Biomechanics of the musculoskeletal system

Prof. Dominique Pioletti
Laboratory of Biomechanical Orthopedics
EPFL

Biomechanics of the musculoskeletal system (2024-2025)

Prof. Dominique Pioletti (EPFL)

Goals of the course

1. Illustrate how an engineering approach can bring new insight into the biomedical field.
2. Develop competencies useful in the biomedical industry.
3. Develop a multi-disciplinary approach to problem-solving.

Objective of formation (to be able to)

1. Translate a (bio)medical need into engineering concepts.
2. Propose a concrete solution to a biomedical problem.
3. Argue the engineering choices made for the solution, considering the biomedical context.

Study plan

Master Course for Mechanical Engineering, Microengineering, Life Sciences, Materials Science, and other Engineering Sections.

Characteristics of the students

Master students with different levels in mechanics, mechanics of continuous mediums, biology, and physiology.

Contents (28 hours)

Part 1: Biomechanics @ the body level (8 h)

1. Functional anatomy (18.02)
2. Muscle biomechanics + example past mini-projects (25.02)
3. Kinematics of joints (04.03)
4. Tissue mechanical remodeling (11.03)

Part 2: biomechanics @ the tissue level (6 h)

5. Sport and muscle performance (18.03)
6. Tissue imaging (25.03)
7. Biomech. of tissues (lin/non lin const. law) (01.04)

Part 3: biomechanics @ the "clinical" level (14 h)

1. Biomechanics in organ-on-a-chip systems (08.04)
2. Biomechanic to treat tracheomalacia (15.04)
3. Biomechanics in traumatology (29.04)
4. Biomechanics in implant development (06.05)
5. Biomechanics sport traumatology (13.05)
6. Mini-projects presentation (20.05)
7. Mini-projects presentation (27.05)

Instructions for the mini-project for ME-482

Group composition

1. Mini-project is done by a group of 4 students from different sections (**max 2 students from the same section per group**).
2. Prof. Pioletti reserves the right to balance the distribution of students in the different groups to match, at best, point 1.
3. Final registration is no later than Friday, **21/02/25,** at 12:00.
4. Registration is made through a link (-> "Registration to the mini-project"), which will be published in Moodle related to course ME-482 on Tuesday, 18/02/25, at 16h00.
5. The list of the projects will be given in Moodle, and two different groups can take the same project (so if you are interested in project 1, put your name either on 1.1 or 1.2, **BUT NOT** on both!)
6. Register for only **ONE** project by writing your **LAST** and **First** name (PLEASE follow this order) and your section (**Smith John (GM)**). Check for the diversity of sections per project before signing (see rule 1. above)!

Description of the expected work

1. Small literature review (max 5 articles)
2. Definition of the biomech/bioeng goals of the project (Specifications)
3. Design, calculation (if needed), and implementation of the project (if possible)

Presentation and follow-up of the work

1. Possibility to contact the (medical/engineering) advisor of your project
2. Brief private discussion based on 3 slides max of the project specifications during a class session (or at the facilities where the project is proposed) on 11/03/25 at 15h00 that you organize with the engineer advisor of our project. The goal is to ensure that you are on a good track.
3. Oral presentation of the project progress on the 20/05/25 or 27/05/25 (8 min presentation + 2 minutes questions). The distribution of the groups between the two days will be communicated on 13/05/25.
4. Written report (one per group, 15 pages max) in pdf format has to be sent to the medical and engineer advisors of your project **as well as** to Prof. Pioletti no later than **03/06/25 at 12h00**. Please include in the front page the names of the Medical and Engineering advisors.

Work evaluation

1. The mini-project mark will essentially count for the mark of the course
2. The mini-project mark will be based 1/2 on the written report, 1/2 on the oral presentation made on 20/05/25 or 27/05/25 (but not on the 3 slides presentation of 11/03/25).
3. The evaluation criteria are:
    a. Understanding of the project (literature review limited but pertinent)
    b. Quality of the presentations (oral and written)
    c. Motivation
    d. Originality
    e. Pertinent engineering analysis
    f. Adequate answers to the questions (during the oral presentation)

Some remarks on the written report

1. Scientific type of report: write only facts, not your feelings or mood
2. List ALL sources used, also in the figure captions
3. Structure the report with a table of contents

1) 3D skeletal muscle cell culture
Research advisor: Dr. Nicolas Place (UNIL, Lausanne)
Engineer advisor: clement.lanfranchi@unil.ch

2) Effects of mouthguard on sportive performances
Research advisor: Dr. Fabio Borrani and Dr. Davide Malatesta
Engineer advisor: naser.nasrollahzadeh@chuv.ch

3) In-field evaluation of sportive performances with portable equipment
Research advisor: Dr. Davide Malatesta
Engineer advisor: yanheng.guo@chuv.ch

4) 3D printed thoracic anatomical models for preoperative planning and education
Medical advisor: Dr. Antoine Dewarrat (CHUV, Lausanne)
Engineer advisor: alexander.nottegar@epfl.ch

5) Whether or not to use steps when climbing a slope in a trail race
Medical advisor: Dr. Fabio Borrani (Institute of Sport Sciences FBM)
Engineer advisor: Jérôme Parent and Olivier Campiche (labo.issul@unil.ch)

6) Improve laboratory evaluation on trail running
Medical advisor: Dr. Fabio Borrani (Institute of Sport Sciences FBM)
Engineer advisor: Jérôme Parent and Olivier Campiche (labo.issul@unil.ch)

7) Efficient fat processing in regenerative medicine
Medical advisor and engineering advisor: philippe.abdel-sayed@epfl.ch

8) Experimental hip fracture device
Medical advisor: Dr. Alicia Bojan
Engineering advisor: antoine.reitzel@epfl.ch

9) Ski helmets optimization
Medical advisor: Dr. Jean-Yves Fournier (Hôpital du Valais, Sion)
Engineering advisor: mi-lane.bouchez@epfl.ch

10) Ice hockey players with knee cartilage problem
Medical advisor: Quirin Soehnlein (Performance coach, LHC)
Engineering advisor: alexander.nottegar@epfl.ch

11) Hydrogel glue with cicatrisation properties
Medical advisor: Dr. Kishore Sandu (CHUV, Lausanne)
Engineering advisor: deniz.turgut@epfl.ch

12) How to diminish air leaks after lung volume reduction surgery?
Medical advisor: Dr. Louis-Emmanuel Chriqui (CHUV, Lausanne)
Engineering advisor: vincent.varanges@epfl.ch

Dr Jean-Yves Fournier
Médecin chef de service
Service de Neurochirurgie
Hôpital du Valais
Jean-Yves.Fournier@hopitalvs.ch
027 603 40 00

How can ski helmets be optimized to increase wearer safety?

Who are the patients/targeted population?
Amateur skiers.

What is the problem?
When comparing traumatology data before and after the general introduction of ski helmets, the occurrence of brain injury in ski accidents seems to have generally increased.

What is the need?
Propose and develop a new helmet concept that can more effectively protect the skier from brain trauma during impact.

What is the benefit (if the problem is solved)?
Even if only a moderate protective effect on brain injury can be obtained with a new ski helmet design, a new approach to designing ski helmets could be proposed.

Wrap-up
Brain injury is a devastating problem in high-speed sports. Solutions to specifically protect the skiers are highly needed.

Biomechanics of the MSS: to do what?

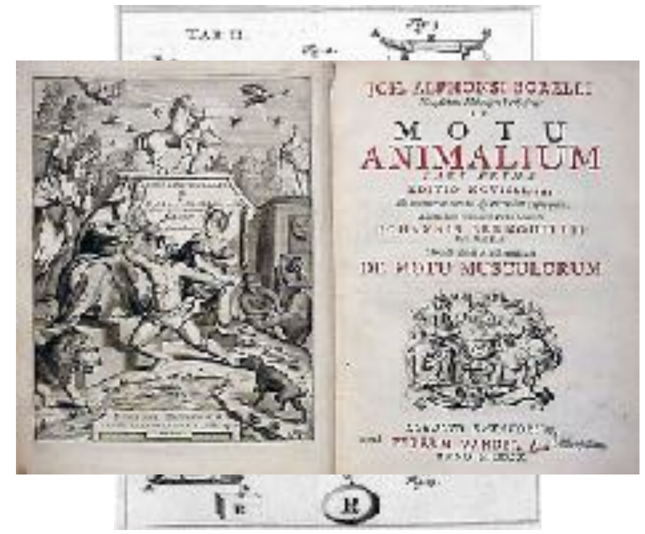
i) Brief historical introduction

ii) Functional anatomy

iii) Pathologies related to biomechanical aspects

Medicine and (bio) mechanics are intrinsically linked since a long time

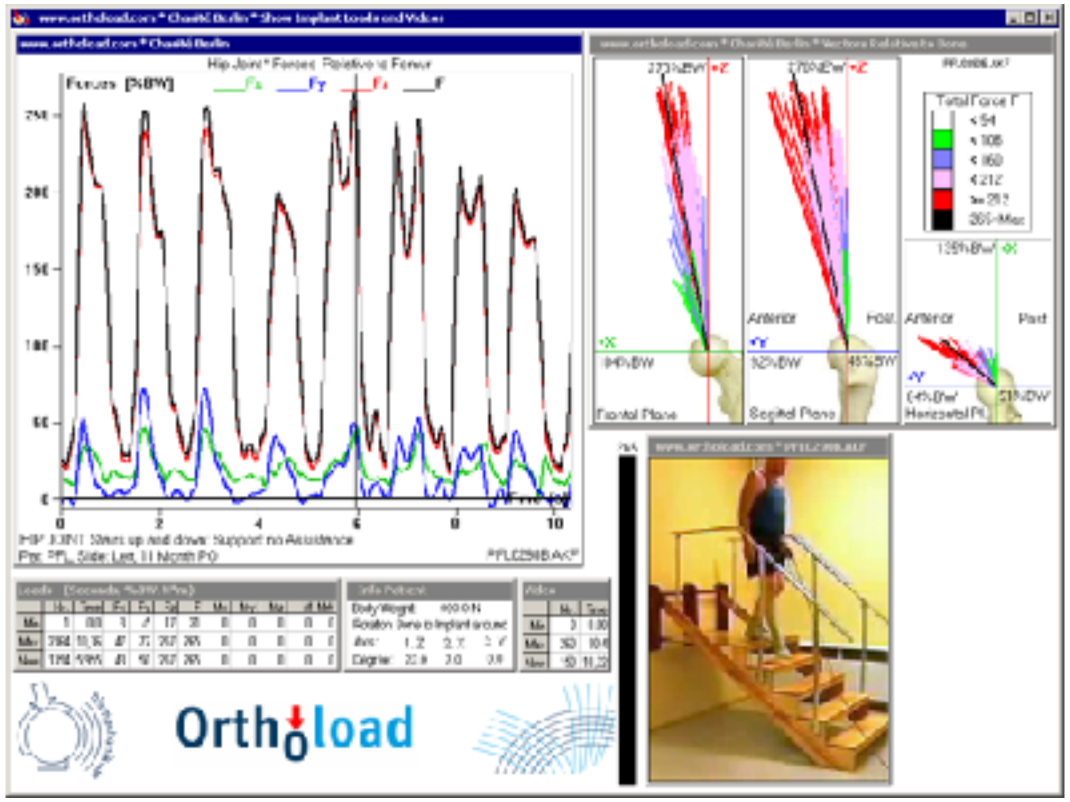
Reduction of a dislocated shoulder
with a Hippocratic device
(350 BC)



