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Research Article

Human Bone strength Evaluation through different Mechanical Tests

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Abstract

Bone mineral density [BMD] generally correlates with bone strength. BMD testing is used to assess bone density and diagnose osteoporosis. The correlation between CT numbers and mechanical property estimated from cortical bone were found to be low (r2<0.2) and cancellous bone were found to be higher (r2>0.6). The specific relationship depending on the types of bone, that predict elastic module from density and CT numbers were suggested for human cortical and cancellous bone. The different mechanical properties give the strength of bone. The mechanical properties can be achieved from the different tests (i.e. Tensile, compression, Torsional, creep etc.)

Keywords: *BMD, Mechanical properties, Testing, Strength Evaluation.*

1. Introduction

The femur, or thigh bone, is the most proximal (closest to the body) bone of the leg Invertebrates capable of walking or jumping, such as most land mammals, birds, many reptiles such as lizards, and amphibians such as frogs. In vertebrates with four legs such as dogs and horses, the femur is found only in the rear legs.

In human anatomy, the femur is the longest and largest bone. Along with the temporal bone of the skull, it is one of the two strongest bones in the body. The average adult male femur is 48 centimeters (18.9 in) in length and 2.34 cm (0.92 in) in diameter and can support up to 2 times the weight of an adult .It forms part of the hip joint (at the acetabulum) and part of the knee joint, which is located above. There are four eminences, or protuberances, in the human femur: the head, the greater trochanter, the lesser trochanter, and the lower extremity. They appear at various times from just before birth to about age 14.

Bone density (or bone mineral density) is a medical term normally referring to the amount of mineral matter per square centimeter of bones. Bone density (or BMD) is used in clinical medicine as an indirect indicator of osteoporosis and fracture risk.This medical bone density is not the true physical density of the bone, which would be computed as mass per volume. It is measured by a procedure called densitometry, often performed in the radiology or nuclear medicine departments of hospitals or clinics. The measurement is painless and non-invasive and involves low radiation exposure. Measurements are most commonly made over the lumbar spine and the upper part of the hip. Average density is around 1500 kg m^{-3}. Cristofolini,et al,2006.

The Hounsfield scale, named after Sir Godfrey Newbold Hounsfield, is a quantitative scale for describing radio density. The Hounsfield Unit (HU) scale is a linear transformation of the original linear `attenuation coefficient measurement into one in which the radio density of distilled water at standard temperature and pressure (STP) is defined as zero Hounsfield units , while the radio density of air at STP is defined as -1000 HU. Dual-energy X-ray absorptiometry (DXA, previously DEXA) is a means of measuring bone mineral density (BMD).When soft tissue absorption is subtracted out, the BMD can be determined from the absorption of each beam by bone. Dual-energy X-ray absorptiometry is the most widely used and most thoroughly studied bone density measurement technology. Carter et al, 2006

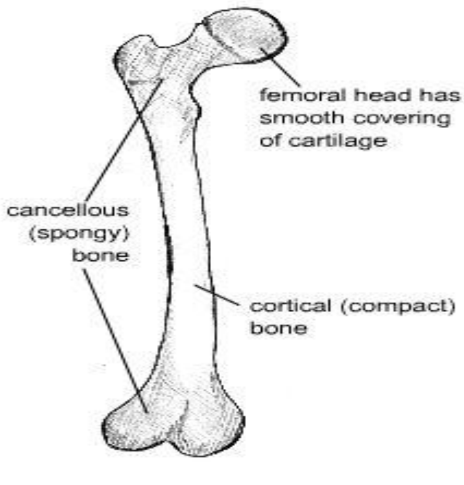

Fig.1 Typical Femur bone

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The DXA scan is typically used to diagnose and follow osteoporosis which is sensitive to certain metabolic diseases of bones in which bones are attempting to heal from infections, fractures, or tumors.

2. Theory

Strength and stiffness are typically used to define the health of a bone. The slope of the curve is called as Young's modulus (E), whereas height of the curve represents the ultimate strength. The yield point represents a transition, above which strains begin to cause permanent damage to the bone structure. Post-yield strain is inversely proportional to the brittleness of the bone. Bone mineral density (BMD) is highly correlated with strength and stiffness, but there is an inverse relationship between bone stiffness (Young's modulus) and ultimate strain.

