Lesson2 - Biomechanical behavior of bone tissue

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This lesson contains 10 screens teaching text, 3 zoomable figures, 1 table, and 9 videos. This lesson requires approximately 2 - 4 hours of study but can vary depending on the student.

Bone tissue is a hard tissue, a type of specialized connective tissue. The mechanical behavior of connective tissue is affected by its mechanical properties.

Viscoelastic behavior of the connective tissues

Connective tissue serves a variety of functions throughout the body. Connective tissue is classified into two subtypes: soft and specialized connective tissue. Generally, mechanical properties of the connective tissues may be described via viscoelastic or poroelastic behavior. Viscoelastic materials are those in which the relationship between stress and strain depends on time, or on frequency. Viscoelastic materials have time-dependent mechanical behavior and specific characteristics.

Let us see these properties in more detail (1, 8):

Viscoelasticity

As the name implies, viscoelasticity incorporates aspects of both fluid behavior (viscous) and solid behavior (elastic). Viscoelastic materials exhibit both viscous and elastic characteristics when undergoing deformation.

Viscosity is the resistance of a fluid (liquid or gas) to a change in shape or motion state.

High viscosity materials might include honey, syrups, or gels – generally, things that resist flow. Water is a low viscosity material, as it flows readily.

Please now watch the following video:
https://www.youtube.com/watch?v=3KU_skfdZVQ

Elasticity is the tendency of solid materials to return to their original shape after forces are applied to them.

Plasticity describes the deformation of a solid material undergoing non-reversible changes of shape in response to applied forces. Plasticity enables a solid under the action of external forces to undergo permanent deformation without rupture.

Please now watch the following video:
https://www.youtube.com/watch?v=cTT1W2uqLas

The elastic materials store 100% of the energy due to deformation, viscoelastic materials do not store 100% of the energy under deformation, but actually, lose or dissipate some of this energy. This dissipation is also known as **hysteresis**.

Mechanical properties of biological tissue can be described using strength and stiffness. The **strength** of a material is its ability to withstand an applied load without failure or plastic deformation. The strength of the bone is defined by the point of failure or by the load sustained before the failure. The strength may also be analyzed in terms of storage of energy, the area under the load-deformation or stress-distension curve. The **stiffness** is the rigidity of a material. Compliance is the inverse of stiffness, so a material that deforms easily is said to be compliant and a material that is resistant to deformation is said to be stiff.

Stress

When a load is applied to a material the material will develop internal resistance to the applied load. The magnitude of this internal resistance to applied loads is dependent upon the stiffness of the material. Stress is related to force applied and is defined as force per unit area. Newton is per square meter, or Pascal is the measurement unit of stress.

Strain

Strain is defined as percentage of change in length of the material in relation to original length. When a force is applied to any material, such as bone, it undergoes deformation. The amount of deformation in the material relative to its original length, is the strain. Strain is usually given in relative units or percent change. Strain = (change in length/original length) x100 Therefore stress is the cause and strain is the effect.

Stress-Strain curve

The relative strength of a material can be quantified by graphing its stress-strain relationship (Fig.1). There is a direct relationship between the strength of a material and its stress-strain curve.

The maximum amount of deformation that a material can withstand and still return to its original shape is defined as the yield point. When the material is loaded beyond the yield point permanent damage occurs to the material and it can no longer return to its original shape. If the force continues the material may break into two or more pieces when the failure point is reached. The region of the stress – strain curve up to and including the yield point is termed the elastic region. In the elastic region, the material will deform during loading and return to its original shape when the load is removed. The region of the stress – strain curve beyond the yield point is termed the plastic region. In the plastic region, the material will deform during loading, when the load is removed the material does not return to its original shape. A plastic deformation results in a permanent change of the material. If the magnitude of loading is just above the yield point the permanent deformation may be microscopic and imperceptible (1, 7).

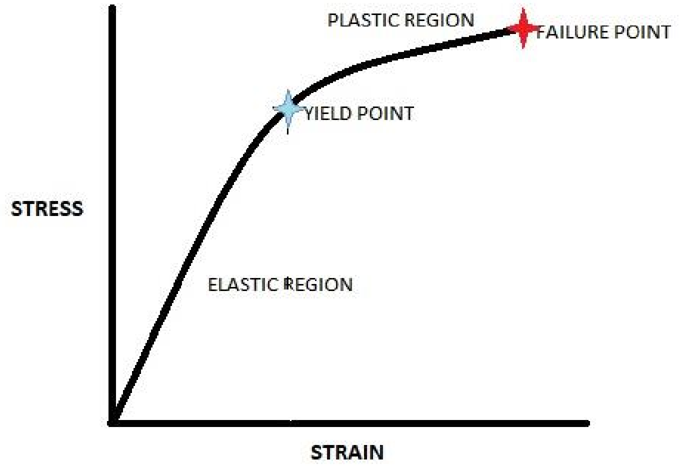

Fig. 1 Stress-stain curve

Rate dependence means that the deformation of the material depends on the rate at which loads are applied. **Creep** is the tendency of a solid material to move slowly or deform permanently under the influence of mechanical stresses.

