Medical Biophysics II.

Biomechanics of Bimolecules and tissues

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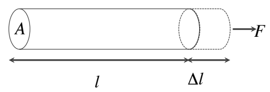
Basics of tissue mechanics

Hooke's law

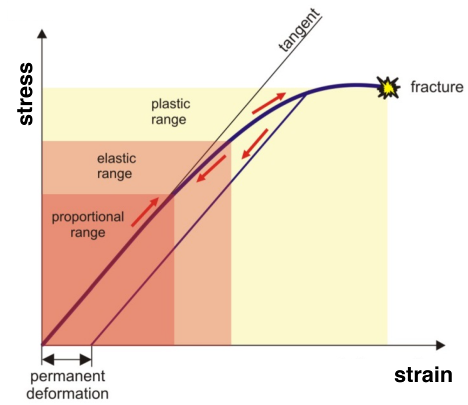


$$\frac{F}{A} = E\,\frac{\Delta l}{l}$$

$$\sigma = E\varepsilon$$

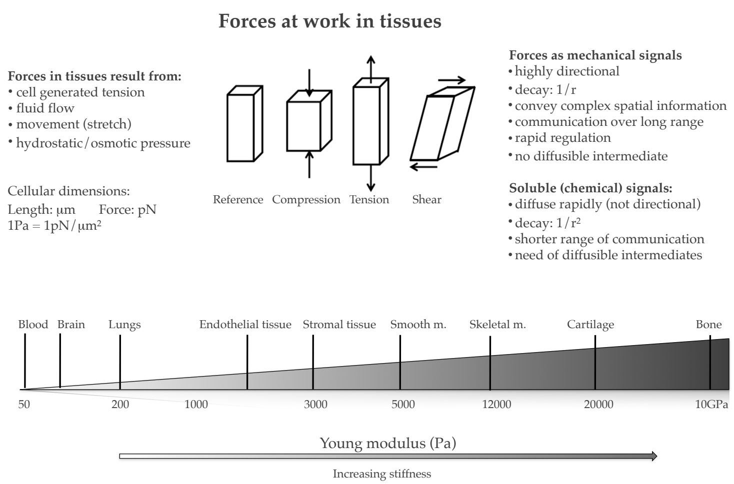
F = force
A = cross sectional area
l = rest length
Δl = extension

Stress-strain diagram



F/A = σ = stress (N/m^2 = Pa)
Dl/l = ε = strain (dimensionless)
E= σ / ε Young's modulus (Pa)
(elastic modulus - the name is misleading! it describes stiffness)

Biomechanics at the cellular level



Flashback: What did you learn about ultrasound propagation…. ?

How much is the speed of sound in different tissues?

Acoustic properties of various tissues are determined by their mechanical properties.

	E (GPa)	*K* (GPa^{-1})	c_{sound} (m/s)
Bone	18	0.05	3600
Muscle	7x10^{-5}	0.38	1568

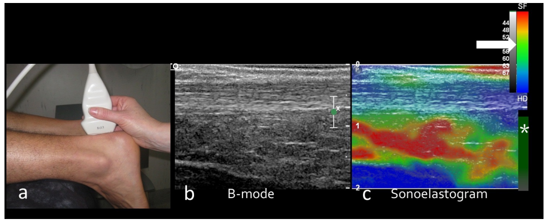
$$c_{sound} = \frac{1}{\sqrt{\rho \cdot \kappa}}$$

$$\kappa = \frac{-\Delta V/V}{\Delta p}$$

strain (−ΔV/V), stress (Δp), compressibility (κ)

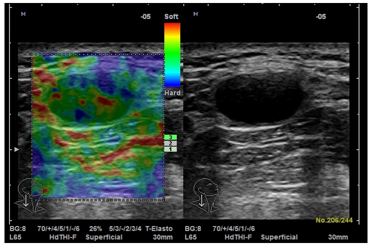
Greater Young-modulus, faster sound speed

