

Physical Bases of Dental Material Science

Biomechanics:
structure, mechanical and other
properties of tissues

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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 Galilei (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

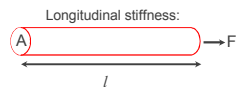
Today biomechanics is an extremely intensely explored research area. One of the main motivations are "tissue engineering" which lend the hope of replacing biological tissues with artificial materials.



Biomechanics principles in brief

Hookean elasticity

- Spring constant ($k=F/\Delta L$) 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)



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

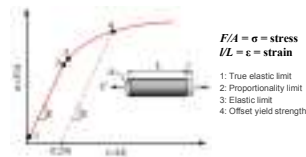
F = force
 A = cross-sectional area
 l = rest length
 Δl = extension

$$F/A = \sigma = \text{stress (N/m}^2 = \text{Pa)}$$

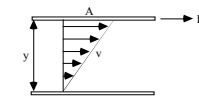
$$\Delta l/l = \epsilon = \text{strain (dimensionless)}$$

$$E = \sigma / \epsilon \text{ Young's modulus (Pa)}$$

Stress-strain curve



Viscosity



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

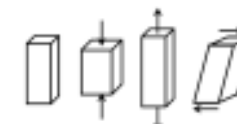
- F = shear force
- A = area of fluid layer
- η = viscosity
- v = flow velocity
- y = distance between fluid layers
- F/A = shear stress (τ)
- $\Delta v/\Delta y$ = velocity gradient (D)

Biomechanics at the Cellular Level

Forces at work in tissues

Forces in tissues result from:

- cell-generated tension
- fluid flow
- stretch
- hydrostatic/osmotic pressure



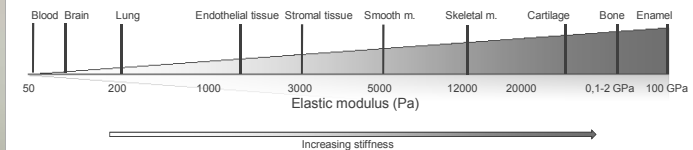
Cellular dimensions:
Length: μm Force: pN
 $1\text{Pa} = 1\text{pN}/\mu\text{m}^2$

Forces as mechanical signals:

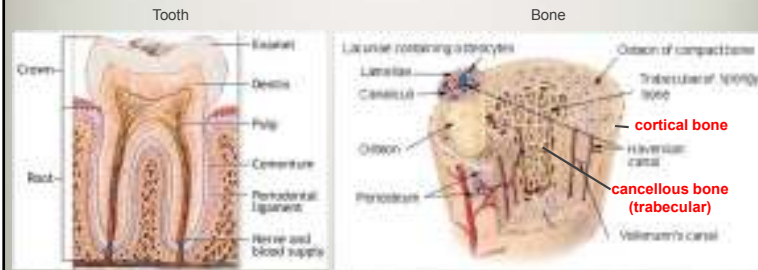
- highly directional
- decay: $1/r$
- convey complex information in 3D
- communication over long range
- rapid regulation
- no diffusible intermediate

Soluble (chemical) signals:

- diffuse rapidly (not directional)
- decay: $1/r^2$
- shorter range of communication
- need of intermediates

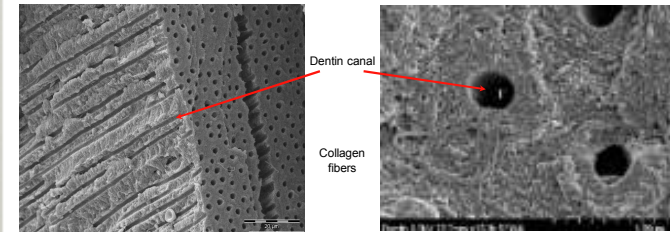


Hard tissues



Major biomaterial components: collagen, apatite

Dentin

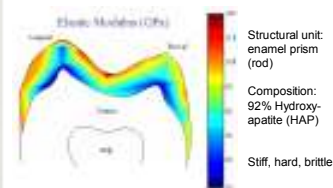
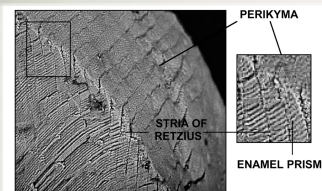


