

Biomechanics Biomolecular and tissue elasticity

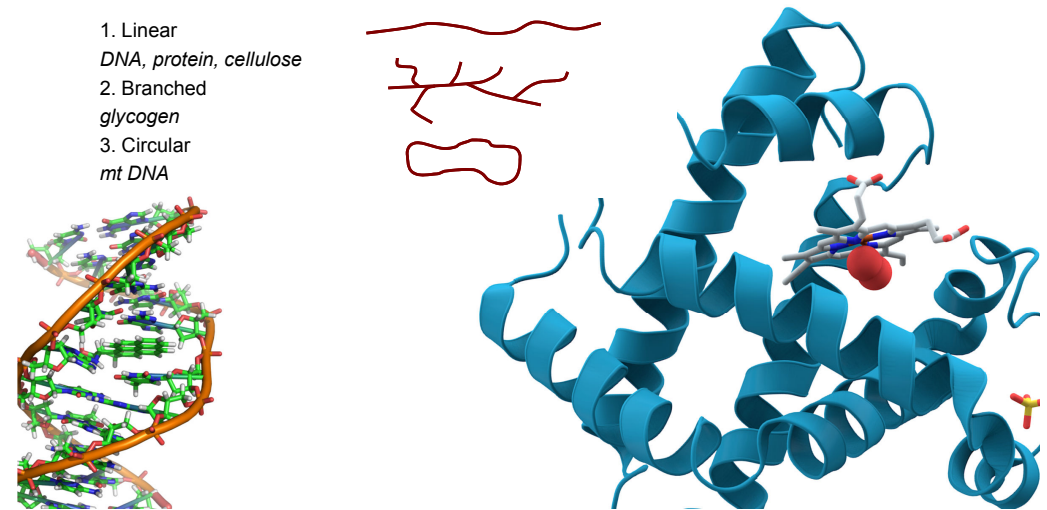
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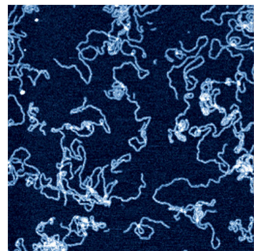
Biomolecules are polymers

Common feature: Linear primary structure (protein, DNA)
Strong bonds between monomers (covalent)
Weaker interactions between distant region of polymer chain

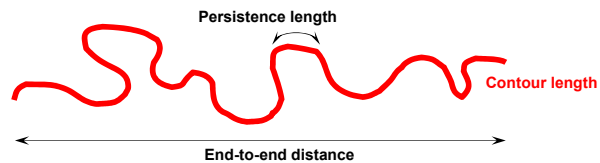


What is the shape of biopolymers?

Parameters to describe the shape of polymer



AFM image of dsDNA

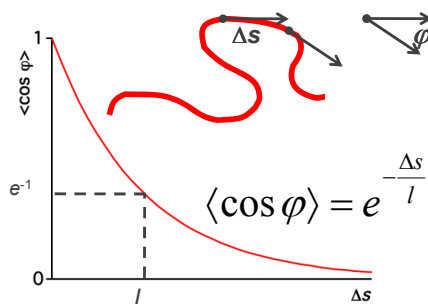


Contour length (L): Full length of the chain

End-to-end distance (R): Distance between chain termini.

Persistence length (l): describe the persistence of chain orientation.

Shorter persistence length polymers are more flexible.

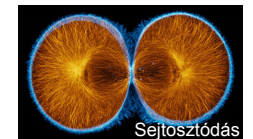
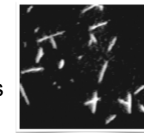


Biopolymer classification based on flexibility

l = persistence length
 L = contour length

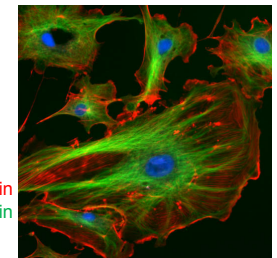
RIGID
 $l \gg L$

Microtubules



SEMIFLEXIBLE
 $l \approx L$

Microfilaments

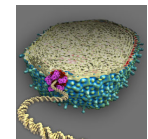
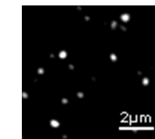


aktin
tubulin

FLEXIBLE
 $l \ll L$



DNA



Are biopolymers elastic?

