Lecture No.: *1*

<u>Mechanical Properties of the Hard Tissue (Bone)</u>

<u>COMPOSITION AND STRUCTURE OF BONE TISSUE</u>

The material constituents and structural organization of bone influence the ways in which bone responds to mechanical loading. The composition and structure of bone yield a material that is strong for its relatively lightweight.

<u>Material Constituents</u>

The major building blocks of bone are calcium carbonate, calcium phosphate, collagen, and water. The relative percentages of these materials vary with the age and health of the bone. **Calcium carbonate and calcium phosphate** generally constitute approximately **60–70% of dry bone weight**. These minerals give bone its **stiffness** and are the primary determiners of its compressive strength. Other minerals, including magnesium, sodium, and fluoride, also have vital structural and metabolic roles in bone growth and development. Collagen is a protein that provides bone with flexibility and contributes to its tensile strength. The **water** content of bone makes up approximately **25–30%** of total bone weight. The water present in bone tissue is an important contributor to bone strength. For this reason, scientists and engineers studying the material properties of different types of bone tissue must ensure that the bone specimens they are testing do not become dehydrated.

<u>Structural Organization</u>

The relative percentage of bone mineralization varies not only with the age of the individual but also with the specific bone in the body. Some bones are

more porous than others. **The more porous the bone, the smaller the proportion of calcium phosphate and calcium carbonate, and the greater the proportion of nonmineralized tissue**. Bone tissue has been classified into two categories based on porosity (Figure 1). If the porosity is low, with 5–30% of bone volume occupied by nonmineralized tissue, the tissue is termed **cortical bone**. Bone tissue with a relatively high porosity, with 30% to greater than 90% of bone volume occupied by nonmineralized tissue, is known as **spongy, cancellous, or trabecular bone**. Trabecular bone has a honeycomb structure with mineralized vertical and horizontal bars, called trabeculae, forming cells filled with marrow and fat.

The porosity of bone is of interest because it directly affects the mechanical characteristics of the tissue. **With its higher mineral content, cortical bone is stiffer,** so that it can withstand greater stress, but less strain or relative deformation, than trabecular bone. **Because trabecular bone is spongier than cortical bone, it can undergo more strain before fracturing.**
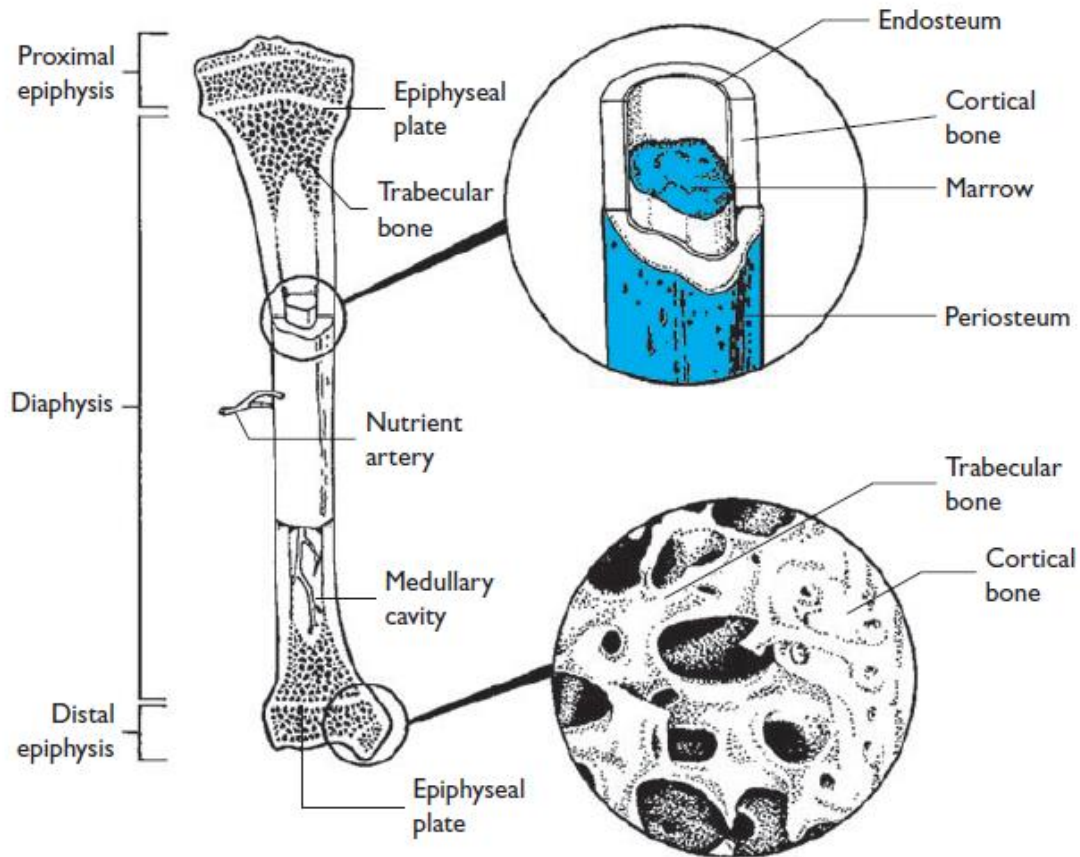
**Figure 1:** Structures of cortical and trabecular bone.

