Biomechanics of the musculoskeletal system

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Biomechanics at the tissue level

i) Continuum mechanics (conservation laws)

ii) Constitutive laws (linear, non-linear)

iii) Tissue characterisation

One important aspect of biomechanics is then to characterise tissues through constitutive laws

$$\rho \frac{d\boldsymbol{v}}{dt} = div\ \boldsymbol{\sigma} + \rho \boldsymbol{b}$$

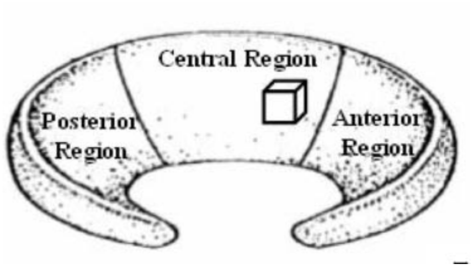
$$\sigma = \sigma(\varepsilon, \dot{\varepsilon}, \varepsilon_p, \ldots)$$

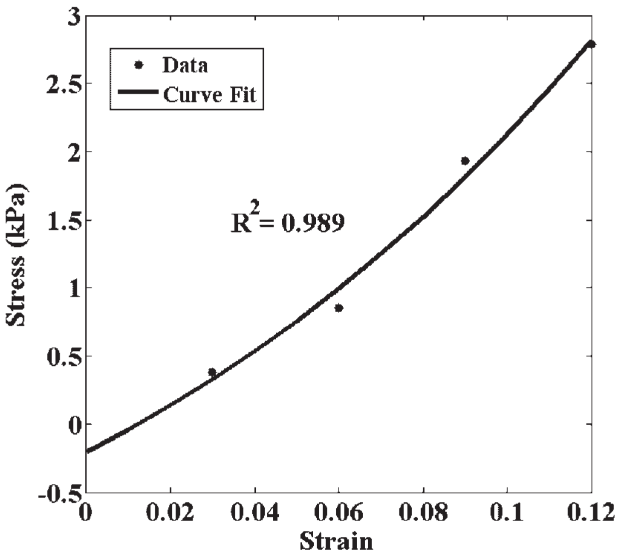
Elasticity -> $\sigma = \sigma(\varepsilon)$

- Linear
- **Non-linear**

There is often a confusion between non-linear elastic behaviour and large deformation. While in general, a material submitted to a large deformation will display a non-linear stress-strain relationship, we can find materials presenting this non-linear behaviour already at low strain or inversely some materials may present a linear elastic behaviour at high strain.

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

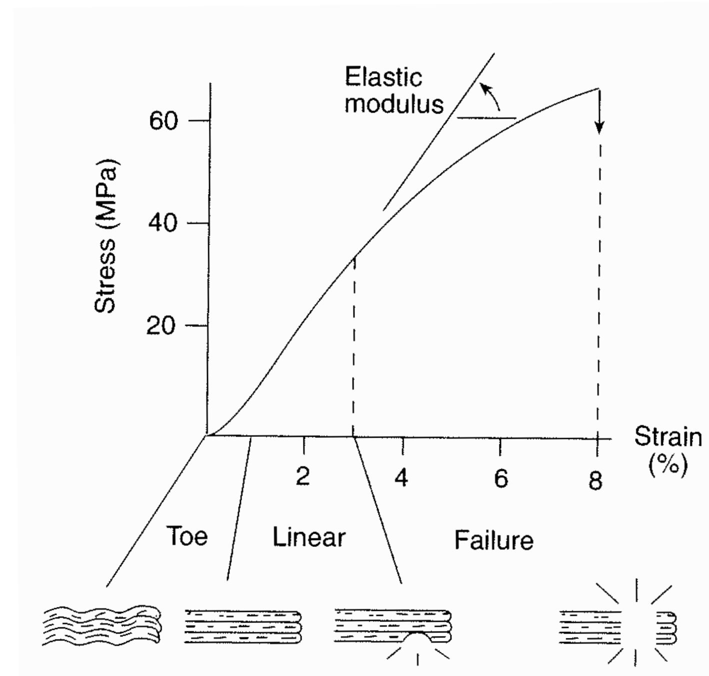




source: Helena and Hull, JOR, 2008

The unconfined compressive tests on meniscus showed a behaviour which deviates from a linear relationship between the stress and the strain. 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.

As well, the ligaments which work under traction, show a non-linear tensile behaviour



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).
- the failure region where progressive failure of the collagen fibres takes place.

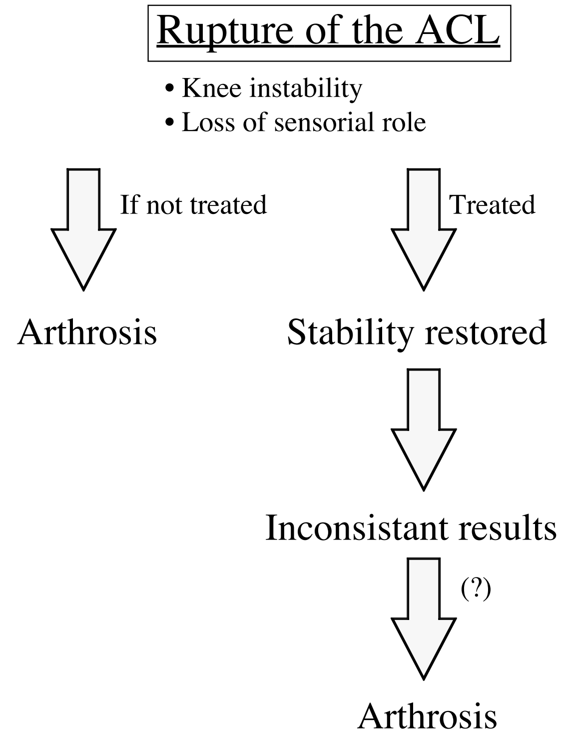
The quantification of the Young's modulus in the linear range of the stress-strain curve gives the approximate value of 300 MPa.

Soft tissues biomechanics represent then a challenge as these tissues have usually a non-linear mechanical behaviour

As a background, ACL rupture is frequent in the young and active population

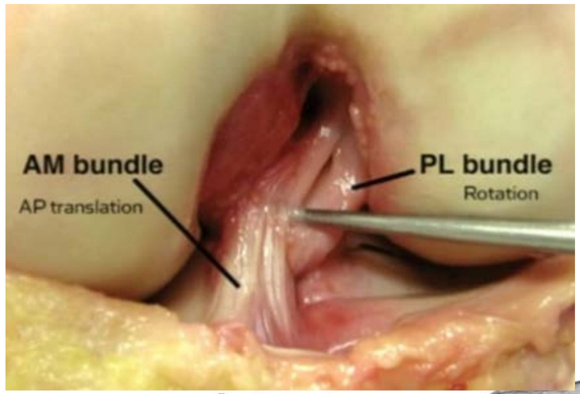
The choice of evaluating the biomechanical properties of the anterior cruciate ligament (ACL) is motivated by the high rate of ruptures for this ligament. As can be seen in many sports, the rupture of this ligament is very common. The video showing an ACL rupture of a ski champion (P. Zurbriggen) does not highlight a clear reason of its rupture. A biomechanical analysis may help to understand what did happen.

The choice of the treatment is not clearly defined



There are mainly two therapeutical approaches following the ACL rupture: surgical (treated) or conservative (not treated). The difference for the long term results is not so clear.

