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 - reducant.
- also makes up core of vertebrae
- trabecular bone of interest (1) osteoporosis (2) osteoarthritis (3) joint replacement

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 severe: 46% 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

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

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 put
  trab. bone: density depends on magnitude of & orientation " " direction of principal stresses
- Mismatch in moduli between metal + bone leads to stress shielding
  \[
  \begin{array}{lll}
  E \text{ (GPa)} & \text{Co - Mo} & 210 \\
  & \text{Ti alloys} & 110 \\
  & \text{316 Stainless steel} & 210 \\
  \end{array}
  \]
  \[
  \begin{array}{ll}
  E \text{ (GPa)} & \text{Cortical Bone} & 18 \\
  & \text{Trab. bone} & 0.01-2 \\
  \end{array}
  \]
  - 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

**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

Images removed due to copyright restrictions.

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

Ralph Muller, ETH Zurich
Micro-CT images
Trabecular Bone Structure

Femoral head  Femoral head  Femoral condyle (knee)

Bone grows in response to loads

- Studies on juvenile guinea fowl (Ponzer et al. 2006)
  (a) running on level treadmill
  (b) " incline " (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

Trabecular architecture and mechanical loading

Properties of solid in trabeculae

- Foam models: require $\rho_s$, $E_s$, $\varepsilon_{ys}$ for the solid.
- Ultrasonic wave propagation $E_s = 15-18$ GPa.
- Finite element models of exact trabecular architecture from micro-CT scan. If do uniaxial compression test - can measure $E^*$ and back calculate $E_s$.
  $E_s = 18$ GPa.
- Find properties of trabeculae (solid) similar to cortical bone.

$\rho_s = 1800$ kg/m$^3$
$E_s = 18$ GPa
$\varepsilon_{ys} = 18.2$ MPa (comp)
$\sigma_{ys} = 115$ MPa (tensile)
Mechanical Properties of Trabecular Bone

- Compressive stress-strain curve - characteristic shape
- Mechanisms of deformation + failure
  - Usually bending followed by post-buckling
  - Sometimes, if trabeculae are aligned or very dense: axial def. deformed
  - Observations by deformation stage in µCT; also FEA modelling
- Tensile σ-ε curve: failure at smaller strains; trabecular micro cracking

- Data for \( E^* \), \( \sigma^c \), \( \sigma^f \) (normalized by values for cortical bone)
- Spread is large - anisotropy, alignment of trabecular orientation + loading direction, variations in solid properties, \( E \), species
- Models - based on open-cell foam
  - Compress. \( E^*/E_s \propto (\rho^*/\rho)^2 \)
  - Buckling \( \sigma^*_b / E_s \propto (\rho^*/\rho)^2 \)
  - Tension \( \sigma^*_T / \sigma^*_T \propto (\rho^*/\rho)^{3/2} \)

Data generally consistent with models

Also: statistical analysis of data

\( E^* \), \( \sigma^c \propto \rho^2 \)

Note: comp: \( E^*_c / E_{c1} \) = 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

Nazarian and Muller 2004

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

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

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**Osteoporosis** (Latin “porous bones”)
- as age, lose bone mass
- bone mass peaks at 25yrs, 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)

Figure 1: Graphs showing the relationship between relative density and relative Young's modulus, as well as relative density and relative compressive strength. The graphs display data points for longitudinal and transverse orientations. The data is from Gibson, L. J., M. Ashby, et al. (2010). *Cellular Materials in Nature and Medicine*. Cambridge University Press. Figures courtesy of Lorna Gibson and Cambridge University Press.