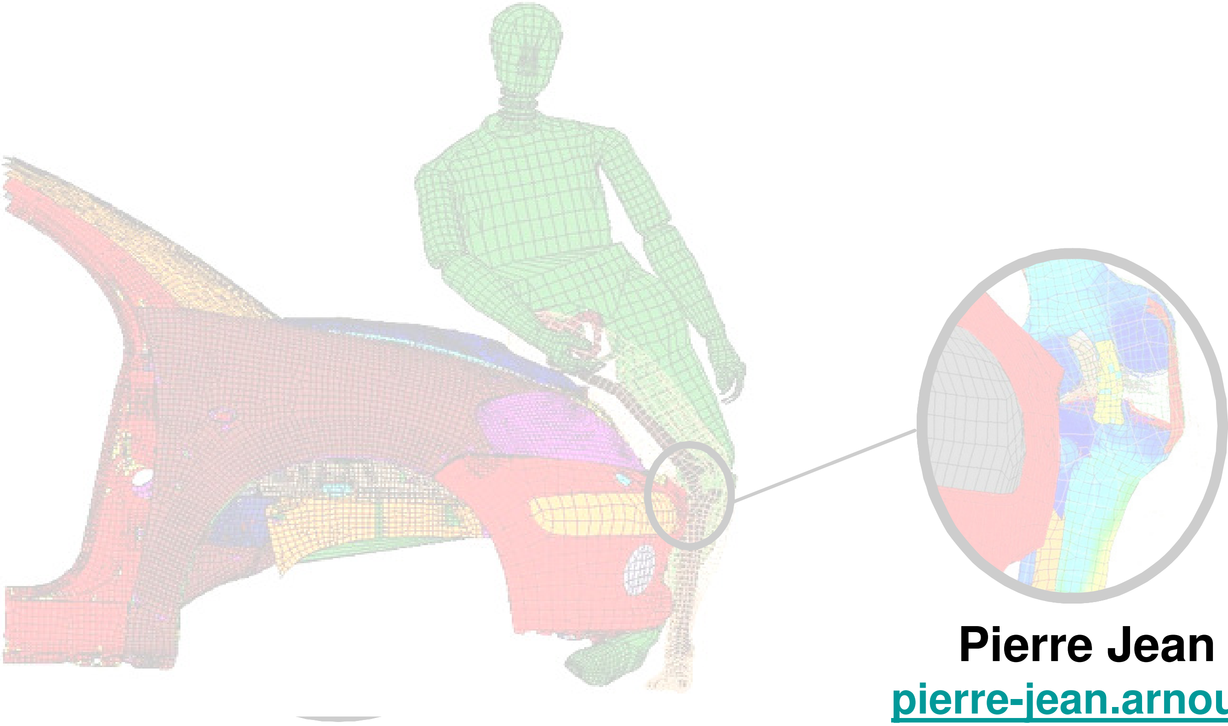
About tissue mechanics and human modeling for trauma understanding



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UMR T 24, INRETS - UNIVERSITE DE LA MEDITERRANEE

Road Safety in EU : a first order societal issue

- > 40.000 lethal injuries
- ~ 1.700.000 injuries
- First death causation < 45 years old
- Cost : 160 Milliard € : (2% EU PIB)

→ A real epidemic

Rapport DG-Tren, commission européenne (2000, 2004, 2008)

An ounce of prevention is worth a pound of cure

« Mieux vaut prévenir que guérir »

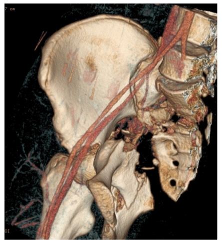
From real crash, trauma understanding…

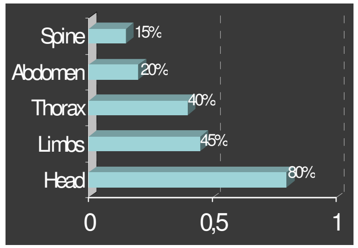
Accident analysis — Clinical data — Epidemology

several minutes — 0,001 s< t < 2 s — *time*

Accident occurrence,
Initial conditions

INRETS-MA Salon de Provence





Trauma identification,
Injury severity,
Surgery,
Consequences

Marseille CHU-Nord Trauma centre (D. Chaumoitre)

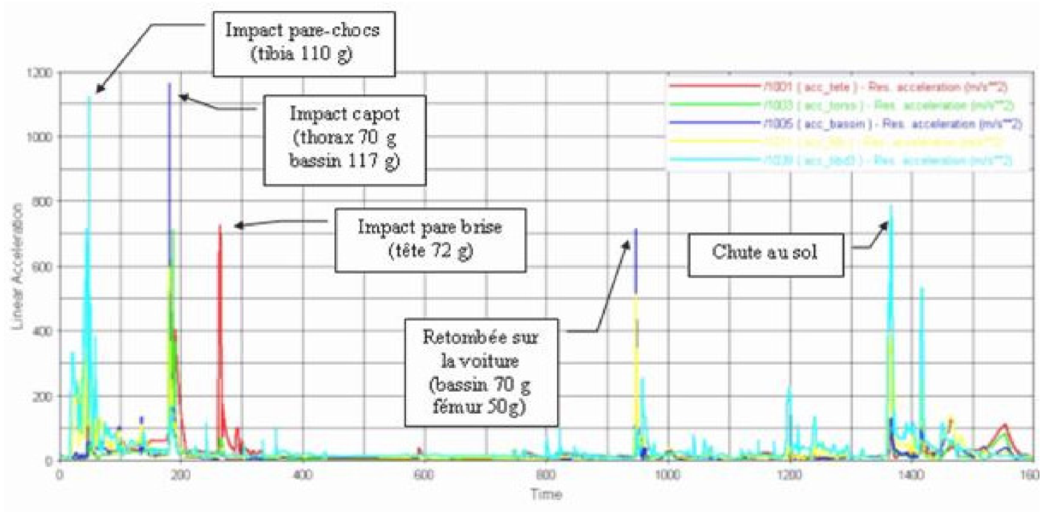
Impact biomechanics for Trauma understanding

Human body structures { *Dynamic loading* / *Damage and failure* }

Experiments & real crash conditions

Pedestrian impact with PMHS

From 1st impact to ground fall



36km/h pedestrian impact (Masson - LBA)

A succession of local impacts with dedicated sub-injuries

Many injuries {
Internal organs and vecels
Bone structures
Joints components
} Different neighboring structures

Rigidity

Mobility

Research questions… and research skills

Which chronology for injuries ?

Which injury mechanisms ?

What about human tolerance ?

Which injury criteria?

Numerical simulation of Human body

A way to investigate virtual trauma

… to improve safety systems

The work plan :

I. Mechanical properties of tissues : *A first step before simulation*

→ **Hard Tissues / Fibrous structures / Soft tissues**

II. On Human body modelling features

→ **Towards explicit detailed FE models**

III. Applications to virtual trauma

→ **Lower limbs, Trunk and Spine**

« après s'être fait la main sur le pied,
l'objectif est de prendre son pied sur le tronc! »
(M. Jean 2005).

