Medical Biophysics II.

Biomechanics:
structure, mechanical and other properties of tissues

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Outline

- 1. History
- 2. Principles and phenomena (stress, strain, Hooke's law, viscosity, viscoelasticity, stress-strain curve)
- 3. Hard tissue (tooth - dentin, enamel, cement; bone)
- 4. Soft tissue (tendon, ligament, cartilage, elastic arteries - collagen, elastin)
- 5. Muscle (titin, desmin)
- 6. Biopolymer mechanics (biopolymers, entropic elasticity, wormlike chain, DNA, cytoskeletal filaments, elastomeric proteins, nanomanipulation)

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.

Étienne-Jules Marey (1830 - 1904) - Used cinematography to scientifically investigate locomotion.

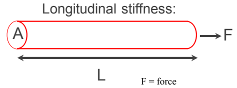
Today biomechanics is an extremely intensely explored research area. One of the main motivations are "tissue engineering" which lend the hope of replacing biological tissues with artificial materials.

Biomechanics principles in brief

Hookean elasticity

- Stiffness or spring constant (k=F/ΔL) is a parameter of material properties.
- Stiffness (k) depends on the shape parameters of a body and the direction of the applied force,
- And expresses the magnitude of extension caused by unit force.

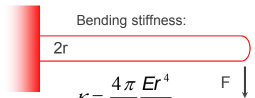
Longitudinal stiffness:



$$\kappa = \frac{F}{\Delta L} = \frac{EA}{L}$$

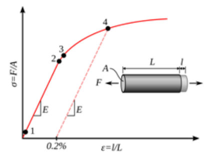
F = force
A = cross-sectional area
L = rest length
⊗L = extension
F/A = σ = stress
⊗L/L = ε = strain
E=Young's modulus (Pa)

Bending stiffness:



$$\kappa = \frac{4\pi}{3}\frac{Er^4}{L^3}$$

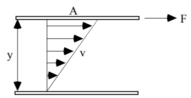
Stress-strain curve



***F/A* = σ = stress**
***l/L* = ε = strain**

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

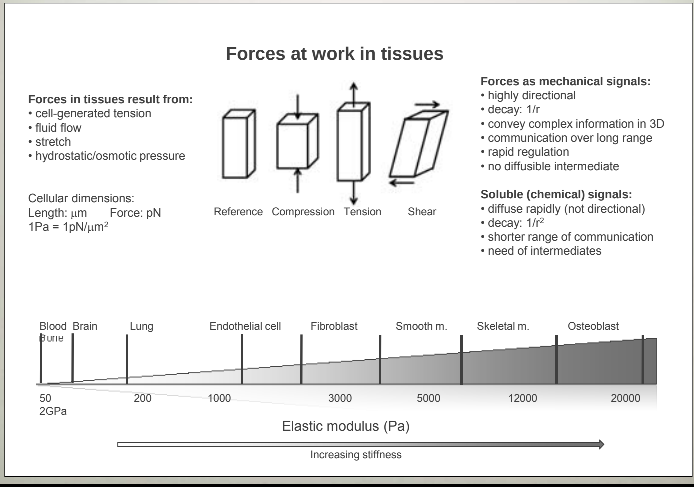
Viscosity



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

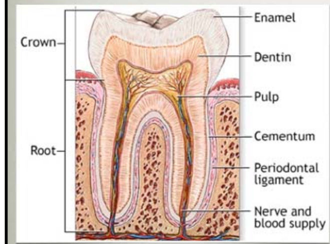
F	=shear force
A	=area of fluid layer
η	=viscosity
v	=flow velocity
y	=distance between fluid layers
F/A	=shear stress (τ)
Δv/Δy	=velocity gradient (D)

