Bone Mechanics

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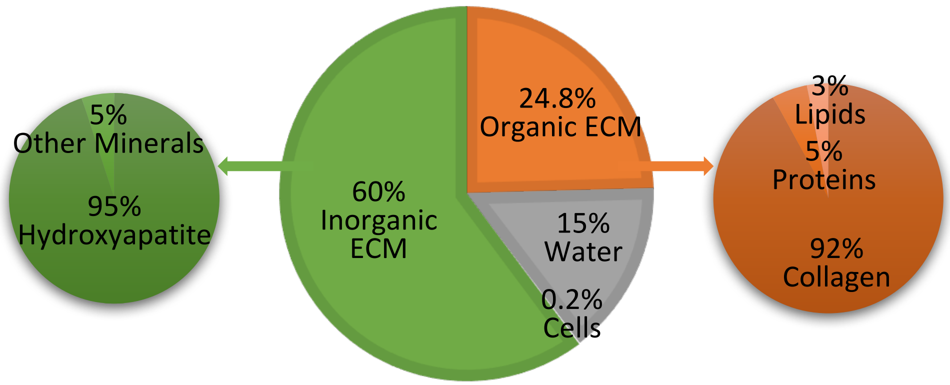
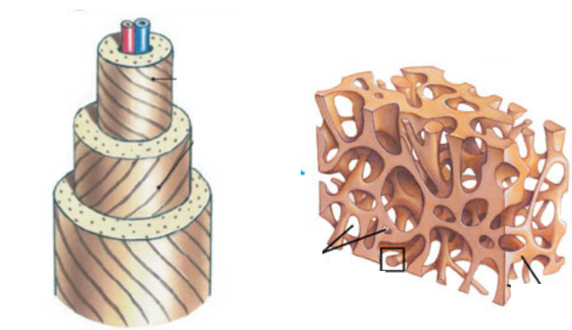
The Tissue Level

	BODY LEVEL	ORGAN LEVEL	TISSUE LEVEL	CELLULAR LEVEL
Biomechanics	Rigid Object Models	Deformable Continuum Models		Statistical Models

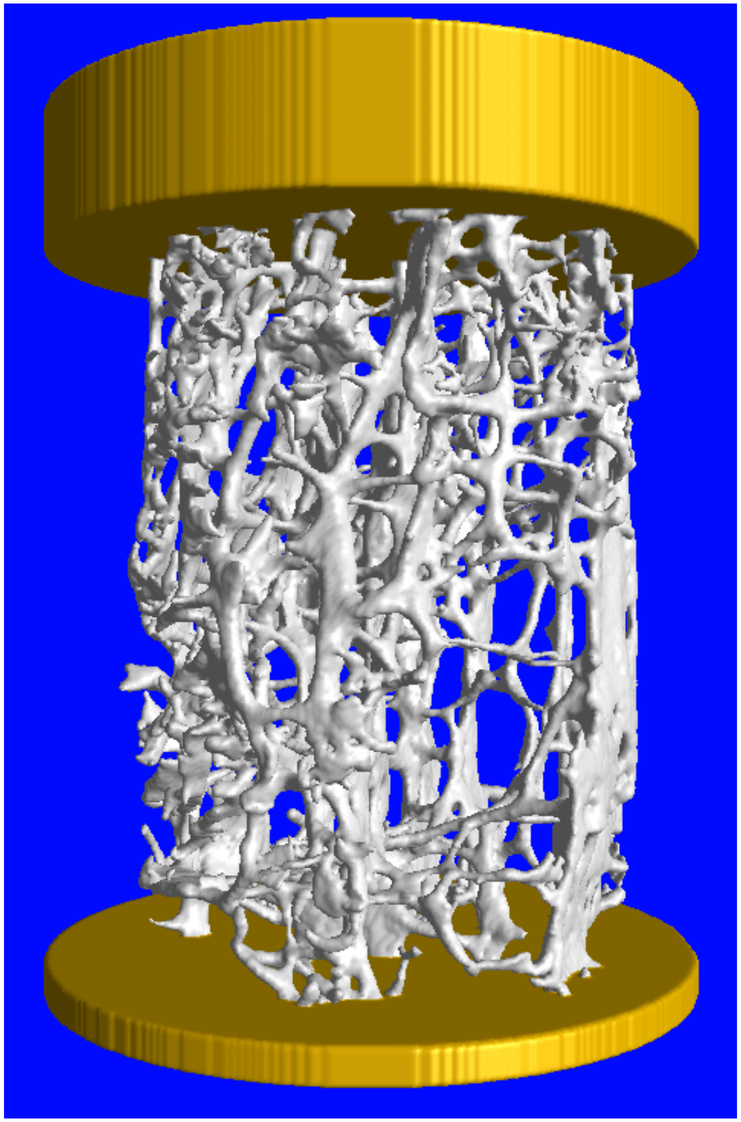
Bone as a Material

- We consider bone as a **material**
  → without a structure or shape
- Bone is an inhomogeneous or **composite** material
- Properties studied separately for cortical and trabecular bone
  - Is cortical bone denser trabecular bone or are they two different tissues? No consensus





Mechanical Testing – Trabecular Bone

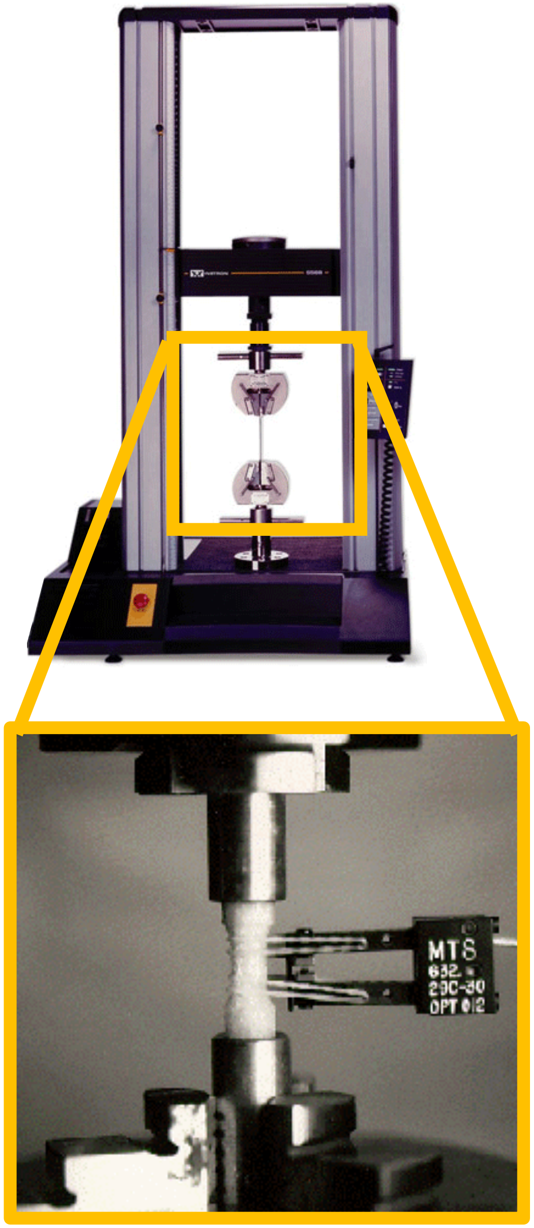


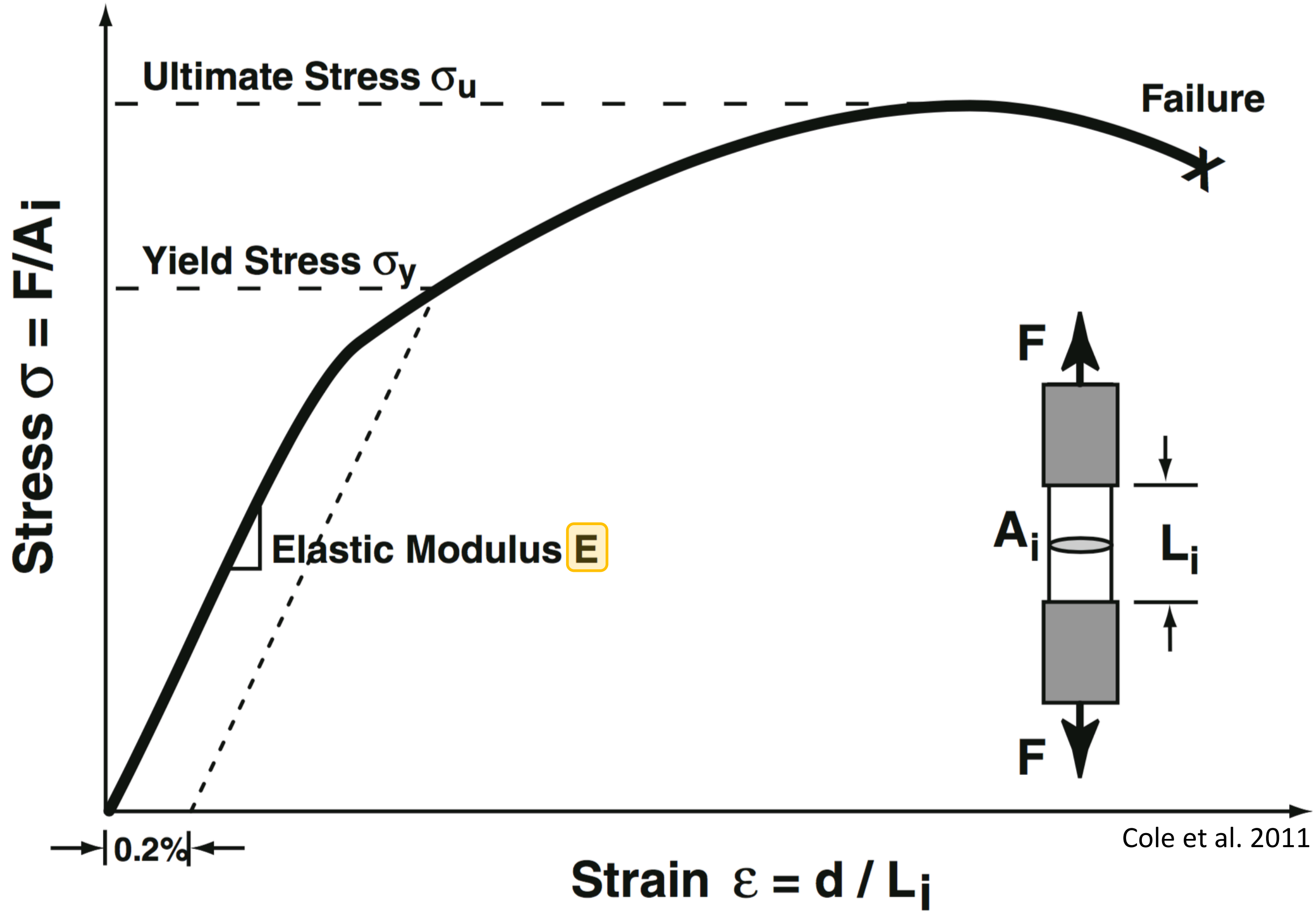
Valenthe et al.

