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Review article

THE STRUCTURAL AND MECHANICAL PROPERTIES OF THE BONE

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ABSTRACT
The work contains basic information on the anatomy and physiology of bone tissue. Basic concepts related to the structure of bone tissue are presented. General issues related to bone reconstruction processes and biomechanical structural adaptations processes were described. Mechanical parameters of bone tissue were presented.
KEYWORDS: bones, biomechanics, cartilage

BUDOWA I WŁASNOŚCI MECHANICZNE TKANKI KOSTNEJ

STRESZCZENIE
Praca zawiera podstawowe informacje z zakresu anatomii i fizjologii tkanki kostnej. Przedstawiono podstawowe pojęcia związane ze strukturą tkanki kostnej. Opisano podstawowe zagadnienia związane z procesami przebudowy tkanki kostnej oraz biomechaniczne procesy dostosowawcze. Zaprezentowano parametry mechaniczne tkanki kostnej.
SŁOWA KLUCZOWE: kości, biomechanika, chrząstki

1. Introduction

Biomechanics is the study of the movement of living organisms (especially referring to humans), based on the laws of mechanics. Knowledge of the biomechanical properties of tissues plays an important role in cases regarding physiological and pathophysiological modelling of the body function, predicting the effects of injuries, monitoring the effects of loads and overloads, and throughout selecting process of biomaterials used for implants.

Bones, joints and muscles create a closely related biomechanical unit called the locomotor system. Bones and muscles form the lever system that corresponds to the lever and spring mechanisms in the field of mechanics. They are the basic elements of the skeletal system. Built of hard tissue, they determine the shape and size of the body. The skeletal system is a passive part of the locomotor system. It is formed out of various, specialised tissues originating from the connective tissue. The passive locomotor system consists of bones, joints and ligaments, while the active locomotor system is built of skeletal muscles. The mature human skeleton is composed of approximately

206 bones, including supporting, structural and movable parts, amongst which following division can be distinguished [1, 2, 3, 4]:
• axial skeleton consisting of a spine with a skull embedded on it,
• skeleton of upper limbs with shoulder rim,
• rib cage,
• lower limb skeleton with pelvis.

The main function of most of the bones is to provide support. This function allows the human body to maintain upright posture. The skeleton acts as a scaffold for the body, and in particular for the muscles. Bones, joints and muscles form a lever system, where joints represent fulcra, bones provide the attachment for skeletal muscle and act as a lever, while muscles generate motor power to produce movement. What is more, bones often provide mechanical protection for many internal organs, such as the skull protecting the brain or vertebrae surrounding the spinal cord. Bones also function as a storage medium. They store mineral salts and play an important role in regulating electrolyte concentrations, but are especially important in the process of calcium homeostasis. Bone marrow is a special tissue localised within the bone myeloid cavities and a primary site for haematopoiesis. The hematopoietic process is responsible for the production of blood morphotic elements. The function of bone marrow is, inter alia, the production of red blood cells, erythrocytes, some white blood cells, granulocytes and platelets [1, 3].

2. Bone structure

Bones form structurally and functionally complex system. The physiological and metabolic dependencies in the body have a significant influence on the biomechanical characteristics of the bone tissue, of which bones are mostly made. In addition, there are several other tissues present in bones, such as fat, haematopoietic or cartilage tissues. Bone structure has a decisive influence on its mechanical properties, and three types of cells that build it can be distinguished. On a macro scale, bone is an organ that performs well defined functions in the body, as well as a tissue composed of bone lamella forming a compact and cancellous bone. The bone is built of cellular components such as: osteoblasts (i.e. cells responsible for bone formation), osteoclasts (i.e. cells that have the ability to dissolve and resorb bone tissue), and mature osteoblasts derived from osteocytes. These three types of cells are responsible for the reconstruction of bone tissue [4, 5, 6, 7, 8].

Bones are made of two components: organic (ossein), which is responsible for flexibility and elasticity, and inorganic (phosphoric and carbonic acid) -- responsible for hardness [4, 7].