I. Mechanical properties of tissues

I. Mechanical properties of living isolated structures

- The framework for tissue identifications

Mechanical identifications performed at structure levels

Dynamical loadings with time scale : from 1 to 10ms

- On difficulties to obtain experiment data

Each tissue is unique : « One shoot for identification ! »

→ *Human variability and response corridor*

Tissue conservation and experimental setups

→ *Loading conditions relevant with trauma ones*
Needs to design dedicated experiments

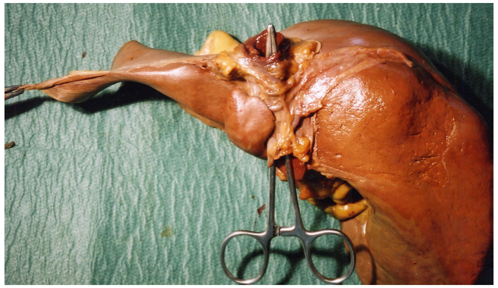
Tissue histology → *Complete damage process analysis*

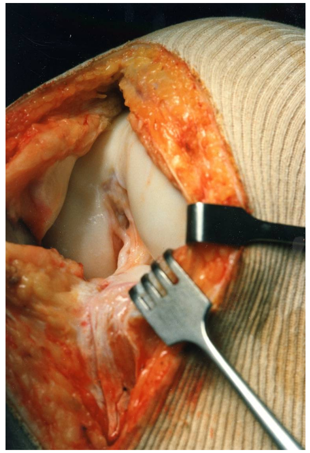
Identify tissues general properties

Model to be implemented in FE analysis

Simplified model to describe the main properties of structures

Ligaments properties identification (1/4)
General properties





Ligaments of the liver
And knee ACL injury

From anatomy to histology

Fibrous structure with a main orientation

Crimpped structure

Different shapes & dimensions

Contribution to joint stability : traction loading

Mechanical features

Anisotropy / inhomogeneity / incompressibility

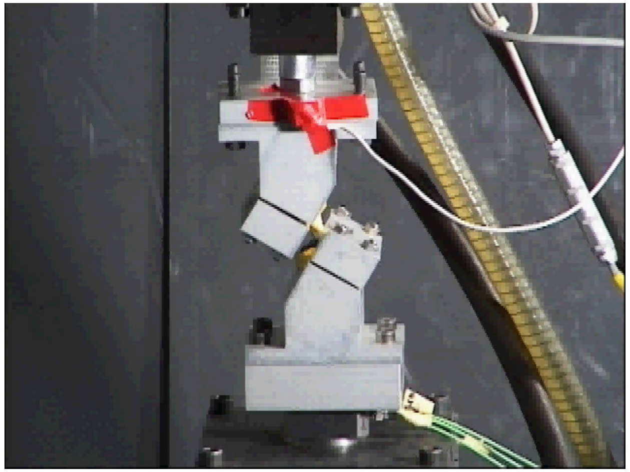
Prestress / An non homogenous strain field

Mechanical behaviour

Viscoelasticity - Non linearity – Large strain

Hyperelasticity

Ligaments properties identifications (2/4)
Experimental identification

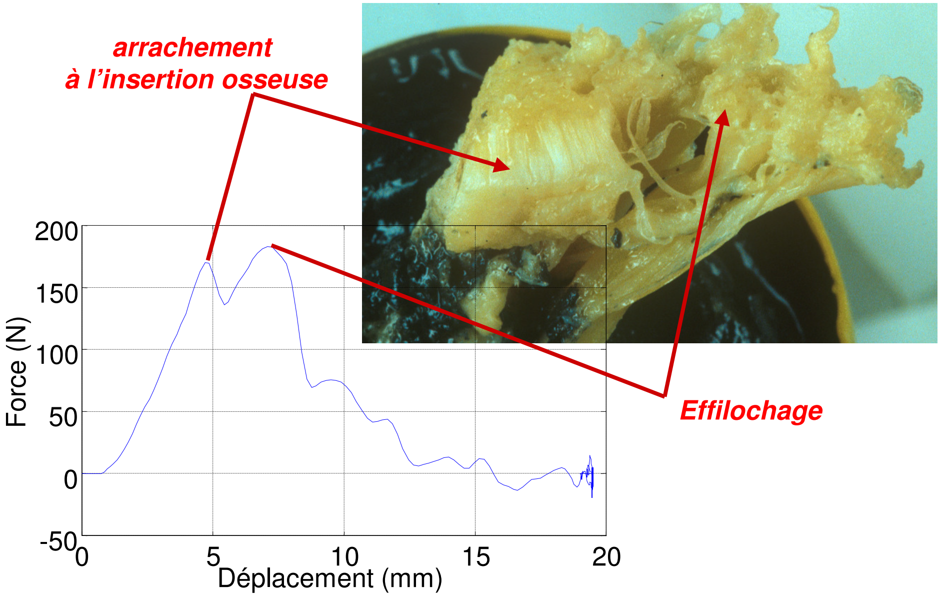


2m/s traction test on knee ligaments

32 ligaments (4 PMHS from 58 to 88 years old) under fibres axes

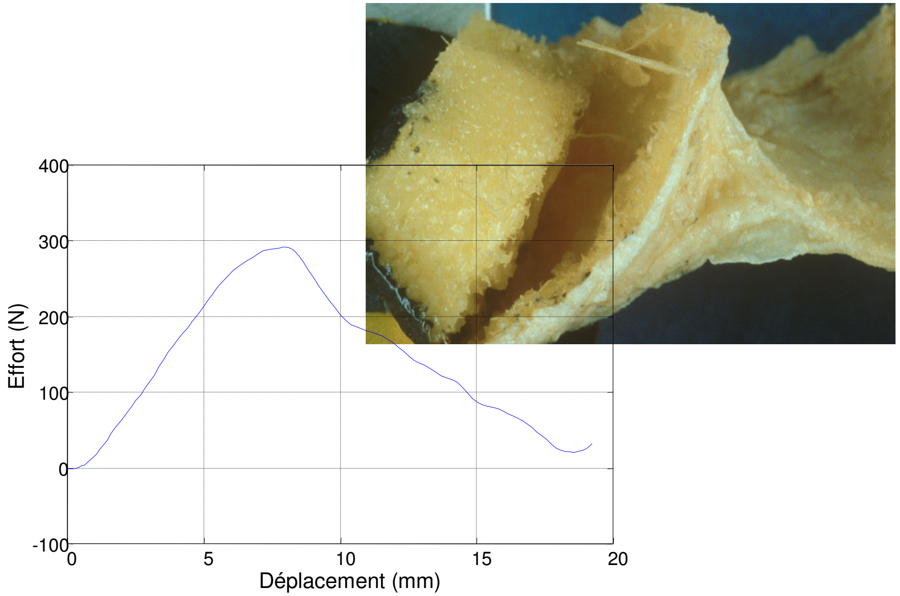
Damage and failure
- Peeling failure
- Avulsion at bone insertion
- Strong failure reproducibility

ligaments croisés



Une déformation maximale : 18 à 24%

ligaments latéraux

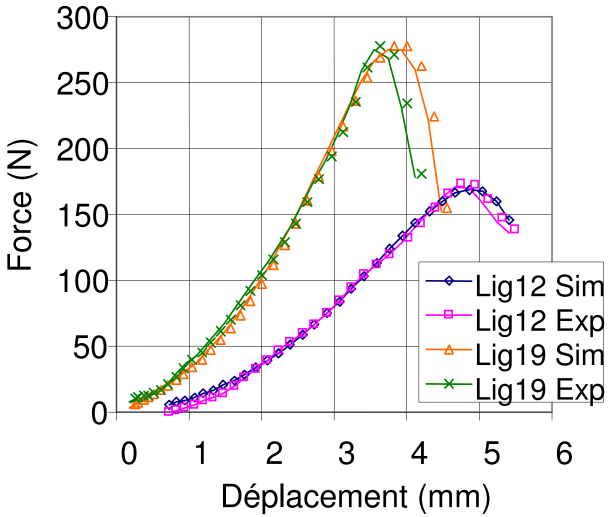


Une déformation maximale : 22 à 38%

Ligaments properties identifications (3/4)

To viscoelastic model with damage and failure

At the macroscopic level: a thermodynamic formulation



$$S = -pC^{-1} + 2(1-D)\left[\left(\frac{\partial W_e}{\partial I_1} + trC\,\frac{\partial W_e}{\partial I_2}\right)Id - \frac{\partial W_e}{\partial I_2}C + \frac{\partial W_v}{\partial \dot{C}}\right]$$