- 5 mm < Sample size < 10mm to avoid structure

Courtesy of M.Levenston

Stress-Strain Curve (Tissue Level)





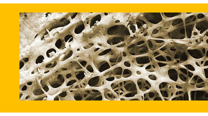
- *Stress [Pa]* = load per unit area
- *Strain [% or με]* = fractional change in dimension
- *Elastic/Young's Modulus E [Pa]* = resistance to being deformed elastically

Issues When Measuring Mechanical Properties of Bone

- Factors influencing test results:
  - Testing method (mechanical testing vs. nano identation)
  - Specimen geometry (size and shape)
  - Specimen support (end caps vs. platens)
  - Specimen preparation (fresh vs. thawed)
  - Specimen alignment (on vs. off axis)
  - Strain rate

  - Age (young vs. old)
  - Sex
  - Ethnicity
  - Subject health (healthy vs. osteoporotic)
  - Anatomy (long bone vs. short bone)
  - Bone tissue (cortical vs. trabecular)

Bone Mechanical Behavior at Organ Level vs. Tissue Level

	Organ Level 	**Tissue Level** 
Bone as	Structure (= geometry + material properties)	Material
Described by	Load-Deformation Curve	Stress-Strain Curve

- A *load-deformation* curve can be converted to a *stress-strain* curve by using appropriate formulas to change load to stress and deformation to strain
  - E.g. Compressed bone shaft

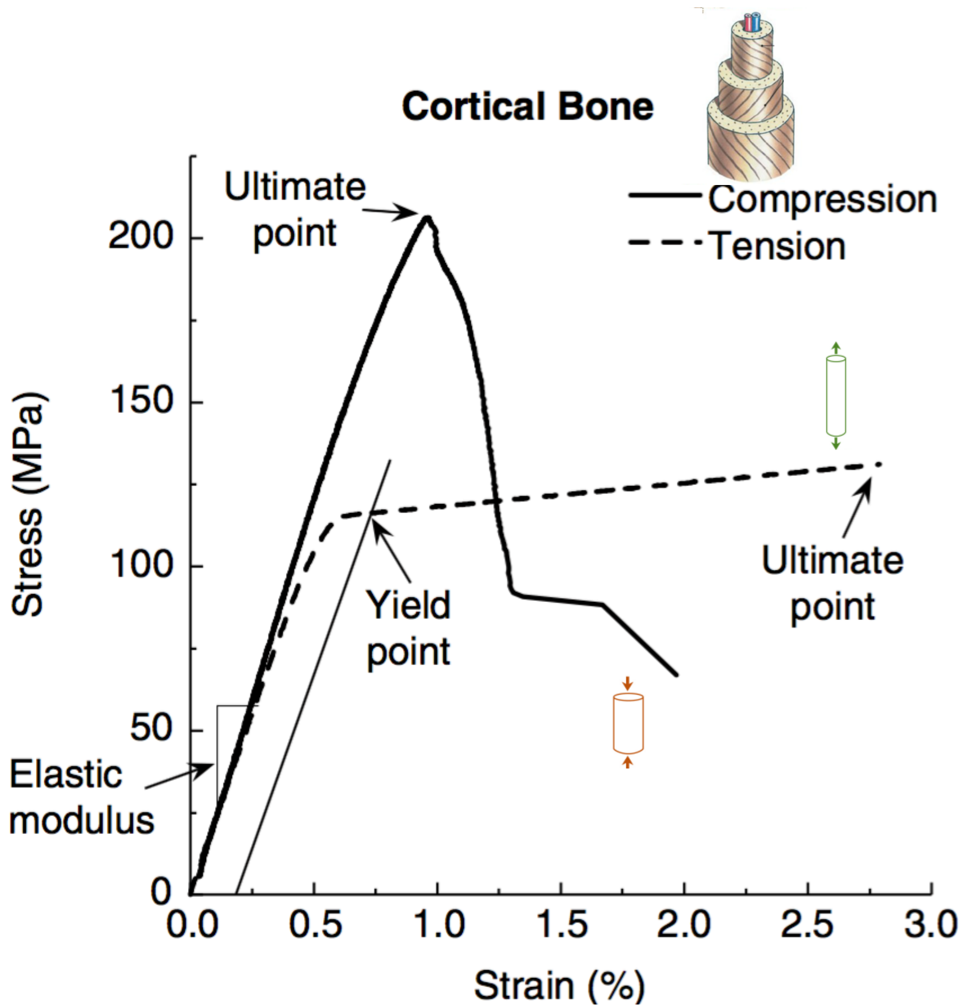
    Stress = Load / Cross-sectional area

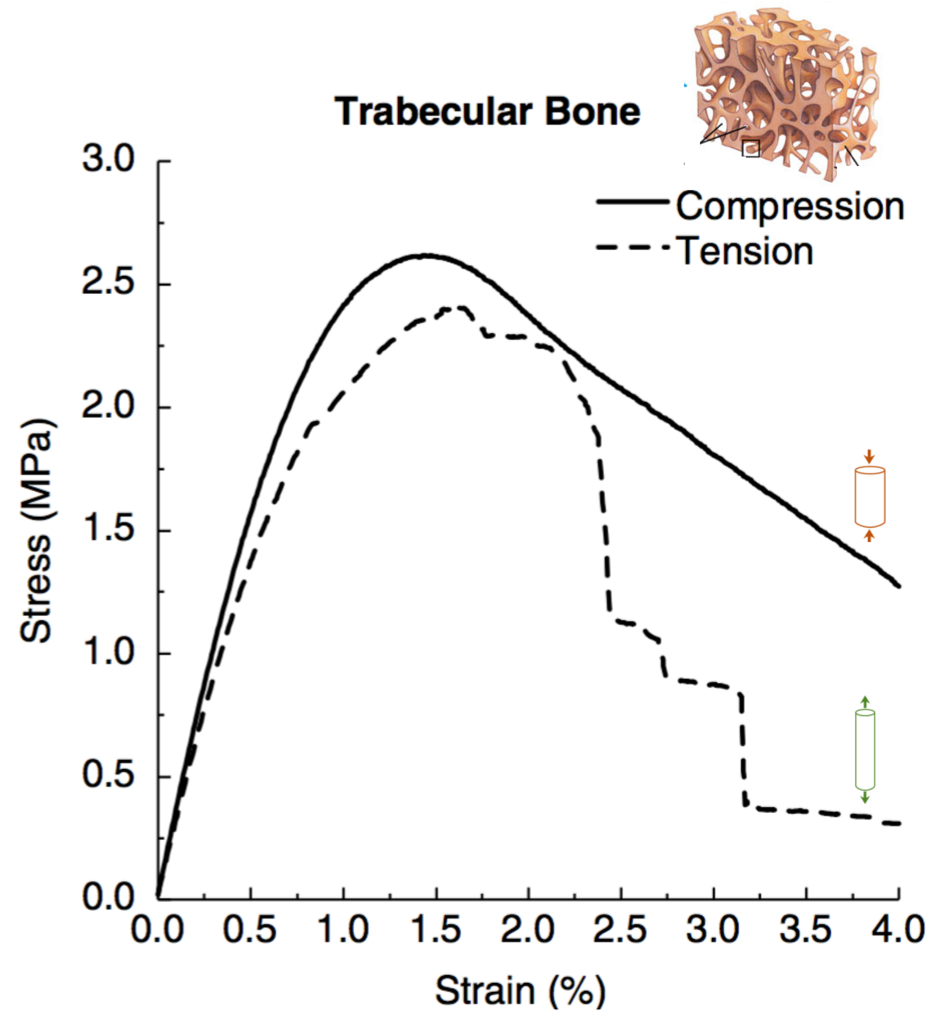
    Strain = Deformation / Shaft length

    Yield, ultimate and failure strengths, structural stiffness → Yield, ultimate and failure stress, elastic modulus