De motu animalium.
Giovanni Alfonso Borelli
(1680)

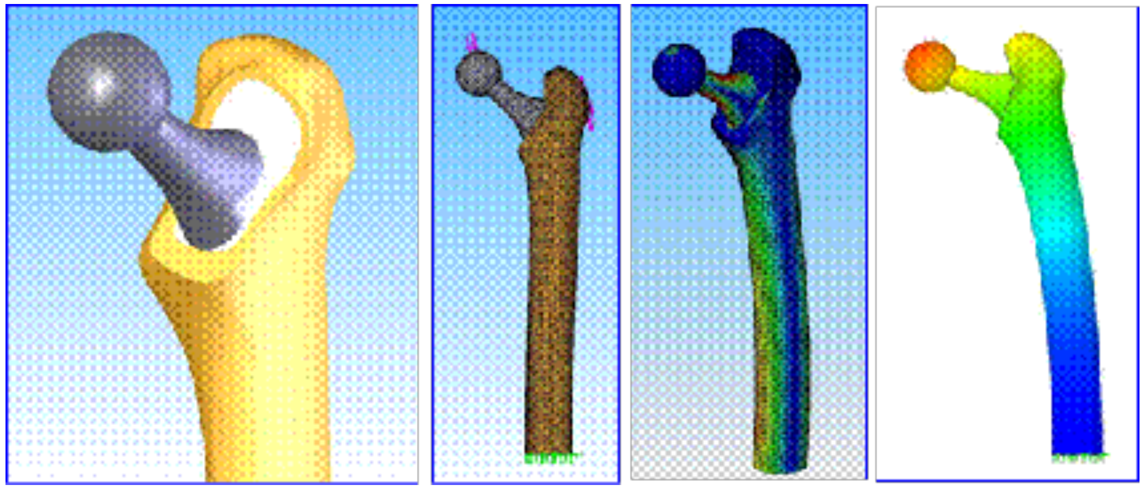
Biomechanics and medicine were linked very early, especially through external manipulations such as reduction of a dislocated shoulder shown in this engraving depicting a Hippocratic device. It was not until the 15th century and the opportunity to dissect human cadavers (Leonardo da Vinci 1452-1519, was indeed one of the first to dissect human beings) that a new knowledge on biomechanical functions of the human body was revealed. Then, in 1656, Giovanni Alfonso Borelli founded the “Academia degli investigandi” dealing with medicine, physiology, mathematics and physics. Borelli wrote a great medical book, “De motu animalium", published after his death, where he tried to explain the movements of animal bodies through mechanical principles. He was the first to show that the internal forces exerted on the bones can be greater than the applied external forces. He is considered to be the "father of the biomechanics."

Contact forces in the articulations



In this course, we will focus on the biomechanics of the musculoskeletal system. In contemporary biomechanics, a key aspect of the interaction between physicians and engineers crystallises during orthopedic implant development. As a biomechanician, it is absolutely necessary to determine the forces at play in the joints in order to ensure the mechanical integrity of the implant during operation.

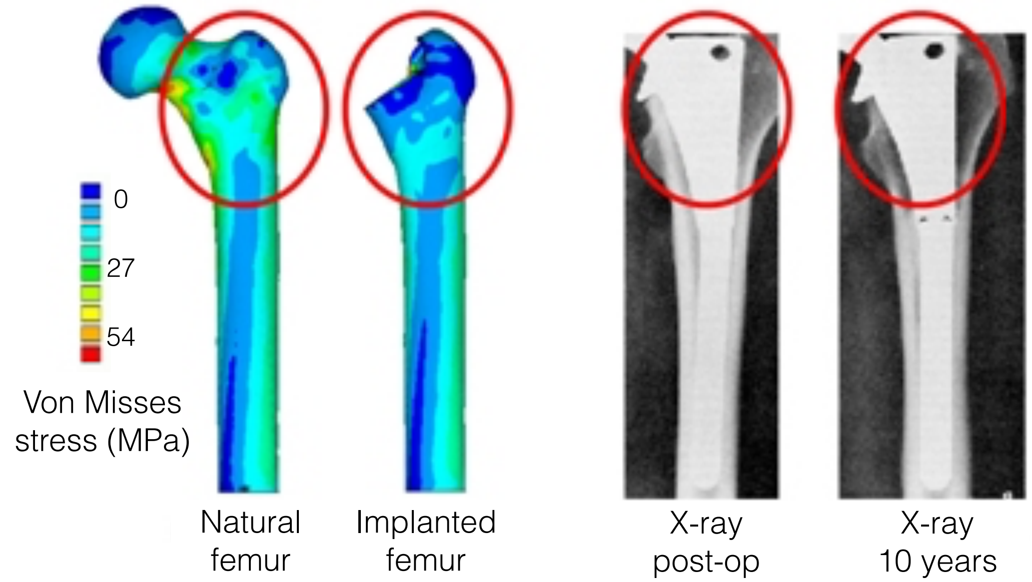
Classical approach of biomechanics



http://www.biohexagon.com/

Once the forces acting on the studied system have been determined, their values can be used as boundary conditions to calculate the stress/strain in the developed implant so that its mechanical performances can be evaluated.

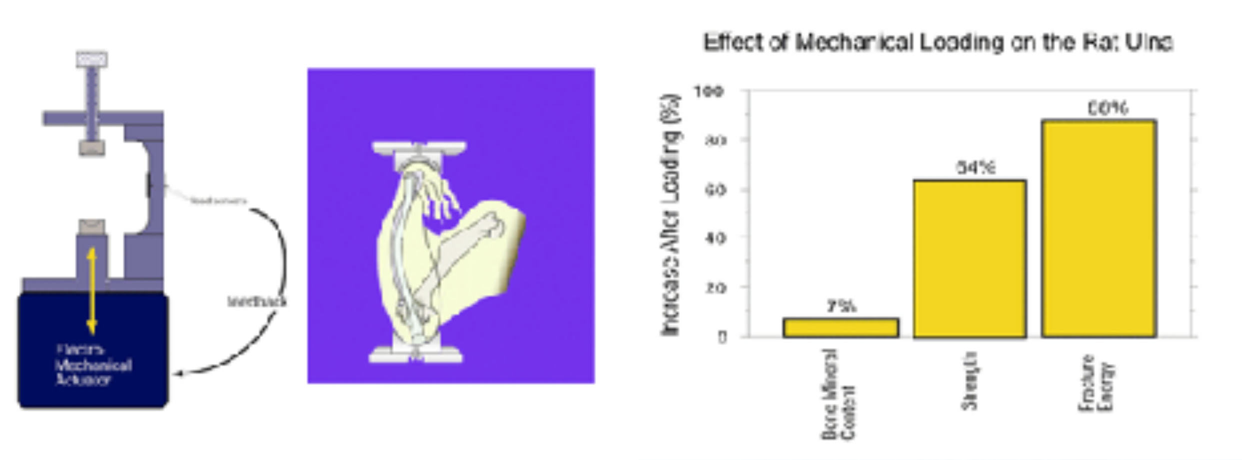
There is a fundamental difference between mechanics and biomechanics



adaptation of mechanical properties of tissues

The mechanical loading in the tissues induces an adaptation of their mechanical properties. This may induce deleterious effects on the implant long term fixation.

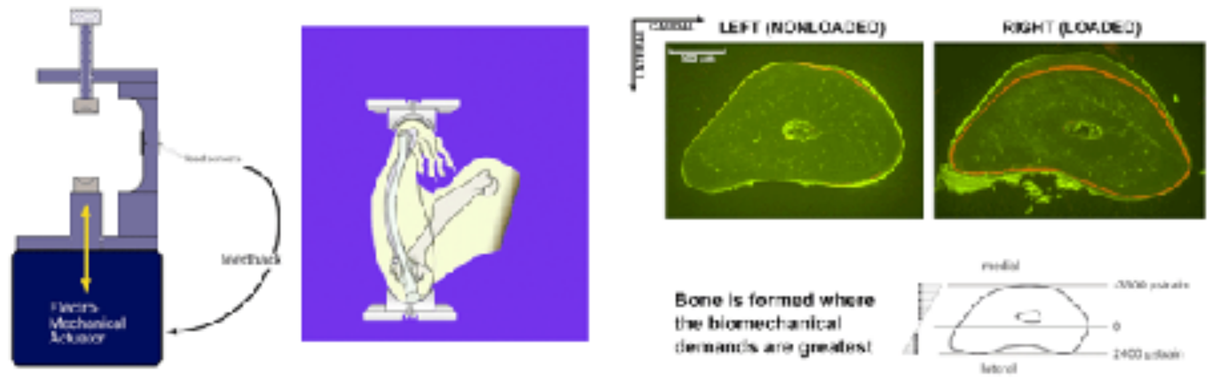
The mechanical constraints influence the development of tissues: example in a mouse study



source: http://anatomy.iupui.edu

In order to better understand the tissue adaptation to mechanical loading, in vivo experiments have been performed. In this slide, the mechanical stimulation of a mouse arm translates by an increase in the mechanical properties of the stimulated bone compared to the non–stimulated one.

