Mechanics of bones

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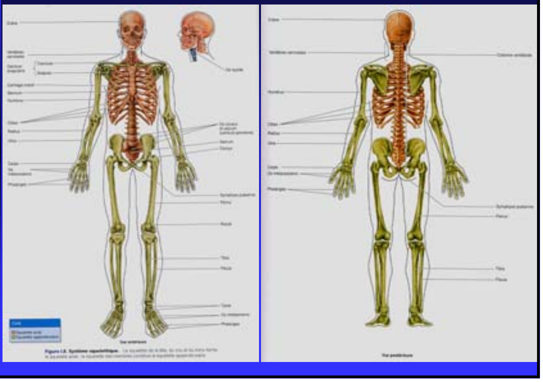
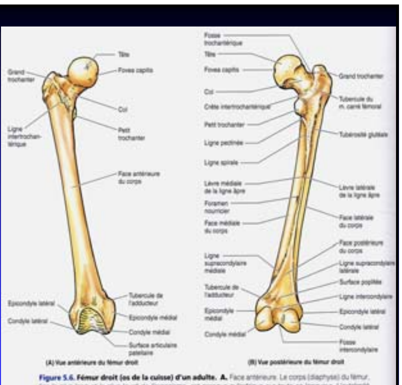
Skeletal system



Femur



(A) Vue antérieure du fémur droit **(B) Vue postérieure du fémur droit**

Figure 5.6. Fémur droit (os de la cuisse) d'un adulte. A. Face antérieure. Le corps (diaphyse) du fémur, l'os le plus long et le plus lourd de l'organisme, est presque cylindrique sur toute sa longueur. L'extrémité proximale du fémur comprend une tête arrondie (sphérique), un col assez court et deux grosses saillies osseuses : le grand et le petit trochanters. Le col est séparé de la diaphyse par la ligne intertrochantérique. L'extrémité distale du fémur est massive et comprend les condyles médial et latéral. **B.** Face postérieure. La ligne âpre correspond au bord postérieur saillant du tiers médian de la diaphyse, elle est délimitée par deux lèvres, l'une médiale et l'autre latérale. On reconnaît également le foramen nourricier creusé dans le corps à proximité de la ligne âpre.

Example of the long bone

- 2 types of materials :
  - Cortical bone
  - Cancellous bone (trabecular bone)
  - Orientation of the bone cells according to the stresses

Figure I.9. Coupes transversales de l'humérus (os du bras). Le corps ou diaphyse d'un os vivant est un cylindre d'os compact ; la cavité médullaire contient de la moelle osseuse rouge ou jaune ou une combinaison des deux.

Structure of the cancellous bone

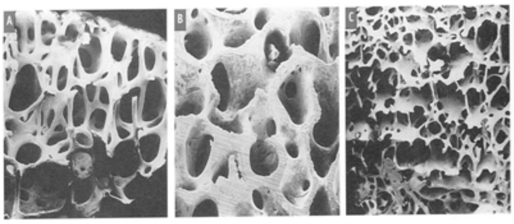
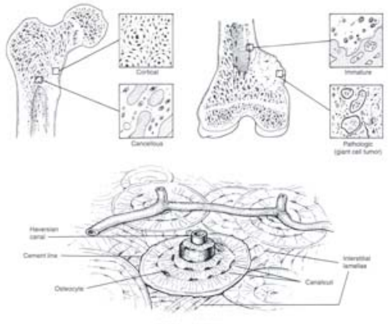


Figure 32

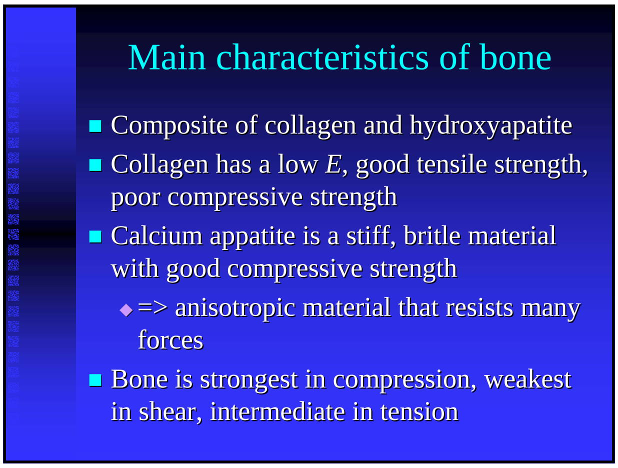
Scanning electron micrographs showing the various basic cellular structures of human trabecular bone: **A,** The rod-rod basic cellular structure, from the femoral head; **B,** The more dense plate-plate cellular structure, also from the femoral head; **C,** The plate-rod cellular structure, from the femoral condyle. (Reproduced with permission from Gibson JL: The mechanical behavior of cancellous bone. *J Biomech* 1985;18:317–328.)

