analysis lies the relationship between stress and strain. Stress refers to the internal force per unit area within a material, while strain represents the relative deformation experienced by the material. In ideal solid materials, these variables are related through Hooke's law:

$$\sigma = E \cdot \epsilon$$

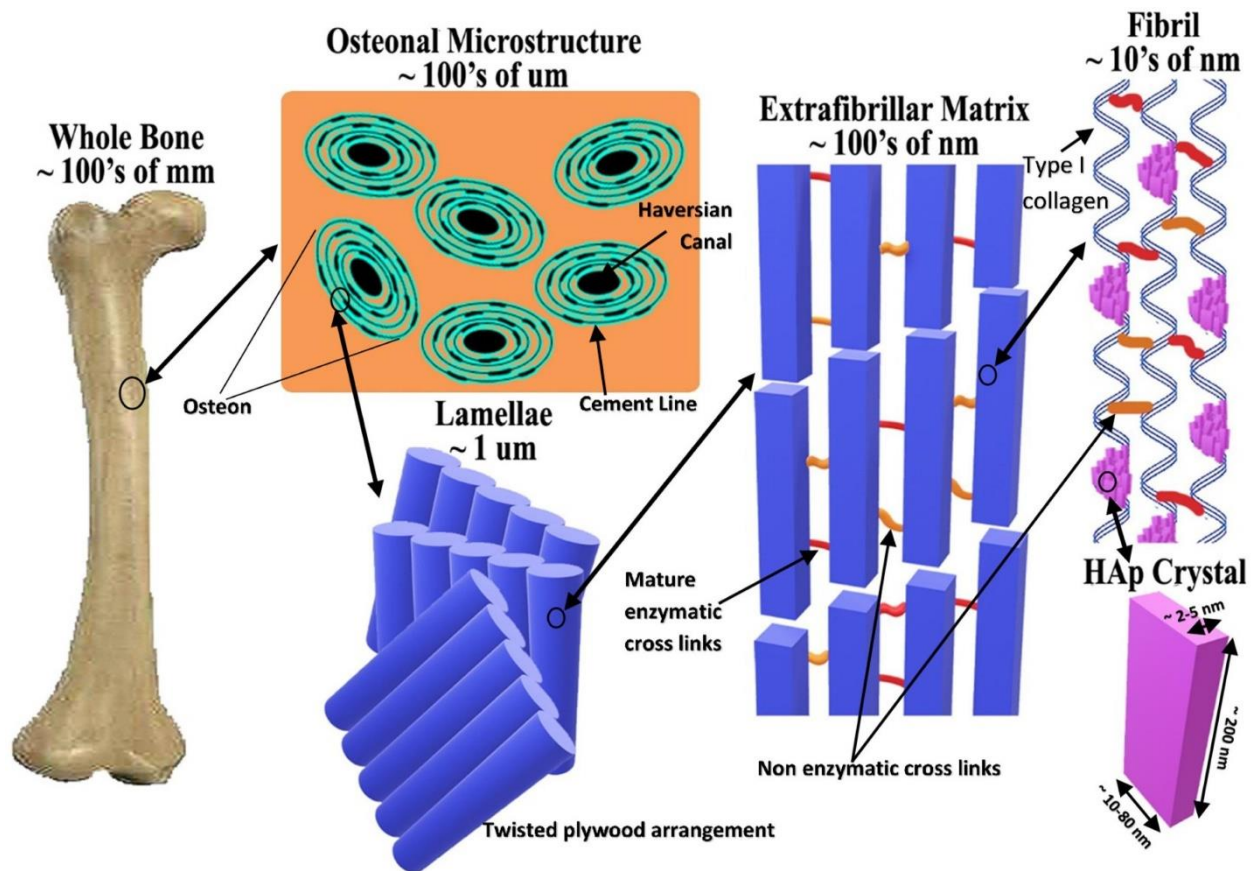
Here, the Young's modulus (E) quantifies the stiffness of a material. Materials with a high modulus, such as metals, resist deformation, whereas those with a low modulus deform more easily.

