

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 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.



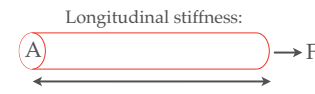
Étienne-Jules Marey (1830 - 1904) - Used cinematography to scientifically investigate locomotion.

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

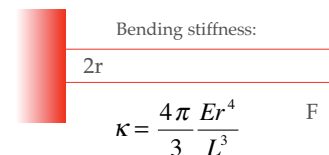
Hookean elasticity

- Stiffness or spring constant ($k=F/\Delta L$) 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.



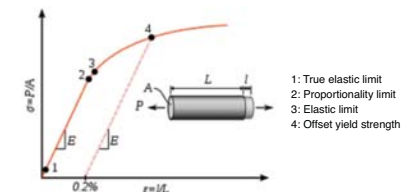
$$\kappa = \frac{F}{\Delta L} = \frac{EA}{L}$$

F = force
A = cross-sectional area
L = rest length
 ΔL = extension
 $F/A = \sigma$ = stress
 $\Delta L/L = \epsilon$ = strain
E = Young's modulus (Pa)

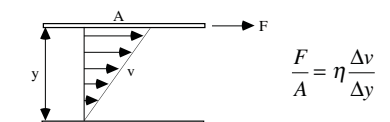


$$\kappa = \frac{4\pi Er^4}{3L^3}$$

Stress-strain curve



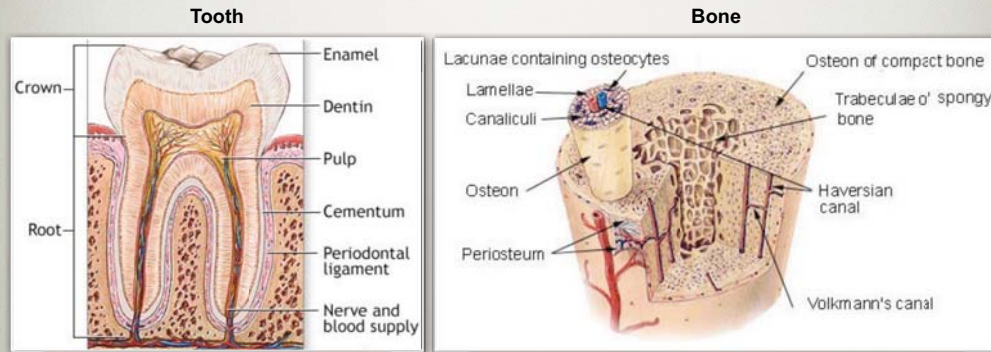
Viscosity



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

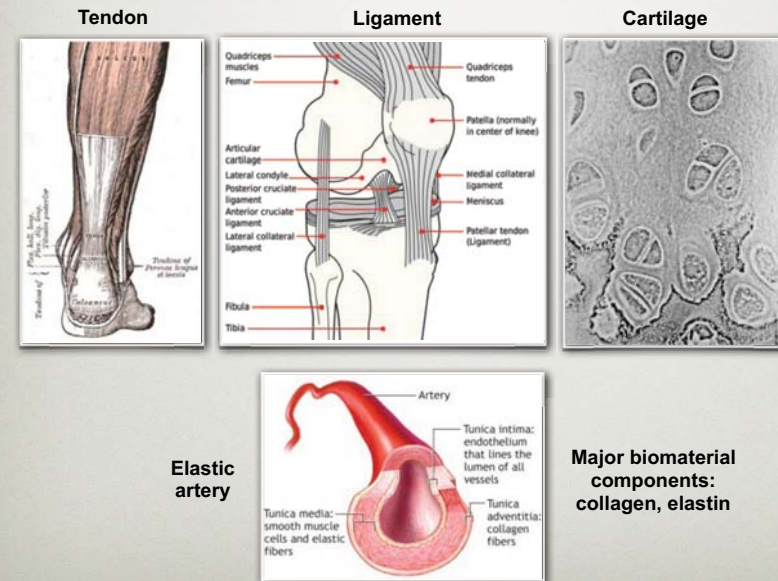
F = shear force
A = area of fluid layer
 η = viscosity
v = flow velocity
y = distance between fluid layers
F/A = shear stress (τ)
 $\Delta v / \Delta y$ = velocity gradient (D)

