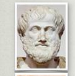
Physical Bases of Dental Material Science

Biomechanics:
structure, mechanical and other properties of tissues

Zsolt Mártonfalvi

History of biomechanics



Aristotle (384-322 BC) - First book on biomechanics, *De Motu Animalium* (On the Movement of Animals).

Leonardo da Vinci (1452-1519) - First to study anatomy in the context of mechanics. He analyzed muscle forces as acting along lines connecting origins and insertions and studied joint function.

Galileo Gailei (1564-1642) - Suggested that bones are hollow, and this affords maximum strength with minimum weight.

René Descartes (1596-1650) - Suggested a philosophic system whereby all living systems, including the human body (but not the soul), are simply machines ruled by the same mechanical laws.

Pierre Fauchard (1678 - 1761) – Father of modern dentistry. – orthodontics

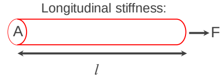
Today biomechanics is an extremely intensely explored research area. One of the main motivations are "tissue engineering" which lend the hope of replacing biological tissues with artificial materials.

Biomechanics principles in brief

Hookean elasticity

- Spring constant (k=F/ΔL) is a parameter of material properties.
- Spring constant (k) depends on the shape parameters of a body and the direction of the applied force,
- It expresses the force needed for unit deformation. (N/m)

Longitudinal stiffness:

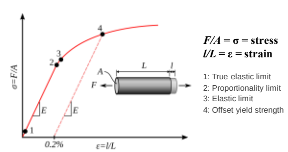


$$\frac{F}{A} = E\frac{\Delta l}{l}$$

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

$F/A = \sigma$ = stress (N/m^2 = Pa)
$\Delta l/l = \varepsilon$ = strain (dimensionless)
$E = \sigma / \varepsilon$ Young's modulus (Pa)

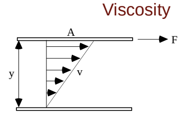
Stress-strain curve



$F/A = \sigma$ = **stress**
$l/L = \varepsilon$ = **strain**

1: True elastic limit
2: Proportionality limit
3: Elastic limit
4: Offset yield strength

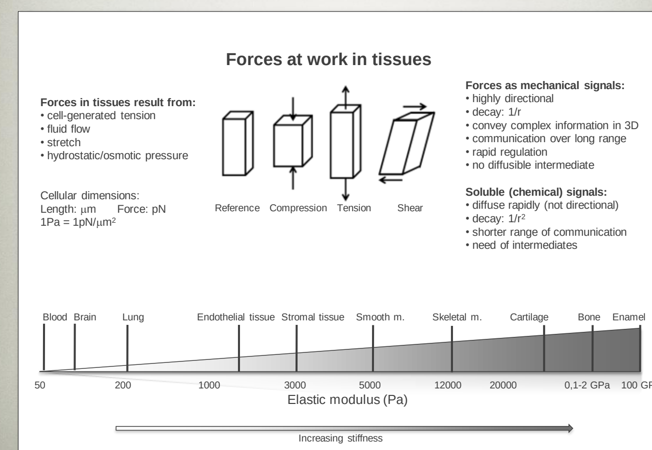
Viscosity



$$\frac{F}{A} = \eta\frac{\Delta v}{\Delta y}$$

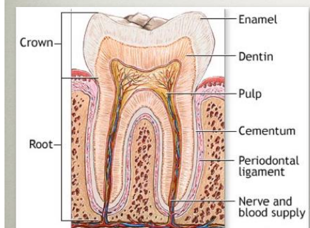
F	=shear force
A	=area of fluid layer
η	=viscosity
v	=flow velocity
y	=distance between fluid layers
F/A	=shear stress (τ)
Δv/Δy	=velocity gradient (D)

