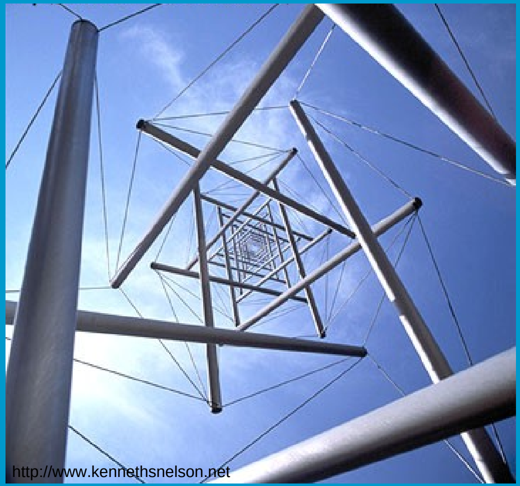
Bio-Inspired Design

Mechanical Stiffness and Motion

Just Herder

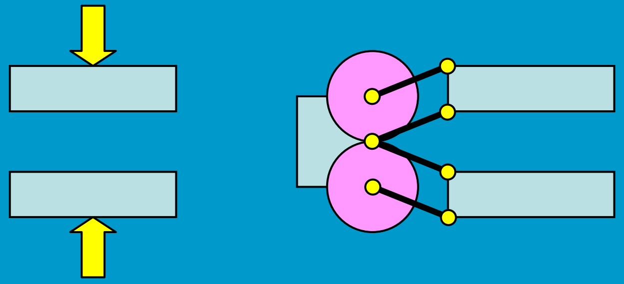
Lecture 2: Bioconstruction
Biostructure & bioenergy (muscle configurations)

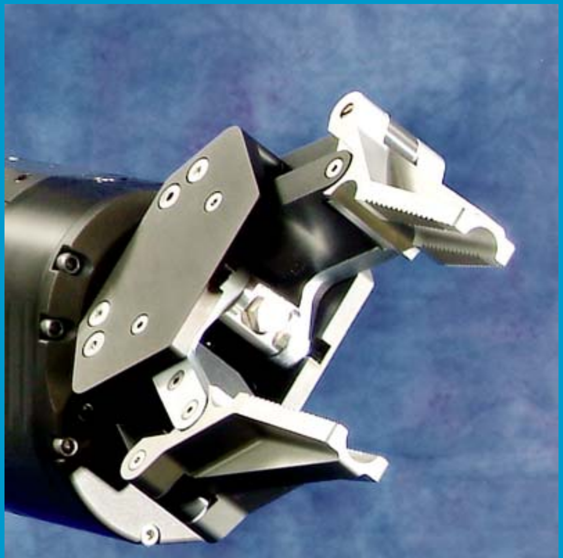
- Contents 1st hour (Just): mechanical stiffness & motion: strength at low weight, redundant structures, etc.
- Contents 2nd hour (Paul): hydrostatic stiffness & motion: energetically efficient muscle configurations, stiffness with soft structures.



Bioconstruction

- Engineering: System, Shape, Material





Raptor by Kraft Telerobotics

- Are there any differences between human engineering and nature, in terms of:
  - System
  - Construction elements
  - Material

?

Cool JC, 1976

TUDelft

Biomaterials

- Tensile materials (Crystalline Polymers, Silk, Collagen, Cellulose, Chitin)
- Flexible materials (Protein Rubbers, Mucopolysaccharides, Pliant Composites, Mesoglea, Uterine Cervix, Skin, Arterial Wall, Cartilage)
- Rigid materials (Bone, Keratin, Cell wall, Wood, Stony Materials)

Biomaterials

- Tensile materials (Crystalline Polymers, Silk, Collagen, Cellulose, Chitin)
- Flexible materials (Protein Rubbers, Mucopolysaccharides, Pliant Composites, Mesoglea, Uterine Cervix, Skin, Arterial Wall, Cartilage)
- Rigid materials (Bone, Keratin, Cell wall, Wood, Stony Materials)

- No metal!

Biocomponents

- Tensile components (Skin, Tendon, Fibre)
- Compressive/bending components (Skeleton)
- Relative motion components (Joints, Compliance)
- Active components (Muscle)

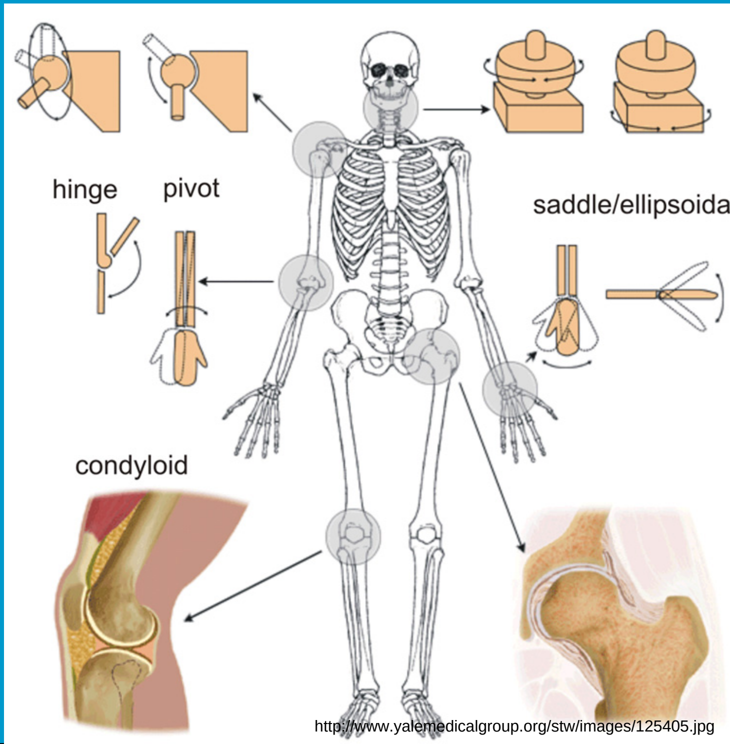
Biocomponents

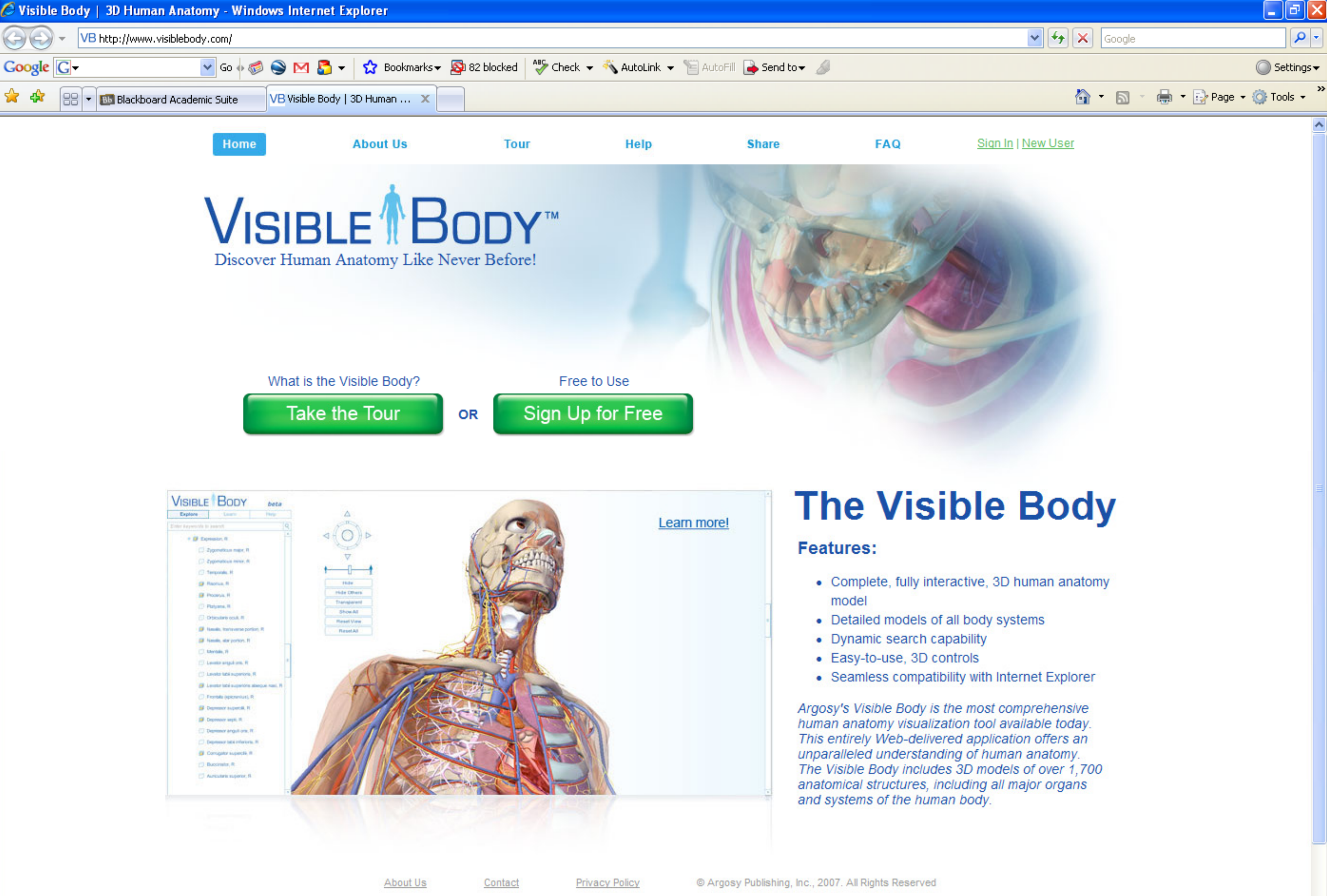
- Tensile components (Skin, Tendon, Fibre)
- Compressive/bending components (Skeleton)
- Relative motion components (Joints, Compliance)
- Active components (Muscle)

- No multirev bearings, no wheels, no fasteners!

Vertebrates: joints

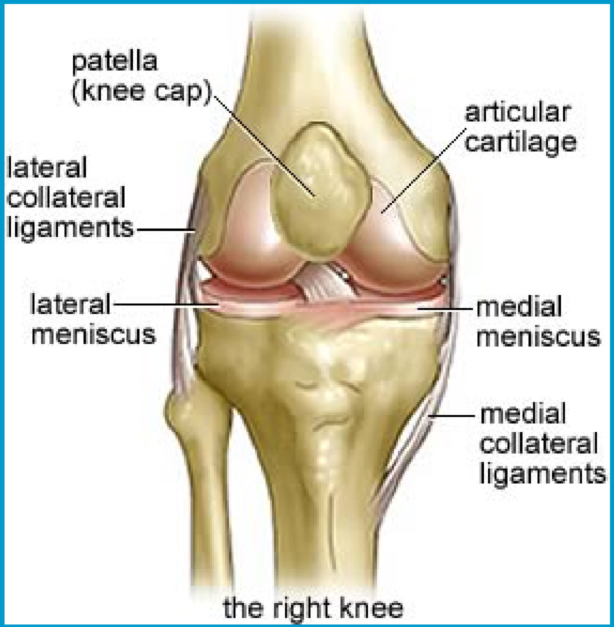
- Synarthroses: hardly movable (sutures in human skull)
- Amphiarthroses: slightly movable (cartilage attachments in ribs and vertebrae disks)
- Diarthroses: Larger motion range:
  - Ball-and socket (e.g. hip, GH-joint)
  - Ellipsoidal (e.g. fingers)
  - Condyloid (e.g. knee joint)
  - Saddle (e.g. part of the wrist joint)
  - Pivot (e.g. radius/ulna joint)
  - Hinge (e.g. elbow joint)
  - Plane/gliding (e.g. scapula joint)