The compact bone (substantia compacta) consists of osteons, composed of delicate layers of lamellae and densely packed ground substance. Numerous longitudinally running Haversian and Volkmann's canals, providing accurate blood supply, are presented. In the skull compact bone co-creates bones that shield the brain. Lamellar bone tissue builds diaphysis of long bones and the (cortical) layer of the epiphysis and flat bones, characterised by parallel spirally arranged collagen fibres. Cortical bone is up to 80% of the skeleton. Compact bone is characterised by a slow process of transformation and considerable resistance to bending and twisting, as well as a relatively high modulus of elasticity [7, 8, 9].

The substance of the cancellous bone (substantia spongiosa) creates a system of crossing bony plates. It is softer and weaker but more flexible due to its lower density. Spaces between trabeculae are filled by the bone marrow. The arrangement of trabeculae depends on the force of gravity and the mechanical force to which the lower part of the bone is affected by muscle contraction. The cancellous structure occurs in the long, short and irregular bones, also as a thin layer of bone called Diploë in flat cranial bone. The structure of the bone is shown in the Figure 1. It is commonly believed that the material and morphological feature of the compacted and cancellous substances are similar. Only differences result from the degree of porosity, which for the cortical bone is in the range of 5% to 30% to 90% [7, 8, 9, 10-20].

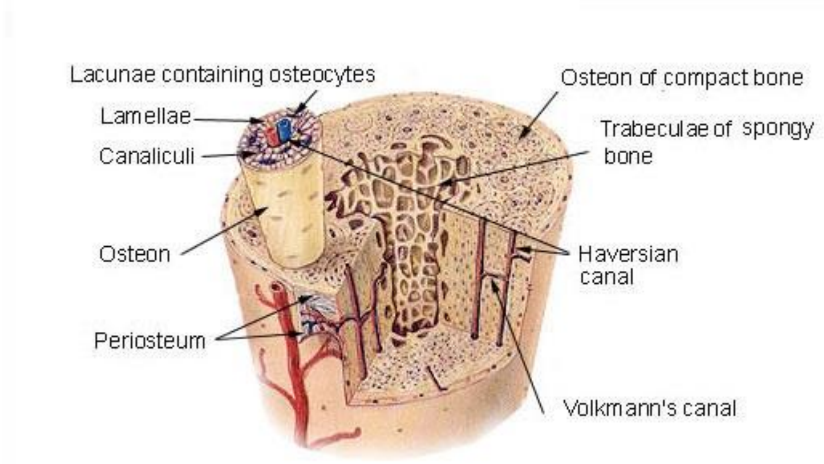

Fig. 1. Bone structure [20]

Bones can also be categorised according to their shape, including 5 main types: long (e.g. femur, humerus, radius), short (carpals and tarsus), flat (such as sternum, scapula) irregular (mandible, vertebrae) and sesamoid (patella). A distinctive feature of long bones (ossa longa) is their length, significantly greater than the other two dimensions. They mainly occur in limbs (humerus, radius). Long bones consist of the middle part – diaphysis, and the two ends – proximal and distal epiphysis. The diaphysis has myeloid cavities containing bone marrow. Flat bones (ossicular planar) have a large surface and are very thin (scapula, pelvis). Short bones (ossus brevis) are rather equally developed in all dimensions (carpal bones, tarsus). Irregular bones (ossis multiforia) have a body of various forms. They cannot be described in three dimensions (circlular). In addition, pneumatic bones can be distinguished (ossapneumatica), which contain empty space inside the mucous membrane filled with air (sphenoid, frontal, temporal, maxillar). The classification of bones by shape is shown in the Figure 2 [1, 2, 3].