Biomechanics at the Cellular Level

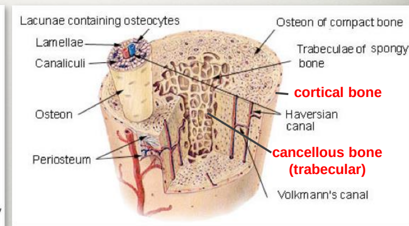


Hard tissues

Tooth

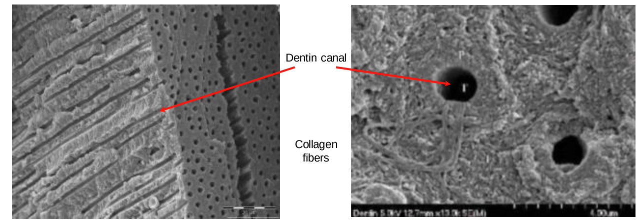


Bone



Major biomaterial components: collagen, apatite

Dentin

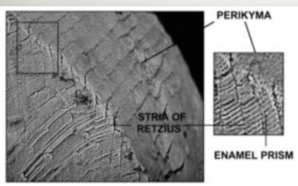


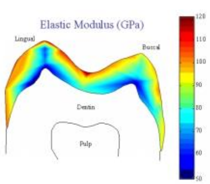
Composition: 35% organic material (collagen) + water, 65% hydroxy-apatite

Structure: collagen matrix with attached hydroxy-apatite crystals

Biomechanics: moderately hard, very strong and tough and flexible

Tooth enamel

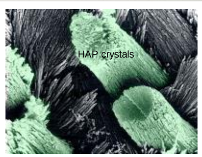




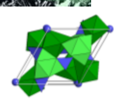
Structural unit: enamel prism (rod)

Composition: 92% Hydroxy-apatite (HAP)

Stiff, hard, brittle



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

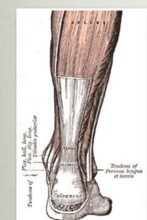


Hexagonal ionic crystal
20-60 nm x 6 nm - dentin, bone
500-1000 nm x 30 nm - enamel

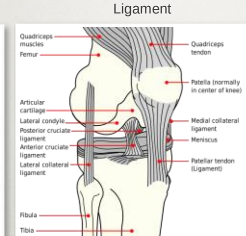
Hardness (Vickers)	Young's modulus	Tensile strength
$HV \approx 6$ GPa	$E \approx 140$ GPa	$\sigma_{EZ} \approx 60$ MPa Bending ≈ 500 MPa Compression
$HV \approx 3\text{-}6$ GPa	$E \approx 90\text{-}100$ GPa	$\sigma_{EZ} \approx 50$ MPa Bending ≈ 400 MPa Compression

Soft tissues

Tendon



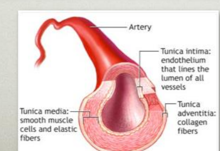
Ligament



Cartilage

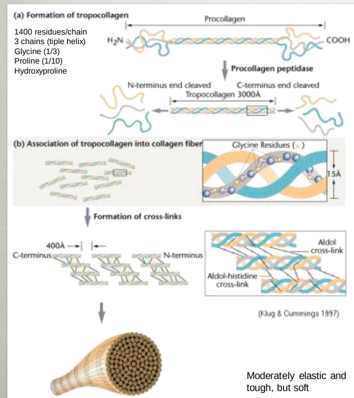
Major biomaterial component: collagen

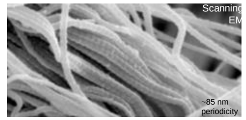
Elastic artery



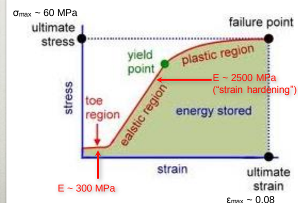
Major biomaterial components: collagen, elastin

Collagen





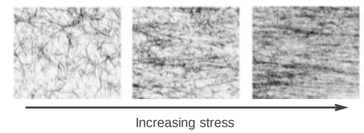
Strain hardening



Collagen responses to force

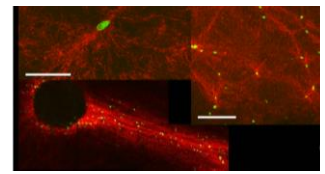
(forces in the extracellular matrix)

Stretched collagen gel



Individual fibers in a stretched collagen matrix align to the direction of stress. The structural alignment of the extracellular matrix depends on the stress.