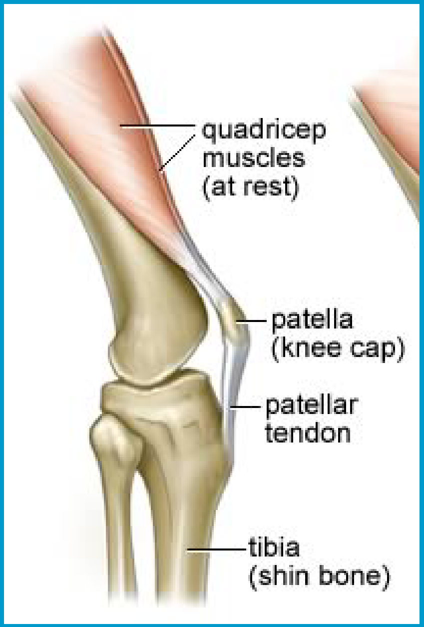


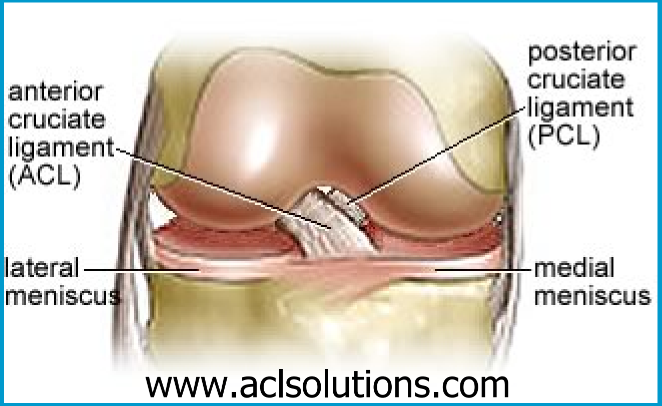

Visible Body | 3D Human Anatomy - Windows Internet Explorer
http://www.visiblebody.com/
Home
About Us
Tour
Help
Share
FAQ
Sign In | New User
VISIBLE BODY™
Discover Human Anatomy Like Never Before!
What is the Visible Body?
Take the Tour
OR
Free to Use
Sign Up for Free
Learn more!
The Visible Body
Features:
• Complete, fully interactive, 3D human anatomy model
• Detailed models of all body systems
• Dynamic search capability
• Easy-to-use, 3D controls
• Seamless compatibility with Internet Explorer
Argosy's Visible Body is the most comprehensive human anatomy visualization tool available today. This entirely Web-delivered application offers an unparalleled understanding of human anatomy. The Visible Body includes 3D models of over 1,700 anatomical structures, including all major organs and systems of the human body.
About Us
Contact
Privacy Policy
© Argosy Publishing, Inc., 2007. All Rights Reserved

TU Delft

Bio-inspired joints

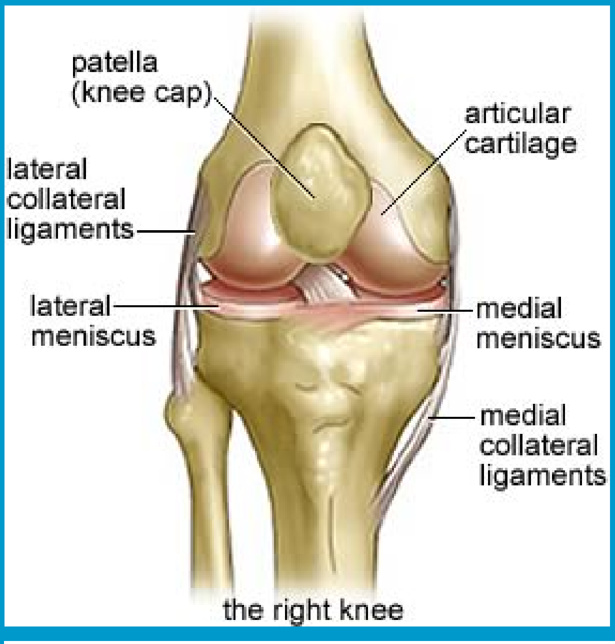


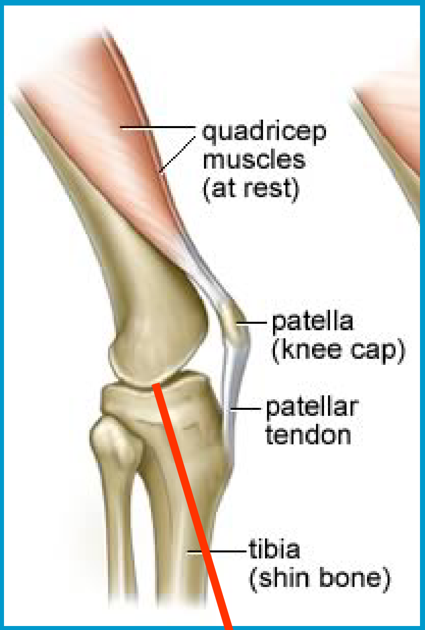


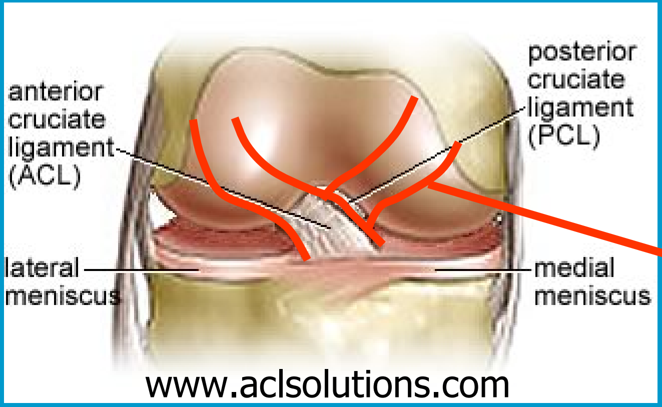


TUDelft

Bio-inspired joints



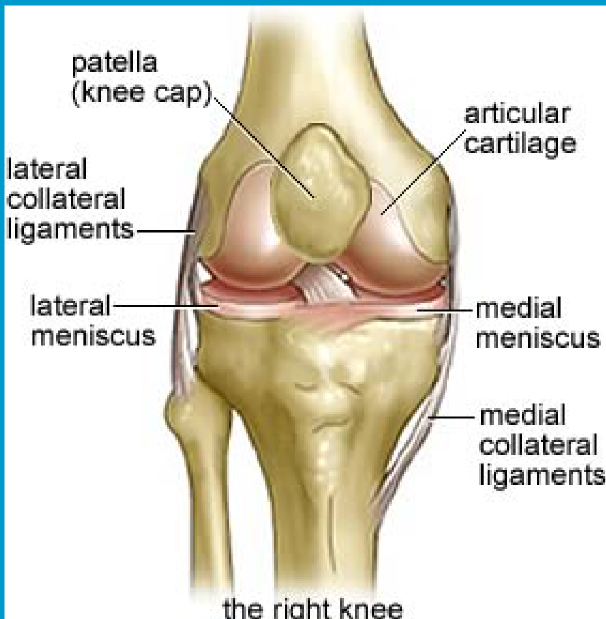


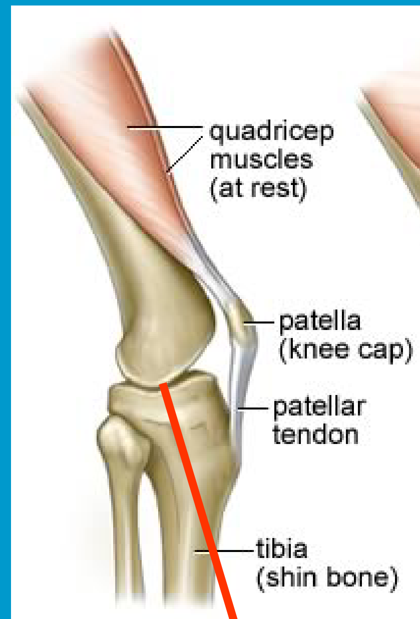


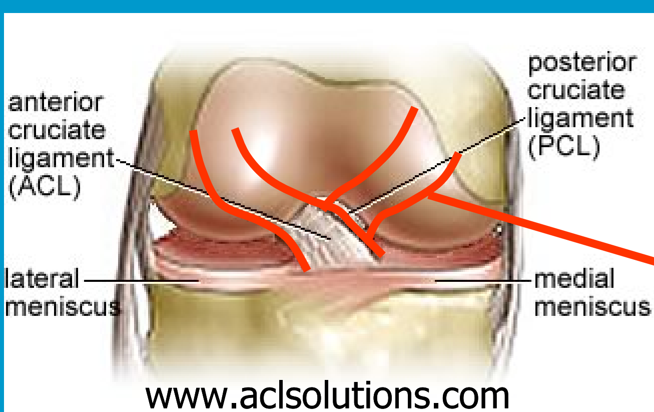
Rolling/sliding contact

Cross-wise arranged bands

Bio-inspired joints

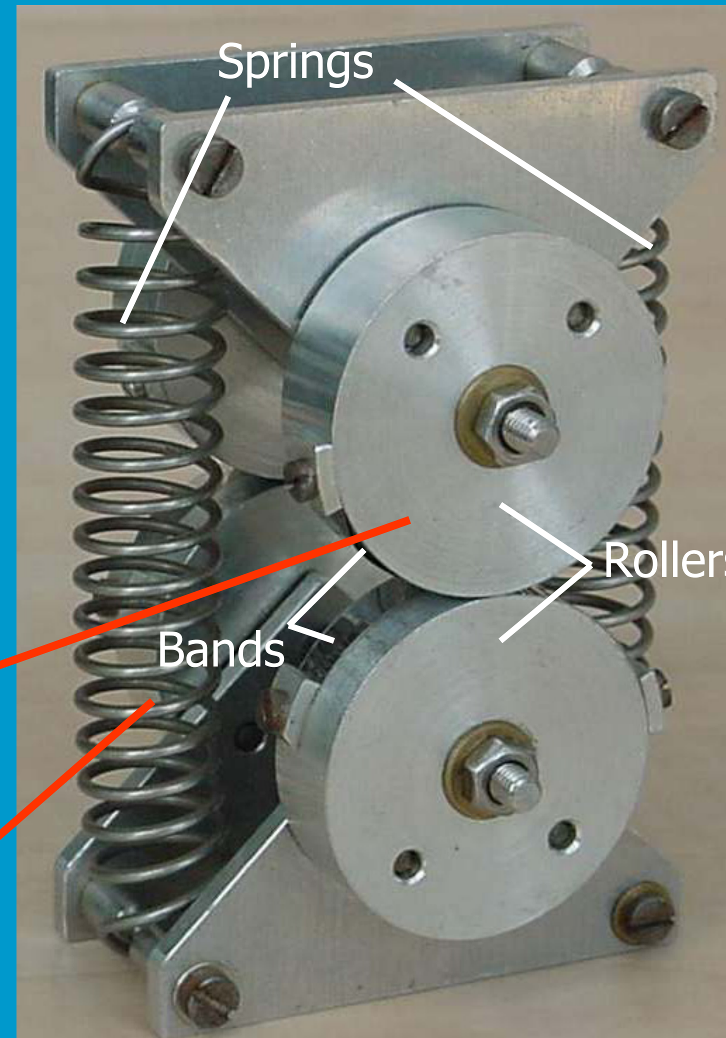






Rolling/sliding contact

Cross-wise arranged bands



J Verbeek, JL Herder

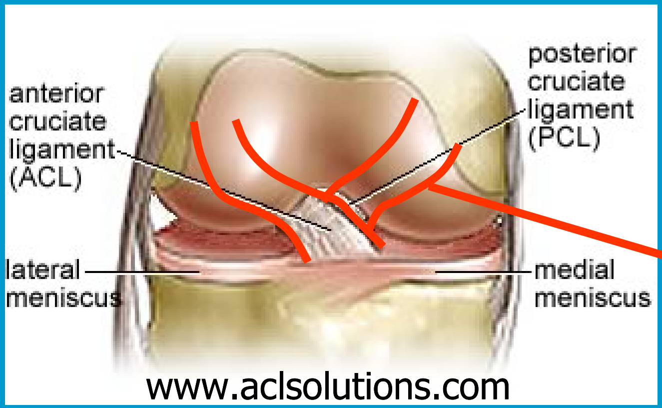
TU Delft

Bio-inspired joints

Nature does not label…

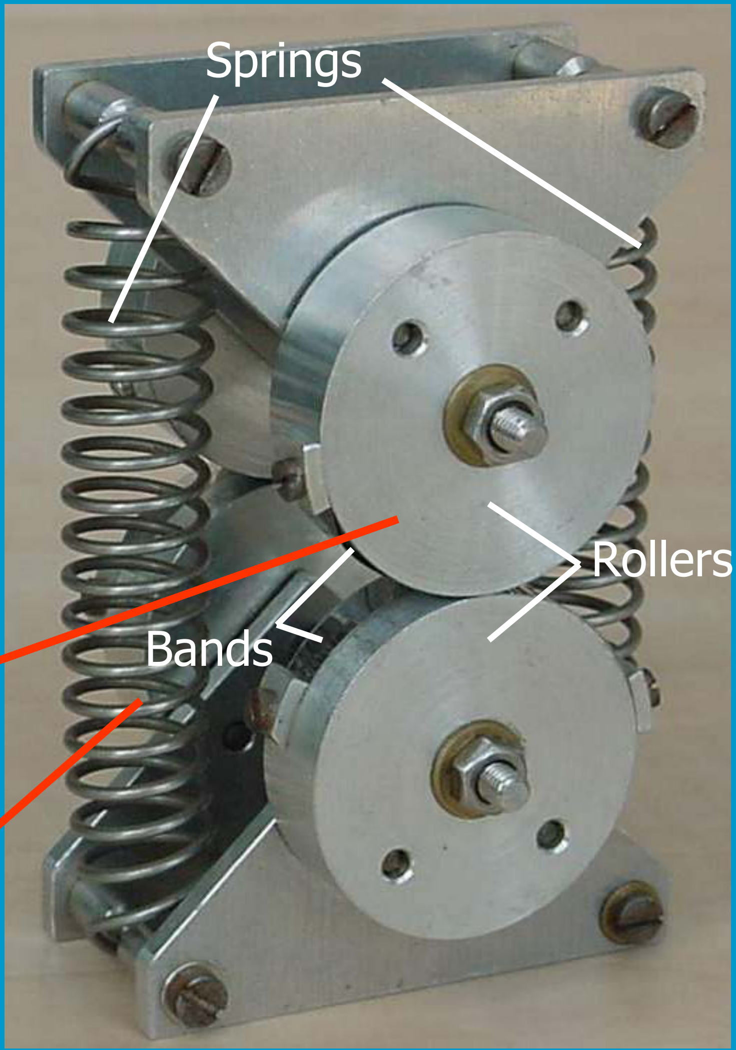
You hypothesize, investigate, and design.