There are several surgical approaches for the treatment



Techniques

- Over-the-top, Macintosh
- Simple (a), double (b)
- Standard, arthroscopy
- Suture anchor

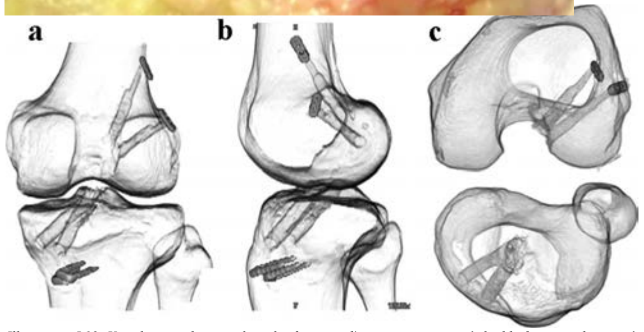
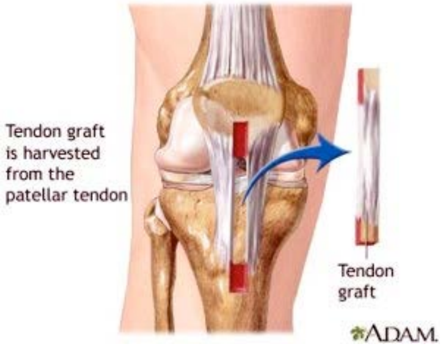


Illustration I 12: Visualisation des tunnels et des fixations d'une reconstruction à double faisceau obtenues à partir de résultats de tomographie 3D. (a) vue postérieure (b) vue sagittale (c) vue dans le plan transversal.

arthrex.com

The choice of the different surgical approaches are not always based on scientific evidences.

The type of grafts and the rehabilitation programs are also diverse



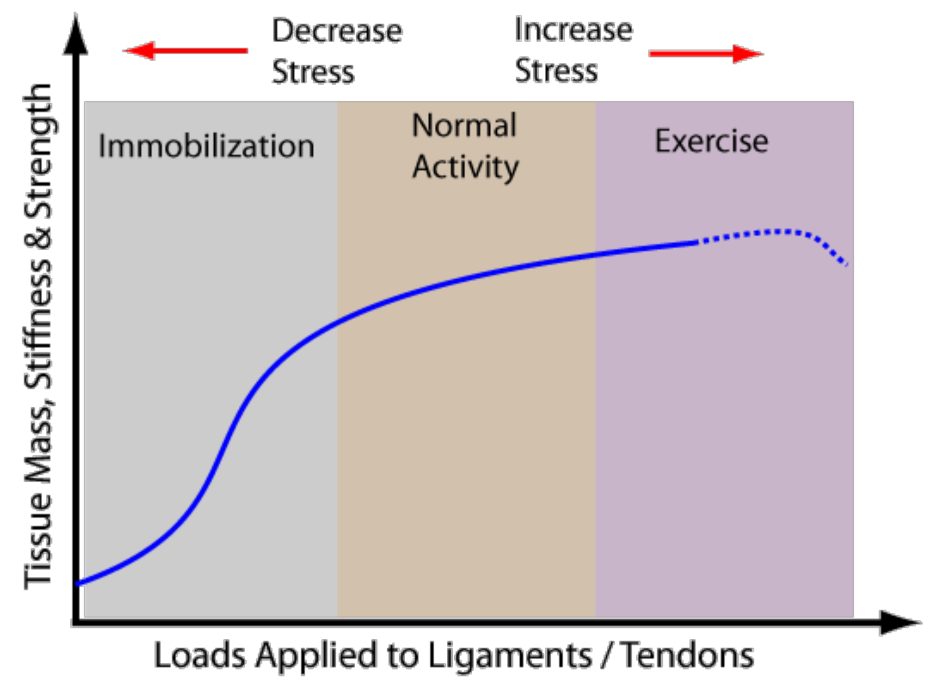
Type of grafts

- Auto, allo or artificial grafts
- Patellar tendon, semi-tendinous

Rehabilitation

- Rapid mobility, rest
- Partial, complete mobility
- Use of brace, tape

Soft tissue mechanical remodeling



Adapted from: Woo 1997 J Biom, 30:431-439.

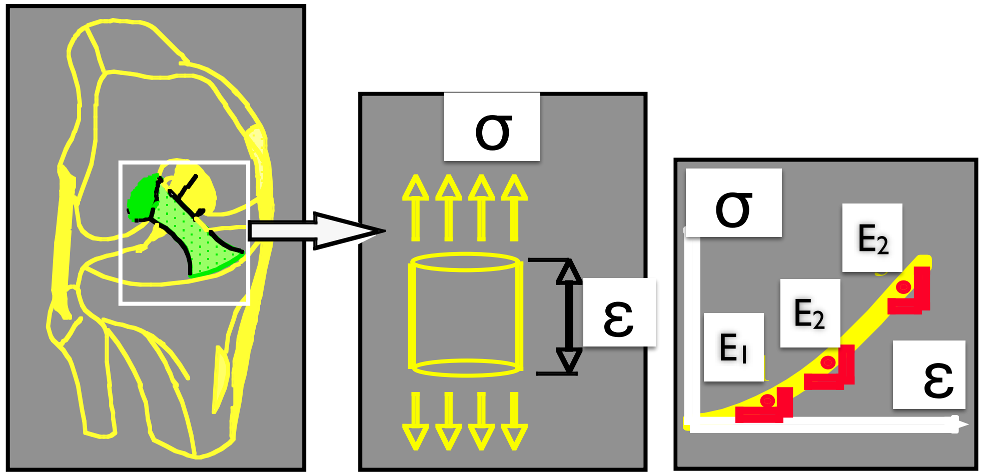
The exercise effect on ligament healing and strength can be easily seen by looking at the historical change in the treatment of ACL injuries. In the 1970’s and early 1980’s when an individual received an ACL injury that required surgery the individual would be placed in a cast for up to 8 weeks. As outlined above immobilisation has adverse effects on the strength and stiffness of ligaments. Thus when a football player tore an ACL in the early season it would take at least one year before the player was safely able to return to play. Today, ACL injuries are treated very differently. First the knee is not placed in a cast, second exercise is used even before the individual leaves the hospital to begin rehabilitating the injured joint. As a result of using exercise, athletes can now fully recover within 3 – 4 months.

A biomechanical description of the ligament is then useful for diverse reasons

- Mechanical role of the ligament
- Kinematics of the knee
- Global model of the knee
- Improvement of surgical technique
- Input for a biological description

There is then no doubt that a biomechanical analysis of the ligament may help to propose optimal solutions, based on scientific facts and not only on empirical approaches. However, we have to realise that even with a scientific approach, it is not always easy to evaluate the impact of a surgical technique as one of the key factor, the surgeon, cannot be modelled :-)

We want to perform mechanical tests on a ligament to obtain a "stress-strain" curve



Interested by the ligament mechanical behaviour, we need to "isolate" it from its natural environment. Then, mechanical tests can be performed.

