Trabecular bone

- foam-like structure
- exists at ends of long bones - ends have larger surface area than shafts to reduce stress on cartilage at joints; trabecular bone reduces weight
- also exists in skull, iliac crest (pelvis) - forms sandwich structure - reduces wt.
- also makes up core of vertebrae
- trabecular bone of interest (1) osteoporosis (2) osteoarthritis (3) joint replacement

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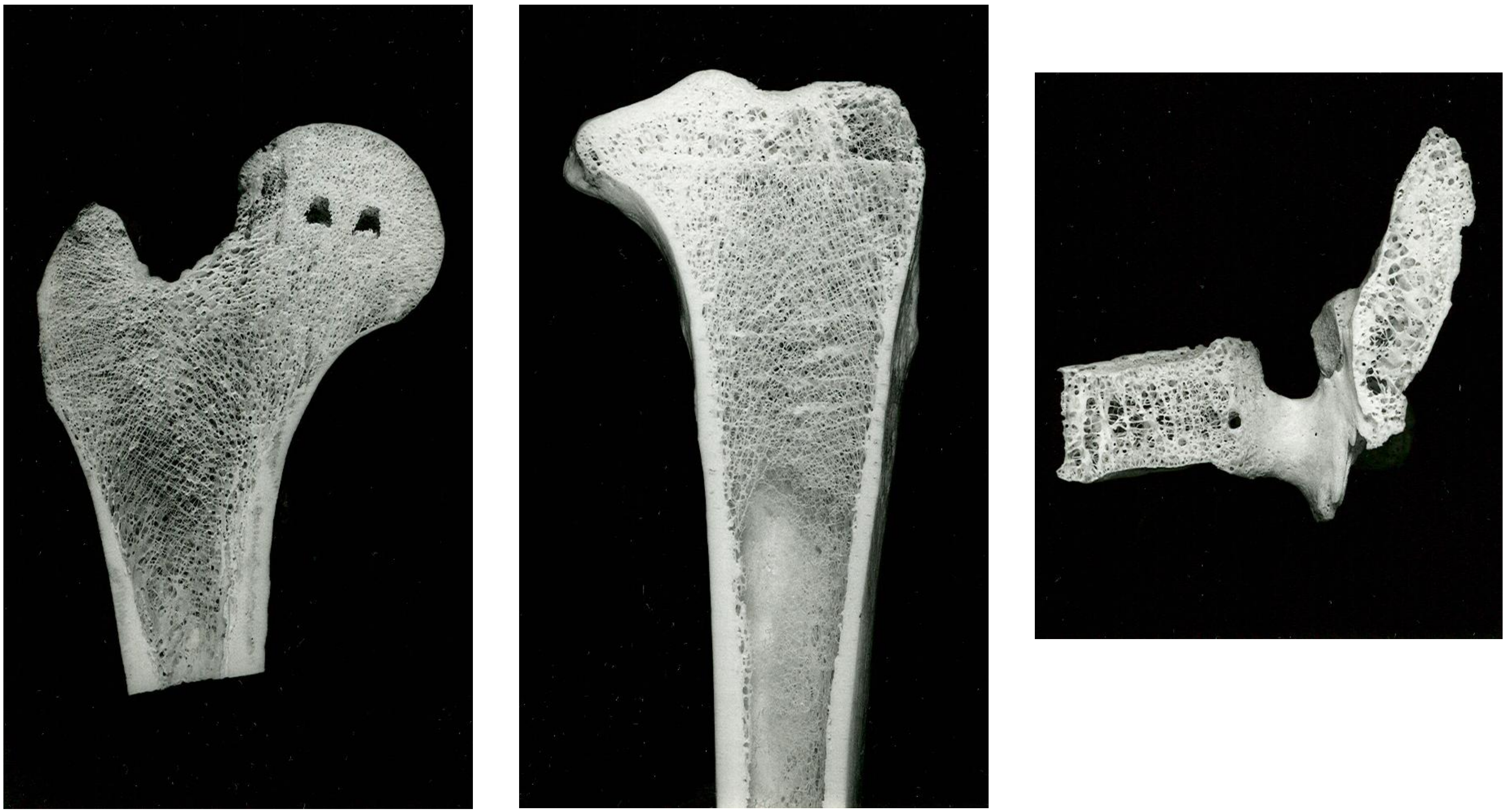
Osteoporosis

- bone mass decreases with age; osteoporosis - extreme bone loss
- Most common fractures : hip (proximal femur)
  vertebrae
- at both sites, most of load carried by trabecular bone
- hip fractures especially serious: 40% of elderly patients (>65 yrs old) die within a year (often due to loss of mobility → pneumonia)
- 300,000 hip fractures/yr in US
- costs $17 billion in 2005

Trabecular bone



Gibson, L. J., and M. F. Ashby. *Cellular Solids: Structure and Properties*. 2nd ed. Cambridge University Press, © 1997. Figures courtesy of Lorna Gibson and Cambridge University Press.