The mechanical constraints influence the development of tissues: example in a mouse study



source: http://anatomy.iupui.edu

An increase in the diameter of the stimulated bone is also observed (red tissue: before stimulation; green tissue: just before sacrifice).

Biomechanics of the MSS: to do what?

i) Brief historical introduction

ii) Functional anatomy

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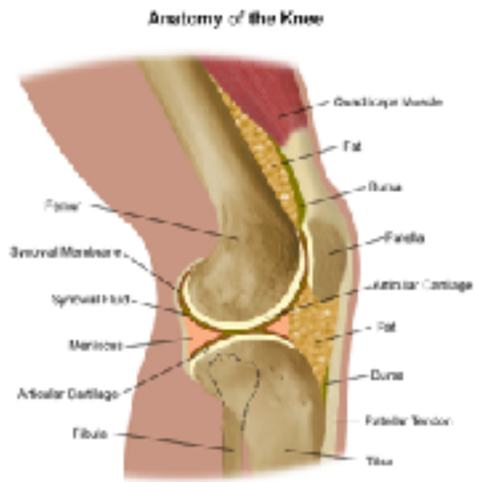
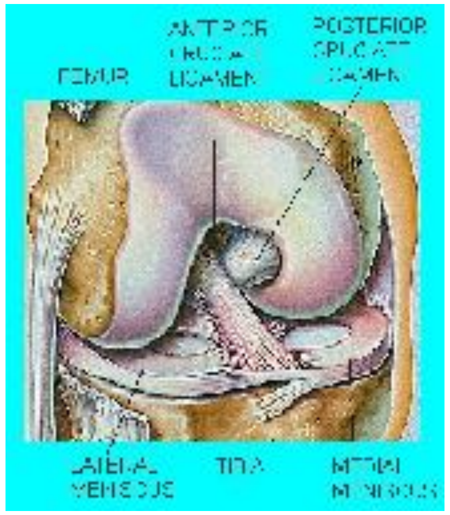
The functional anatomy describes the different parts composing the body with respect to their function. Thus in our biomechanical approach, the description of the tissues is done according to their biomechanical role (damping, transmission of the forces, stiffness, etc).

The knee illustrates perfectly the complexity of the structures composing the MSS



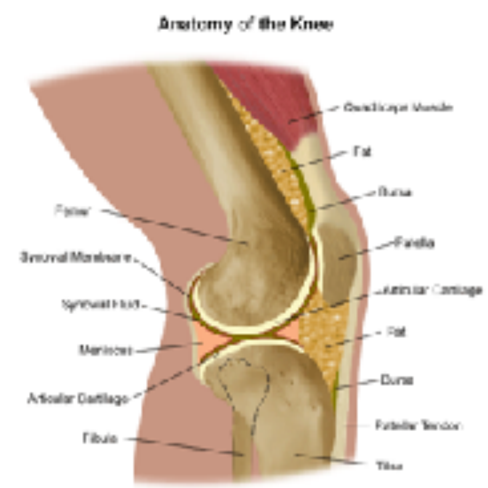


source: http://www.arthroscopy.com

The correct operation of the knee is the result of the correct operation of various tissues being in or around the knee.

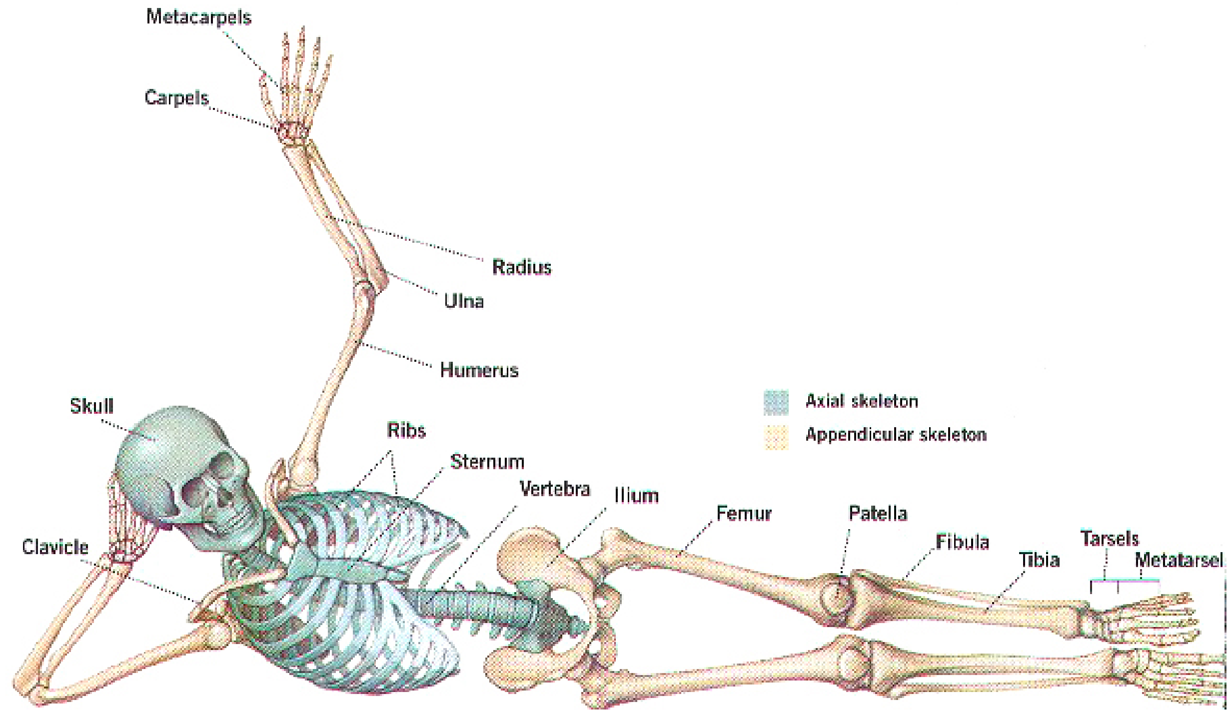
The different tissues of the knee have specific biomechanical functions

Tissue	Function
Bone	Insures the body rigidity and allows motion
Cartilage	Allows sliding of bones between each others
Meniscus	Restores the congruency then the sliding between articular surfaces Damps shocks
Ligaments	Link bones together
Muscles	By contraction, pull on bones allowing motions
Tendons	Link muscles to bones
Synovial fluid	Promotes sliding in joints



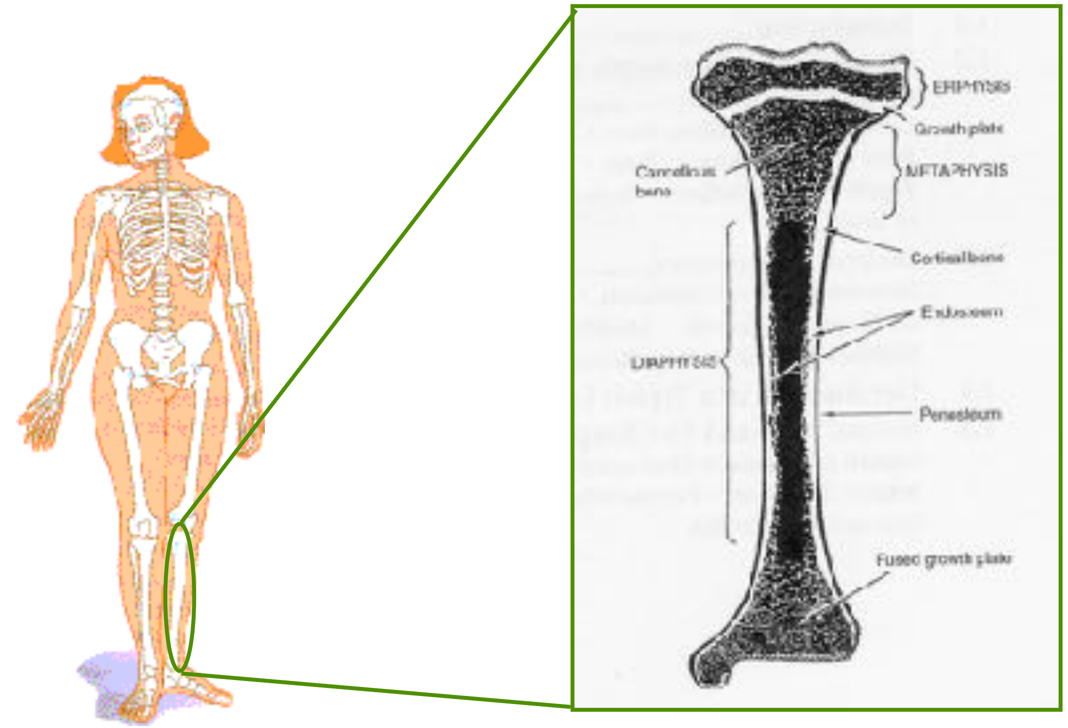
Each tissue has a specific biomechanical function.

The skeleton is composed of 2 parts



One distinguishes the axial skeleton which has a major role of protection and the appendicular skeleton which has a role of forces transmission.

The skeleton is composed of bone and cartilage



The cartilage is located on the ends of the long bones. The bone is composed of 2 types of bone: cortical and trabecular. The trabecular bone is found in the proximal and distal parts of the bone, which allows a good distribution of the loads. The cortical bone is in the central part of the bones where the constraints are high (surface of the bone limited).

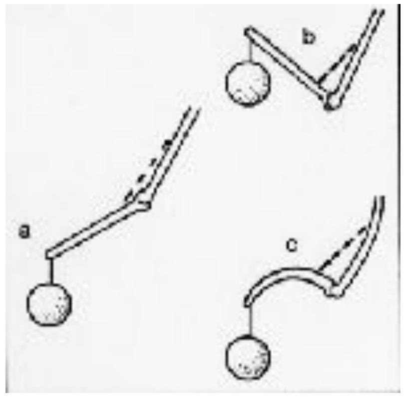
The function of the bone can be divided into 4 parts

1. Mechanical support
2. Protection of the vital structures
3. Hematopoesis
4. Mineral homeostasis

Function of the bone: “mechanical” aspects

“Fight” against gravity

Respiratory motion



Transmission of the forces

The mechanical properties of the bones depend on their functions. The bone used as protection is mainly made up of cortical bone.