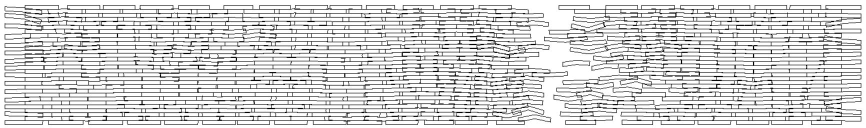
$$W_v = \frac{\eta}{4}tr\left(\dot{C}\right)^2(I_1-3) \quad W_e = \alpha\exp\left[\beta(I_1-3)\right] + \gamma(I_2-3)$$

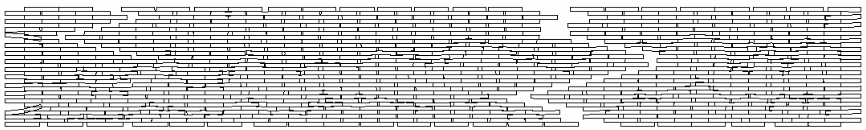
$$\dot{D} = \begin{cases} \dfrac{n(D+D_0)\dot{\lambda}\left[\alpha\beta\exp\left(\beta\left(\lambda^2+\dfrac{2}{\lambda}-3\right)\right)-\dfrac{\alpha\beta}{\lambda}\right]}{Q\sqrt[n]{D+D_0}} \\ 0 \end{cases}$$

Isotropy, homogeneity, incompressibility
Fading memory neglected

At the microscopic level : failure process evaluation on collagen fibril

Elastic brick model with Mohr-Coulomb adhesion law : **micro fibril – collagen fibril**

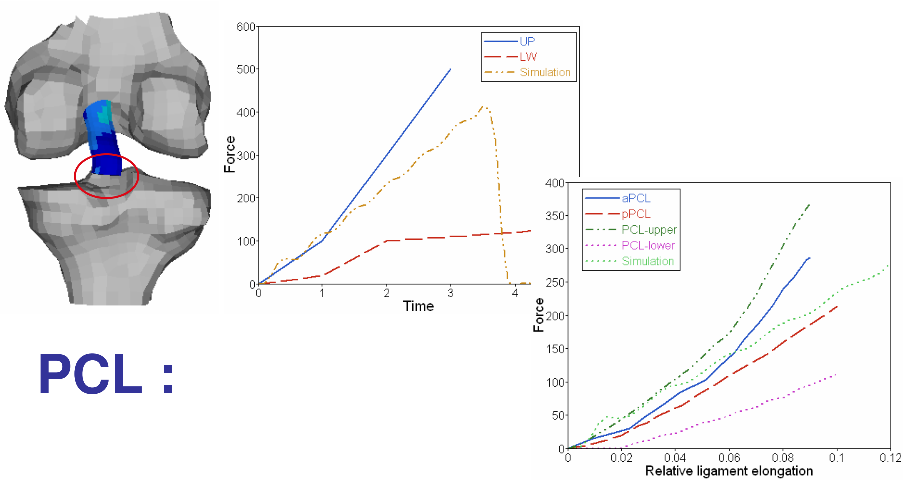




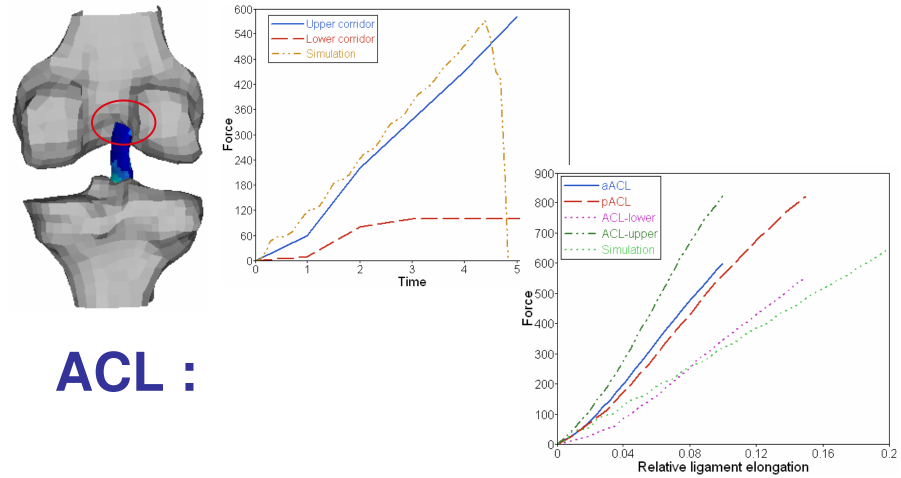
Ligaments properties (4/4)

integration & evaluation on FE model

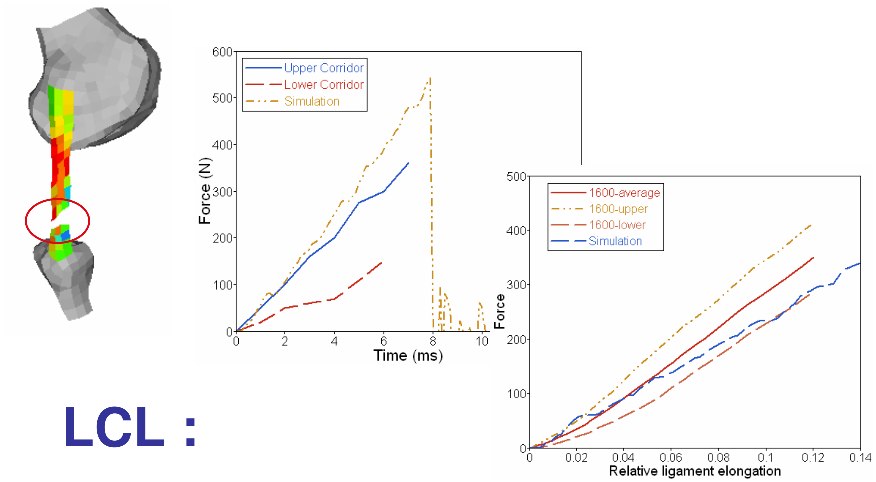
Failure : / Ultimate deformation
Kill element methods



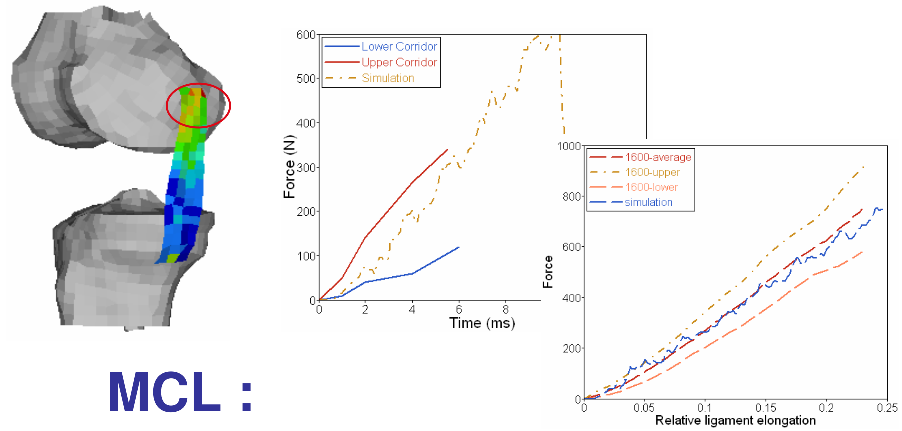
PCL :



ACL :



LCL :