Biomechanics at the Cellular Level

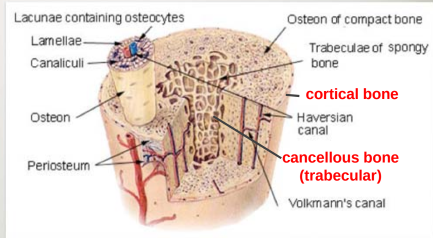


Hard tissues

Tooth



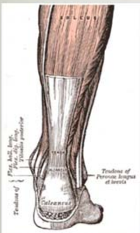
Bone



Major biomaterial components:
collagen, apatite

Soft tissues

Tendon

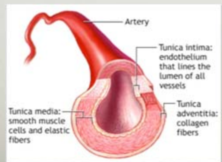


Ligament

Cartilage

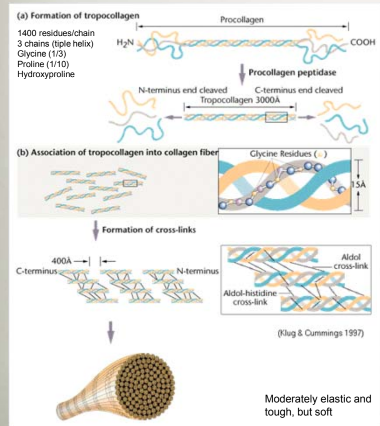
Major biomaterial component:
collagen

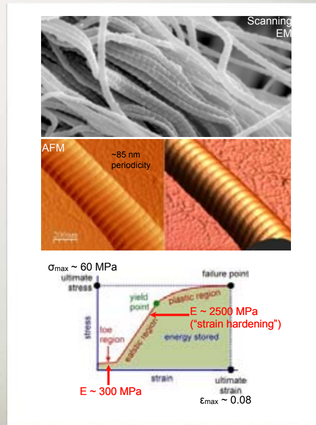
Elastic artery



Major biomaterial components:
collagen, elastin

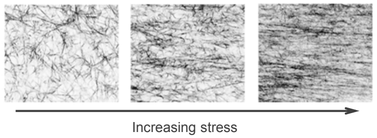
Collagen





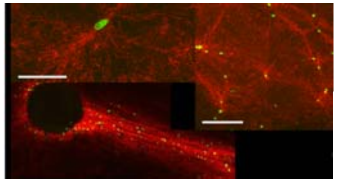
Collagen responses to force
(forces in the extracellular matrix)

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.

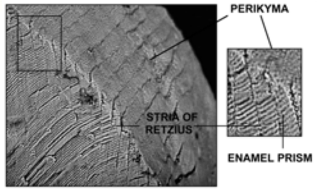
Cells in collagen matrix

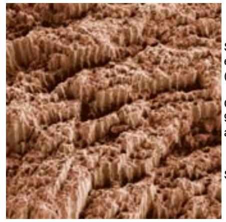


Green: nucleus
Red: collagen fibers

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

Tooth enamel

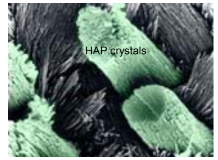




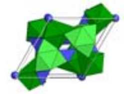
Structural unit: enamel prism (rod)

Composition: 92% Hydroxy-apatite (HAP)

Stiff, hard, brittle



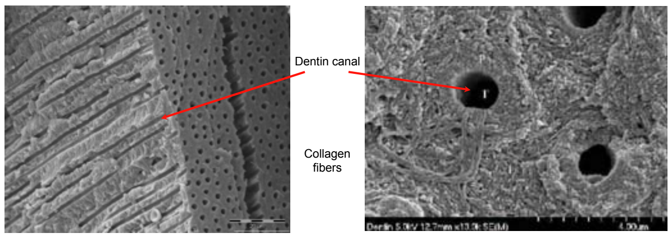
$Ca_{10}(PO_4)_6(OH)_2$
$Ca_{10}(PO_4)_6F_2$



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	$\sigma_{BZ} \approx 60$ MPa Bending ≈ 500 MPa Compression
$HV \approx 3\text{-}6$ GPa	$E \approx 90\text{-}100$ GPa	$\sigma_{BZ} \approx 50$ MPa Bending ≈ 400 MPa Compression

Dentin

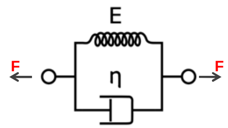


Composition: 35% organic material (collagen) + water, 65% hydroxy-apatite

Structure: collagen matrix with attached hydroxy-apatite crystals

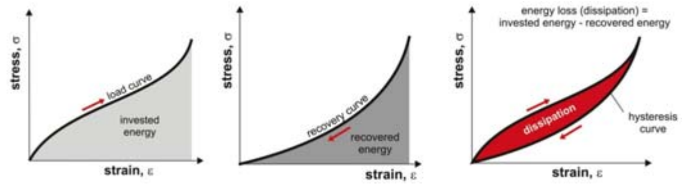
Biomechanics: moderately hard, very strong and tough and flexible

Visco-elasticity
(mechanical model)