Structure of cortical bone



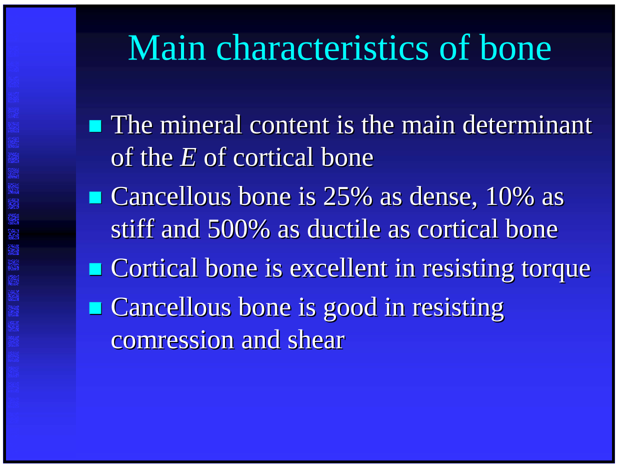
CORTICAL BONE DETAIL

FIGURE 1-1 ■ Types of bone. Cortical bone consists of tightly packed osteons. Cancellous bone consists of a meshwork of trabeculae. In immature bone, there is unmineralized osteoid lining the immature trabeculae. In pathologic bone, atypical osteoblasts and architectural disorganization are seen. (From Brinker, M.R., and Miller, M.D.: Fundamentals of Orthopaedics. Philadelphia, WB Saunders, 1999, p. 2.)



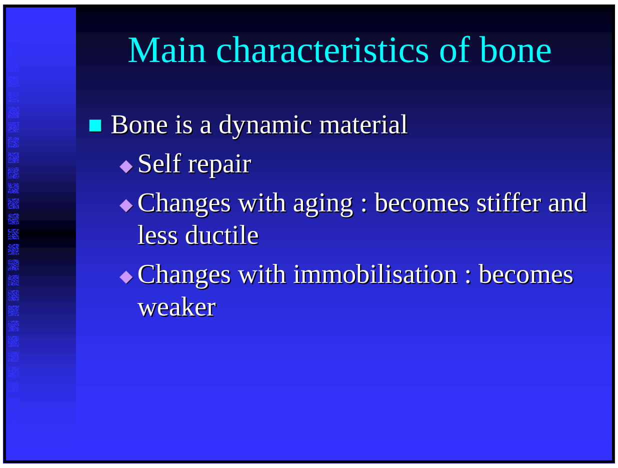
Main characteristics of bone

- Composite of collagen and hydroxyapatite
- Collagen has a low *E*, good tensile strength, poor compressive strength
- Calcium appatite is a stiff, britle material with good compressive strength
  - => anisotropic material that resists many forces
- Bone is strongest in compression, weakest in shear, intermediate in tension



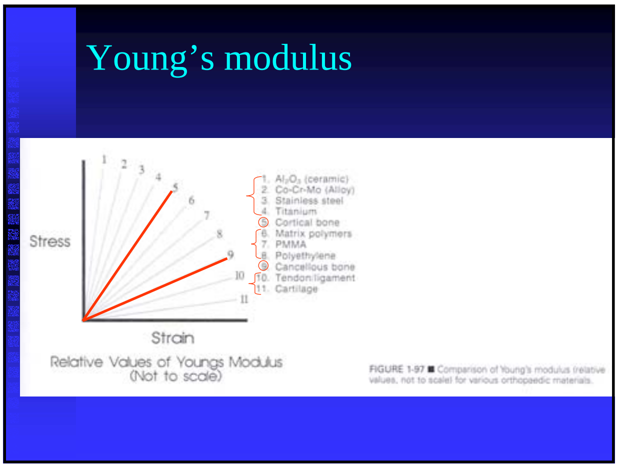
Main characteristics of bone

- The mineral content is the main determinant of the *E* of cortical bone
- Cancellous bone is 25% as dense, 10% as stiff and 500% as ductile as cortical bone
- Cortical bone is excellent in resisting torque
- Cancellous bone is good in resisting comression and shear