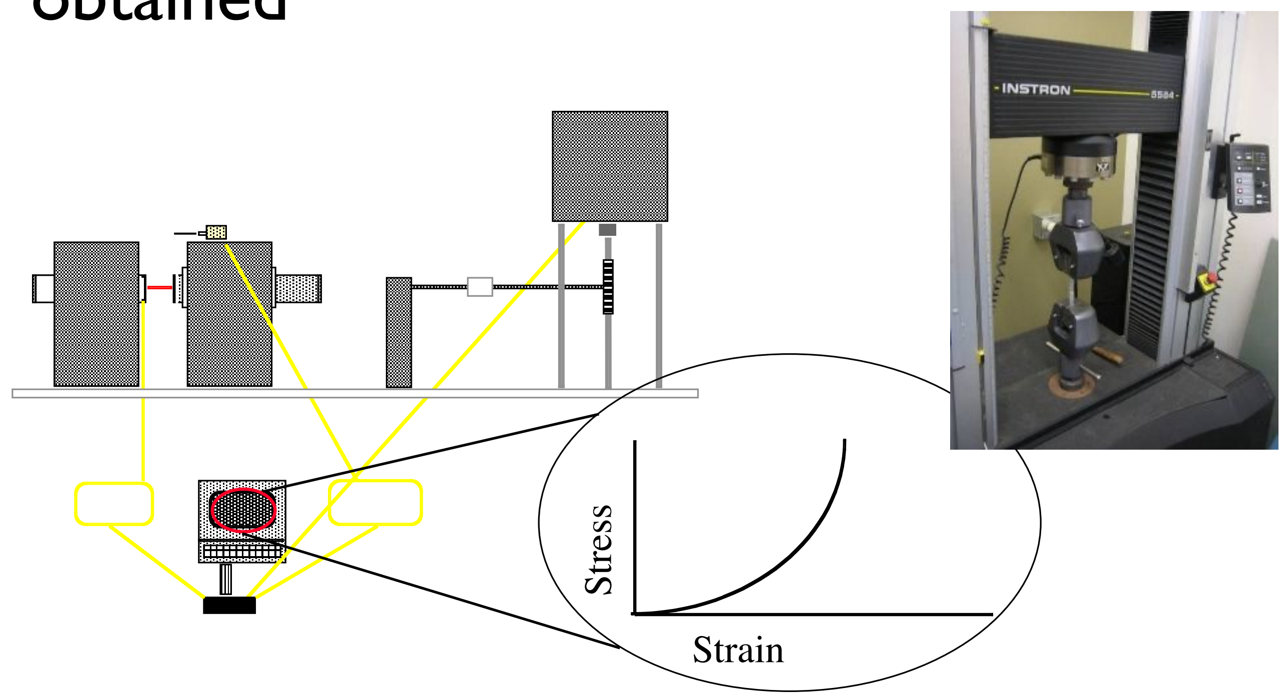
We first have to evaluate the parameters which may influence the stress-strain curves

- age
- sex
- temperature
- hydration
- conservation mode
- orientation
- ...

EM image highlighting the importance of the specimen orientation before performing a biomechanical test

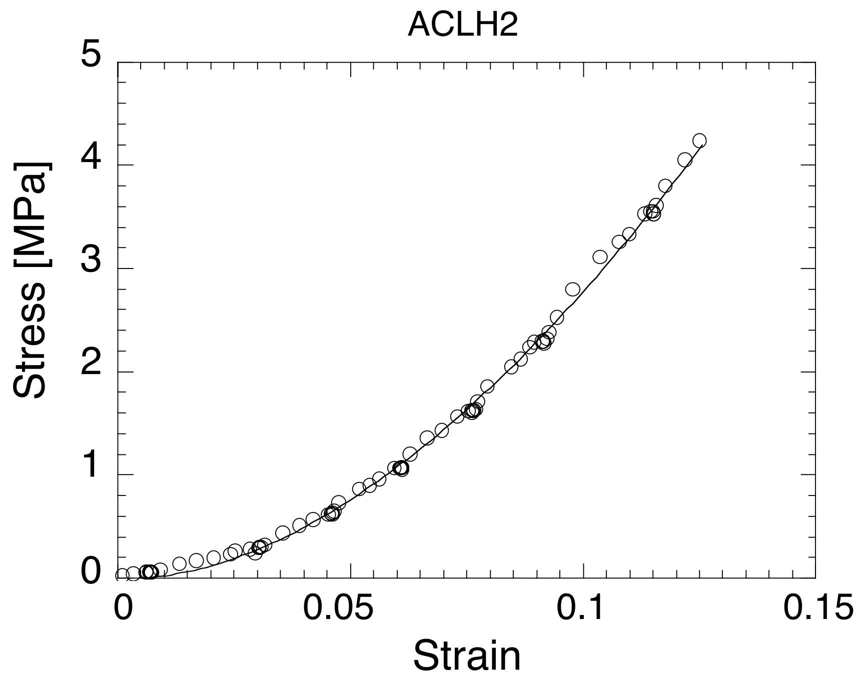
By definition, biomechanics focuses on biological samples. We need then to be aware that, unlike “usual” mechanics, there are many parameters that we cannot control. In order to decrease the variance of the results, it would be advantageous to have an “homogeneous” sample population.

Stress-strain curves are experimentally obtained



A mechanical test machine is used to obtained the stress-strain curves of the ligament. To minimise the effect of environmental parameters, the tests are performed under a controlled environment (37°C, 100% humidity).

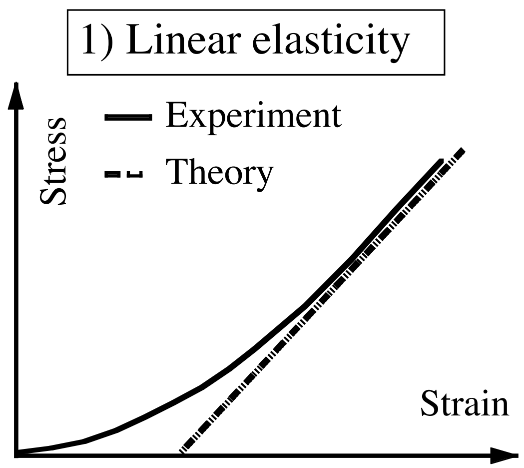
Experimental stress-strain curve of a human ACL specimen



Identification theory-experiment

1) Linear elasticity
2) Non-linear elasticity

=> $\sigma = \sigma(\varepsilon)$



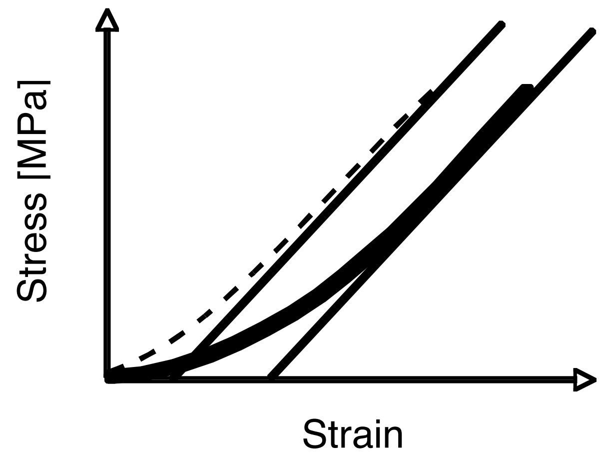
Elastic modulus: one figure (Young modulus)

Human PCL:

- Butler, 1986: 345 ± 107 MPa
- Race, 1994: 248 ± 119 MPa

The experimental stress-strain curve being now obtained, there are several ways to analyse them. In the literature, the mechanical behaviour of the ligament is often considered as linear elastic. There are several limitations to this approach.

The linear elastic description is restrictive



Patellar tendon
Young modulus

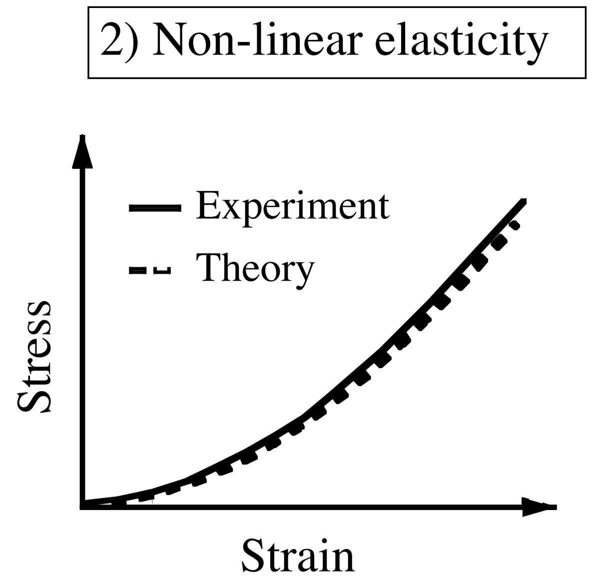
Dog	Human
360 MPa	337 MPa
(Burks, 1990)	(Flahiff, 1994)

curve 1 ≠ curve 2

Young modulus 1 = Young modulus 2

As the toe region (first part of the curve) plays an important biomechanical role in soft tissue, the linear elastic description will not allow to discriminate between different stress-strain curves!

