Biomedical Engineering - Bachelor degree

Biomechanics & Simulation of Biomedical Devices

Lecture 1. Course introduction

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Course outline

Course introduction

What is Mechanics?
What is Bio-mechanics?
Current applications and research activities
Basic concepts on classical mechanics

Material point

Kinematics
Equilibrium

Rigid body

Kinematics
Equilibrium

A simple case of deformable body: uniaxial traction

Tensional state: an introduction
Deformation state: an introduction
Basic experimental material response
Comments on material response features

Course outline

Notations

- Compact vs indicial vs engineering notation
- Vectors and tensors
- Basic operations

3D deformable body

- Kinematics
  - change of configuration
  - compatibility requirements
  - strain tensor
- Equilibrium
  - integral format
  - stress tensor
  - differential format
- Constitutive relationship
  - elasticity

Saint-Venant problem

- Pure traction
- Pure bending
- Torsion

Course outline (possible topics !!)

3D constitutive relationship

Elasticity (isotropy, anisotropy)
Inelasticity (viscosity, plasticity)

Limit criteria

Numerical methods

Basics on Finite Element Methods
Use of a commercial code: Abaqus
Some simple mechanical problems

Investigation of some case studies

Orthopedic prosthesis
Cardio-vascular prosthesis

Mechanics: an introduction

Mechanics is a branch of Engineering

Engineering: scientific-technological branch using mathematical tools to analyze problems, design solutions (and organizes resources)

(from Linguistica Garzanti)

- Engineering is: *discipline, art, and profession of acquiring and applying scientific, mathematical, economic, social, and practical knowledge to design and build structures, machines, devices, systems, materials and processes that safely realize improvements to the lives of people* (from wikipedia)

- The American Engineers' Council for Professional Development has defined "engineering" as:

  The creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behavior under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property

Mechanics: an introduction

Mechanics:

- a branch of physics concerning **motion** and **deformation** of bodies on which forces are acting (from Linguistica Garzanti)

- a branch of physics concerned with behavior of physical bodies when subjected to forces or displacements, and the subsequent effects of the bodies on their environment (from wikipedia)

- The discipline has its roots in several ancient civilizations (see History of classical mechanics and Timeline of classical mechanics)

- During early modern period, scientists such as Galileo, Kepler, and especially Newton, laid the foundation for what is now known as classical mechanics

Engineering materials

Mechanics:

- response (i.e. motion, change of configuration, displacements) of a body under forces
- response clearly depends on the **nature of material constituent**

Material: (from wikipedia)

- material is anything made of matter, constituted of one or more substances
- wood, cement, hydrogen, air and water are all examples of materials
- sometimes the term "material" is used more narrowly to refer to substances or components with certain physical properties that are used as inputs to production or manufacturing. In this sense, materials are the parts required to make something else, from buildings and art to stars and computers

Many on-line databases: www.m-w.com

Traditional engineering materials: polymers, metals and alloys (aluminum, cobalt, copper, lead, magnesium, nickel, steel, superalloys, titanium and zinc alloys), ceramics, etc.
Innovative engineering materials: adaptive, smart, functional materials (shape-memory alloys, shape-memory polymers, active polymers, etc.)

Traditional engineering materials

Type	Chemical bond type	microstructure	advantages	Drawbacks
Metals and alloys	metallic	Crystal grains	• Resistant • Ductile • Conductive	• Fatigue • Fracture
Polymers	covalent	Molecular chains	• Low cost • Light • Corrosion	• Low resistance • Low rigidity • Viscous
Ceramics/ Glass	Ionic/covalent	Crystal grains, amorphous	• Resistant, • Hard • High temp. • Corrosion	• Fragile
Composites	Several types	Fiber matrix	•Resistant, rigid	• High cost • Delamination
Adapted from L.Vergani "Meccanica dei Materiali" McGraw Hill 2001				

There is clearly a huge amount of engineering application involving mechanical investigation related to specific materials

Mechanics: an introduction

Engineering: scientific-technological branch which uses mathematical tools to analyze problems, design solutions (and organizes resources) [Garzanti]

Mechanics: a branch of physics concerning **motion** and **deformation** of bodies on which there are forces acting (bodies implies **material** concept)

There are three basic concepts

- ✓ Observe a phenomena and transform into equations
- ✓ Equations should represent three different aspects:

1. Deformation ➔ Kinematics
2. Motion ➔ Equilibrium
3. Material ➔ Constitutive equations

Mechanical model investigated in the course

- **Rigid body model**
  - Kinematics
  - Equilibrium (Static / Dynamics)
- **Deformable body model**
  - Kinematics
  - Equilibrium (Static / Dynamics)
  - Constitutive law (material dependent)
    - Solid: elasticity
    - Solid: inelasticity
    - Fluid: viscous

What is Biomechanics?

"Biomechanics is the mechanics applied to biology"

Biomechanics: Mechanical properties of Living tissues- Y Fung – 1993- Springer Ed.

Important & challenging science

Complexity of tissue structure

Lack of data

Geometric complexity: cells, tissue, and organs

Morbidity (incidence of disease) and mortality

→

Sophisticated theoretical ideas

Clever experiments

Robust computational methods

Improved modalities of diagnosis and treatment

Modern subject with ancient roots

Leonardo Da Vinci's notebook (sketch): contraction of the biceps brachii muscle and flexion (bending) of the elbow

Leonardo Da Vinci (1452-1519):

- articulating joints within context of levers
- muscles as supplying the requisite force

Galileo Galilei (1564-1642):

- pendulum clock to measure the human pulse
- Bones hollowed to supply max strength with min weight

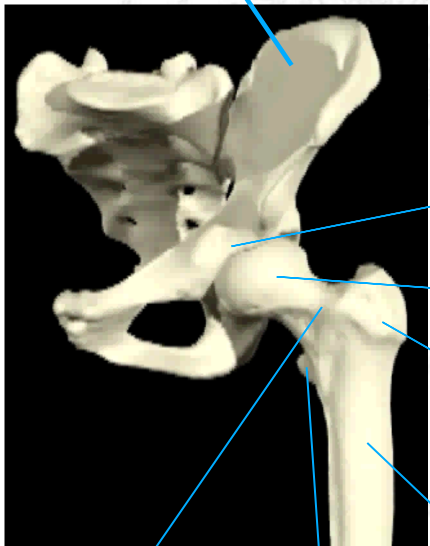
Biomechanics: wide application fields

Fundamental Topics - Biomechanics of cardiovascular, respiratory, musculoskeletal systems; mechanics of solid hard and soft tissues; bio-fluid mechanics; mechanics of cells

Cardiovascular and Respiratory Biomechanics – Mechanics of blood-flow, air-flow, mechanics of the soft tissues, flow-tissue or flow-prosthesis interactions
Dental Biomechanics – Design and analysis of dental tissues and prostheses, mechanics of chewing
Orthopedic Biomechanics – Mechanics of fracture & fracture fixation, mechanics of implants & implant fixation, bone & joint mechanics, natural/artificial joints wear
Rehabilitation Biomechanics – Analyses of gait, mechanics of prosthetics & orthotics
Sports Biomechanics – Mechanics of sport performance
Cell Biomechanics – Biomechanical analyses of cells, membranes and sub-cellular structures; relationship of mechanical environment to cell and tissue response
Functional Tissue Engineering – Biomechanical factors in engineered tissue replacements/regenerative medicine
Molecular Biomechanics – Mechanics of biomolecules

See more in http://www.techscience.com/mcb/ or http://www.jbiomech.com/

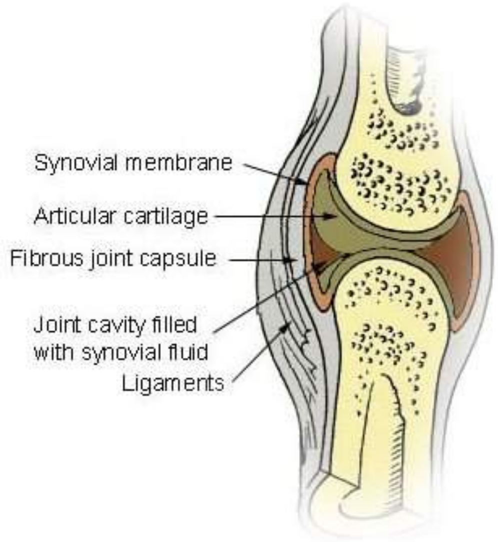
Biomechanical application: an orthopedic example (1)