Physical principles.



Rolling/sliding contact

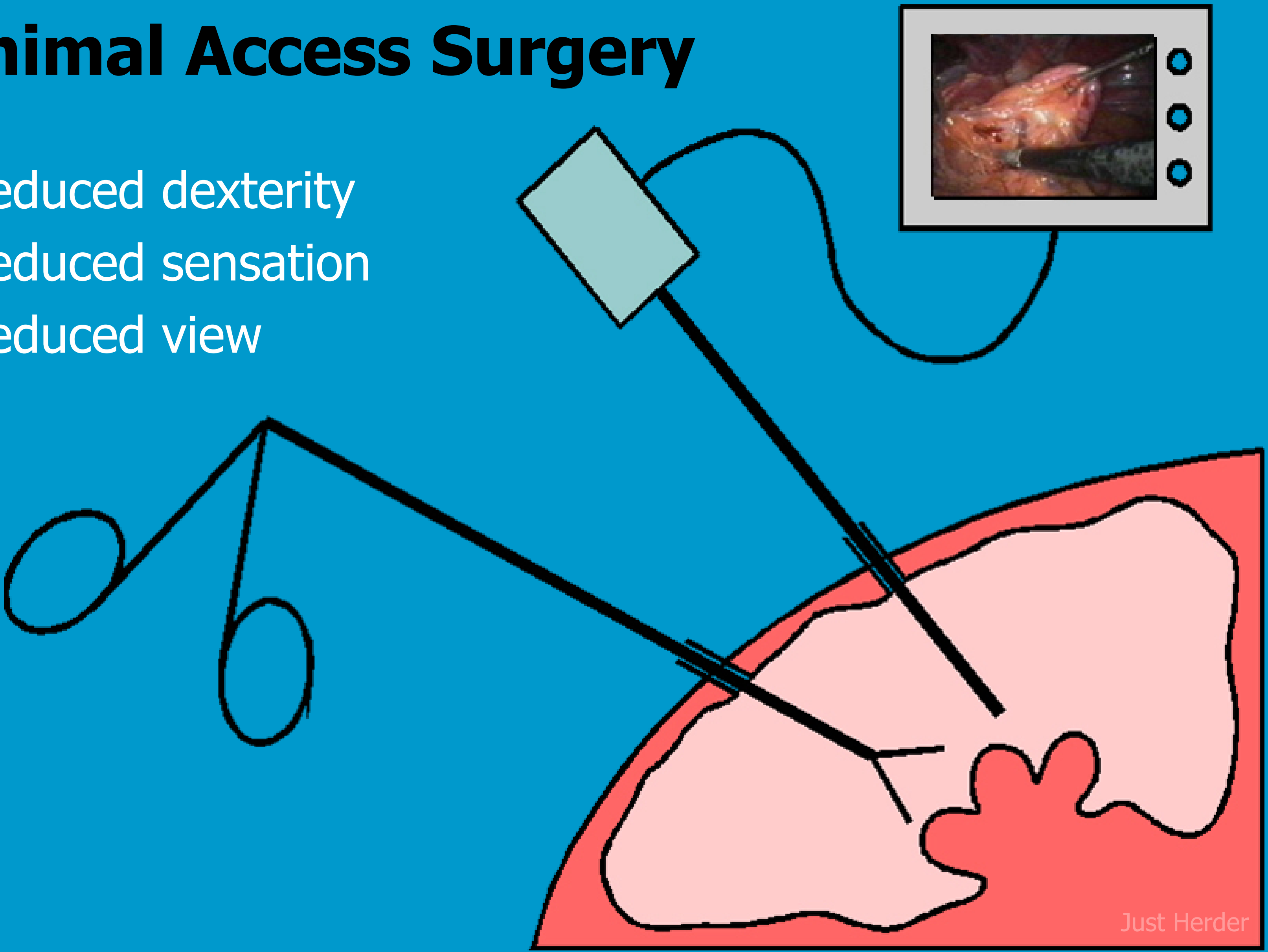
Cross-wise arranged bands



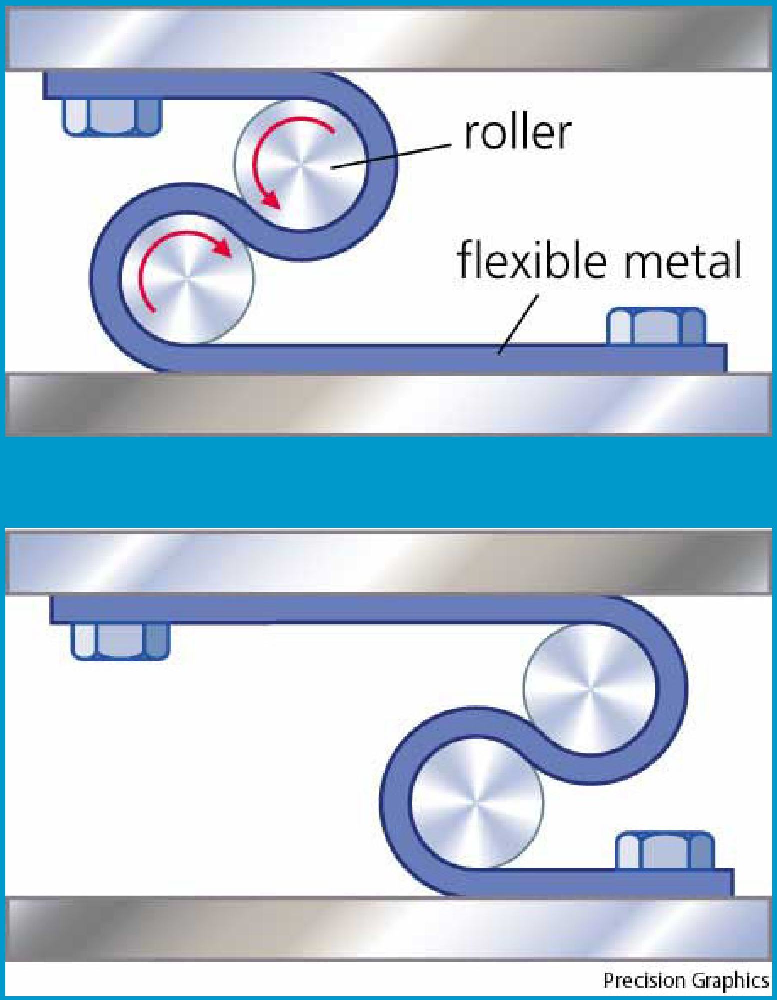
TU Delft

Minimal Access Surgery

- Reduced dexterity
- Reduced sensation
- Reduced view

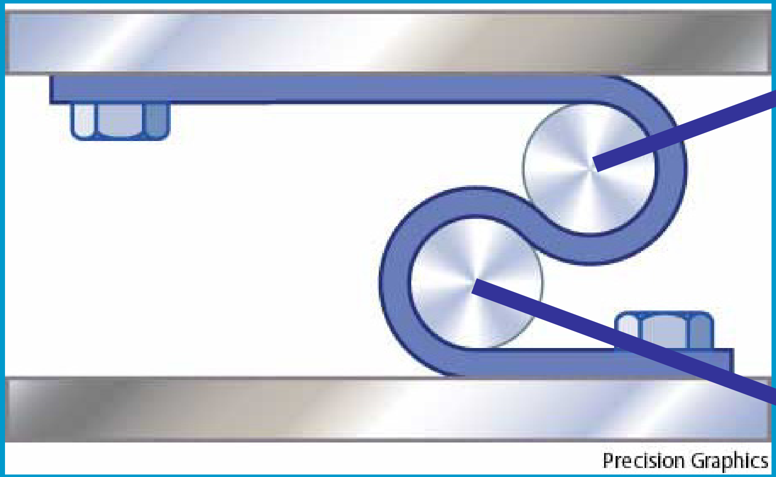


Bio-Inspired rolling joints



TUDelft

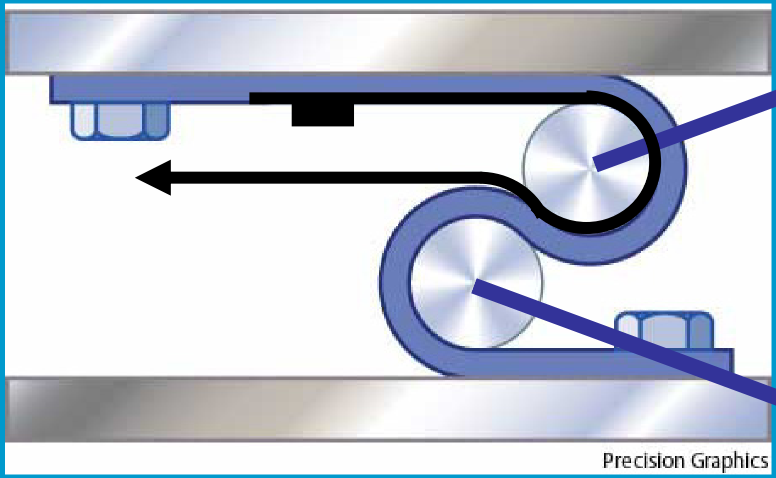
Bio-Inspired rolling joints



Bio-Inspired rolling joints

Band is compromise between bending and tension

Most vulnerable parts take highest forces!