Yes, but Hooke's law is not valid! Non-linear elasticity.

Entropic elasticity

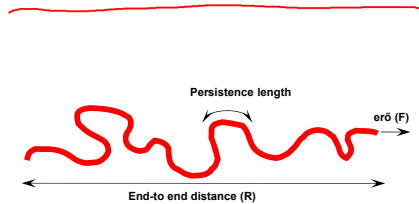
Thermal energy ($k_B T$) excites bending movements in the chain



The chain's disorder (entropy) increases



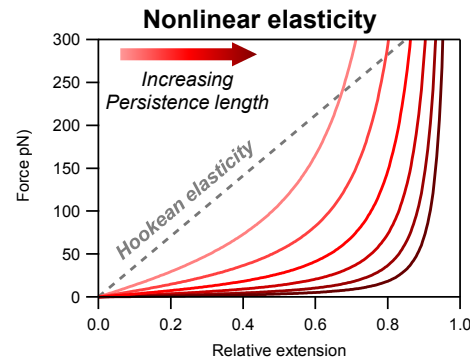
The chain shortens



Force is needed to stretch an entropic chain

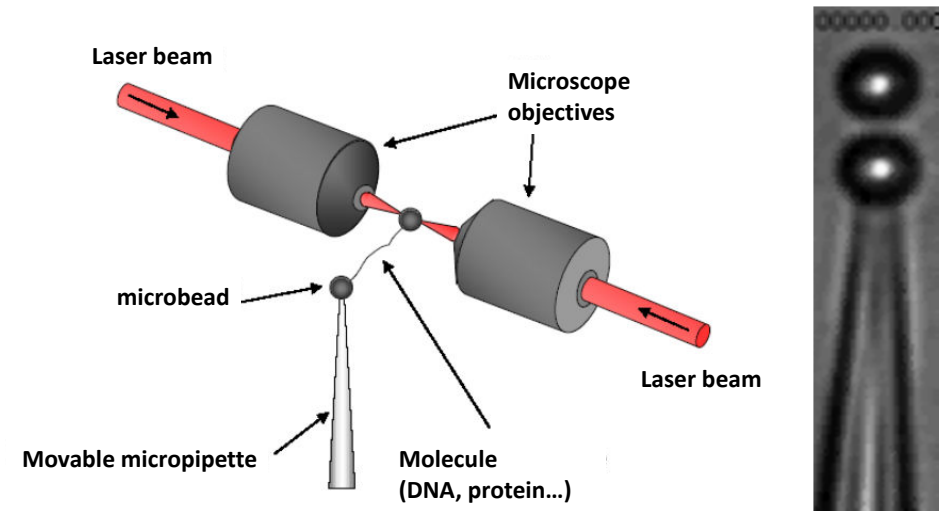
$$F \sim \frac{k_B T}{l} \cdot \frac{R}{L} + \left(\frac{R}{L}\right)^a$$

F = force
 l = persistence length
 k_B = Boltzmann constant
 T = absolute temperature
 L = contour length
 R = end-to-end distance
 R/L = relative extension



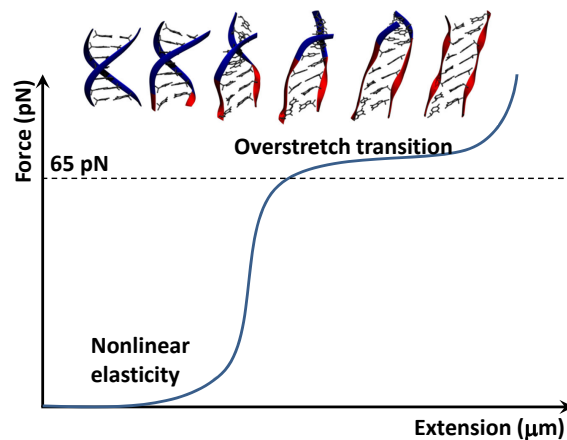
How to stretch single molecules?

