Bone: Structure and Function

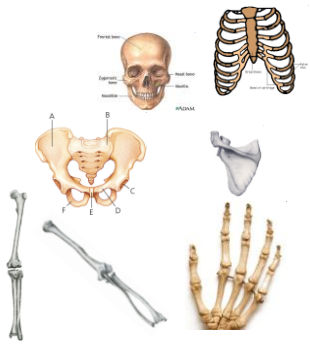
Dr. Warren Macdonald

Bone

- Structure
- Function
- Mechanical properties

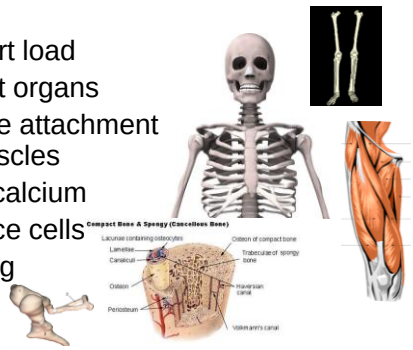
Types of bones

- Flat bones
  - Skull
  - Ribs, sternum
  - Scapula
  - Pelvis
- Long bones
  - Arms
  - Legs



Functions of Bone

- Support load
- Protect organs
- Provide attachment for muscles
- Store calcium
- Produce cells
- Hearing



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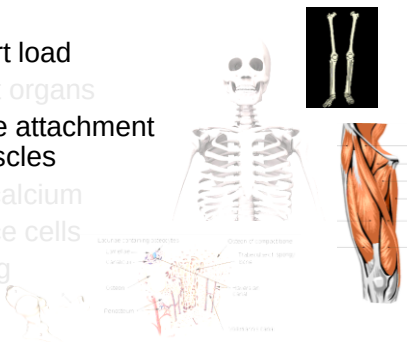
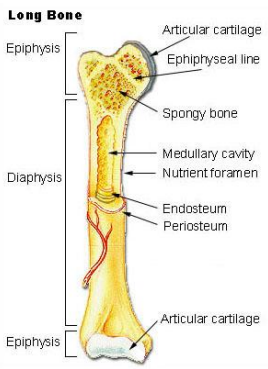


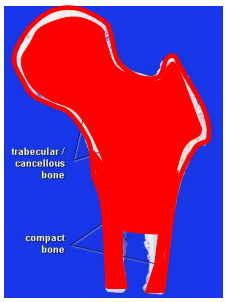
Terminology

- diaphysis
- epiphysis
- metaphysis
- articular cartilage
- periosteum
- endosteum
- medullary canal

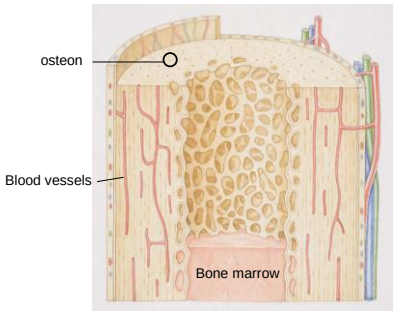


Structure of bone

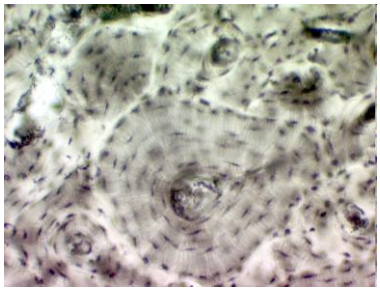
- Cortical bone
  - Compact bone
- Trabecular bone
  - Spongy bone
  - Cancellous bone



Cortical bone

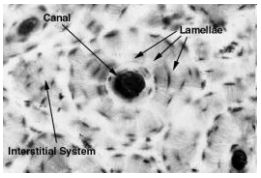


Osteon



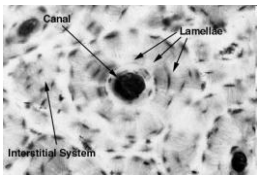
Osteon

- Lamellae – concentric rings of bone tissue
  4-20 lamellae/osteon
  3-7 μm width



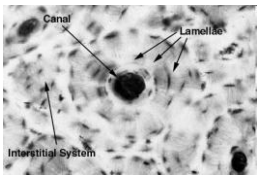
Osteon

- Lamellae – concentric rings of bone tissue
- Cement line – outer ring of osteon