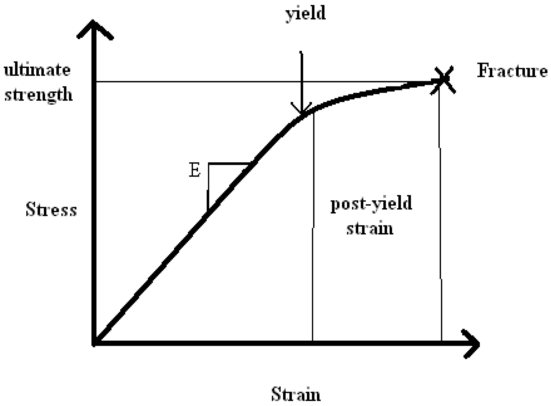

Fig. 2 Stress-Strain Diagram for bone

2.1. Mechanical properties of bone

Before and during the process of testing bone mechanical properties, the researcher has to learn the basic structural and mechanical properties of bone. These properties include cortical and cancellous bone at the level of whole bones, bone tissues, osteons or trabeculae, bone lamellae,and ideally the nano or ultrastructure such as collagen fibers, fibrils, molecules, and mineral components. These basic structural and mechanical data are searchable in the journal literature and also have been written about in numerous textbooks.

2.2 Mechanical properties of cortical bone

a. Bone Density

The material density of cortical bone is the wet weight divided by the specimen volume. It is a function of both the porosity and mineralization of the bone materials. Cortical bone has an average apparent density of approximately 1.9 g/cm3.For cortical bone, apparent density and material density are basically the same, as there is no marrow space in compact bone. Therefore, cortical bone density is commonly used to describe the density of cortical bone. There is a positive correlation between apparent density of cortical bone and its mechanical properties. The true meaning of bone mineral density (BMD) is bone mineral mass per unit bone volume, or ash density if an ashing (or burning) method is used. Similarly, the true meaning of bone mineral content (BMC) describes the ratio of unit weight of the mineral portion to dry bone unit weight and is frequently reported as a percentage. BMD and BMC are positively correlated with the strength and stiffness of various bones, such as human ulna, human femur and tibia, bovine femur and tibia,32,46 feline femur,49 and a wide variety of animal bones.50 Many reports have shown linear or exponential increases in bone stiffness with increasing mineralization, such as the one proposed by Schaffler and Burr:

E=89.1M391

Where E is compressive elastic modulus and M is mineralization of bovine cortical bone. A. Matani et al,2001

b. Porosity

The strong effects of porosity of cortical bone on mechanical properties have been well studied. It is easy to understand that a more porous bone has a weaker mechanical strength. Porosity (p) is defined as the ratio of void volume to total volume, which is commonly measured on two dimensional histologic sections (traditionally point counting)29,46 or X rays.55 In cortical bone, the mechanical properties are affected by Haversion canals and related resorption cavities and vascular channels. There are reports on the correlations of porosity and mechanical properties, such as the equation proposed by Schaffler and Burr on bovine cortical bone using tensile tests:

$E = 33.9\ (1 - p)^{10.9}$

Where E is the elastic modulus and $(1 - p)$ is the bone volume fraction, and the equation by Currey for cortical bone of a wide variety of species under tension is

$E = 23.4\ (1 - p)^{5.74}$

McElhaney et al found that

$E = 12.4\ (1 - p)^{3}$

For compression of human skull bones.

2.3 Mechanical properties of cancellous bone

a) Structural Properties

The structural properties of cancellous bone are commonly measured by compression, tensile, or bending tests. The common phrase mechanical properties of cancellous bone means the structural properties. It is known that the strength and elastic modulus by tensile tests are smaller than that by compression tests. For example, the strength by tensile test is approximately 60% of the value by compression test reported by Kaplan et al.and the elastic modulus by tensile test is approximately 70% of the value by compression test reported by Keaveny et al.According, the values of strength and elastic moduli of cancellous bone are 1.5 to 38 MPa and 10 to 1570 MPa, respectively. The structural properties of cancellous bone are much smaller than those of cortical bone. The average values of elastic modulus are several hundred mega Pascal for cancellous bone, compared with 5 to 21 GPa for cortical bone.