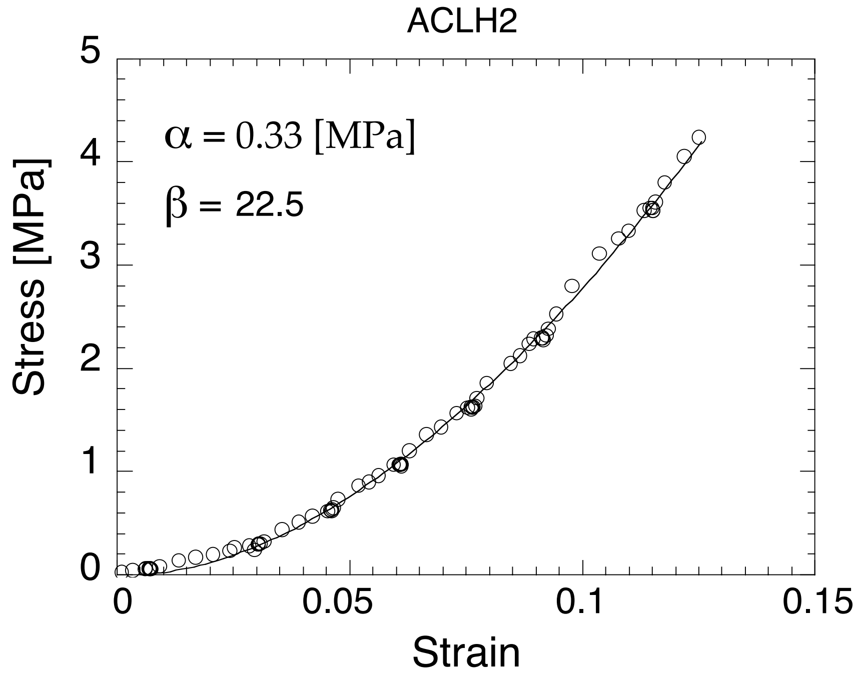
The non-linear elastic description allows to describe the entire stress-strain curve



Elastic modulus:
mathematical function

If we want to take into account also the toe region, then the description becomes non-linear as the elastic modulus is different at each point on the stress-strain curve.

The stress-strain curve is described through an exponential function



$$\sigma = \alpha(e^{\beta\varepsilon} - 1)$$

source: D. Pioletti, Europ J Mechanics, 2000

The mathematical function describing the best the experimental stress-strain curve is an exponential having 2 parameters: α and β (why only two parameters?).

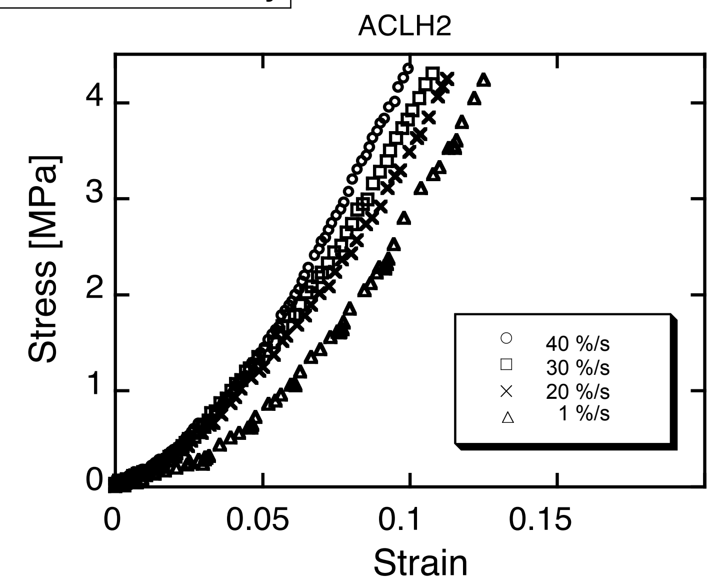
Traction tests performed at different strain rates highlight the viscoelastic behaviour of the ligament

1) Linear elasticity
2) Non-linear elasticity

} Not enough to capture the observed ligament behaviour

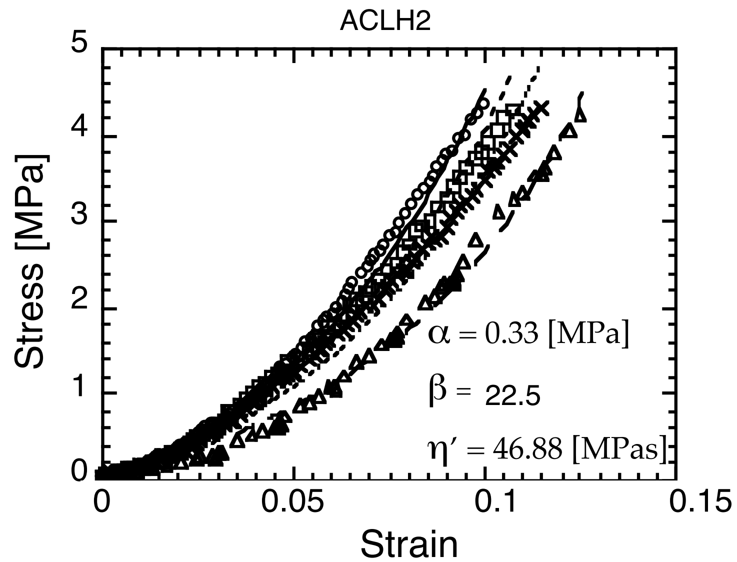
→ 3) Non-linear viscoelasticity

$$\sigma = \sigma(\varepsilon, \dot{\varepsilon})$$



Indeed, if we performed traction tests on the ligament at different strain rates, we obtained different stress-strain curves. This is typical to a material presenting a viscoelastic behaviour. Strain rate effect should then be incorporated in a theoretical description either implicitly by identifying the elastic parameters in the different stress-strain curves obtained at different strain rates or explicitly by taking into account of the variable “strain rate” in the constitutive law.
The non-linear viscoelastic description allows us to describe the entire stress-strain curve + strain rate effect.

The viscous part is determined on the curves obtained at different strain rates



$$\sigma = \alpha(e^{\beta\varepsilon} - 1) + \eta'\dot{\varepsilon}$$

Once we have determined the non-linear elastic parameters from the curve obtained with the lowest elongation rate (we call this curve by definition the elastic curve), we can further proceed with the viscous ones. In the particular example here, we consider that our viscoelastic constitutive law corresponds to the addition of two elements (the elastic and the viscous) in parallel. Then we determine the value of the viscous parameter so that our constitutive law can nicely describe the experimental stress-strain curves obtained at different strain rates.