Osteoarthritis

- degradation of cartilage at joints
- stress on cartilage affected by moduli of underlying bone
- cortical bone shell can be thin (e.g. <1 mm)
- mechanical properties of trabecular bone can affect stress distribution on cartilage

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Joint replacements

- if osteoarthritis bad + significant damage to cartilage, may require joint replacement
- cut end of bone off + insert stem of metal replacement into hollow of long section of bone
- metals used: titanium, cobalt-chromium, stainless steel
- bone grows in response to loads on it

  trab. bone: density depends on magnitude of σ
  orientation " " direction of principal stresses

- mismatch in moduli between metal + bone leads to stress shielding

	E (GPa)		E (GPa)
Co - 28Cr - Mo	210	Cortical bone	18
Ti alloys	110	Trab. bone	0.01-2
316 Stainless steel	210		

- after joint replacement, remodelling of remaining bone affected
  - stiffer metal carries more of load, remaining bone carries less
  - bone may resorb - can lead to loosening of prosthesis
  - can cause problems after ~15 yrs.
  - reason surgeons don't like to do joint replacements on younger patients

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Structure of trabecular bone

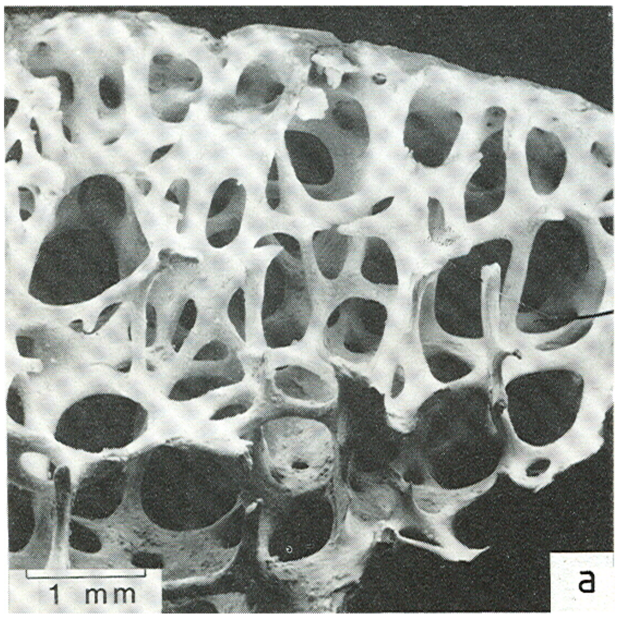
- resembles foam : "trabecula" = little beam (Latin)
- relative density typically 0.05 - 0.50
- low density trab. bone - like open cell foam
- higher density - becomes like perforated plates
- can be highly anisotropic, depending on stress field.

Trabecular Bone Structure

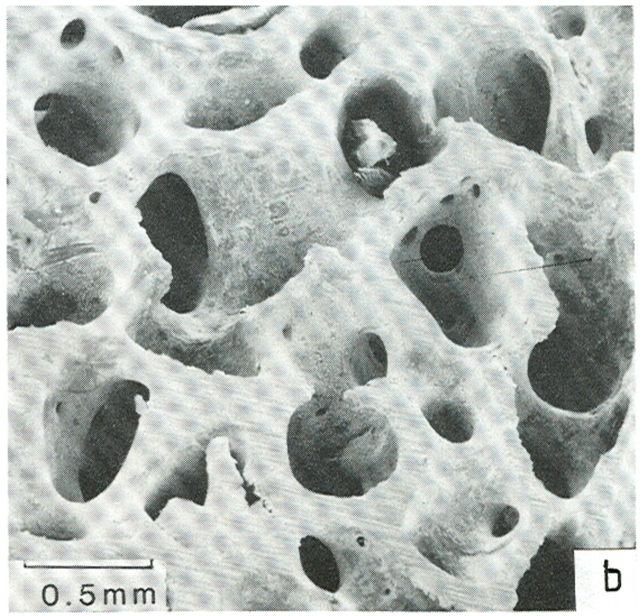
Lumbar spine	Femoral head	Lumbar spine
11% dense	26% dense	6% dense
42 year old male	37 year old male	59 year old male