Optical tweezers

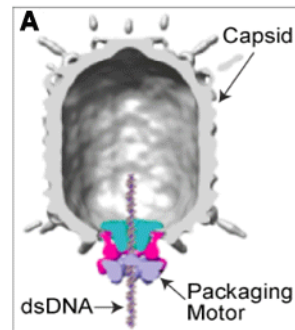


<http://glass.phys.uniroma1.it/dileonardo/Applet.php?applet=TrapForcesApplet>

Stretching dsDNA with optical tweezers



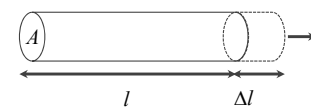
DNA packaging of bacteriophage



$F = 55 \text{ pN}$

Basics of tissue mechanics

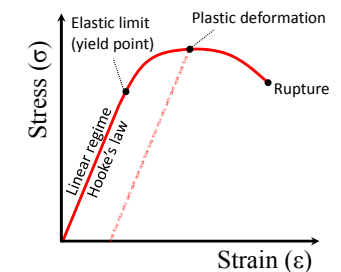
Hookean elasticity



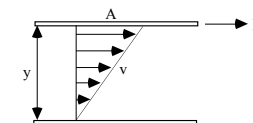
$$\frac{F}{A} = E \frac{\Delta l}{l}$$

F = force
 A = cross sectional area
 l = rest length
 Δl = extension
 $F/A = \sigma$ = stress ($\text{N/m}^2 = \text{Pa}$)
 $\Delta l/l = \epsilon$ = strain (dimensionless)
 $E = \sigma / \epsilon$ Young's modulus (Pa)

Stress-strain diagram



Viscosity



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

F = shear force
 A = fluid surface
 η = viscosity

y = distance between surfaces
 v = flow velocity

F/A = shear stress
 $\Delta v/\Delta y$ = velocity gradient (strain)

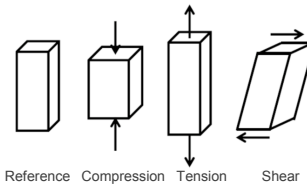
Biomechanics at the cellular level

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 at work in tissues

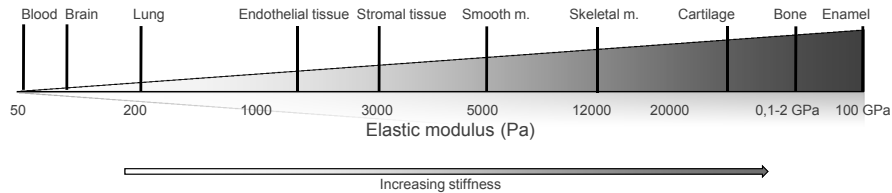


Forces as mechanical signals:

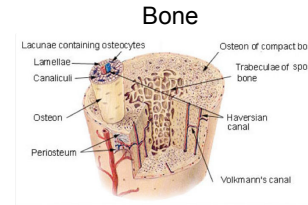
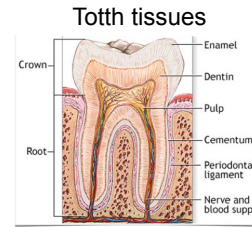
- highly directional
- decay: $1/r$
- convey complex information in 3D
- communication over long range
- rapid regulation
- no diffusible intermediate

Soluble (chemical) signals:

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



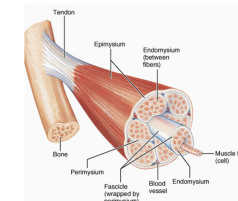
Hard tissues



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

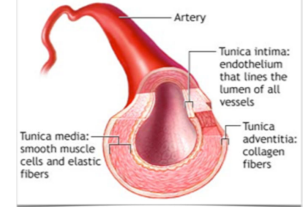
Soft tissues

Skeletal muscle



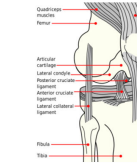
Passive mechanics: titin, desmin
Active mechanics: actin, myosin

Elastic artery



collagen, elastin

Ligament



Tendon



Cartilage



Collagen, proteoglycans (water)

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

What is the speed of sound in different tissues?

