Mechanical analysis of bone and its internal fixation

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Abstract. Biomechanics can help people understand the work of the human body and organs, as well as the changes of various effects under the action of external loads, to carry out artificial control and prediction. Bone biomechanics is an important branch of biomechanics, and bone materials are divided into four hierarchical structures, starting from the lowest molecular level, to woven bones, lamellar bones, and Haversian bones, then a higher level of large woven bones and primary woven bones, Harversian bone system and laminar bones, at last to the macroscopic level compact bones and cancellous bones. The analysis of bone mechanical properties focuses on the elasticity modulus parameters, the elasticity modulus of dry bones is usually greater than that of wet bones, and the elasticity modulus of compact bones is usually greater than that of cancellous bones. As well as the stress relaxation and creep behavior of compact bone, the 8 microstructure parameters of cancellous bone. Combined with the mechanical analysis of fracture and internal fixation in clinical medicine, the connection method between the steel plate and the bone, the position of the steel plate relative to the bending direction, the selection of materials and other factors affect the mechanical properties, so that various factors need to be paid attention to in the analysis of surgery.

Keywords: bone biomechanics, elasticity modulus, microstructure parameters, fracture, internal fixation.

1. Introduction
Biomechanics is the mechanics applied to biology. It is a new interdisciplinary subject between biology and mechanics. It studies the mechanics of the growth, movement and change laws of objects and their tissues and organs [1-2]. As far as the biomechanics of the human body is concerned, biomechanics will help us understand the normal functions of the human body and organs, as well as the occurrence and development of various effects under the action of external loads, and predict further changes in organs, limbs, etc., so as to provide artificial control [3-4]. Bone-muscle mechanics is a sub-field of biomechanics that is most accepted and recognized by clinical medicine. The thesis mainly focuses on human bones as the main body of research, and summarizes it from the perspective of mechanics. Starting from the most basic structure, the structure of bone involves molecular level bone, macroscopic structure-woven bones, lamellar bones and Haversian bones; large woven bones and primary woven bones, Harversian bone system and laminar bones; compact bones and cancellous bones. Going deeper into bone properties include different new methods to study elasticity modulus and its comparison, as well as other mechanical properties of compact bones and cancellous bones. Finally, combined with the
clinical operation, the fracture and its internal fixation are introduced, and the mechanical method is used for quantitative analysis.

2. The four levels of bone structures
Bone is a living organ, capable of self-regeneration and repair, and it is an extremely abnormal and complex substance. In mechanical terms, bone is a composite material composed of different solid-fluid two-phase substances, including organic material, inorganic salts, and water [5]. The solid part is the main organic component of all connective tissue outside the cell, the elastic collagen matrix, which is mainly filled with hydroxyapatite $\text{Ca}_10(\text{PO}_4)_6\cdot\text{OH}_2$ or other similar mineral substances [6] to increase bone strength. The liquid phase contains blood and extracellular hydro. The structures of bone can usually be discussed on four levels, namely, bone at the molecular level; woven bones, lamellar bones and Haversian bones; large woven bones and primary woven bones, Harversian bone system and laminar bones; compact bones and cancellous bones [7-9].

2.1. Molecular level
At the molecular level, that is, at the lowest level, bone be formed by parallel arrangement of collagen fibers filled with dense calcium phosphate, in addition to some water, unshaped polysaccharides and proteins [10]. Collagen is a structural protein, and only in vertebrates can collagen be transformed into a mineralized bone structure. In fully mineralized bone, the collagen fibers are surrounded by bone salt. It is generally believed that some components of bone mineral are the transformation of calcium phosphate, called hydroxy phosphate, and its shape is generally needle-like or plate-like.

2.2. woven bones, lamellar bones and Haversian bones
Woven bones and lamellar bones are bones that are higher than the molecular level. Woven bones generally appear in the compact and cancellous bones of growing young animals and the injured bones of some adult animals, and are gradually replaced by plate-shaped bones in the mature period. The plate-shaped bone is composed of many concentrically arranged thin slices, which appear in the middle of the backbone of mature long bones. The lamellae are surrounded by the reticular blood vascular system, and some lamellar bones will eventually be transformed into Haversian bones [11]. The proportion of Haversian bones in the human body increases with ages. In addition, the mineral density of woven bone varies greatly, but in plate-shaped bone and Haversian bone, minerals and collagen are related to each other, and there should not be too much minerals.