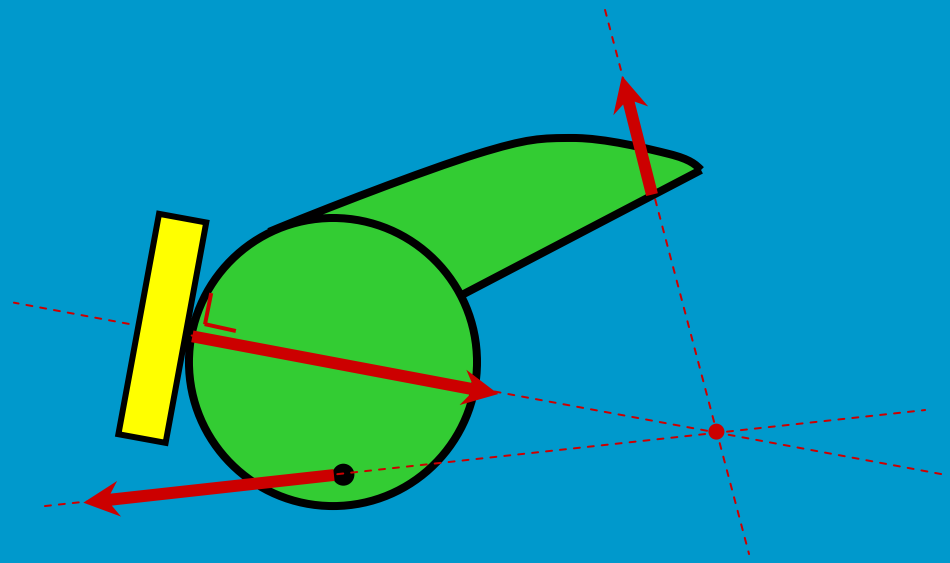


$$\sigma = \frac{F}{A} + \frac{My}{I}$$

$$Bernouilli - Euler : \kappa = \frac{1}{R} = \frac{d\theta}{ds} = \frac{M}{EI}$$

$$\sigma = \frac{F}{A} + \frac{Ey}{R} \quad = \quad \frac{F}{bd} + \frac{Ed}{2R}$$

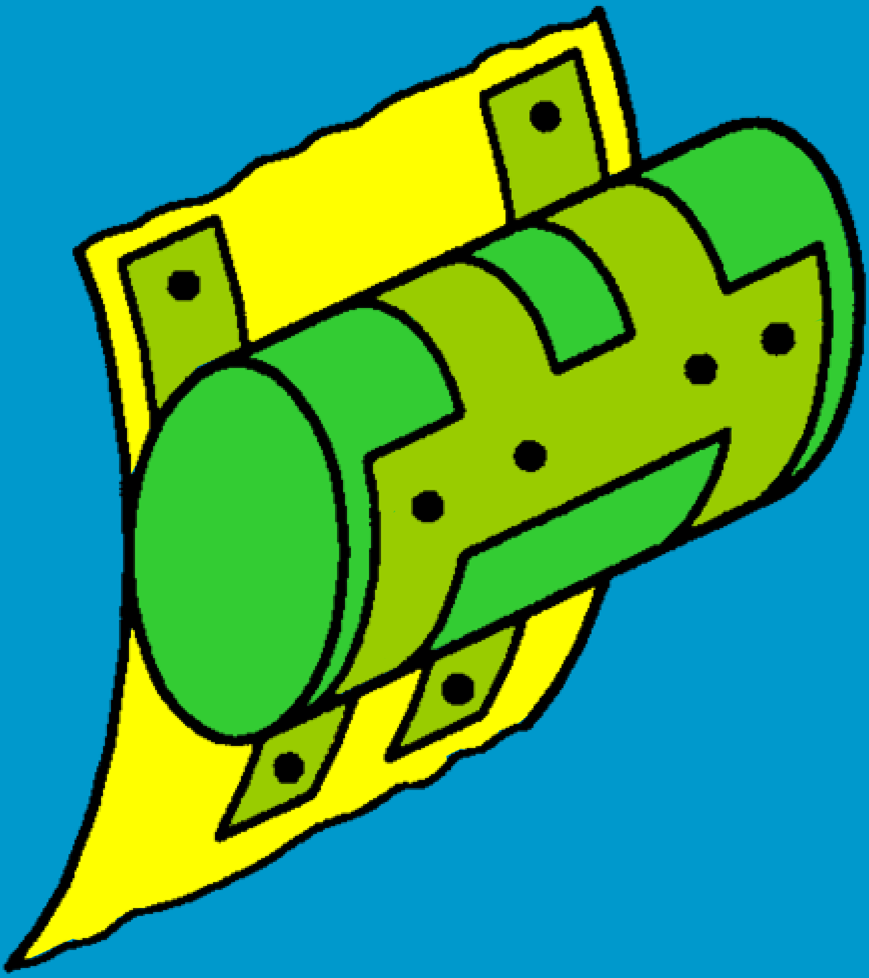
Force directed design



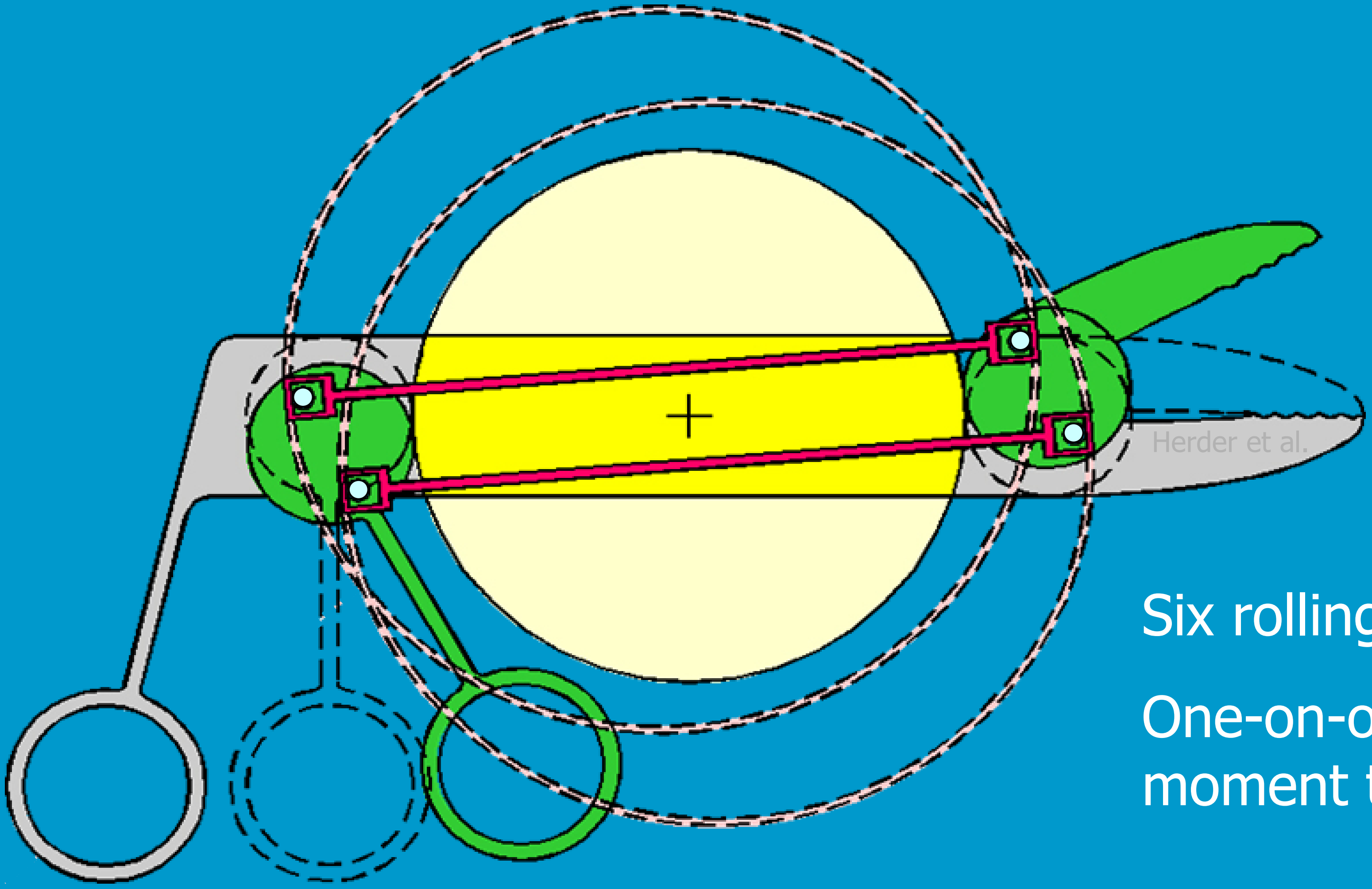
Low friction forceps

- Rolling joint
- Flexible band

- Negligible friction
- No backlash
- No need for lubrication



Low friction forceps



Six rolling joints

One-on-one moment transfer

TU Delft

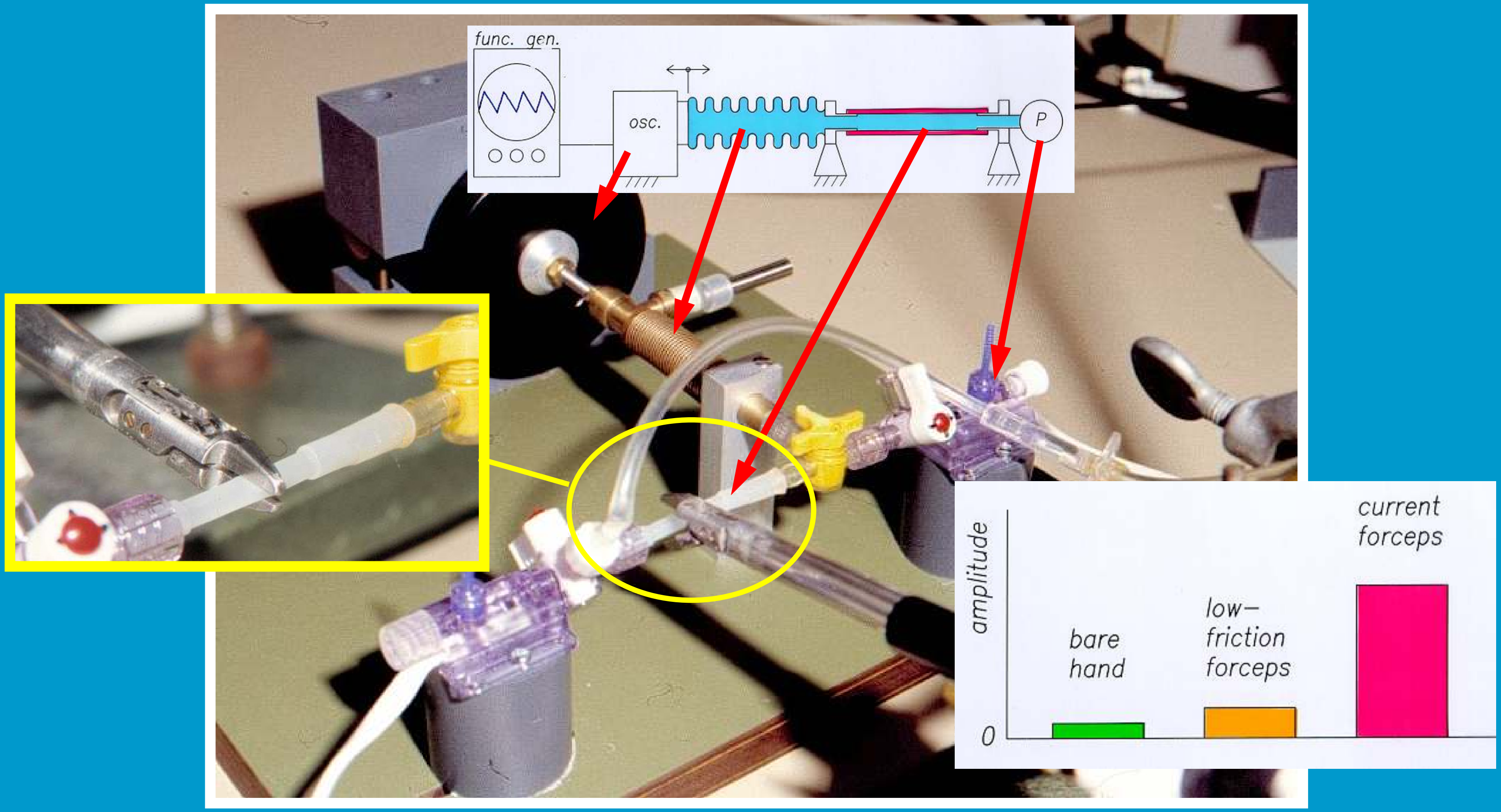
Low friction forceps

Mechanical efficiency 96%

. Ambroise

Patent pending: US 6447532 Herder and Horward, 1997

Low friction forceps



Pulse in artificial artery can be perceived clearly

K den Boer et al. (1999)

BioDesign

- Unknown loads
  - Long or short period
  - Suddenly or slowly
  - Once or repeatedly
  - Move while transmitting considerable forces
  - Accidental overload
  - Energy-efficient
- Design Principles
- Real Organisms