Acoustic properties of various tissues are determined by their flexibility

	E (GPa)	κ (GPa ⁻¹)	c_{sound} (m/s)
Bone	18	0.05	3600
Muscle	7×10^{-5}	0.38	1568

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

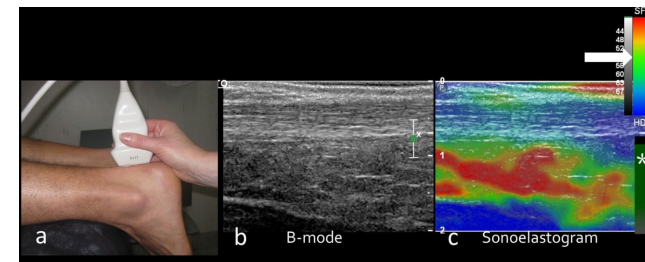
compressibility

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

strain stress

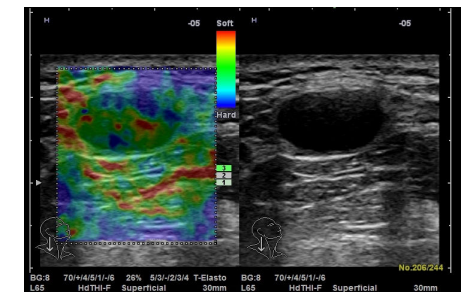
Greater Young's modulus, faster sound speed

Diagnostic usage: sonoelastography



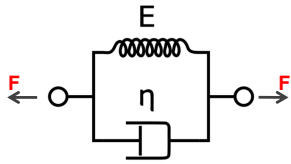
Achilles examination

Lymph node examination



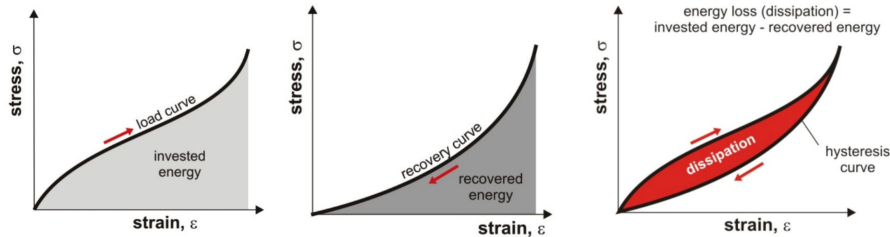
Visco-elasticity

(mechanical model)



model: parallel connection of a spring and a dashpot (Kelvin-body)

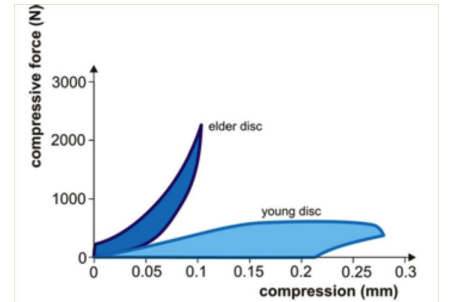
Spring: ideally elastic (Hooke) body
Dashpot: ideally viscous (Newton) body



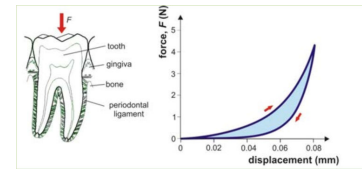
Visco-elasticity

(examples)