<u>Hip joint: an essential joint for body kinematics and the best example inthe body of ball and socket joint</u>

Hip joint:

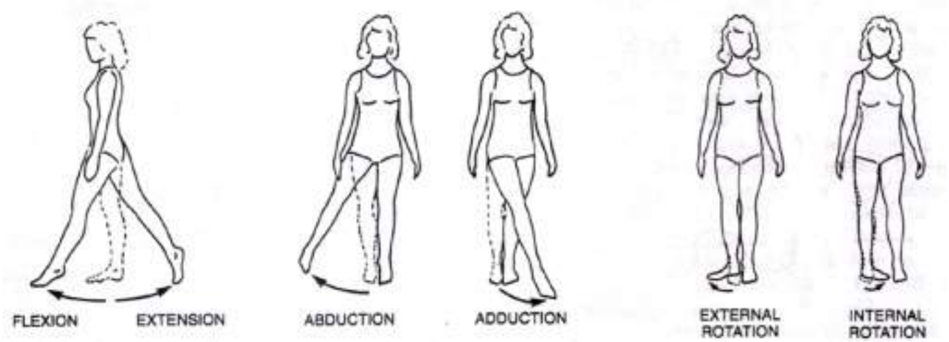
- Big size
- diarthrosis (synovial joint): freely movable joint



Components:

- <u>Femoral head</u> : rounded upper ending of femoral bone covered with smooth joint cartilage
- <u>Acetabulum</u>: large part of socket's concave surface is covered by smooth joint cartilage

Biomechanical application: an orthopedic example (2)



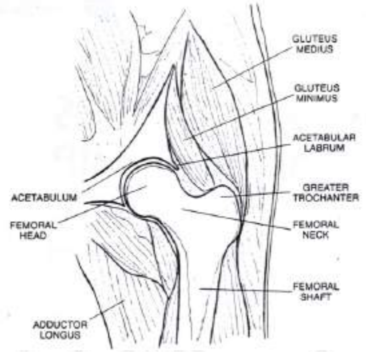
Complex kinematics

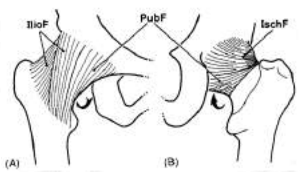
- Flexion-extension: sagittal plane*
- Abduction-adduction: frontal (coronal) plane**
- Int/external rot.: trasverse (axial) plane***

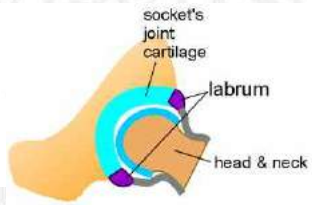
* A vertical plane running from front to back; divides the body or any of its parts into right and left sides.

** A vertical plane running from side to side; divides the body or any of its parts into anterior and posterior portions.

***A horizontal plane; divides the body or any of its parts into upper and lower parts.

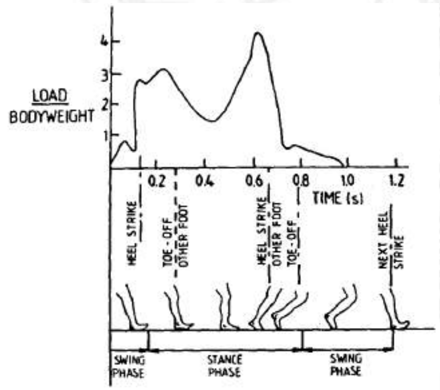






Complex structure

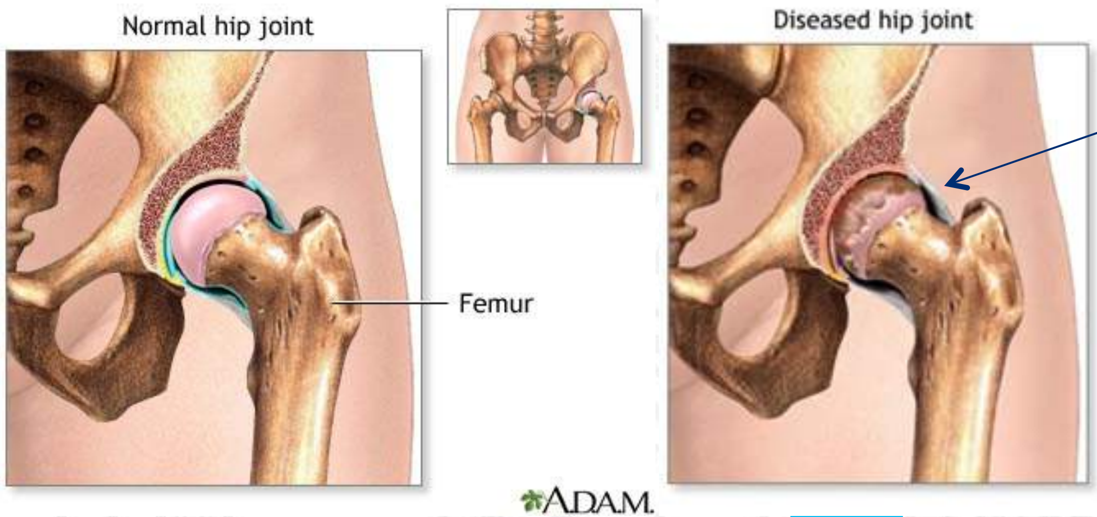
- ligaments
- muscles
- Cartilage layer



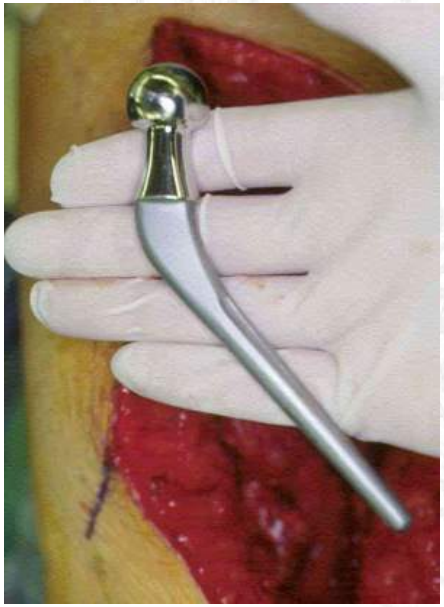
Several and cyclic loads

Activity	JOINT FORCE (compared to the body weight)
Plane walk, normal rate	4,9
Fast rate, fast rate	7,6
Stairs (going up)	7,2
Stairs (going down)	7,1

Biomechanical application: an orthopedic example (3)

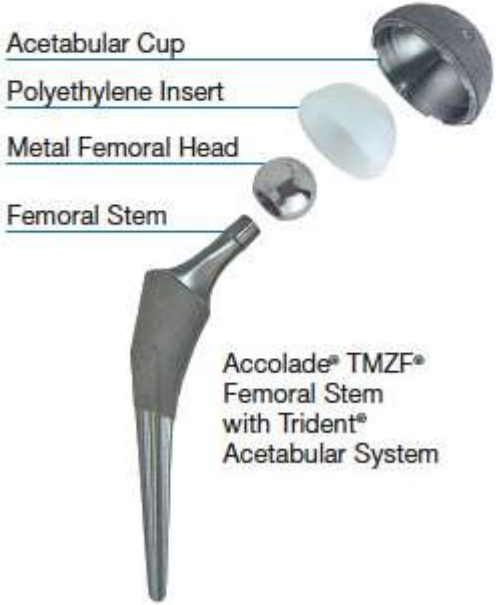


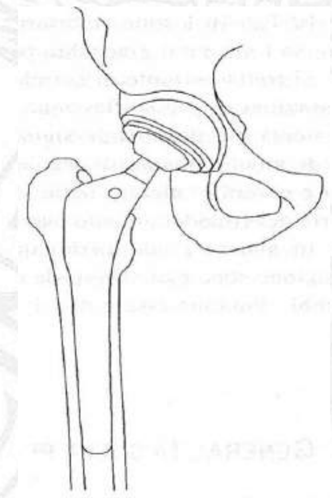
Joint disease
- osteoarthritis
- external traumas
- etc.