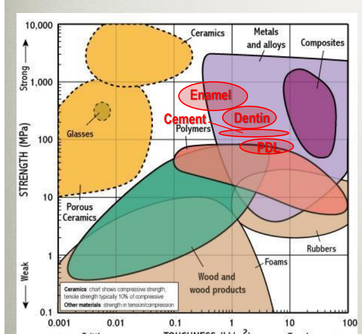
Cells in collagen matrix



Green: nucleus
Red: collagen fibers

The presence of cells in a collagen network induces stress variations and modifies the network texture in its vicinity.

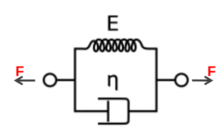
Summary of dental biomechanics



	PDL (≈ collagen)	Dentin (≈ 1/3 collagen, 2/3 apatite)	Enamel (≈ apatit)
Young's modulus (E) (GPa)	0,3-2,5	10-20	90-100
Tensile Strength (σ_{max}) (MPa)	60	110 (stretch) 300 (compression)	50 (stretch) 400 (compression)
Toughness (kJ/m²)	1-10	0,5-5	0,1-1
Hardness HV (GPa)		0,5-1	3-6

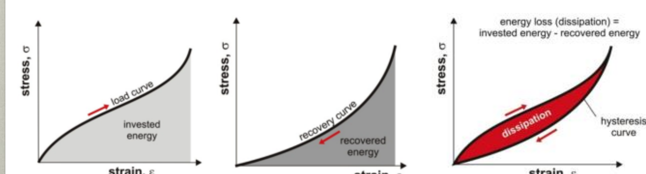
Visco-elasticity

(mechanical model)

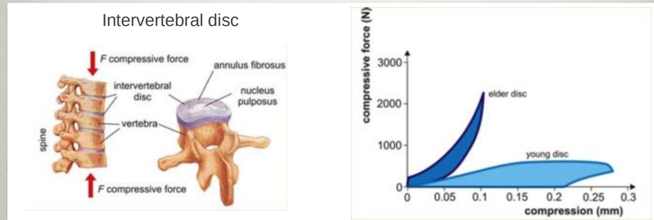


model: parallel connection of a spring and a dashpot

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

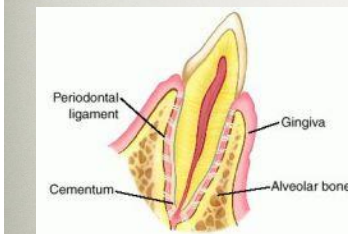


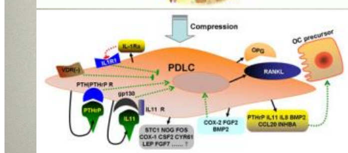
Visco-elasticity
(examples)



The periodontal ligament

Attaches the root to the bone and serves as a shock absorber.





FUNCTIONS

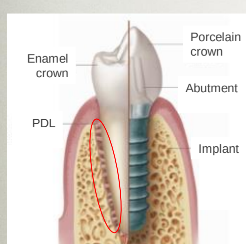
Proprioception: provides dental sensory function – perception of masticatory forces

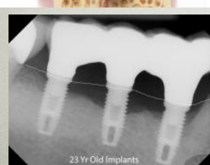
Host of cell lines: osteoclasts, osteoblasts, fibroblasts, cementoblasts, stem cells (orthodontics)

Dental force sensor
PDL cells convert mechanical signal to chemical signals. - Bone remodelling

Collagen based elastic properties

Implants vs nastural tooth
PDL makes the difference!