Main characteristics of bone

- Bone is a dynamic material
  - Self repair
  - Changes with aging : becomes stiffer and less ductile
  - Changes with immobilisation : becomes weaker

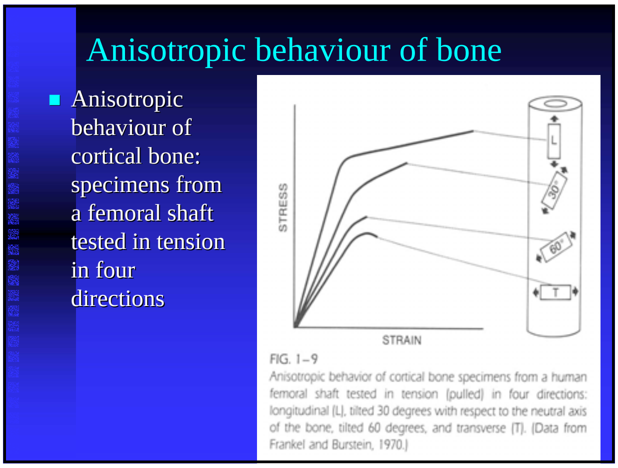


Young’s modulus

1. Al_2O_3 (ceramic)
2. Co-Cr-Mo (Alloy)
3. Stainless steel
4. Titanium
5. Cortical bone
6. Matrix polymers
7. PMMA
8. Polyethylene
9. Cancellous bone
10. Tendon/ligament
11. Cartilage

Relative Values of Youngs Modulus
(Not to scale)

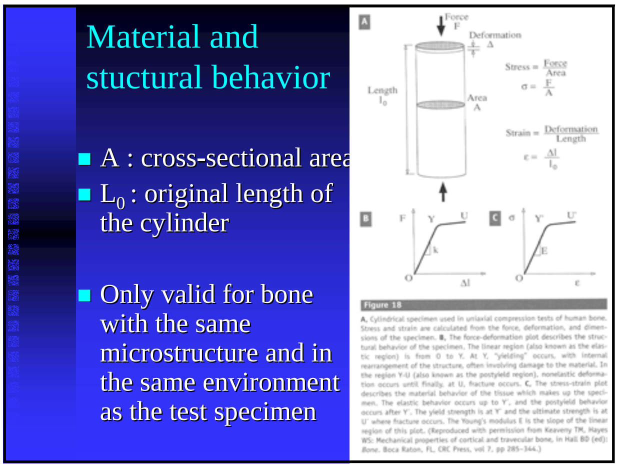
FIGURE 1-97 ■ Comparison of Young's modulus (relative values, not to scale) for various orthopaedic materials.



Anisotropic behaviour of bone

- Anisotropic behaviour of cortical bone: specimens from a femoral shaft tested in tension in four directions

FIG. 1–9
Anisotropic behavior of cortical bone specimens from a human femoral shaft tested in tension (pulled) in four directions: longitudinal (L), tilted 30 degrees with respect to the neutral axis of the bone, tilted 60 degrees, and transverse (T). (Data from Frankel and Burstein, 1970.)



Material and stuctural behavior

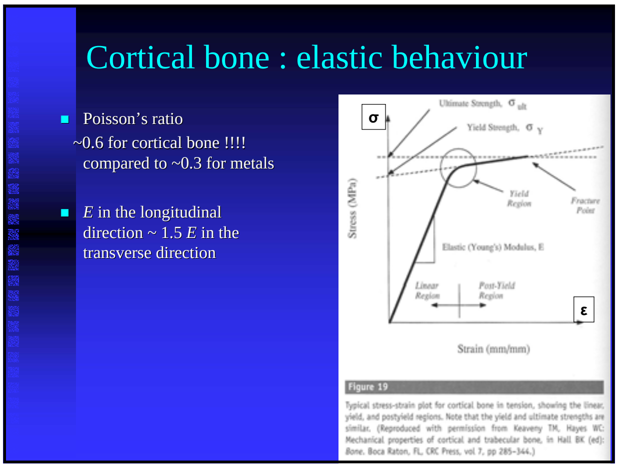
- A : cross-sectional area
- L_0 : original length of the cylinder
- Only valid for bone with the same microstructure and in the same environment as the test specimen

$$\text{Stress} = \frac{\text{Force}}{\text{Area}} \qquad \sigma = \frac{F}{A}$$

$$\text{Strain} = \frac{\text{Deformation}}{\text{Length}} \qquad \varepsilon = \frac{\Delta l}{l_0}$$