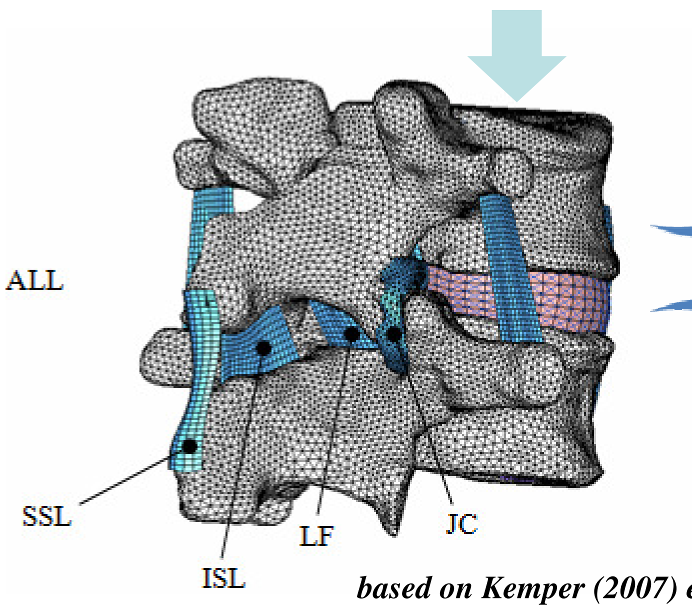


MCL :

Based on previous test (Arnoux 2002) & Dommelen 2005 data

Intervertebral disc properties modelling (1/3)

Using inverse analysis identification
Hyperelasic properties assumption



based on Kemper (2007) experiments

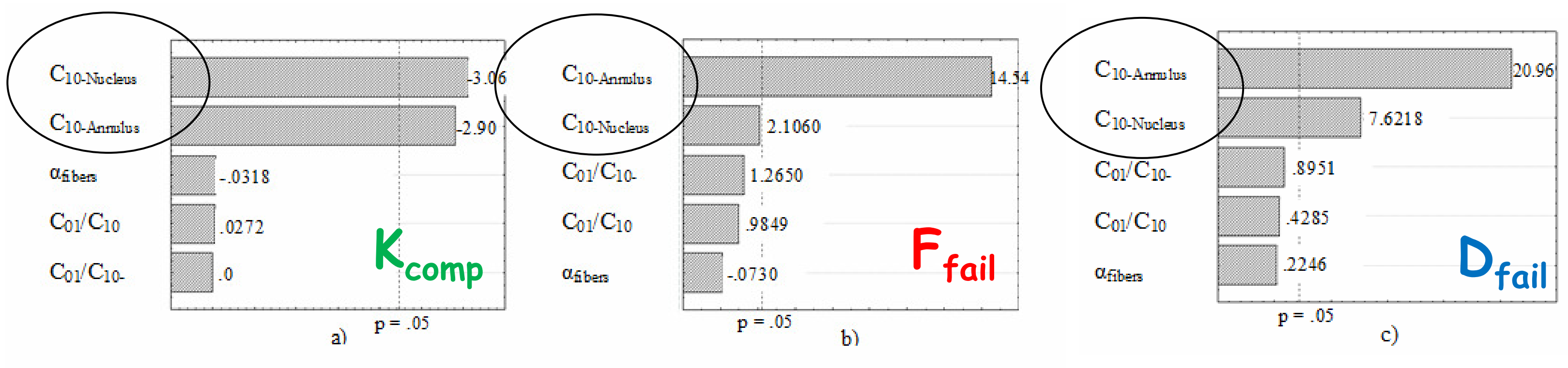
Hyperelastic material formulation (Mooney-Rivlin)

$$W = c_{10}(I_1 - 3) + c_{01}(I_2 - 3) + (J-1)^2/d_1$$

Output :

- Compressive stiffness (K_{comp})
- Failure load (F_{fail})
- Displacement to failure (D_{fail})

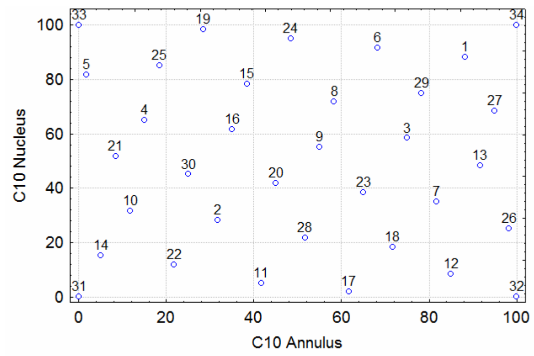
1. Evaluation of influent parameters using exploration and sensitivity analysis (Pareto)



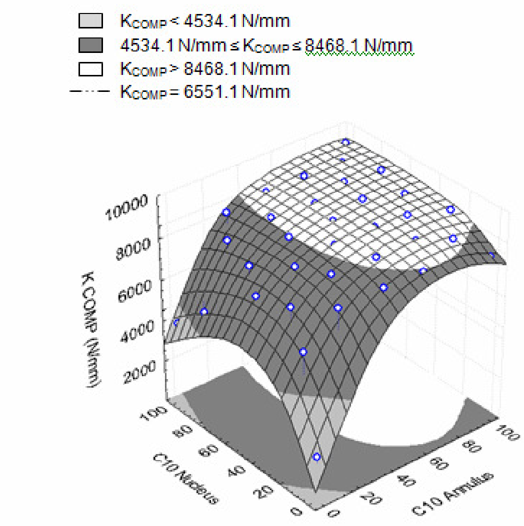
Intervertebral disc properties modelling (2/3)