Joint replacement → prosthesis by surgical procedure

Biomechanical application: an orthopedic example (4)





Material Prosthesis requirements

- Biocompatibilty
- Corrosion resistance
- Mechanical resistance

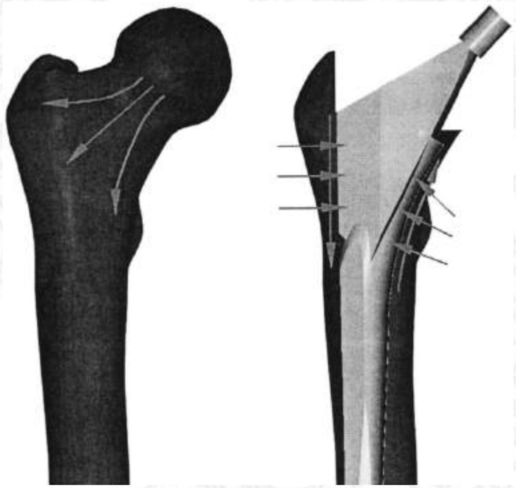
Several materials involved

- Steel
- Polymers
- Ceramics
- Alloys (Co based, Ti based alloy)

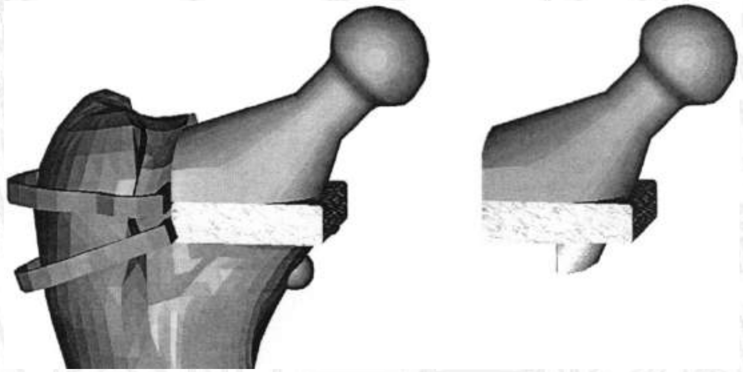
Design specifics **→ femoral prosthesis has to take into account:**

- Degrees of freedom as provided by the natural joint
- Ability to resist over all the several loads generating during the daily life
- Fatigue resistance (cyclic loads: ≈10^6 cycles /year per patient with a standard life style)
- Joint surfaces able to resist to the mechanical friction and degeneration
- Inclusion of biocompatible materials
- Stability of the joint
- Easy insertion and replacement
- Biomechanical behavior able to not change the mechanical features of hip-femur system
- Induction of adequate stress on the bone tissue in order to avoid irregular bone remodeling and absorption

Biomechanical application: an orthopedic example (5)



Schematic representation of the load transfer before and after hip arthro plastiy (THA)



Prosthesis design investigation to reduce stress shielding:

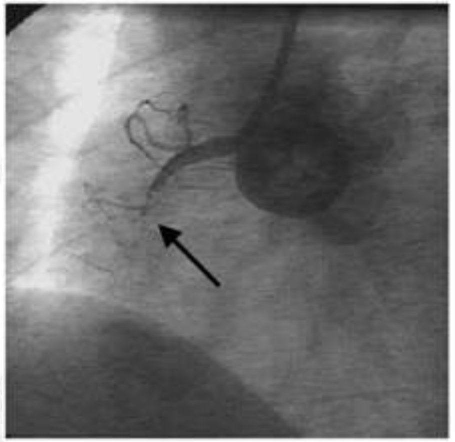
- Stress shielding: When an implant is introduced, it will carry a portion of the load, causing a reduction of stress in some regions of the remaining bone
- Hypothesis and generation of a new design
- Numerical and experimental investigation

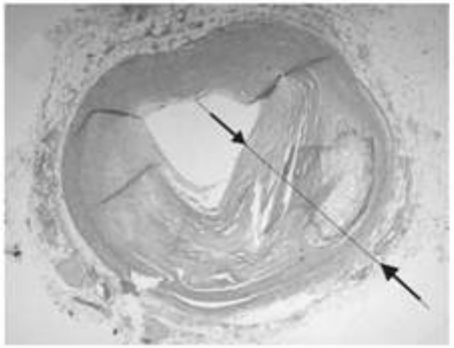
Joshi et al. (2000) Analysis of a femoral hip prosthesis designed to reduce stress shielding J Biomech 33: 1655-1662

Proposed design:

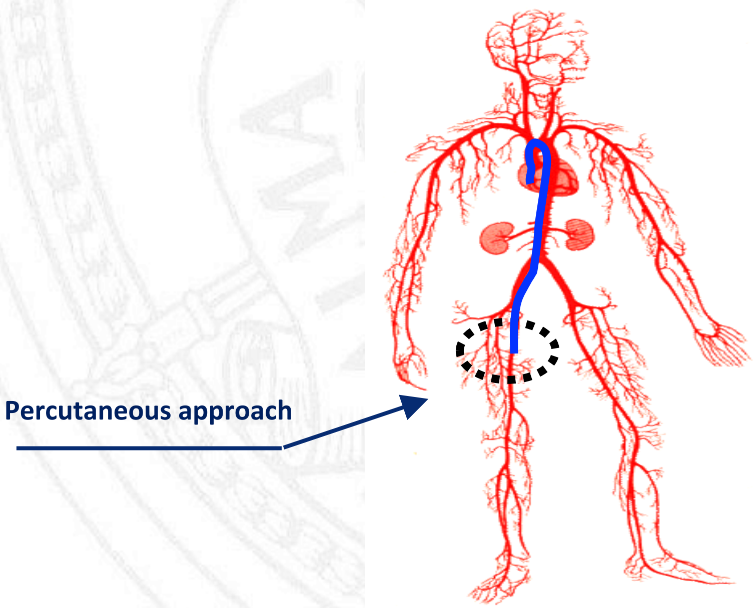
- Proximal plate added to distribute the contact load over the entire cross section of the femur
- Cabling system developed not only anchor the prosthesis to the bone but also to help produce a more natural bending load over the cross section of the femur
- A short screw into the stem is used to hold the plate against the medial calcar on the medial side

Biomechanical application: a cardiovascular example (1)





Narrowed coronary artery



<u>Coronary arteries</u>: arteries that arise one from the left and one from the right side of the aorta immediately above the semilunar valves and supply the tissues of the heart itself

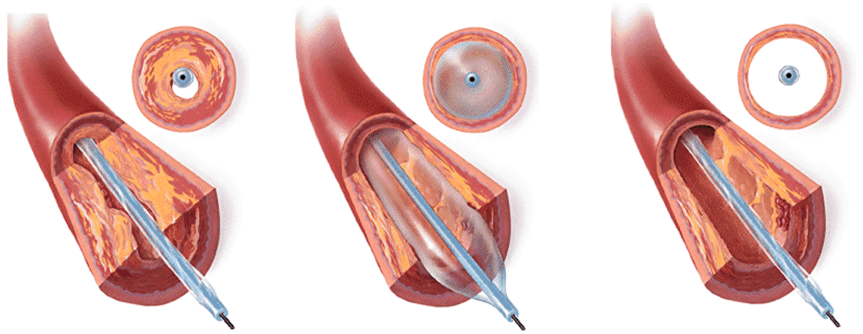
<u>Atherosclerosis</u>: degeneration of the vessel wall tissue

<u>Stenosis</u>: a condition usually the result of disease in which the vessel lumen is abnormally narrow

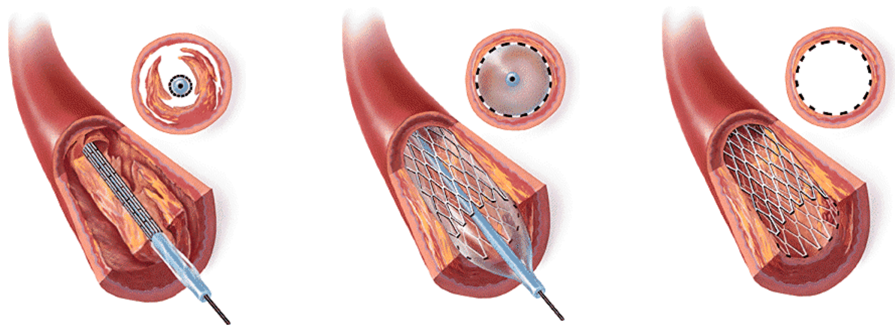
<u>Minimally invasive approach</u>: reduction of surgical risks, speed up patient's recovery