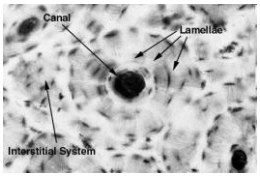
Osteon

- Lamellae – concentric rings of bone tissue
- Cement line – outer ring of osteon
- Haversian canal – blood vessels
  50-100 μm in diameter



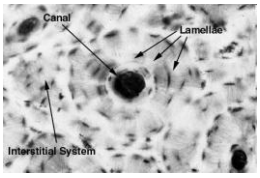
Osteon

- Lamellae – concentric rings of bone tissue
- Cement line – outer ring of osteon
- Haversian canal – blood vessels
- Lacunae - holes for osteocytes



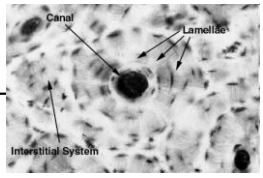
Osteon

- Lamellae – concentric rings of bone tissue
- Cement line – outer ring of osteon
- Haversian canal – blood vessels
- Lacunae - holes for osteocytes
- Canaliculi- osteocyte communication



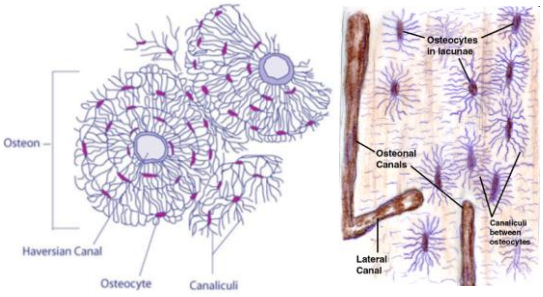
Osteon

- Lamellae – concentric rings of bone tissue
- Cement line – outer ring of osteon
- Haversian canal – blood vessels
- Lacunae - holes for osteocytes
- Canaliculi- osteocyte communication
- Volkmann's canal – transverse blood vessels

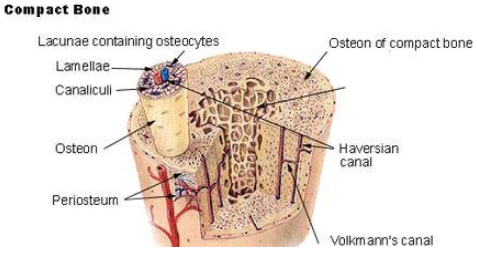


Cross section

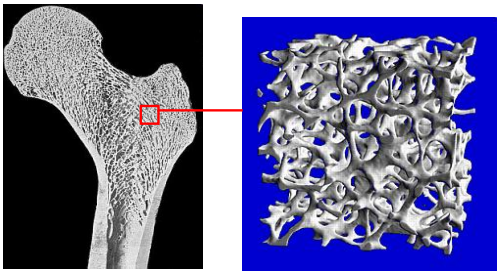
Longitudinal



Cortical bone



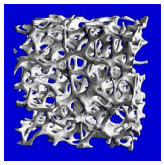
Trabecular bone



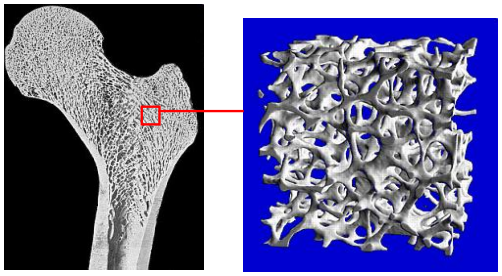
- Found in epiphysis and metaphysis of long bones

Trabecular bone

- Structure
  - Low density, high surface area
  - Surrounded by red marrow
  - Highly vascular
- Quantifiable
  - Bone volume/total volume
  - Trabecular thickness
  - Trabecular spacing
  - Trabecular shape (rod, plate)
  - Anisotropy



Trabecular bone



Bone structure

- Apparent density (ρ_{app})
  = bone mass/total volume
- Cortical bone density: 1.86 ± 0.06 g/cm^3
  10% porosity (volume of spaces/volume bone)
- Trabecular bone density: 0.3 ± 0.09 g/cm^3
  50-90% porosity
- Tissue density (ρ_{tiss})
  = bone mass/bone volume = 2.0 g/cm^3