Please watch this video about the creep:

https://www.youtube.com/watch?v=sMKJvYSYiOs

Stress relaxation refers to the behavior of stress reaching a peak and then decreasing or relaxing over time under a fixed level of strain.

Please watch this video about the stress relaxation:
https://www.youtube.com/watch?v=IJP92CCVjAk

Primary mechanical function of the skeletal system

The skeletal system is a system composed of bones and cartilage and performs the following critical functions for the human body:

- supports the body
- facilitates movement – by serving as points of attachment for muscles.
- protects internal organs
- produces blood cells
- stores and releases minerals and fat

Bones provide structural support for the entire body. Bone is a strong, flexible and semi-rigid supporting tissue. Bone is resistant to bending, twisting, compression, and stretch. It is hard, because it is calcified, and the collagen fibers help the bone to resist tensile stresses (7).

Type, composition, and structure of bone tissue

Types of the bones

The 206 bones that compose the adult skeleton are divided into five categories based on their shapes. Bones may be classified based on their shape, as you can see on table 1 (3).

Bone classification based on shape	Features	Function	Examples
Long	longer than they are wide	support the weight of the body, leverage	humerus, ulna, femur, metacarpals, metatarsals
Short	as long as they are wide	provide stability	carpals, tarsals
Flat	thin and curved shape	provide protection and large areas of attachment for muscles	scapulae, sternum, ribs, cranial bones
Sesamoid	small, round bones	protect tendons from stress and wear	patellae
Irregular	vary in shape	helps protect internal organs	vertebrae

Table 1 Classification based on the shape of bones

Please watch this video about the types of bones:

https://www.youtube.com/watch?v=vDjW00S29l0

The composition of the bone tissue (1)

1. **Bone matrix –** intercellular substance

    ❖ Inorganic components → Ca, P, Mg, K, Na → hydroxyapatite crystals (65%)
    Crystals lie alongside collagen fibrils and are surrounded by amorphous ground substance

    ❖ Organic components:
    - Fibers: collagen fibers – approximately 95% of the extracellular matrix
    - Amorphous/gelatinous ground substance: noncollagenous proteins (glycosaminoglycans)

2. **Cells** - Under normal circumstances, the activity of these cells is balanced
    - Osteoprogenitor cells (preosteoblasts)
    - Osteoblasts (bone forming cells)
    - Osteocytes (inactive osteoblast)
    - Osteoclasts (bone resorbing cells)

3. **Water** (25%-30% of total weight of bones)

Structure of the bones

There are two main types of bone tissue**, compact bone**, and **spongy bone**.

Now please brush up your knowledge about bone structure with these videos:

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https://www.youtube.com/watch?v=BhDzEXvG4Fg

https://www.youtube.com/watch?v=eQnsAxgIc_0

Biomechanical properties of bone

Stiffness and strength are the chief properties of bone tissue. Bone strength and stiffness are influenced by bone architecture. Because of the viscoelasticity of collagen fibers and non-fibrous proteins in the bone matrix, the bone itself has noticeable viscoelasticity (8).

Different types of loads, such as bending or torsion, can be applied to whole bones in vitro to determine the structure's stiffness and failure load (structural strength).

The ***structural stiffness*** is a measure of the resistance to deformation under the applied load, and the ***structural strength*** is the load required to cause the whole bone to fail.

Load - deformation curve

The relationship between the amount of force applied to the bone tissue and the bone response is illustrated by the load-deformation curve below (Fig. 2):

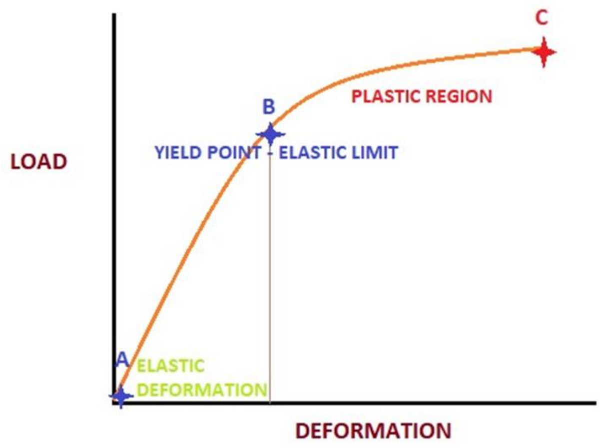

Fig. 2 Load-deformation curve for bone tissue

The elastic region of the curve is between points A and B. With initial loading bone can change shape (up to ~3% deformation) When the deformation is < 3%, bone is more likely to return to its original shape after the load is removed (elastic deformation). The plastic region of the curve is between points B and C. If loading continues beyond the yield point, plastic deformation is likely to occur. The transition from the elastic to the plastic region is called the yield point (elastic limit).