2.4 Bone Density

There is a strong correlation between the mechanical properties of cancellous bone, both for strength and stiffness, and its apparent density and mineral (or ash) density. The apparent density of cancellous bone ranges from 0.14 to 1.10 g/cm3 (average: 0.62 g/cm3, *n* = 16;. The compressive strength (6 in MPa) of cancellous bone is related to its apparent density by a power law of the form:

$$\sigma = 60\rho^2$$

The compressive modulus (*E* in MPa) of cancellous bone is related to the apparent density

$$E = 2915\rho^2$$

ed data of ash densities of human and animal cancellous bones are a they range from 0.19 to 0.56 g/cm3 with an average of 0.37 ± 0.10 g/cm3 (*n* = 12), which is about 60% of the value of apparent density as shown in the following equation:

$$\rho_{Ash} \approx 0.6 \times \rho_{Apparent}$$ H.G.Hanumantharaju et al, 2010

3. Mechanical Testing Methods

Mechanical testing studies of bone have been directed at determining the mechanical properties of whole bone and bone tissue under different loading conditions. In general, determination of mechanical properties of bone is done by the same methods used to study similar properties in metal, woods, and other structural materials and composites. These methods are based on fundamental principles of mechanics.

Consequently, some basic knowledge of mechanics and the terminology employed is essential in order to apply these principles. Bone is a viscoelastic, composite material. The organization of the composite varies from animal to animal and is strongly influenced by aging, activity, and disease. Unlike engineering composite materials, however, bone has a fibrous structural component (collagen) as its matrix and exhibits a composite behavior microscopically as well as macroscopically Lengsfeld,M et al, 1996

3.1 Tensile Testing

Tensile testing can be one of the most accurate methods for measuring bone properties, but bone specimens must be relatively large and should be carefully machined. Tensile test specimens for cortical bone and cancellous bone. Dimensions are derived from ASTM standard the ratio d/D should be around½ and the parallel length of the narrow section should be at least three times the size of the gaugediameterd. The radius of curvature R should be very large to avoid stress concentrations and should have the same dimensions as the parallel length A. The grip length M is one quarter of the whole specimen length L. Because of the relatively homogeneous microstructure of cortical bone, cortical bone specimens can be made comparatively small in size (gauge diameter = d ≈ 3 mm). In principle, the same geometry used for cortical bone tensile test specimens applies to trabecular bone. However, because of the intrinsic lattice and inhomogeneous structure of trabecular bone, a minimum gauge diameter of 5 mm is required to ensure that continuum scale criteria are met. Tensile test specimens are designed so that the highest strains will occur in the central portion or gauge region of the specimen. Strain measurements can be obtained by attaching a clip-on extensometer to the gauge section of the specimen. Stress is calculated as the applied force divided by the bone cross-sectional area measured in the specimen midsection.

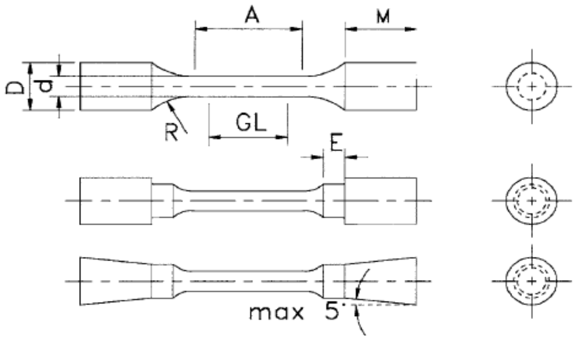

Fig.3 Tensile test specimen geometry for cortical bone tests.

Where**,**

A = parallel length, GL = gauge length, M = grip length, E = neck length, R = curvature radius, D = specimen outer diameter, d = specimen gauge diameter.