Bone content

- Organic components (osteoid)
  - 90% collagen

Bone content

- Organic components (osteoid)
  - 90% collagen I
  - 10% GAGs, glycoproteins

Organic components = 50% bone volume
25% bone by weight

Bone content

- Organic components (osteoid)
- Mineral
  - Hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$
  - Crystals 2-5 nm thick, 15 nm wide, 20-50 nm long
  - Ca/P ratio changes
  - PO_4 sometimes carbonate

Bone content

- Organic components (osteoid)
- Mineral components

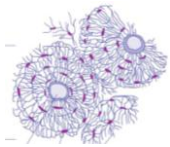
Organic components = 50% bone volume
25% bone weight
Mineral components = 50% bone volume
75% bone weight

Bone content

- Organic components (osteoid)
  - Tensile strength
- Mineral components
  - Compressive strength

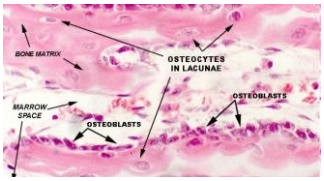
Bone cells

- Osteocytes
  - Sit within bone matrix
  - Communicate with canaliculi
  - Live for 25 years
  - Function = mechano-sensing, maintenance



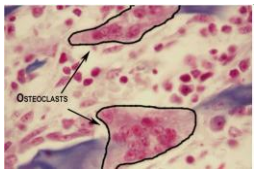
Bone cells

- Osteocytes
- Osteoblasts
  - Lay down bone
  - Make collagen fibers and proteoglycans
  - Deposit apatite
  - Can become osteocyte



Bone cells

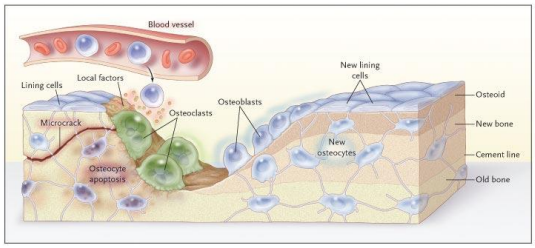
- Osteocytes
- Osteoblasts
- Osteoclasts
  - Remove bone
  - Multinucleated, larger than osteoblasts
  - Secrete H^+ to dissolve mineral
  - Secrete collagenase to clear protein



Bone turnover

- All bone in your body is replaced in 3 years
- Basic multicellular units (BMUs)
  - Bone lining cells
  - Osteoclasts
  - Osteoblasts

BMU



BMU

- Origination – damage or mechanical stimuli triggers start of process
- Bone lining cells recruit osteoclasts
- Osteoclasts resorb bone – create resorption pit
- Osteoclasts die (apoptosis)
- Osteoblasts fill pit with osteoid
- Mineralization of matrix
- Maturation of matrix

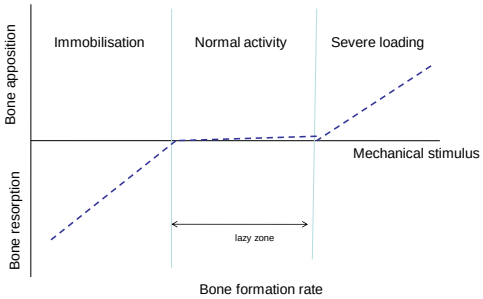
BMU Time line

- Activation – 3 days
  - Sense damage, recruit osteoclasts
- Resorption – 30 days
  - Osteoclasts to dig a pit
- Formation – 90 days
  - Osteoblasts lay down osteiod
- Mineralization – 6 months
  - 60% occurs within 24 hours

Bone turnover

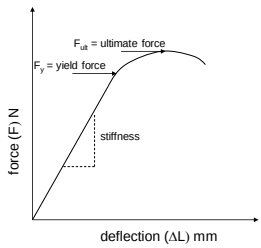
- Trabecular bone
  - On the surface
- Cortical bone
  - Within an osteon