Selection of 34 sets of C10-Annulus and C10-Nucleus values using a OLH algorithm

→ 34 simulations

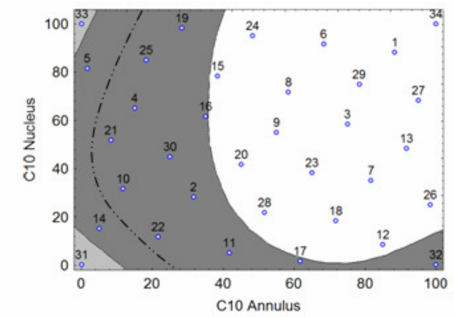


From surface regression and contour plots

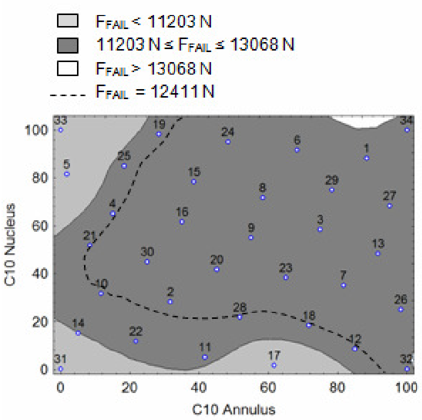


Descriminate and identify admissible set of parameters According output data

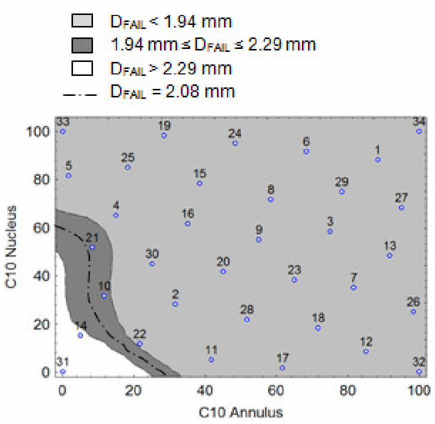
Kcomp



Ffail

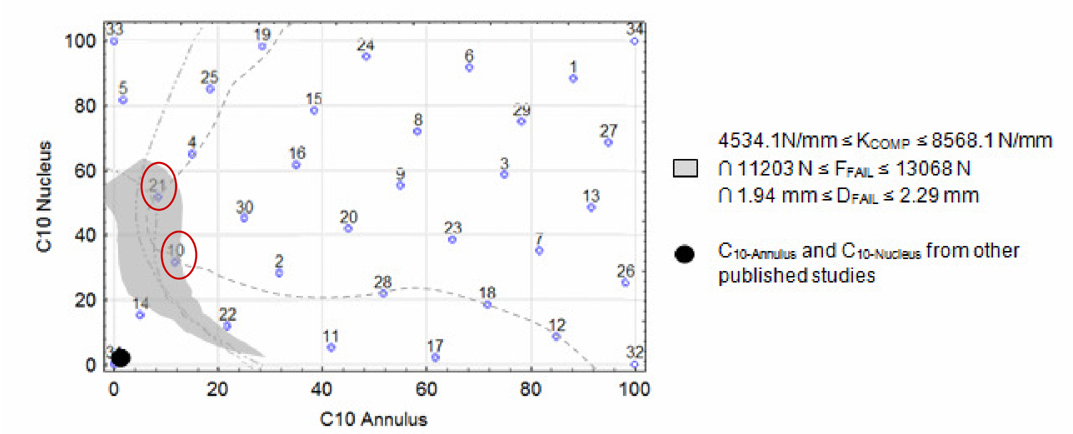


Dfail

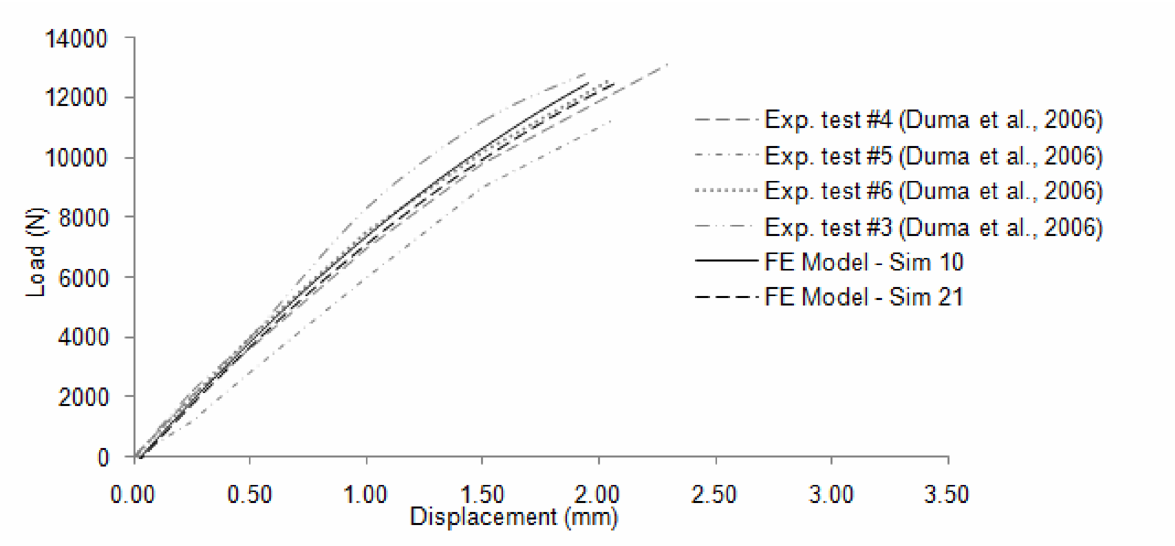


Intervertebral disc properties modelling (3/3)

Final solution : superimpostion & intersection of Kcomp, Ffail & Dfail domain



Relevancy of solutions to experimentals data

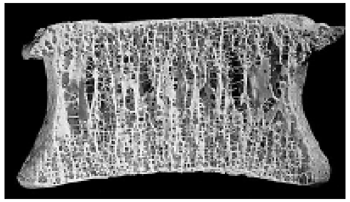


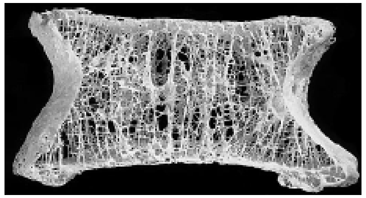
Bones properties (1/4)

Complexes structure – *many fracture & classifications*

Some differences :

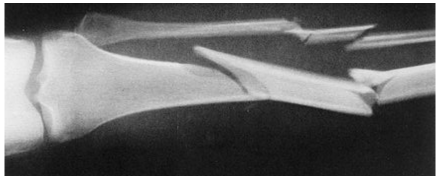
- **Shape**
- **Composition (compact and spongious bone et os spongieux)**
- **Spatial distribution & organisation (ex: diaphysis & epiphysis)**



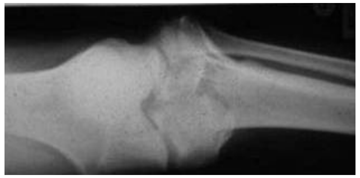


Bones injuries

Loaded under
- *compression*
- *flexion*
- *torsion*



Communitive spiroïd fracture



Proximal failure

Simple failure

Mechanical behaviour

Anisotropic (transverse isotropic) material

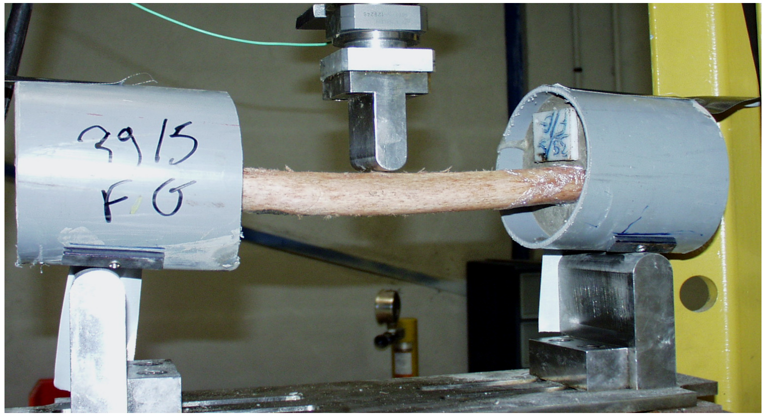
Heterogeneity & brittle behaviour

Elastoplastique dissymetric behaviour,

Bones properties (2/4)

Long bones properties

3 point bending tests on long bones



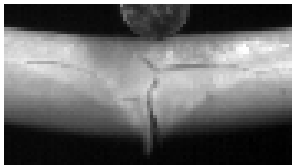
Objectives :

- Data for model validation
- Failure behaviour for long bones
- Variability
  - ***âge, sexe***
  - ***orientation***
  - ***minéralisation***

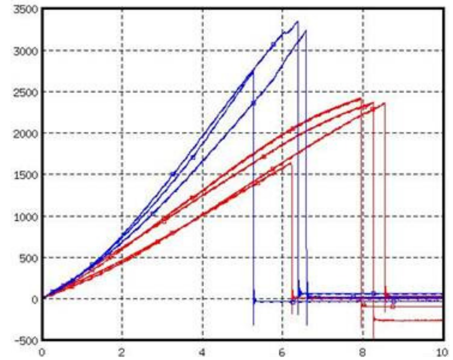
21 femur et 38 tibia tested

Results :

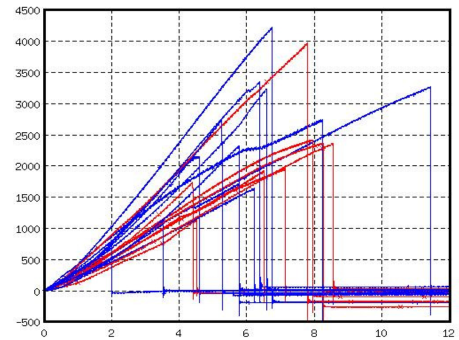
- An opening failure proces (which spend 2ms) :



- Age and gender, orientation influence on results

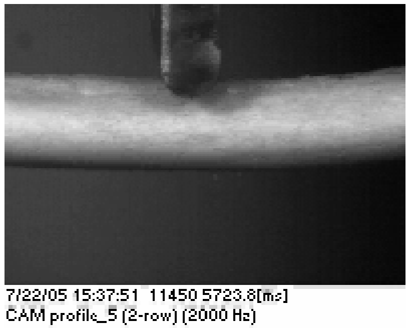


Gender influence (by age group)