<u>Coronary angioplasty(PTCA)</u>: common clinical non-surgical procedure to treat coronary vessel stenosis by balloon inflation

Biomechanical application: a cardiovascular example (2)



Coronary angioplasty



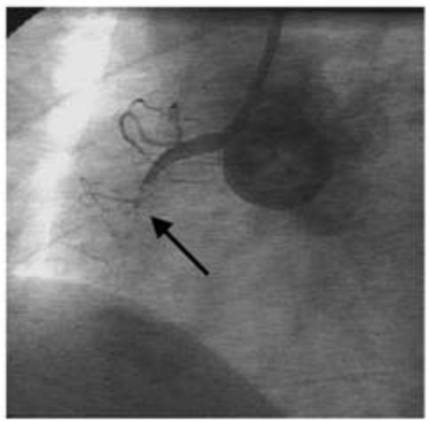
Stent deployment

Stent: medical device having a tubular shape designed to restore the vessel lumen

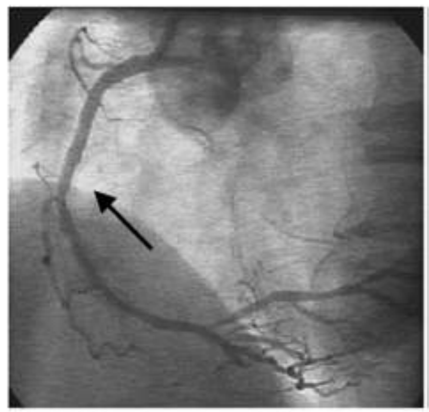
Stent as support post PTCA:

- short term task
- long term task

In stent restenosis: re-occlusion of the vessel lumen driven by healing process (neointimal hyperplasia)

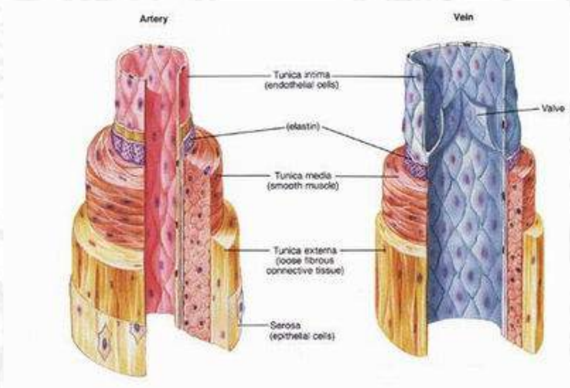


Pre procedure



Post procedure

Biomechanical application: a cardiovascular example (3)



Stent ≈ small complex (metallic) structure

Stenotic vessel ≈ small complex biological structure

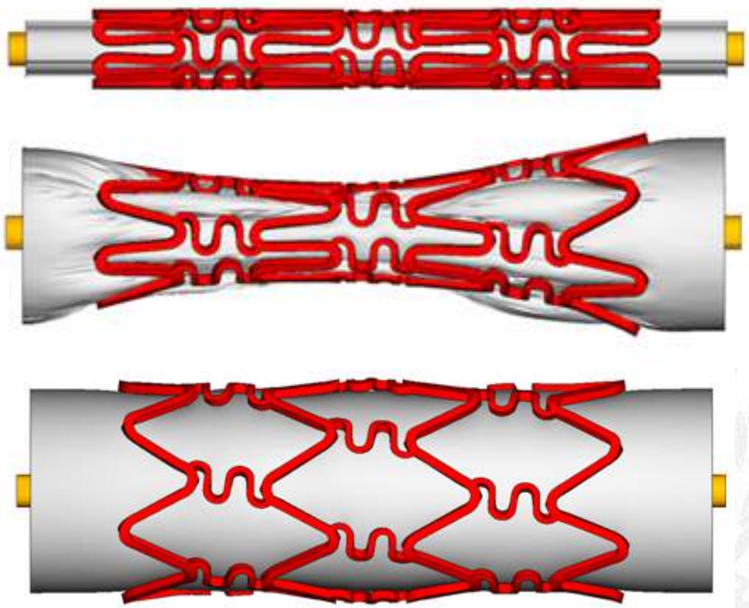
Stent mechanical behavior ?

(Diseased) vessel mechanical behavior ?

Interaction between those structures ?

Structural analysis by Finite Element Modeling

Biomechanical application: a cardiovascular example (4)



Impact of the balloon folding on the stent expansion (De beule et al. 2008)

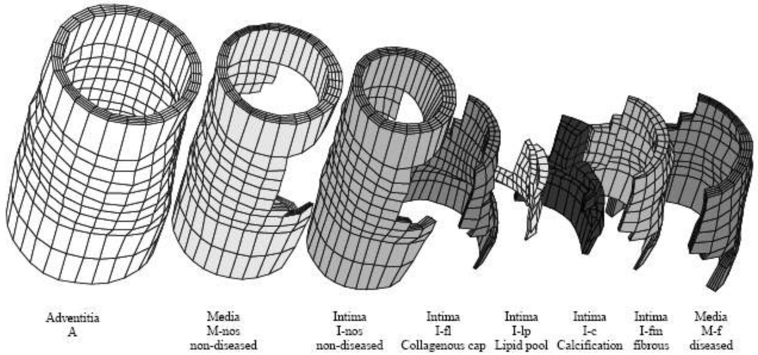


Figure 4. Finite element separation into different types of material.

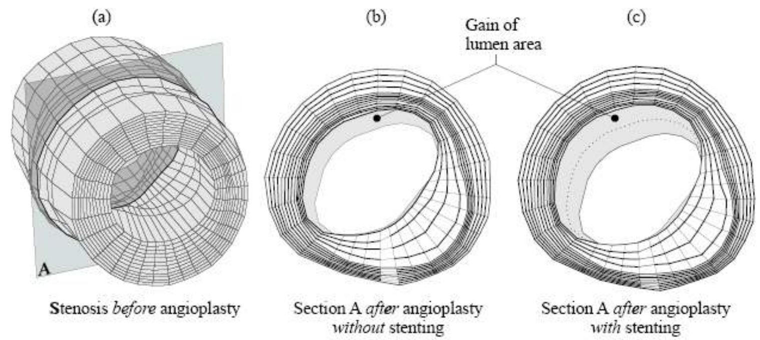
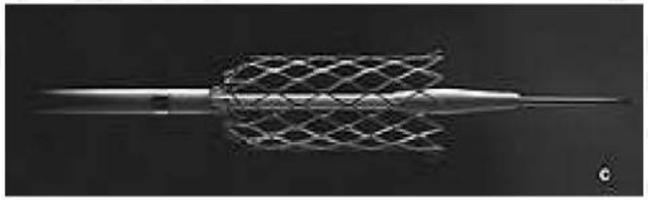


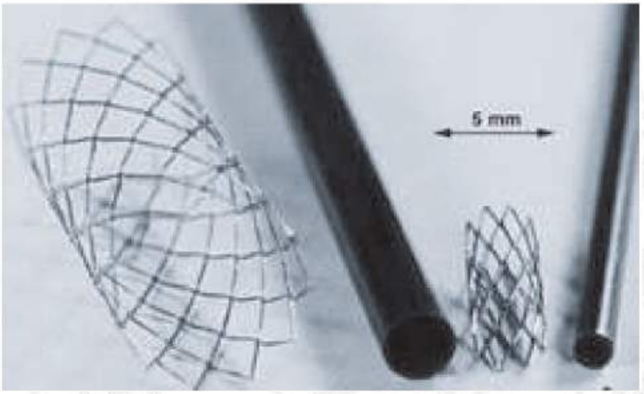
Figure 5. 3D FE-mesh of the stenosis *before* angioplasty (a). Section with maximum grade of stenosis *after* angioplasty without, (b), and with, (c), stenting showing the gain of lumen area at the load-free configuration.