Cortical and Trabecular Bone in Tension and Compression

- Bone strength in compression > tension > shear

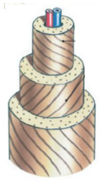


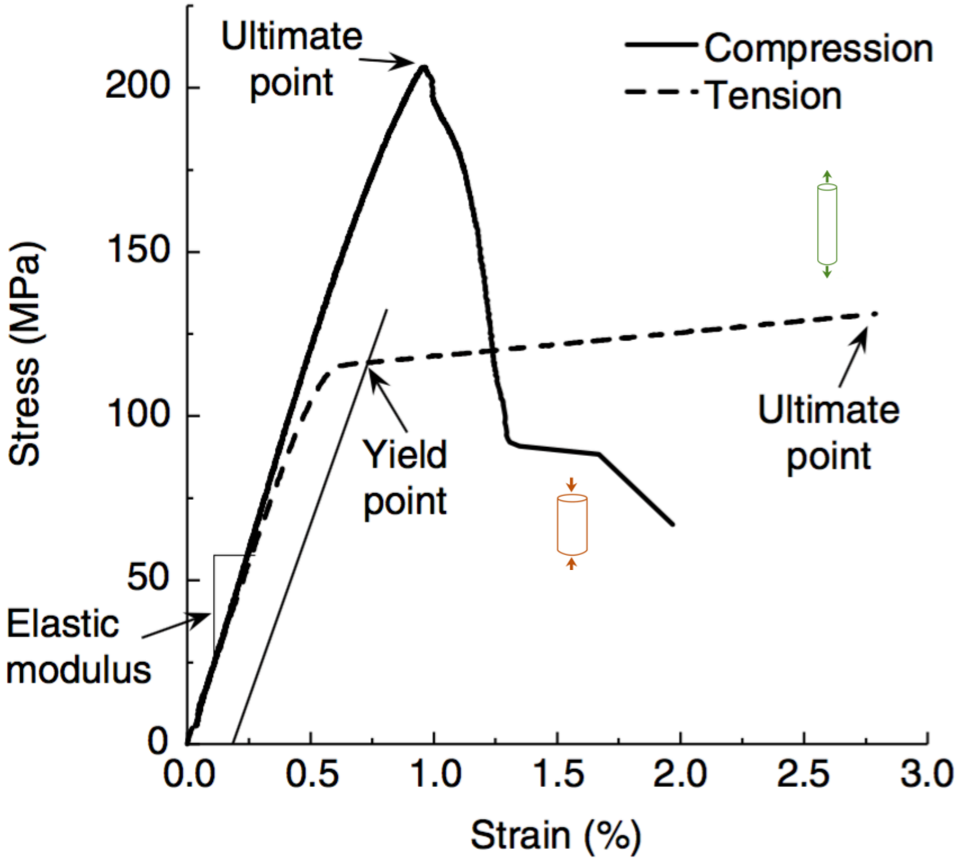


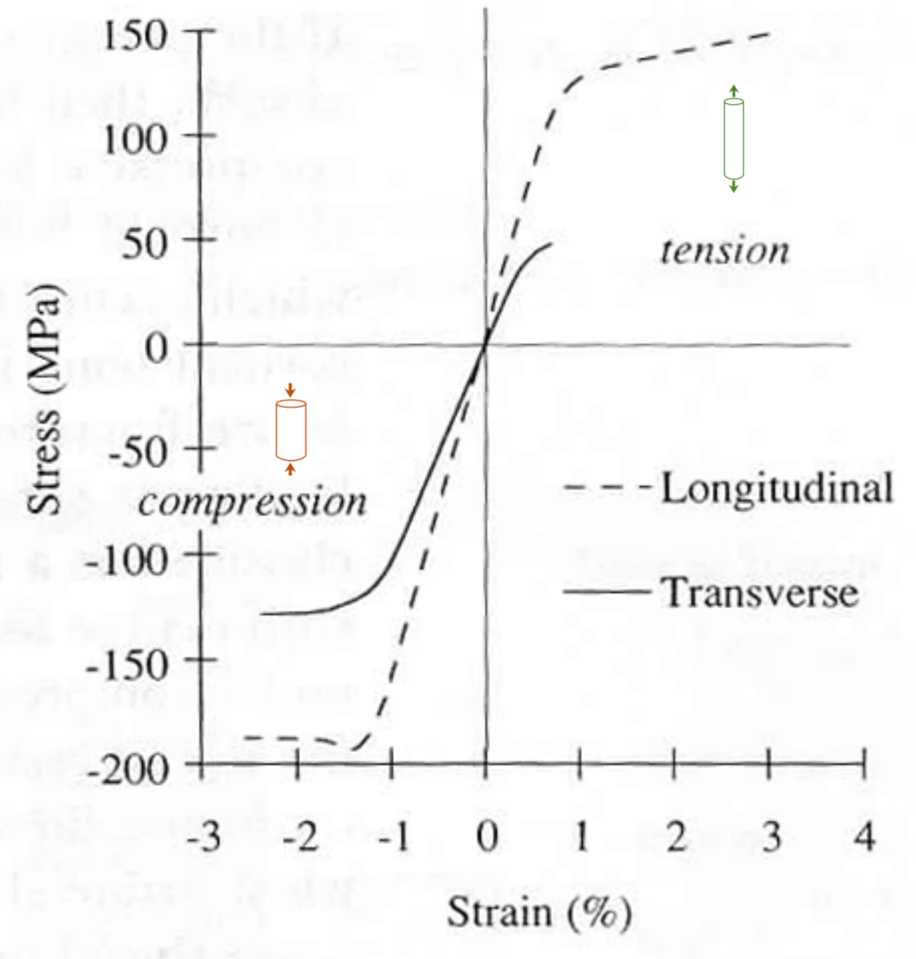
Morgan, 2008

Bone tissue	Young's modulus	Yield strain	Ultimate strain
Cortical bone	12-20GPa	0.6-1.2%	2.5%
Trabecular bone	70-673MPa	0.6-1.2%	1.59-7.6%

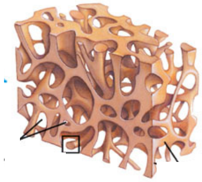
Variability in Literature – Cortical Bone