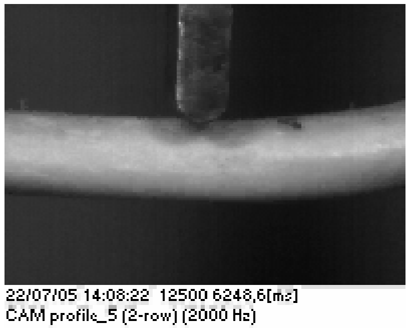


Impact direction

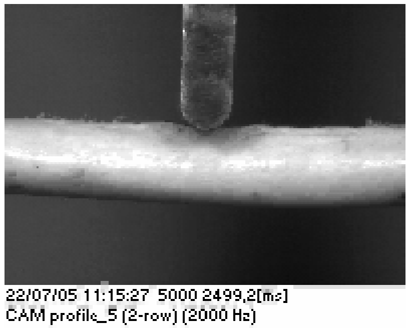
fracture simple oblique ≥ 30°



fracture à coin de flexion entier



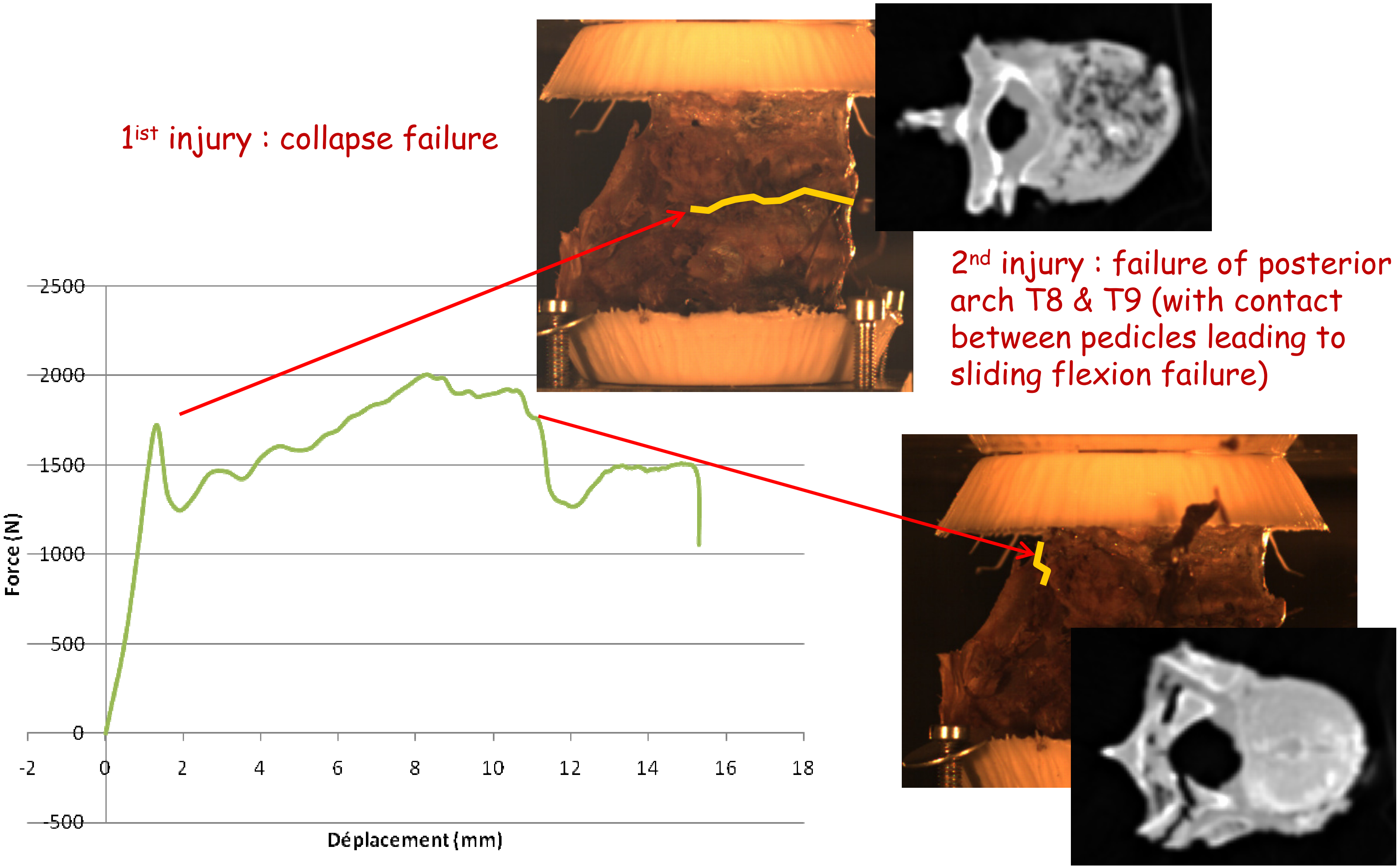
fracture simple transversale < 30°



Bones properties (3/4)

Spine : combine spongious and cortical bones structures

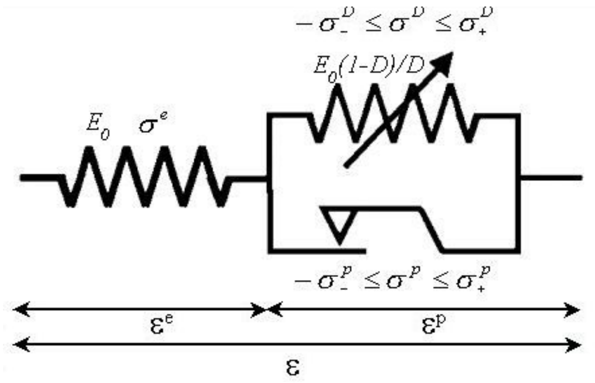
A multiple fracture level process with a gradation in injury severity



Applications to Bones structure (1/4)

Long bones properties

- ''Elastoplastic'' model with damage (Curnier, Garcia, Zysset)



Constitutives equations : $\sigma = E_0\left(\varepsilon - \varepsilon^p\right) \quad \sigma^p = E_0\left(\varepsilon - \varepsilon^p\right) - E_0 \frac{1-D}{D}\varepsilon^p$

Dammage law : $\dot{D} = \frac{\sigma_+^D \dot{\varepsilon}^p}{E\left(\varepsilon^p + \frac{\sigma_+^D}{E}\right)^2}$ / $Y = \frac{1}{D^2}\frac{E_0}{2}{\varepsilon^p}^2$

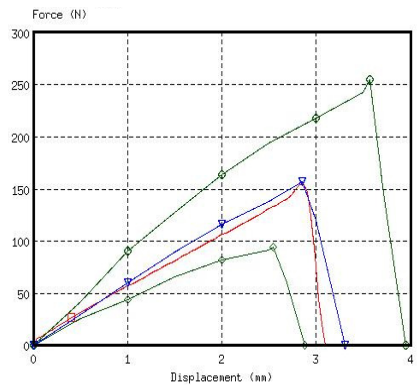
Failure : Energy criteria – Kill element method