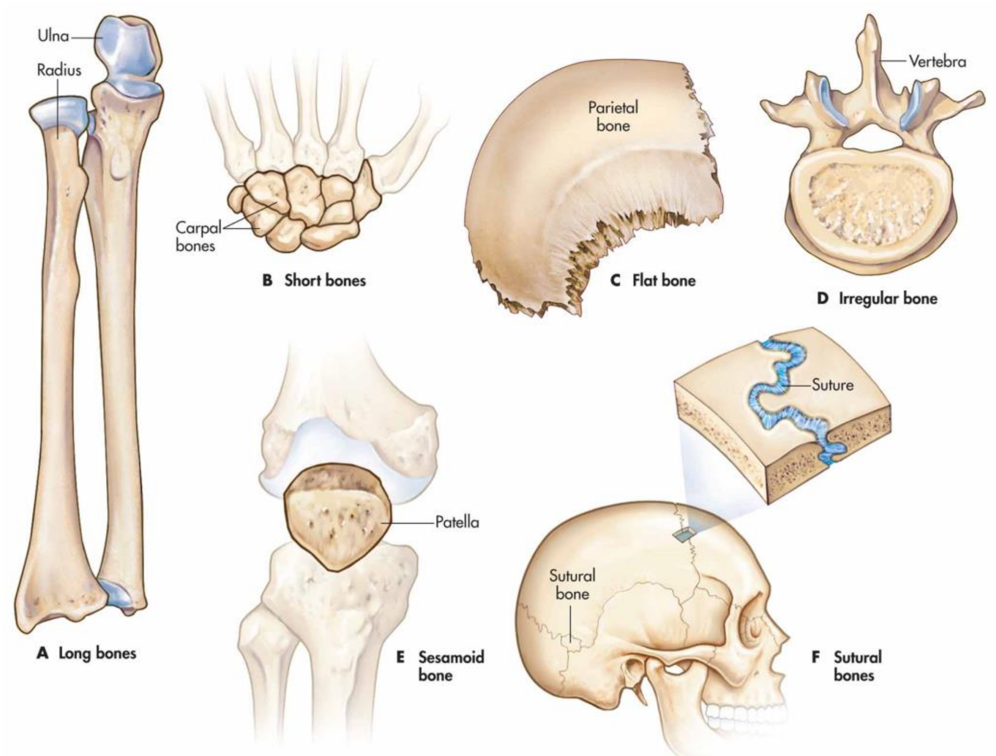

Fig. 2. The classification of bones by shape a) long bones b) short bones c) flat bone d) irregular bone e) sesamoid bone f) sutural bones [21]

Bones are covered by the connective tissue membrane -- periosteum (priostecum). This membrane is abundantly vascularised. It contains fibroblasts in the outer layer (fibrous periosteum) and progenitor cells in the inner layer (osteogenic periosteum), which produce the bone tissue. Thanks to them, bone can grow thicker, and defects in the bone structure can be filled with callus. Bone growth is achieved through epiphyseal plate (metaphysis), which separates epiphysis and diaphysis. During the growth of the body, the bones elongate. This process ends in puberty when the growth of epiphyseal plate stops and plates ossify into solid bone. Periosteum delivers blood and nutrients encouraging growth and development. Numerous blood vessels and periosteal lymphatic vessels are connected to vessels in Haversian and Volkmann's canals [1, 2, 3, 4].

Bones have very good blood supply and contain about 5% of the total blood volume. Long bones are supplied with blood by three circulatory systems: nutrient artery system, metaphyseal-epiphyseal system and periosteal system. Rich blood supply to bone tissue is associated with the hematopoietic role and calcium management of the body. Calcium ions play a key role in the body. Their concentration determines the activity of muscle and nerve cells, affects the permeability of cell membranes and the activity of certain enzymes. Almost 99% of this element in the human body is stored in the bones [2, 3, 4].