HARD TISSUES

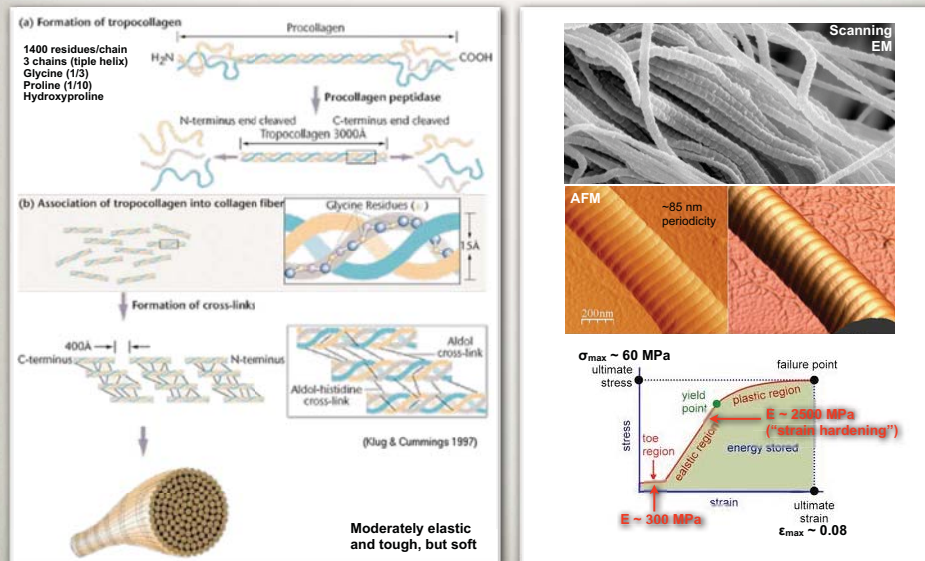


Major biomaterial components:
collagen, apatite

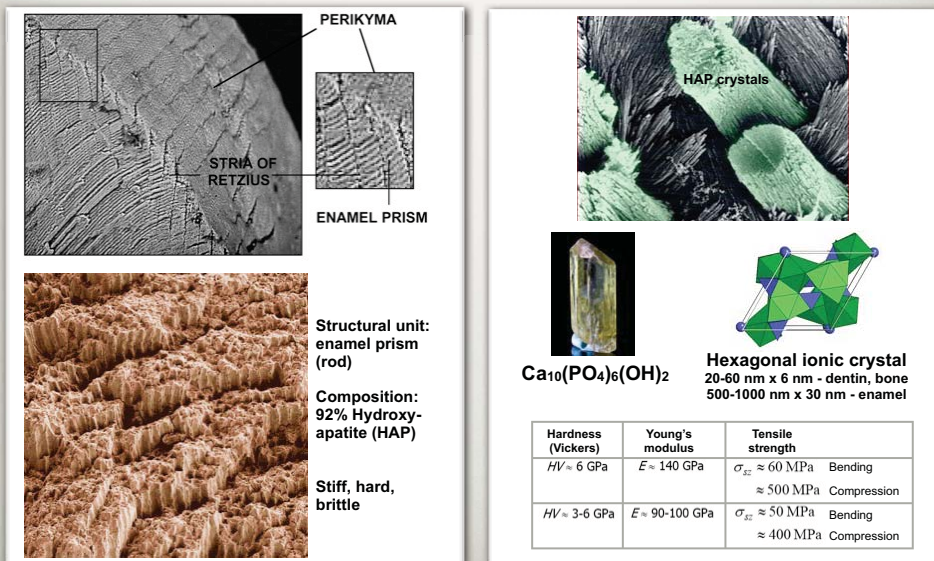
SOFT TISSUES



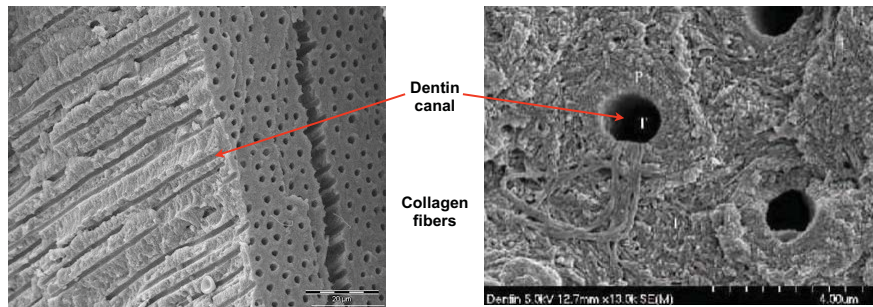
COLLAGEN



TOOTH ENAMEL



DENTIN

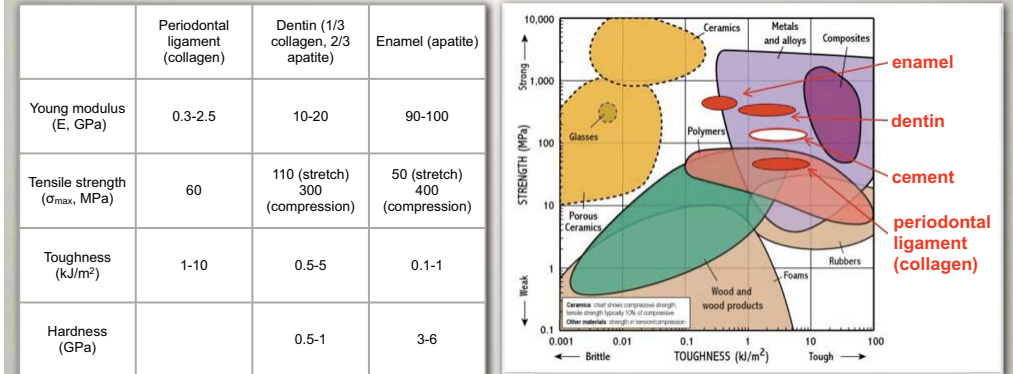


Composition: 35% organic material (collagen) + water, 65% hydroxy-apatite

Structure: collagen matrix with attached hydroxy-apatite crystals

Biomechanics: moderately hard, very strong and tough

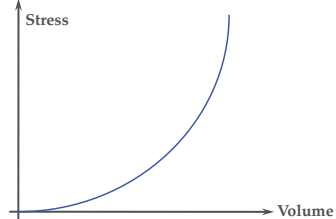