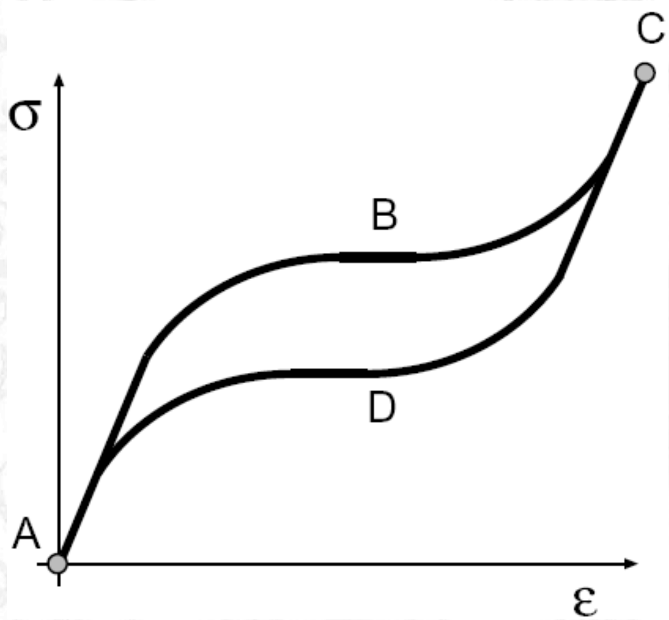
Mechanics of angioplasty: wall, balloon and stent (Holzapfel et al. 2005)

Biomechanical application: a cardiovascular example (5)

Stent design: alternative approach → **use of 'smart' material**
→ **self expandable (SX) stents**







Stress strain curve: no residual inelastic deformation

The SX stent:

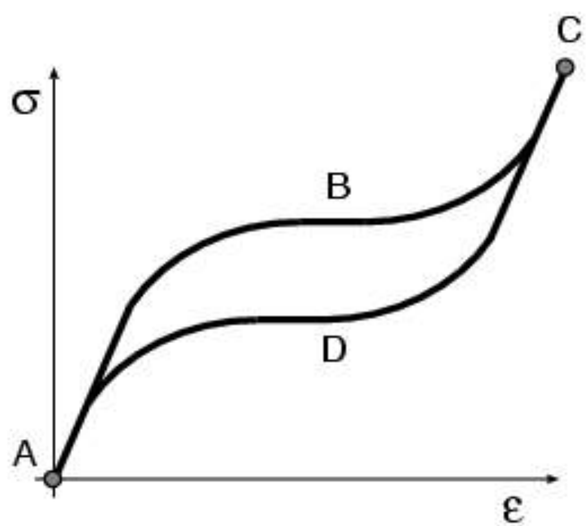
- constrained within a deploying system
- recovers original shape when pushed out the catheter
- applies constant radial force against vessel wall
- used for superficial applications (carotid artery, femoral artery)

Shape memory alloys (SMA): metalli con capacità intrinseca di ricordare una forma iniziale anche dopo elevate deformazioni

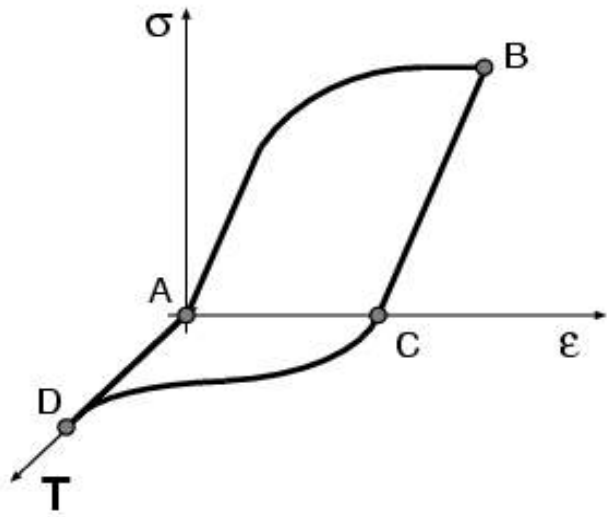
Punto di vista macroscopico: due effetti non standard, ovvero non presenti nei materiali tradizionali

Effetto superelastico
[Superelastic effect]

Effetto a memoria di forma
[Shape memory effect]



Mechanical recovery



Thermal recovery

SMA: campi di applicazione

Effetti macroscopici non presenti in materiali tradizionali
&
Applicazioni innovati e valide commercialmente

SMA: leghe metalliche. Caratterizzate da elevate proprietà meccaniche ed elevata capacità di compiere lavoro

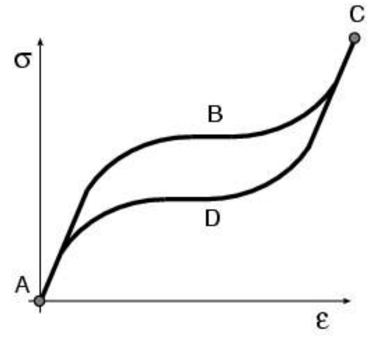
Settore biomedico ortodonzia, ortopedia, chirurgia vascolare, ottica, micro-attuatori

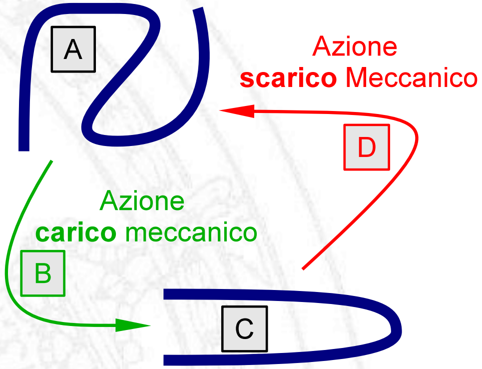
Settore meccanico attuatori, valvole termiche, connettori, sistemi apertura/chiusura

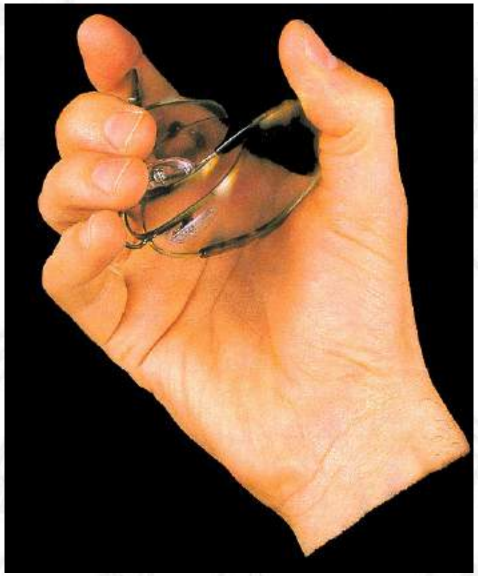
Settore strutturale controllo forma & vibrazioni, dissipazione di energia (ingegneria civile, aeronautica, settore automobilistico)

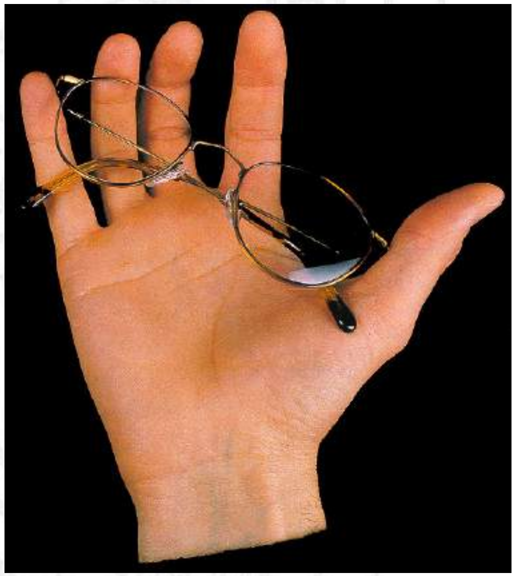
Superelasticità: applicazioni

Effetto superelastico (SE)