Composition: 35% organic material (collagen) + water, 65% hydroxy-apatite

Structure: collagen matrix with attached hydroxy-apatite crystals

Biomechanics: moderately hard, very strong and tough and flexible

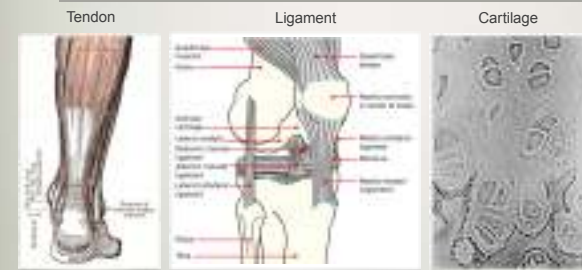
Tooth enamel



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
$HV \sim 6 \text{ GPa}$	$E \sim 140 \text{ GPa}$	$\sigma_{t2} \sim 60 \text{ MPa}$ Bending
		$\sim 500 \text{ MPa}$ Compression
$HV \sim 3-6 \text{ GPa}$	$E \sim 90-100 \text{ GPa}$	$\sigma_{t1} \sim 50 \text{ MPa}$ Bending
		$\sim 400 \text{ MPa}$ Compression

Soft tissues

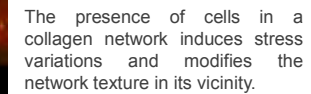
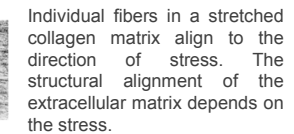
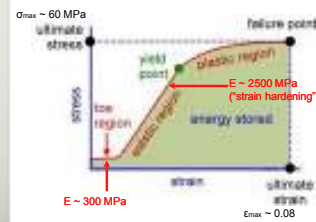


Major biomaterial component: collagen

Elastic artery

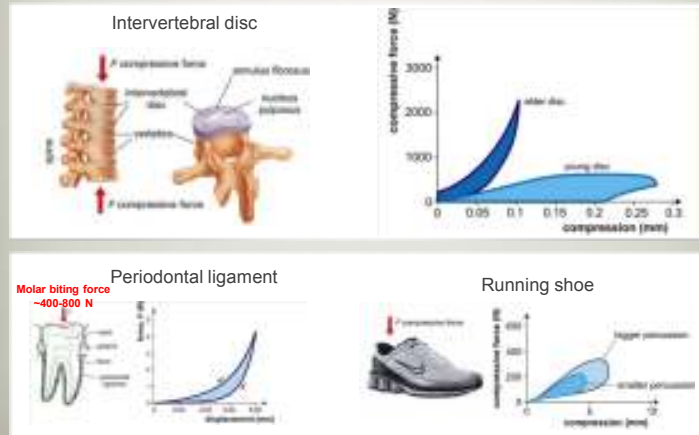


Major biomaterial components: collagen, elastin



Visco-elasticity

(examples)



The periodontal ligament

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

FUNCTIONS

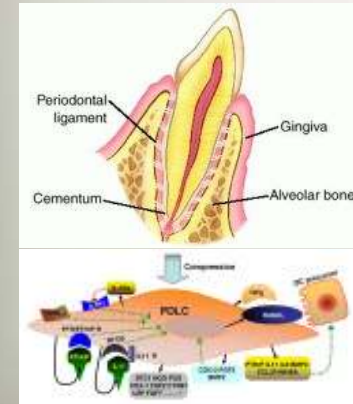
Proprioception: provides dental sensory function – perception of masticatory forces

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

Dental force sensor

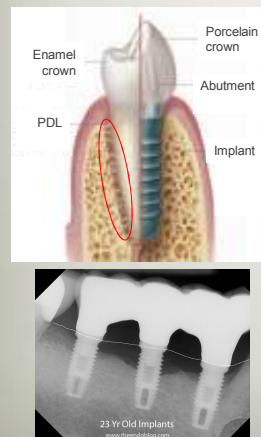
PDL cells convert mechanical signal to chemical signals. - Bone remodelling