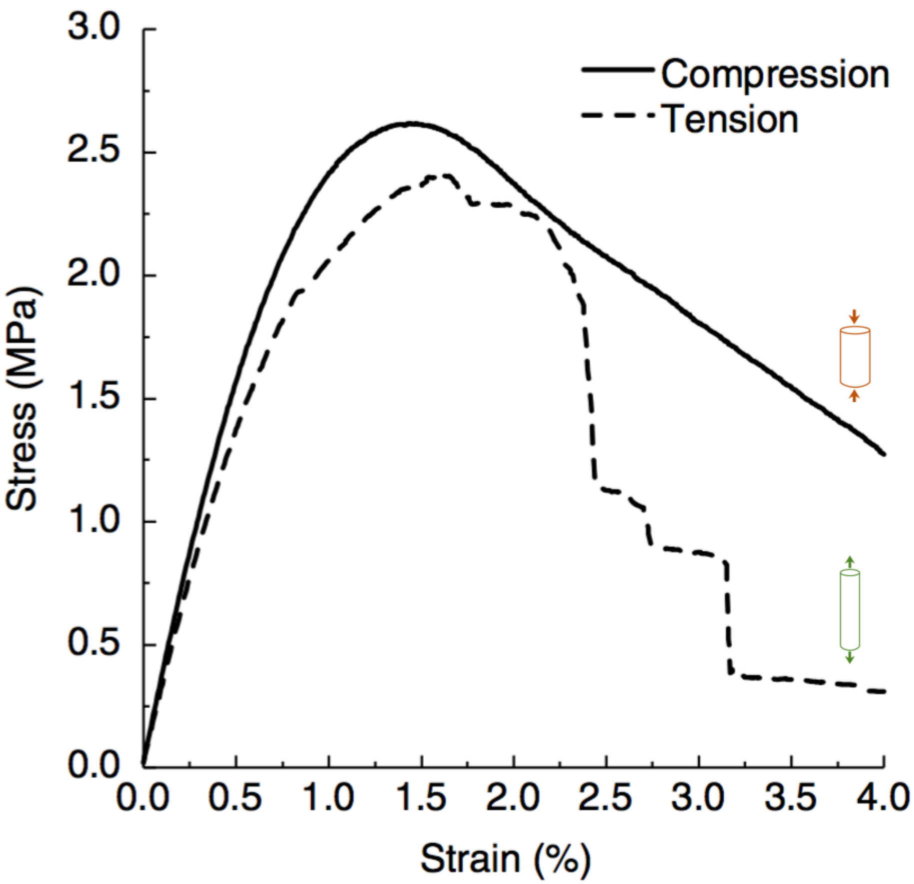


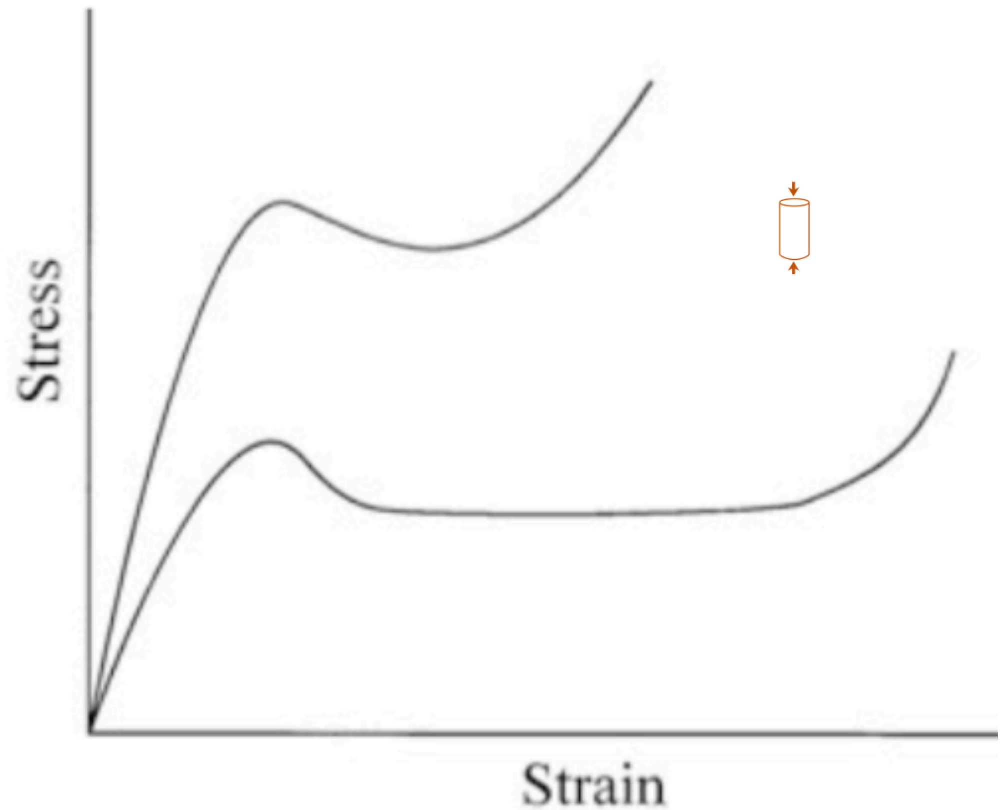




Variability in Literature - Trabecular Bone







Variability in Literature - Bone

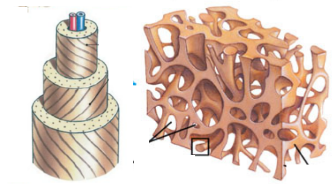


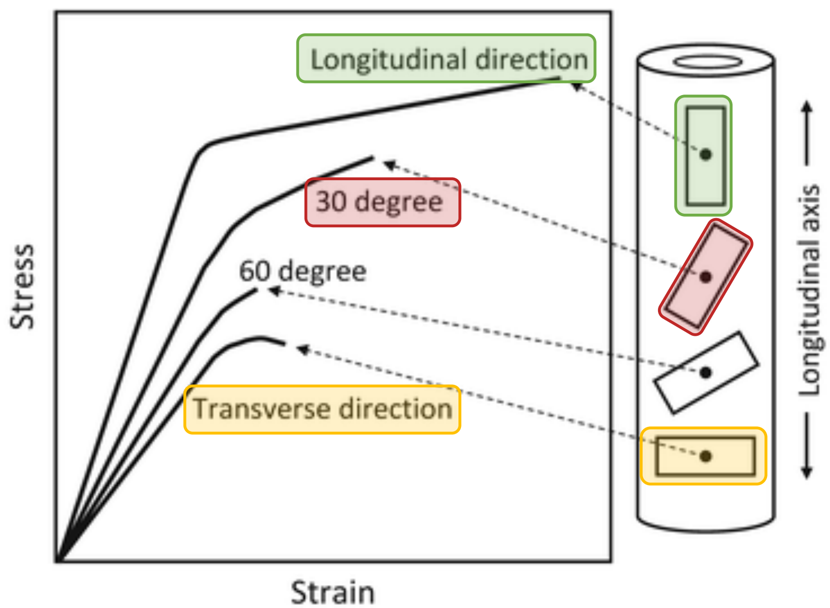
Table 1 Previous studies to determine the mechanical properties of bone tissue

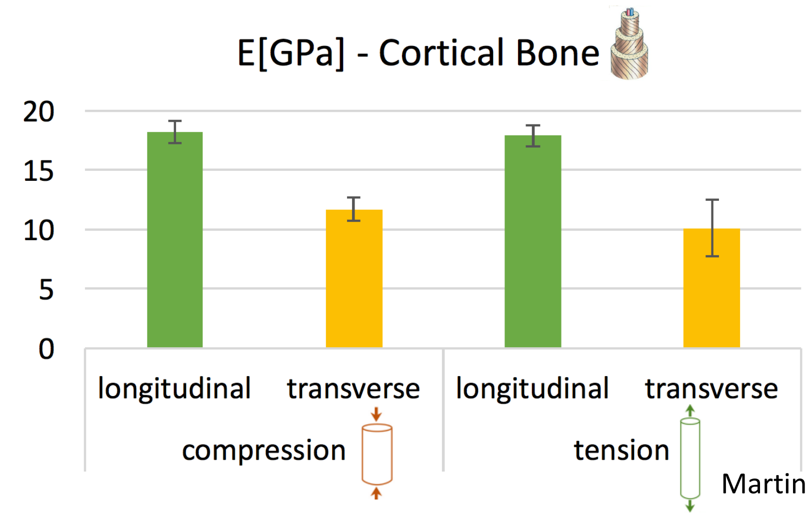
Study	*Property*	*Mechanical test*	*Specimen origin*	*Elastic modulus (GPa) mean (SD)*
McNamara *et al.* (2005, 2006a,b)	Elastic modulus, yield strength, post yield Strain	Tensile testing	Rat proximal tibia	2.81 ± 2.09
Townsend *et al.* (1975)	Elastic modulus	Buckling	Human medial tibia	14.1 (dry); 11.3 (wet)
Runkle and Pugh (1975)	Elastic modulus	Buckling	Human subchondral bone	8.7 (3.2)
Mente and Lewis (1989)	Elastic modulus	Cantilever beam	Dried human femur	6.2 (1.2)
			Fresh human tibia	11.2 (10.1)
Ryan and Williams (1989)	Elastic modulus	Tensile	Bovine distal femurs	–
Ryan and Williams (1989)	Elastic modulus	Compression	Bovine femora	0.8 (0.4)
Kuhn *et al.* (1989)	Elastic modulus	Three-point bending	Human iliac crest	3.8
Choi and Goldstein (1992)	Fatigue strength	Three-point bending	Proximal tibia	–
Choi *et al.* (1990)	Elastic modulus	Three-point bending	Proximal tibia.	4.6 (1.3)
Rho *et al.* (1993)	Elastic modulus	Ultrasonic/microtensile	Proximal human tibia	10.4 (3.5)
Choi and Goldstein (1992)	S–N curve	Four-point bending	Proximal tibia	–
van Rietbergen *et al.* (1995)	Elastic modulus	High-resolution FE modeling	Proximal human tibia	5.91
Rho *et al.* (1997)	Elastic modulus	Nanoindentation	Human vertebrae	13.5 (2.0)
Turner *et al.* (1999)	Elastic modulus	Nanoindentation	Human distal femur	18.14 (1.7)
		Acoustic microscopy		17.5 (1.12)

McNamara 2017

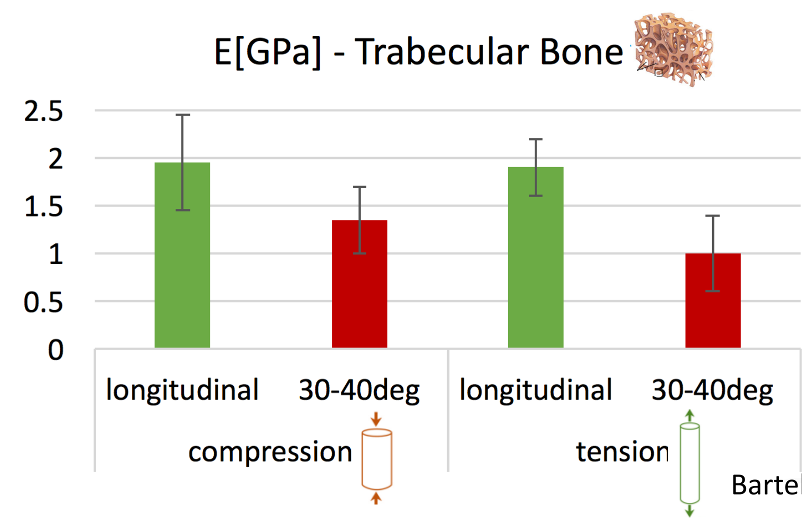
Bone Anisotropy

- Bone response to the applied load depends on the *direction* of the load relative to the directionality of the *material*