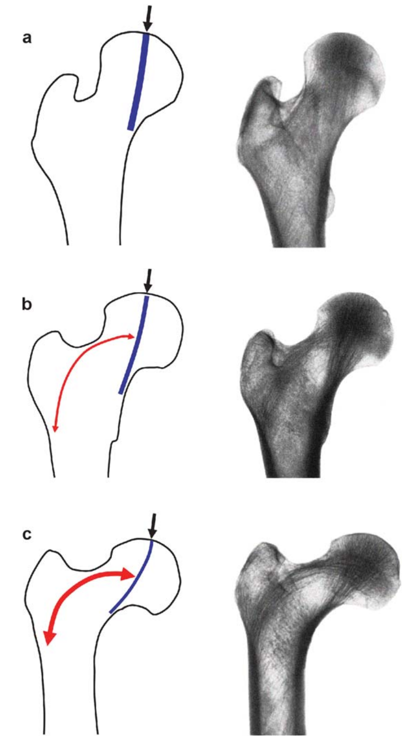
Function of the bone: "biological" aspects

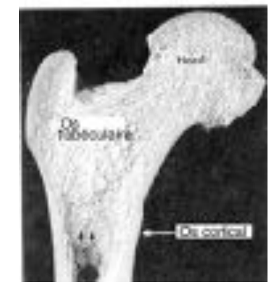
3. Hematopoesis: production of the various blood cells

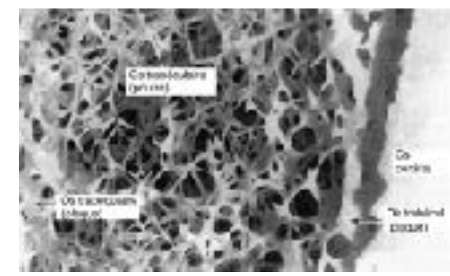
4. Mineral homeostasis: regulation of the concentrations of various minerals

Our body continuously needs new cells to fulfil various physiological functions. The "tank" of the hematopoetic stem cells is in the bone marrow, inside the bones. The minerals (calcium, phosphorus, sodium, potassium, iron) are necessary to the good operation of our body. The majority of these minerals are in the bones. For example, 99% of the calcium of the human body are fixed in the bones.

Structure of the bone:
from macroscopic to microscopic





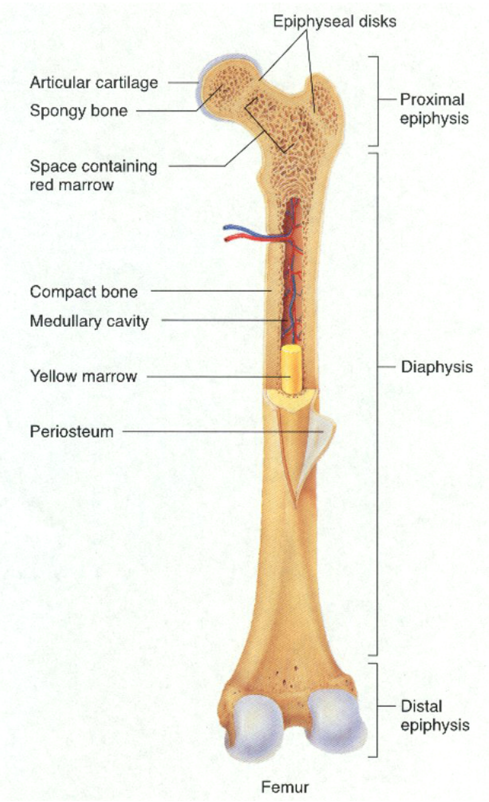


In the MSS, there is a hierarchical structure which makes it possible to transmit the loads of the macroscopic structure to the microscopic structure.

The bone, at the macroscopic level

Cortical bone

- 80% of bone weight
- diaphysis
- dense
- solid
- mechanical support
- protection

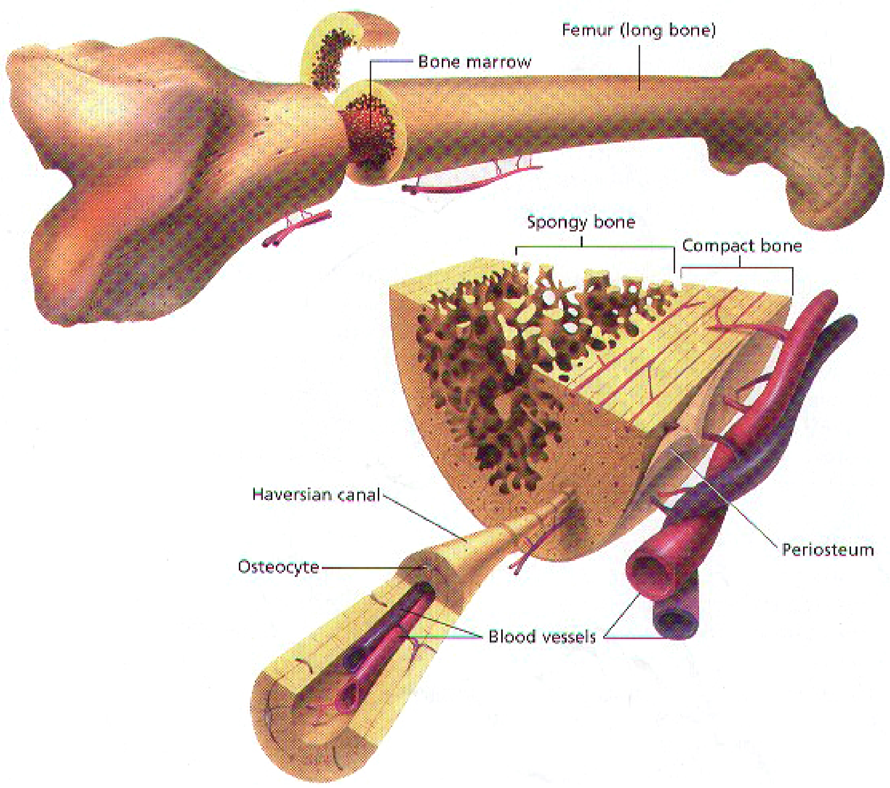


Trabecular bone

- 20% of bone mass
- épi., métaphysis
- porous
- biol and chem dynamic
- “tank” of stem cells

The cortical and trabecular bones have complementary functions.

The bone is a well vascularised structure



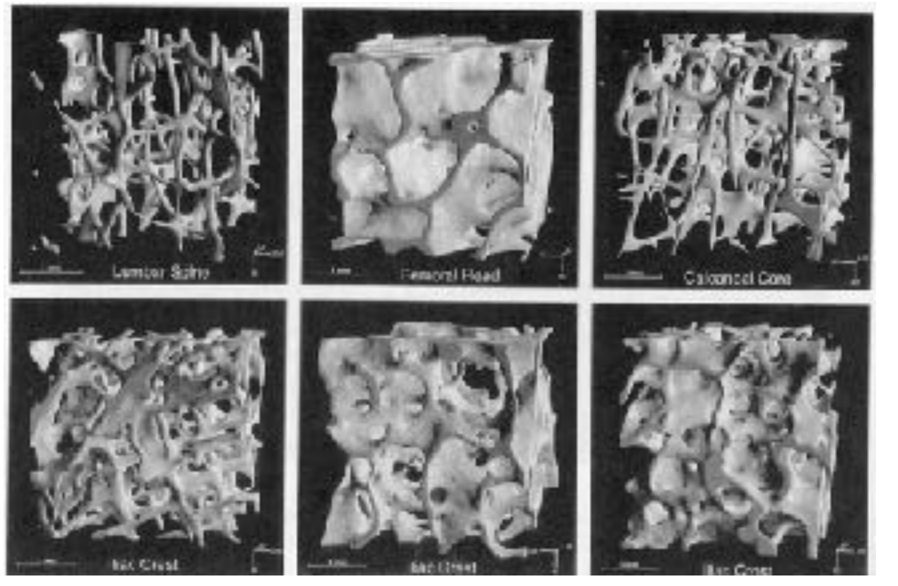
The bone is a dynamic structure from a biological point of view. An important blood supply is thus necessary to this dynamism.

The bone at the microscopic level

Trabecular bone

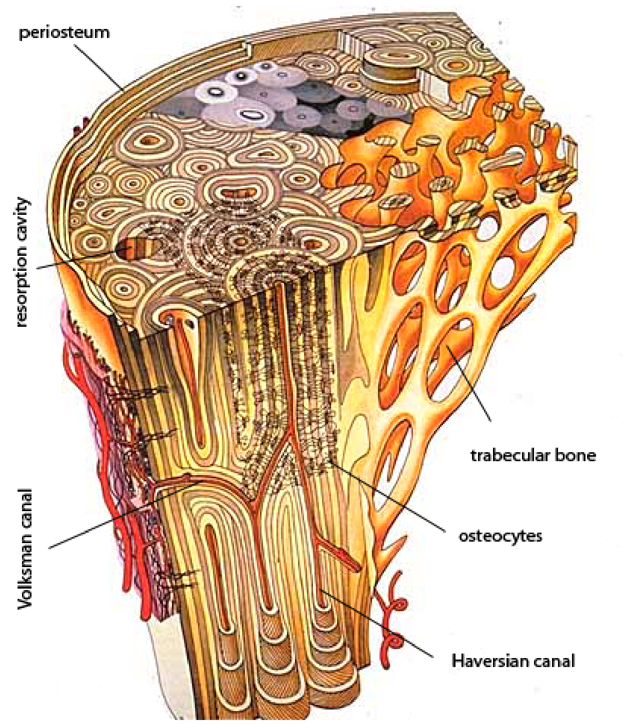
Various sites (same patient)

Various patients (same site)



The morphology of the trabecular bone is different at the various sites of the skeleton, the mechanical requests being also different. At the same site, morphology is dependent on the patient. Each patient having a different “mechanical” history, the morphology of the trabecular bone is unique for each patient. At the same site for the same patient but at different ages, one could observe different trabecular structures because mechanical stimulation evolves during “ageing”.