The function of a given bone determines its structure. **The shafts of the long bones are composed of strong cortical bone.** The relatively high trabecular bone content of the vertebrae contributes to their shock absorbing capability. Both cortical and trabecular bone are anisotropic; that is, they exhibit different strength and stiffness in response to forces applied from different directions. **Bone is strongest in resisting compressive stress and weakest in resisting shear stress (Figure 2).**

A

Remnant of epiphyseal plate   Trabecular bone   Cortical bone

B

Trabecular bone   Cortical bone
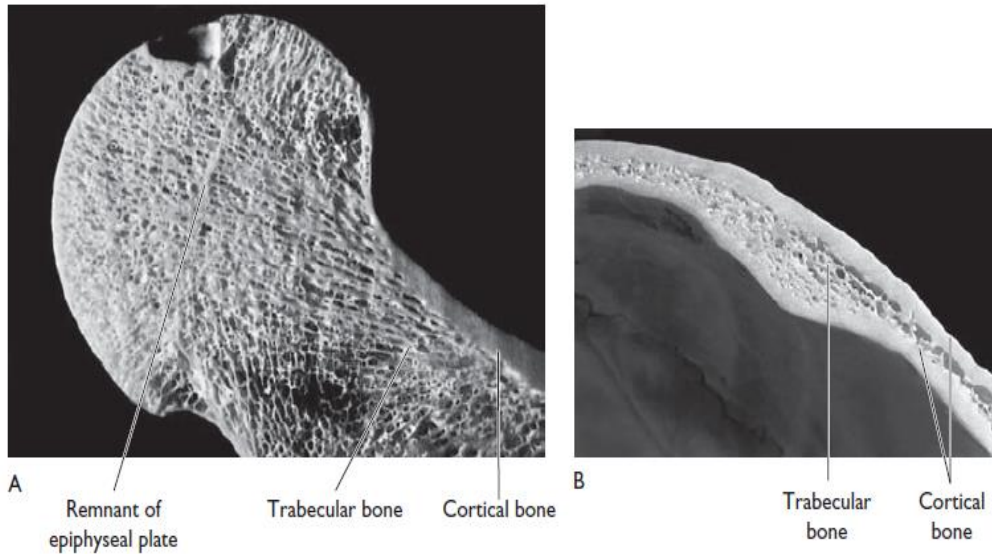
(A) In the femur, trabecular bone is encased by a thin layer of cortical bone.
(B) In the skull, trabecular bone is sandwiched between plates of cortical bone.
From Shier, Butler, and Lewis. *Hole's Human Anatomy and Physiology*, © 1996. Reprinted by permission of The McGraw-Hill Companies, Inc.
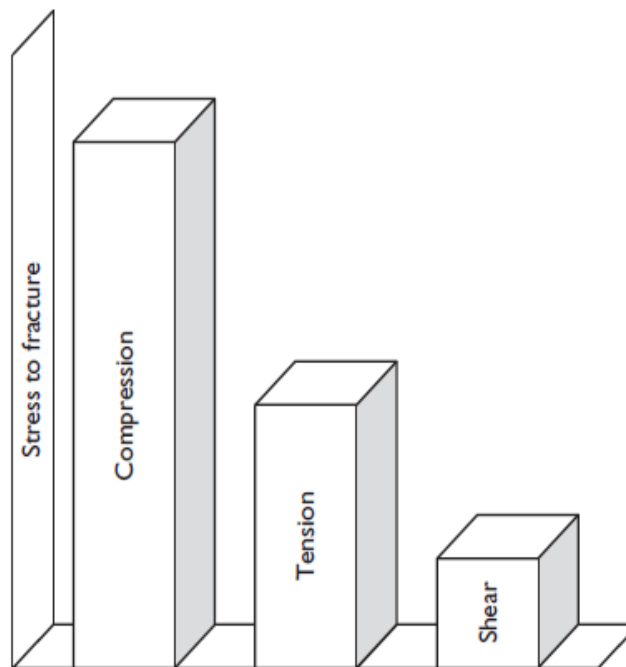
Figure 2: Relative bone strength in resisting compression, tension, and shear.