Diagnostic usage: sonoelastography

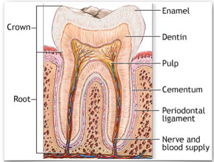


Achilles examination

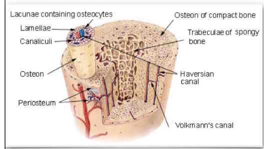
Lymph node examination



Tooth



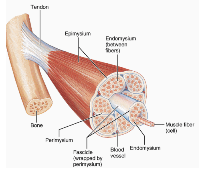
Bone



Main components:
collagen (organic),
apatite (inorganic)

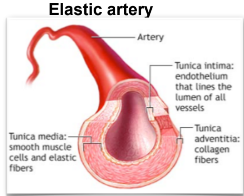
Organic compound gives toughness
Inorganic compound gives stiffness

Skeletal muscle



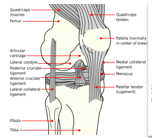
Passive mechanics: titin, desmin
Active mechanics : actin, myosin

Elastic artery



collagen, elastin

Ligament

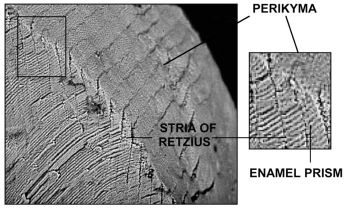


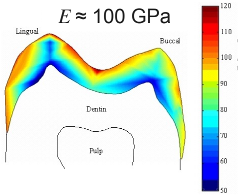
Tendon

Cartilage

Collagen, proteoglycans (water)

Tooth enamel

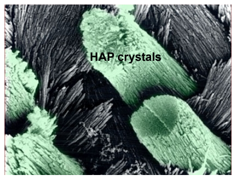




Structural unit: enamel prism (rod)

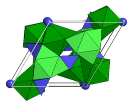
Composition: 92% Hydroxy-apatite (HAP)

Stiff, hard, brittle



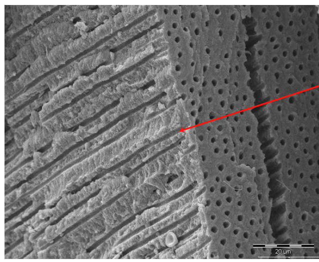
The stiffest and hardest material of the human body, but brittle!

$Ca_{10}(PO_4)_6(OH)_2$
$Ca_{10}(PO_4)_6F_2$



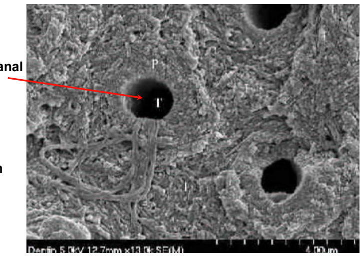
Hexagonal ionic crystal
20-60 nm x 6 nm - dentin, bone
500-1000 nm x 30 nm - enamel

Dentin



Dentin canal

Collagen fibers



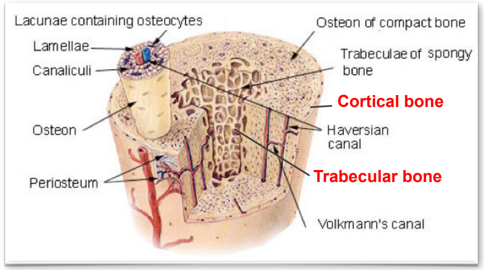
Composition: 35% organic material (collagen) + water, 65% hydroxy-apatite

Structure: collagen matrix with attached hydroxyapatite crystals

The two components (organic and inorganic) provide the exceptional mechanical properties of dentin: moderately hard, stiff and tough. $E \approx 15$ GPa