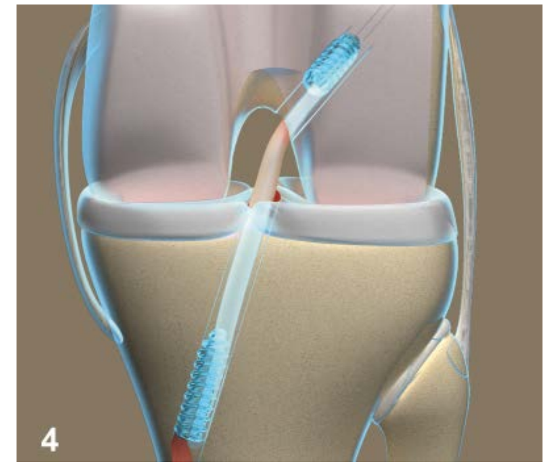
You can now propose a scenario explaining the rupture of Zurbriggen ACL

Once the rupture of the ligament is confirmed, it may be necessary to repair it

-> ligamentoplasty

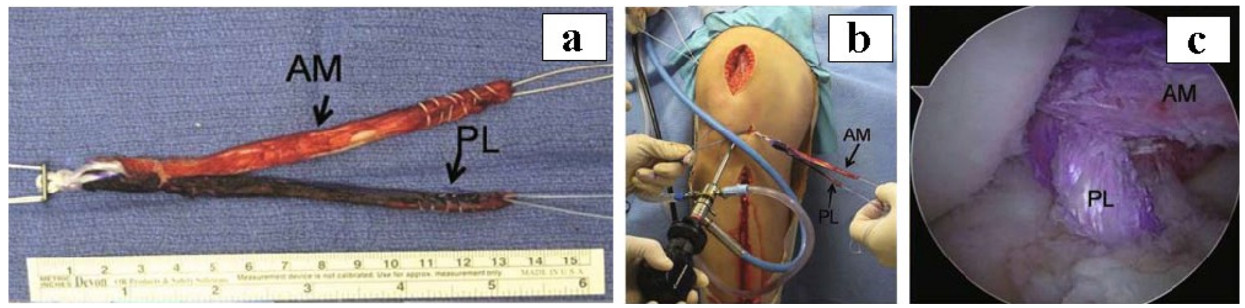
One-bundle graft

Double-bundle graft



Depending on the physical activity of the patient, a reconstruction of the injured ligament (ligamentoplasty) may be necessary. As mentioned above, the surgeon is left with different options for this surgery, one of which concerns the type of graft used. In particular, he could decide to use a one or a double-bundle graft. The double-bundle graft is supposed to better mimic the natural anatomy of the anterior cruciate ligament which presents a double-bundle structure. However, an objective comparison of the performance of these two techniques is difficult to achieve. A biomechanical analysis may help.

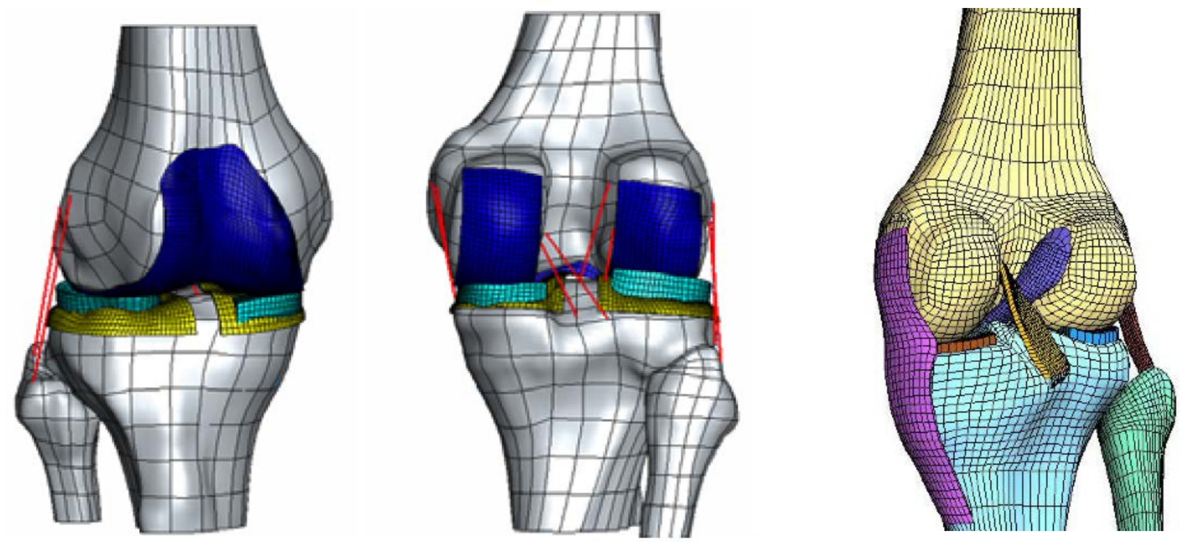
The surgery can be performed through an arthroscopic approach



Kato, 2010

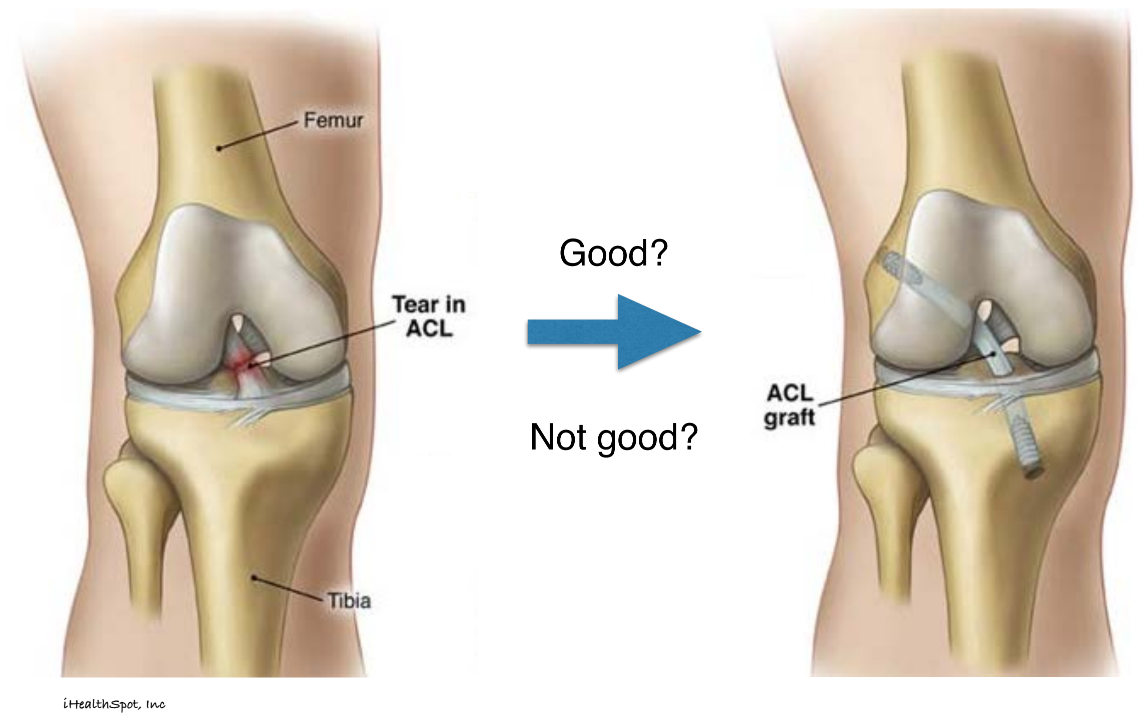
The success of the ligamentoplasty is obviously also highly related to the surgeon skills. It is then important to understand also the surgical reality so that a better interpretation of the biomechanical analysis can be obtained.

To evaluate the outcome of a complicated biomechanical situation, a numerical analysis is often used



These are typical representations of Finite Element Model (FEM) for a knee joint. This tool can then be used to evaluate the biomechanical performance for example of a ligamentoplasty using a single or a double bundle graft. However, before this, several steps are necessary in the construction of a FE model. And in particular, the definition of the evaluated output is fundamental.