Figure 18

A, Cylindrical specimen used in uniaxial compression tests of human bone. Stress and strain are calculated from the force, deformation, and dimensions of the specimen. **B,** The force-deformation plot describes the structural behavior of the specimen. The linear region (also known as the elastic region) is from 0 to Y. At Y, "yielding" occurs, with internal rearrangement of the structure, often involving damage to the material. In the region Y-U (also known as the postyield region), nonelastic deformation occurs until finally, at U, fracture occurs. **C,** The stress-strain plot describes the material behavior of the tissue which makes up the specimen. The elastic behavior occurs up to Y', and the postyield behavior occurs after Y'. The yield strength is at Y' and the ultimate strength is at U' where fracture occurs. The Young's modulus E is the slope of the linear region of this plot. (Reproduced with permission from Keaveny TM, Hayes WS: Mechanical properties of cortical and travecular bone. In Hall BD (ed): *Bone*. Boca Raton, FL, CRC Press, vol 7, pp 285–344.)

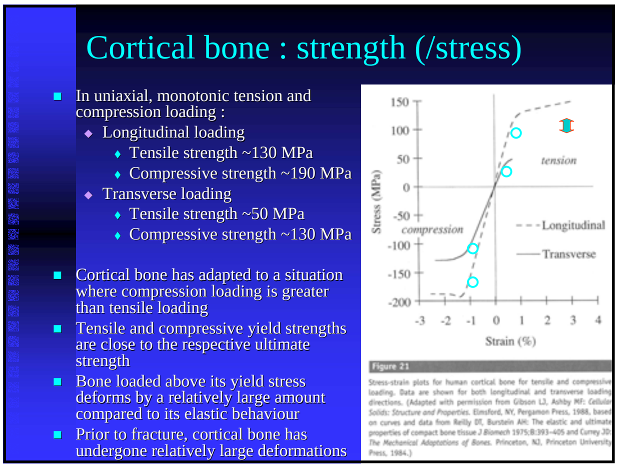


Cortical bone : elastic behaviour

- Poisson's ratio
  ~0.6 for cortical bone !!!!
  compared to ~0.3 for metals
- *E* in the longitudinal direction ~ 1.5 *E* in the transverse direction

Figure 19

Typical stress-strain plot for cortical bone in tension, showing the linear, yield, and postyield regions. Note that the yield and ultimate strengths are similar. (Reproduced with permission from Keaveny TM, Hayes WC: Mechanical properties of cortical and trabecular bone, in Hall BK (ed): *Bone*. Boca Raton, FL, CRC Press, vol 7, pp 285–344.)

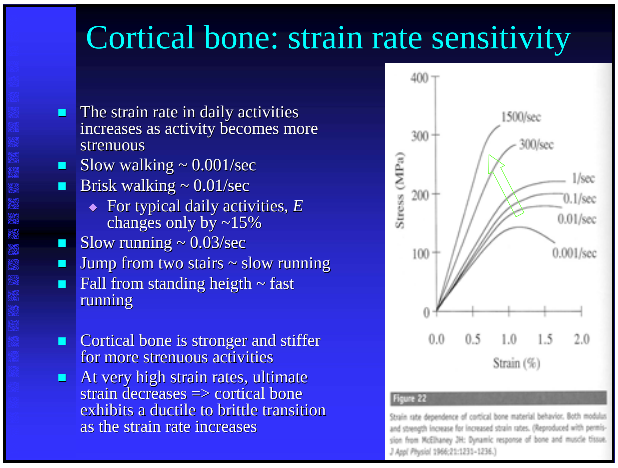


Cortical bone : strength (/stress)

- In uniaxial, monotonic tension and compression loading :
  - Longitudinal loading
    - Tensile strength ~130 MPa
    - Compressive strength ~190 MPa
  - Transverse loading
    - Tensile strength ~50 MPa
    - Compressive strength ~130 MPa
- Cortical bone has adapted to a situation where compression loading is greater than tensile loading
- Tensile and compressive yield strengths are close to the respective ultimate strength
- Bone loaded above its yield stress deforms by a relatively large amount compared to its elastic behaviour
- Prior to fracture, cortical bone has undergone relatively large deformations

Figure 21

Stress-strain plots for human cortical bone for tensile and compressive loading. Data are shown for both longitudinal and transverse loading directions. (Adapted with permission from Gibson LJ, Ashby MF: *Cellular Solids: Structure and Properties*. Elmsford, NY, Pergamon Press, 1988, based on curves and data from Reilly DT, Burstein AH: The elastic and ultimate properties of compact bone tissue *J Biomech* 1975;8:393–405 and Currey JD: *The Mechanical Adaptations of Bones*. Princeton, NJ, Princeton University Press, 1984.)