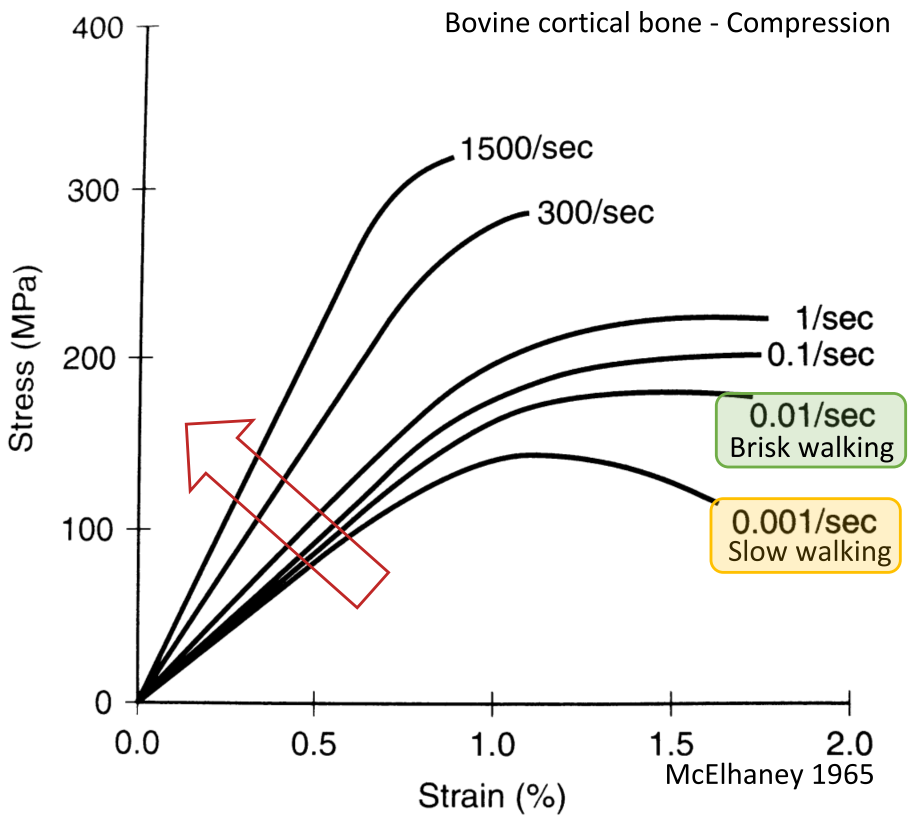
Martin et al. 2015

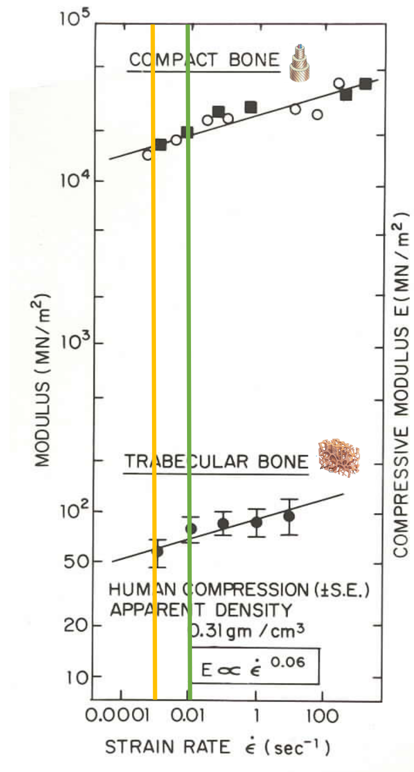


Bartel et al. 2006

Bone Viscoelasticity

- Bone response on *rate* of applied load
  - In non-strenuous conditions we can consider bone as a purely **elastic** material





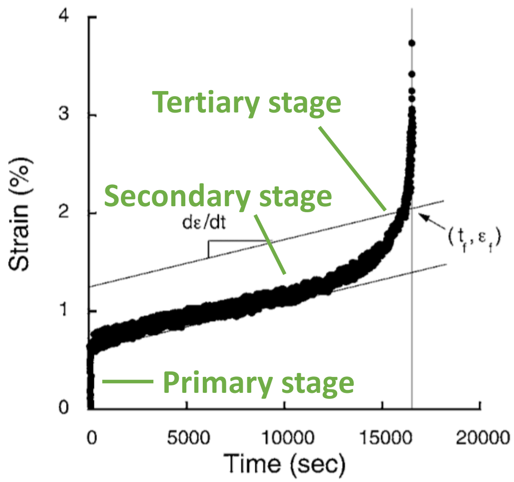
- Daily activities: E changes ~ 15%
- Strain rate⇧, bone from ductile to brittle

- Similar behavior for cortical and trabecular bone

Bone Creep and Fatigue (Time-Dependence)

Creep

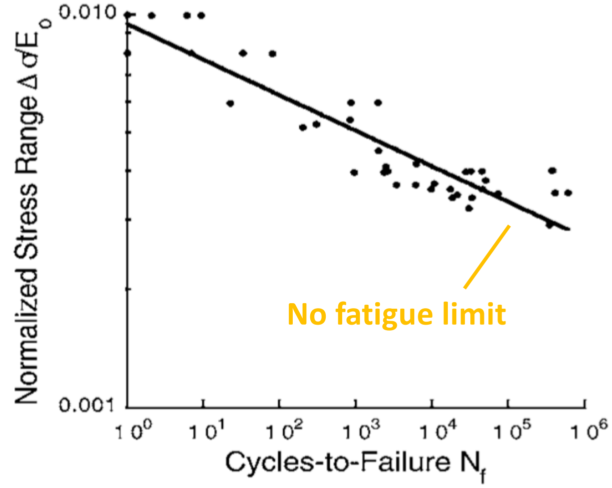
- Load: constant



Bowman et al., 1998

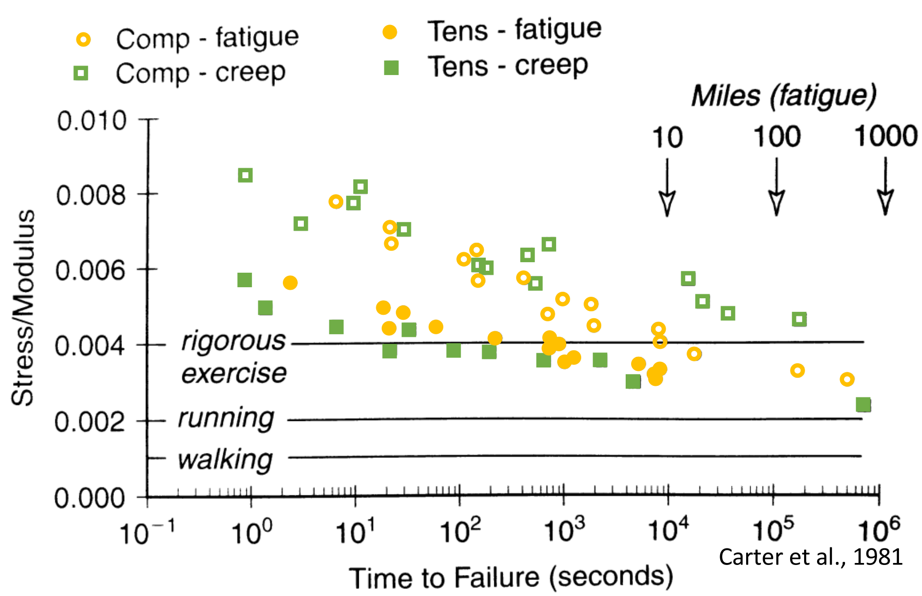
Fatigue

- Load: pre-yield dynamic load



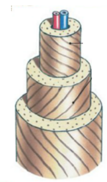
Bowman et al., 1998

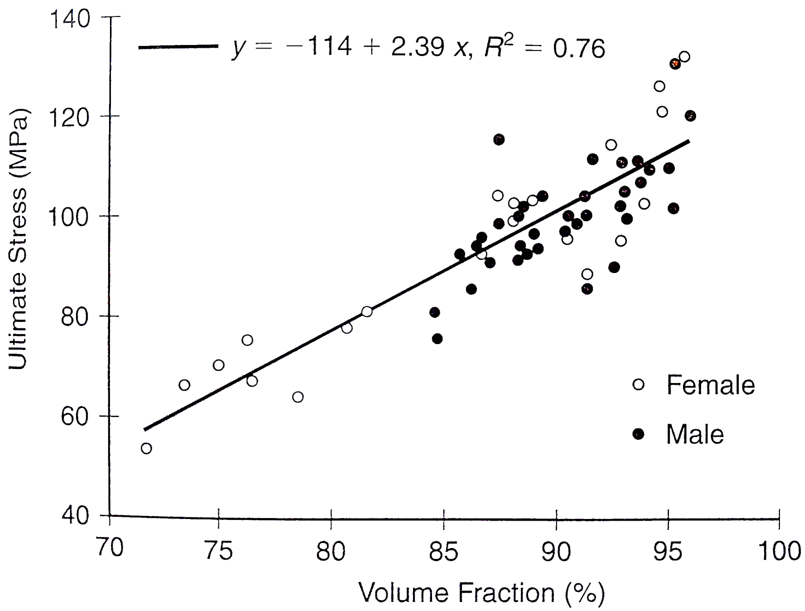
- Bone shows similar behavior in creep and fatigue



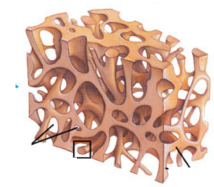
Carter et al., 1981

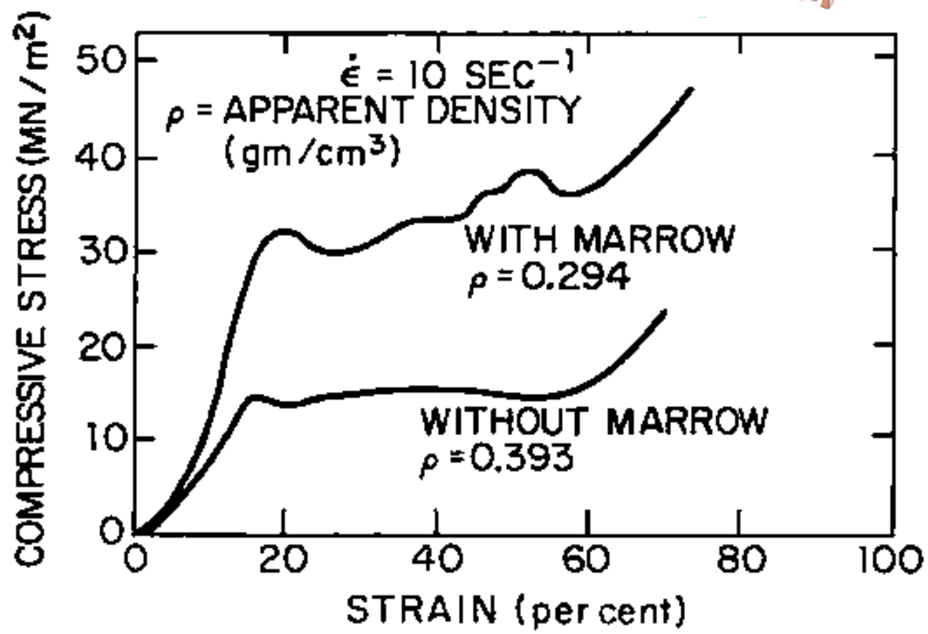
Material Properties as Function of Bone Porosity