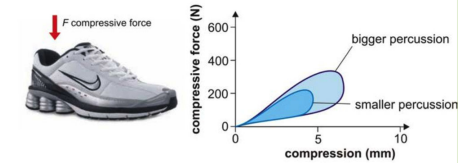
Intervertebral disc



Periodontal ligament

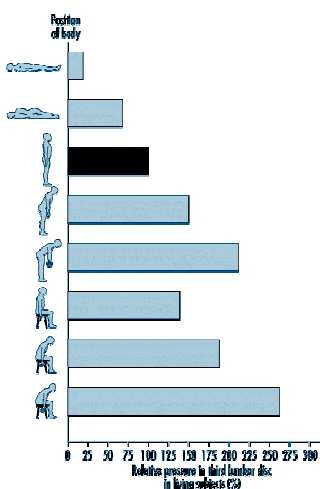


Running shoe

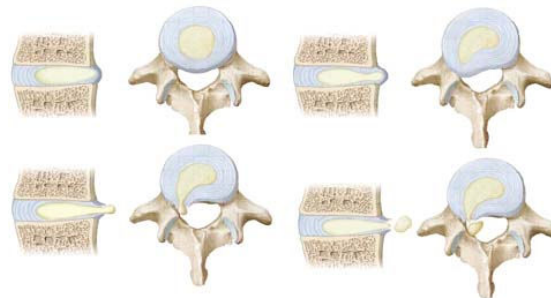
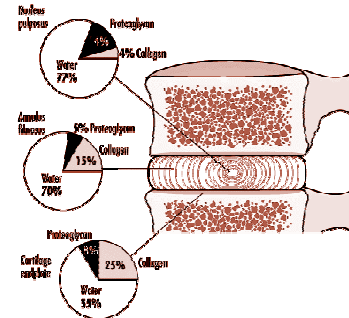


Example I: Consequences of increased mechanical stress on intervertebral discs (*discus hernia*)

Relative stress on L3 intervertebral disc at various positions

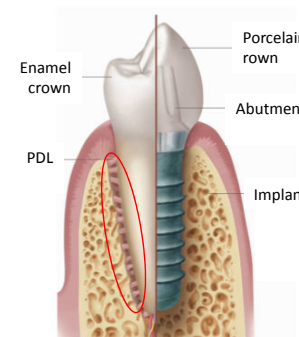


Source: Adapted from Mechanism 1992.



Example II: Implants vs natural tooth

PDL makes the difference!



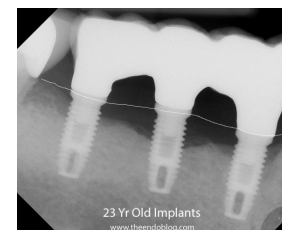
- Absence of PDL result in :**
- loss of masticatory force perception
 - loss of visco-elastic (damper) effect
 - loss of force sensory mechanisms
 - No implant movement

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



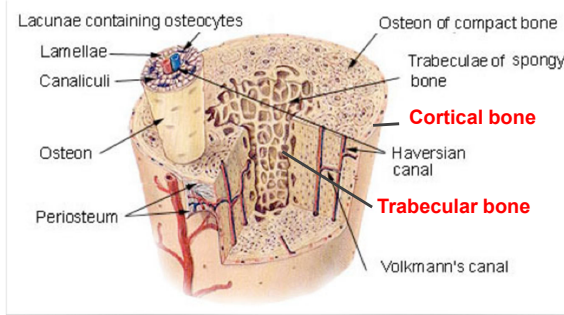
Bone

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

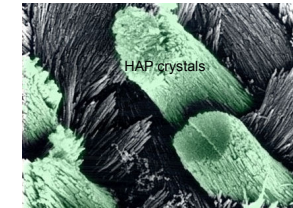
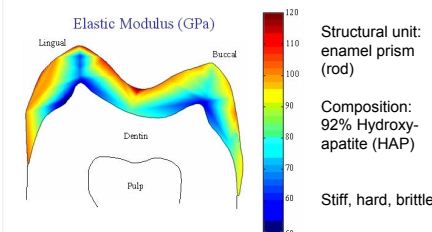
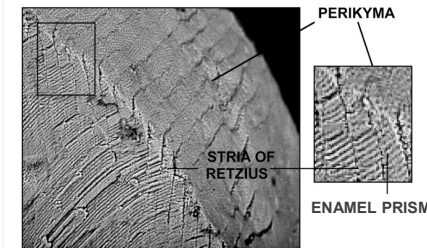
Removal of organic compounds (heating): brittle



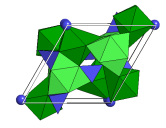
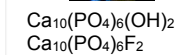
Calculation:

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.

