Physical foundations of dental materials science

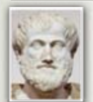
Biomechanics: structure, mechanical and other properties of tissues

Miklós Kellermayer

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.

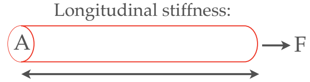
Today biomechanics is an extremely intensely explored research area. One of the main motivations are "tissue engineering" which lend the hope of replacing biological tissues with artificial materials.

Biomechanics principles in brief

Hookean elasticity

- Stiffness or spring constant (k=F/ΔL) is a parameter independent 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.

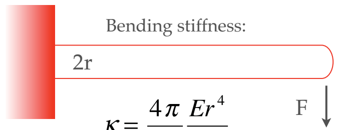
Longitudinal stiffness:



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

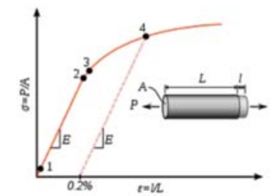
F = force
A = cross-sectional area
L = rest length
ΔL = extension
F/A = σ = stress
ΔL/L = ε = strain
E=Young's modulus (Pa)

Bending stiffness:



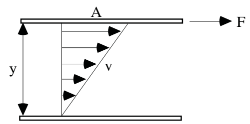
$$\kappa = \frac{4\pi}{3}\frac{Er^4}{L^3}$$

Stress-strain curve



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

Viscosity

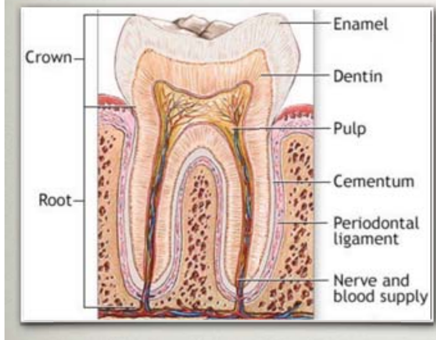


$$\frac{F}{A} = \eta \frac{\Delta v}{\Delta y}$$

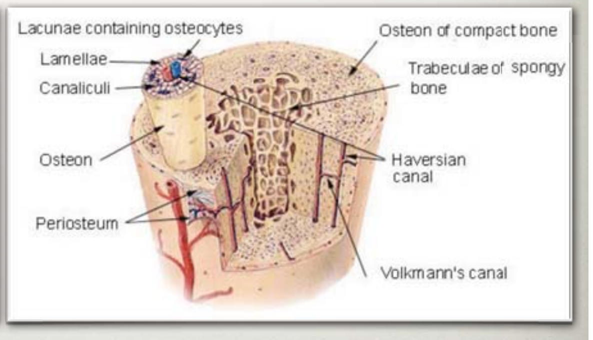
F	=shear force
A	=area of fluid layer
η	=viscosity
v	=flow velocity
y	=distance between fluid layers
F/A	=shear stress (τ)
Δv/Δy	=velocity gradient (D)

Hard tissues

Tooth



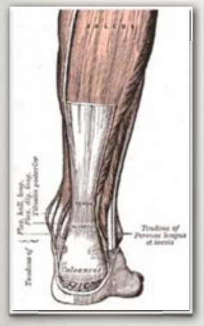
Bone



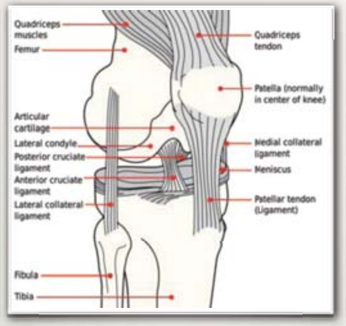
Major biomaterial components: collagen, apatite