Collagen based elastic properties



Implants vs natural 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



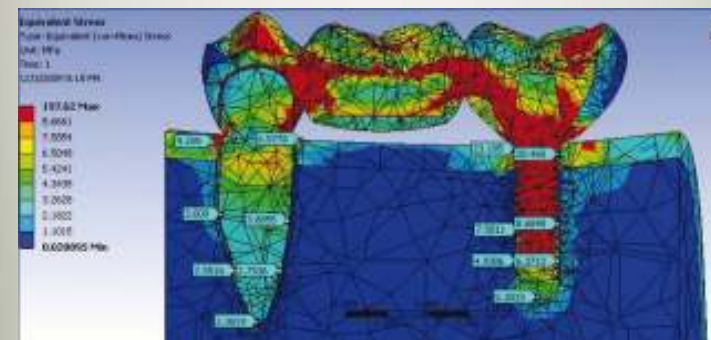
Increased compressive stress



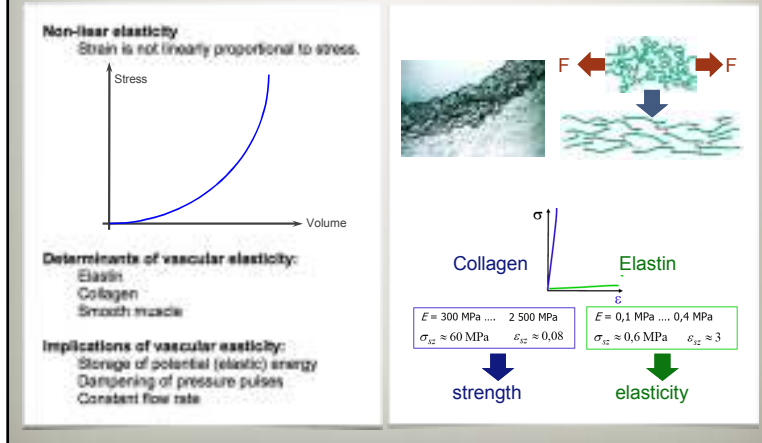
Bone loss (0.2 mm / year)
Loss of gingival height