Tooth enamel

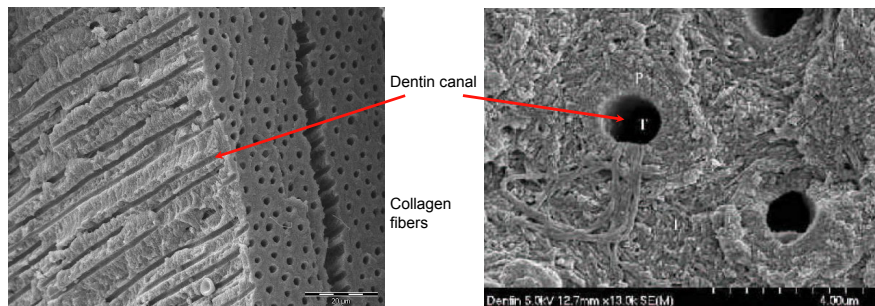


The hardest material in human body



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

Dentin

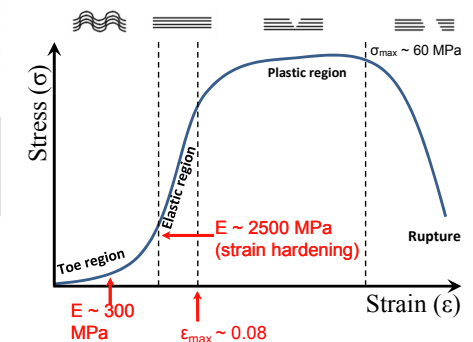
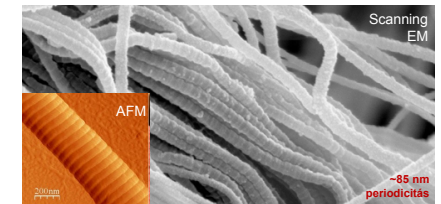
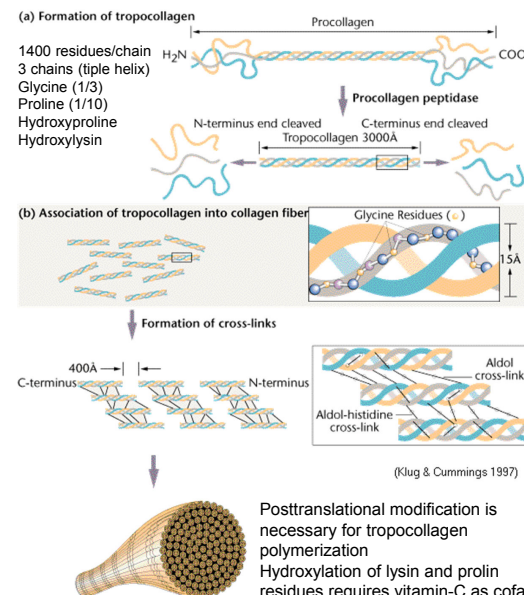


Composition: 35% organic material (collagen) + water, 65% hydroxy-apatite

Structure: collagen matrix with attached hydroxy-apatite crystals

Biomechanics: moderately hard, very strong and tough and flexible

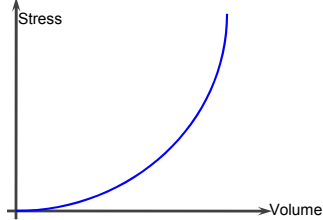
Collagen



Moderately elastic and tough, but soft

Biomechanics of elastic arteries

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

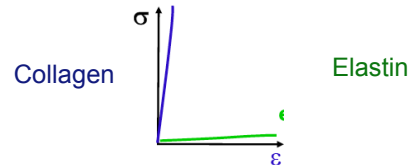
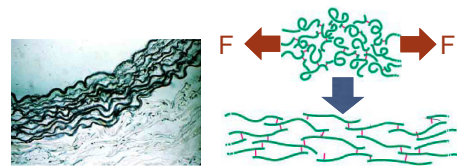