Soft tissues

Tendon



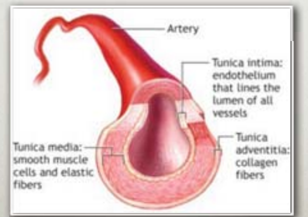
Ligament



Cartilage

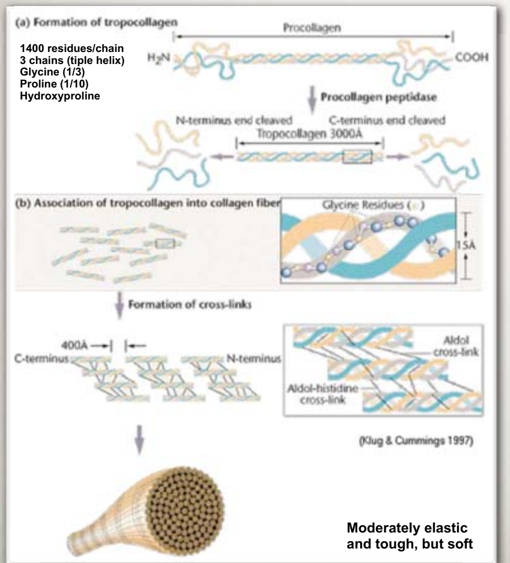
Major biomaterial component: collagen

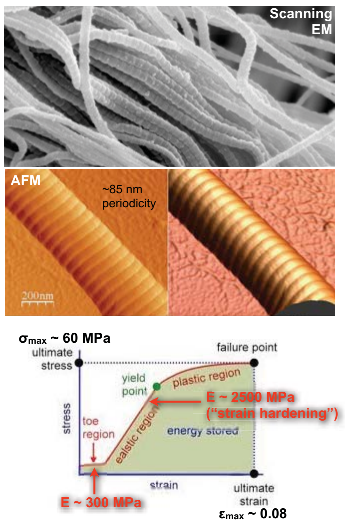
Elastic artery



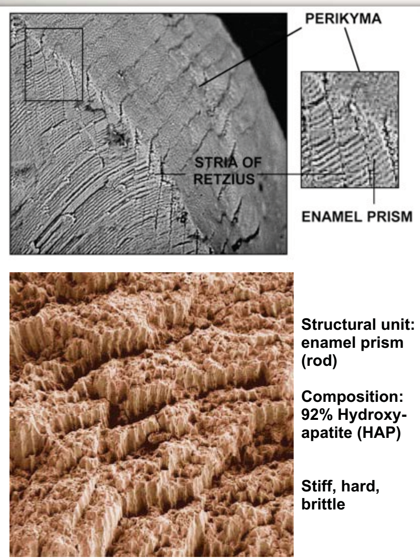
Major biomaterial components: collagen, elastin

Collagen





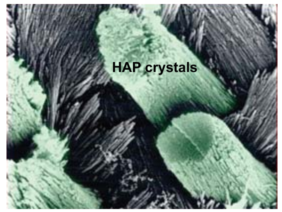
Tooth enamel



Structural unit: enamel prism (rod)

Composition: 92% Hydroxy-apatite (HAP)

Stiff, hard, brittle

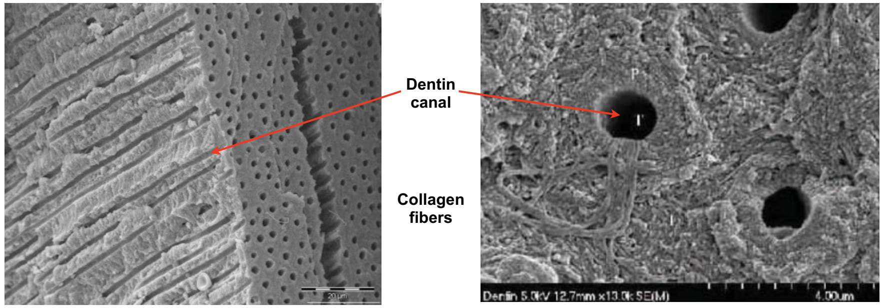


$Ca_{10}(PO_4)_6(OH)_2$

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

Dentin



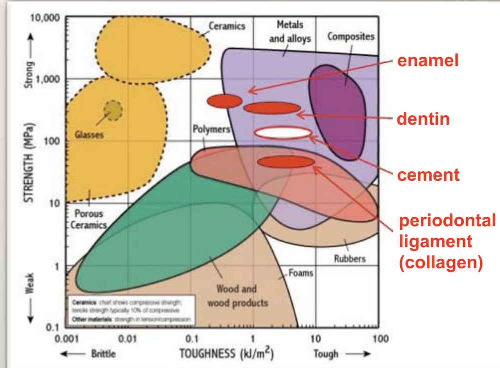
Composition: **35% organic material (collagen) + water, 65% hydroxy-apatite**

Structure: **collagen matrix with attached hydroxy-apatite crystals**

Biomechanics: **moderately hard, very strong and tough**

Summary of dental tissue biomechanics

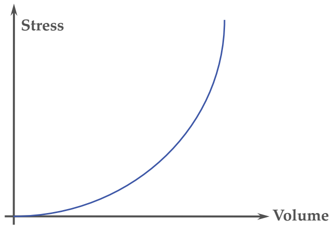
	Periodontal ligament (collagen)	Dentin (1/3 collagen, 2/3 apatite)	Enamel (apatite)
Young modulus (E, GPa)	0.3-2.5	10-20	90-100
Tensile strength (σ_{max}, MPa)	60	110 (stretch) 300 (compression)	50 (stretch) 400 (compression)
Toughness (kJ/m^2)	1-10	0.5-5	0.1-1
Hardness (GPa)		0.5-1	3-6



Biomechanics of elastic arteries

Non-liear elasticity

Strain is not linearly proportional to stress.