- Cortical porosity due to Haversian and Volkmann's canals
- 50% variation of VF → 30% variation of σ_u
- Porosity increases with age

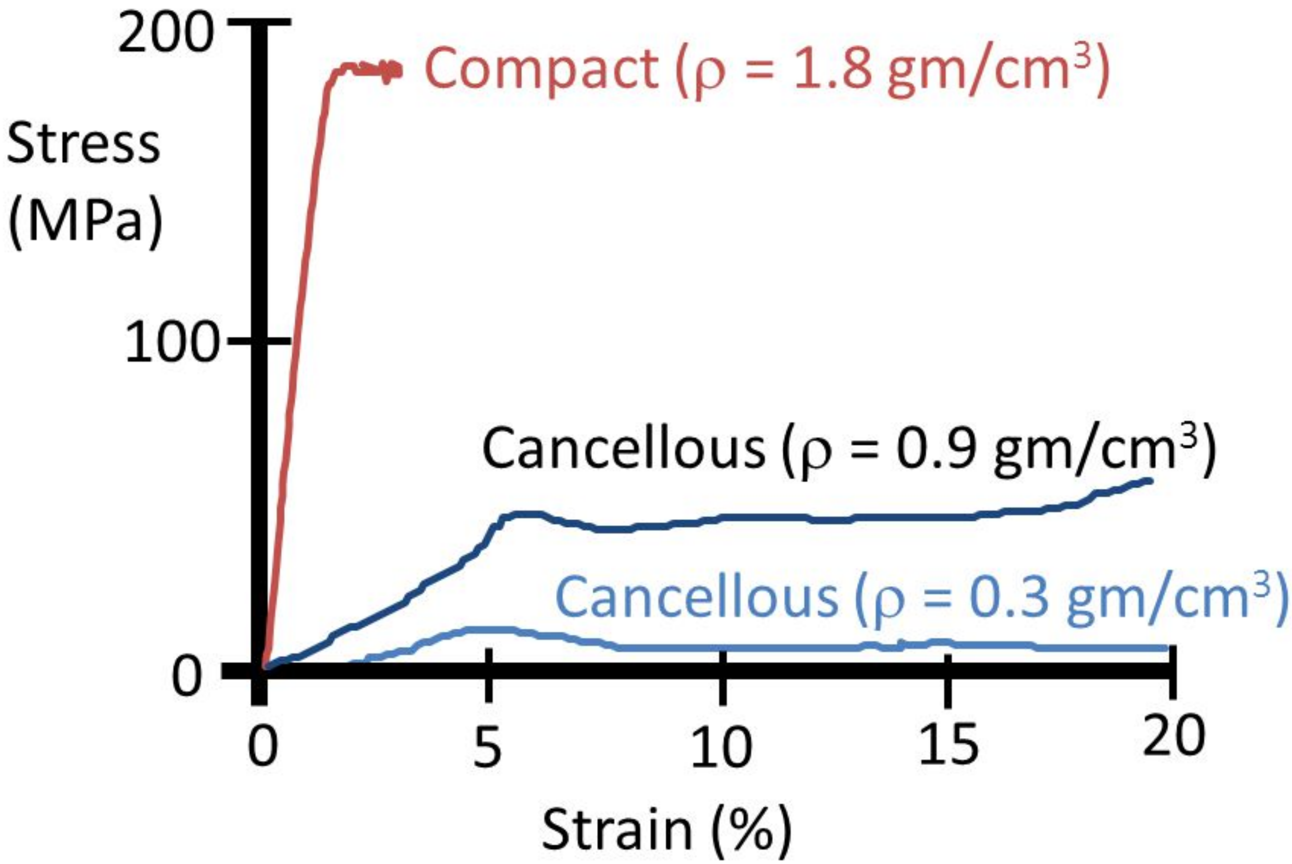




- Trabecular porosity due to space between trabeculae
- Properties change with/without marrow
- Porosity increases with age

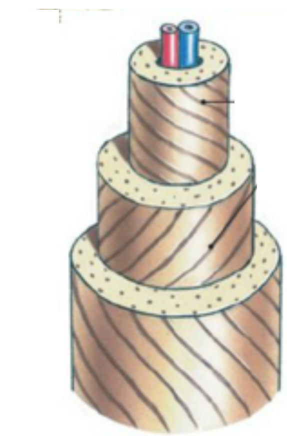
Material Properties as Function of Bone Density

- High variability of mechanical properties depending on bone density
- Bone density is used as a measure of severity of disease, e.g. osteoporosis = measured *in-vivo* from x-Ray based images
- Prosthesis design



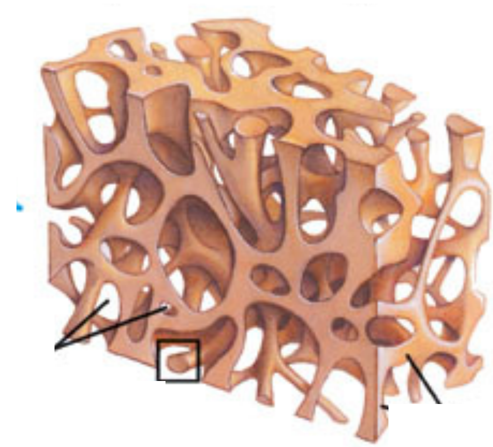
What is Bone Density (=Mass/Volume)?

$$\rho_{app} = \text{actual density} = \frac{\text{total specimen mass}}{\text{total specimen volume}}$$



$$\rho_{app} = \rho_{wet} = \text{apparent density} = \frac{\text{hydrated tissue mass}}{\text{total specimen volume}}$$

$$\rho_{dry} = \text{apparent dry density} = \frac{\text{dry tissue mass}}{\text{total specimen volume}}$$

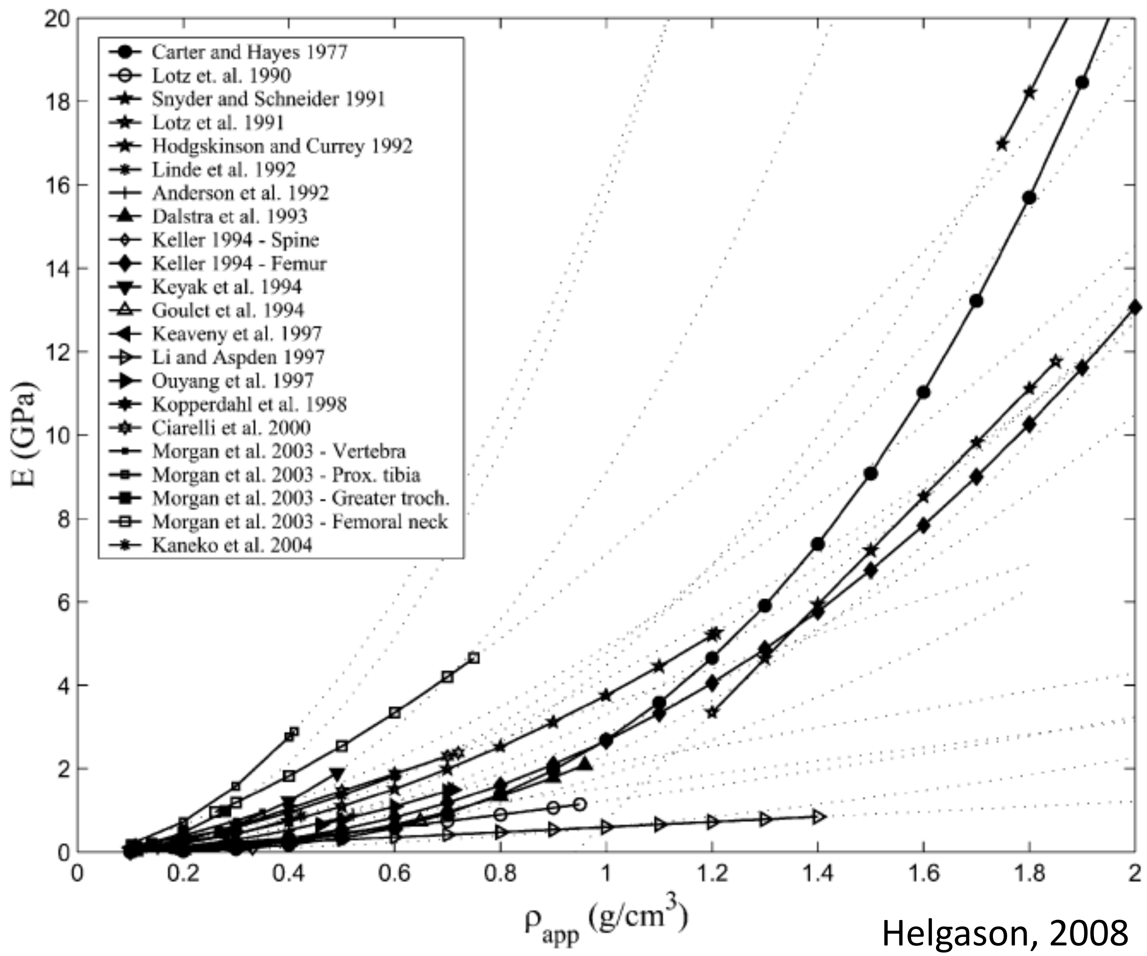


$$\rho_{ash} = \text{ash density} = \frac{\text{ash mass}}{\text{total specimen volume}}$$