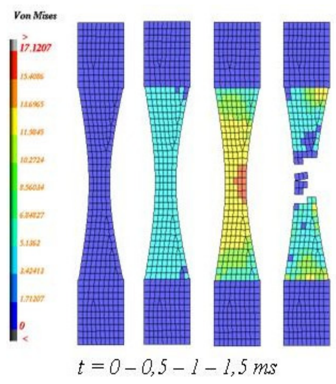
A dissymétrique behaviour law

- Johnson Cook models also used

- Implementation in FE software as users laws

- Inverse analysis to identify model parameters

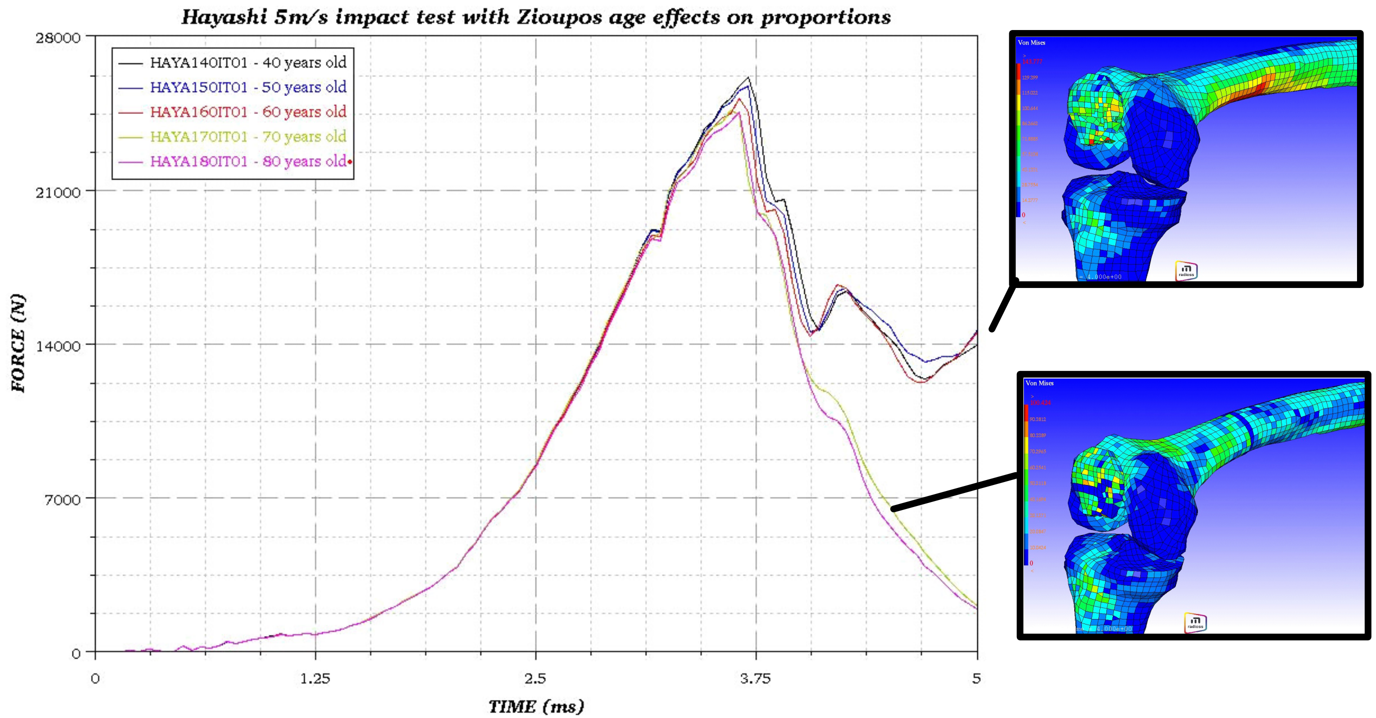




Implementation of human variability in bone structures (1/2)

Age effects

- Density
- Geometry (shap, thickness)
- Mechanical properties E, σ_{max}, ε_{max}, …
- Amplified with impact velocity



40-60 ans

70-80 ans

Lower limb under frontal impact (car occupant impact)

Towards fully personalized model

Model geometry and properties obtained from calibrated CT scan

For $BMD_{QCT} < 0{,}06\ mg/cm^3$:

$$E(MPa) = 2980 * BMD_{QCT}^{1.05}$$

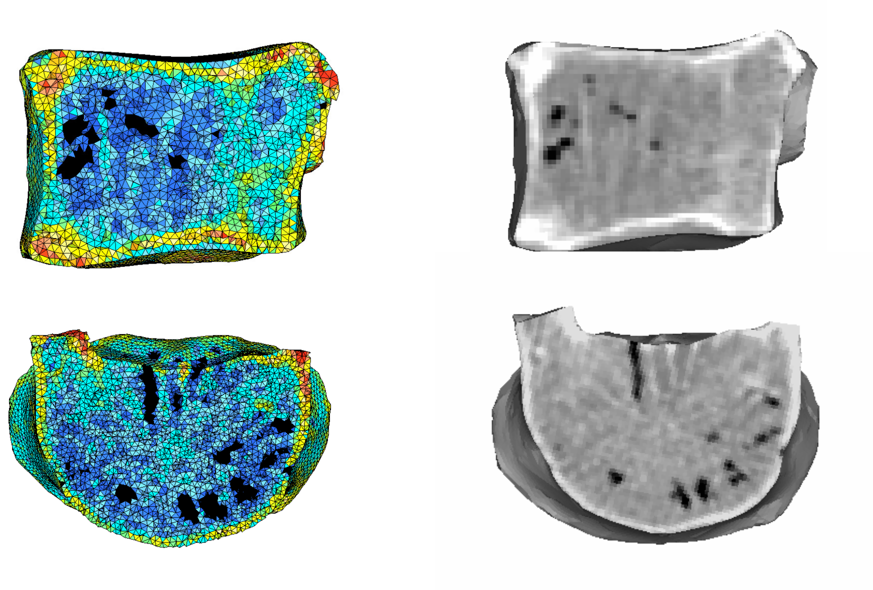
$$\sigma_y(MPa) = 37.4 * BMD_{QCT}^{1.39}$$

For $BMD_{QCT} > 0{,}06\ mg/cm^3$:

$$E(MPa) = -34.7 + 3230 * BMD_{QCT}$$

$$\sigma_y(MPa) = -0.750 + 24.9 * BMD_{QCT}$$

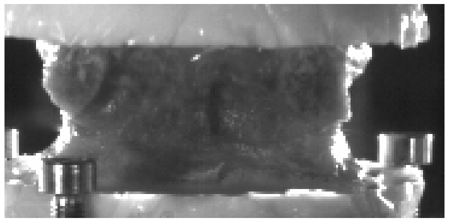
$$\sigma_{\max}(MPa) = 1.2 * \sigma_y$$

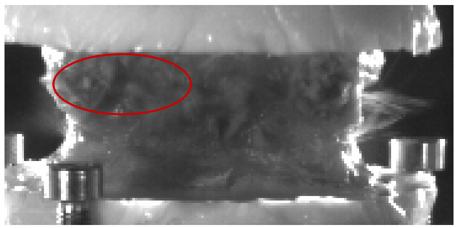


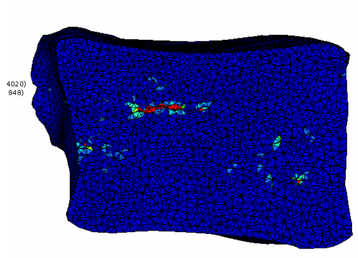
→ **Relationship valid for Quasi-static loading**

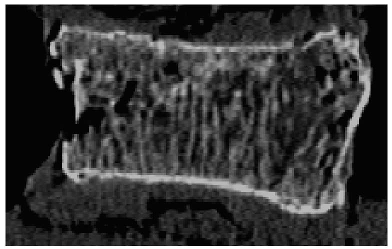
Corrective coefficient to be implemented for dynamic loadings

Validated with experimental compression tests (1m/s)









II. On human body modeling

II. On Human body modeling

Which models for which applications ?