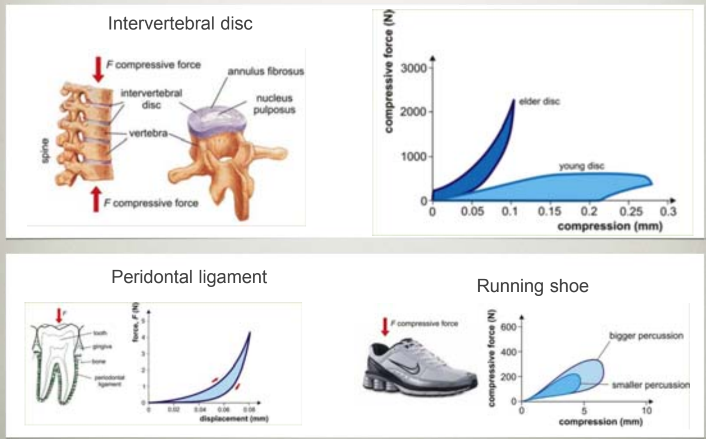


model: parallel connection of a spring and a dashpot

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

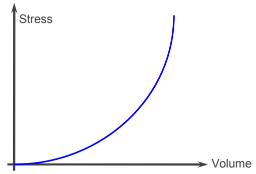


Visco-elasticity
(examples)



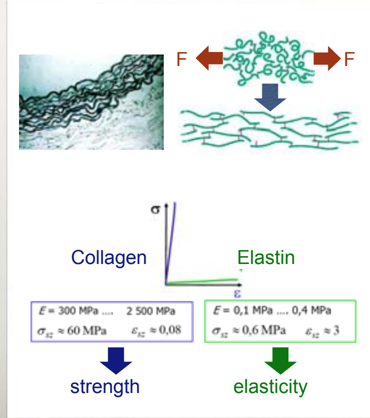
Biomechanics of elastic arteries

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

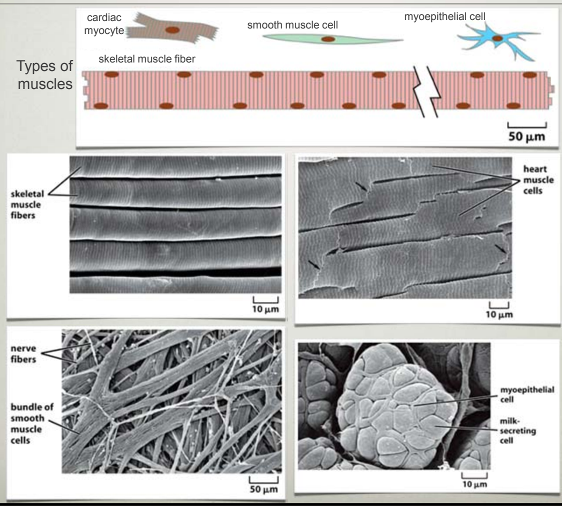


Determinants of vascular elasticity:
- Elastin
- Collagen
- Smooth muscle

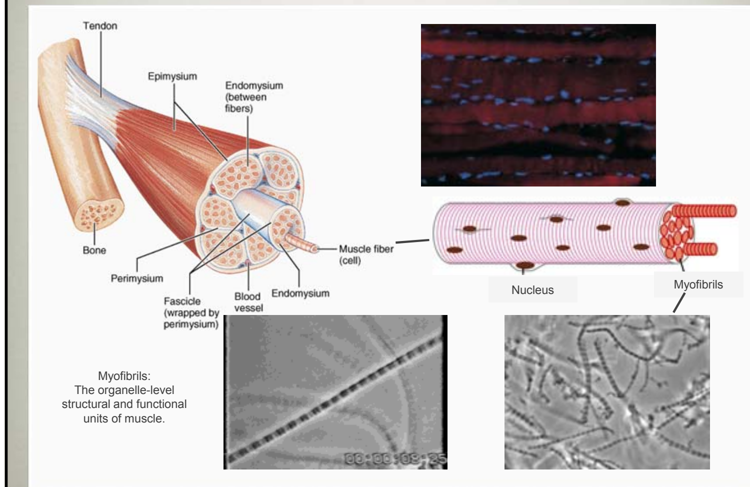
Implications of vascular easticity:
- Storage of potential (elastic) energy
- Dampening of pressure pulses
- Constant flow rate