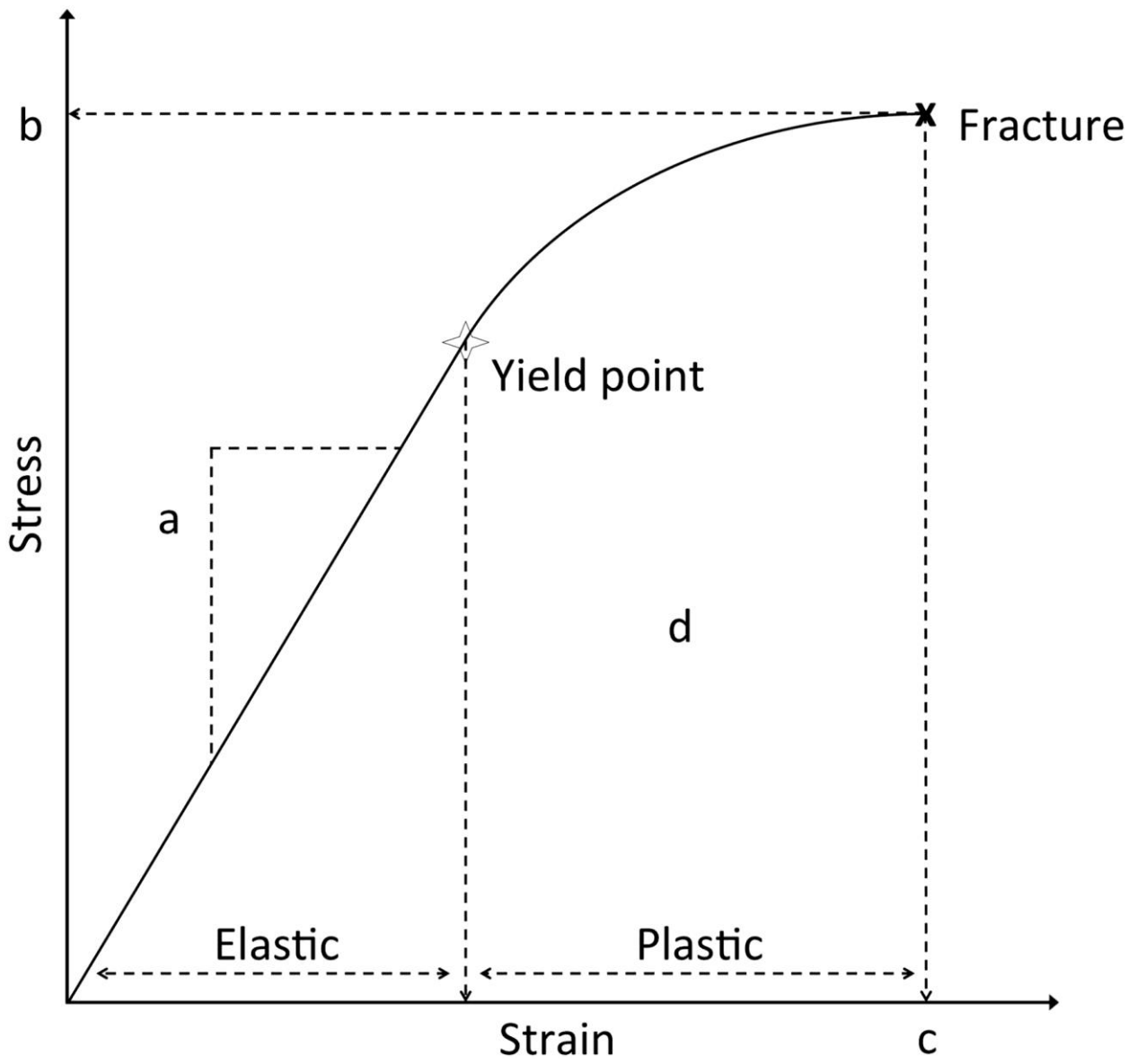




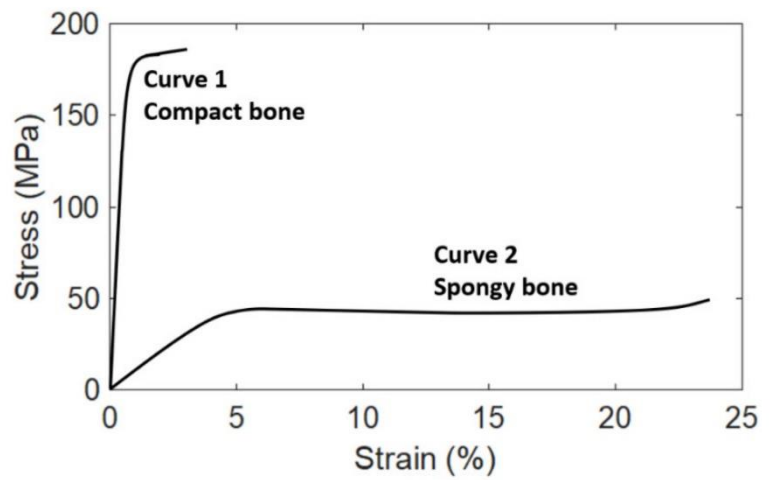
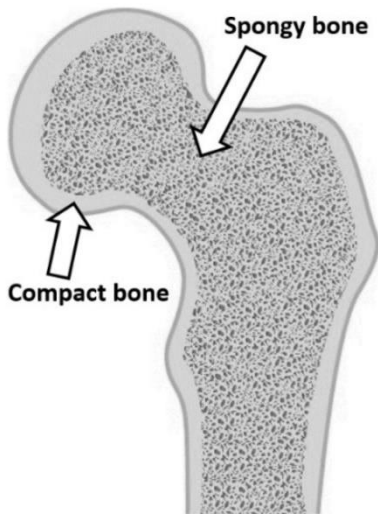
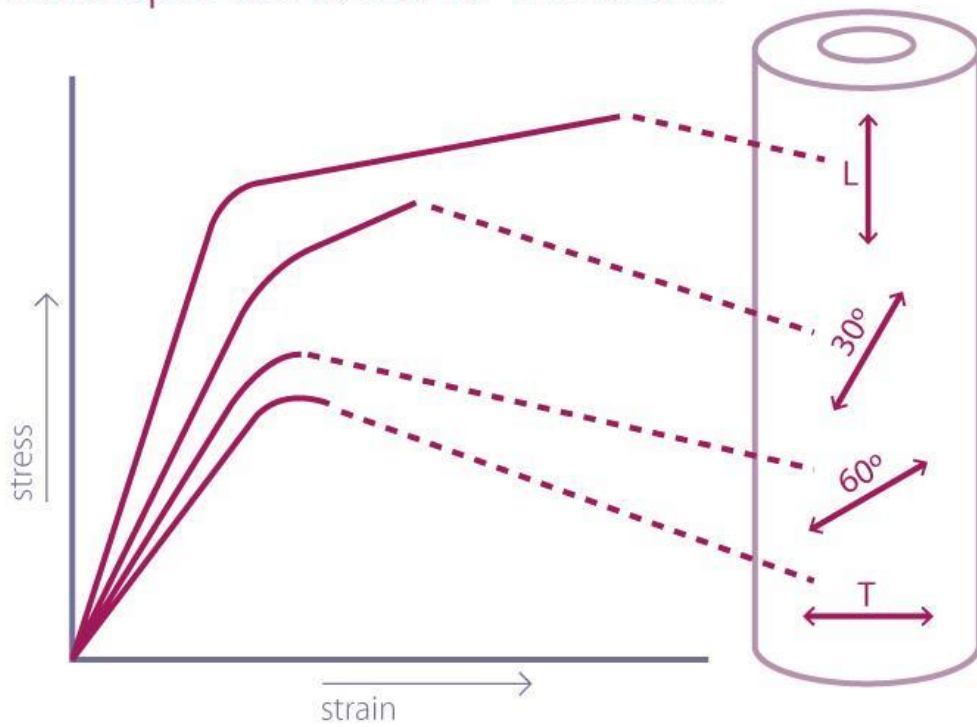


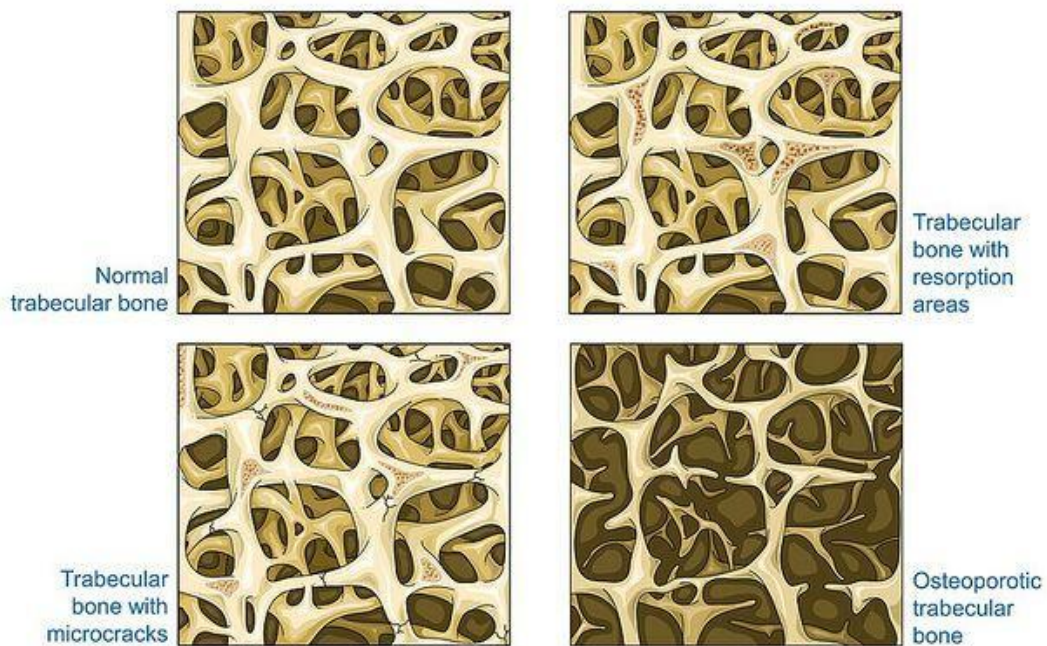
In contrast to these simplified systems, biological tissues demonstrate nonlinear stress–strain relationships. For instance, bone tissue combines rigidity with a certain degree of flexibility. This dual property arises from its composite structure: a mineral phase (hydroxyapatite) provides strength, while collagen fibers impart elasticity. As a result, bone can absorb energy before fracturing, a feature essential for preventing catastrophic failure under physiological loads.