Helgason, 2008

Material Properties as Function of Bone Density

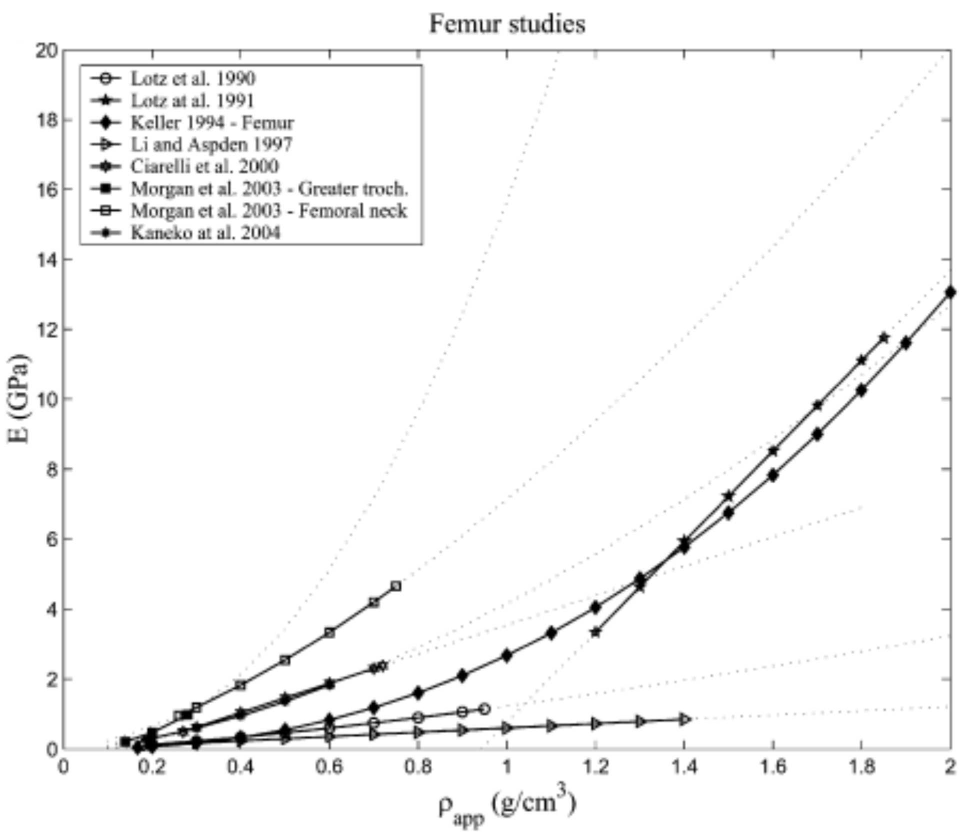
- Power laws: $E = a\,\rho^b$

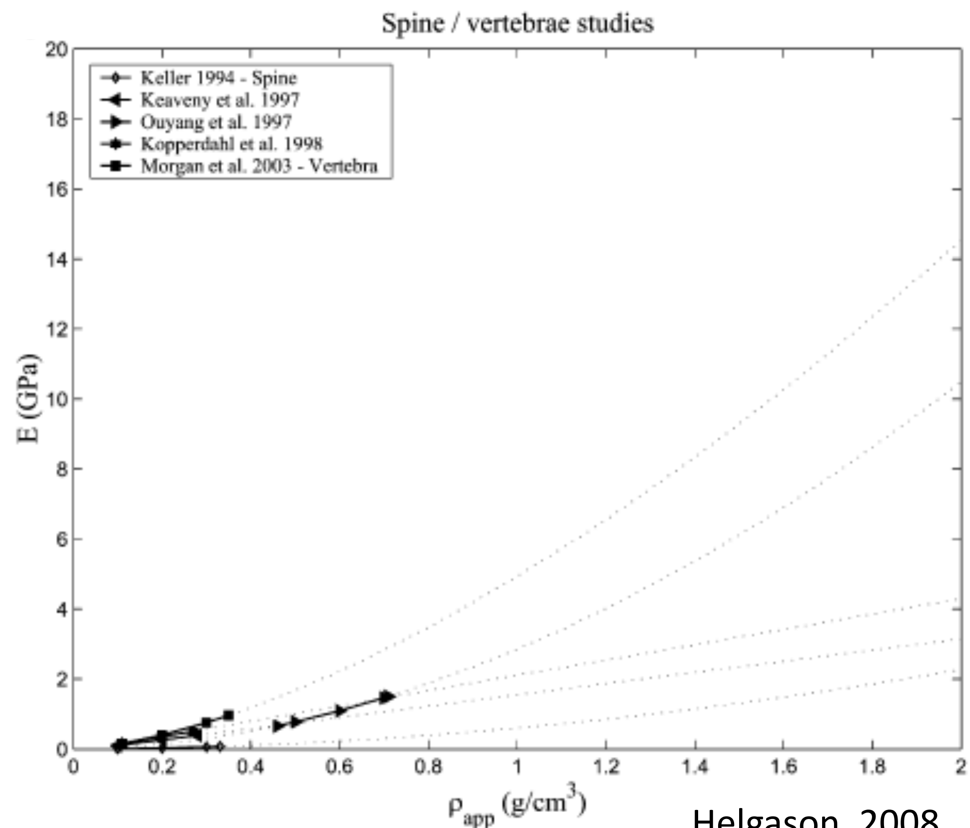


Helgason, 2008

Material Properties as Function of Bone Density

- Dependence on *anatomic site*

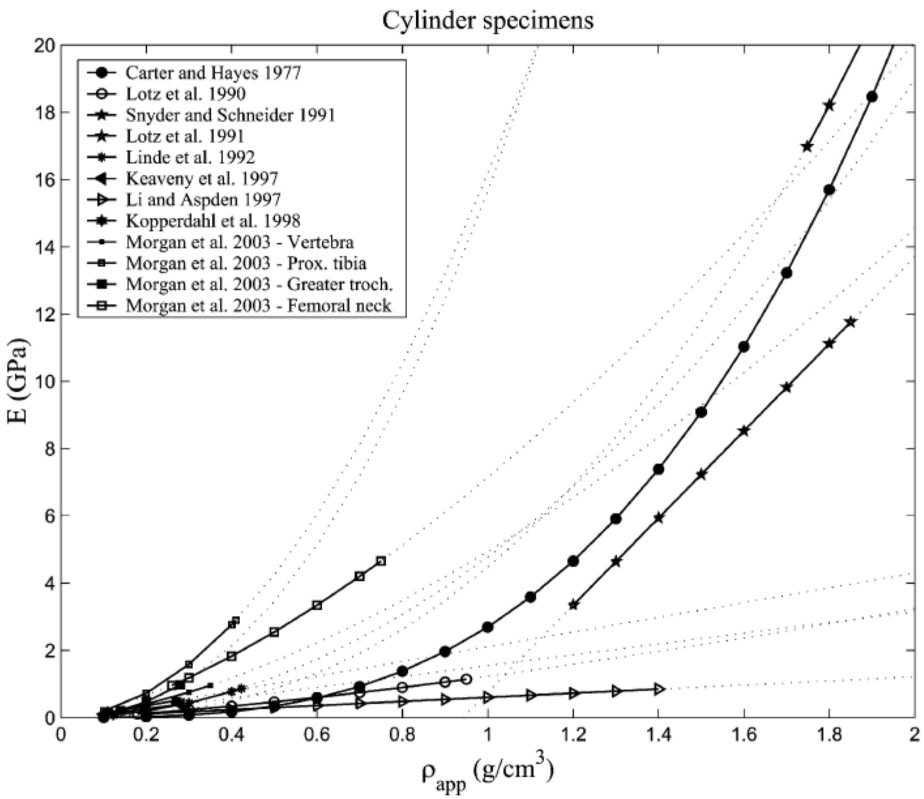


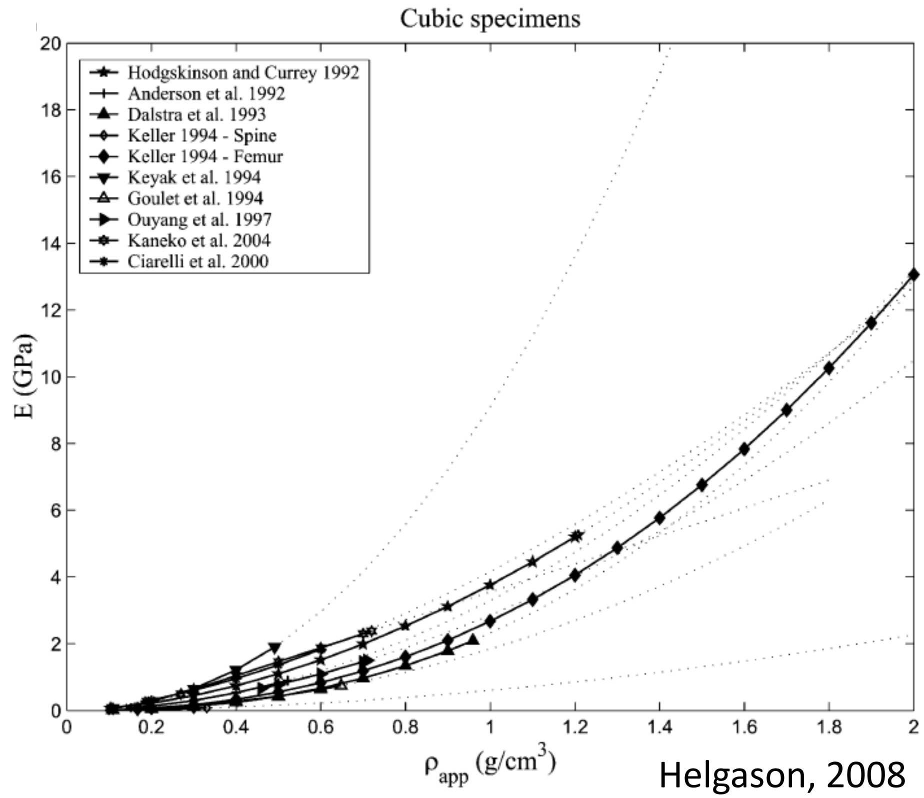


Helgason, 2008

Material Properties as Function of Bone Density

- Dependence on *experimental setup*





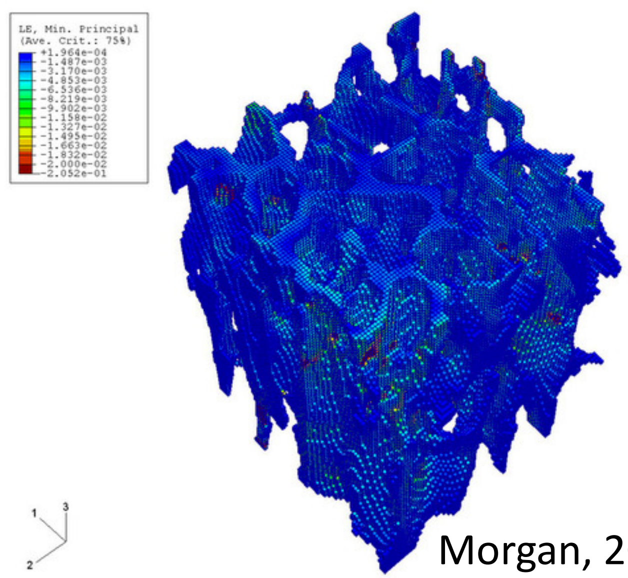
Helgason, 2008

µFEM

- Same principles as at FEM at the Organ Level

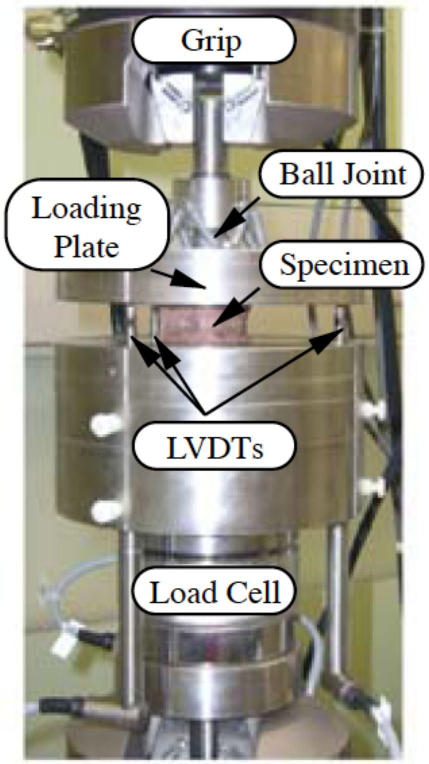
Creating the Model	Solving PDEs	Analysis and Interpretation of Results (Validation)
1. Geometry 2. Material Properties 3. Boundary Conditions		

- Differences:
  - Trabecular bone: e.g. distribution of stresses and strains)
  - Mesh elements = voxels
  - Millions of Element
  - Constant Mechanical Properties

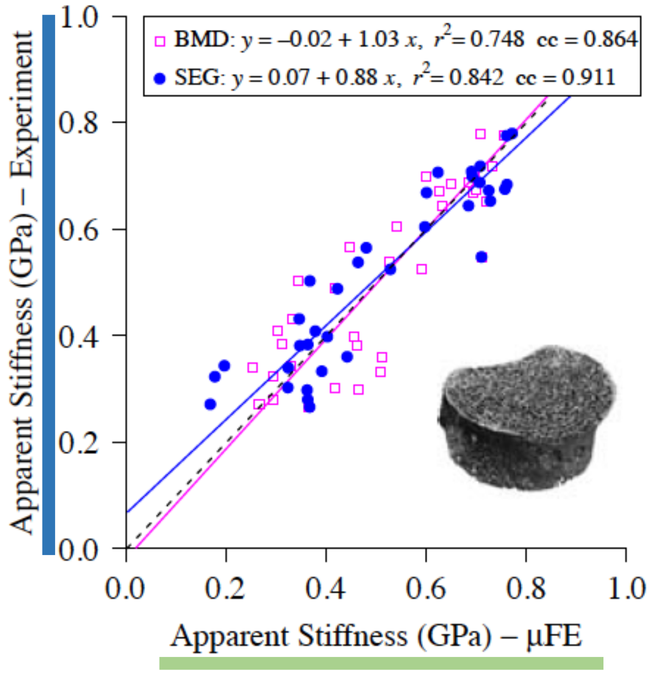


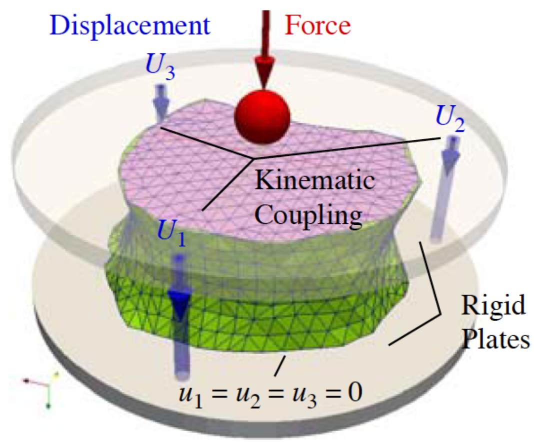