If the magnitude of applied load does not exceed the bone's elastic limits, the fracture does not occur, and the bone, elastically deformed, returns to its prestrained state. Shortly beyond the elastic limit, however, failure takes place (1, 7).

Biomechanical behavior of bone

The load-bearing capacity of a bone depends on the amount of bone, the shape of bone as a spatial distribution of the bone mass and the intrinsic mechanical properties of the materials that consist of the bone tissue (7).

The mechanical behavior of a bone will depend on the direction and the magnitude of the loads applied to it.

Loading modes

Cortical bone strength is strongly dependent on the mode of loading.
The bone may be loaded in tension, compression, bending, shear, torsion, or a combination of these modes.

Axial loading refers to forces that are parallel to the bone's long axis. Transverse loading refers to forces that are perpendicular to a structure's long axis.

Tension: may be described as the pulling force transmitted axially.

Compression: a compressive force acts along the long axis of a bone.

Bending force: A bending force is a combination of tension and compression. Bending places maximum tension on the convex surface of a bent object and maximum compression on the concave surface of a bent object.

Shear forces: pairs of equal, parallel and opposing forces acting on opposite sides of an object.

Torsion: the twisting of an object due to an applied torque. If you are applying a force to a manual screwdriver, you are applying torsion. Similarly, a bone being turned by a mechanism around its longitudinal axis is experiencing a torsion force.

The bone behavior will change depending on the direction of the load application because bone tissue is an anisotropic material (1, 7).

Anisotropy is the property of being directionally dependent, which implies different properties in different directions, as opposed to isotropy.

The bone tissue may lead to higher loads in the longitudinal direction and a lesser quantity of load when applied over the bone surface. The bone is strong to support loads in the longitudinal direction (e.g. compression or tension) because it is used to receive loads in this direction (7).

Influence of muscle activity on stress distribution in bone

Muscle activity can also influence loads that can be managed by the bones. The **neutralizer muscles** change the strengths applied to the bone creating tensive and compressive strengths. These muscle strengths can reduce tensive strengths or redistribute the strengths on the bone. Since most bones can withstand large amounts of compressive strengths, the total amount of load may increase due to the contribution of muscles. However, if the muscle fatigues during a series of movements, this decreases its ability to reduce the load on the bone (7).

The altered distribution of stress or increase in tensile strengths leads to **fatigue of bone** and prone to injury. Fatigued bone tissue lacks the ability to store the higher levels of energy, particularly in areas where the bone material is inhomogeneous, as at tendon and ligament attachment sites. Repetitive stress in such areas can cause a tendon or ligament to pull off a section of bone to which it is attached, resulting in an avulsion fracture (5). Consequently, the bone tissue can develop a **stress fracture** in response to compressive or tensive loads that overwhelm the system, either by a magnitude of excessive strength applied to one or a few times, or by applying strength in a low or moderate level, but with an excessive frequency. Therefore bone fractures may result from a single exposure that exceeds the ultimate strength of the tissue or repeated applications of normal magnitude loads. The typical stress fracture occurs during load application, which produces a shear distension or tension (1). The stress fractures usually occurred during continuous physical activity, which leads to muscle fatigue and reduces the neutralizer muscles ability to contract.

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You find the process of the fatigue fracture development on figure 3 below:

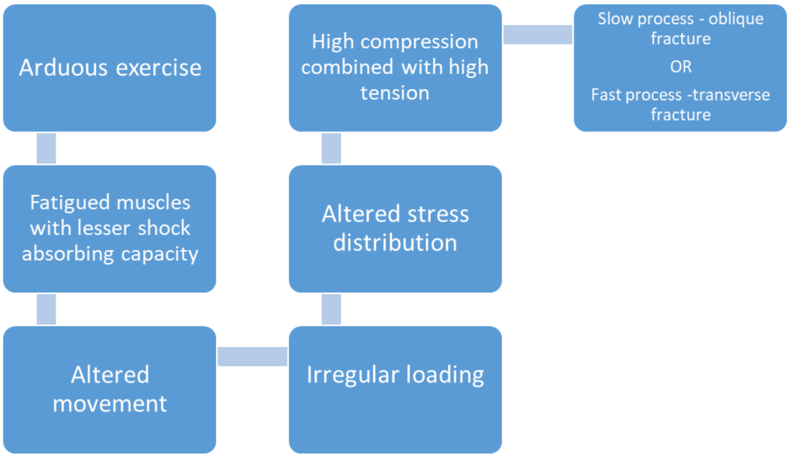

Fig. 3 The process of the fatigue fracture development.