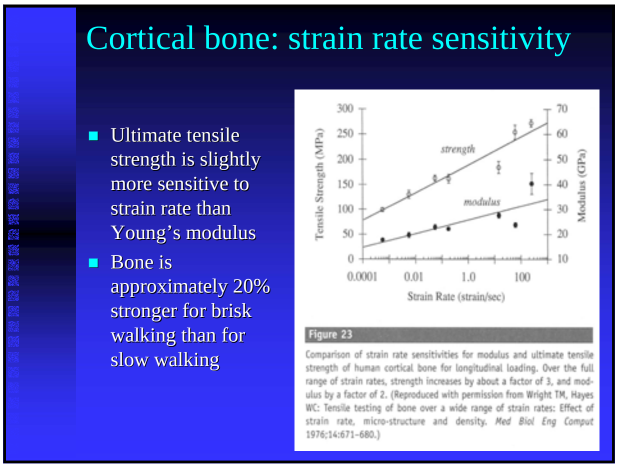
Cortical bone: strain rate sensitivity

- The strain rate in daily activities increases as activity becomes more strenuous
- Slow walking ~ 0.001/sec
- Brisk walking ~ 0.01/sec
  - For typical daily activities, *E* changes only by ~15%
- Slow running ~ 0.03/sec
- Jump from two stairs ~ slow running
- Fall from standing heigth ~ fast running

- Cortical bone is stronger and stiffer for more strenuous activities
- At very high strain rates, ultimate strain decreases => cortical bone exhibits a ductile to brittle transition as the strain rate increases

Figure 22

Strain rate dependence of cortical bone material behavior. Both modulus and strength increase for increased strain rates. (Reproduced with permission from McElhaney JH: Dynamic response of bone and muscle tissue. *J Appl Physiol* 1966;21:1231–1236.)

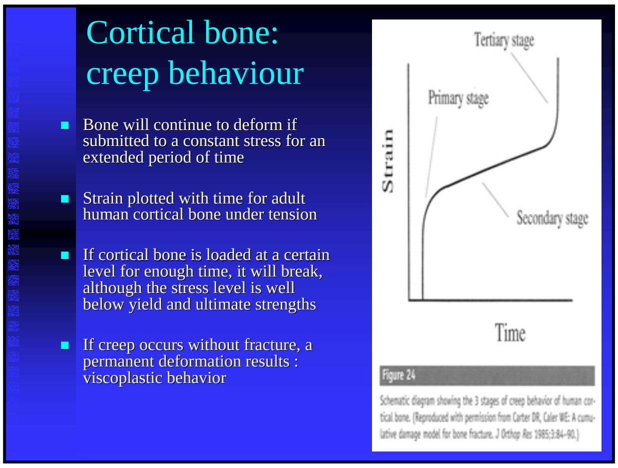


Cortical bone: strain rate sensitivity

- Ultimate tensile strength is slightly more sensitive to strain rate than Young's modulus
- Bone is approximately 20% stronger for brisk walking than for slow walking

Figure 23

Comparison of strain rate sensitivities for modulus and ultimate tensile strength of human cortical bone for longitudinal loading. Over the full range of strain rates, strength increases by about a factor of 3, and modulus by a factor of 2. (Reproduced with permission from Wright TM, Hayes WC: Tensile testing of bone over a wide range of strain rates: Effect of strain rate, micro-structure and density. *Med Biol Eng Comput* 1976;14:671–680.)