Morgan, 2005

μFEM - Validation



Experiment





FE simulation

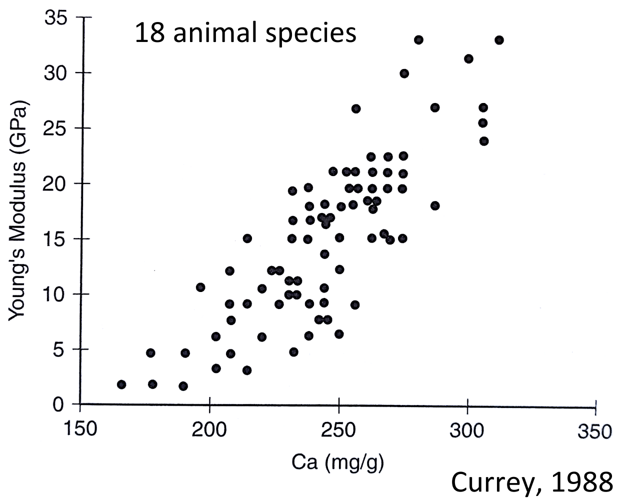
Pahr, 2011

The Cellular Level

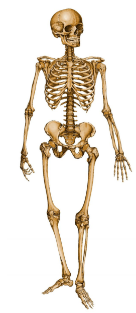
	BODY LEVEL	ORGAN LEVEL	TISSUE LEVEL	CELLULAR LEVEL
Biomechanics	Rigid Object Models	Deformable Continuum Models		Statistical Models

Influence of Bone Mineral Component and Collagen

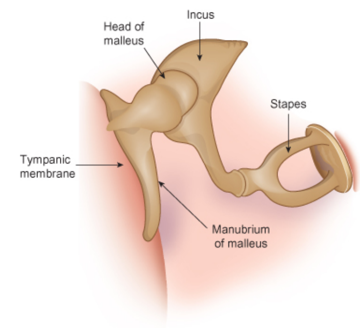
- Hydroxyapatite (HA) makes bone stiff



40% HA



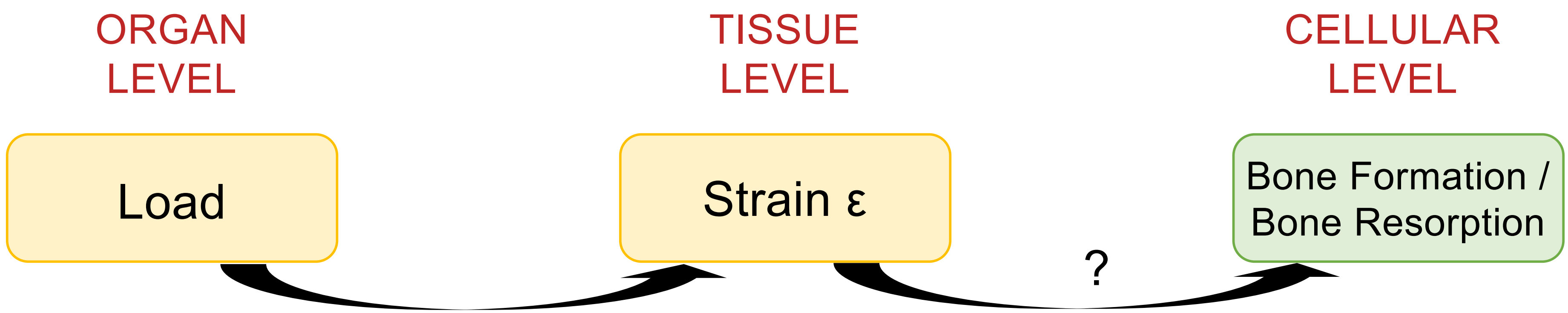
60% HA



90% HA

- Collagen makes bone flexible
  - Dependence on cross-linking among fibers:
    - Few cross-linking = helix might separate
    - Many cross-links = less ability to absorb energy

Cells as sensors - Bone Mechanobiology



- To date the mechanism that links matrix deformation to regulation of cellular activity is not identified
- There are hypothesis:
  - Osteocytes sense strains
  - Osteocytes sense fluid shear stress
  - Osteocytes are affected by change of chemical environment
  - …