Ralph Muller, ETH Zurich
Micro-CT images

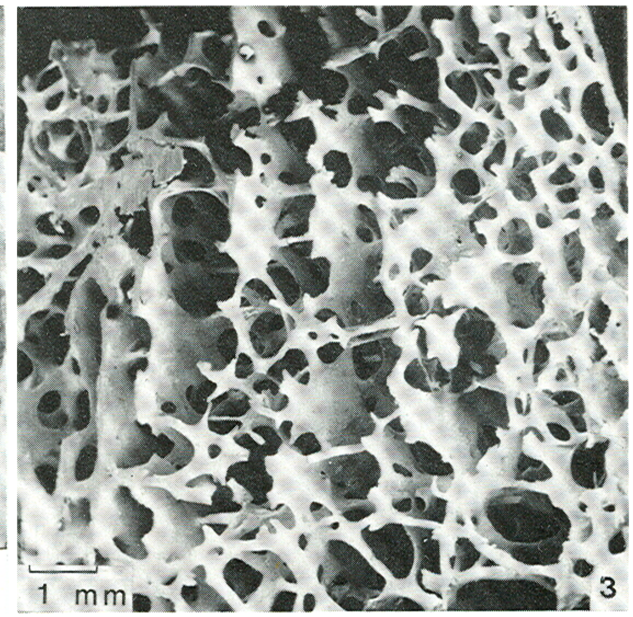
Trabecular Bone Structure



Femoral head



Femoral head



Femoral condyle (knee)

Source: Gibson. L. J. "The Mecahnical Behaviour of Cancellous Bone." *Journal of Biomechanics* 18 (1985): 317-28. Courtesy of Elsevier. Used with permission.

Bone grows in response to loads

- studies on juvenile guinea fowl (Ponzer et al. 2006)
  - (a) running on level treadmill
  - (b) " " inclined " (20°)
  - (c) control - no running.
- measured knee flexion angle at max force on treadmill
- after ~6 wks, sacrificed birds + measured orientation of peak trabecular density (OPTD)

- knee flexion angle changed by 13.7° with incline vs. level treadmill running
- OPTD " " 13.6 " " " " "
- orientation of trabecula changed to match orientation of loading
- video: Concord Field station (Science Friday)

Trabecular architecture and mechanical loading

Figure removed due to copyright restrictions. See Figure 1: Pontzer, H., et al. "Trabecular Bone in the Bird Knee Responds with High Sensitivity to Changes in Load Orientation." *The Journal of Experimental Biology* 209 (2006): 57-65.

Trabecular architecture and mechanical loading

Figure removed due to copyright restrictions. See Figure 7: Pontzer, H., et al. "Trabecular Bone in the Bird Knee Responds with High Sensitivity to Changes in Load Orientation." *The Journal of Experimental Biology* 209 (2006): 57-65.

Video: "Studying Locomotion With Rat Treadmills, Wind Tunnels." March 9, 2012. Science Friday. Accessed November 12, 2014.

Properties of solid in trabeculae

- foam models: require ρ_s, E_s σ_{ys} for the solid
- ultrasonic wave propagation $E_s = 15-18$ GPa
- finite element models of exact trabecular architecture from micro-CT scans
  if do uniaxial compression test - can measure E^* + back calculate E_s
  $E_s = 18$ GPa
- find properties of trabeculae (solid) similar to cortical bone

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$\rho_s = 1800$ kg/m^3

$E_s = 18$ GPa

$\sigma_{ys} = 182$ MPa (comp)

$\sigma_{ys} = 115$ MPa (tension)

Mechanical Properties of Trabecular Bone

- compressive stress-strain curve - characteristic shape
- mechanisms of deformation + failure
  - usually bending followed by inelastic buckling
  - sometimes, if trabeculae are aligned or very dense: axial def^{n}
  - observations by deformation stage in μCT; also FEA modelling
- tensile σ-ϵ curve: failure at smaller strains; trabecular microcracking

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- data for E^* σ_c^* σ_T^* (normalized by values for cortical bone)
  - spread is large - anisotropy, alignment of trabecular orientation + loading direction, variations in solid properties, $\dot{\epsilon}$, species
- models - based on open-cell foams

comp.