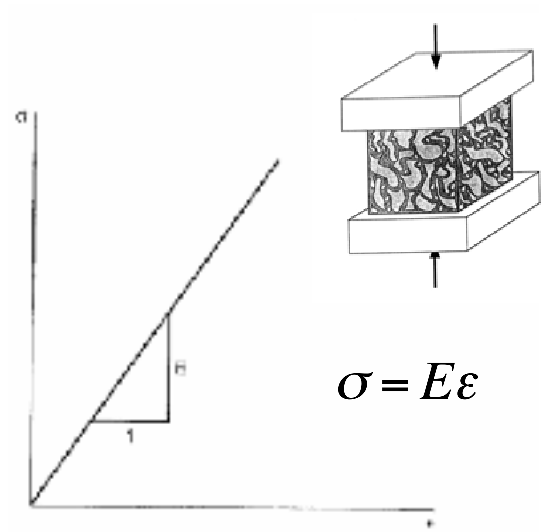
There is a continuity at the level of the trabecular/cortical structure



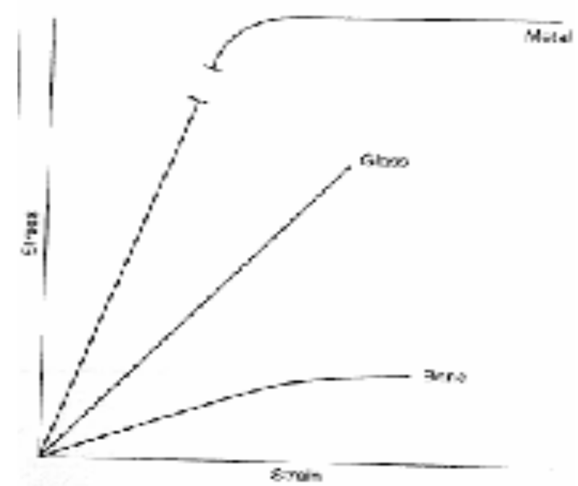
Source: http://www.mednote.co.kr

In order to be able to transmit the loads as effectively as possible, there is a continuity between the trabecular and cortical structures.

Bone is considered as a linear elastic material in a first approximation



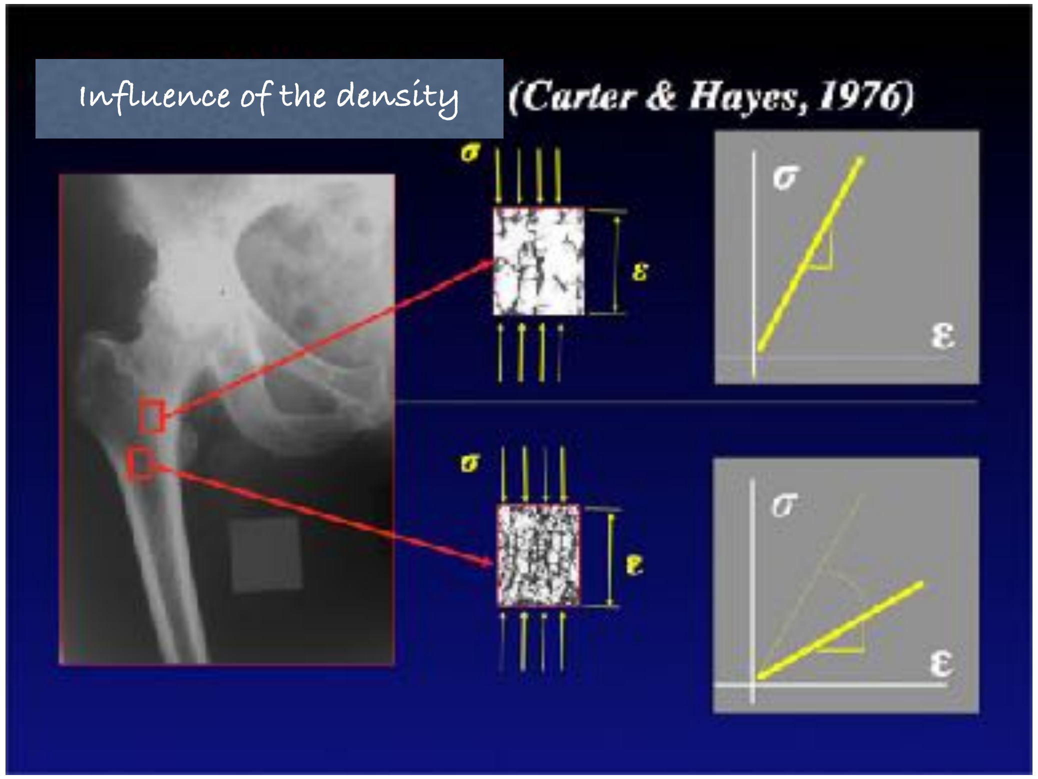
$$\sigma = E\varepsilon$$



source: Nordin, 2001

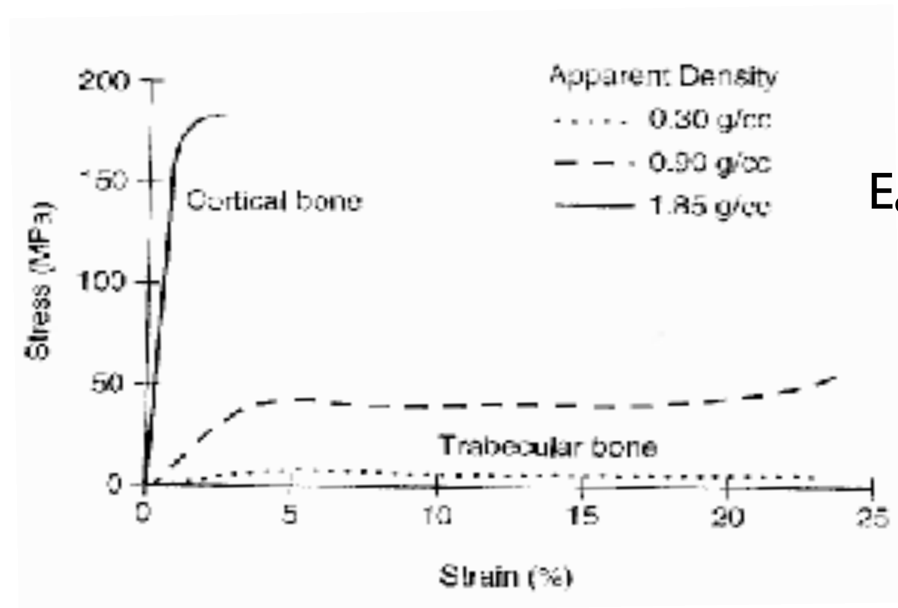
Experimental mechanical tests on bone allow us to verify that a linear relationship exists between the applied stress and the obtained strain. In the limit of sufficiently small strains, we can then consider the bone as a linear elastic material, the constant of proportionality between the stress and the strain is called the Young's modulus or the elastic modulus. As can be seen on the graph on the right, the mechanical properties of bone (its Young's modulus) are not too far from "strong" metallic materials.

Bone mechanical properties vs bone density



Indeed, the Young's modulus of the bone is not identical in all parts of the bone. There is a strong dependency between Young's modulus and bone density. A relationship has been established between grey levels of x-ray picture and bone density and another between bone density and Young's modulus. X-rays pictures allow us then to obtain an indirect evaluation of the bone mechanical properties.