Bone

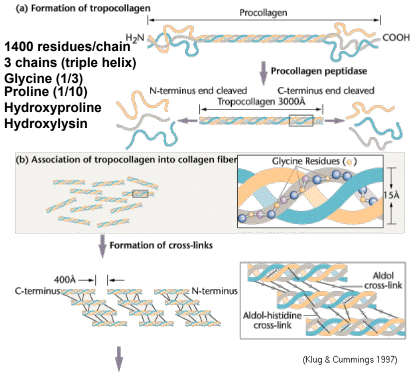
Due to the different structure of bone tissue along the cross section of long bones, the **Young's modulus distribution is anisotropic**. Denser cortical bone has greater Young's modulus vs. the trabecular bone..
Young's modulus: 5-20 GPa
Decalcified bone (acid treatment): flexible
Removal of organic compounds (heating): brittle

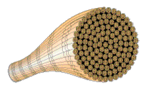


Calculation:

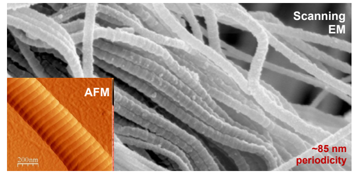
Bone has a Young's modulus of about 18 GPa. Under compression, it can withstand a stress of about 1.60×10^{8} Pa before breaking. Assume that a femur (thigh-bone) is 46 cm long, and calculate the amount of compression this bone can withstand before breaking.

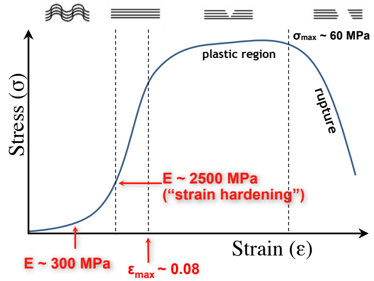
Collagen





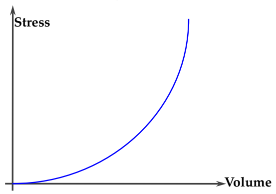
Post translational modification is necessary for tropocollagen polymerization
Hydroxylation of lysin and praline residues requires vitamin-C as cofactor!





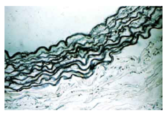
Elastic arteries

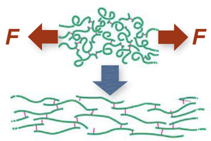
Non-liear elasticity
Strain is not linearly proportional to stress.

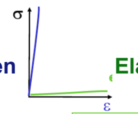


Determinants of vascular elasticity:
- Elastin
- Collagen
- Smooth muscle

Implications of vascular easticity:
- Storage of potential (elastic) energy
- Dampening of pressure pulses
- Constant flow rate

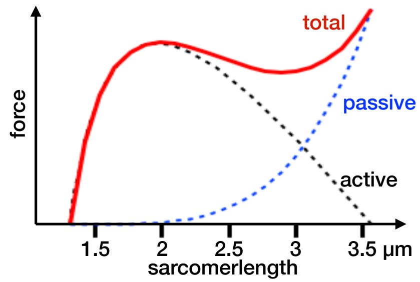


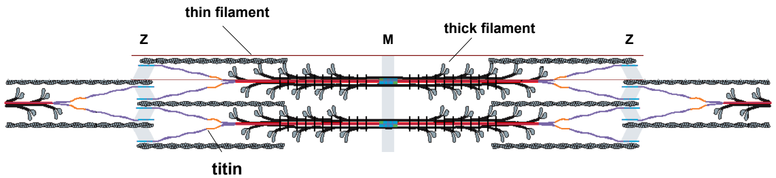




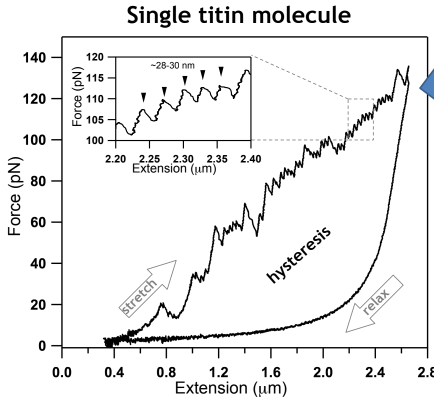
Collagen	**Elastin**
E = 300 MPa .... 2 500 MPa	E = 0,1 MPa .... 0,4 MPa
$\sigma_{sz} \approx 60$ MPa $\varepsilon_{sz} \approx 0{,}08$	$\sigma_{sz} \approx 0{,}6$ MPa $\varepsilon_{sz} \approx 3$
strength	**elasticity**