3.2 Compressive Testing

Compression testing of bone specimens is a popular technique, especially for cortical bone because relatively small specimens can be used. Compressive tests, however, tend to be less accurate than tensile tests due to friction and compression-platen end effects imposed on the bone specimen during the test. Friction at the load platen–bone surface interface can be minimized using polished stainless steel plates lubricated with a coating of lightweight machine oil. A surface roughness of 2 μm cm^{-1} is recommended. If the load faces of the bone specimen are slightly misaligned with respect to the compression loading platen, then large stress concentrations can occur, resulting in 18618an underestimation of both Young's modulus and compressive strength.

Another problem associated with compressive testing of trabecular bone is the previously noted end effect created by cutting or machining the faces of trabecular bone test specimens. At the boundary where the specimen contacts the loading platen, the cut surfaces of the trabeculae lattice are unsupported, and the strain tends to be much greater in the boundary region than in the middle of the specimen.48 Elevated strains at the ends of the specimen result in an overestimation of the average specimen strain and concomitant underestimation of modulus. Thus, simple strain calculations tend to be inaccurate. More accurate specimen strain measurements can be obtained by directly measuring the local strain at the midsection of the specimen. Mechanical or optical extensometers can be used for local strain measurements in trabecular bone. Rodríguez Lelis et al,2007

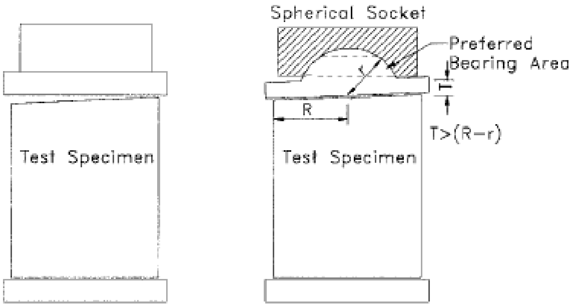

Fig.4 Spherical socket used to compensation for nonparallel load-bearing surfaces during compression Testing.

3.3 Four-Point Bending

Four-point bending occurs when two force couples acting on a structure produce two equal moments. A force couple refers to a pair of parallel forces of equal magnitude but opposite direction applied to a structure .The bending moment magnitude is the same throughout the area between the force couples; hence, the structure being tested should fracture at its weakest point. This arrangement is advantageous for testing where one might be uncertain about the strongest or weakest point and does not wish to influence the test by locating the maximum bending moment at a specific place. A clinical example of a four-point bending fracture is a femoral fracture through a previous fracture site resulting from one force couple formed by the posterior knee joint capsule and tibia and the other by the femoral head and hip joint capsule.

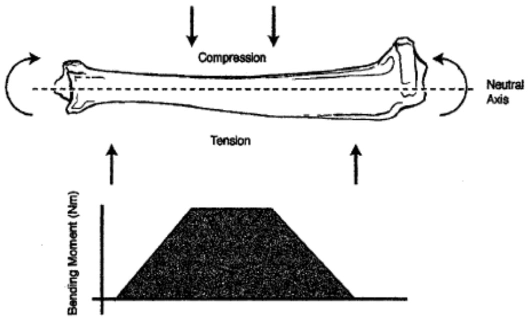

Fig. 5 Typical bending moment diagram for four point bending

Four-point bending occurs when two force couples acting on a structure produce two equal moments. The bending moment magnitude is the same throughout the area between the force couples.

3.4 Torsional Testing

A diaphyseal segment from a long bone might be grossly approximated as a hollow cylindrical shaft made from a homogeneous, linear elastic material. Such a shaft might have a certain inner radius, *ri*, an outer radius, *ro*, and a length, *L*. If one end, *A*, of the shaft is fixed, and a torsional force, *T*, is applied to the opposite end, *B*, then end *B* will rotate in its own plane through some angle _ with respect to end *A*, the theoretical torional share stress can be calculate by using following equation,

$$\tau_{max} = \frac{T r_o}{J}$$

And angle can be calculated by using following equation, Rho et al,1998

$$\phi = \frac{TL}{JG}$$

3.5 Creep Testing

The creep test is the simplest test to operate from a machine perspective, yet it can be the most difficult test to instrument. It will always be performed under load control. As with the fatigue test, however, the servo hydraulic machine may be difficult to start in the load control mode. Rather, the test may be started under stroke control, and the operator may manually adjust the controller to obtain a desired static preload. Once the preload is achieved, the machine may be switched to load control, at which point the machine will maintain the set preload for as long as is desired. Over time, the bone will begin to creep, and the resulting machine displacement or strain feedback signals can be monitored. Since creep is a very slow and small-scale phenomenon, the displacement feedback will most likely be of little use. Resistive strain gauges, on the other hand, can provide more detailed information about what changes have taken place over a small region of the bone.