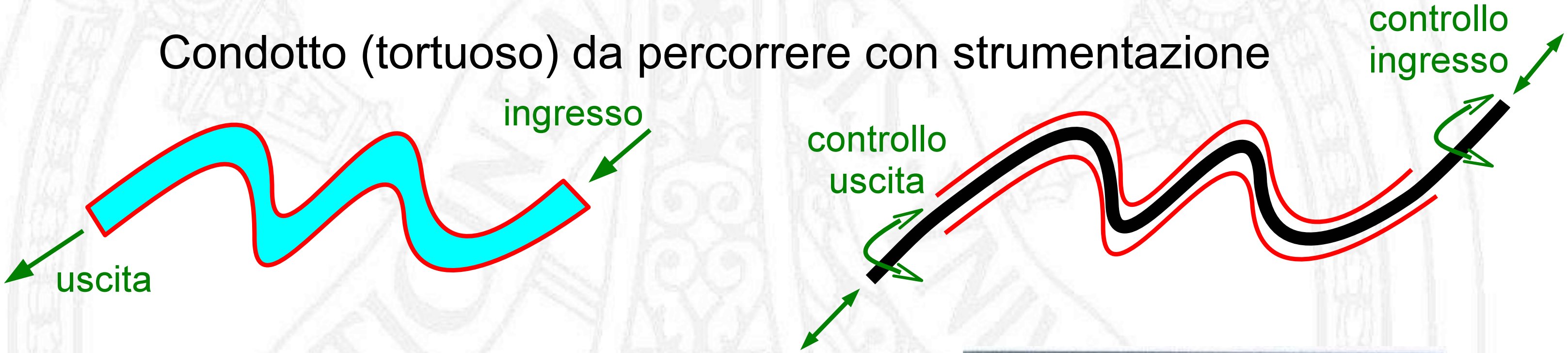




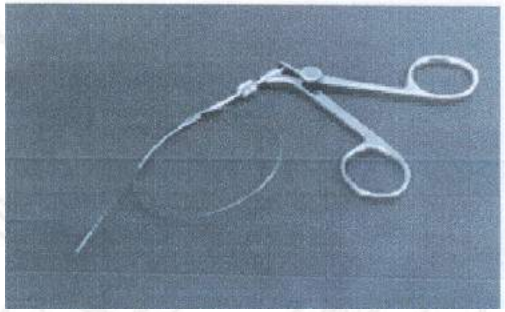


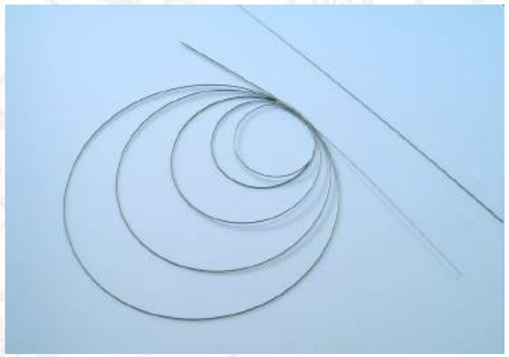
Molte applicazioni in campo biomedico:
in particolare per chirurgia non-invasiva

Capacità di flettersi / piegarsi con raggi piccoli (< 3 cm) senza punti angolosi (“kink”)



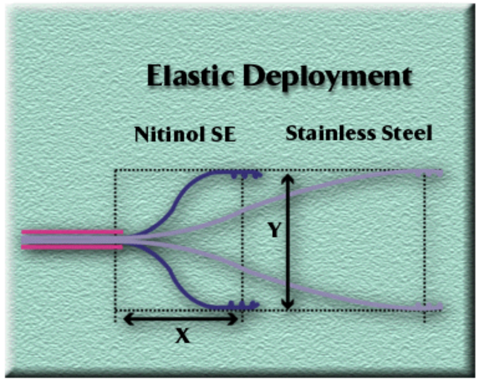
- Forcipe da biopsia
  - Tubo Nitinol + filo Nitinol all’interno
  - **Operabilità e controllabilità** (anche in presenza di un nodo)
- Cannule / cateteri / fili guida
  - Assenza di spigoli anche per anatomie tortuose
  - Essenziale per la navigazione intravascolare



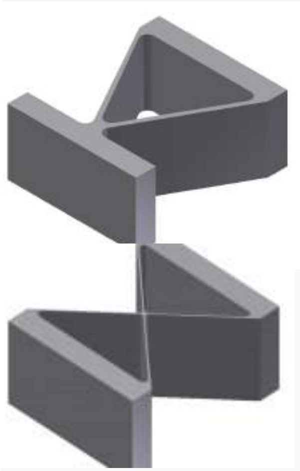


Flessibilità in assenza di cerniere

- Flessibilità senza cerniere
  - Apertura / chiusura sistema afferraggio
  - Facile da pulire e sterilizzare
  - Elevata capacità di apertura ed afferraggio
- Applicazioni in ambito biomedicale
  - Strumenti chirurgici da comandare a distanza
  - Controllo della forza applicata all’afferraggio
  - Utilizzato per il prelievo di calcoli renali



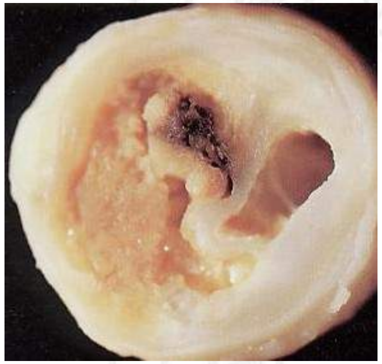
- Elementi cedevoli
  - Cerniere senza meccanismi
- Applicazioni in ambito meccanico
  - Assenza di problemi di lubrificazione
  - Meccanismi silenziosi

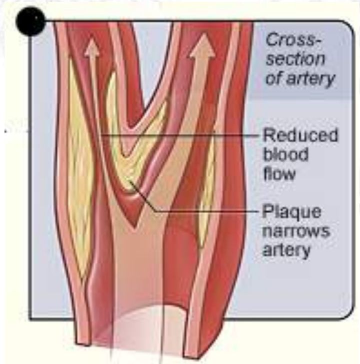


Superelasticità: applicazioni

Trattamento occlusioni vasi / patologie vascolari

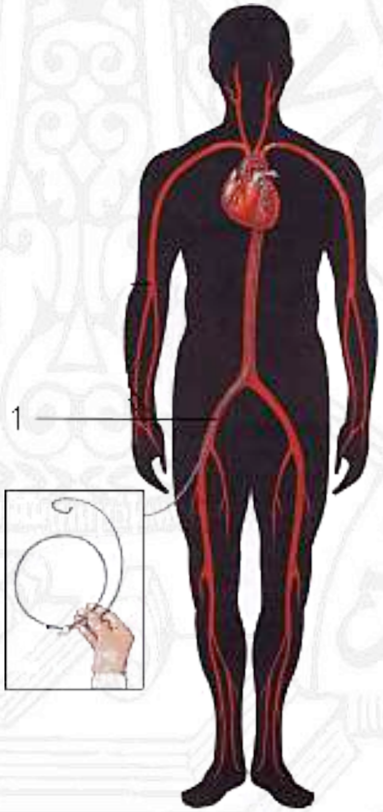
Stenosi:
occlusione di vaso fisiologico



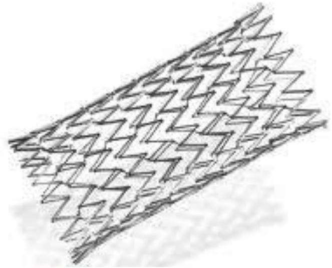


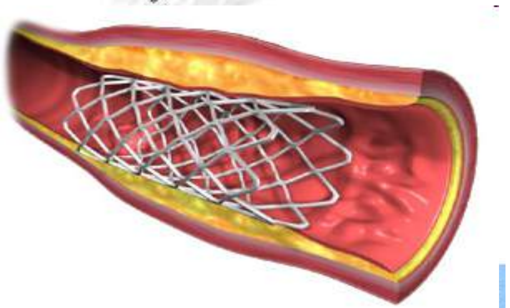
Strumentazione
geometrie e ruoli complessi

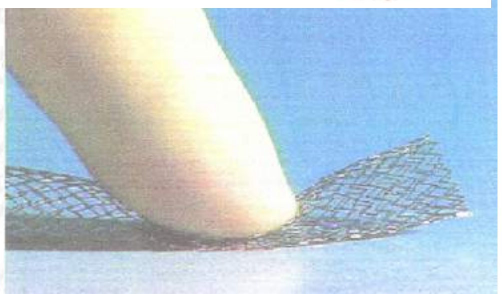
Trattamento non-invasivo
accesso periferico



Stent SMA intravascolari:
strutture tubulari auto-espandibili a sostegno del vaso