How do we evaluate the success of a ligamentoplasty in general and in particular from a biomechanical point of view?



The definition of a successful orthopedic surgery is not so obvious. Any suggestions?
At least from a biomechanical point of view, we may evaluate if the contact force between the different structures of the joint is restored to its initial value.

Finite Element Analysis

5 steps are necessary

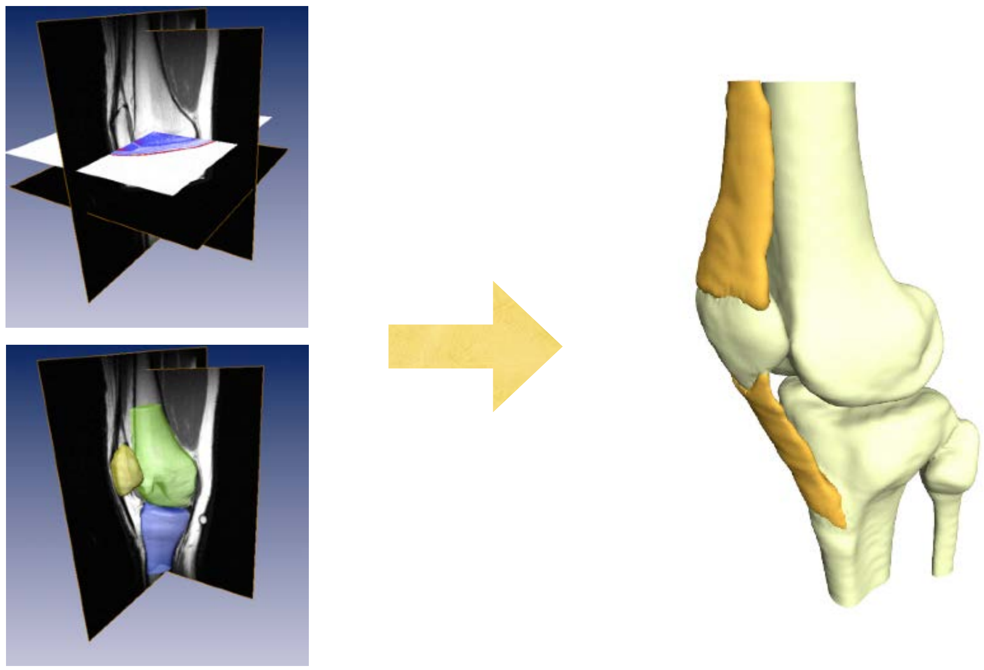
1. Geometry (obtained by MRI or CT)
2. Constitutive laws (mechanical behaviour)
3. Boundary conditions (force or displacement)
4. Meshing
5. Resolution of conservation laws (numerical solver)

-> evaluation of the outcome chosen parameter
(in our case, the contact force)

As the geometry, material properties and the boundary conditions of the problem of interest in the musculoskeletal system are usually complex, a numerical approach is needed to solve the conservation of the linear momentum and to obtain information on stress and strain in the studied tissues or implants. The point 1. is concerned with the domain of the study. The points 2. and 3. describe the physics of the problem. The points 4. and 5. deal with numerical considerations of the problem. Then, only after the completion of these 5 steps, we can get an answer to the evaluation of the outcome.

Finite Element Analysis

1. Geometry (obtained by MRI and/or CT)



Images of the different tissues composing the knee joint cannot be obtained with a single imaging technique. For the hard tissue (essentially bone), an x-ray (CT scan) is necessary to obtain a good spatial resolution while for the soft tissues (ligament, tendon, cartilage and meniscus) a MRI must be used (as these tissues are transparent in an x-ray image). The two types of image obtained with the different modalities have then to be fused to form only one image which could be used as geometry input in our FEM analysis.

Finite Element Analysis

2. Constitutive laws (mechanical behavior)

Linear

Bone -> linear elastic isotropic -> $\boldsymbol{\sigma} = \lambda(\mathrm{tr}\boldsymbol{\varepsilon})\mathbf{I} + 2\mu\boldsymbol{\varepsilon}$ -> λ_{bone}, μ_{bone}

Cartilage -> linear elastic isotropic -> $\boldsymbol{\sigma} = \lambda(\mathrm{tr}\boldsymbol{\varepsilon})\mathbf{I} + 2\mu\boldsymbol{\varepsilon}$ -> λ_{cart}, μ_{cart}

Meniscus -> linear elastic isotropic -> $\boldsymbol{\sigma} = \lambda(\mathrm{tr}\boldsymbol{\varepsilon})\mathbf{I} + 2\mu\boldsymbol{\varepsilon}$ -> λ_{menis}, μ_{menis}

Non-linear

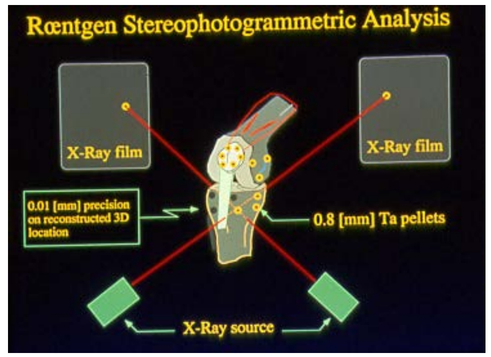
Ligament -> non-linear elastic isotropic -> $\sigma = \alpha(e^{\beta\varepsilon} - 1)$ -> α_{lig}, β_{lig}

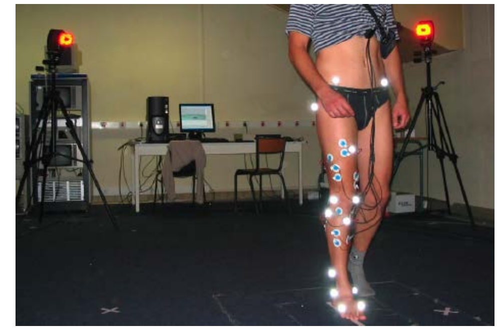
Graft -> non-linear elastic isotropic -> $\sigma = \alpha(e^{\beta\varepsilon} - 1)$ -> α_{graft}, β_{graft}

As a first approximation, we may consider bone as a linear elastic isotropic material. The value of the two Lamé parameters for bone have then to be considered. The same approach is followed for the cartilage and the meniscus. For the ligament and graft, we consider them as non-linear elastic isotropic materials. The corresponding values of the two parameters for both tissues have to be considered.

Finite Element Analysis

3. Boundary conditions (force or displacement)





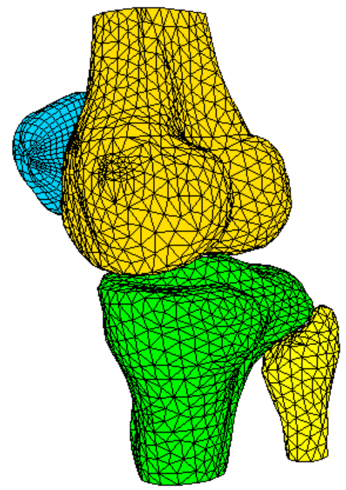
source: Analyse du mouvement, Prof. L. Cheze

source: Prof.. K. Aminian (LMAM/EPFL)

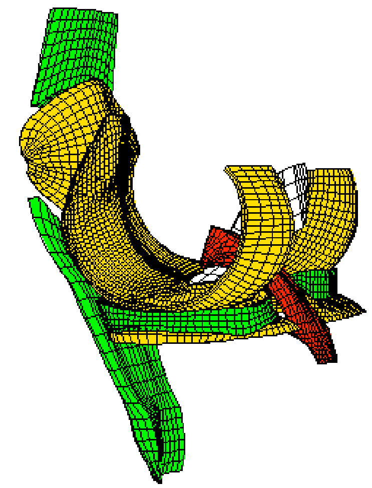
The knee kinematics can be used as input (boundary conditions) for the biomechanical model. The kinematics of the knee can be obtained through different systems such as with in vitro set-up by using the RSA technique (a minimum of 3 radio-opaque pellets is placed in each segment tibia, femur, patella and an x-ray is performed at different flexion angles). The precise relative motion between each segment composing the joint can be obtained and be used as boundary conditions. In vivo knee kinematics can also be obtained by using external markers placed on the subject and tracked with several cameras or independent external sensors. If we want to use force as boundary conditions, we have to take the action of muscles in the model. This is especially difficult for various raisons: complicated geometries, soft tissues, active components, lack of precise experimental data. So muscles are often replaced in FEM model by cables transmitting a load. The application force is then reduced to a point instead of being distributed over a surface. This is probably one of the major limitations of such models.