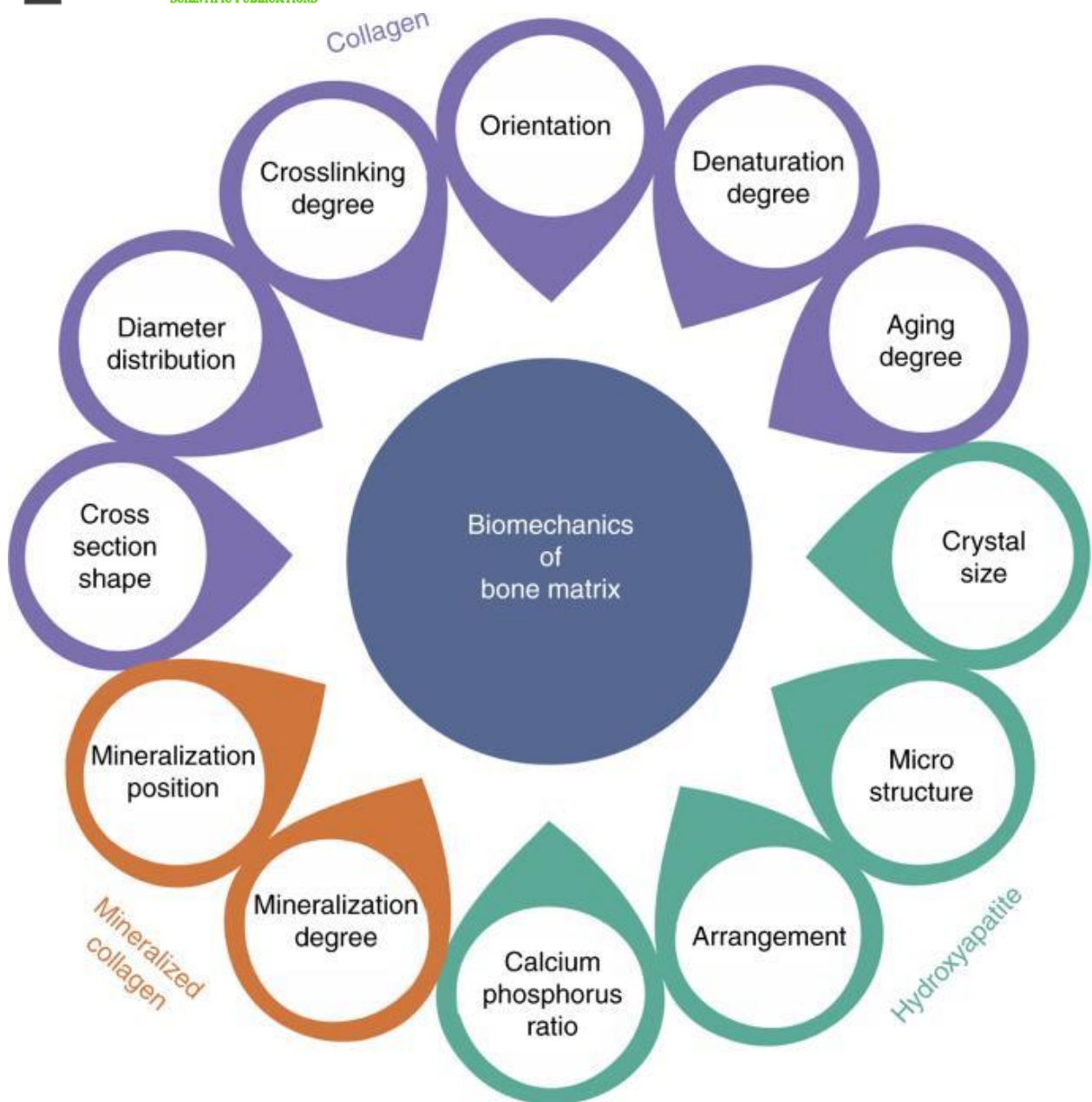


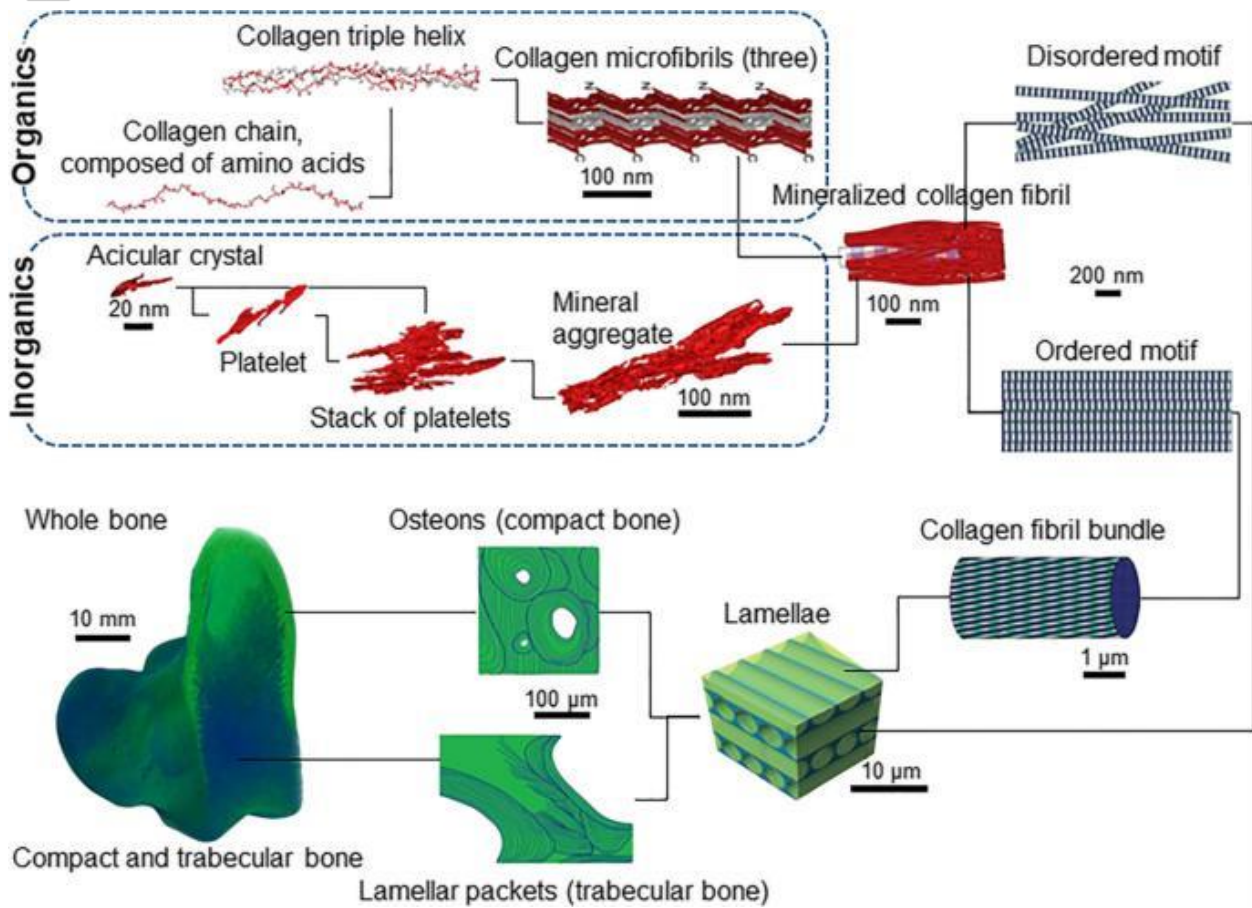


anisotropic behavior of the bone