Implants ↔ Root Canal Treatment

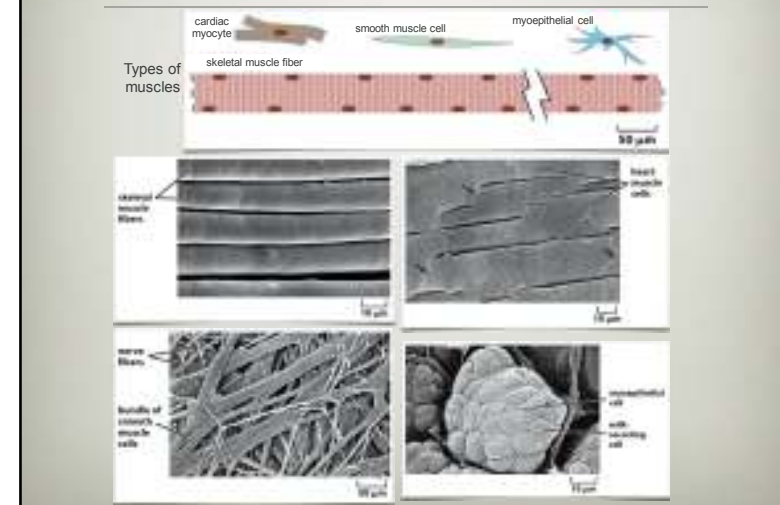
Stress distribution on tooth vs implant



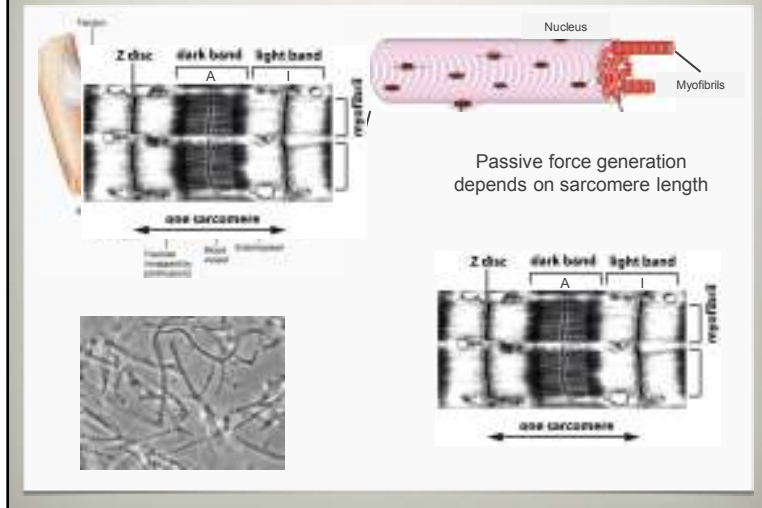
Biomechanics of elastic arteries



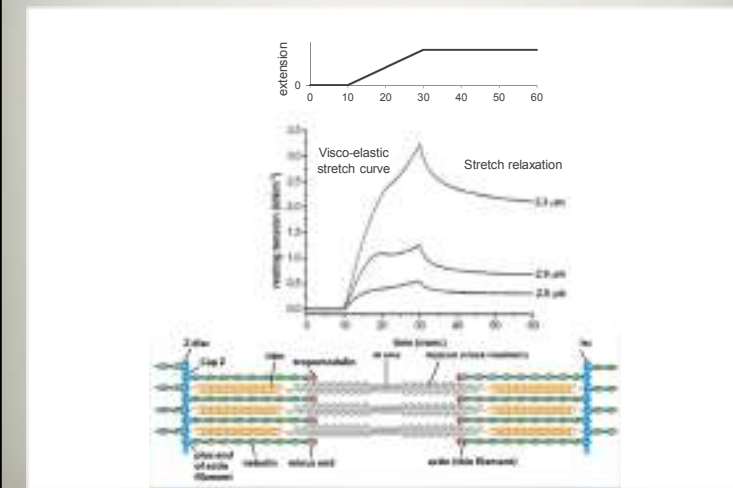
Muscle biomechanics



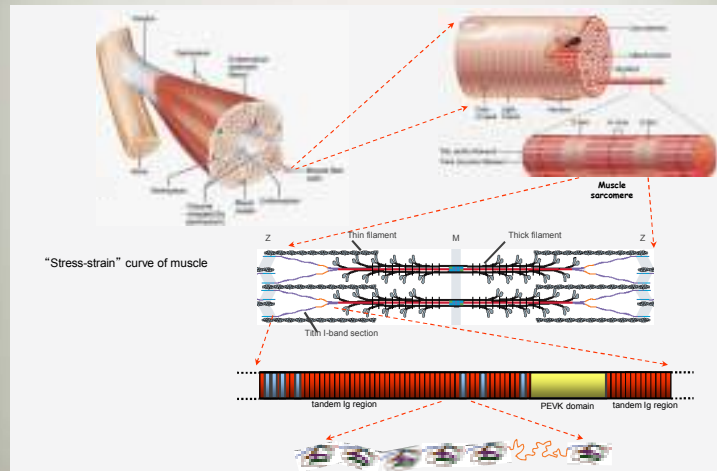
Skeletal muscle



Passive force of muscle depends on sarcomere length



Titin: Elastic filament in the muscle sarcomere



biopolymers mechanics

Polymers:
chains built up from monomers

Number of monomers: $N \gg 1$;
Typically, $N \sim 10^2 - 10^4$,
but, in DNA, e.g.: $N \sim 10^9 - 10^{10}$

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

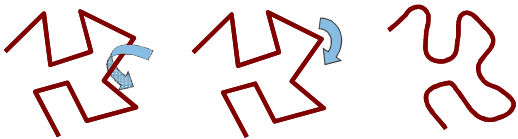
Shape of polymers

1. Linear
2. Branched
3. Circular



Shape of polymer chain changes dynamically. Possible mechanisms:

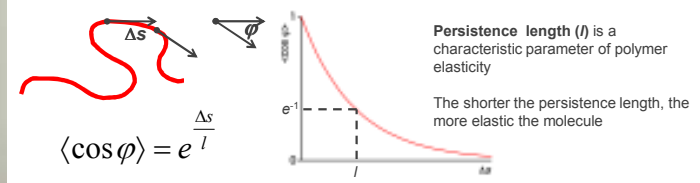
1. Rotation around CC-bonds
2. Freely jointed chain (FJC)
3. Bending, wormlike chain (WLC)



Parameters of an elastic biopolymer



dsDNA molecules



Mechanics of polymers

Entropic elasticity mechanism

Thermal fluctuations of the polymer chain

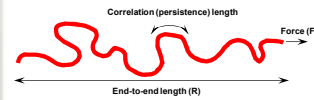
↓
Configurational entropy (orientational disorder of elementary vectors) increases.

↓
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 =contour length
 R/L =relative extension

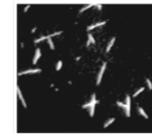
Biopolymer elasticity

l = persistence length
 L = contour length

Rigid chain
 $l \gg L$



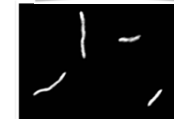
Microtubule



Semiflexible chain
 $l \sim L$



Actin filament



Flexible chain
 $l \ll L$

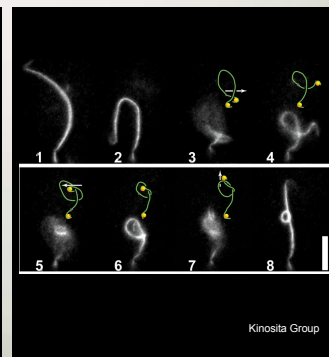
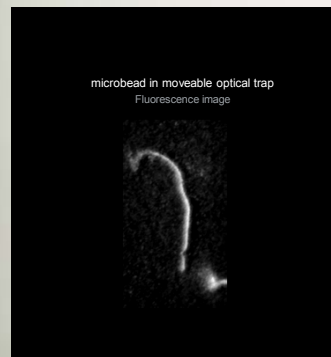


DNA



Visualization of biopolymer elasticity

Tying a knot on a single DNA molecule



Kinosita Group