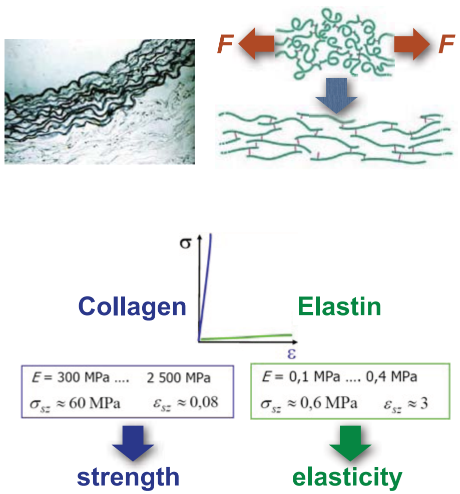


Determinants of vascular elasticity:

- Elastin
- Collagen
- Smooth muscle

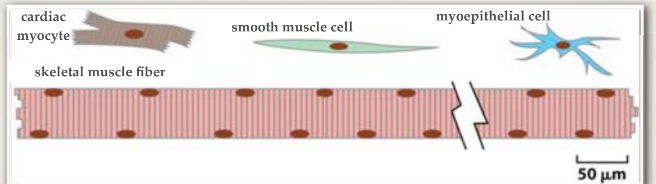
Implications of vascular easticity:

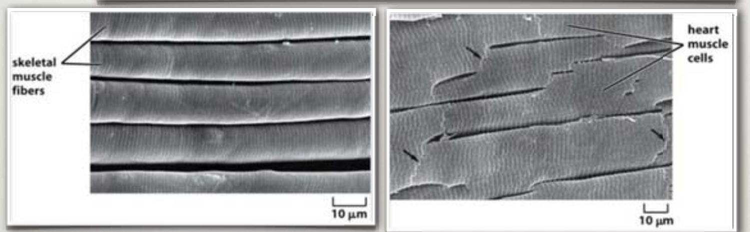
- Storage of potential (elastic) energy
- Dampening of pressure pulses
- Constant flow rate