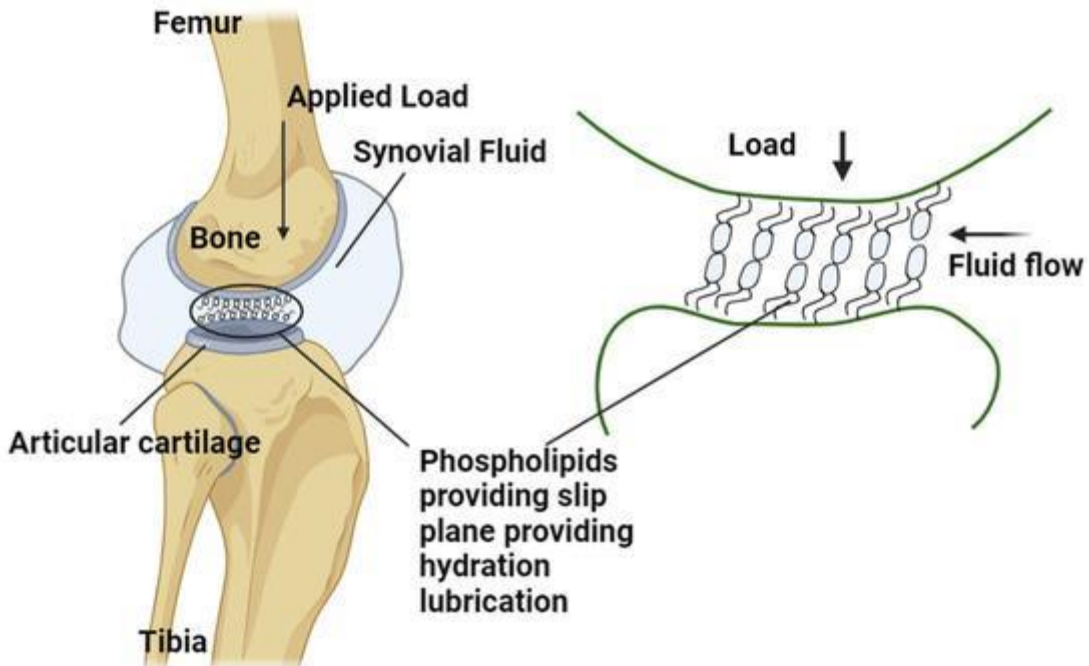
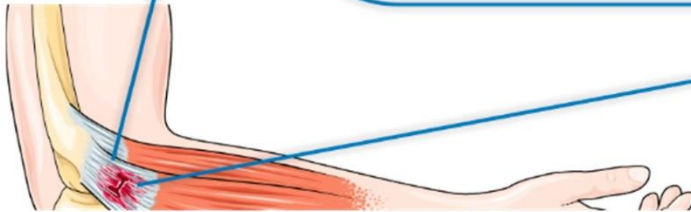
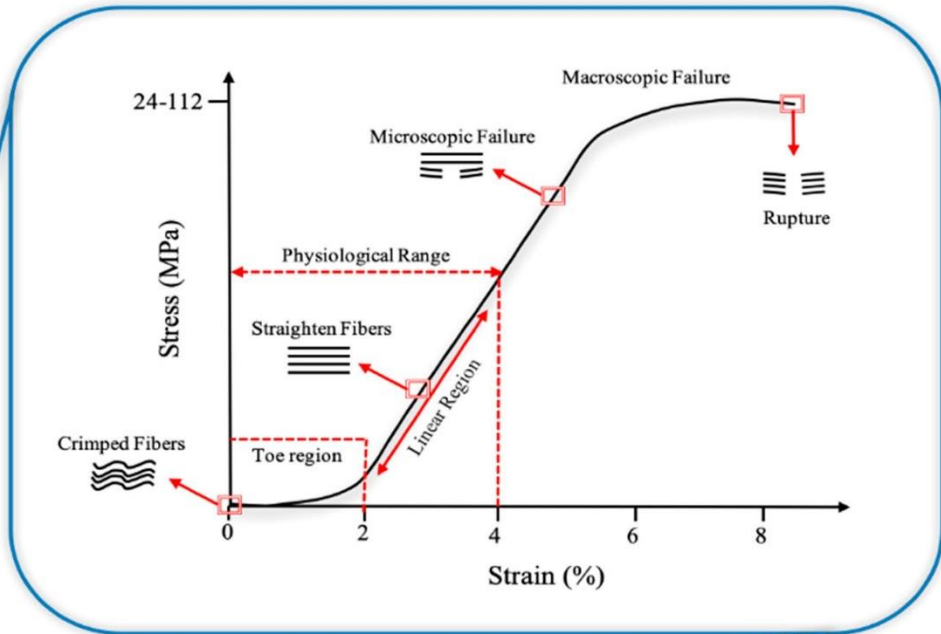