BioDesign

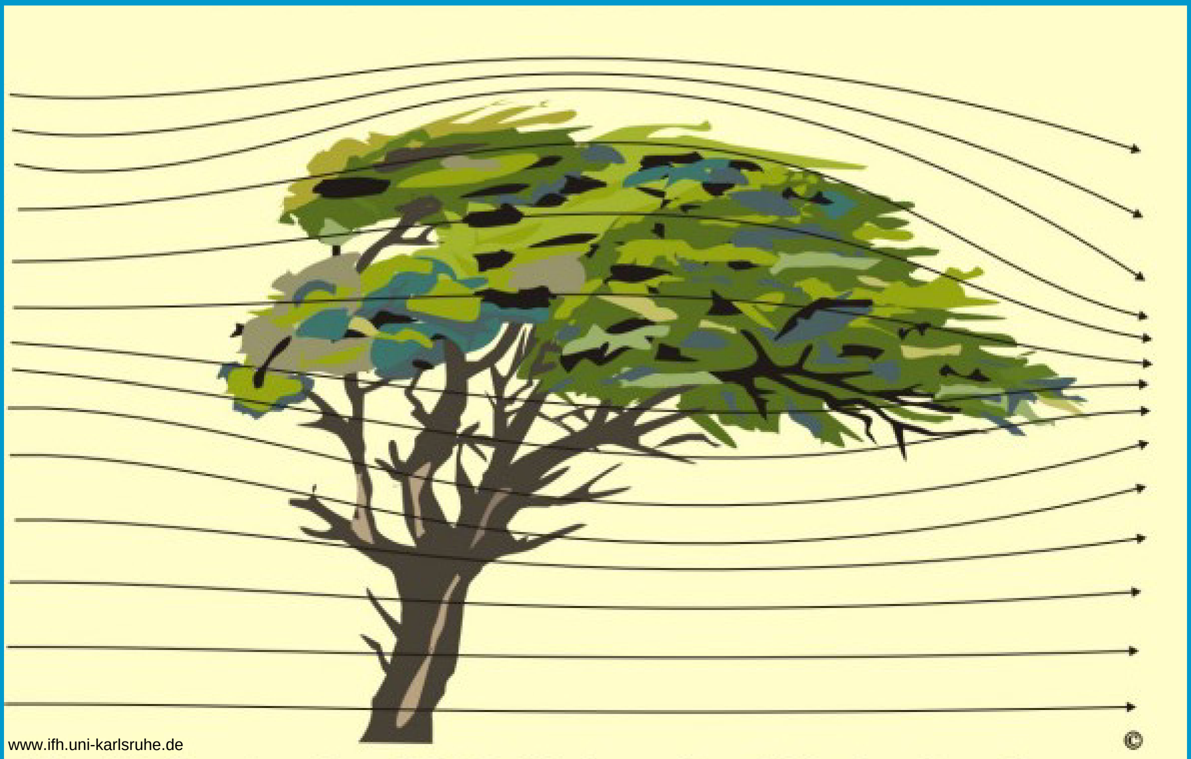
- Unknown loads
  - Long or short period
  - Suddenly or slowly
  - Once or repeatedly
  - Move while transmitting considerable forces
  - Accidental overload
  - Energy-efficient
- Design Principles
- Real Organisms

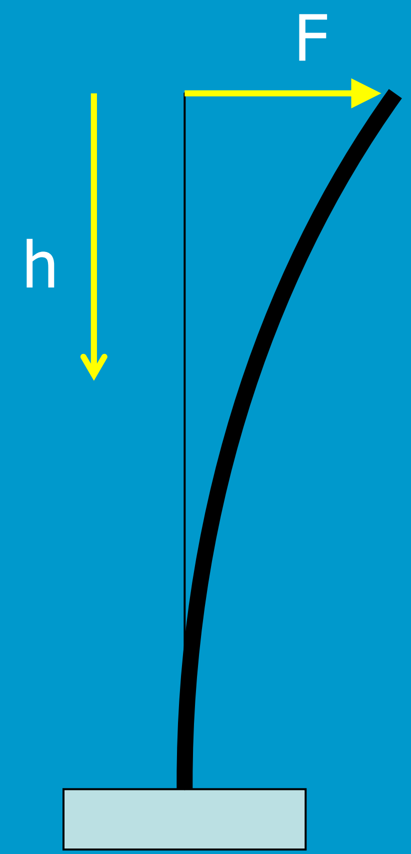
We cannot see physical principles, we have to hypothesize. From real organisms we can at best find that it might be right

BioDesign Principles

- Lightweigth: only tension or compression
- Reduce tension members to wires, maximize I in other members
- Minimize use of compression members and maximize use of tensile members, isolate compessive members
- In composite material, the stiffer element used to control strain and maximize resistance to stress
- Thin-walled cylinders effectively reinforce against explosion and buckling by cross-helical fibres
- Either resist or permit great forces/deflections

BioDesign





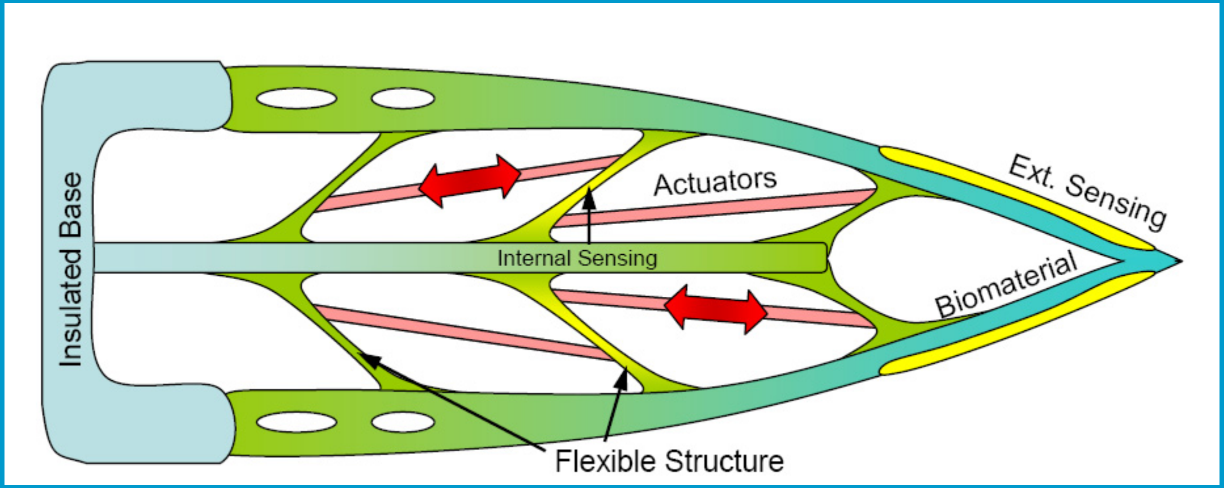
Linear beam theory: $M=Fh$, with $=\sigma My/I$ and $I=\pi r^4/4$:

$\sigma=4Fh/\pi r^3$ hence $r_{min}=(4Fh/\pi\sigma)^{1/3}$ → non-prismatic trunk

Note: in reality many more factors than aerodynamic drag

TU Delft

Compliance in design



B Trease, S Kota, Univ of Michigan at Ann Arbor

Compliance in design

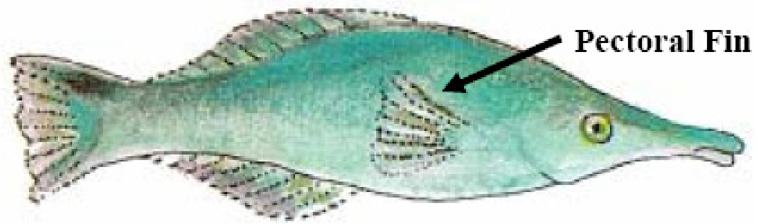
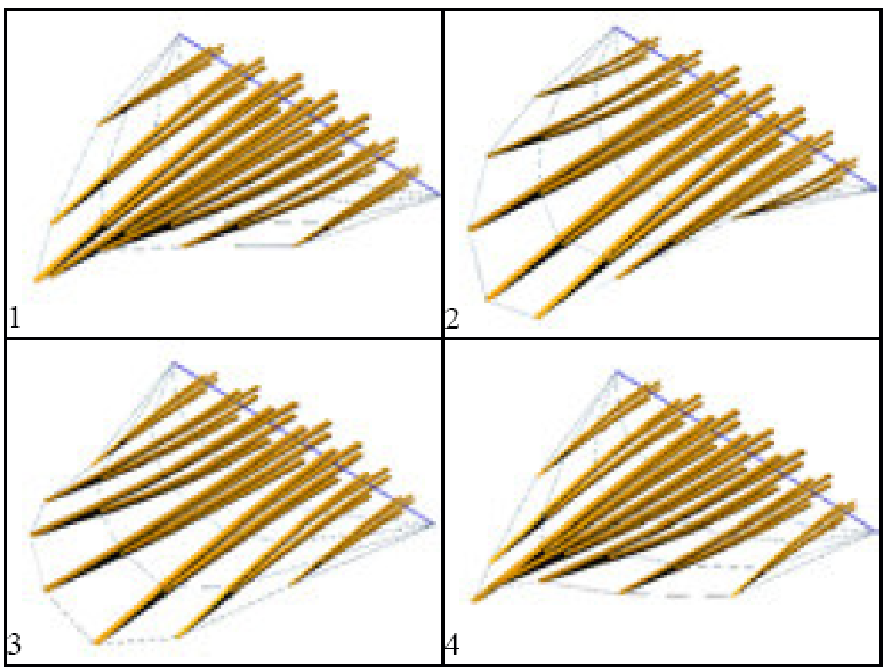
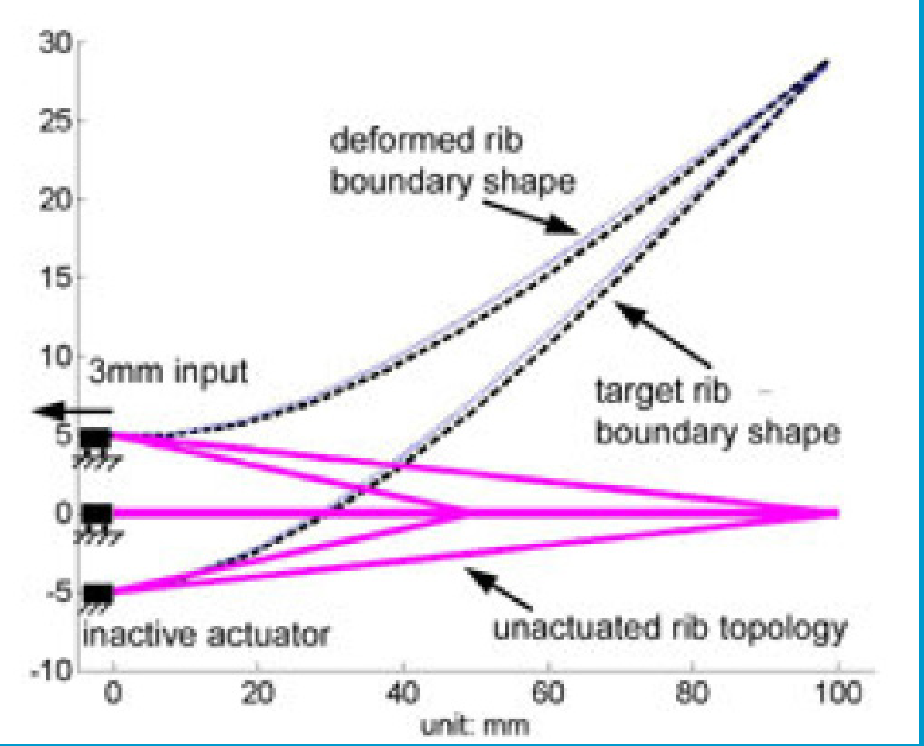


Figure 1: Bird Wrasse (Gomphosus caeruleus)
Image Copyright © 1996-2003 by Paolo Vecchi