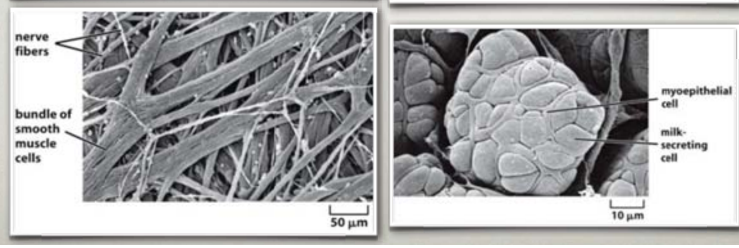


Muscle biomechanics

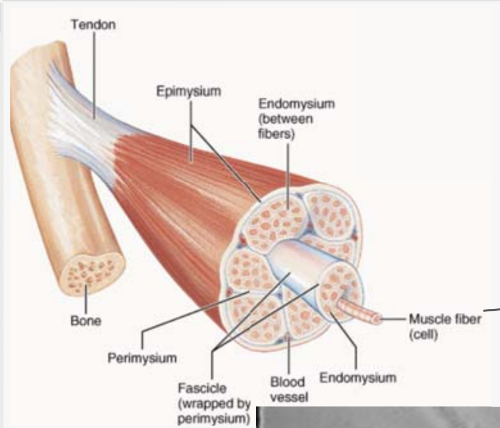
Types of muscles

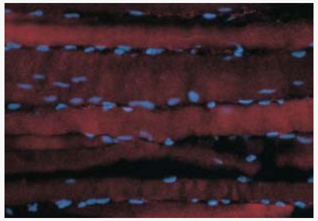


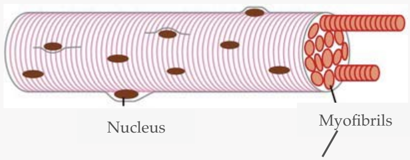




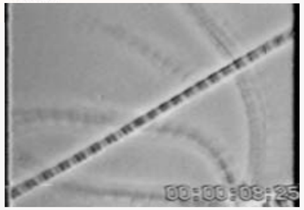
Skeletal muscle

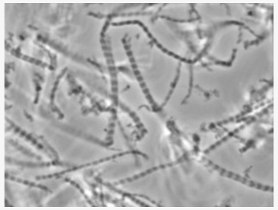




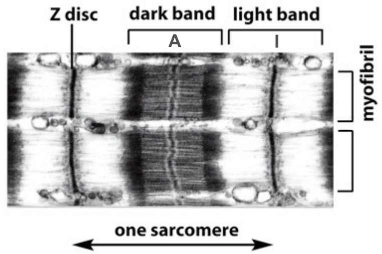


Myofibrils:
The organelle-level structural and functional units of muscle.

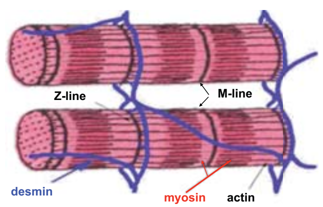


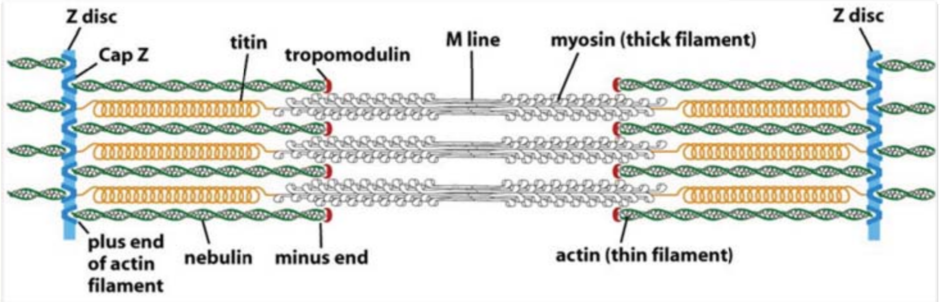


The sarcomere

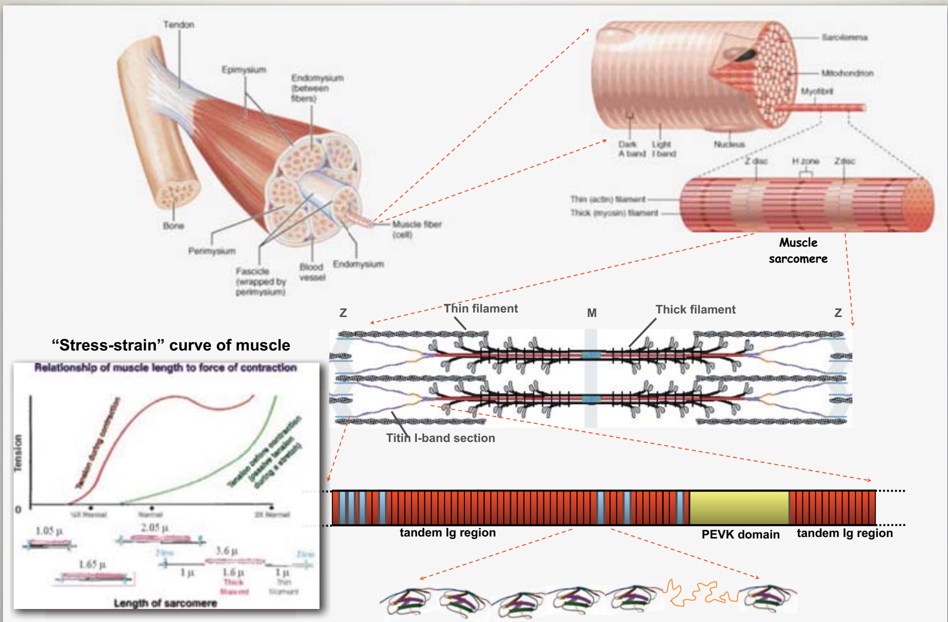


sarcos: meat (Gr), mera: unit
the smallest structural and functional unit of striated muscle.