2.3. large woven bones and primary woven bones, Harversian bone system and laminar bones
They are all higher-level bones composed of woven bones, lamellar bones and Haversian bones. Large woven bone is formed by woven bone spreading several millimeters uniformly in all directions, and can only be found in young bones or large calluses. Lamellar bone can expand to form native lamellar bone in some parts, and the native lamellar bone is often replaced by the Haversian system. The bones with the Haversian system also contain secondary bones, which are also called laminar bones or parallel fibrous bones.

2.4. compact bones and cancellous bones
At the macro level, bone be composed of compact bones and cancellous bones. Compact bone is located outside the bone, has the characteristics of high strength, rigidity, and density, and bears the main load of the bone. Compact bone is further divided into bone unit, interstitial bone, and plexiform bone [12]. Among them, the bone unit is the main tissue that constitutes compact bone and supports the nutrients required for the bone regeneration process. The cancellous bone is located inside the compact bone, which has relatively low strength, stiffness, and density, but high impact resistance. The cancellous bone at both ends of the long bone can play a role in dispersing the load.
3. Biomechanical properties of bone tissue

3.1. Elasticity modulus analysis of bone tissue

Bone tissue is the main load-bearing organ of the human body, and its carrying capacity is closely related to its own biomechanical properties. As a complex multi-level biomaterial, the biomechanical properties of bone tissue are determined by factors such as its own structure and biological characteristics [13]. Under different degrees of mechanical load, bone tissue exhibits different biomechanical properties. Due to the experimental difficulties and the complexity of the bone structure, we only discuss the mechanical properties of the highest-level compact bones and cancellous bones.

In recent years, with the improvement of experimental equipment and experimental technology, some new methods have been developed to determine the mechanical properties of bones. The elasticity modulus of bovine femur and human femur are summarized and sorted out by the key technologies, as shown in Table 1.

| Mechanical properties of bone | Elasticity modulus (GPa) |
|------------------------------|-------------------------|
| bovine femur                 |                         |
| osteon                       |                         |
| Dried bone                   | 24.4±2.2[a]             |
| Wet bone                     | 21.1±2.0[a]             |
| Intermediate lamella         |                         |
| Dried bone                   | 27.5±1.2[a]             |
| Wet bone                     | 25.1±1.6[a]             |
| human femur                  |                         |
| Compact bone                 |                         |
|                             | 25.0±4.3[b]             |
|                             | 17.73±0.22[c]           |
|                             | 20.02±0.27[d]           |
| Cancellous bone              |                         |
|                             | 6.9±4.3[b]              |
|                             | 17.50±1.12[c]           |
|                             | 18.14±1.70[d]           |

Note: [a] Measured by Rho et al. through nanoindentation technology [14] [b] Measured by Zysset et al. through nano-probing technology [15] [c] Measured by Turner et al. through acoustic microscope technology [16] [d] Measured by Turner et al. through nanoindentation technology [16]

Comparing the data of bovine femur and human femur in the table, the elasticity modulus of former is generally higher than the latter, which is consistent with the actual situation [17]. From the data in the analysis table, it can be found that the elasticity modulus of dried bone is usually greater than that of wet bone, and the elasticity modulus of compact bone is usually greater than that of cancellous bone. In addition, with different technical methods, although the elastic modulus is different, the difference is small, and the average value can be roughly regarded as the elasticity modulus.

Compared with other engineering materials, the properties of bone are usually affected by many factors, and they vary with the age, sex, bone type, location, and freshness of the specimen [18].

3.2. Other mechanical properties of compact bones and cancellous bones

Compact bone is a composite material with multi-level microstructures nested in each other. It is difficult to determine the macro-elastic parameters. The four-level microstructure model of compact bone proposed by Park [19] is usually used to establish homogenization of the multi-level structure. The unit cell model of the homogenization method is established for the multi-level structure, the finite element numerical method is used to solve the governing equation on the unit cell, and the homogenization theory is applied to calculate the macroscopic equivalent parameters of the level structure. The material properties and content of collagen fibers and hydroxy phosphate groups have a certain effect on the elasticity modulus of compact bone, but have little effect on Poisson's ratio. In addition, compact bone has stress relaxation and creep behavior [20]. The mechanical behavior of compact bone has obvious time dependence, that is, it exhibits viscoelastic characteristics. It has obvious strain rate dependence.
Its mechanical properties, such as elasticity modulus and strength, vary with the strain rate. Similarly, the value of the elasticity modulus of compact bone changes little within 10 days after death, and suddenly drops rapidly within a few days. After more than 15 days, the elasticity modulus hardly changes.

