Physics of the skeleton

Bones

Bone has at least six functions in the body:

1. Support.
2. Locomotion.
3. Protection of various organs.
4. Storage of chemicals.
5. Nourishment.
6. Sound transmission (in the middle ear).

Composition of bone

The detailed chemical composition of bone is given in table 1. Note the large percentage of calcium (Ca) in bone. Since calcium has a much heavier nucleus than most elements of the body, it absorbs x-rays much better than the surrounding soft tissue. This is the reason x-rays show bones so well.

Bone consists of two quite different materials plus water:

1. Collagen is the major organic fraction, which is about 40% of the weight of solid bone and 60% of its volume.
2. Bone mineral is the so-called inorganic component of bone, which is about 60% of the weight of the bone 40% of its volume.

Table 1 Composition of Compact Bone

Element	Compact Bone, Femur (%)
H	3.4
C	15.5
N	4.0
O	44.0
Mg	0.2
P	10.2
S	0.3
Ca	22.2
Miscellaneous	0.2

Bone remodeling

Continuous process of destroying old bone and building new bone by specialized bone cells.

Trabecular bone (Fig. 1):

1. **1.** It made up of thin thread.
2. **2.** It predominately found in the ends of the long bones.
3. **3.** It is considerably weak due to the reduced amount of bone in a given volume.

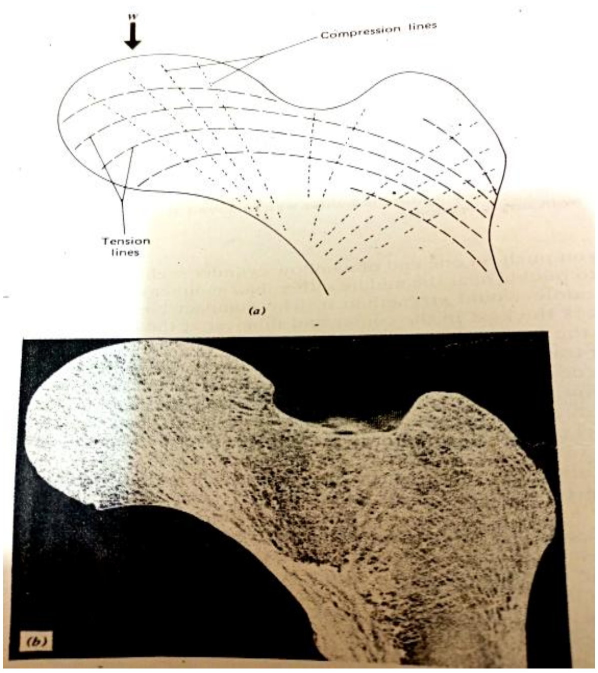

Figure 1

Compact bone (Fig. 2):

1. **1.** It made up of thick plates.
2. **2.** It predominately found in the central shaft of the bone.
3. **3.** It is considerably strong due to the large amount of bone in a given volume.

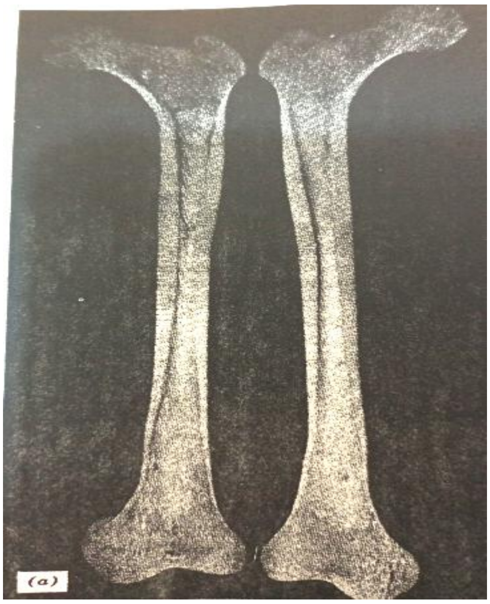

Figure 2

Stress-strain curve

All materials change in length when placed under tension or compression. When a sample of fresh bone is placed in a special instrument for measuring the elongation under tension a curve similar to that in Fig. 3 is obtained. The strain ΔL/L increases linearly at first, indicating that it is proportional to the stress (F/A) – Hooke's law. As the force increases the length increases more rapidly, and the bone breaks at stress of about 120 N/mm^2 . The ratio of stress to strain in the initial linear portion is Young's modulus Y. That is,

$$Y = \frac{LF}{A\Delta L} \dots\dots\dots\dots\dots (1)$$

Young's moduli for bone and a few common structural materials are given in table 2. It is usually of more interest to calculate the change in length ΔL for a given force F. Equation 1 can be rewritten as