Bone remodeling

Bone is continuously remodeled in order to maintain the integrity of the tissue. During this process, old bone is resorbed by osteoclasts and replaced with new osteoid, secreted by osteoblasts. First, osteoclasts are activated, and the resorption phase takes approximately 10 days. The action of osteoblasts and osteoclasts continually work to increase, decrease, or reshape bone tissue (2, 4).

Bone remodeling involves the balance of osteoblast and osteoclast activity or the maintenance or loss of bone mass due to osteoclast activity. **Bone modeling**, or bone hypertrophy is a process increase in bone mass resulting from a predominance of osteoblast activity. Bone hypertrophy, the gain of bone density occur to respond to regular physical activity, not only in the regions that are particularly forced but all over the skeletal system. **Bone atrophy** means the response of the bone tissue to reduced mechanical stress (2, 4).

Please now watch the following video:

www.youtube.com/watch?v=vDjW00S29l0

Changes in bone associated with immobilization and aging

Effect of immobilization on bone

If the bone is not subjected to the usual mechanical loads (weight bearing or the normal stresses exerted on bone by muscle contractions) the immobilization lead to decrease the strength and the stiffness of the bone tissue. Immobilization results in **disuse osteoporosis** - loss of bone density due to increased resorption. When there is little force acting on the body for any length of time, a drastic reduction in the mineral content of bone tissue is seen, leading to a fall in bone density and reduced strength (7).

Effects of aging on bone

The major age-related change in the skeletal system is the loss of calcium in the bone. Calcium homeostasis is critical to maintaining bone structure. As one age this homeostasis is disrupted, which results in a weakening of the bones. In addition to the loss of calcium as one ages protein synthesis also slows. As a result, there is little to no new formation of collagen fibers. These fibers are what give the bones strength and flexibility. Without them, bones become brittle resulting in a higher rate of fracture (6).

The balance between bone resorption and formation changes with increasing age, resulting in loss of bone tissue. As people age the rate of the bone resorption by osteoclast cells exceeds the rate of bone formation so bone weakens (6).

The aging bone has reduced mineral content and is prone to **osteoporosis** – a condition in which bones are less dense, more fragile, and prone to fractures. Lack of physical activity, muscle weakness/atrophy, neuromuscular disease, and impairment in gait, balance, and proprioception are those factors which may predispose elderly population to falls, resulting in subsequent osteoporotic fractures (4, 7).

Please watch the following video about the postmenopausal osteoporosis:

https://www.youtube.com/watch?v=c5tc01WFYks

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Study questions

Multiple-choice questions

Read each question and answer choice carefully and choose the ONE best answer.

1. **For which loads does the human tibia offer the greatest resistance?**
    - A. Torsion
    - B. Shear
    - C. Compression
    - D. Bending

2. **In which region of the load-deformation relationship of bone do microfractures of the tissue begin to occur?**
    - A. Plastic
    - B. Elastic
    - C. Failure
    - D. Initial

3. **What is the basic functionally unit of bone?**
    - A. Osteoblast
    - B. Osteon
    - C. Extracellular matrix
    - D. Collagen

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4. Which of the following is not a part of the process of fatigue fracture?

A. Altered movement
B. Altered stress distribution
C. Regular loading
D. Strenuous exercise

5. Which term describes the force due to the combination of tension and compression?

A. Shear
B. Compression
C. Bending
D. Torsion

TRUE/FALSE questions

Read each statement below carefully. Choose the T if you think a statement is TRUE. Choose the F if you think the statement is FALSE.

1. The aging bone has increased mineral content and is prone to osteoporosis. **T or F**
2. Bone atrophy means the response of the bone tissue to reduced mechanical stress. **T or F**
3. Neutralizer muscle strengths can increase tensive strengths or redistribute the strengths on the bone. **T or F**
4. Bone strength and stiffness are influenced by the water content of the bone tissue. **T or F**
5. Flat bones are thin and have curved shape, its protect tendons from stress and wear. **T or F**

Matching questions

In this exercise, you have to match each word with a definition.

1. **Strength**
2. **Stiffness**
3. **Strain**
4. **Anisotropy**
5. **Viscosity**

A. **Property of being directionally dependent, which implies different properties in different directions.**

B. **It is the rigidity of a material.**

C. **It is the amount of deformation in the material relative to its original length when a material undergoes deformation due to the applied force.**

D. **It is the resistance of a fluid to a change in shape or motion state.**

E. **It is the ability of a material to withstand an applied load without failure or plastic deformation.**

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