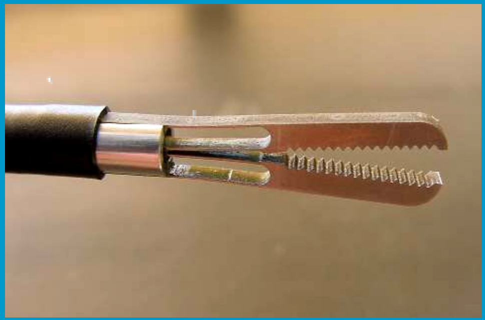


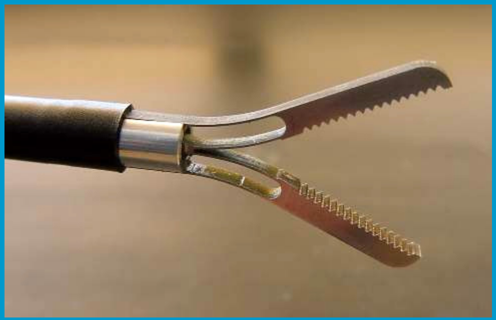


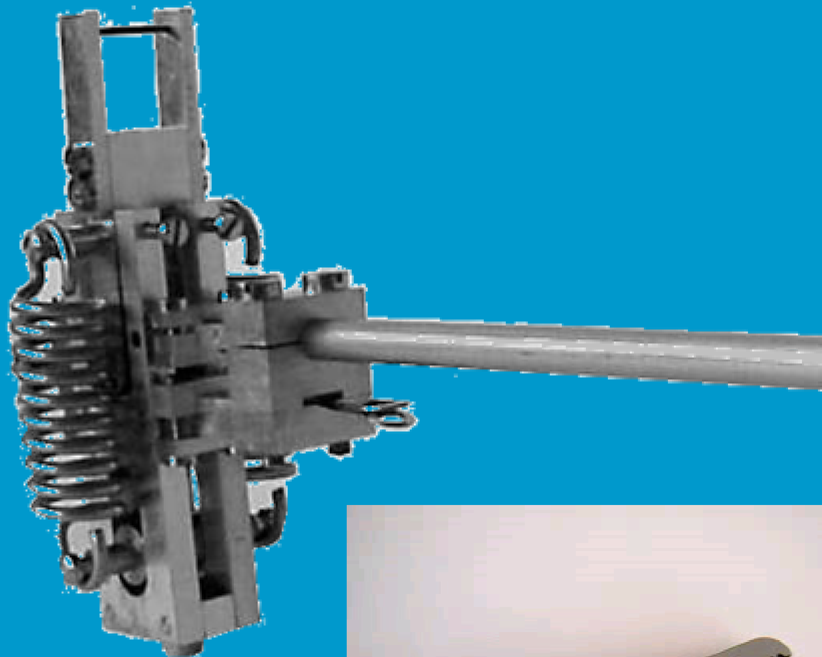
B Trease, S Kota, Univ of Michigan at Ann Arbor