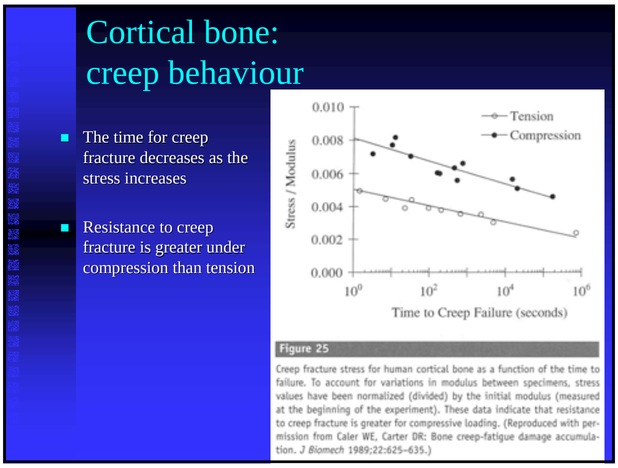


Cortical bone: creep behaviour

- Bone will continue to deform if submitted to a constant stress for an extended period of time
- Strain plotted with time for adult human cortical bone under tension
- If cortical bone is loaded at a certain level for enough time, it will break, although the stress level is well below yield and ultimate strengths
- If creep occurs without fracture, a permanent deformation results : viscoplastic behavior

Figure 24

Schematic diagram showing the 3 stages of creep behavior of human cortical bone. (Reproduced with permission from Carter DR, Caler WE: A cumulative damage model for bone fracture. *J Orthop Res* 1985;3:84–90.)

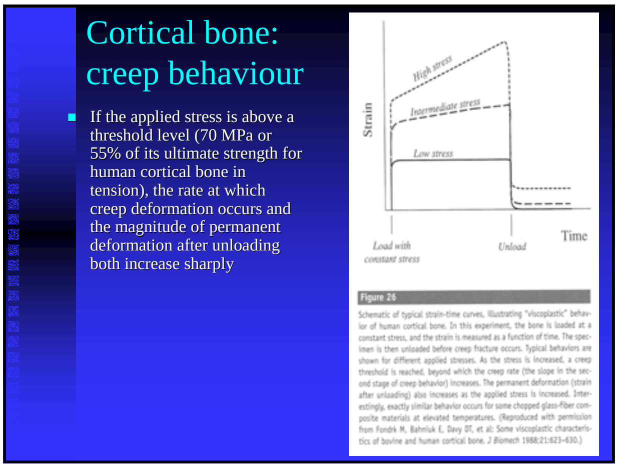


Cortical bone: creep behaviour

- The time for creep fracture decreases as the stress increases
- Resistance to creep fracture is greater under compression than tension

Figure 25

Creep fracture stress for human cortical bone as a function of the time to failure. To account for variations in modulus between specimens, stress values have been normalized (divided) by the initial modulus (measured at the beginning of the experiment). These data indicate that resistance to creep fracture is greater for compressive loading. (Reproduced with permission from Caler WE, Carter DR: Bone creep-fatigue damage accumulation. *J Biomech* 1989;22:625–635.)

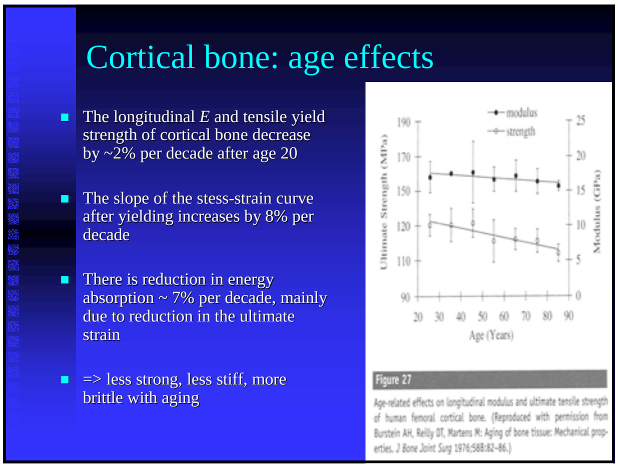


Cortical bone: creep behaviour

- If the applied stress is above a threshold level (70 MPa or 55% of its ultimate strength for human cortical bone in tension), the rate at which creep deformation occurs and the magnitude of permanent deformation after unloading both increase sharply

Figure 26

Schematic of typical strain-time curves, illustrating "viscoplastic" behavior of human cortical bone. In this experiment, the bone is loaded at a constant stress, and the strain is measured as a function of time. The specimen is then unloaded before creep fracture occurs. Typical behaviors are shown for different applied stresses. As the stress is increased, a creep threshold is reached, beyond which the creep rate (the slope in the second stage of creep behavior) increases. The permanent deformation (strain after unloading) also increases as the applied stress is increased. Interestingly, exactly similar behavior occurs for some chopped glass-fiber composite materials at elevated temperatures. (Reproduced with permission from Fondrk M, Bahniuk E, Davy DT, et al: Some viscoplastic characteristics of bovine and human cortical bone. *J Biomech* 1988;21:623–630.)