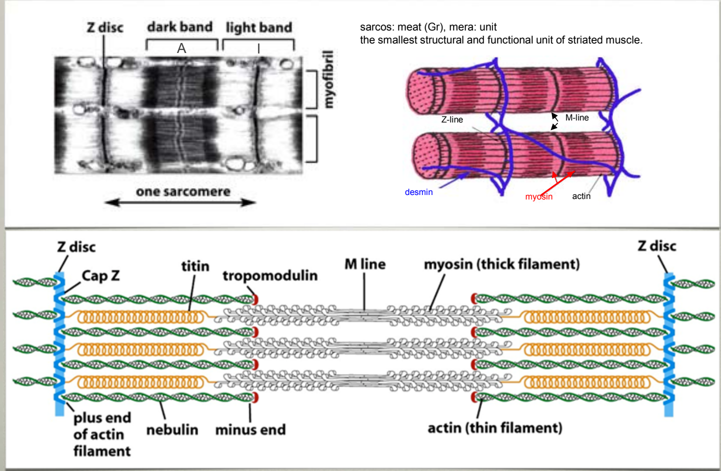
Muscle biomechanics



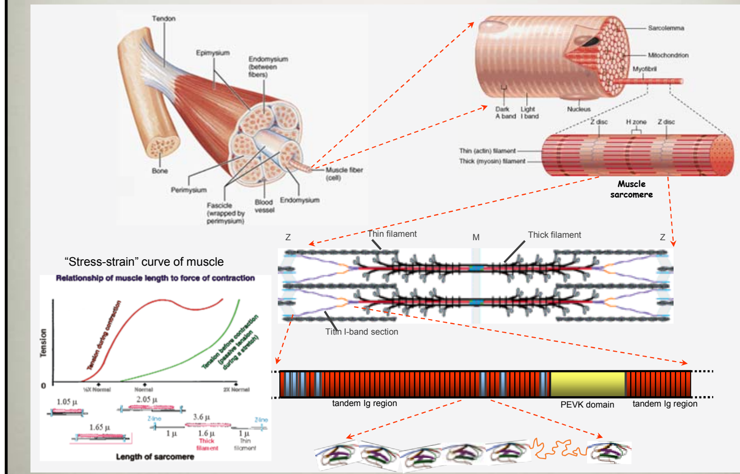
Skeletal muscle



The sarcomere



Titin:
Elastic filament in the muscle sarcomere



biopolyers mechanics

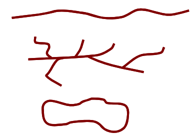
Polymers:
chains built up from monomers

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

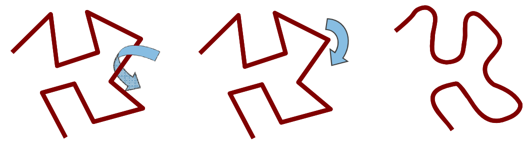
Shape of polymers

1. Linear
2. Branched
3. Circular

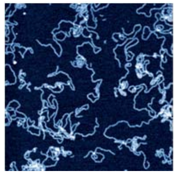


Shape of polymer chain changes dynamically. Possible mechanisms:

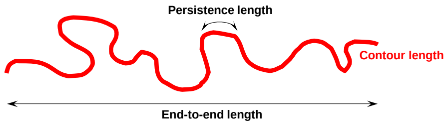
1. Rotation around CC-bonds
2. Freely jointed chain (FJC)
3. Bending, wormlike chain (WLC)

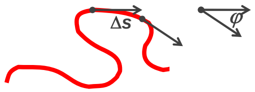


Parameters of an elastic biopolymer

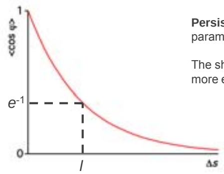


dsDNA molecules





$$\langle \cos \varphi \rangle = e^{-(s/l)}$$



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

↓

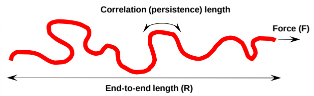
Configurational entropy (orientational disorder of elementary vectors) increases.

↓

The chain shortens.

Force needed to stretch an entropic chain

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



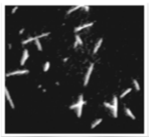
F=force
l=correlation length (**persistence length, describes bending rigidity**)
k_B=Boltzmann's constant
T=absolute temperature
L=contur length
R/L=relative extension