Finite Element Analysis

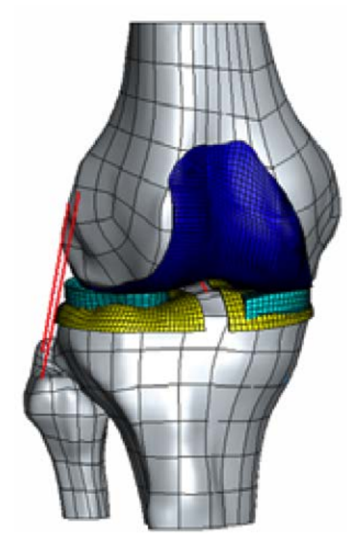
4. Meshing



Hard tissue (bone)



Soft tissues



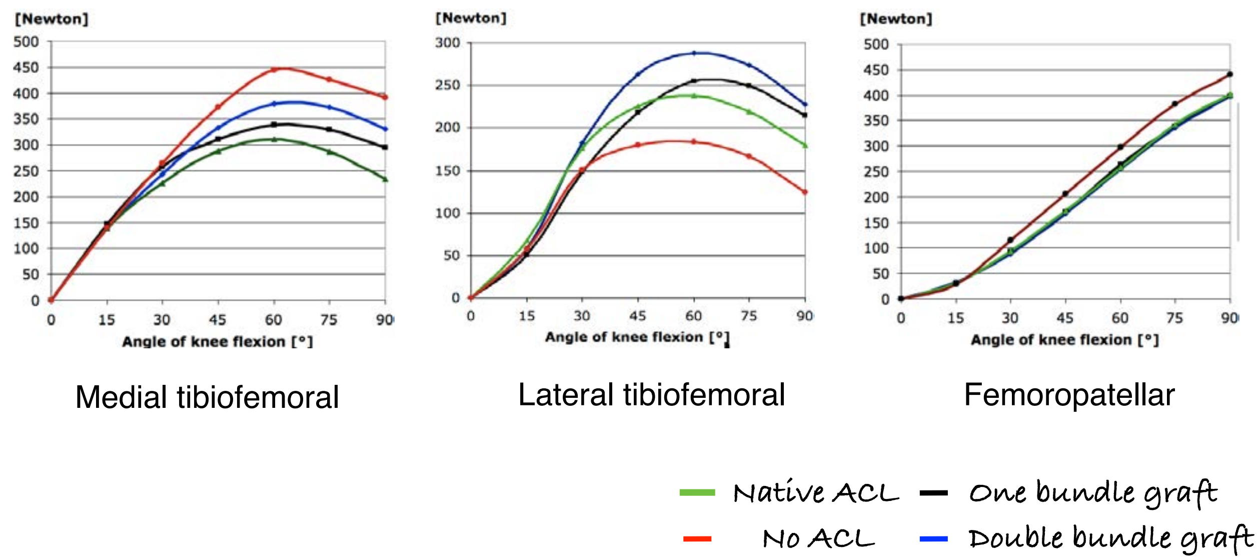
Full model

The geometries are then transformed in finite elements through the meshing process with their corresponding physical properties (constitutive laws). As the geometries are complex, the mesh generation is semi-automatic and a good mesh can be obtained only after some “empirical” experiences have been acquired. This process is time consuming and a finite element model of a knee is still challenging.

Finite Element Analysis

5. Resolution of conservation laws (numerical solver)

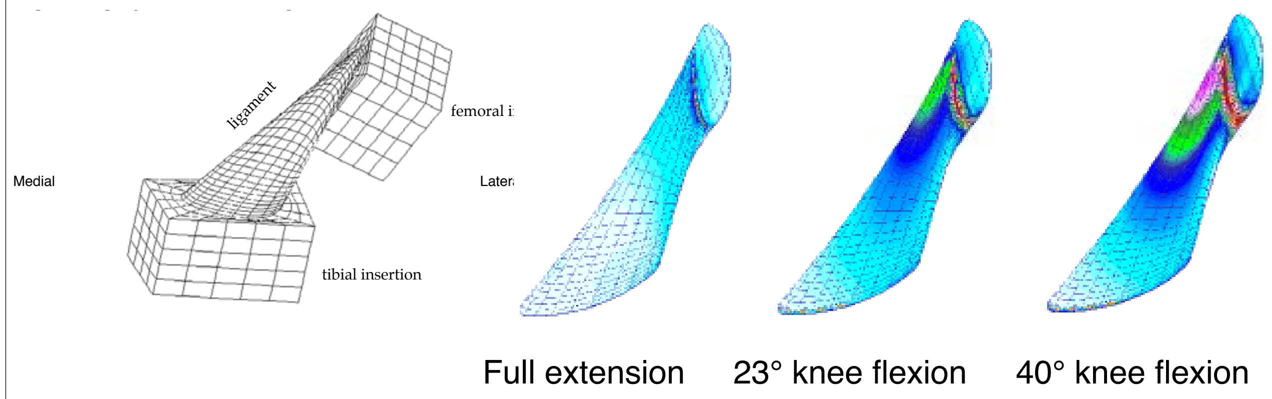
Contact force in the different knee compartment



The effect of a surgical procedure (reconstruction of the ACL) can then be finally evaluated with the chosen comparison outcome being the contact force. The rupture of ACL induces the highest contact force in the medial tibiofemoral compartment and the lowest contact force in the lateral tibiofemoral compartment. The one and double-bundle grafts did not restore contact force in the different compartments similarly to the “native” ACL situation. The one-bundle graft seems to induce a slightly closer contact force distribution to the native situation compared to the double-bundle situation. As the one-bundle graft technique is easier from a surgical point of view, it may then be favoured.

Biomechanical analysis can also help us to understand the pathophysiology of ruptured tissue such as in ACL

Neutral knee rotation



source: Viscoelastic properties of soft tissues, D.P. Pioletti, PhD thesis EPFL, 1997

During increase knee flexion, the model shows that a stress concentration may occur close to the femoral insertion of the ligament. This observation is correlated to the clinical situation where ACL usually tears off in this area.