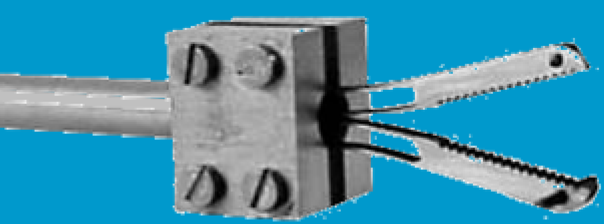
TU Delft

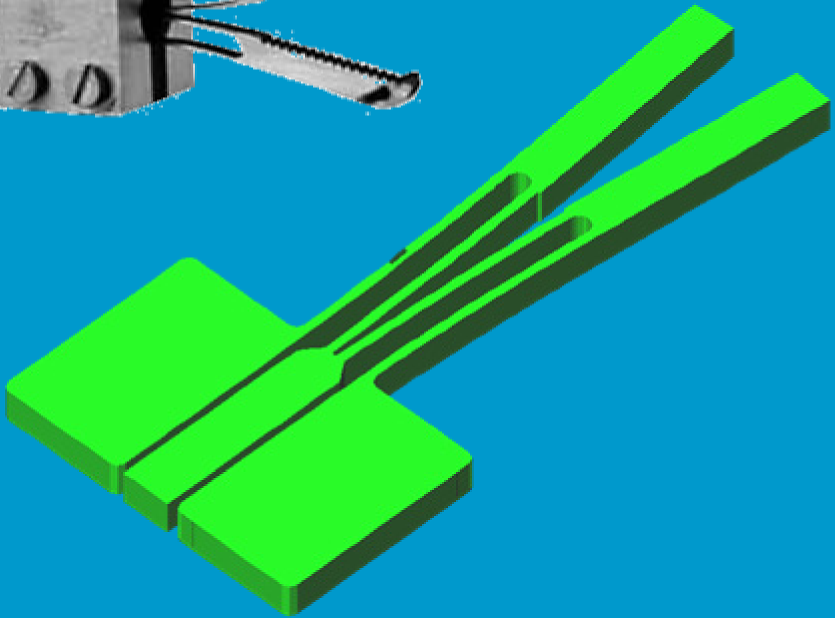
Compliance in design





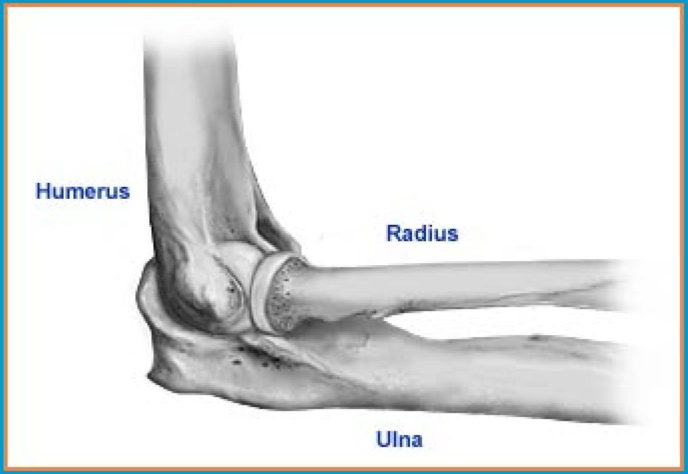


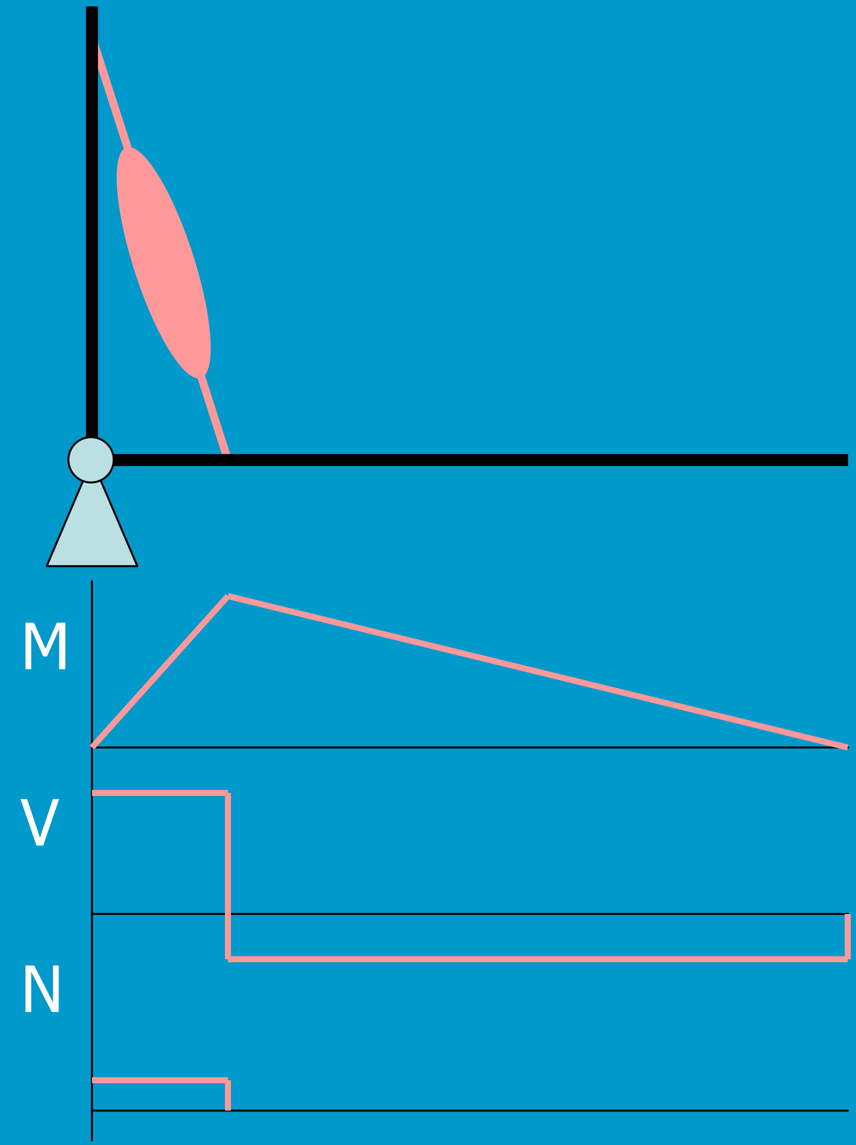




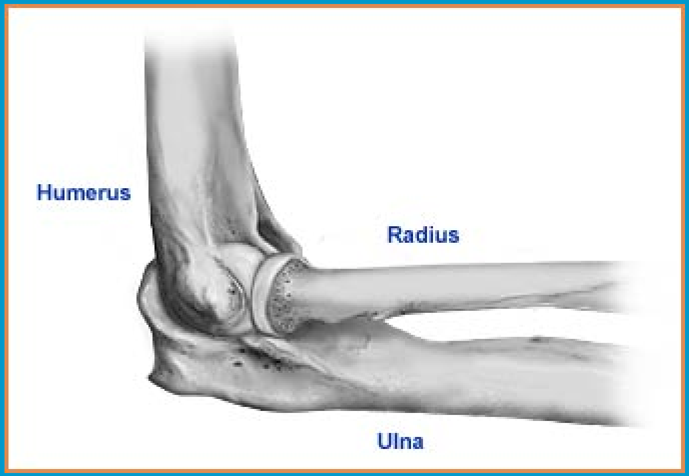
F vd Berg, JL Herder

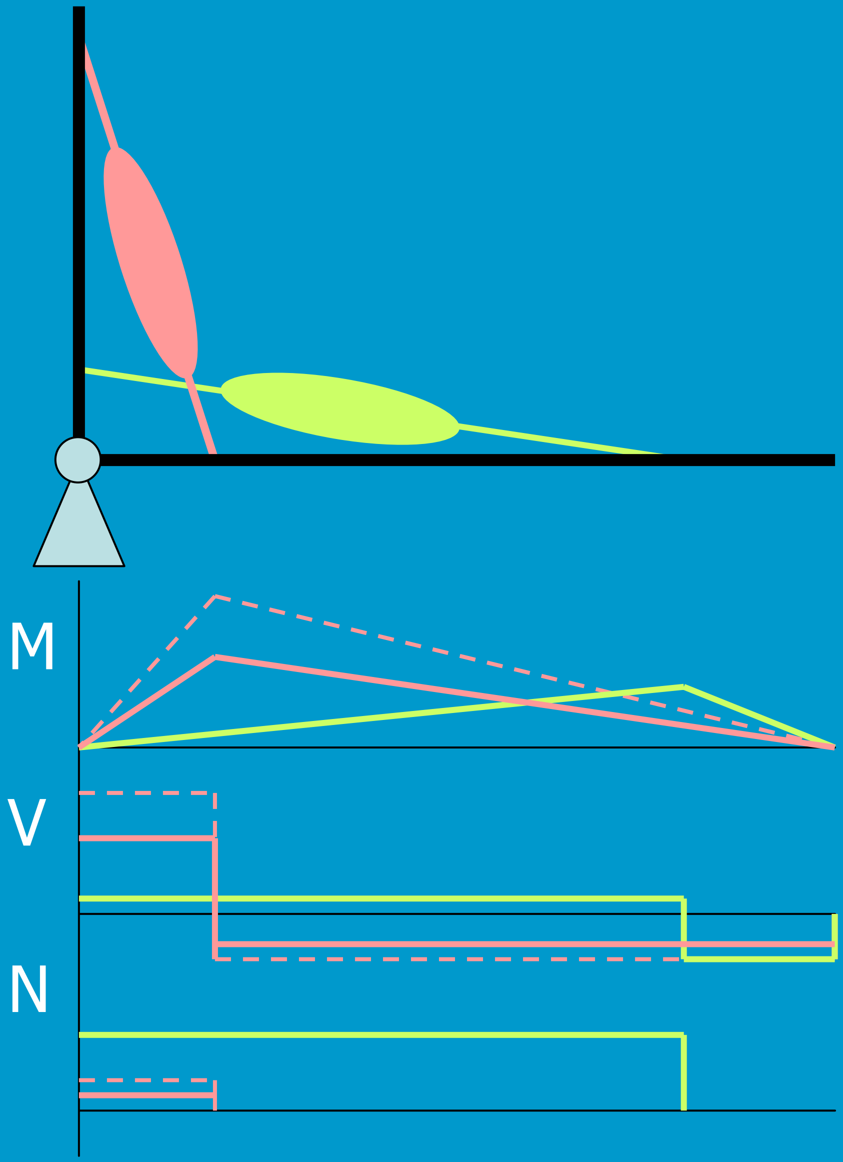
BioDesign



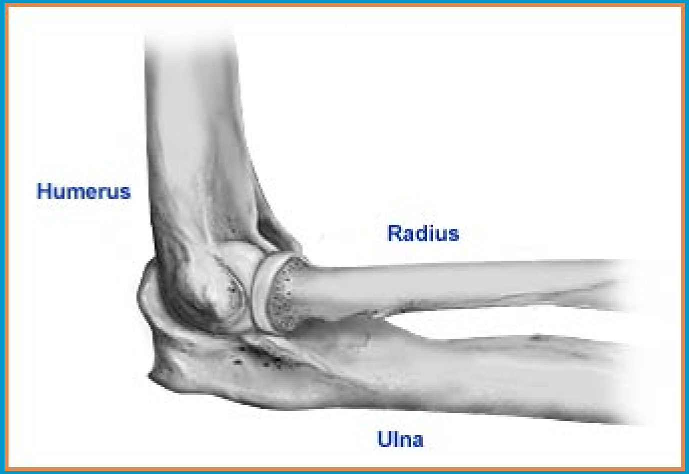


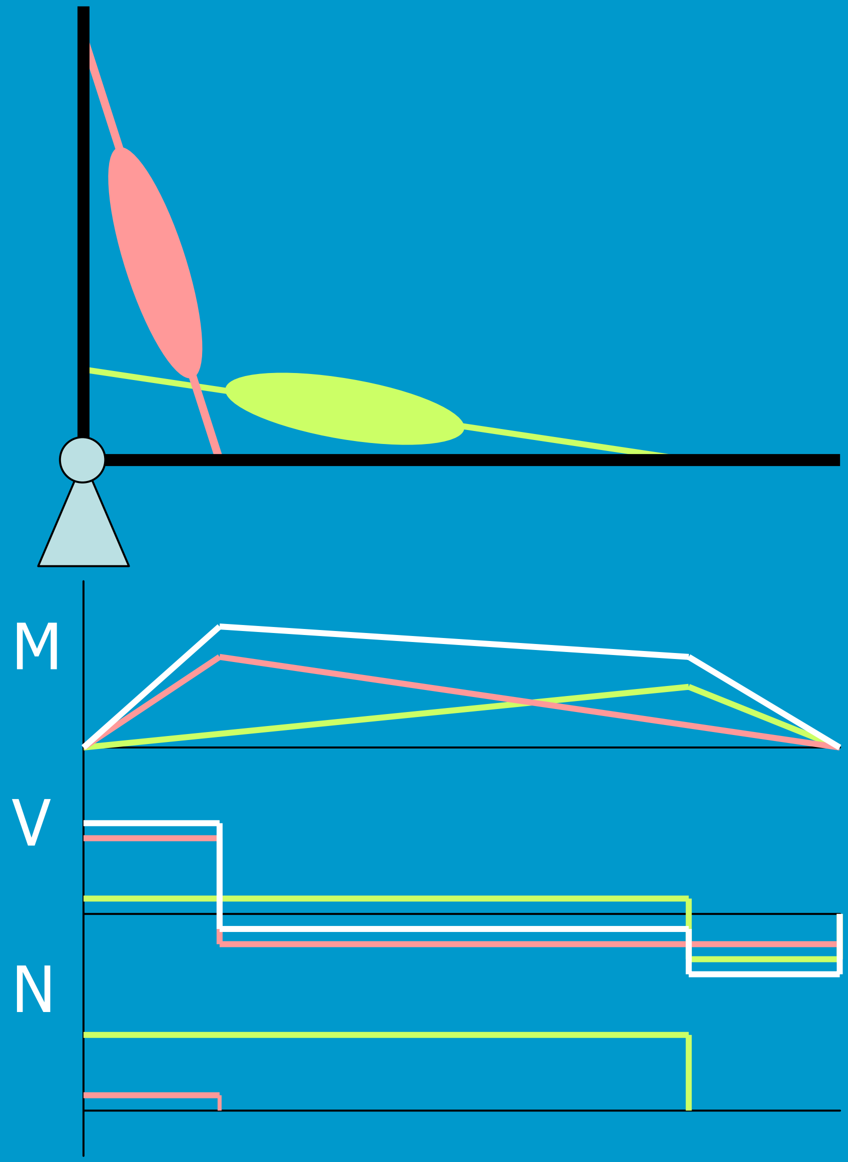
BioDesign





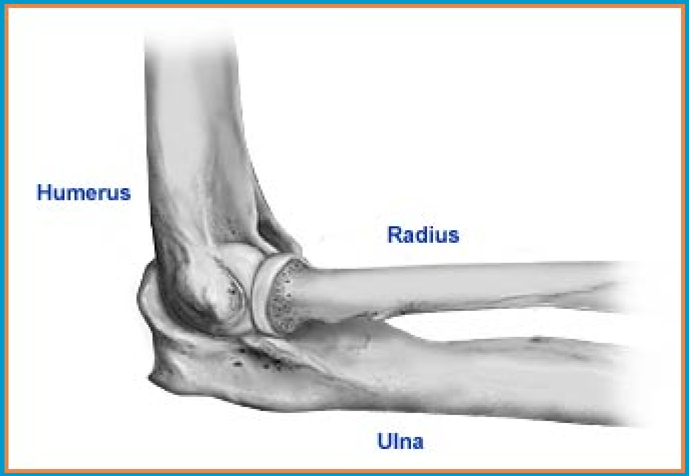
BioDesign

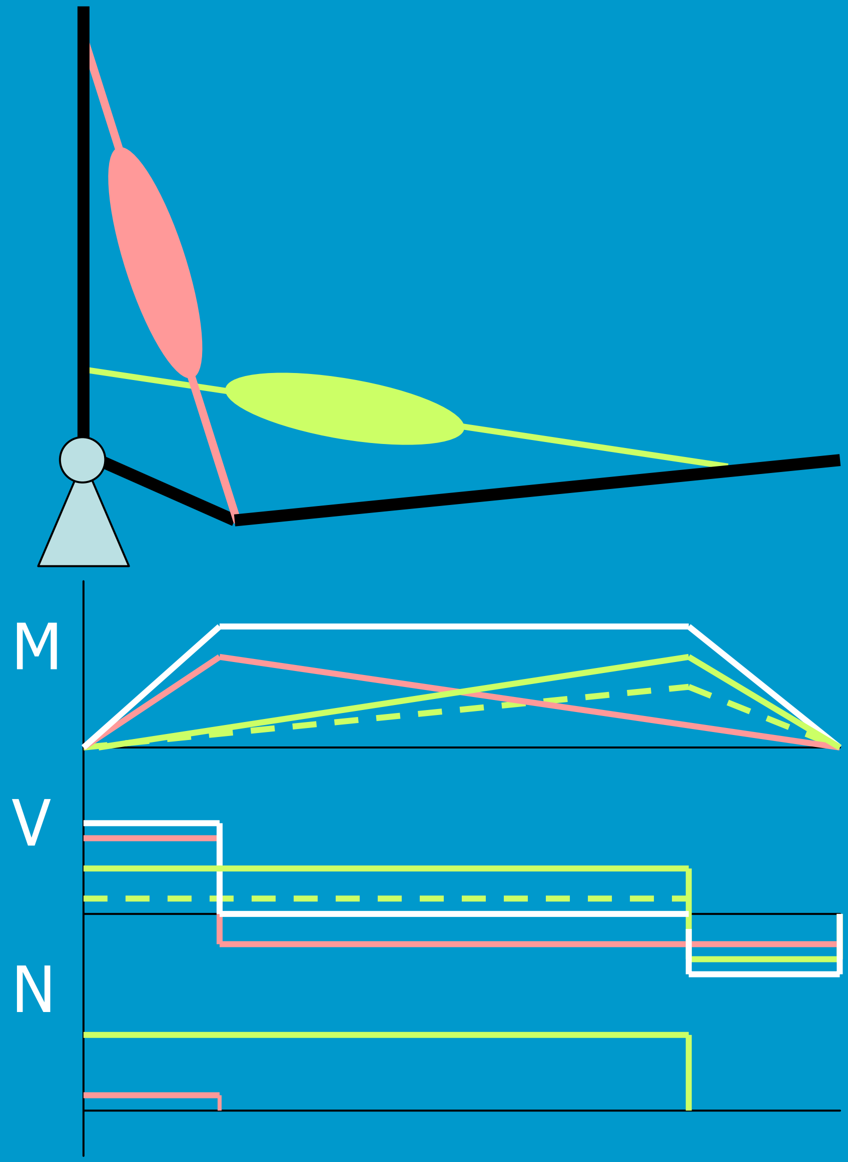




TUDelft

BioDesign

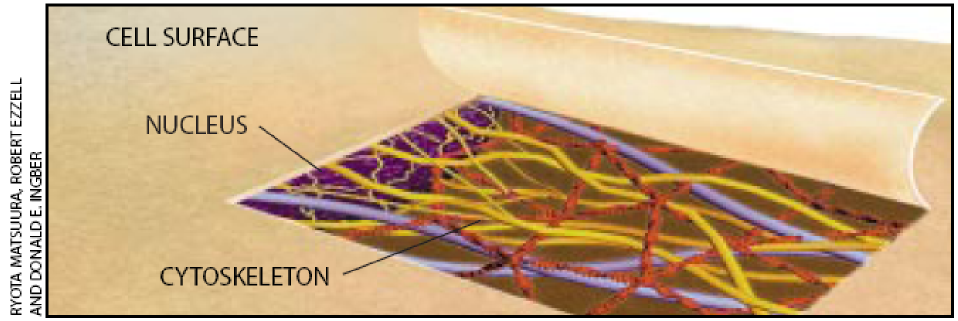




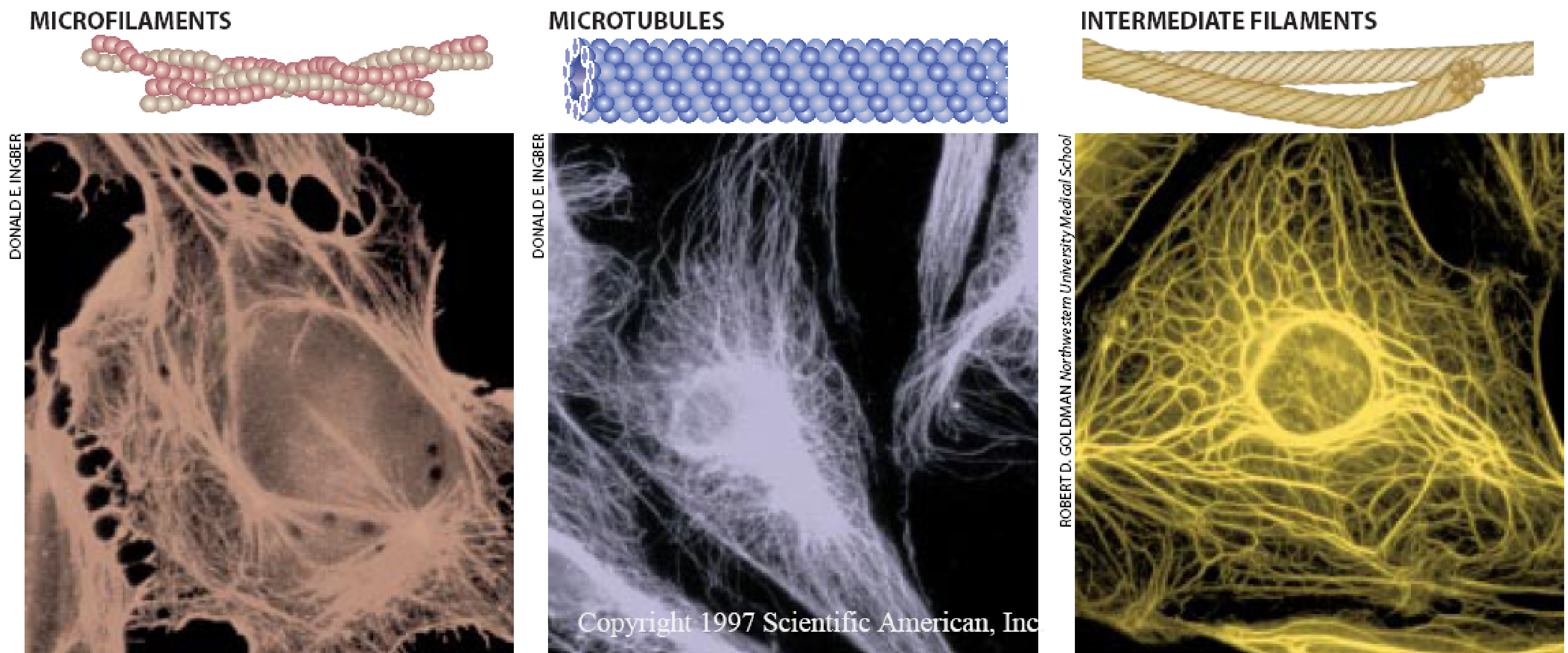
BioDesign: Stuctural Optimization

- Other static loading: cross-sectional shape and material properties, deflection by EI
- Careful with maximizing I, e.g. wall thickness in tubes
- Minimum weight/strength ratio: minimize density (since modulus generally fixed), especially wrt buckling
- Energy absorption dominant: uniform cross-section, no local stress raisers, preferably solid round rod
- Pure tension: governed by specific strength and maximum allowable deformation, any shape → rods