Titin:
Elastic filament in the muscle sarcomere



Biopolyers mechanics

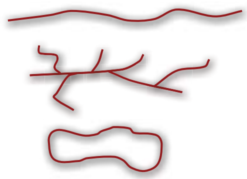
Polymers:
chains built up from monomers

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

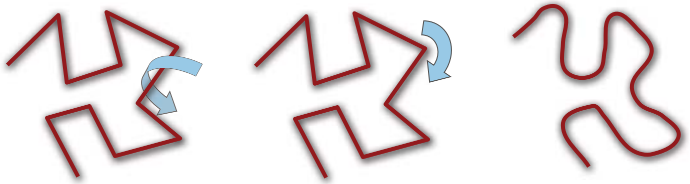
Shape of polymers

1. Linear
2. Branched
3. Circular



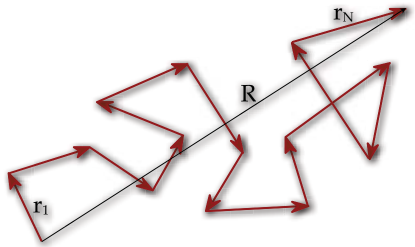
Shape of polymer chain changes dynamically. Possible mechanisms:

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



Shape of the polymer chain resembles random walk

Brown-movement - "random walk"



"Square-root law":

$$\langle R^2 \rangle = Nl^2 = Ll$$

R = end-to-end distance
N = number of elementary vectors
$l = |\vec{r}_i| =$ correlation length
r_i = elementary vector
$Nl = L$ = contour length
l is related to **bending rigidity**.

Mechanics of polymers

Entropic elasticity mechanism

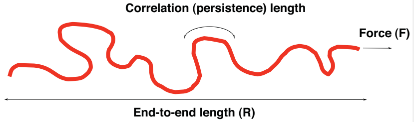
Thermal fluctuations of the polymer chain

Configurational entropy (orientational disorder of elementary vectors) increases.

The chain shortens.

Force needed to stretch an entropic chain

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



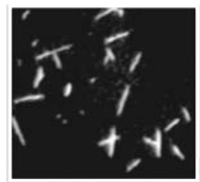
F=force
l=correlation length (**persistence length, describes bending rigidity**)
k_B=Boltzmann's constant
T=absolute temperature
L=contur length
R/L=relative extension