Bone mechanical properties



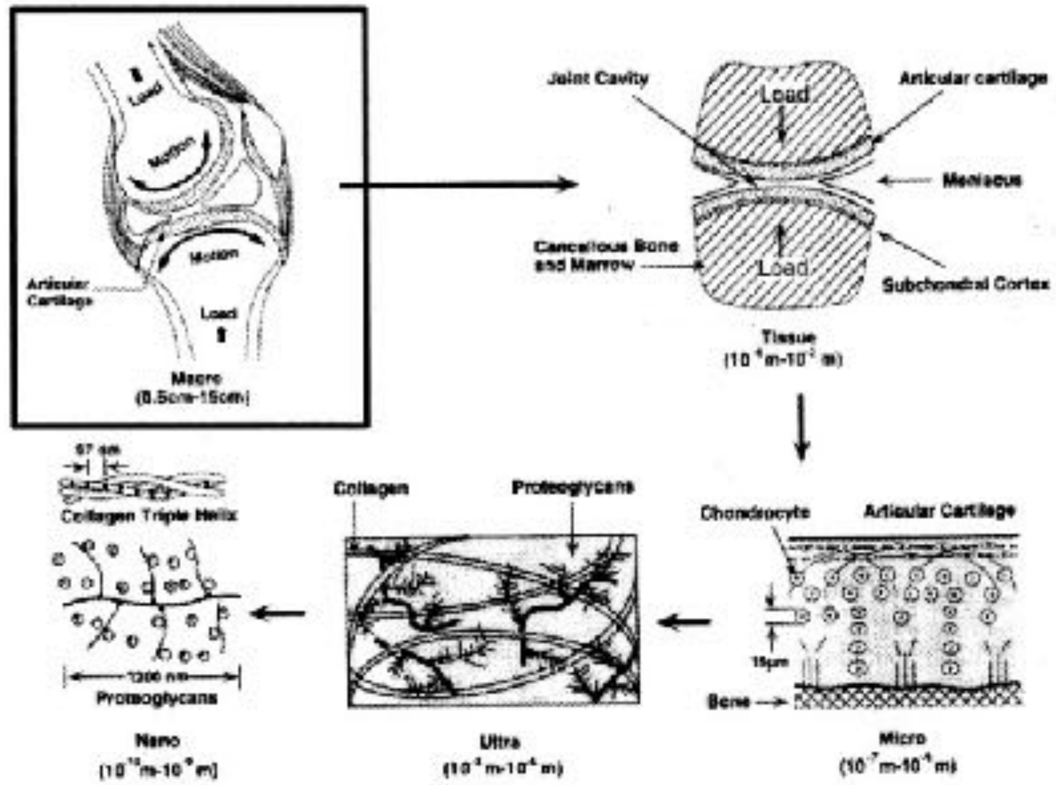
$E_{trab} \approx 300$ MPa

$E_{cort} \approx 17'000$ MPa

source: Nordin, 2001

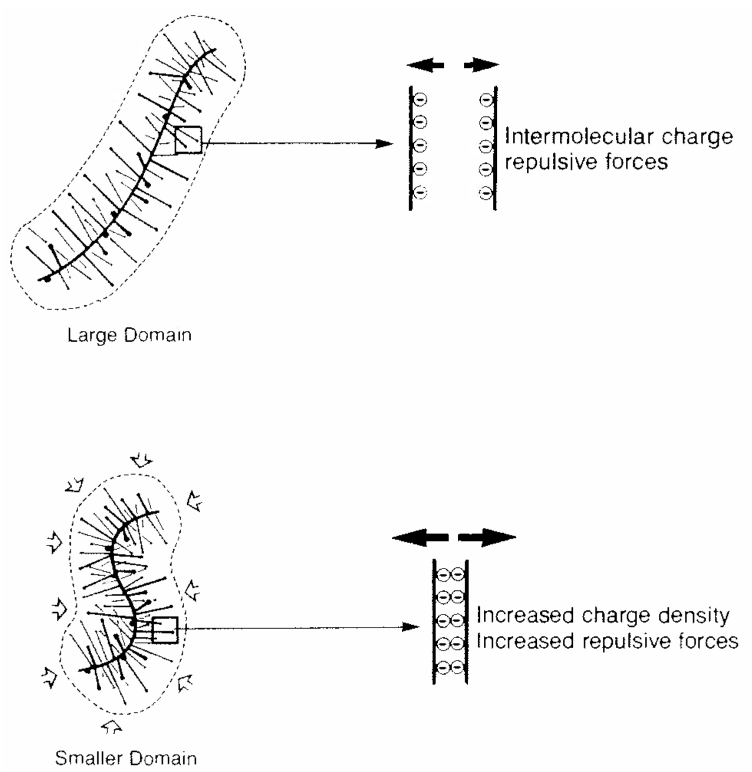
As cortical and trabecular bones have a different bone density, it is then not surprising that they present different mechanical behaviours. If we focus only on the linear part of stress-strain curve, the Young's modulus can be measured (as the slope of the linear part) and we observe that there is at least one order of magnitude difference between the trabecular and cortical values of Young's modulus. As a comparison, titanium has a Young's modulus of around 100'000 MPa (= 100 GPa).

The cartilage allows an almost frictionless contact between bones



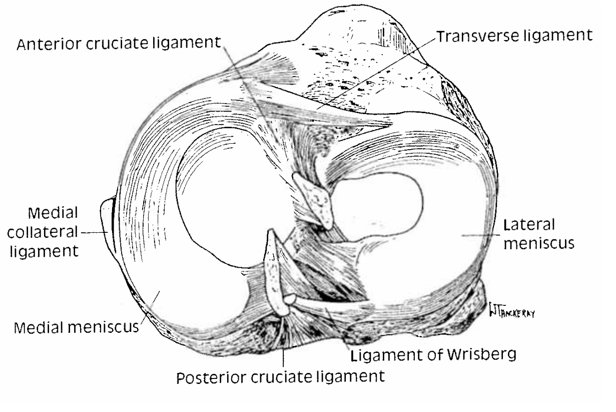
The cartilage is a smooth tissue, lubricant, supporting the load with a minimum of wear. The cartilage is not innervate and is avascular. The nutrition and the evacuation of waste are obtained by phenomena of transport. This physiological situation induced a low potential of healing, the damaged cartilage has a limited self-healing capability.

The mechanical resistance of the cartilage is partly assured by electrical forces



The proteoglycans constituting the cartilage have a great density of charged groups (SO_4^-, COO^-). The compression of this tissue brings closer these charged groups increasing consequently the repulsive electrical forces.

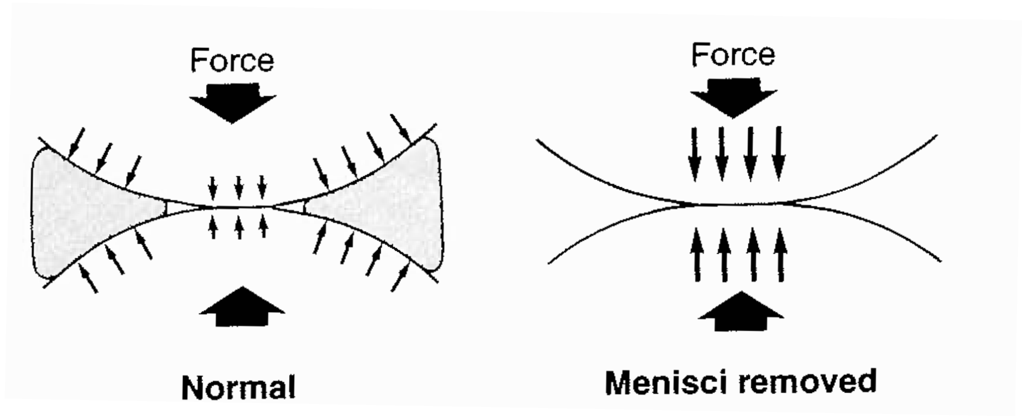
The meniscus, shock absorber of the knee



source: Biomechanics of diarthrodial joints, Van Mow et al., 1990

The meniscuses are fibrocartilage discs in C form interposed between the condyles of the femur and the tibia. They deepen the cartilage surfaces of the tibia in order to better adapt the condyles of the femur. The menisci are relatively avascular and are innervate. The menisci repaired themselves at the time of lesions, however, the resulting scars can be unfavourable from a biomechanical point of view.

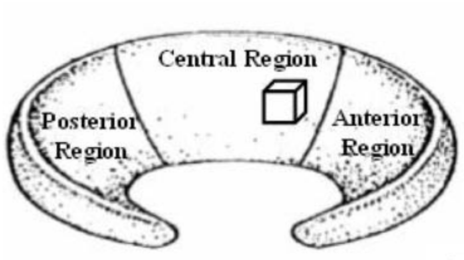
The meniscus makes it possible to distribute the forces on a larger surface

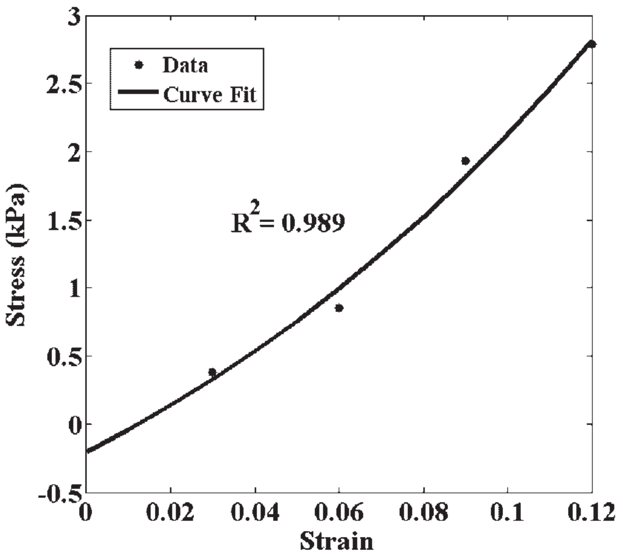


source: Basic biomechanics of the musculoskeletal system, M. Nordin and V. Frankel, 2001

The meniscus acts like a hydrostatic cushion, uniformly distributing the forces between its surfaces.

The compressive behaviour of the meniscus samples depends on their location and deformation

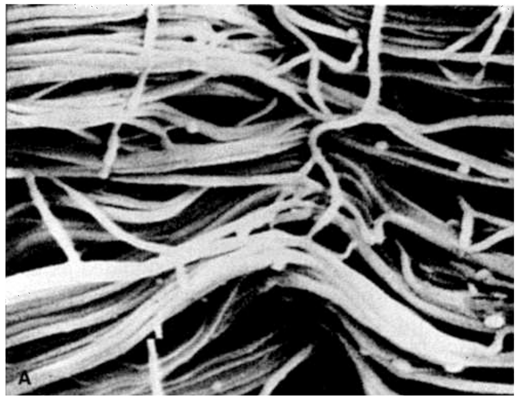




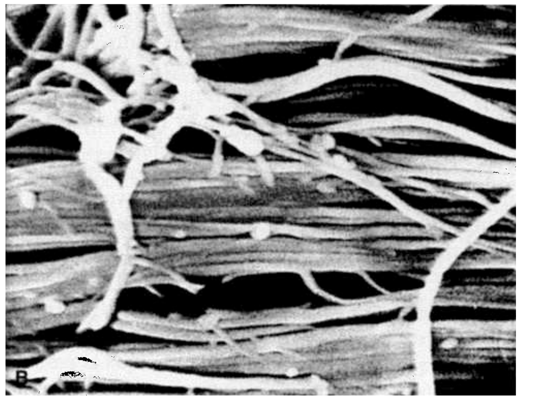
source: Helena and Hull, JOR, 2008

The unconfined compressive tests on meniscus showed a behaviour which deviates from a linear behaviour. If we calculate the Young's modulus at different strain values on the stress-strain curve, it can be observed that the modulus increased with increasing strain (79.2 kPa at 3% strain vs. 662 kPa at 12% strain). This is indeed typically the characteristic of a non-linear elastic mechanical behaviour.

The ligaments passively control the relative motions of bones in a joint



Unloaded collagen fibres have a wavy configuration

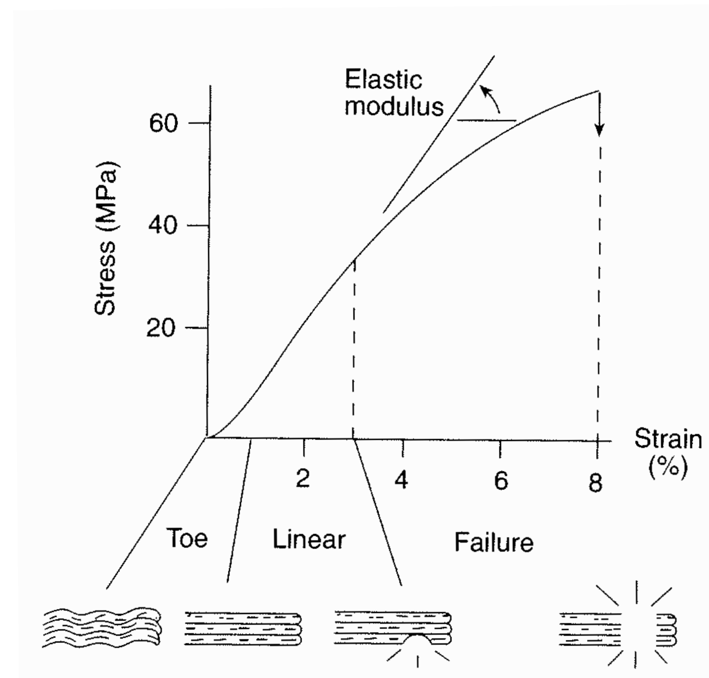


The collagen fibres are aligned under load

source: Kennedy et al., J Bone Joint Surg, 1976

The ligaments present a partial alignment of their collagen fibres which allows important elongation of the ligaments without damaging their structure. The unidimensional alignment of fibres makes ligament an ideal tissue to resist longitudinal forces. On the other hand the ligaments do not have any mechanical properties in compression and shear.