Absence of PDL result in :
- **loss of masticatory force perception**
- **loss of visco-elastic (damper) effect**
- **loss of force sensory mechanisms**
- **No implant movement**

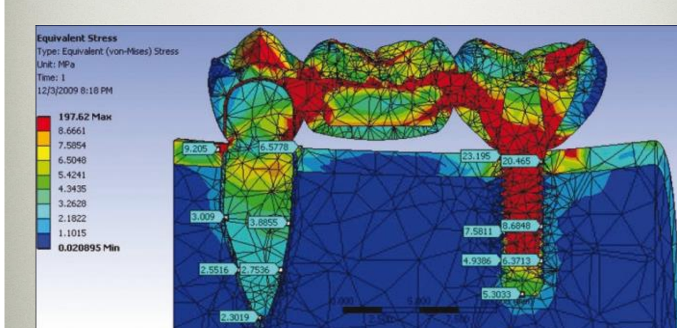
Implant is in direct contact with bone tissue

Increased compressive stress

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

Implants ⟷ Root Canal Treatment

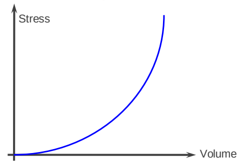
Stress distribution on tooth vs implant



Biomechanics of elastic arteries

Non-liear elasticity

Strain is not linearly proportional to stress.

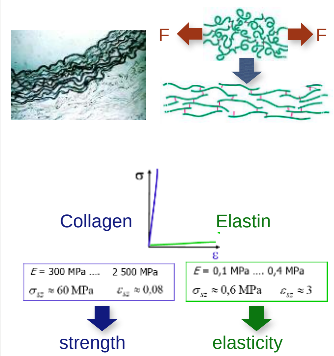


Determinants of vascular elasticity:

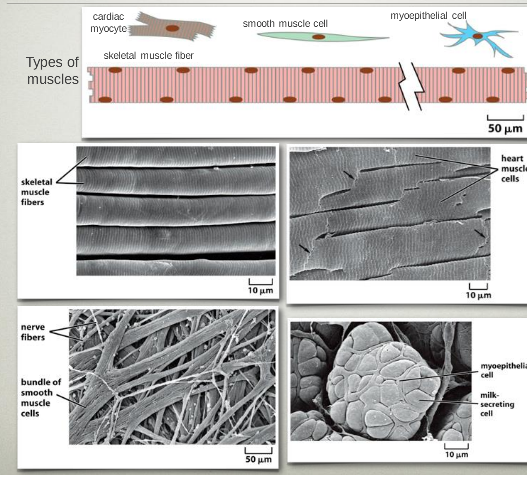
- Elastin
- Collagen
- Smooth muscle

Implications of vascular elasticity:

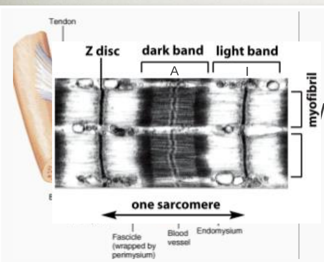
- Storage of potential (elastic) energy
- Dampening of pressure pulses
- Constant flow rate