SUMMARY OF DENTAL TISSUE BIOMECHANICS



BIOMECHANICS OF ELASTIC ARTERIES

Non-linear elasticity

Strain is not linearly proportional to stress.

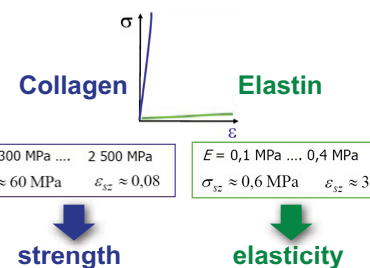
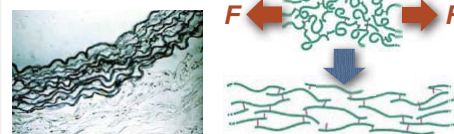


Determinants of vascular elasticity:

Elastin
Collagen
Smooth muscle

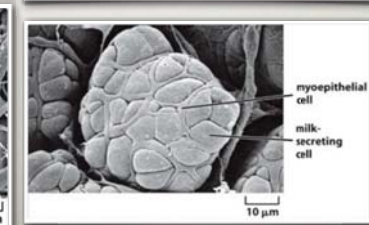
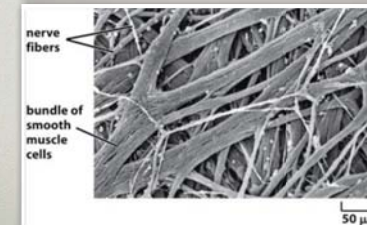
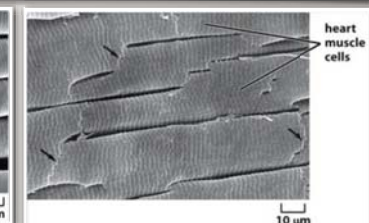
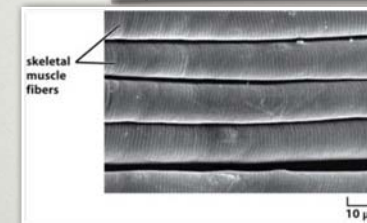
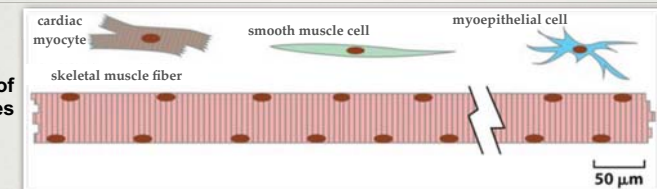
Implications of vascular elasticity:

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

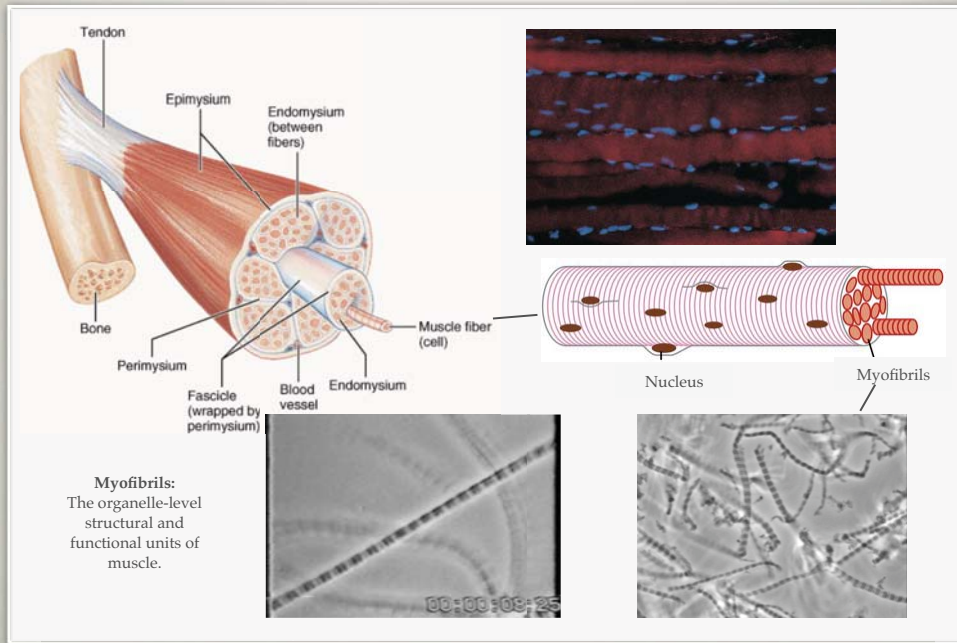


MUSCLE BIOMECHANICS

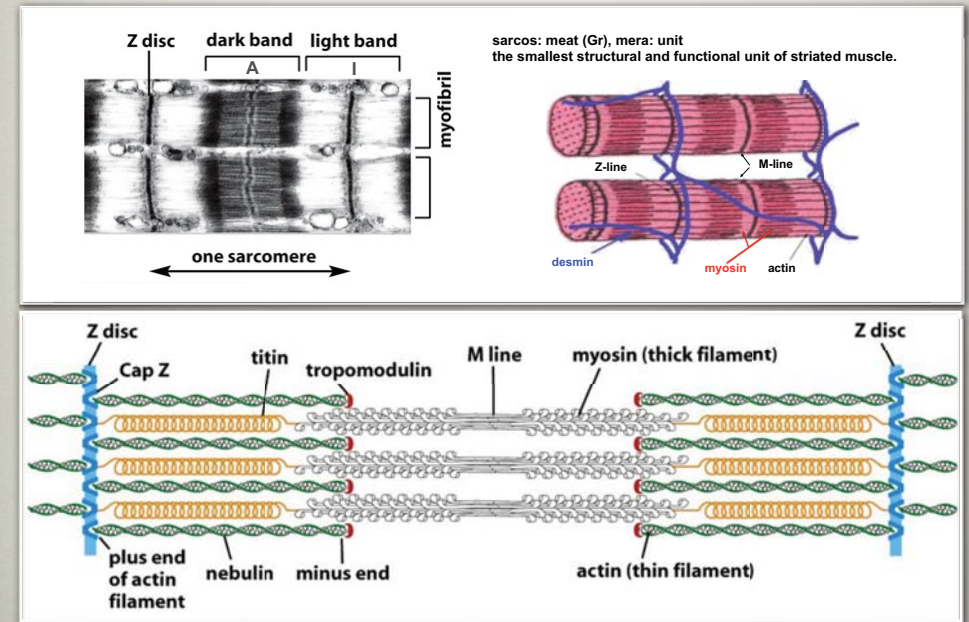
Types of muscles



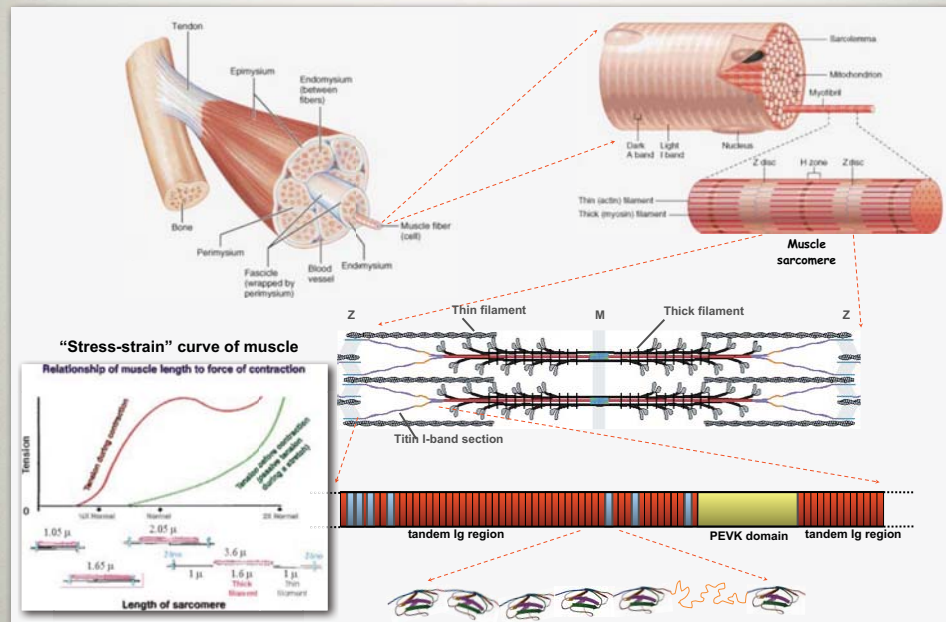
SKELETAL MUSCLE



THE SARCOMERE



TITIN: ELASTIC FILAMENT IN THE MUSCLE SARCOMERE



BIOPOLYMERS MECHANICS

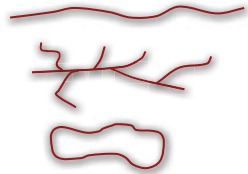
Polymers:
chains built up from monomers

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

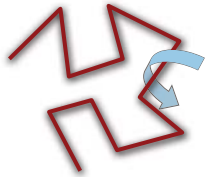
SHAPE OF POLYMERS

1. Linear
2. Branched
3. Circular

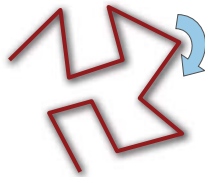


Shape of polymer chain changes dynamically. Possible mechanisms:

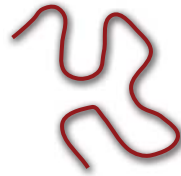
1. Rotation around CC-bonds



2. Freely jointed chain (FJC)

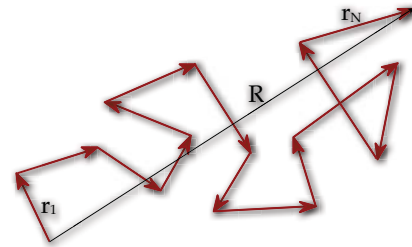


3. Bending, wormlike chain (WLC)



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

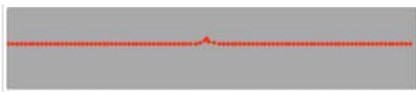
Thermal fluctuations of the polymer chain



Configurational entropy (orientational disorder of elementary vectors) increases.