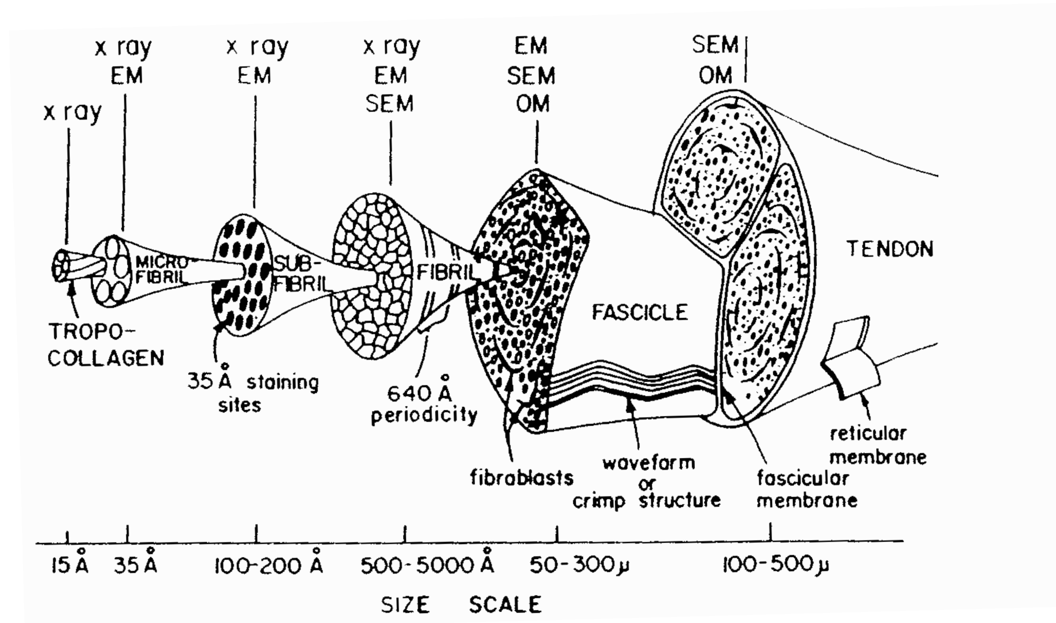
The ligaments mechanically work under traction



source: *Biomechanics of the musculoskeletal injury,W. Whiting and R. Zernicke, 1998*

The stress-strain curve of a ligament can be schematised by 3 regions. The toe region which corresponds to a slackened ligament where the fibres are not completely aligned. The linear region where the fibres are aligned conferring a linear elastic behaviour for the ligaments. The physiological range is comprised between the toe region and the end of the linear region. In the failure region, progressive rupture of the collagen fibres takes place. The quantification of the Young's modulus in the linear range of the stress-strain curve gives the approximate value of 300 MPa.

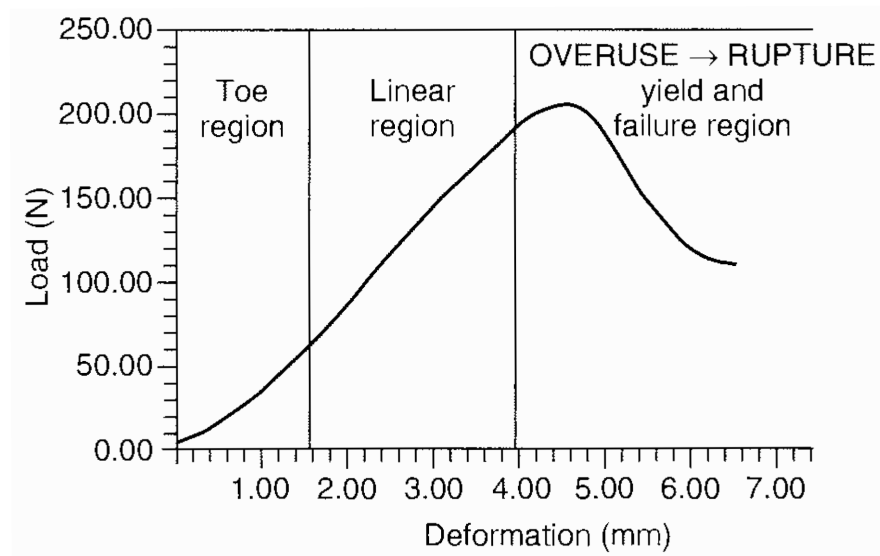
The tendons transmit the muscular forces to the bone



source: Basic orthopedics biomechanics, C.Van Mow and W.C. Hayes, 1997

The gross anatomy of tendon is similar to the one of ligament. The tendon is made of small fibres which by association make a larger fibre, and so on (like the structure of a cable-car for example).

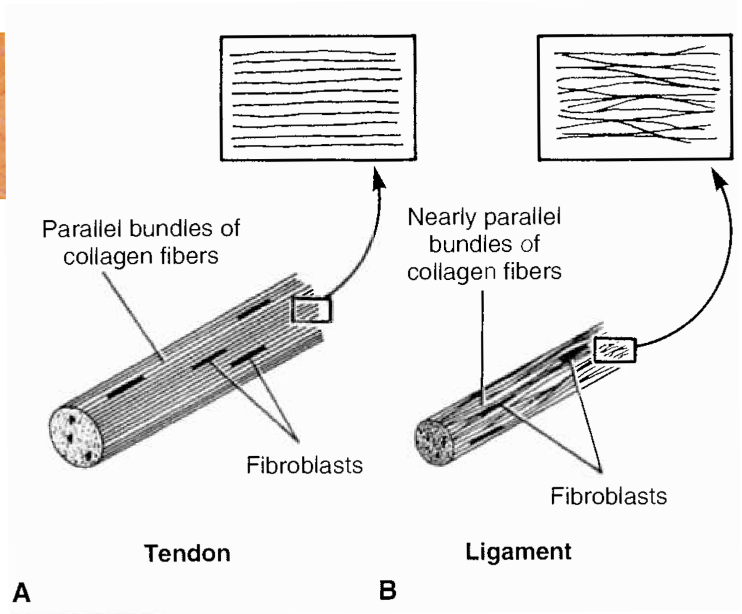
The tendons mechanically work under traction



source: Basic biomechanics of the musculoskeletal system, M. Nordin and V. Frankel, 2001

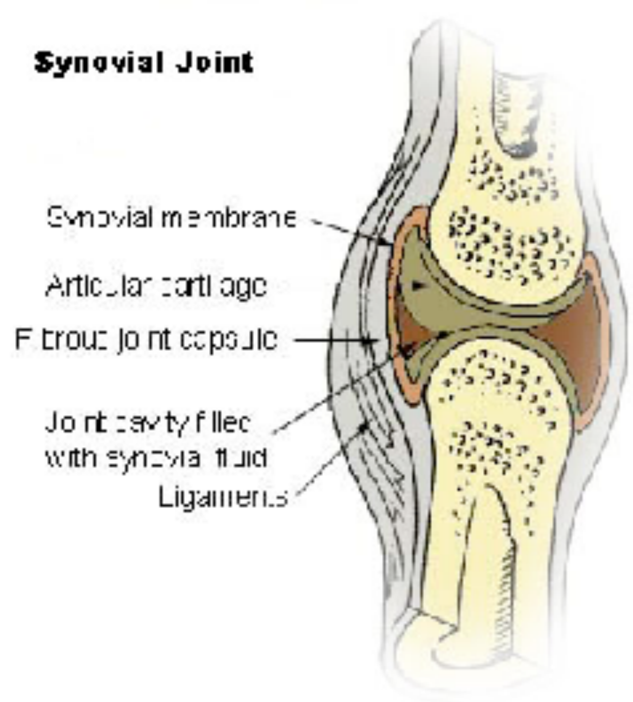
As for the ligament, the load-deformation (or stress-strain) curve can be schematised by 3 regions. However, we observe that the toe region is less marked for the tendon curve than for the ligament curve due to the fact that the tendon function is to transmit “completely” the load from the muscle to the bone.

Even for tissues working only on traction, anatomical differences exist



The difference in the alignment of fibres between tendon (A) and ligament (B) affects the toe region which is less marked in the tendon stress-strain curve compared to the ligament's one.

The synovial fluid lubricate the joint

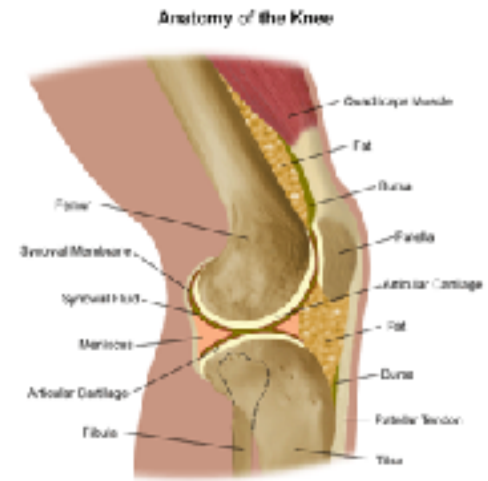


source: http://training.seer.cancer.gov/module_anatomy/images/illu_synovial_joint.jpg

Synovial joints allow for much more range of motion than cartilaginous joints. Cavities between bones in synovial joints are filled with synovial fluid. This fluid helps to lubricate the articulations.

The different tissues of the knee have specific biomechanical functions

Tissue	Function
Bone	• Insures the body rigidity and allow motion
Cartilage	• Allows sliding of bones between each others
Meniscus	• Restores the congruency then the sliding between articular surfaces • Damps shocks
Ligaments	• Link bones together
Muscles	• By contraction, pull on bones allowing motions
Tendons	• Link muscles to bones
Synovial fluid	• Promote sliding in joints



The correct function of the knee is due to the adapted mechanical properties of all its different tissues. If one tissue fails to fulfil its role, this may hamper the subtile equilibrium between stability and high range of motion of the knee inducing other tissues to be damaged.

Biomechanics of the MSS: to do what?