Types of Bones

The structures and shapes of the 206 bones of the human body enable them to fulfill specific functions. The skeletal system is nominally subdivided into the central or axial skeleton and the peripheral or appendicular skeleton**. The axial skeleton includes the bones that form the axis of the body, which are the skull, the vertebrae, the sternum, and the ribs.** The other bones form the body appendages, or the appendicular skeleton. Bones are also categorized according to their general shapes and functions.

Short bones: which are approximately cubical, include only the carpals and the tarsals. These bones provide limited gliding motions and serve as shock absorbers.

Flat bones: are also described by their name. These bones protect underlying organs and soft tissues and also provide large areas for muscle and ligament attachments. The flat bones include the scapula, sternum, ribs, patellae, and some of the bones of the skull.

Irregular bones: have different shapes to fulfill special functions in the human body. For example, the vertebrae provide a bony, protective tunnel for the spinal cord; offer several processes for muscle and ligament attachments; and support the weight of the superior body parts while enabling movement of the trunk in all three cardinal planes. The sacrum, coccyx, and maxilla are other examples of irregular bones.
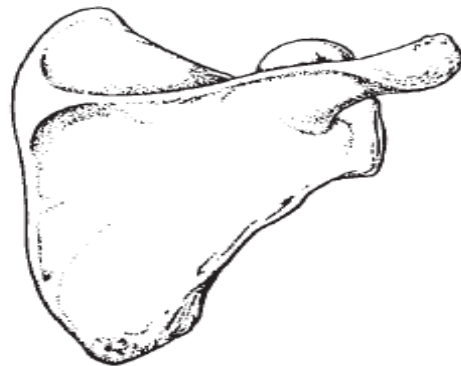
Long bones: form the framework of the appendicular skeleton. They consist of a long, roughly cylindrical shaft (also called the body, or diaphysis) of cortical bone, with bulbous ends known as condyles, tubercles, or tuberosities. A self-lubricating articular cartilage protects the ends of long bones from wear

at points of contact with other bones. Long bones also contain a central hollow area known as the medullary cavity or canal.

The long bones are adapted in size and weight for specific biomechanical functions. The tibia and femur are large and massive to support the weight of the body. The long bones of the upper extremity, including **the humerus, radius, and ulna, are smaller and lighter to promote ease of movement.** Other long bones include the clavicle, fibula, metatarsals, metacarpals, and phalanges.
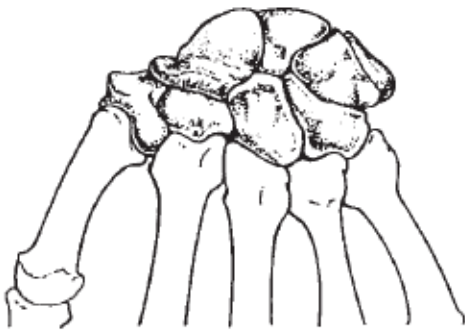
The carpals are categorized as short bones   The scapula is categorized as a flat bone
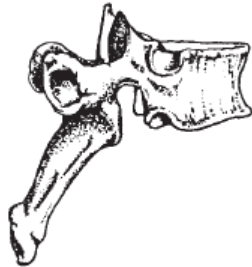
The vertebrae are examples of irregular bones.   The femur represents the long bones.

BONE GROWTH AND DEVELOPMENT

Bone growth begins early in fetal development, and living bone is continually changing in composition and structure during the life span. Many of these changes represent normal growth and maturation of bone.