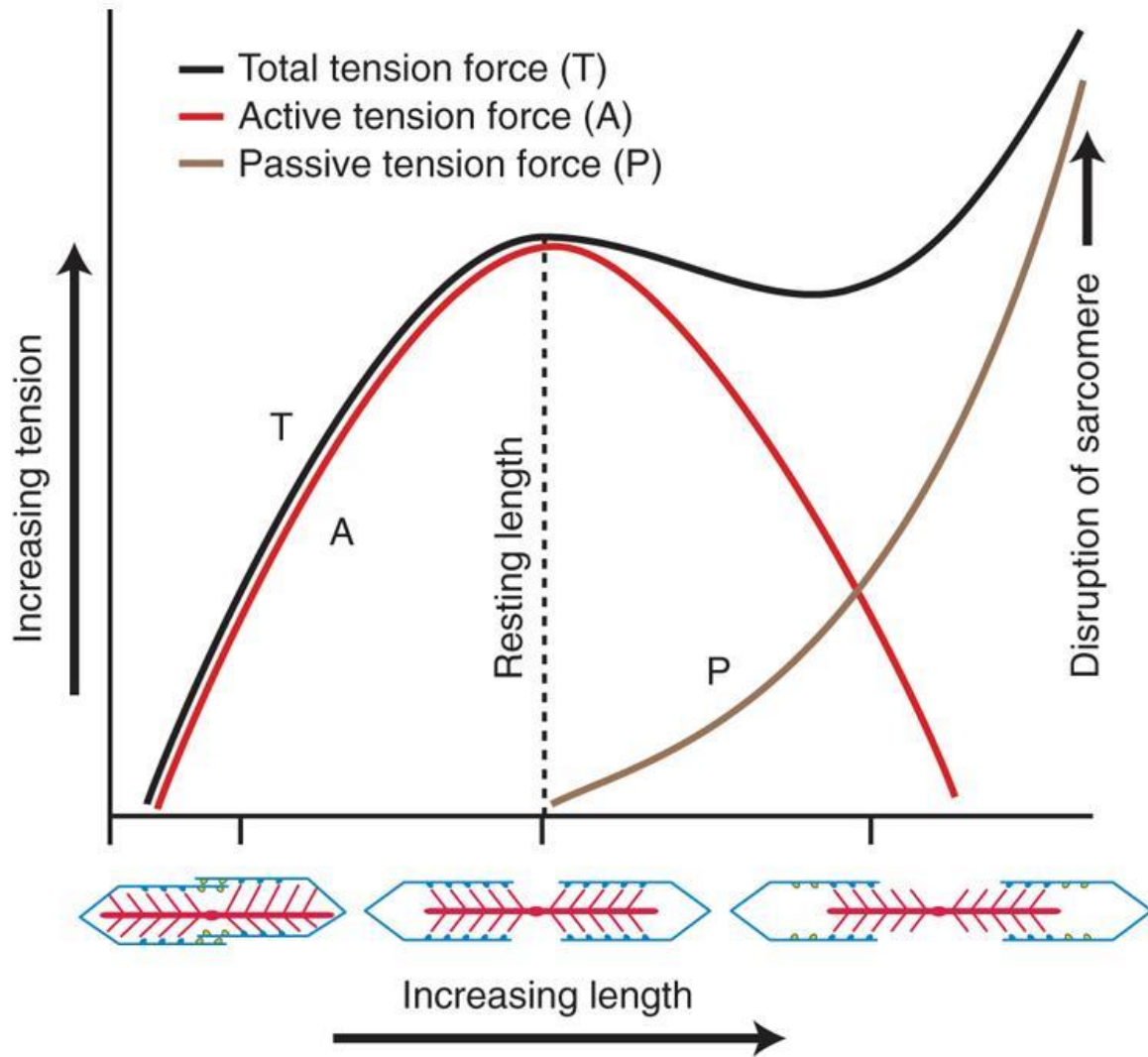






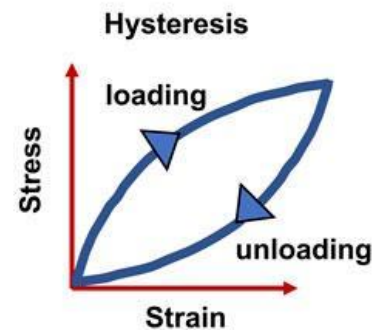
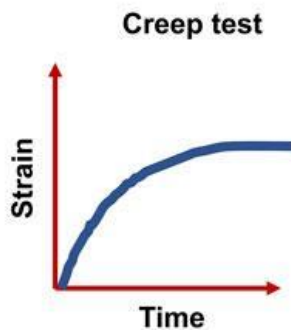
Soft tissues exhibit even more complex behavior. Tendons and ligaments, primarily composed of collagen, display a characteristic “toe region” in their stress–strain curve, where initial stretching aligns the collagen fibers before true elastic deformation