Bone Maintenance



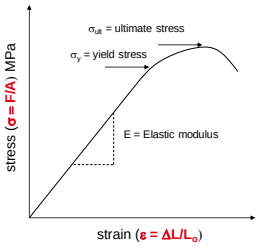
Bone mechanics

- Force/displacement

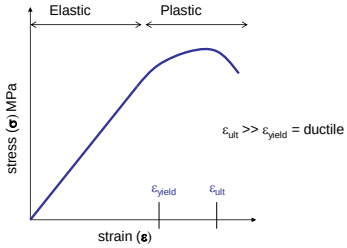


Bone mechanics

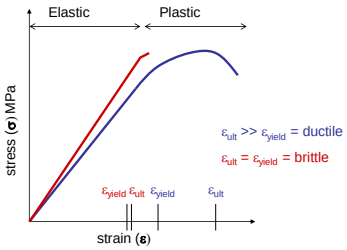
- Stress/strain curve



Bone mechanics

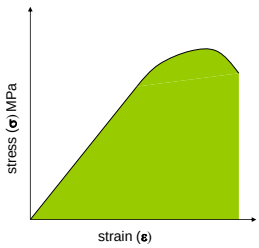


Bone mechanics

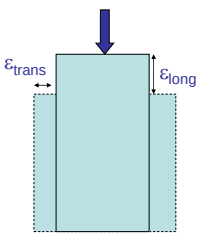


Bone mechanics

- Absorbed energy = area under curve



Bone biomechanics



Poisson's ratio

$\nu = \varepsilon_{trans} / \varepsilon_{long}$

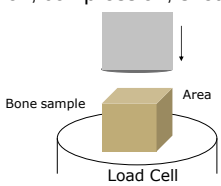
$\nu_{bone} = 0.3$

$\varepsilon = \delta L / L_{init}$

Bone biomechanics

Determining bone strength

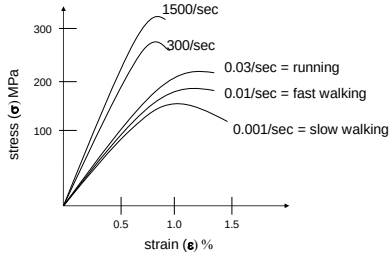
- Load machined samples of bone
- Tension, compression, shear, bending



Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate



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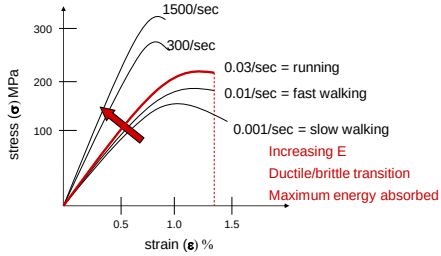


Bone biomechanics

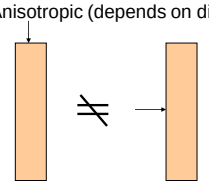
Factors that affect mechanical properties:

1. Loading rate
   - Viscous behaviour = E increases with load rate
   - Bones adapted for strain rates during strenuous activity (absorb maximum energy)

Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   – Anisotropic (depends on direction)



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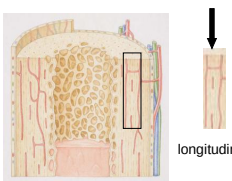

longitudinal

	Ultimate strength (σ) MPa	Modulus (E) MPa
Longitudinal		
Compression	193	17

Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
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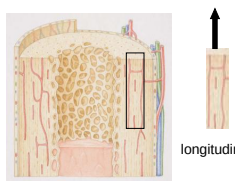

longitudinal

	Ultimate strength (σ) MPa	Modulus (E) MPa
Longitudinal		
Compression	193	17
Tension	133	17

Bone biomechanics

Factors that affect mechanical properties:

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2. Orientation
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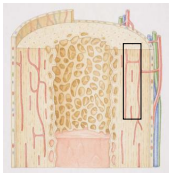

	Ultimate strength (σ) MPa	Modulus (E) MPa
Longitudinal		
Compression	193	17
Tension	133	17
Shear	68	3.3

Bone biomechanics

Factors that affect mechanical properties:

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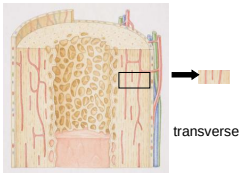
2. Orientation
   - Anisotropic (depends on direction)