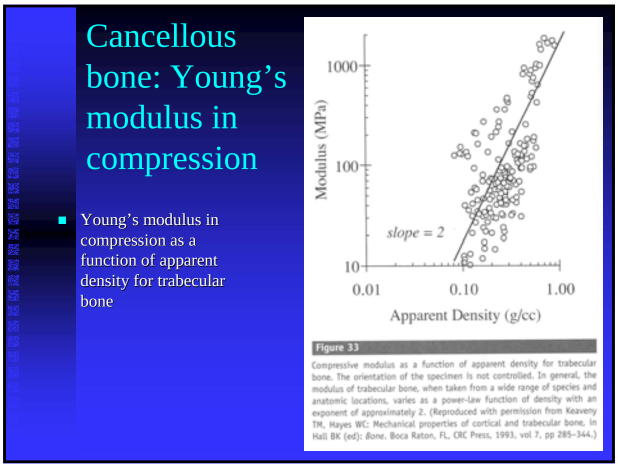


Cortical bone: age effects

- The longitudinal *E* and tensile yield strength of cortical bone decrease by ~2% per decade after age 20
- The slope of the stess-strain curve after yielding increases by 8% per decade
- There is reduction in energy absorption ~ 7% per decade, mainly due to reduction in the ultimate strain
- => less strong, less stiff, more brittle with aging

Figure 27

Age-related effects on longitudinal modulus and ultimate tensile strength of human femoral cortical bone. (Reproduced with permission from Burstein AH, Reilly DT, Martens M: Aging of bone tissue: Mechanical properties. *J Bone Joint Surg* 1976;58B:82–86.)

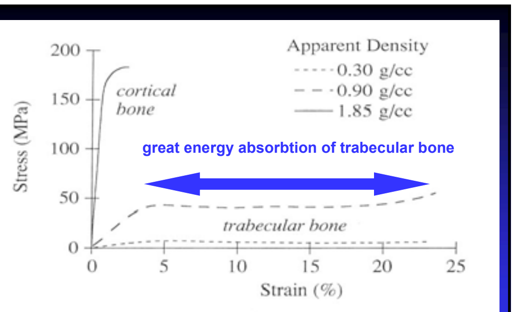


Cancellous bone: Young's modulus in compression

- Young's modulus in compression as a function of apparent density for trabecular bone

Figure 33

Compressive modulus as a function of apparent density for trabecular bone. The orientation of the specimen is not controlled. In general, the modulus of trabecular bone, when taken from a wide range of species and anatomic locations, varies as a power-law function of density with an exponent of approximately 2. (Reproduced with permission from Keaveny TM, Hayes WC: Mechanical properties of cortical and trabecular bone, in Hall BK (ed): *Bone*. Boca Raton, FL, CRC Press, 1993, vol 7, pp 285–344.)



great energy absorbtion of trabecular bone

Figure 35

Example of typical compressive stress-strain behaviors of trabecular and cortical bone for different apparent densities. (Reproduced with permission from Keaveny TM, Hayes WC: Mechanical properties of cortical and trabecular bone, in Hall BK (ed): *Bone*. Boca Raton, FL, CRC Press, 1993, vol 7, pp 285–344.)

Cancellous bone: ultimate strength in compression

- Ultimate strength in compression as a function of apparent density for trabecular bone