Determinants of vascular elasticity:

Elastin
Collagen
Smooth muscle

Implications of vascular elasticity:

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

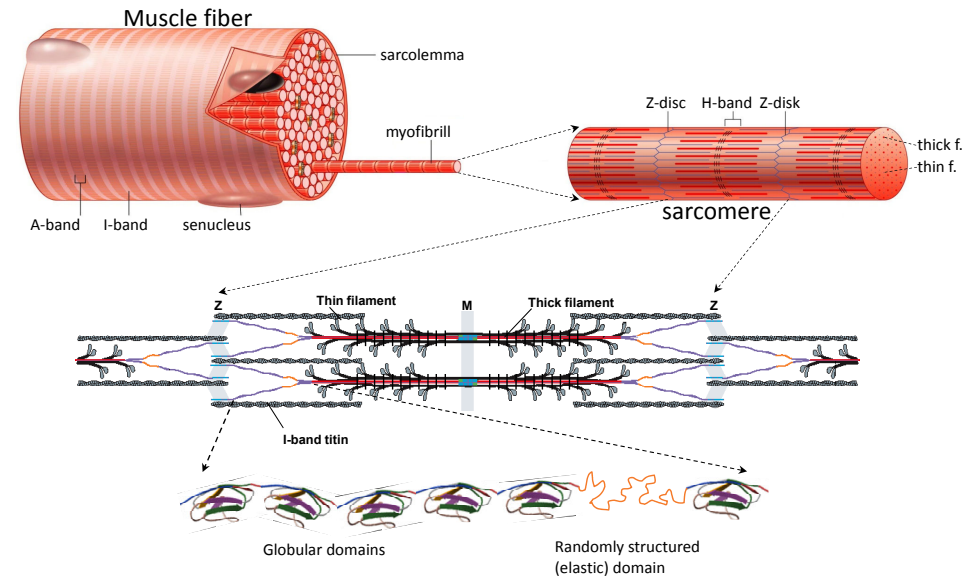


$E = 300 \text{ MPa} \dots 2500 \text{ MPa}$ $\sigma_{sz} \approx 60 \text{ MPa}$ $\epsilon_{sz} \approx 0,08$	$E = 0,1 \text{ MPa} \dots 0,4 \text{ MPa}$ $\sigma_{sz} \approx 0,6 \text{ MPa}$ $\epsilon_{sz} \approx 3$
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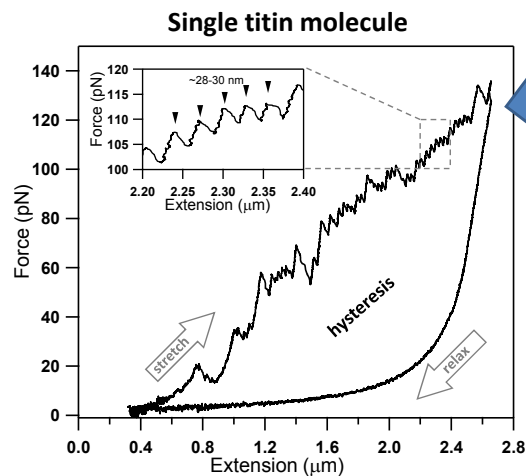
strength

elasticity

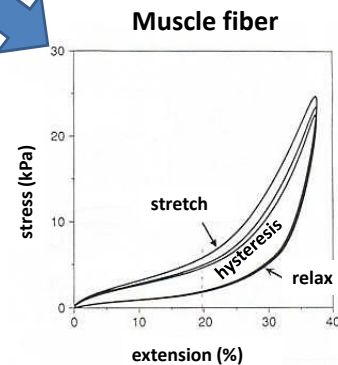
Titin: elastic filament of the sarcomere



Titin is the main determinant of muscle elasticity



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



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? ($F = 2 \text{ N}$, $E = 24 \text{ mJ}$)