$E^*/E_s \propto (\rho^*/\rho_s)^2$ bending

$\sigma^*_{el}/E_s \propto (\rho^*/\rho_s)^2$ buckling

tension

$\sigma^*_T/\sigma_{ys} \propto (\rho^*/\rho_s)^{3/2}$ plastic hinges

data generally consistent with models

also: statistical analysis of data

$E^*, \sigma_c^* \propto \rho^2$

note: comp: ϵ^*_{el} = constant = 0.7%

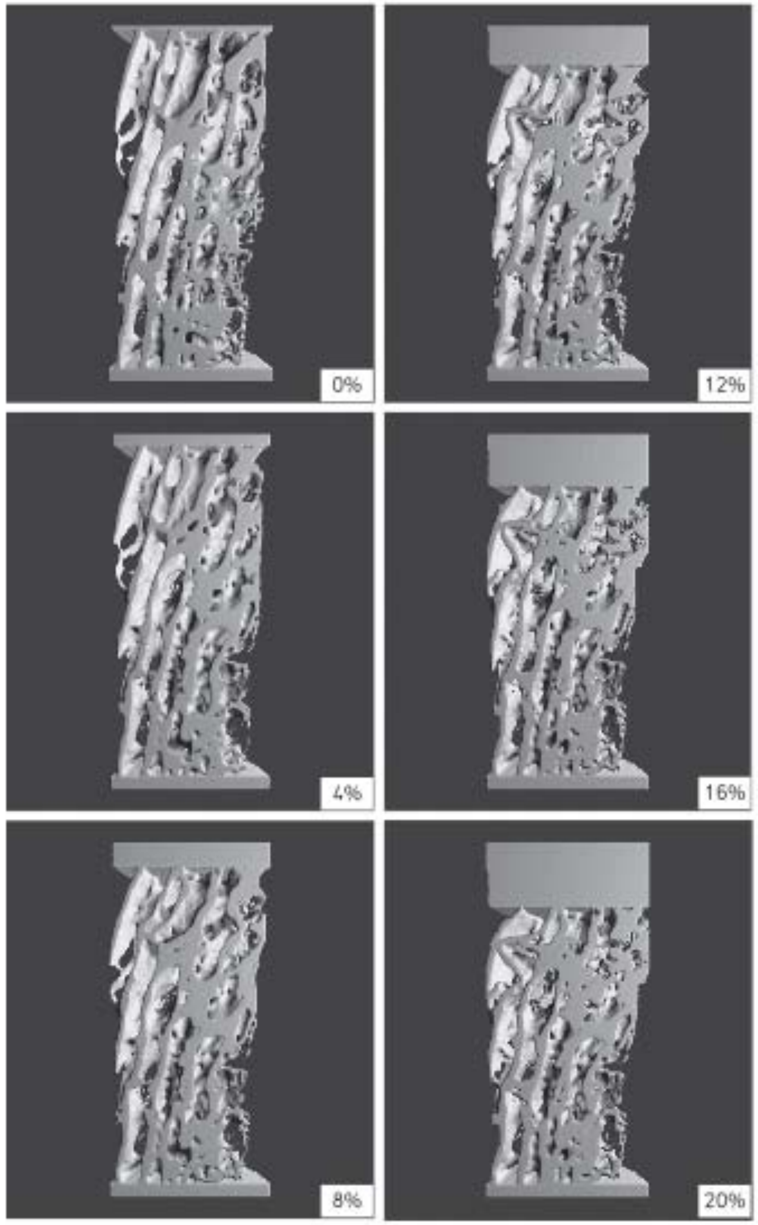
Compressive stress-strain curves

Figure removed due to copyright restrictions. See Fig. 1: Hayes, W. C., and D. R. Carter. "Postyield Behavior of Subchondral Trabecular Bone." *Journal of Biomedical Materials Research* 10, no. 4 (1976): 537-44.

Hayes and Carter, 1976

Compression
Whale Vertebra

Muller et al, 1998



Nazarian and Muller 2004

Images removed due to copyright restrictions.