Tensegrity on cell level

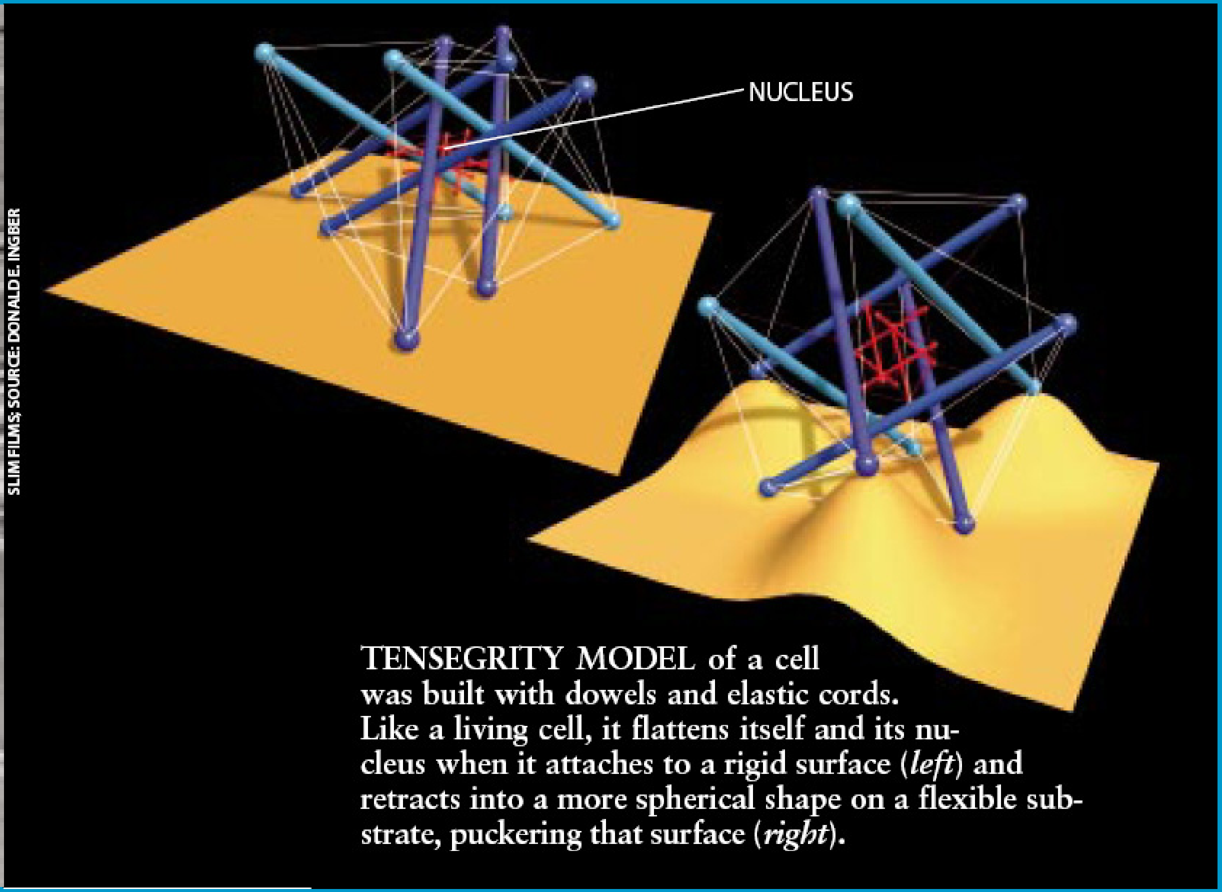


CYTOSKELETON of a cell consists of microfilaments (*bottom left*), microtubules (*bottom center*) and intermediate filaments (*bottom right*), all of which are nanometers wide. The rounded shape near the center in each of these photographs is the cell nucleus. The three components interconnect to create the cytoskeletal lattice, which stretches from the cell surface to the nucleus (*top left*). The molecular structure of each component is shown above the corresponding photograph and is color coded to the top left illustration.



D.E. Ingber

Tensegrity on cell level

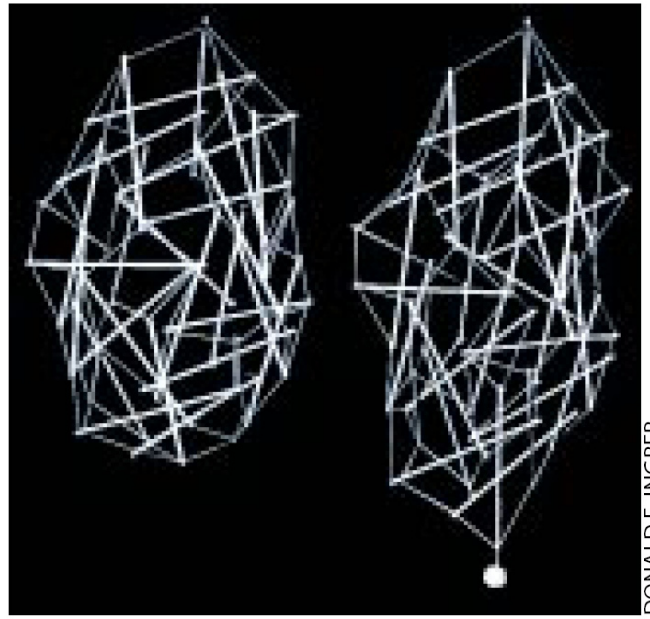


D.E. Ingber

TUDelft

Tensegrity on tissue level

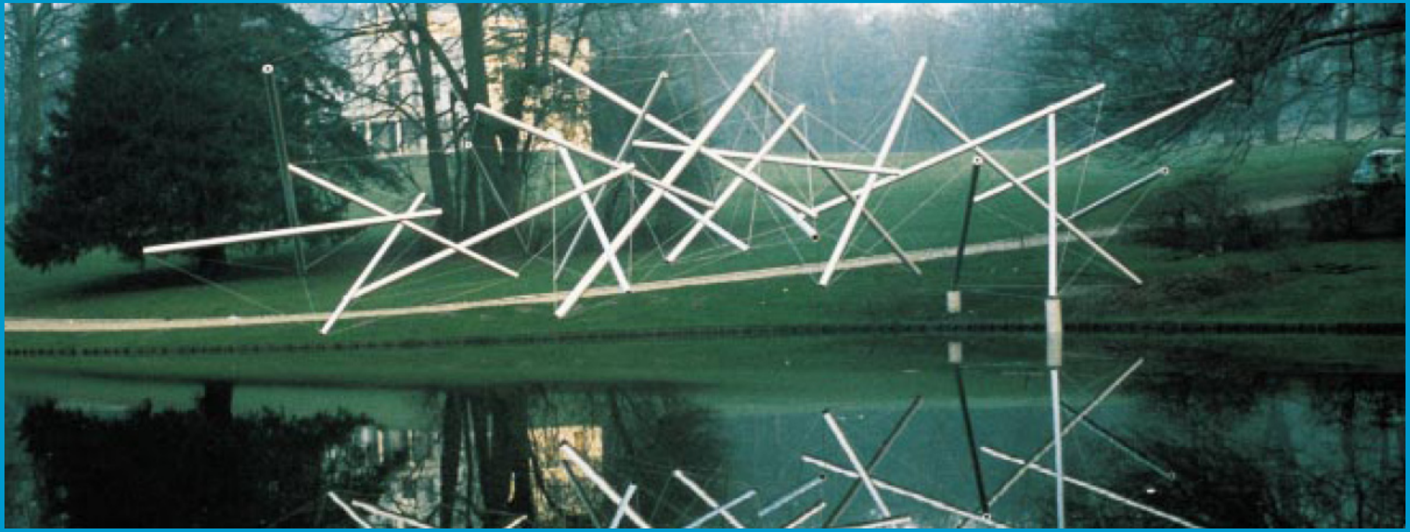
LINEAR STIFFENING occurs in a tensegrity structure because structural members reorient themselves to lie more in the direction of applied stress (downward in the right-hand view).



- Linear stiffening: stiffness increases with elongation (non-linear stiffness)
- Similar to biological tissue (pull your skin!)
- Stress in all members varies

D.E. Ingber

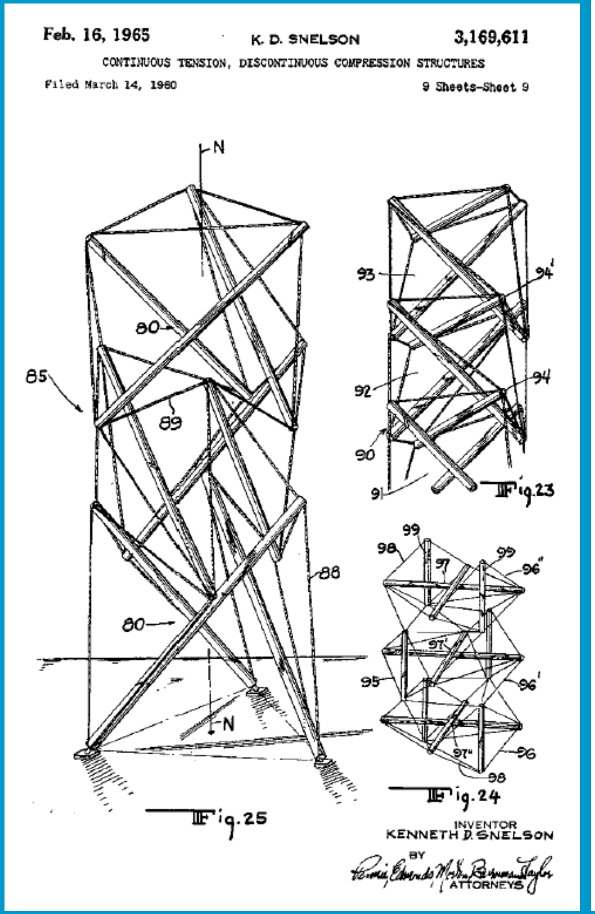
Tensegrity on organ level



D.E. Ingber, K. Snelson

Tensegrity in growth…

- Deployable
- Disjointed struts
- Axially stiff
- Axial stiffening
- Weak in bending
- Bending softening



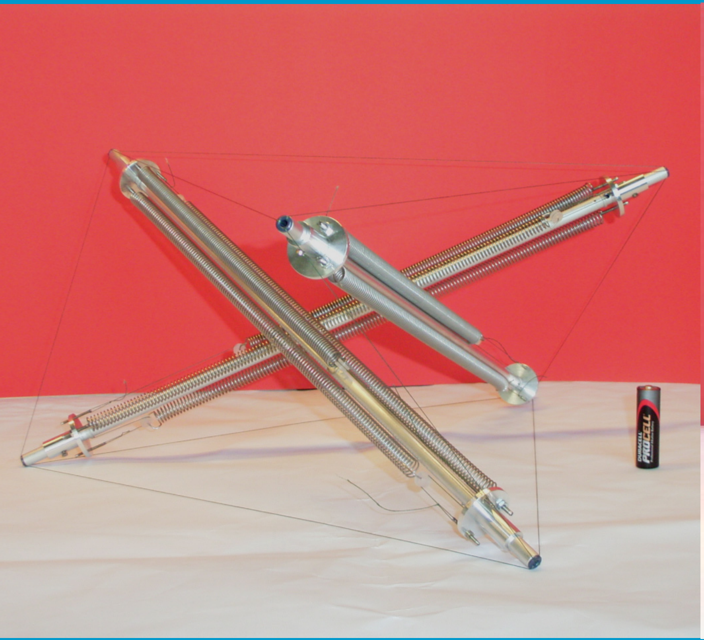
A.G. Tibert, S. Pellegrino, K. Snelson

TU Delft

Tensegrity in Delft

9 cables → 9 springs

Tensegrity *Mechanism*



Mark Schenk, Simon Guest, Just Herder

Conclusion

- Different materials
- Different components
- Different concepts
- Different perspective
- Big gap
- Lots to do