Titin: the elastic filament of the sarcomere

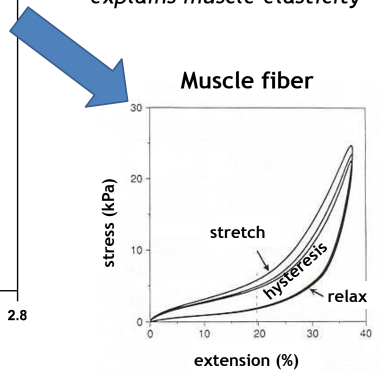




Titin is the main determinant of muscle elasticity

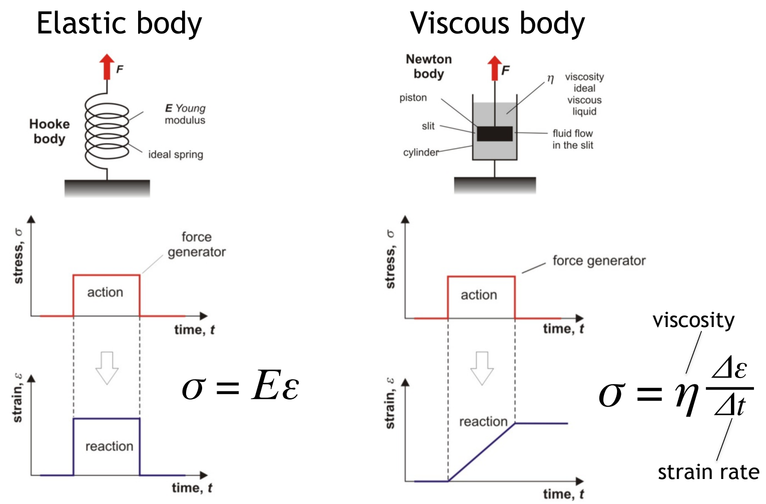


From molecule to tissue
Titin's molecular elasticity explains muscle elasticity



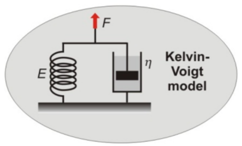
Viscoelasticity

(mechanical model)



Viscoelasticity

(mechanical model)

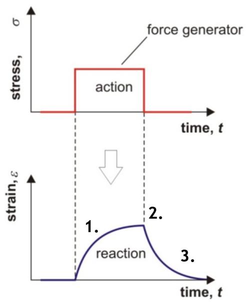


Viscoelasticity means to co-appearance of viscous and elastic behavior. A

model: parallel connection of spring and dashpot

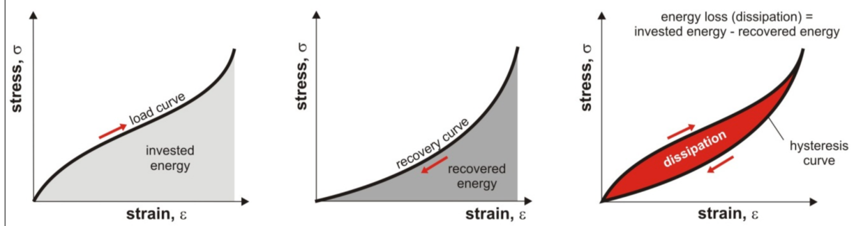
(Kelvin-Voight model)

