Modern American Journal of Medical and Health Sciences
ISSN (E): 3067-803X
Volume 01, Issue 09, December, 2025
Website: usajournals.org

MECHANICAL PROPERTIES OF BIOLOGICAL TISSUES

Begisheva Nailya Rinadovna
Acting Associate Professor of the Department of
Pharmaceuticals and Chemistry, Alfraganus University
n.begisheva@afu.uz
nelli2.05@mail.ru
+998935782587

Abstract
This article studies the active and passive mechanical properties of biological tissues. Biological tissues are analyzed as composite materials with pronounced viscoelastic properties.
The mechanical properties of bone, skin, muscle, and vascular tissues are described in detail. The main mechanical models and analytical relationships used to quantitatively describe the deformation of biological structures are presented.
The practical importance of studying the mechanical properties of tissues for various fields of medicine is shown.

Keywords: Biomechanics, biological tissues, elasticity, viscoelastic properties, collagen, elastin, blood vessels.

Introduction

The mechanical properties of biological tissues are a key characteristic determining their behavior under external and internal loads. In biomechanics, a distinction is made between active and passive mechanical properties of biological systems.
Active mechanical properties are associated with biological processes of movement: muscle contraction, cell growth, chromosome movement during cell division, and other processes. These phenomena are caused by chemical

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reactions and are supplied with energy by adenosine triphosphate (ATP). Their nature is studied in biochemistry courses.

Passive mechanical properties manifest themselves under external mechanical stress and do not require energy expenditure. This paper focuses on the passive mechanical properties of biological tissues.

Biological Tissues as Composite Materials

From a mechanical perspective, biological tissue is a natural composite material consisting of a large set of chemically and structurally distinct components. The mechanical properties of biological tissue differ significantly from the properties of each component taken separately. Methods for determining the mechanical properties of biological tissues are largely similar to those used in the mechanics of engineering materials.

Mechanical Properties of Bone Tissue

Bone is the primary material of the musculoskeletal system. In simplified terms, compact bone tissue can be considered a composition in which approximately two-thirds of the mass (approximately 50% of the volume) is made up of an inorganic component—the bone mineral, represented by hydroxyapatite $3Ca3(PO4)2Ca(OH)2$.

The mineral phase is present in the form of microscopic crystals located between collagen fibrils. The organic component of bone is primarily collagen, a high-molecular-weight fibrous protein with high elasticity.

The density of bone tissue is approximately $\rho = 2400$ kg/m3.

The mechanical properties of bone depend on age, developmental conditions, and anatomical location.

The composite structure imparts high rigidity, elasticity, and strength to bone tissue. At low strains, the relationship between mechanical stress and relative strain is nearly linear:

$\sigma = E\varepsilon$,

where $E \approx 10$ GPa is the effective modulus of elasticity of bone, and the ultimate strength reaches approximately 100 MPa.

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Bone tissue exhibits creep—a slow increase in strain under constant load—as well as residual strain after the load is removed, which is due to the viscoelastic properties of the collagen matrix.
The mineral phase of bone deforms rapidly, while the polymer (collagen) portion deforms much more slowly, explaining the presence of stress relaxation and residual strain.

Mechanical Properties of Skin

Skin consists of collagen fibers, elastic fibers, and the underlying intercellular matrix. Collagen accounts for approximately 75% of the dry weight of skin, and elastin for approximately 4%. Elastin has the capacity for large reversible deformations (up to 200–300%), while collagen stretches up to 10%, which is comparable to the properties of nylon fiber.
Table — Mechanical Properties of Skin Components

Material	Young's Modulus, GPa	Tensile Strength, MPa
Collagen	10–100	100
Elastin	0.1–0.6	5

Thus, skin is a viscoelastic material with high elasticity and the capacity for significant deformations.

Mechanical Properties of Muscle Tissue

Muscles contain connective tissue containing collagen and elastic fibers, which results in their mechanical properties being similar to those of polymeric materials.
In smooth muscle, stress relaxation is well described by Maxwell's model, in which stress decays exponentially.
This allows smooth muscles to stretch significantly even under slight tension, increasing the volume of hollow organs such as the bladder.
Mechanical Properties of Blood Vessel Tissue
The mechanical properties of blood vessels are determined by the ratio of collagen, elastin, and smooth muscle fibers. This ratio changes along the vascular

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system: in large arteries, elastin predominates, while in arterioles, smooth muscle fibers become the primary element.

Generally, a blood vessel can be considered a thin-walled elastic cylinder of radius r and wall thickness h, subject to internal pressure p. The stress in the vessel wall is determined by the Lamé equation:

When the vessel is stretched, it is assumed that the wall volume remains constant: 2πrh=const," i.e., "rh=b=const

Taking into account the elastic properties of the wall and Hooke's law, we obtain the relationship between the vessel radius and pressure:

For large values of the elastic modulus:

These relationships are used in analyzing the propagation of pulse waves in blood vessels. N. S. Khamin made a significant contribution to the experimental study of the mechanical properties of blood vessels.

Practical Significance

In conclusion, we note the areas and fields of medicine where knowledge of the mechanical properties of biological tissues is considered most important:

- in space medicine, as it exposes humans to new, extreme living conditions;
- the effectiveness of achievements in sports and its growing trend draw the attention of physicians working in sports medicine to the physiological capabilities of the human musculoskeletal system;
- hygienists must consider the mechanical properties of tissues when protecting humans from the effects of vibration;
- when replacing natural organs and tissues with artificial ones, it is even more important to know the mechanical properties and parameters of biological objects;
- in forensic medicine, it is necessary to know the resistance (strength) of biological structures to various deformations;
- in traumatology and orthopedics, the main methods are those that address mechanical effects on the body.

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Conclusion

Biological tissues have complex mechanical properties due to their composite structure and viscoelastic nature. Quantitative description of these properties using mechanical models and analytical relationships is a necessary basis for solving a wide range of medical and bioengineering problems.

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