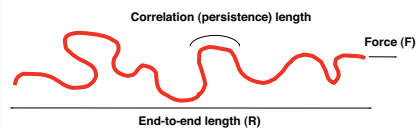


The chain shortens.



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 =contour length
 R/L =relative extension

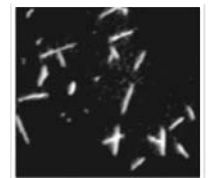
BIOPOLYMER ELASTICITY

l = correlation length
 L = contour length

Rigid chain
 $l \gg L$



Microtubule



Semiflexible chain
 $l \sim L$



Actin filament



Flexible chain
 $l \ll L$

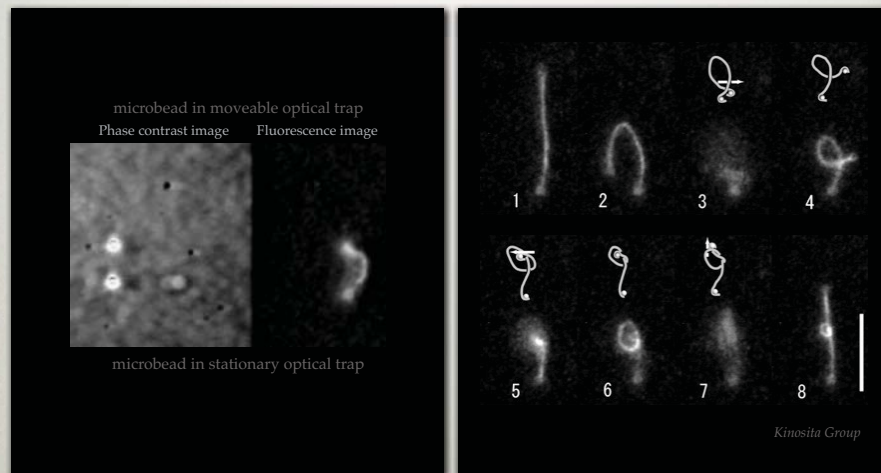


DNA

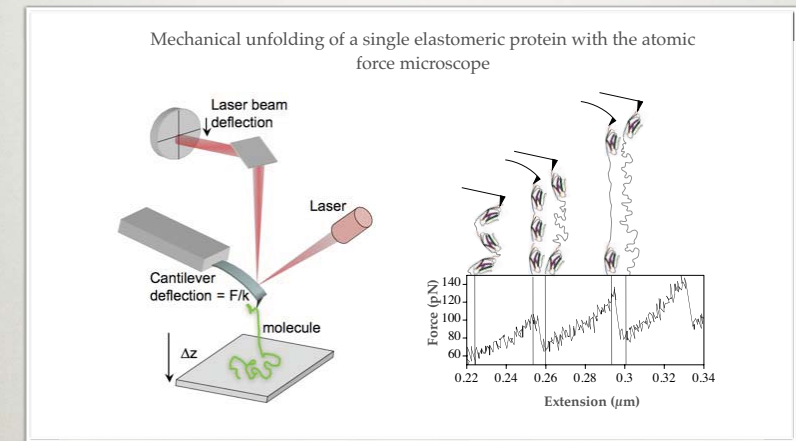


VISUALIZATION OF BIOPOLYMER ELASTICITY

Tying a knot on a single DNA molecule

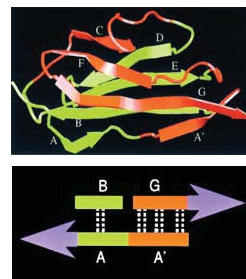
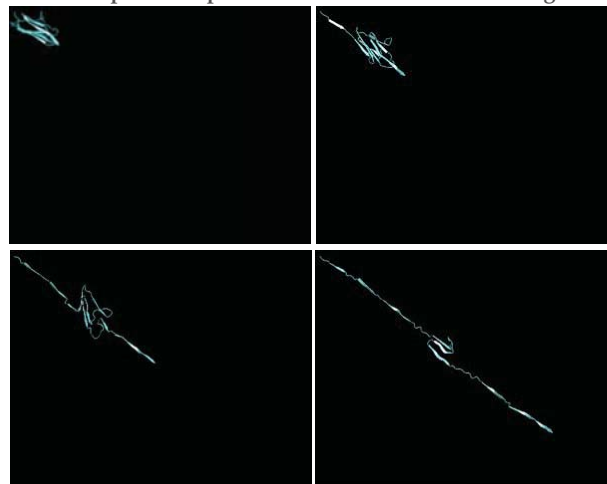