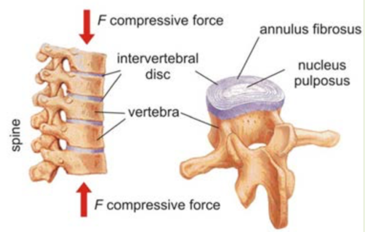
Spring: ideal elastic (Hooke) body
Dashpot: ideal viscous (Newton) body

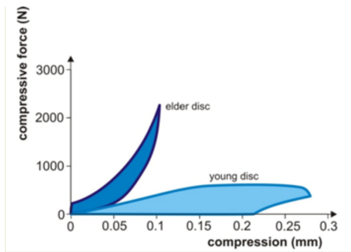


1. Upon stretch, the extension of the spring is slowed down by the dashpot.
2. Extension stops when the elastic spring force equals the external force.
3. When the external force is quenched, the contraction of the spring is slowed down by the dashpot.

Energy dissipation in viscoelastic system

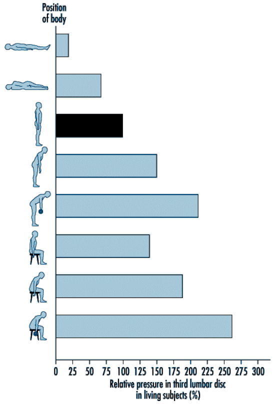




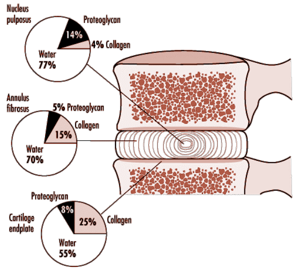


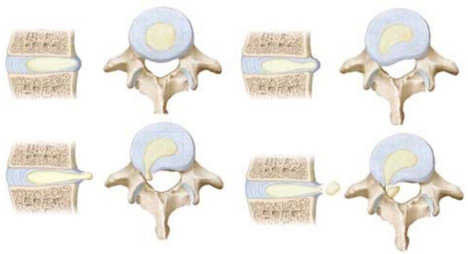
Example I. Consequences of increased mechanical stress on intervertebral discs (*discus hernia*)

Relative stress on L3 intervertebral disc at various positions



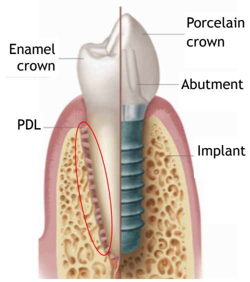
Source: Adapted from Nachemson 1992.

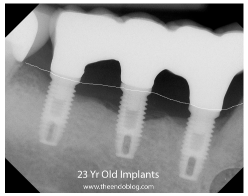




Example II: Implants vs natural tooth

PDL makes the difference!





Absence of PDL results in:

- **loss of masticatory force perception**
- **loss of viscoelastic dampening**
- **loss of force sensory mechanism**
- **no implant movement**

Implant is in direct contact with bone tissue

⬇

Increased compressive stress during mastication

⬇

Bone loss (0.2 mm /yearv)
Loss of gingival height

Implants ⇔ Root canal treatment

Calculations

To stretch a relaxed biceps muscle 3 cm requires a force of 25 N. To do the same stretch of a contracted muscle at its maximal tension requires a force of 500 N. Find the Young's modulus for both relaxed and tense muscle tissue. Assume the biceps is a uniform cylinder of length 20 cm and diameter 6 cm. (59 kPa, 1.18 MPa)

Collagen fiber is stressed with 12 N force. The cross-sectional area of the fiber is 3 mm^2, its coefficient of elasticity is 500 MPa. Give the percentage of relative extension. (0.8 %)

The length of an elastic thread used in orthodontics is 6 cm, its cross-sectional area is 1 mm^2, its coefficient of elasticity is 5 MPa. We extend the thread with 40 %. How large is the retracting force and what is the amount of elastic energy stored in the thread?(F=2N,E=24mJ)