Biopolymer elasticity

l = persistence length
L = contour length

Rigid chain
l >> L

Microtubule

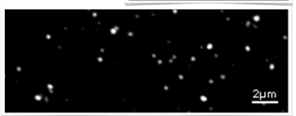


Semiflexible chain
l ~ L

Actin filament

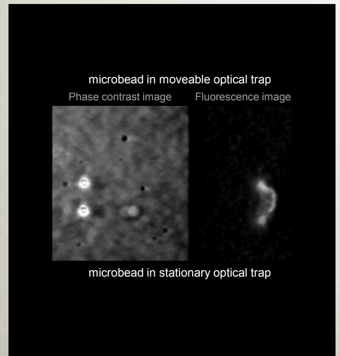
Flexible chain
l << L

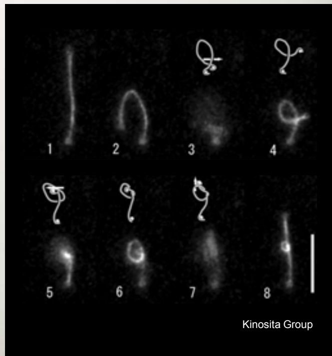
DNA



Visualization of biopolymer elasticity

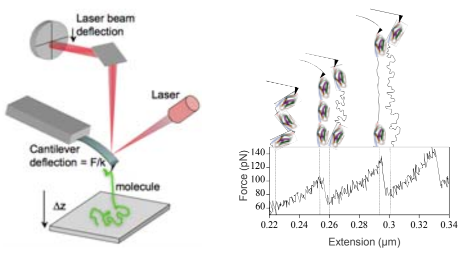
Tying a knot on a single DNA molecule





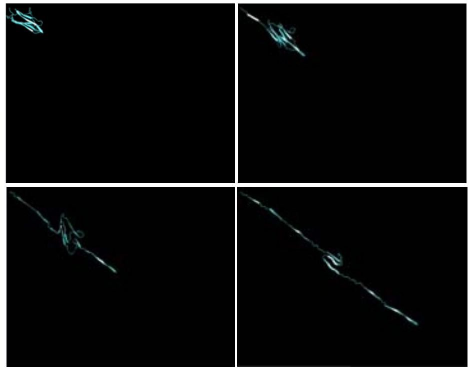
Stretching a biopolymer with AFM

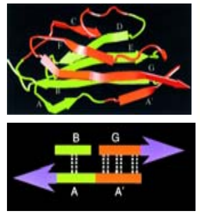
Mechanical unfolding of a single elastomeric protein with the atomic force microscope



Mechanical unfolding of an elastomeric protein

Steps of computer-simulated domain unfolding





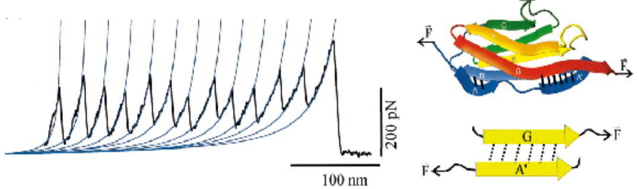
Basis of mechanical stability:

H-bridges between the first and last ß-strands of the domain

Biological logic behind mechanical stability I.

Mechanical stability provided by shear pattern of H-bond patch

Force spectrum of $I27_{12}$

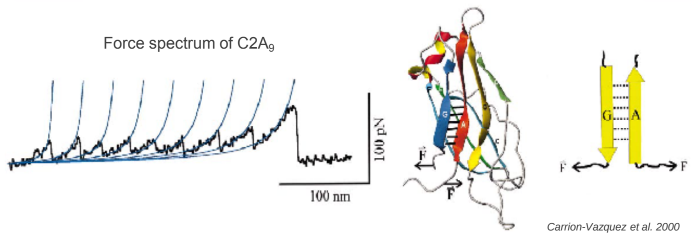


Carrion-Vazquez et al. 2000

Biological logic behind mechanical stability II.

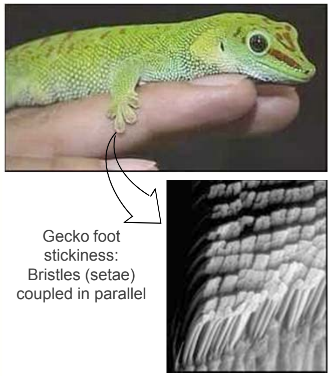
Low mechanical stability due to zipper pattern of H-bond patch

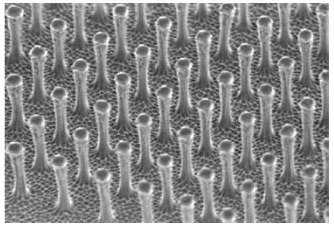
Force spectrum of $C2A_9$



Carrion-Vazquez et al. 2000

Mechanical stability in real-life applications
Principle of parallel bond coupling





Artificial gecko foot