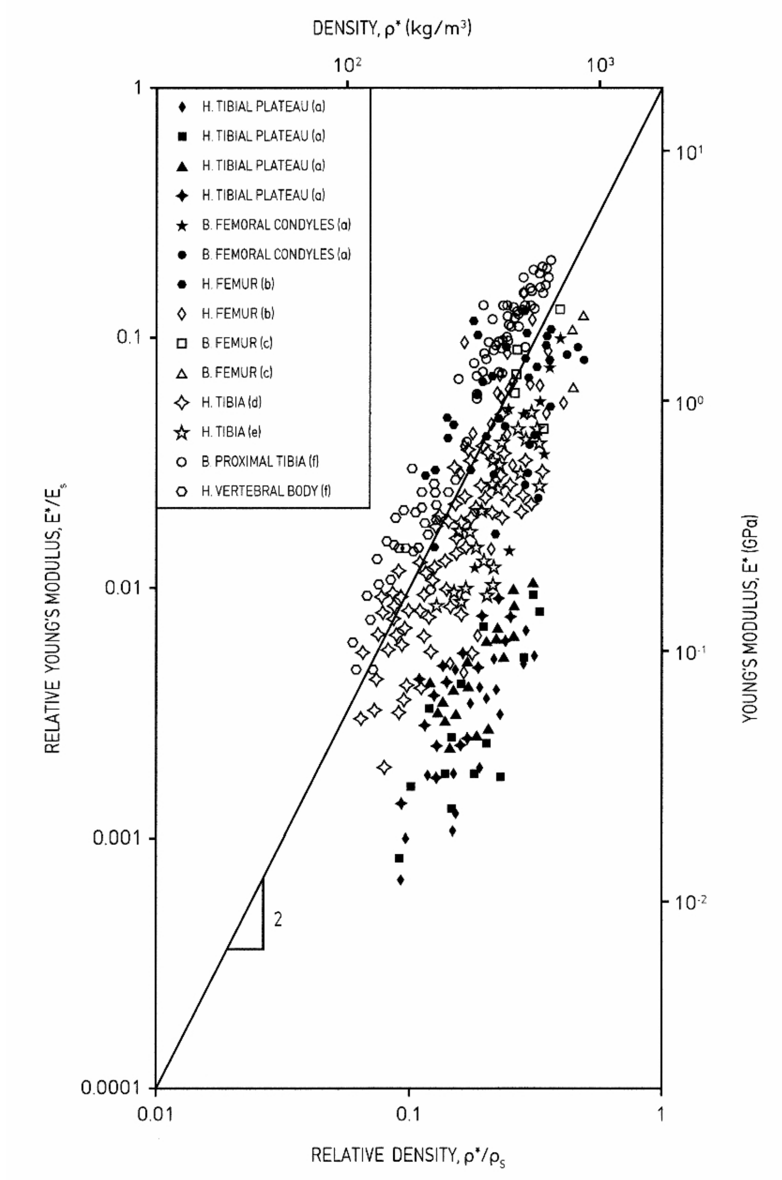
Human Vertebral Bone

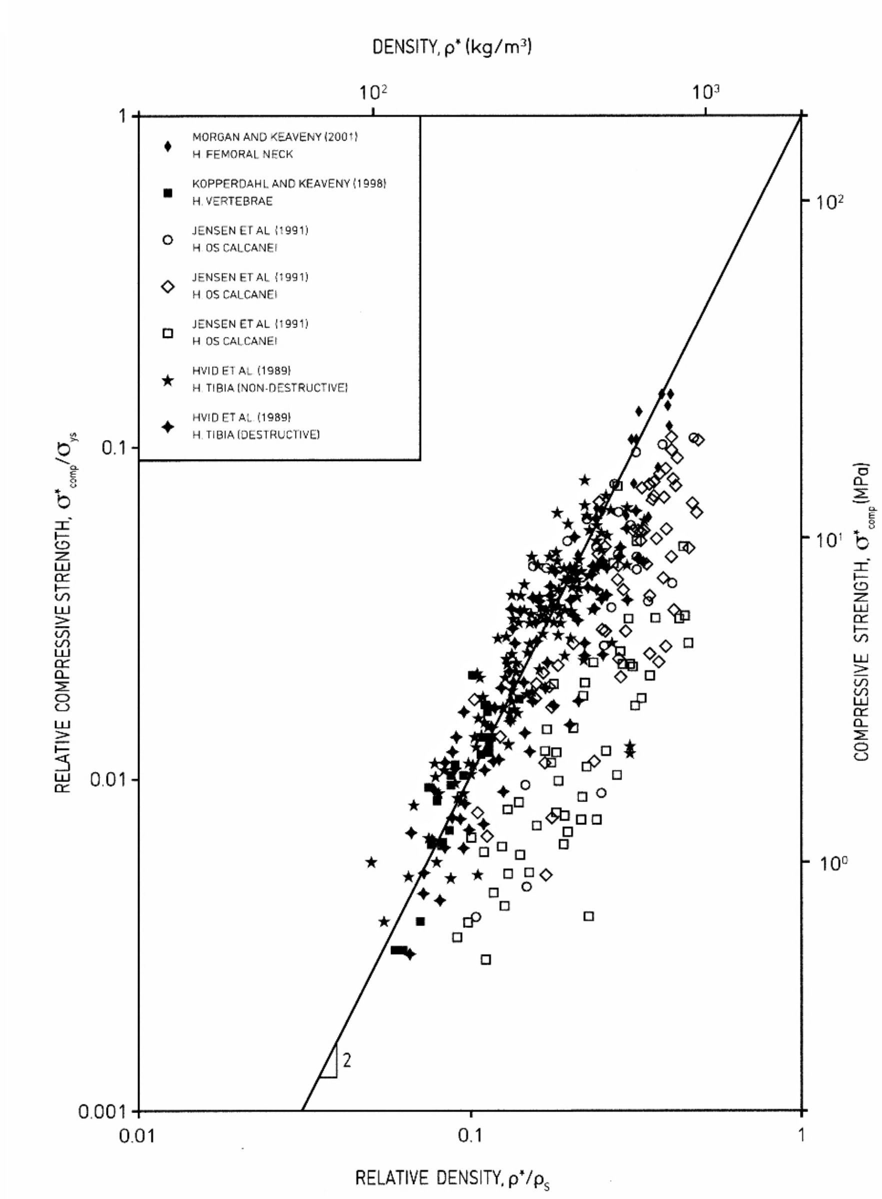
Mueller, ETH

Tension

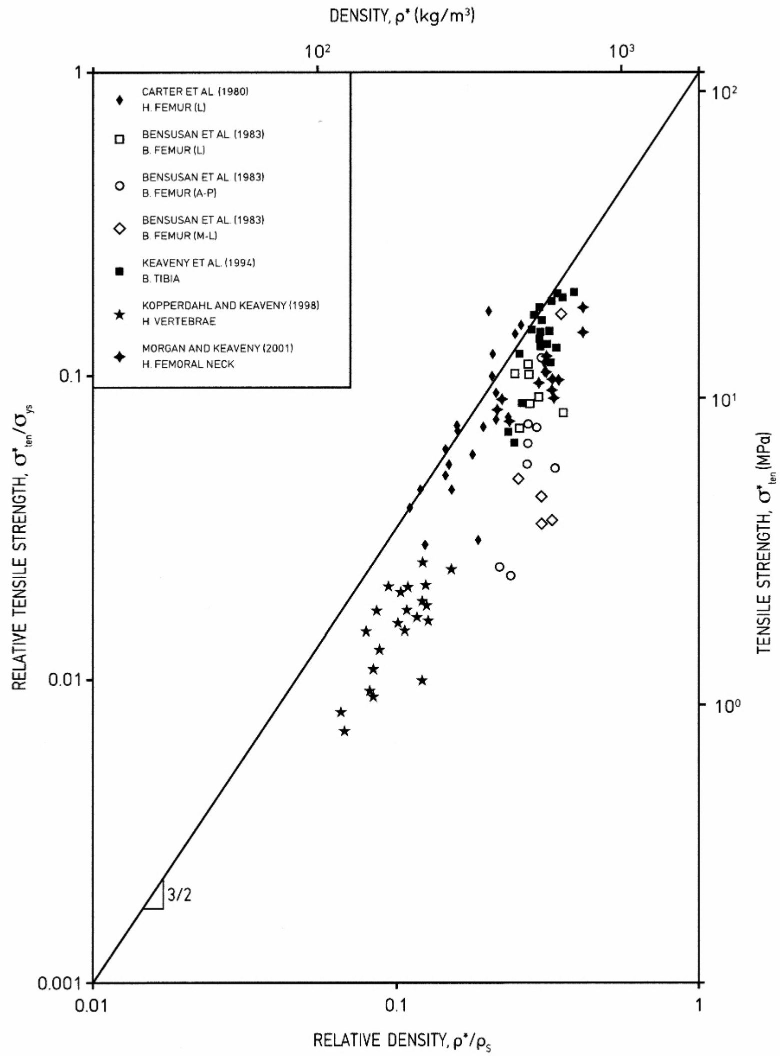
Figure removed due to copyright restrictions. See Fig. 5.6: Gibson, L. J., et al. *Cellular Materials in Nature and Medicine*. Cambridge University Press, 2010.

Carter et al., 1980





Gibson, L. J., M. Ashby, et al. *Cellular Materials in Nature and Medicine*. Cambridge University Press, © 2010. Figures courtesy of Lorna Gibson and Cambridge University Press.