Biopolymer elasticity

l = correlation length
L = contour length

Rigid chain
$l >> L$

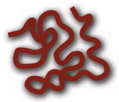
Microtubule



Semiflexible chain
$l \sim L$

Actin filament

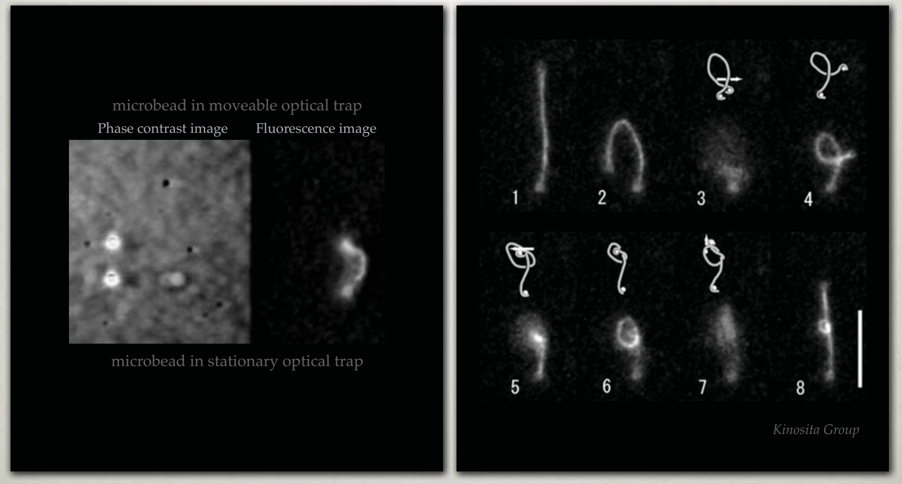
Flexible chain
$l << L$



DNA

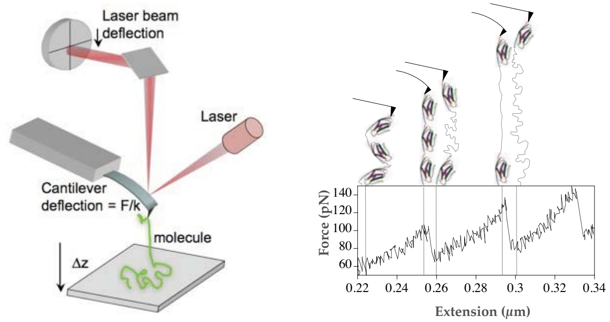
Visualization of biopolymer elasticity

Tying a knot on a single DNA molecule



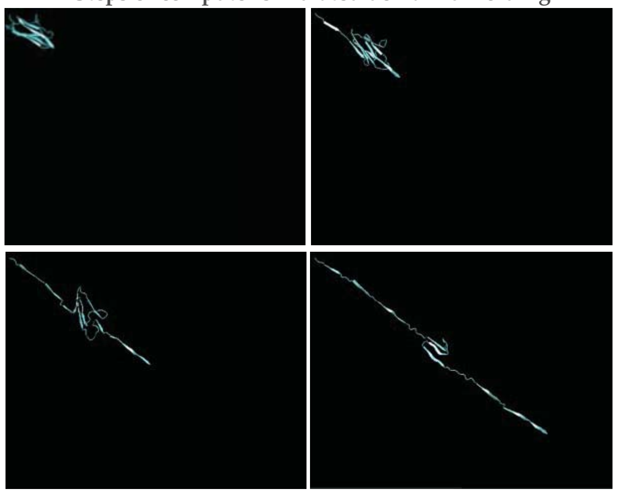
Stretching a biopolymer with AFM

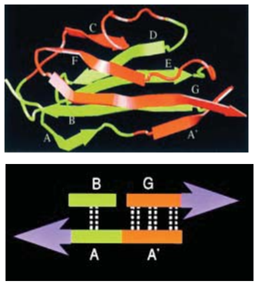
Mechanical unfolding of a single elastomeric protein with the atomic force microscope



Mechanical unfolding of an elastomeric protein

Steps of computer-simulated domain unfolding





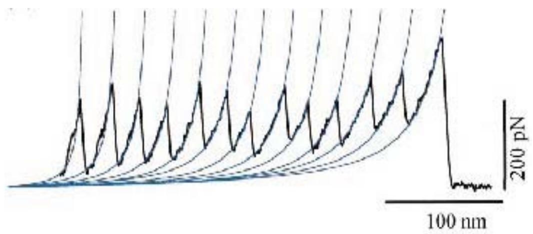
Basis of mechanical stability:

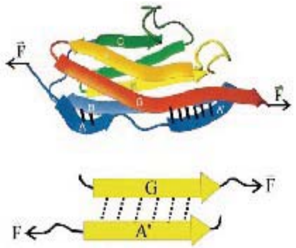
H-bridges between the first and last ß-strands of the domain

Biological logic behind mechanical stability I.

Mechanical stability provided by shear pattern of H-bond patch

Force spectrum of $I27_{12}$



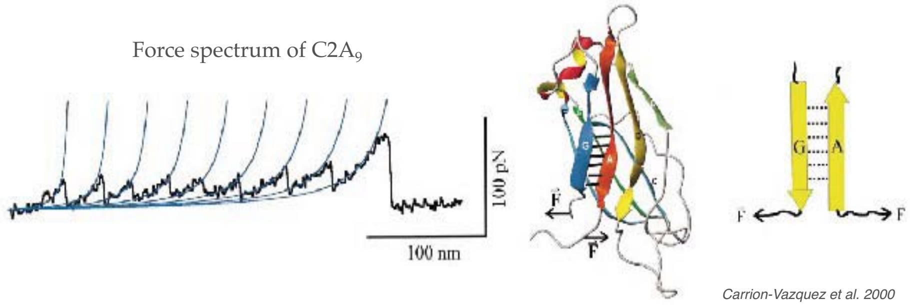


Carrion-Vazquez et al. 2000

Biological logic behind mechanical stability II.

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

Force spectrum of $C2A_9$

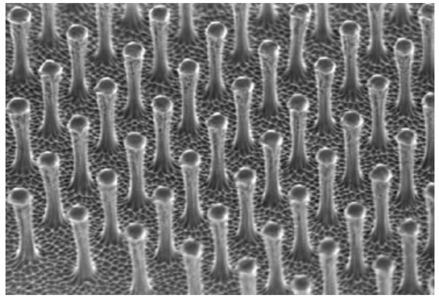


Carrion-Vazquez et al. 2000

Mechanical stability in real-life applications

Principle of parallel bond coupling

Gecko foot stickiness: Bristles (setae) coupled in parallel



Artificial gecko foot