begins. Muscles, in addition to passive elasticity, generate active force through actin–myosin interactions, making them unique among biological materials. Cartilage, rich in water and proteoglycans, resists compressive forces and plays a crucial role in joint mechanics by distributing loads and minimizing friction.

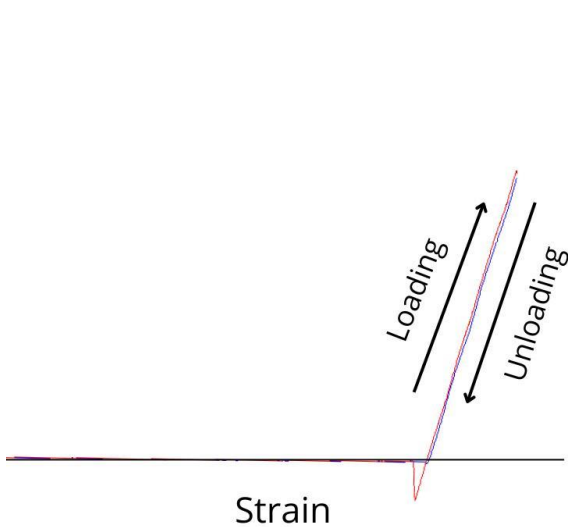
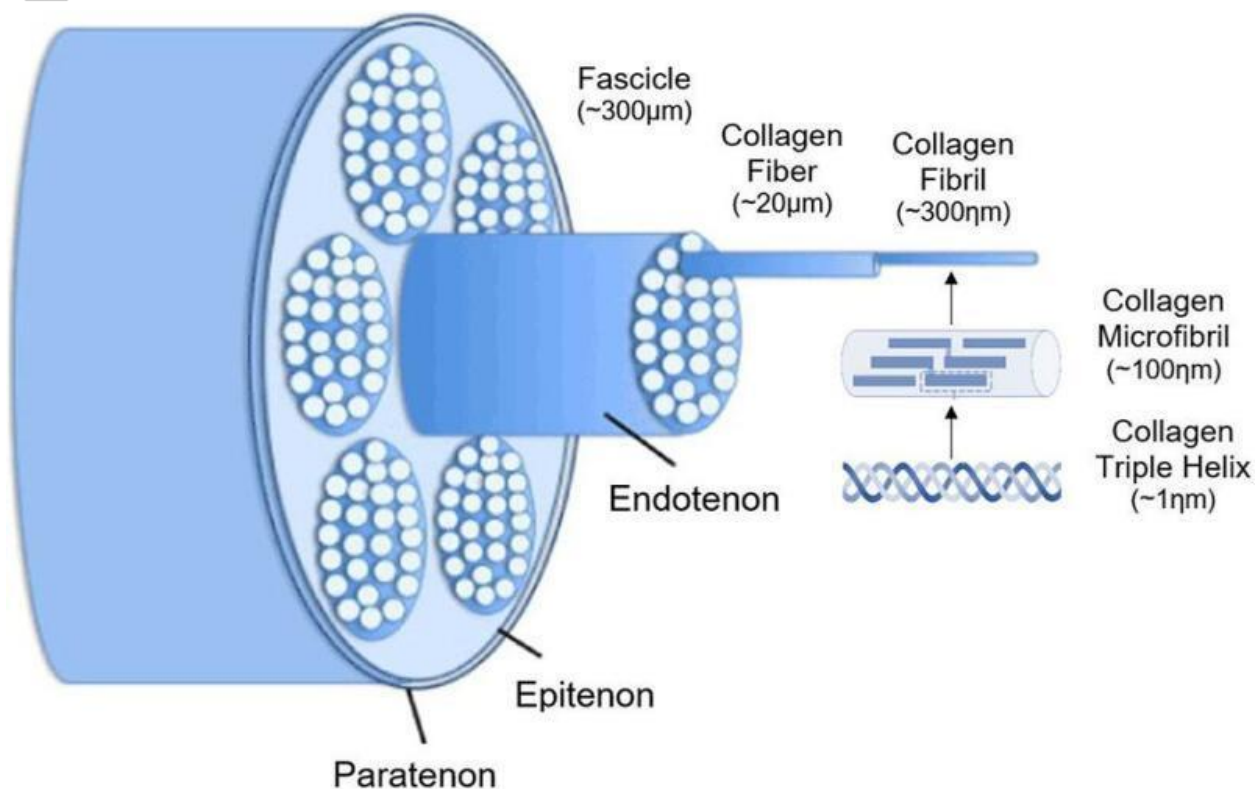