Gibson, L. J., M. Ashby, et al. *Cellular Materials in Nature and Medicine*. Cambridge University Press, © 2010. Figure courtesy of Lorna Gibson and Cambridge University Press.

- in some regions, trab. may be aligned e.g. parallel plates
  - deformation then axial (in longitudinal direction) $E^* \propto \rho$, $\sigma^* \propto \rho$

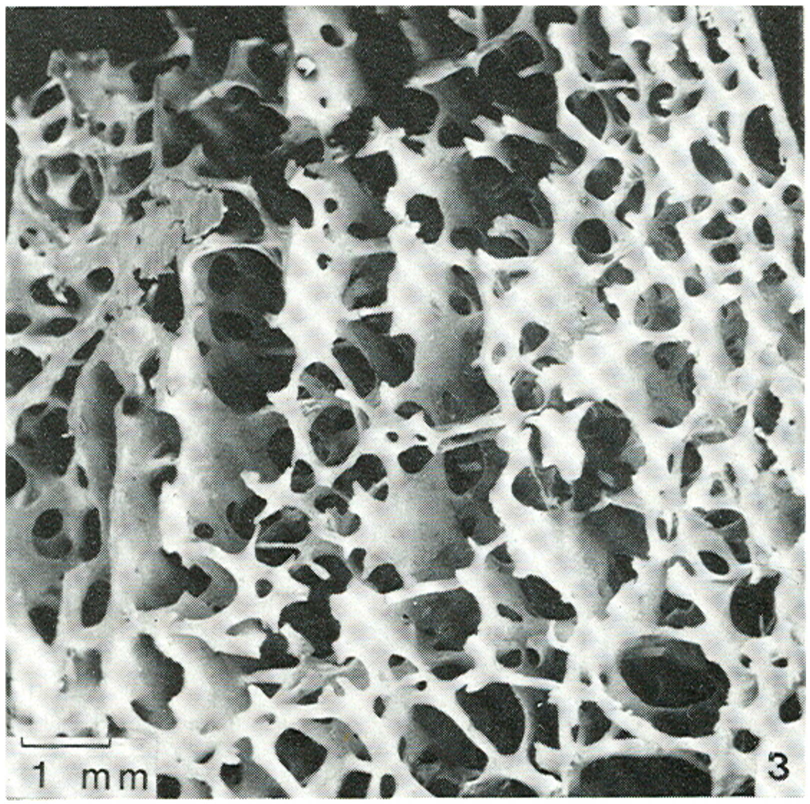
- can also summarize data for solid trabeculae + trabecular bone (similar to wood)