One important aspect of biomechanics is then to characterise tissues through constitutive laws

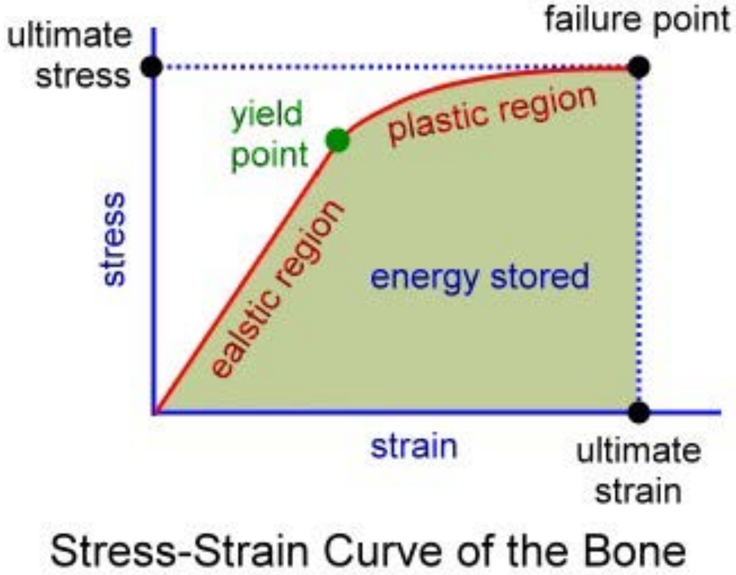
$$\rho \frac{d\boldsymbol{v}}{dt} = div\ \boldsymbol{\sigma} + \rho \boldsymbol{b}$$

$$\sigma = \sigma(\varepsilon, \dot{\varepsilon}, \varepsilon_p, \ldots)$$

Elasticity -> $\sigma = \sigma(\varepsilon)$ → Linear / Non-linear

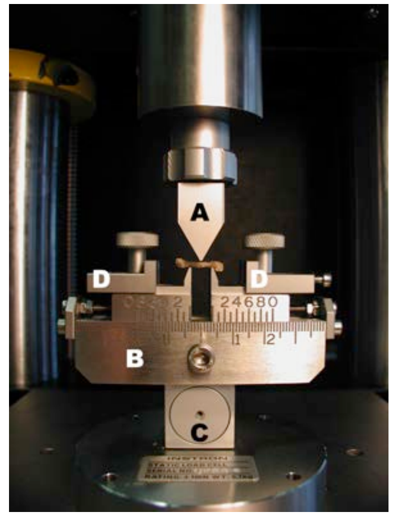
Beside the choice of the material symmetry used for the description of a material, the consideration of its mechanical behaviour is then at least as important. One of these mechanical behaviours can be to consider or not non-linear elastic behaviour.

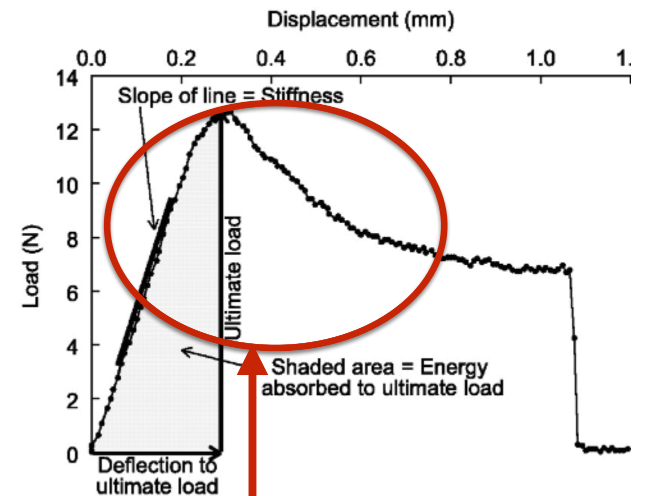
Elasticity represents only a limited part of the bone or tissue material behaviour



The physiological range of bone mechanical function is in the elastic region. If we are interested in pathological situations, a different mechanical description has to be accounted for, where plasticity and fracture mechanics become important. In particular, it would be interesting to link the fracture risk to the bone density/architecture in order to determine if a patient needs to be treated with anti-resorptive drug such as the bisphosphonates for example.

Bone damage -> a non-elastic behaviour is observed



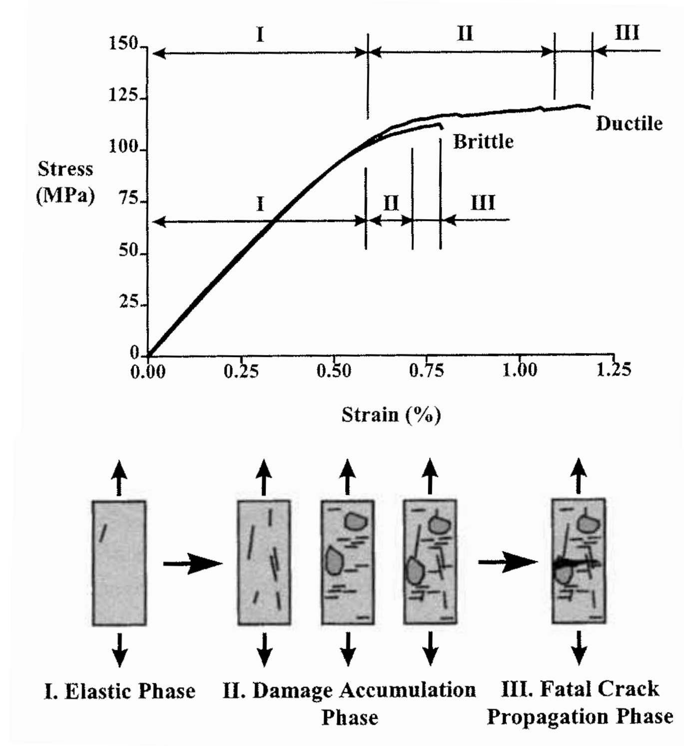


source: American Journal of Physiology 2007 Vol. 293 no. 5, R2015-R2026

~~$\sigma_{33} = E\varepsilon_{33}$~~

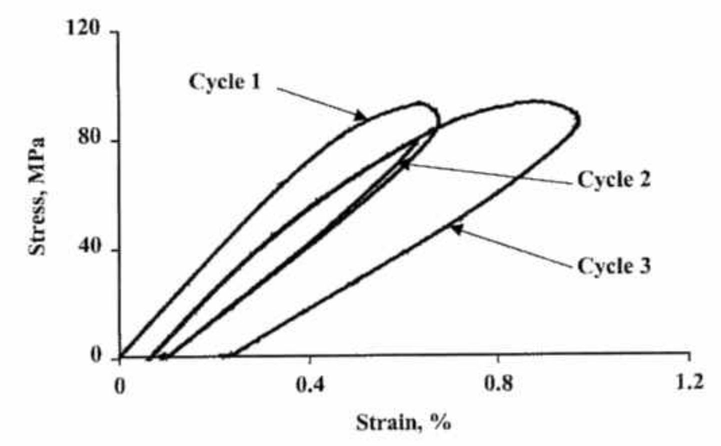
If a linear elastic model is chosen to describe the bone behaviour, this description will not be adapted to characterise for example the decrease behaviour of bone being damaged by successive mechanical loadings. For this, a specific model allowing to take into account the damage phenomenon should be used.

Bone damage -> a non-elastic behaviour is observed



If we closely look at a stress-strain curve outside the range of elasticity, we can observed 3 domains (which have a different range depending if the material is brittle or ductile) related to 3 different stages of damage.

Successive (over)loadings decrease the bone mechanical properties by generating more damages



~~$\sigma_{33} = E\varepsilon_{33}$~~ → $\sigma_{33} = E(1\text{-}D)\varepsilon_{33}$

D: damage parameter

An effective stress-strain relationship can be written with D as a new damage parameter. D is often interpreted as the ratio of the damaged area (which no longer carries the load) to the total area. This corresponds to a material with an effective modulus $E_{effective} = E(1-D)$ (if D = 0, no damage; if D = 1 material ruptures).
This example highlights that the choice of the constitutive law depends on different factors such as first the nature of the material, the details of information needed, or the regime under which the material mechanically behaves. There is then no correct or incorrect constitutive law, but a constitutive law with a specific range of validity.

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