Longitudinal Growth

Longitudinal growth of a bone occurs at the epiphyses, or epiphyseal plates (Figure 3). The epiphyses are cartilaginous discs found near the ends of the long bones. The diaphysis (central) side of each epiphysis continually produces new bone cells. During or shortly following adolescence, the plate disappears and the bone fuses, terminating longitudinal growth. Most epiphyses close around age 18, although some may be present until about age 25.

Figure 3: Epiphyseal plates are the sites of longitudinal growth in immature bone.

Circumferential Growth

Long bones grow in diameter throughout most of the life span, although the most rapid bone growth occurs before adulthood. The internal layer of the **periosteum (double-layered membrane covering bone; muscle tendons attach to the outside layer, and the internal layer is a site of osteoblast activity**) builds concentric layers of new bone tissue on top of existing ones. At the same time, bone is resorbed or eliminated around the circumference of the medullary cavity, so that the diameter of the cavity is continually enlarged. This occurs in such a way that both bending stresses and torsional stresses on the bones remain relatively constant.

These changes in bone size and shape are the work of specialized cells called **osteoblasts (specialized bone cells that build new bone tissue)** and **osteoclasts (specialized bone cells that resorb bone tissue)**, which respectively form and resorb, bone tissue. In healthy adult bone, the activity of osteoblasts and osteoclasts is largely balanced.

Adult Bone Development

There is a progressive loss of collagen and increase in bone brittleness with aging. Thus, the bones of children are more pliable than the bones of adults. Bone mineral normally accumulates throughout childhood and adolescence, reaching a peak at about age 25–28 in women and age 30–35 in men. Following this peak, researchers disagree as to the length of time that bone density remains constant. However, an age-related, progressive decline in bone density and bone strength in both men and women may begin as soon as the early twenties. **This involves a progressive diminishment in the mechanical properties and general toughness of bone, with increasing loss of bone substance and increasing porosity. Trabecular bone is particularly affected, with progressive disconnection and disintegration of trabeculae compromising the integrity of the bone's structure and seriously diminishing bone strength.** These changes are much more pronounced in women than in men, however. **In women, there is a notable decrease in both volume and density of cortical bone, and a decrease in the density of trabecular bone with aging**. Approximately 0.5–1.0% of bone mass is lost each year, until women reach about age 50 or menopause. Following menopause, there appears to be an increased rate of bone loss, with values as high as 6.5% per year reported during the first five to eight years (36). Although similar changes occur in men, they do not become significant

before a more advanced age. **Women at all ages tend to have smaller bones and less cortical bone area than do men, although volumetric bone mineral density is similar for both genders**.

BONE RESPONSE TO STRESS

Other changes that occur in living bone throughout the life span are unrelated to normal growth and development. Bone responds dynamically to the presence or absence of different forces with changes in size, shape, and density. This phenomenon was originally described by the German scientist **Julius Wolff** in 1892:

"The form of a bone being given, the bone elements place or displace themselves in the direction of functional forces and increase or decrease their mass to reflect the amount of the functional forces"

Bone Modeling and Remodeling

According to Wolff's law, the densities and, to a much lesser extent, the shapes and sizes of the bones of a given human being are a function of the magnitude and direction of the mechanical stresses that act on the bones. Dynamic mechanical loading causes bones to deform or strain, with larger loads producing higher levels of strain. These strains are translated into changes in bone shape and strength through a process known as remodeling. **Remodeling involves resorption of fatigue-damaged older bone and subsequent formation of new bone. Bone modeling is the term given to formation of new bone that is not preceded by resorption, and is the process by which immature bones grow.**

Adult bones gain or lose mass in accordance with Wolff's law. When strain on a bone exceeds a certain threshold, new bone is laid down at the strain sites, and overall bone mass and density are increased. When strain magnitudes stay below a lower threshold, bone remodeling occurs, with bone removed close to the marrow. Strain magnitudes in between these two thresholds occur in what is termed the "lazy zone" and do not trigger bone adaptation. Remodeling can occur in either "conservation mode," with no change in bone mass, or "disuse mode," with a net loss of bone mass characterized by an enlarged marrow cavity and thinned cortex. Bone is a very dynamic tissue, with the modeling and remodeling processes continuously acting to increase, decrease, or reshape bone.