These gauges must be carefully placed over the region of interest with cyanoacrylate adhesives. They are delicate instruments, and it is most useful to monitor the small feedback signals with a computerized acquisition system. Some authors have used a specially designed apparatus to study the torsional creep behavior of compact bone. Such equipment can be built inexpensively by applying the torque by means of dead loads with pulleys and lever arms.

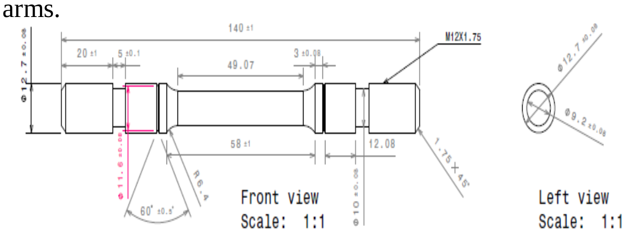

Fig. 6 Typical creep test specimen

3.6 Fatigue Testing

Fatigue testing is almost always performed with a sinusoidally varying command signal, and the function generator of the controller should be set to operate in that capacity with the desired frequency and load/strain ranges. Many controllers operate based on the half-cycle amplitude of the function. Be sure to check the manufacturer’s instructions for calculating the function parameters correctly. Fatigue tests can be conducted in either load or strain control mode. However, it may be easier to start it in displacement control mode and then transfer to load or strain control after the preloading conditions has been achieved. Rotational and axial fatigue can both be performed in five different capacities: positive-positive, negative-negative, zero-positive, zero-negative, and positive-negative. As an example, take the case of positive-positive torsional fatigue under load control. The specimen will experience positive torsional loading at all times. Ascenzi et al,1990

A positive torsional preload, or *mean level*, is placed on the specimen, and subsequent loading cycles are superimposed over that level. For example, the preload may be equal to 5 N·m while the half-cycle amplitude is 1 N·m. The test will then cycle between 4 and 6 N·m. Negative-negative tests behave the same way, but in the reverse direction. Zero-positive and zero-negative tests have no preload. Positive-negative tests may use any type of preload (or none at all) as long as the torsional direction reverses at some point in each cycle. Load-controlled tests will obtain their feedback from the load/torque cell, while strain controlled tests require the use of external gauges. The latter must be calibrated to work properly with the system controller and its function generator. As with the ramp test, the displacement ranges should also be set to provide the appropriate amplification of the LVDT/RVDT feedback signal if the displacement is to be monitored.

Conclusions

1. According to the data collected, the strength and elastic modulus by compression tests range from 133 to 295 MPa (200 ± 36 MPa) and from 14.7 to 34.3 GPa (average 23 ± 4.8 GPa), respectively.
2. The strength and elastic modulus by tensile tests range from 92 to 188 MPa (average 141 ± 28 MPa) and from 7.1 to 28.2 GPa (average 19.6 ± 6.2 GPa), respectively.
3. The strength and elastic modulus by torsional tests range from 53 to 76 MPa (average 65 ± 9 MPa) and from 3.1 to 3.7 GPa, respectively
4. The tensile strength is about ²/3 that of compression strength.
5. The torsional (shear) strength is approximately ¹/3 to ¹/2 of the values of the longitudinal strength (tested by bending, tensile, or compressive tests) And the torsional (shear) modulus is only about ¹/6 to ¹/5 of the longitudinal modulus.
6. The values of strength and elastic moduli of cancellous bone are 1.5 to 38 MPa and 10 to 1570 MPa, respectively.
7. The structural properties of cancellous bone are much smaller than those of cortical bone.
8. The average values of elastic modulus are several hundred MPa for cancellous bone,compared with 5 to 21 GPa for cortical bone

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