$$\Delta L = \frac{LF}{AY} \dots\dots\dots\dots\dots (2)$$

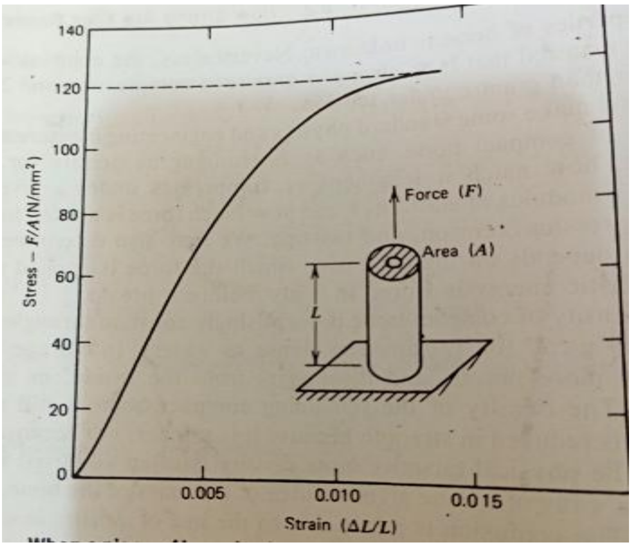

Figure 3

Table 2 Strengths of Bone and Other Common Materials

Material	Compressive Breaking Stress (N/mm^2)	Tensile Breaking Stress (N/mm^2)	Young's Modulus of Elasticity ($\times 10^2\ N/mm^2$)
Hard steel	552	827	2070
Rubber	—	2.1	0.010
Granite	145	4.8	517
Concrete	21	2.1	165
Oak	59	117	110
Porcelain	552	55	—
Compact bone	170	120	179
Trabecular bone	2.2	—	0.76

Equations 1 and 2 are valid for both tension and compression (see example 1).

Example 1

Assume a leg has a 1.2 m shaft of bone with an average cross-sectional area of 3 cm^2. What is the amount of shortening when all of the body weight of 700 N is supported on this leg?

$$\Delta L = \frac{LF}{AY} = \frac{(1.2m)(7 \times 10^2 N)}{(3 \times 10^{-4} m^2)(1.8 \times 10^{10}\ N/m^2)} = 1.5 \times 10^{-4} m = 0.15\ mm$$

Bone joints

There are two major diseases that affect the joints-rheumatoid arthritis, which results in overproduction of synovial fluid in the joint and commonly causes swollen joints, and osteoarthrosis, a disease of the joint itself.

The main components of a joint are shown in Fig. 4. The synovial membrane encases the joint and retains the lubricating synovial fluid. The surfaces of the joint are articular cartilage, a smooth, somewhat rubbery material that is attached to solid bone. A disease that involves the synovial fluid, such as rheumatoid arthritis, quickly affects the joint itself.

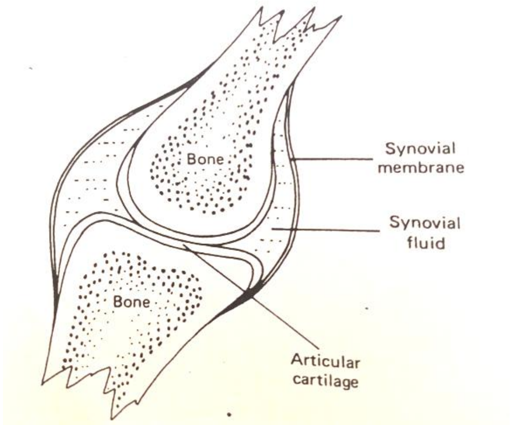

Figure 4

The lubricating properties of a fluid depend on its viscosity; thin oil is less viscous and a better lubricant than thick oil. The viscosity of synovial fluid decreases under the large shear stresses found in the joint. The good lubricating properties of synovial fluid are thought to be due to the presence of hyaluronic acid and mucopolysaccharides (molecular weight, ~ 500,000) that deform under load.

The coefficient of frication of bone joints is difficult to measure under the usual laboratory conditions. Little, Freeman, and Swanson described the arrangement shown in Fig. 5. A normal hip joint from a fresh cadaver was mounted upside down with heavy weights pressing the head of the femur into its socket. The weight on the joint could be varied to study the effects of different loads. The whole unit acted like a pendulum with the joint serving as the pivot. From the rate of decrease of the amplitude with time, the coefficient of frication was calculated. The coefficient of friction was found to be independent of the load from 89 to 890 N and independent of the magnitude of the oscillations. It was concluded that fat in the cartilage helps to reduce the coefficient of friction. For all healthy joints studied, the coefficient of friction was found to be less than 0.01, much less than that of a steel blade on ice-0.03.

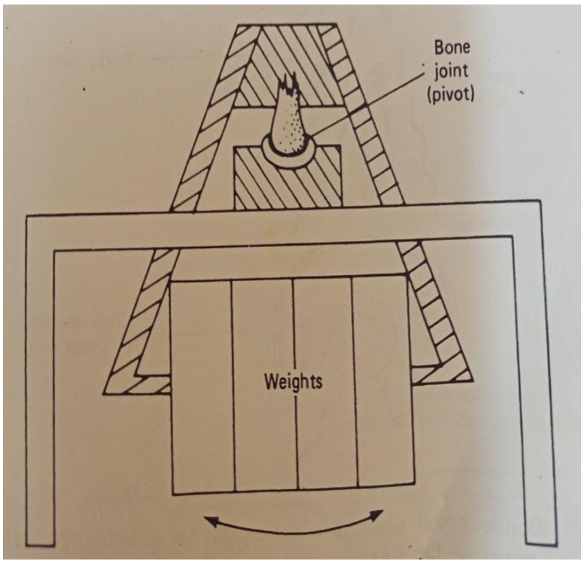

Figure 5