Thus, bone mineralization and bone strength in both children and adults are a function of stresses producing strains on the skeleton. Since body weight provides the most constant mechanical stress to bones, bone mineral density generally parallels body weight, with heavier individuals having bones that are more massive. Adults who gain or lose weight tend to also gain or lose bone mineral density. However, a given individual's physical activity profile, diet, lifestyle, and genetics can also dramatically influence bone density. Factors such as lean body mass, muscle strength, and regular participation in weight bearing exercise have been shown to exert stronger influences on bone density than weight, height, and race. Dynamic loading during participation in gymnastics has been shown to affect bone size and strength more than muscle mass. Even in young, nonathletic children, bone appears to remodel in response to the presence or absence of physical activity.

The malleability of bone is dramatically exemplified by the case of an infant who was born in normal physical condition but missing one tibia, the major

weight-bearing bone of the lower extremity. After the child was walking for a time, X-rays revealed that modeling of the fibula in the abnormal leg had occurred to the extent that it could not be distinguished from the tibia of the other leg.

Another interesting case is that of a construction worker who had lost all but the fifth finger of one hand in a war injury. After 32 years, the metacarpal and phalanx of the remaining finger had been modeled to resemble the third finger of the other hand.

Mechanical Properties of Bone

Whereas most soft tissues (e.g., skin, tendons, arteries, lung tissue, myocardium) exhibit nonlinear material behaviors over finite (large) strains, teeth and bones tend to exhibit a linearly elastic behavior over small strains. Hooke's law is thus applicable and the associated stress analysis is easier than that for soft tissues. Therefore, let us consider bone in some detail.

According to Dorland's Medical Dictionary, bone is the hard form of connective tissue that constitutes the majority of the skeleton of most vertebrates; it consists of an organic component (the cells and matrix) and an inorganic, or mineral component; the matrix contains a framework of collagen fibers and is impregnated with the mineral component, chiefly calcium phosphate (85 percent) and calcium carbonate (10 percent).

Specifically, the type I collagen fibers tend to be organized in layers, locally parallel within a layer with the orientation varying approximately 90 from layer to layer. This layering may suggest a local transverse isotropy with the preferred direction changing from layer to layer or, more grossly, an overall orthotropic behavior at each point. Whereas the collagen endows bone with

its tensile stiffness, the embedded calcium endows it with a high compressive stiffness.

Two primary cell types within mature bone are responsible for growth and remodeling: the osteoblasts, which secrete bone matrix, and the osteoclasts, which degrade it. These cells thus allow for a continuous turnover of the matrix material (Alberts et al. 2008) (i.e., a continuous maintenance or, in times of altered loading, a mechanism for adaptation). It is for this reason that bedridden patients and astronauts each suffer bone atrophy, particularly in the legs and arms, whereas athletes may have a buildup of bone. Indeed, it was the work of Meyer, Wolff, and Roux in the late nineteenth century on bone that revealed a strong relationship between mechanical factors and biological growth and remodeling. For more recent work in this important and active research area, see Mow and Hayes (1991), Cowin (2001) or Carter and Beaupre´ (2001).

Bone typically consists of two to three layers, depending on its location within the body: an outer, dense cortical layer, a middle trabecular layer, and, in certain regions, an innermost layer of bone marrow. It is the marrow that forms blood cells. Bone thus serves several important, diverse mechanical and physiological functions: It supports and protects soft tissues and organs and it serves as a primary store of calcium and producer of blood cells.

TABLE 2.1: Physical properties of bone

Variable	Bone	Value
Density	Cortical	1,700–2,000 kg/m^3
	Lumbar vertebra	600–1,000 kg/m^3
Mineral content	All	60–70 %
Elastic modulus	Femur	5–28 GPa
Tensile strength	Femur	80–150 MPa
	Tibia	95–140 MPa
Compressive strength	Femur	131–224 MPa
	Tibia	106–200 MPa

The 206 distinct bones that constitute the adult human skeleton are often classified into one of five groups according to their shape (see Table 1.2 from Nigg and Herzog (1994)): long (e.g., femur), short (e.g., carpal), flat (e.g., sternum), irregular (pubis), and sesamoid (e.g., patella). Table 2.1 lists some of the physical properties of bone. In particular, the order of magnitude of the stiffness (Young's modulus) is ~16 GPa for cortical bone and ~1 GPa for cancellous bone. As noted earlier, however, bone does not exhibit an isotropic behavior.