  solid - composite of hydroxyapatite + collagen

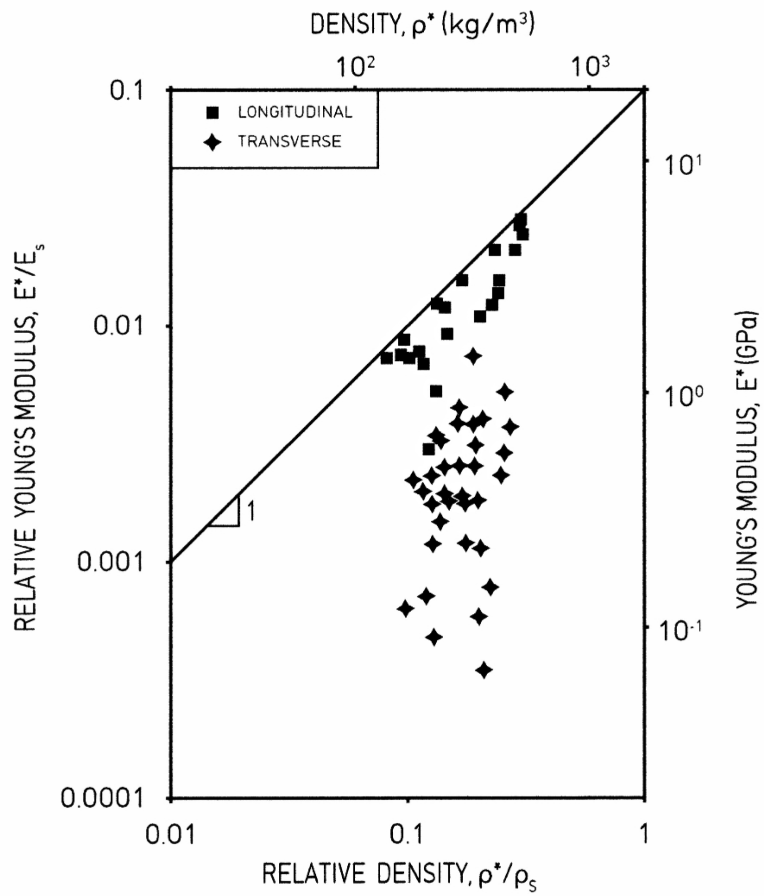
Osteoporosis (Latin "porous bones")

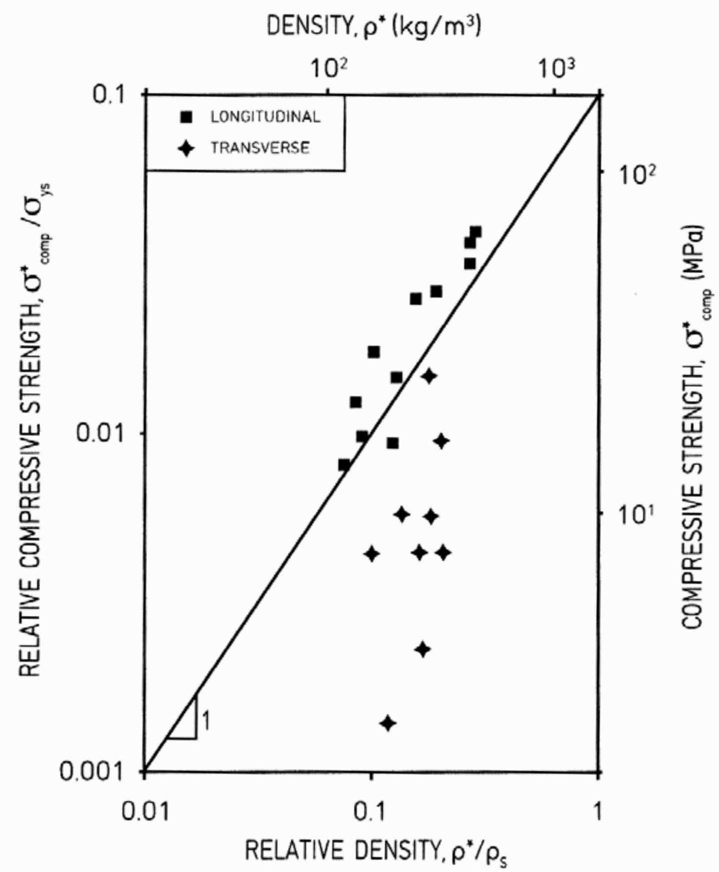
- as age, lose bone mass
- bone mass peaks at 25 yrs, then decreases 1-2%/yr.
- women, menopause - cessation of estrogen production, increases rate of bone loss
- osteoporosis defined as bone mass 2.5 standard deviations (or more) below young normal mean
- trabeculae thin & then resorb completely