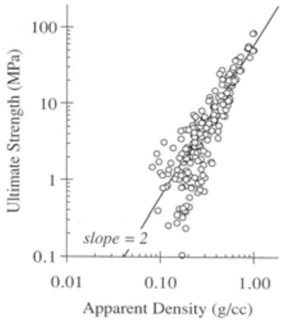


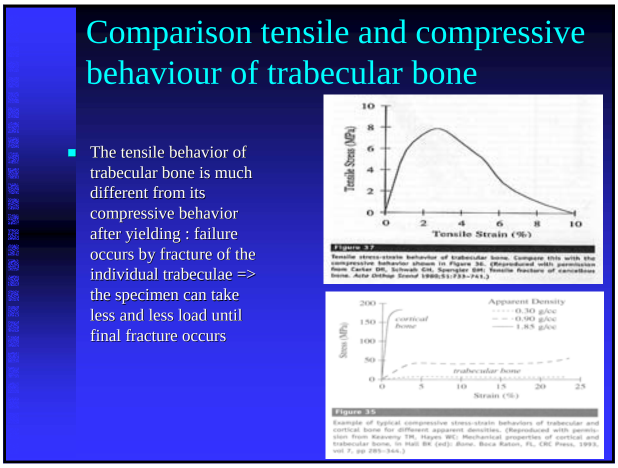
Figure 36

Ultimate compressive strength as a function of apparent density for trabecular bone. In general, compressive strength varies as a power-law function of density with an exponent of approximately 2. (Reproduced with permission from Keaveny TM, Hayes WC: Mechanical properties of cortical and trabecular bone, in Hall BK (ed): *Bone*. Boca Raton, FL, CRC Press, vol 7 pp 285–344.)

Apparent density / modulus and strength

- The relationships between apparent density and both modulus and strength have important clinical consequences

1. Bone can easily regulate its strength
2. Stiffness can easilly be regulated by adjusting apparent density



Comparison tensile and compressive behaviour of trabecular bone

- The tensile behavior of trabecular bone is much different from its compressive behavior after yielding : failure occurs by fracture of the individual trabeculae => the specimen can take less and less load until final fracture occurs

Figure 37

Tensile stress-strain behavior of trabecular bone. Compare this with the compressive behavior shown in Figure 36. (Reproduced with permission from Carter DR, Schwab GH, Spengler DM: Tensile fracture of cancellous bone. *Acta Orthop Scand* 1980;51:733–741.)

Figure 35

Example of typical compressive stress-strain behaviors of trabecular and cortical bone for different apparent densities. (Reproduced with permission from Keaveny TM, Hayes WC: Mechanical properties of cortical and trabecular bone, in Hall BK (ed): *Bone*. Boca Raton, FL, CRC Press, 1993, vol 7, pp 285–344.)

Age and osteoporosis

- The loss of trabeculae in osteoporosis is more damaging for the overall structural integrity and strength of a trabecular bone structure than thinning of the trabeculae because lamellar new bone can only form on existing surfaces
- Decrease in bone density must be futher analysed as the result of thinning or loss of trabeculae

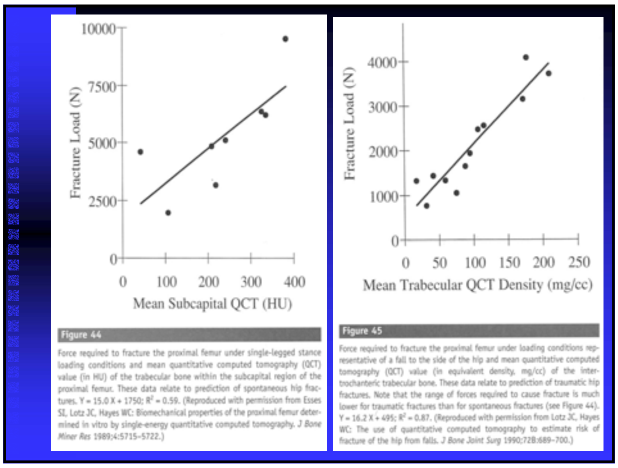


Figure 44

Force required to fracture the proximal femur under single-legged stance loading conditions and mean quantitative computed tomography (QCT) value (in HU) of the trabecular bone within the subcapital region of the proximal femur. These data relate to prediction of spontaneous hip fractures. $Y = 15.0 X + 1750$; $R^2 = 0.59$. (Reproduced with permission from Esses SI, Lotz JC, Hayes WC: Biomechanical properties of the proximal femur determined in vitro by single-energy quantitative computed tomography. *J Bone Miner Res* 1989;4:5715–5722.)

Figure 45

Force required to fracture the proximal femur under loading conditions representative of a fall to the side of the hip and mean quantitative computed tomography (QCT) value (in equivalent density, mg/cc) of the intertrochanteric trabecular bone. These data relate to prediction of traumatic hip fractures. Note that the range of forces required to cause fracture is much lower for traumatic fractures than for spontaneous fractures (see Figure 44). $Y = 16.2 X + 495$; $R^2 = 0.87$. (Reproduced with permission from Lotz JC, Hayes WC: The use of quantitative computed tomography to estimate risk of fracture of the hip from falls. *J Bone Joint Surg* 1990;72B:689–700.)