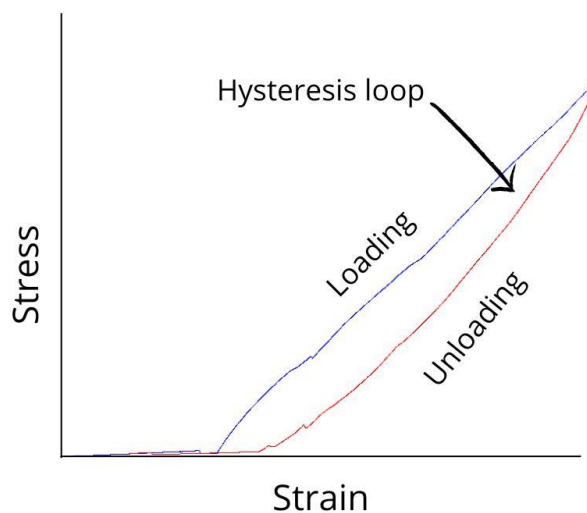
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Viscoelastic cells





Purely elastic material



Viscoelastic material

A defining feature of biological tissues is **viscoelasticity**, which means their mechanical response depends on both time and loading conditions. When subjected to a constant load, tissues gradually deform over time (creep). Conversely, when held at a constant deformation, internal stress decreases (stress relaxation). Additionally, energy loss during loading and unloading cycles results in hysteresis, reflecting the damping capacity of tissues. These properties enable biological systems to absorb shocks and adapt to repetitive mechanical stress.



DISCUSSION

The comparison between solid materials and biological tissues highlights the remarkable adaptability of living systems. While engineered materials often fail abruptly once their elastic limit is exceeded, biological tissues undergo progressive changes, redistributing stress and delaying failure. This adaptive capacity is particularly evident in bone remodeling, where mechanical loading stimulates structural reinforcement according to Wolff's law.

Clinically, these principles have profound implications. Fracture patterns in bones depend on the type and direction of applied forces, while tendon injuries are often associated with repetitive strain exceeding viscoelastic limits. Degenerative conditions such as osteoarthritis involve alterations in cartilage mechanics, leading to impaired load distribution and joint dysfunction.

Furthermore, the design of biomedical implants and prosthetics requires careful consideration of tissue mechanics. Materials must closely match the mechanical properties of surrounding tissues to prevent complications such as stress shielding or implant failure. Advances in biomaterials and tissue engineering increasingly rely on replicating the viscoelastic and anisotropic nature of biological tissues.

CONCLUSION

The mechanical properties of solid materials and biological tissues share common physical foundations but differ significantly in complexity and behavior. Biological tissues are characterized by nonlinear, anisotropic, and time-dependent responses, which allow them to withstand dynamic physiological conditions.

A thorough understanding of these properties is essential for modern medicine, particularly in orthopedics, rehabilitation, and biomedical engineering. By integrating mechanical principles with biological knowledge, clinicians and researchers can develop more effective strategies for diagnosis, treatment, and tissue replacement.

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