3. Bone’s structural adaptations

Throughout humans’ life the skeleton undergoes continuous remodelling. Bone tissue as a living structure is subject to continuous growth, consolidation, weakening, mineralisation, demineralisation, sorption and resorption, and all these phenomena are called remodelling, reconstruction or adaptation of bone structure to prevailing working conditions. In the 19th century, Mayer, Culman and Wolff showed that the internal structure of the bone depends on the distribution of stresses and deformations in it. This dependence is described by Wolf's law, which states that bone can adapt, by changing its size, shape and structure to the mechanical demands placed on it. The theory of internal transformation assumes that the density of bone tissue changes with stress. As the load increases, through the absorption and internal strengthening, its density increases. The theory of internal remodelling refers to the change of bone dimensions because of the absorption and deposition of bone material on the outer surface of the bone. Modelling the structure of the bones, and thus the changes in their mechanical properties, is related to two different processes of various dynamics. Reconstruction processes are believed to be triggered by a chemical and mechanoelectrical process. Slow changes over months and years depend on the activity of bone cells in osteoblasts and osteoclasts. The first one is responsible for producing the components of the second bone matrix, but they are responsible for the resorption process. The state of the bone depends on the balance between the activity of both types of cells. It is believed that the phenomenon of mechanoelectrical processing affects the balance of activity of these cells. The hypothesis about the impact of this effect on bone structure is supported by numerous experimental evidence. So far, it has been confirmed that mechanical stress generates electrical potential. It can be assumed that this process is similar to the process of water binding by proteoglycan, occurring in cartilage tissue. Piezoelectric effect attracts or repels calcium ions and other elements leading to their rearrangement. Because of the repetitive stress occurrence, calcium concentration is impacted and greater intensity of chemical reactions occur [5, 11, 12, 13, 14].

The bone can adapt to the external environment. According to Fung's theory, any change in the tissue structure of living organisms is linked to the process of metabolism. For correct understanding of growth processes and changes in bone structures, it is necessary to evaluate the stress states and deformities of the body during the transition (growth, atrophy, healing processes) [7].

4. Mechanical strength of bones

The mechanical characteristics of the bone depend on the material from which the bone is built as well as on its shape, size and structure. There are two kinds of mechanical and structural strength. Both types have a significant dynamic component: each of the strengths is constantly tuned to the type of mechanical stimulus that affects the locomotor system. Decreased physical activity can cause pathological changes in mechanical strength of bone tissue. Negative changes in this tissue may also be related to injuries and conditions such as damage to the nervous system, hormonal or trophic disorders. Mechanical parameters depend on the content of organic and inorganic materials. Inorganic materials are responsible for giving the bones elastic properties, are related to the activity of cells which in turn depends on the correct blood supply of the bone tissue. The occurrence of ischemia as well as deprivation induces dramatic changes in mechanical properties [4, 7, 15].

The forces to which the bone is usually exposed include compression, tension, torsion, bending and shear stress. In case of compression, the bone is exposed to two forces - the compressive force itself and the reaction force, in accordance with Newton's third law of dynamics. In pure compression, the compressive and reaction force vectors are directly opposite to each other, creating uniaxial compression (these are crushing forces) [13, 16].

The compressive strength of the bone tissue ranges from 12.56 to 16.87 kg / mm^2 in cross section and is a value that approaches the tensile strength of the bone. The mechanical strength of individual bones for compression forces varies. The patella is broken down by the force of 192 kg, the humerus 600 kg, the femur 756 kg, and the tibiae 450 kg. These values reflect the forces usually causing bone fracture, it is worth remembering that fractures are rarely the result of compression itself. Some of the compression forces are absorbed by indirectly located soft tissues, e.g. articular cartilage [4, 17, 18,].

Tensile strength of the dry bone is 10 kg / mm^2 cross-sectional area, while for newly formed compact bone the tensile strength is 12.41 kg / mm^2. For stretching, cortical bone is characterized by greater stress, with less deformation compared to cancellous bone. In the range of elastic deformations, the length of the cancellous bone may increase by 50% at 1.5 to 2% of cortical bone growth. Thanks to the porous structure, the cancellous bone has a high energy storage capacity. It was determined that the mature cortical bone elastic modulus was 18GPa at axial force application, 12 GPa at transverse and 3.3 GPa at shear forces. The mechanical properties of the femoral cortex bone for different age groups are presented in Table 1 [4, 7, 13, 19].

The mechanical properties of bone tissue are also affected by many diseases, the most common being osteoporosis. It is a systemic disease characterized by bone mass loss and microarchitectural disorders, leading to the weakening of the bone structure. Osteoporosis is the reduction of bone mass and density and the deterioration of bone quality. This reduction is a cause of increased resorption, which is not accompanied by proper deposition of the new bone, initially it occurs in the cancellous bone, and then the changes also occur within compact bones. After adolescence, only a small increase in bone mass is observed, and after the age of 30 years, the bone density decreases by approximately 0.7% per year. Changes in bone density according to age are shown in the Figure 3 [4, 8].