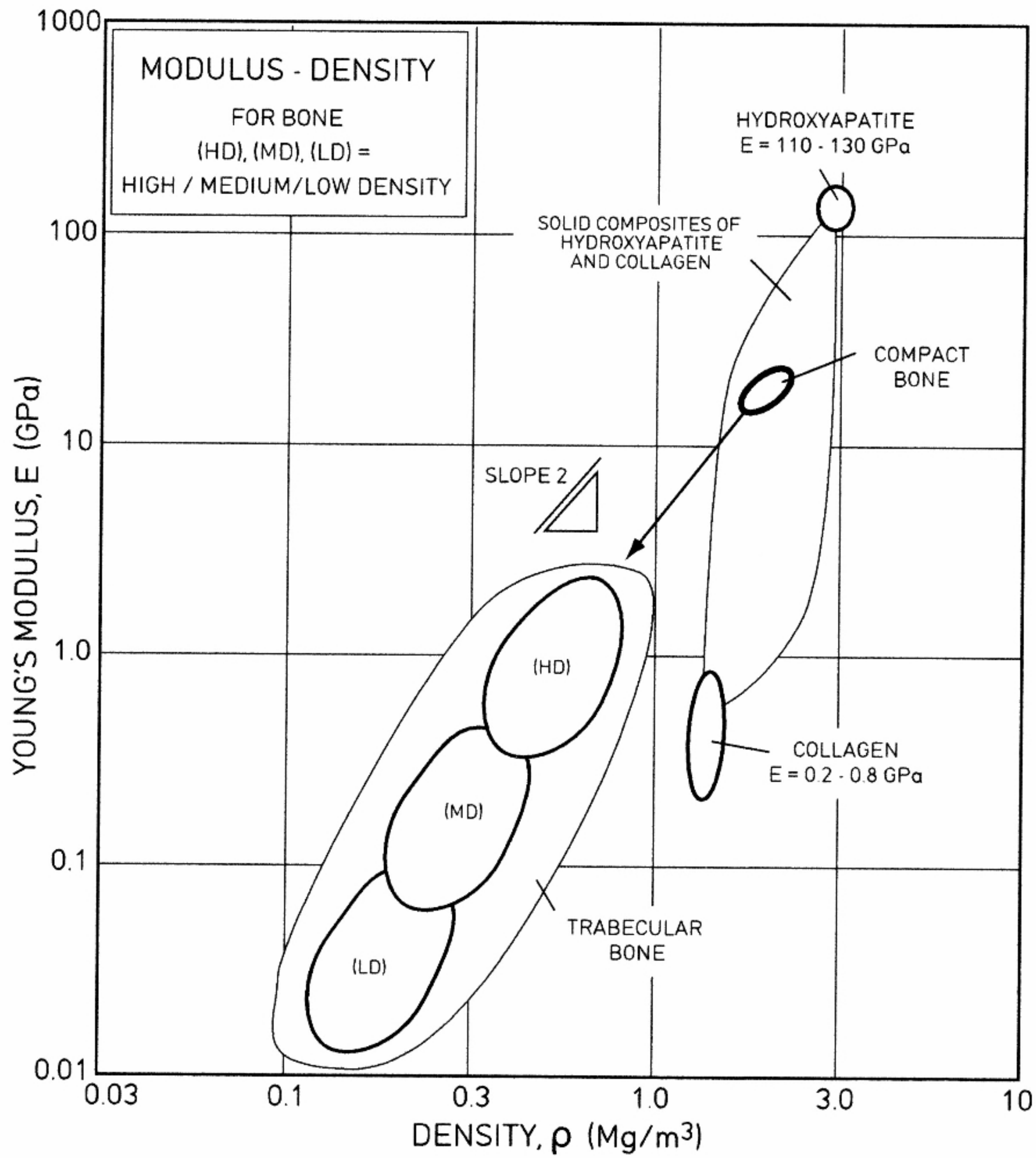
Aligned Trabeculae



Femoral Condyle (Knee)


DENSITY, ρ* (kg/m³)
10²
10³
0.1
0.01
0.001
0.0001
LONGITUDINAL
TRANSVERSE
1
10¹
10⁰
10⁻¹
RELATIVE YOUNG'S MODULUS, E*/Es
YOUNG'S MODULUS, E* (GPa)
0.01
0.1
1
RELATIVE DENSITY, ρ*/ρs


DENSITY, ρ* (kg/m³)
10²
10³
0.1
0.01
0.001
LONGITUDINAL
TRANSVERSE
1
10²
10¹
RELATIVE COMPRESSIVE STRENGTH, σ*comp /σys
COMPRESSIVE STRENGTH, σ*comp (MPa)
0.01
0.1
1
RELATIVE DENSITY, ρ*/ρs



Gibson, L. J., M. Ashby, et al. *Cellular Materials in Nature and Medicine*. Cambridge University Press, © 2010. Figure courtesy of Lorna Gibson and Cambridge University Press.