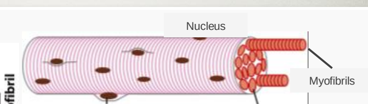


Muscle biomechanics

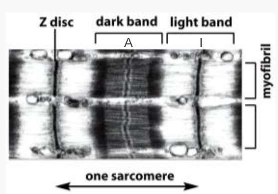


Skeletal muscle

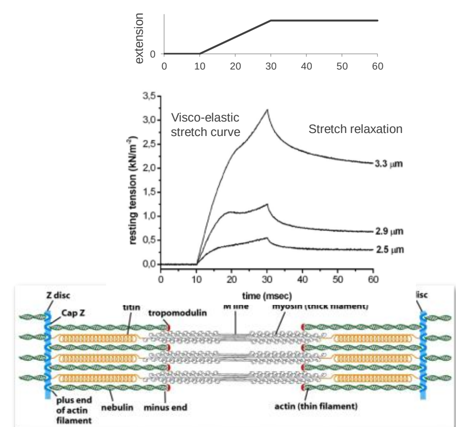




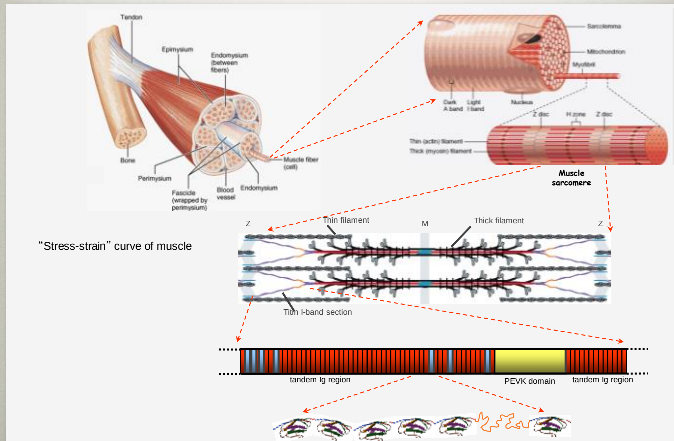
Passive force generation depends on sarcomere length



Passive force of muscle depends on sarcomere length



Titin:
Elastic filament in the muscle sarcomere



biopolyers mechanics

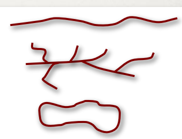
Polymers:
chains built up from monomers

Number of monomers: N>>1;
Typically, N~10^2-10^4,
but, in DNA, e.g.: N~10^9-10^{10}

Biopolymer	Monomer	Bond
Protein	Amino acid	Covalent (peptide bond)
Nucleic acid (RNA, DNA)	Nucleotide (CTUGA)	Covalent (phosphodiester)
Polysaccharide (e.g., glycogen)	Sugar (e.g., glucose)	Covalent (e.g., α-glycosidic)
Protein polymer (e.g., microtubule)	Protein (e.g., tubulin)	Secondary

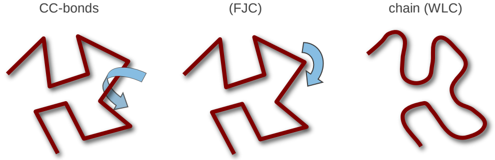
Shape of polymers

1. Linear
2. Branched
3. Circular

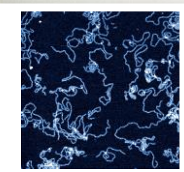


Shape of polymer chain changes dynamically. Possible mechanisms:

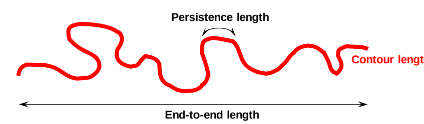
1. Rotation around CC-bonds
2. Freely jointed chain (FJC)
3. Bending, wormlike chain (WLC)

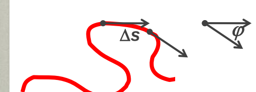


Parameters of an elastic biopolymer

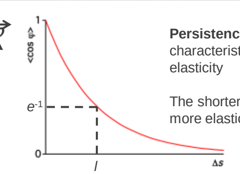


dsDNA molecules





$$\langle \cos\varphi \rangle = e^{-\frac{\Delta s}{l}}$$



Persistence length (*l*) is a characteristic parameter of polymer elasticity

The shorter the persistence length, the more elastic the molecule

Mechanics of polymers

Entropic elasticity mechanism

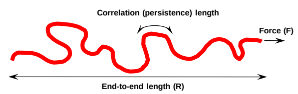
Thermal fluctuations of the polymer chain

Configurational entropy (orientational disorder of elementary vectors) increases.

The chain shortens.

Force needed to stretch an entropic chain

$$\frac{Fl}{k_B T} \sim \frac{R}{L}$$



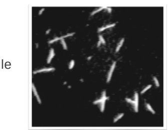
F=force
l=**persistence length**
k_B=Boltzmann's constant
T=absolute temperature
L=contur length
R/L=relative extension

Biopolymer elasticity

l = persistence length
L = contour length

Rigid chain
l >> L

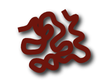
Microtubule



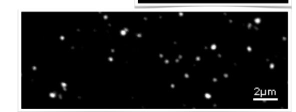
Semiflexible chain
l ~ L

Actin filament

Flexible chain
l << L



DNA



Visualization of biopolymer elasticity

Tying a knot on a single DNA molecule