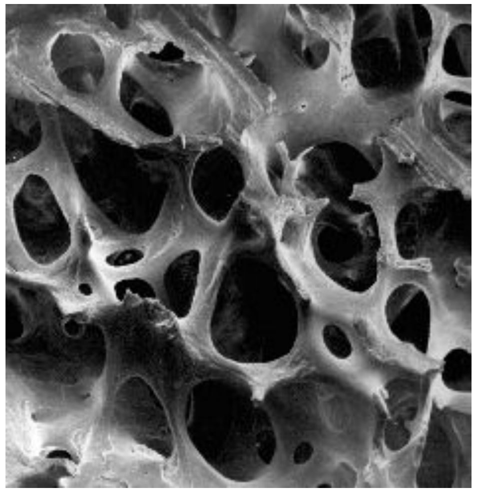
i) Brief historical introduction

ii) Functional anatomy

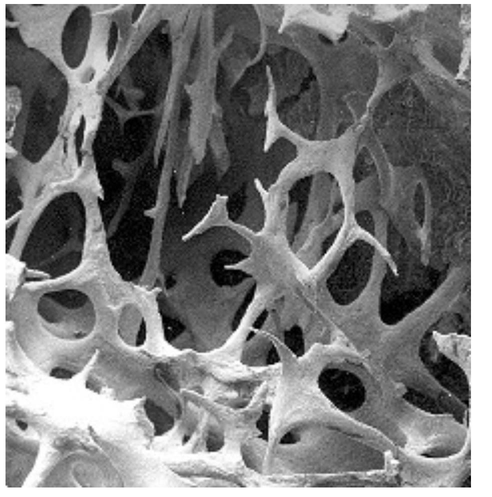
iii) Pathologies related to biomechanical aspects

In this last part, we will establish a link between the mechanical properties of a tissue and a related pathology. Several examples will be presented.

The bone ageing process weakens its mechanical properties



Normal trabecular structure

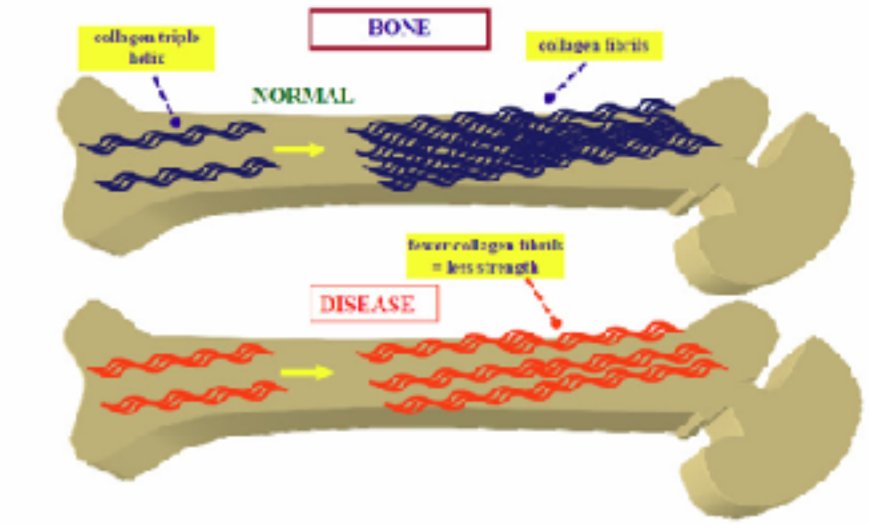


Osteoporotic trabecular structure

The hallmark of osteoporosis is bone fracture. The process leading to these fractures is due to a decrease in bone mass and affected bone structure. The thickness of the trabeculae as well as their interconnection decrease especially in postmenopausal women (oestrogen deficiency). The clinical examination usually only relies on bone mineral density which may lead to an inappropriate estimation of the bone mechanical properties.

Osteogenesis imperfecta

Michel Petrucciani

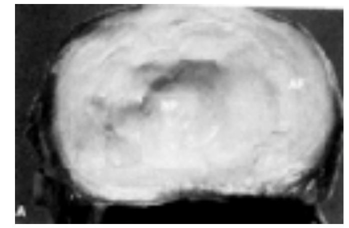


http://www.wohproject.org

Bone is made of inorganic (ceramics such as CaP) and organic (proteins such as collagen type I) elements. Both have a specific biomechanical role (CaP allows bone to resist to compression and collagen allows bone to resist to tension). The bone can then be seen as a composite material and the ratio of organic to inorganic elements affects its mechanical behaviour. If the amount of collagen is too low, then the bone will behave more as a glass so it will show a brittle behaviour. This is why osteogenesis imperfecta is sometimes also referred as “brittle bone disease”.

There are several type of osteogenesis imperfecta. The one presented on the right part of this slide is a type I. In type I, the triple collagen helices have difficulties to interact to form collagen fibrils.

Low back pain has been proposed to be linked to the degenerescence of the intervertebral disc



child

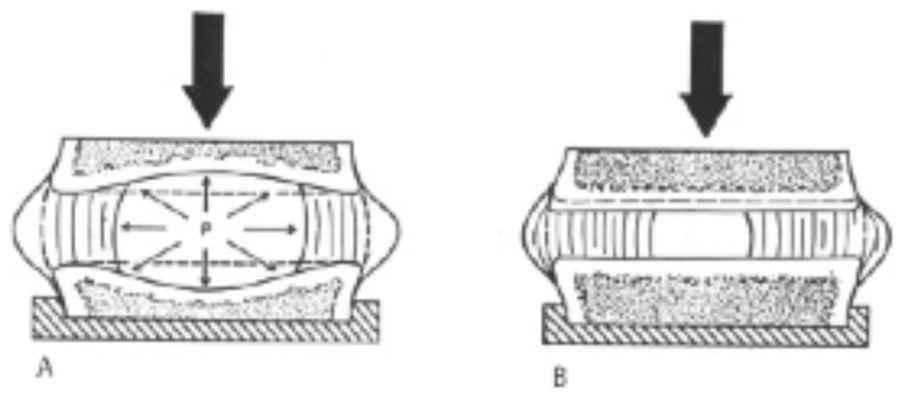
young adult

less young ...

Nordin, 2001

The degeneration of the intervertebral disc is related to different factors, one could be the high mechanical loading these tissues are exposed to. During the ageing, the quality of the tissue decreases until a clear difference may be observed between “healthy” and “degenerated” tissues. This tissue degeneration induces a change in the biomechanical function of the intervertebral disc.

Disc degeneration affects its mechanical mode of operation



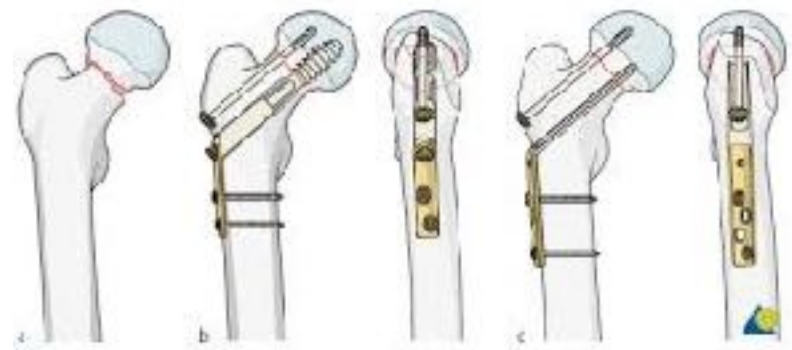
Nordin, 2001

In a healthy intervertebral disc, the nucleus pulposus plays perfectly its role of “hydrostatic cushion” by distributing the pressure evenly around it. This mechanical behaviour is due to the composition of the nucleus pulposus which is mainly water. The distribution of pressure imposes to the annulus fibrosus to work under tensile stresses (the annulus fibrosus is composed of fibres, this structure is quite suitable to withstand mechanical stresses in tension). When the nucleus pulposus becomes dehydrated, following the loss of proteoglycans (protein in the nucleus pulposus), the lack of water in this tissue avoids it to function as “hydrostatic cushion”. The pressure is then no longer distributed by the nucleus pulposus on the annulus fibrosus, but it is indeed only the annulus fibrosus which supports the compression load which is not adapted to its structure.

Orthopedic implant aseptic loosening

As previously mentioned, due to an adaptation of the tissue to a new mechanical loading situation, bone can resorb below implants (knee implant in this example). The bone lost in the tibia may hamper the mechanical stability of the implant tibial tray which ultimately may be related to the aseptic loosening of the implant.

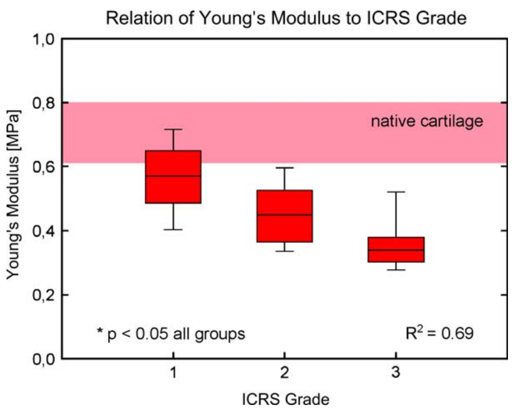
Implant fixation low quality bone



Femoral fracture is a common situation in the old population. The fracture is usually due to the low bone quality of the patient (could be due to osteoporosis). The low bone quality could also be a problem in the aspect of fracture treatment. Indeed, as the fracture treatment imposes the stabilisation of the damaged bone, the use of screws and plate may be a challenge in elderly as the screw anchorage could be very difficult to achieve.

The cartilage ageing process weakens its mechanical properties

Osteoarthritic knee



source: Kleemann et al., OsteoArthritis and Cartilage, 2005.

ICRS grading based on the Outerbridge score[6]

Grade	Property
1	Superficial lesions, fissures and cracks, soft indentation
2	Fraying, lesions extending down to <50% of cartilage depth
3	Partial loss of cartilage thickness, cartilage defects extending down >50% of cartilage depth as well as down to calcified layer
4	Complete loss of cartilage thickness, bone only

A link between clinical practice (grade of cartilage degeneration) and biomechanical evaluation can be made. Human tibia plateaus were collected during total knee arthroplasty from patients with knee joint osteoarthritis. The mechanical compression tests show that the Young's modulus decreases with increasing cartilage degeneration.

i) Brief historical introduction

ii) Functional anatomy

iii) Pathologies related to biomechanical aspects