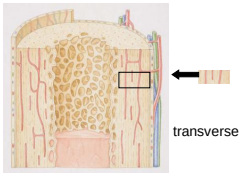


	Ultimate strength (σ) MPa	Modulus (E) MPa
Longitudinal		
Compression	193	17
Tension	133	17
Shear	68	3.3
Transverse		
Compression	133	11.5

Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)

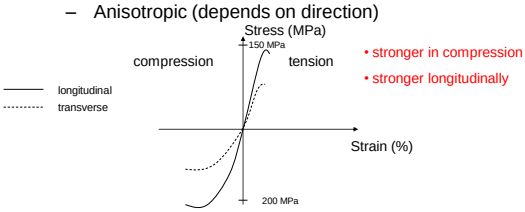


	Ultimate strength (σ) MPa	Modulus (E) MPa
Longitudinal		
Compression	193	17
Tension	133	17
Shear	68	3.3
Transverse		
Compression	133	11.5
Tension	51	11.5

Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)



Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)
   - Required constants

   E_l, E_t, G, ν_l, ν_t,

Bone biomechanics

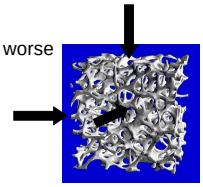
Failure of bone:

1. Tends to occur in shear (so a
2. Orientation
   - Under bending or compression, at 45° to long axis (butterfly fragment)
   - Under torsion – spiral fracture

Bone biomechanics

Factors that affect mechanical properties:

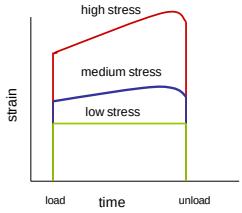
1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)
   - Required constants
     E_l, E_t, G, ν_l, ν_t,
   - Trabecular bone even worse
   - E_1, E_2, E_3,
   - G_{12}, G_{23}, G_{13},
   - ν_{12}, ν_{23}, ν_{31}



Bone biomechanics

Factors that affect mechanical properties:

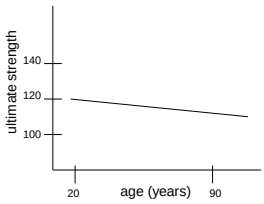
1. Loading rate
2. Orientation
3. Creep
   - strain changes with constant load
   = viscoplastic



Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
3. Creep
4. Age
   - less stiff
   - less strong
   - more brittle

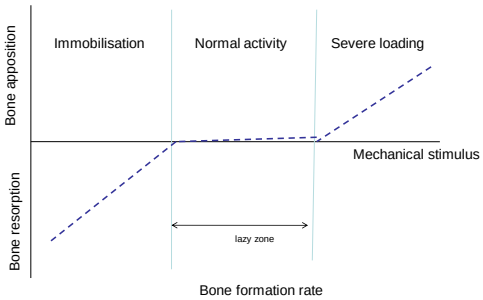


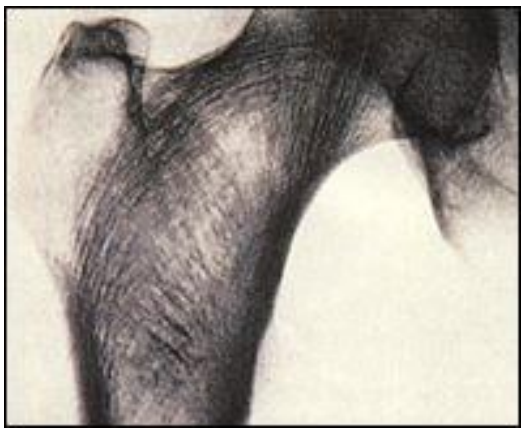
Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
3. Creep
4. Age
   - less stiff: elastic modulus decreases
     30 yr = 17 GPa, 90 yr = 15.6 GPa
   - less strong: ultimate strength decrease
     2% / decade
   - more brittle: energy absorption decreases
     7% / decade

Bone Maintenance





Summary

- Function
- Structure
  - Cortical
  - Trabecular
- Contents
  - Mineral
  - Protein
- Material properties
  - Viscoelastic
  - Anisotropic
  - Viscoplastic