STRETCHING A BIOPOLYMER WITH AFM



MECHANICAL UNFOLDING OF AN ELASTOMERIC PROTEIN

Steps of computer-simulated domain unfolding

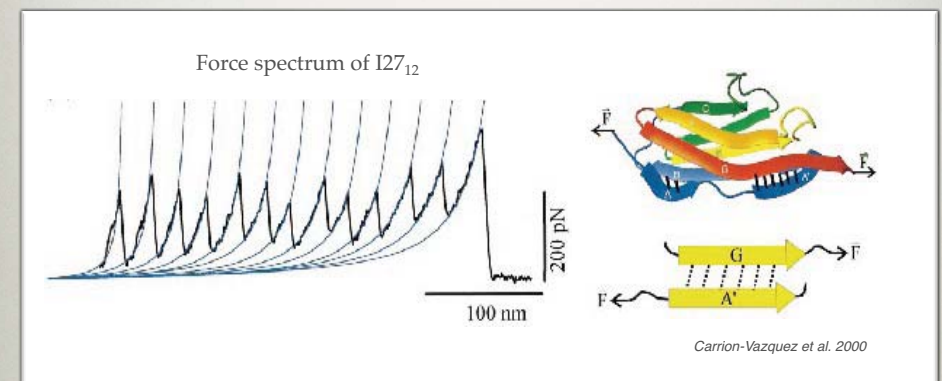


Basis of mechanical stability:

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

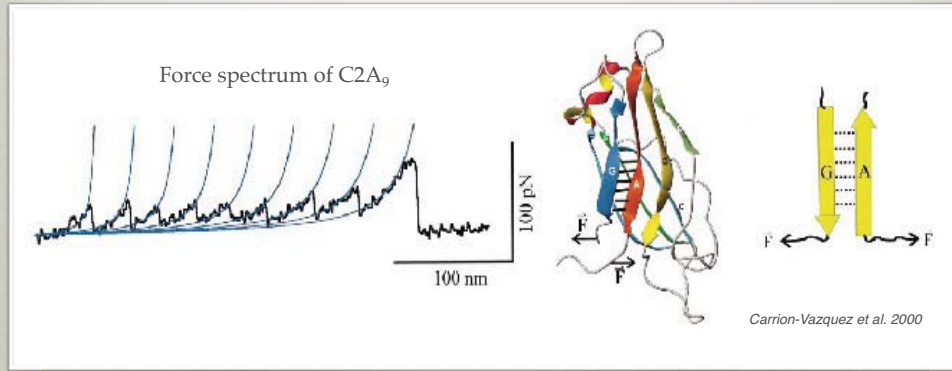
BIOLOGICAL LOGIC BEHIND MECHANICAL STABILITY I.

Mechanical stability provided by shear pattern of H-bond patch



BIOLOGICAL LOGIC BEHIND MECHANICAL STABILITY II.

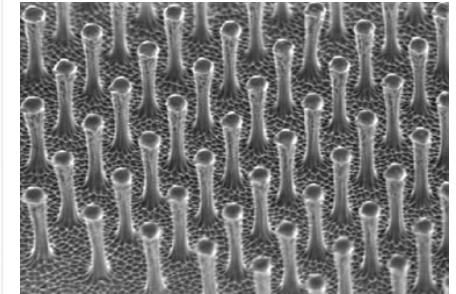
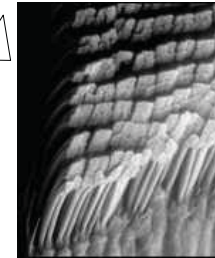
Low mechanical stability due to zipper pattern of H-bond patch



MECHANICAL STABILITY IN REAL-LIFE APPLICATIONS PRINCIPLE OF PARALLEL BOND COUPLING



Gecko foot stickiness:
Bristles (setae)
coupled in parallel



Artificial gecko foot