Cancellous bone mainly includes 8 microstructure parameters [21-22], which are Trabecular Number (Tb.N), which refers to the number of intersections between bone tissue and non-bone tissue within a given length, which is understandable. It is the number of trabeculae per unit distance. Trabecular Thickness (Tb. Th) refers to the average thickness of trabecular bone. Trabecular Separation (Tb. Sp) refers to the average width of the medullary cavity between trabecular bones. Bone Volume to Tissue Volume (BV/TV), the ratio of bone volume to tissue volume. The ratio of bone surface to bone volume (BS/BV) represents the surface density of bone. The Structure Model Index (SMI) describes the degree of plate-like and rod-like bone trabeculae by calculating the curvature of the bone surface. The degree of anisotropy (DA) is used to measure the directionality and symmetry of the trabecular bone structure. Connectivity Density means the number of connections between trabecular bone networks.

There is a good correlation between the microstructure parameters of cancellous bone and its mechanical strength. BV/TV can be regarded as the three-dimensional form of BMD, which is positively correlated with the mechanical strength of cancellous bone. Perilli et al. [23] found that if only the lowest BV/TV value of a certain area in the overall cancellous bone block is considered, the prediction ability of BV/TV for the ultimate stress of cancellous bone can be increased to the maximum. This is because cancellous bone, as a porous material, has obvious heterogeneity [24]. The anisotropy of cancellous bone refers to the numerical difference of a certain parameter in different directions of trabecular bone. For cancellous bone, anisotropy can be used to account for changes in strength in the direction of the load. At the same time, the elasticity modulus of trabecular bone is not equal in different load directions, and the strength is also different, indicating that trabecular bone still has anisotropic characteristics [25]. In addition, Silva et al. [26] established a two-dimensional model of human vertebrae for finite element analysis and found that when the same amount of bone is lost, the decrease in modulus and strength caused by the loss of trabecular bone is caused by the thinning of trabecular bone thickness. The effect is 2 to 5 times. Mittra et al. [27] used the cancellous bone study of the femoral condyle of sheep to find that the ultimate strength of bone. The correlation of Tb. N is significantly better than that of Tb. Th, visible, Tb. N and Tb. Th is positively correlated with the mechanical strength of cancellous bone, that is, the more bone trabeculae, the thicker the thickness, the higher the bone strength.

4. Mechanical analysis of fracture and its internal fixation

4.1. Overview of fracture and internal fixation

Fractures are caused by the uneven distribution of stress and function on the bones. Sudden structural fracture occurs when the internal stress caused by the load exceeds the strength limit [28]. All fractures cause compound damage to the bones and surrounding soft tissues. Once a fracture occurs and in its repair phase, local circulatory disturbances and inflammation will be seen quickly, and pain will be generated as a result. The three factors of circulatory disturbance, inflammation and pain will cause the use of joint and muscle function, which will lead to the occurrence of the so-called "fracture disease" [29-31]. The treatment and recovery after the fracture is very important. It is one of the necessary ways to treat and repair the fracture with surgery. Internal fixation is an important way to restore the fracture. To be precise, internal fixation refers to the use of surgical methods to fix bones in the body to repair fractures, following the following four principles [32-33]. Whether the anatomical reduction of the first fracture end is in place, especially in the case of intra-articular fractures. The second is a strong internal fixation designed to meet the needs of local biomechanics. The third application of non-invasive surgical techniques to protect the blood supply of the fractured end and soft tissues. Early, active and painless activities of the fourth muscle and the fracture site adjacent to the joints to prevent the occurrence of fractures. The internal fixation of steel plates and screws to treat fractures has become one of the most used orthopedic operations and is widely used at home and abroad. Krikler [34] et al. proved that the
eccentric load of the bone is tension on one side of the cortex and pressure on the other side. The position of the steel plate is very different from the rigidity of the steel plate to the bone and the load to be borne by the steel plate. Generally, the steel plate and bone that bear the bending moment and eccentric axial force are simplified into composite beams. The composite beam theory determines the mechanical properties of the steel plate-skeletal system. The linear bending composite beam theory and finite element method are usually used to study.