Table 1. Mechanical properties of cortical part of human femoral bone for various age groups [4, 19]

Mechanical parameters	Age group (years)							Mean values
	19-20	20-29	30-39	40-49	50-59	60- 69	70-79	
Tensile strength limit (Mpa)	116±1,5	125±1	122±1,9	114±2,5	95±1,4	88±2,4	88±2,4	109
Percentage of elongation limit (%)	1,48	1,44	1,38	1,31	1,28	1,26	1,26	
Compressive strength limit (Mpa)	-	170±4,4	171±4,2	164±3,7	158±4,4	148 ±2,3	-	162
Shortening percentage limit (%)	-	1,9	1,8	1,8	1,8	1,8	-	
Bending strength limit (Mpa)	154	177±11	177±11	165±21	157±20	142±29	142±29	160
Compressive deformation limit (Mpa)	0,086	0,075	0,066	0,062	0,062	0,053	0,053	
Torsional strength limit(Mpa)	-	58,2±1,1	58,2±1,1	53,7±0,5	53,7±0,5	49,6 ±1,2	49,6 ±1,2	54,1
Torsional deformation limit (Mpa)	-	0,028	0,028	0,025	0,025	0,027	0,027	
Modulus of torsion (Mpa)	-	3500	3500	3200	3200	3000	3000	3200

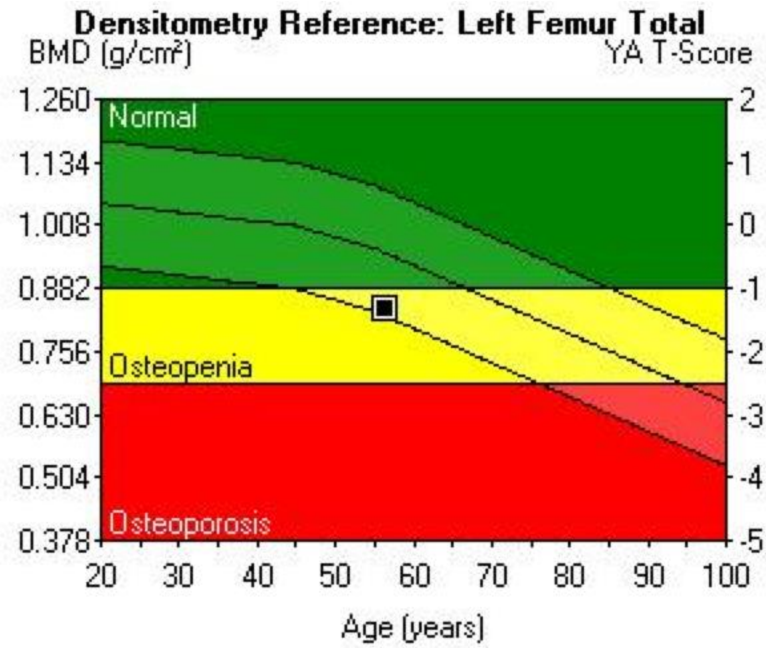

Fig. 3. Changes in bone density according to age [22]

5. Summary

The functional architecture of cancellous and compact bone is subject to the same principle that apply to the mechanics of arch and lever construction. Therefore, when evaluating biomechanics of bone tissue, the principles and terms used in the classical mechanics of the physical systems of elastic bodies are used. The knowledge of mechanical parameters of bone tissue allows to evaluate the distribution of stresses and deformations occurring in bones under the influence of external loads. Understanding the mechanisms responsible for pathological changes in bone tissue can contribute to the development of more effective diagnostic methods, as well as bone tissue treatments, that will provide better outcome for patients. On the other hand, it is also important to know the relationship between the mechanical properties and the structure of bone tissue. Thus, knowledge of the interplay between the structure of the tissue and its mechanics will allow for the refinement of bone tissue diagnostics and therapy. This will also allow to determine the mechanisms of change of normal bone tissue in pathological cases.

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