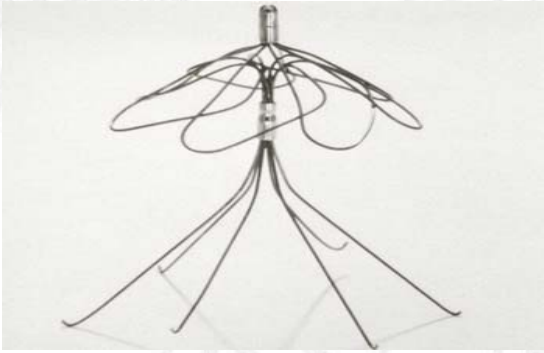






Smart materials: a wide range of medical applications

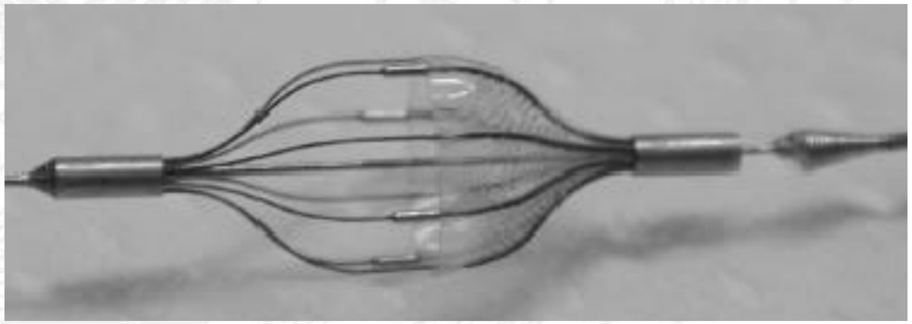
Simon vena cava filter
(thermal deployment)



Biopsy forceps
(kink resistance)

Orthodontic archwire
(costant force)

Embolic protection devices
(Superelasticity)



Smart materials and further scenarios

- **Trend:**
  - increase sophistication
  - reduce weight
  - increase performances

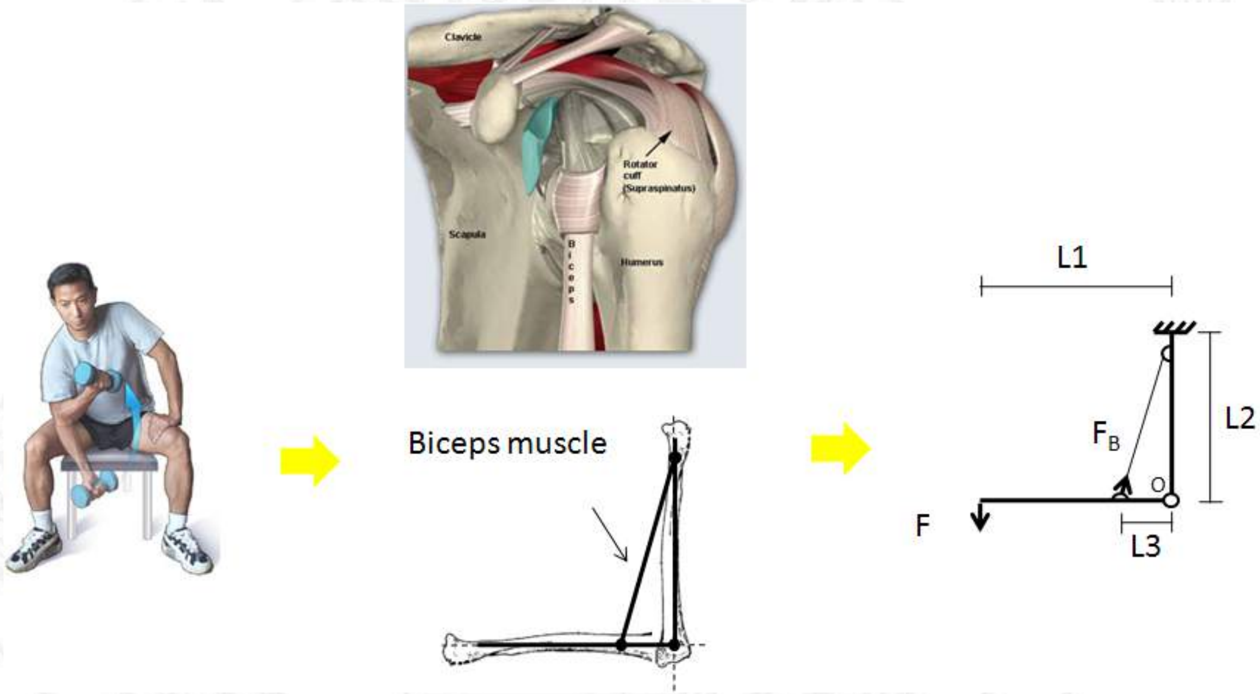
- **Composite materials:**
  - combination of ceramics, metals, plastics
  - combination of different direction preferred materials (fiber materials)

- **Materials for the Future:**
  - **Functional materials:** materials which combine structural properties with a specific functional attitude
  - **Multi-functional materials:** materials which combine structural properties with a several functional attitude
  - **Biodegradable materials:** materials which disappear at the end of their task

Modeling: an essential step of (bio) mechanical investigation

Modeling needs

- Model → hypothesis and assumption on reality under investigation based on the purpose of the study
    - Arm movement
    - Several models can be used to describe the same reality

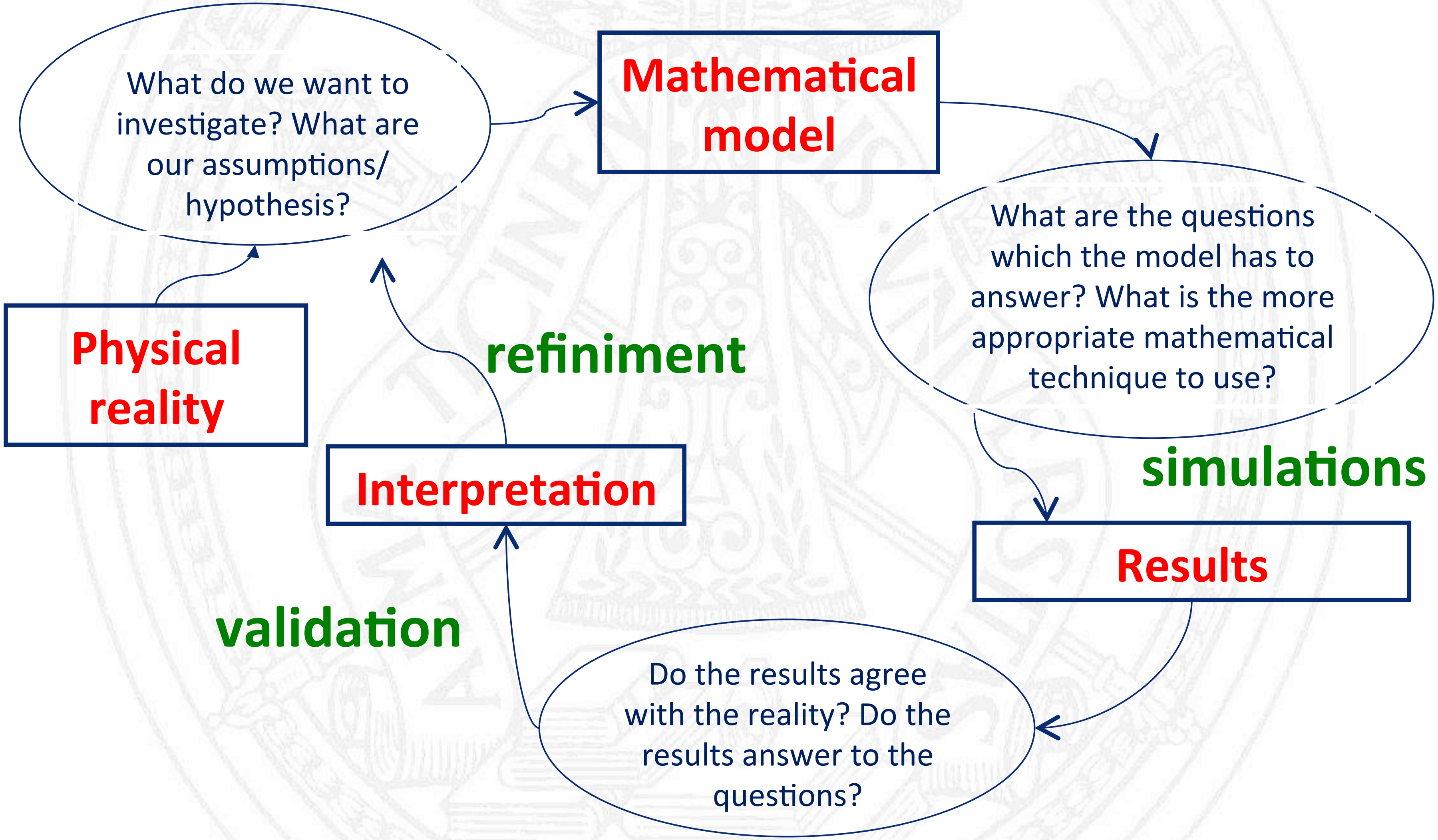


Mathematical modeling of the physical reality

- **Essential components of mechanics:**
  - **Kinematics:** investigation of the configuration change
  - **Equilibrium:** investigation of equilibrium conditions [Statics / Dynamics]
  - **Constitutive behavior:** material behavior definition