4.2. The influence of steel plate position on internal fixation

The bending stiffness of a composite beam is the sum of the bending stiffness of the bone alone, the bending stiffness of the steel plate alone, and the increase in stiffness due to the offset of the neutral axis [35]. The solid section has a greater bending stiffness than the circular section, so the solid section has less deformation under the same load [36]. Generally speaking, the cross-section of compact bone is close to a circular solid cross-section. Due to the large gap, the cross-section of cancellous bone is close to a circular ring. The two ends of the entire bone are cancellous bone, and the middle diaphysis is compact bone [37-38]. Therefore, the steel plate should be installed in the middle of the bone as far as possible during internal fixation, where the bending stiffness is relatively large.

The composite bone-steel beam structure not only depends on the mechanical properties of the steel plate and the bone, but also depends on the connection between the steel plate and the bone and the position of the steel plate relative to the bending direction [39]. When the bone-steel composite beam system is bent along its long axis and short axis, its bending stiffness reaches the maximum and minimum respectively. When the steel plate is bent along its long axis, the rigidity of the steel plate itself reaches the maximum, but because there is no deviation of the central axis in the bending direction, the stiffness of the total bone-steel composite beam is the smallest; when the steel plate is bent along its short axis When the steel is placed on the tension side of the bone, the stiffness of the steel plate itself reaches the minimum, but due to the maximum deviation of the central axis in the bending direction, the stiffness of the total bone-steel composite beam reaches the maximum [40]. In the actual operation process, it will not be placed on the tension side of the bone very accurately, so the bending stiffness is between the maximum and minimum. In addition, the material will also affect the internal fixation. The material used for the internal fixation must first be able to complete the temporary fixation of the fracture to allow functional treatment. Therefore, this material needs to have good anti-fatigue properties and must be tough enough to maintain its strength after being attached to the bone surface. Not only that, the material must also be available frequently, ensure quality, have an acceptable price, and be easy to process and shape in surgery [41]. At present, pure titanium with inertness and good histocompatibility is mostly used. From the viewpoint of histocompatibility and avoiding low-level immune complications, pure titanium is the best metal [42]. By comparing different materials of steel plate and pure titanium on the tension side or at 90° from the tension side, the stiffness of the composite beam system varies greatly [43], see Table 2.

Table 2. Steel plate and pure titanium composite material system stiffness changes at different positions

| The material used for the internal fixation | Position of the material composite beam system stiffness |
|-------------------------------------------|--------------------------------------------------------|
| steel plate                               | tension side                                           |
| at 30° to the tension side                | 83%EI                                                  |
| at 60° to the tension side                | 55%EI                                                  |
| at 90° to the tension side                | 38%EI                                                  |
| pure titanium                             | tension side                                           |
| at 90° to the tension side                | 87%EI                                                  |

The analysis in Table 2 shows that the position of pure titanium on the tension side relative to the steel plate composite beam system stiffness decreases by 11%, and is reduced by 13% at 90° to the
tension side; while the position of the steel plate is at 90° to the tension side, the stiffness of the composite beam system is reduced by 62%, which shows that the stiffness of the bone-plate is very sensitive to the position of the bending direction of the plate, so the placement of the plate during the operation is very important.

5. Conclusion
The structure of bone can be divided into four levels. Starting from the lowest molecular level, bone is mainly composed of calcium phosphate, water, amorphous polysaccharides, and protein; woven bones, lamellar bones are bones that are one level higher than the molecular level. Among the growing young animals and injured adult animal bones, some will be transformed into Haversian bones; the next higher level are large woven bones and primary woven bones, Harversian bone system and laminar bones; Finally, in the macroscopic it can be divided into compact bones with high strength, high stiffness and high density and cancellous bone with low strength, low stiffness and low density. For further analysis of the mechanical properties of bones, firstly, the latest technology to study the elasticity modulus parameters shows that the elasticity modulus of dry bone is usually greater than that of wet bone, and the elasticity modulus of compact bone is usually greater than that of cancellous bone. Further analysis of different types of bones, the material properties and content of collagen fibers and hydroxy phosphate groups are obtained, which have a certain effect on the elasticity modulus of compact bones, but have little effect on Poisson's ratio. Cancellous bone mainly includes 8 microstructure parameters, which have a good correlation with its mechanical strength. The more bone trabeculae, the thicker the thickness, the higher the bone strength. The application of bone mechanical properties is to combine with clinical medicine fractures and internal fixation, using linear bending composite beam theory and finite element method to study related mechanical properties. During internal fixation, the steel plate should be installed in the middle of the bone as far as possible, where the bending stiffness is relatively large. Through comparative analysis, various factors such as the connection method between the steel plate and the bone, the position of the steel plate relative to the bending direction, the selection of materials and other factors affect the mechanical properties, there are so many factors need to be considered in the operation.

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