- **Peculiar aspects of biomechanics:**
  - biological system → complex structures and systems
  - biological adaptively (plasticity) and remodeling (current system results from remodeling and optimization process → active system)

Mathematical modeling of the physical reality



Modeling

More complex model → more accurate
more complex to solve

Less complex model → less accurate
more easy to solve

- ✧ **Note:** simpler model → less capability to catch the complex reality
  - If too simple, model could not the describe the problem under investigation

- ✧ **Mechanical Models:**
  - Material point
  - Rigid body
  - Deformable body

References: fundamental texts and advanced reading

Basic structural mechanics text

- **Lubliner, Papadopoulos "Introduction to Solid Mechanics: An Integrated Approach", Springer 2014**
- **Comi, Corradi Dell'Acqua, "Introduzione alla meccanica strutturale" McGraw Hill (2007)**

Basic biomechanics text

- C.Oomens, M.Brekelmans, F.Baaijens, "Biomechanics Concepts and Computation" Cambridge Texts in Biomedical Engineering (2010)
- C.R.Ethier, C.A. Simmons, "Introductory Biomechanics - From Cells to Organisms", Cambridge University Press (2007)
- N.Özkaya, M.Nordin, D.Goldsheyder, D.Leger "Fundamentals of Biomechanics: Equilibrium, Motion, and Deformation" (2012)

Further readings

- D.Gross, W.Hauger, J.Schröder, W.Wall, N.Rajapakse, "Engineering Mechanics 1: Statics", Springer (2009)
- D.Gross, W.Hauger, J.Schröder, W.Wall, J.Bonet, "Engineering Mechanics 2: Mechanics of Materials", Springer (2011)

- R. Pietrabissa, "Biomateriali per protesi e organi artificiali", Patron (1996)
- Carpinteri, "Scienza delle Costruzioni" Ed. Pitagora, vol. 1

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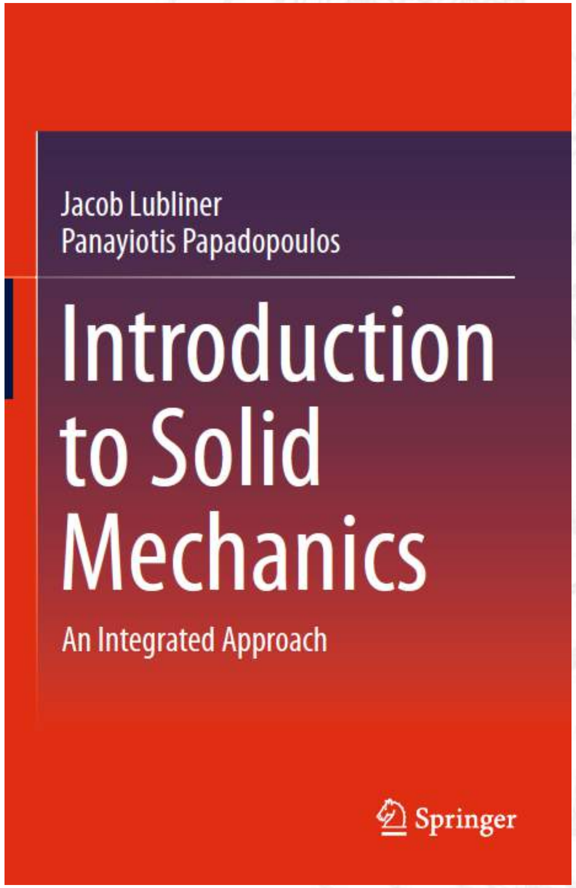
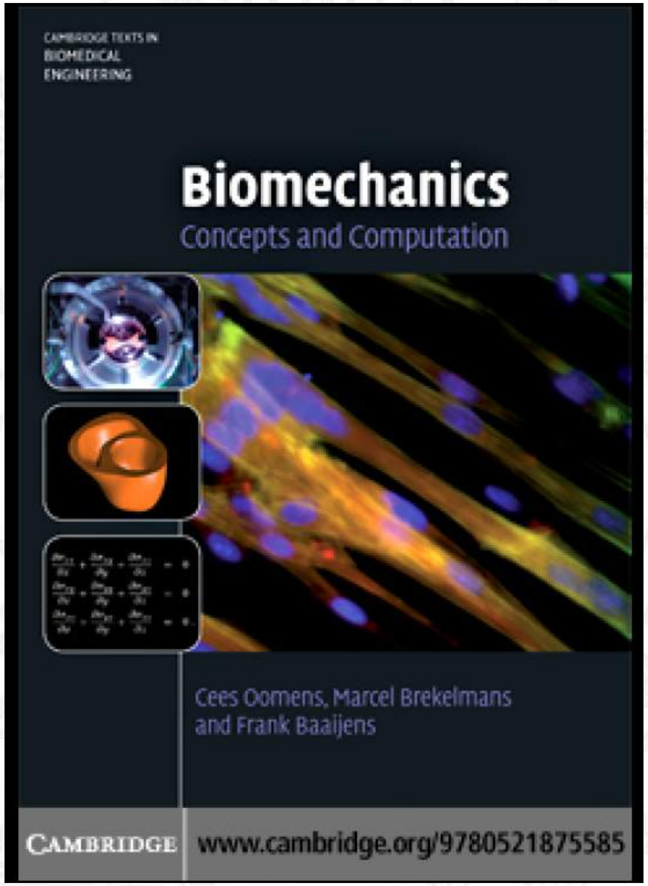
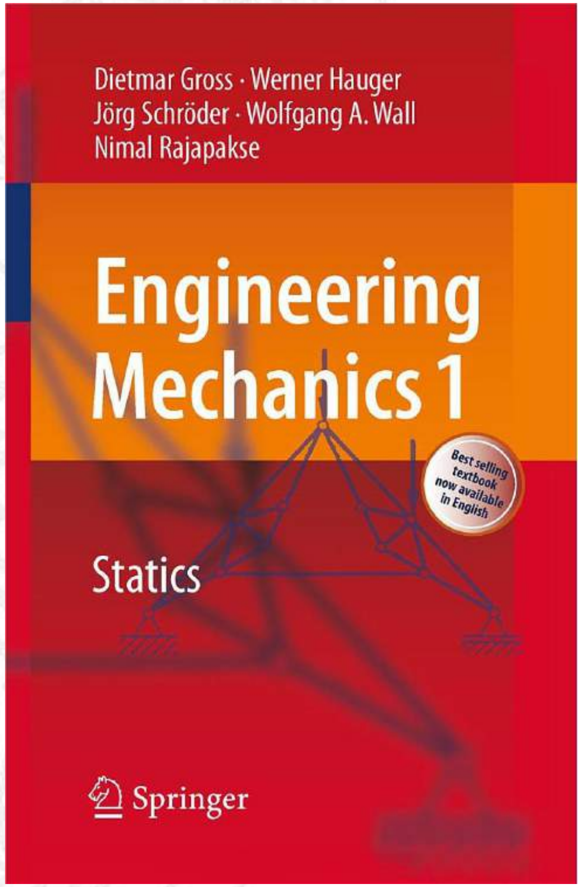

Jacob Lubliner
Panayiotis Papadopoulos
Introduction to Solid Mechanics
An Integrated Approach
Springer


CAMBRIDGE TEXTS IN BIOMEDICAL ENGINEERING
Biomechanics
Concepts and Computation
Cees Oomens, Marcel Brekelmans and Frank Baaijens
CAMBRIDGE
www.cambridge.org/9780521875585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Jörg Schröder · Wolfgang A. Wall
Nimal Rajapakse
Engineering Mechanics 1
Best selling textbook now available in English
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