Human body model for dynamic loadings *& constraints to explicits FE platforms*

Simplified models

Particularities :

Rigid Body in FE simulations
Tuned validations

Advantage :

Calculation time

Drawbacks :

Model validity and biofidelity

Applications :

Optimisation
Globale vision

Robusts deformable models

Particularities :

Description anatomique
Structures ayant une contribution mécanique

Advantage :

Robustesse % calculation time

Drawbacks :

Sensitivity to model

Applications :

Global injury mechanisms understanding
Safety systems evaluation

Detailed models

Particularities :

Complete anatomical description

Advantages :

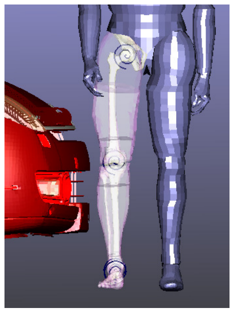
Results quality

Drawbacks :

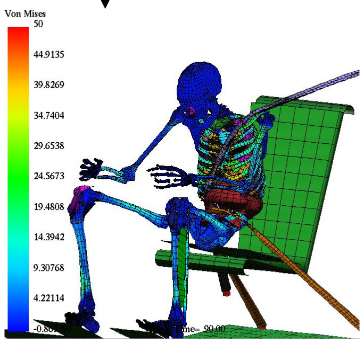
Calculation time

Applications :

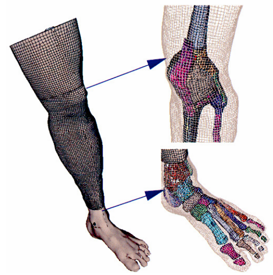
Accurated local analysis
Enlarged applications to crash



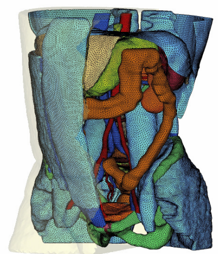
LLMS Hybride



Modèle HUMOS



Modèle LLMS

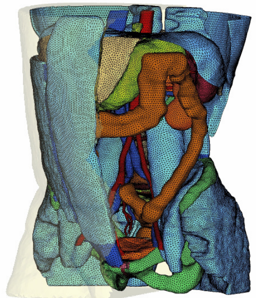


Modèle MELBA

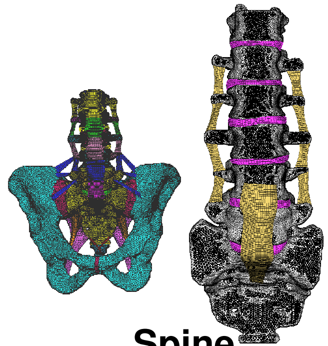
From medical data to modelling

- An accurate geometrical description to investigate structure effects

- **Structures with a mechanical contribution**
- **Structures with physiological functions**



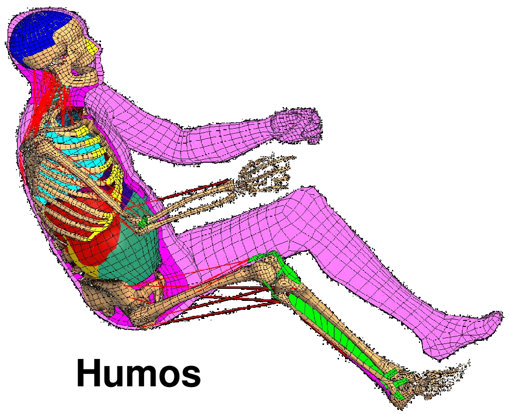
Trunk
Abdomen and plevis



Spine

- Coupled / Compatibles model

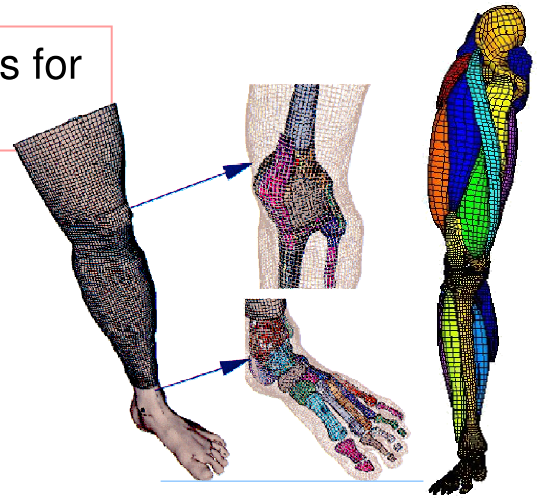
Multi-level analysis of injuries



Humos

1997: 50 000 elements for a body model

2009: 3 000 000 elements for the abdomen



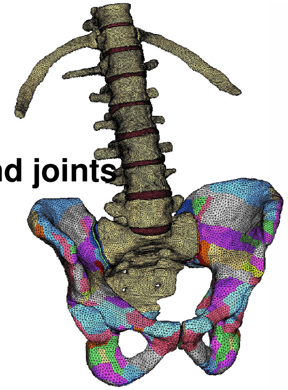
Lower limb

II. On Human body modeling

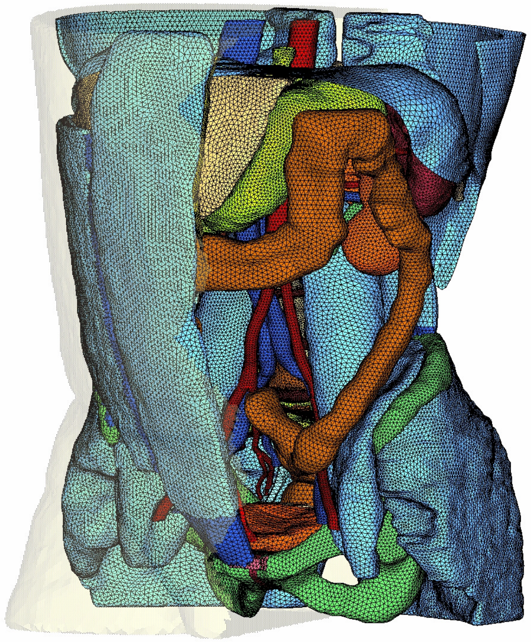
The abdominal segment

From mechanical contribution to injury indication

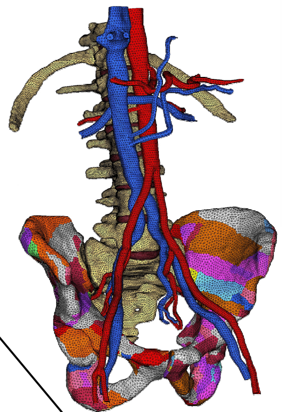
Bones and joints



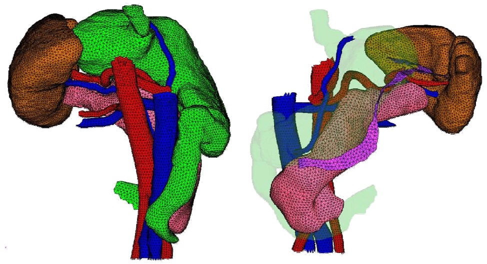
Stability



Vessels

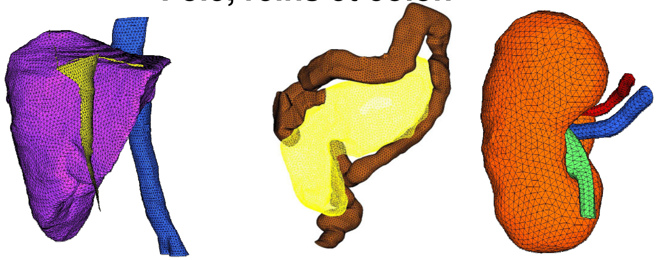


Organs attachment

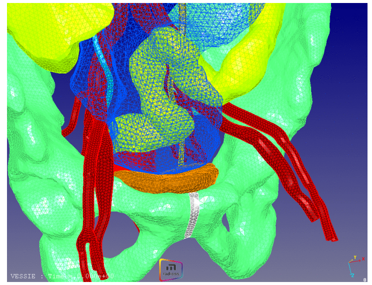


estomac-duodéum-pancréas-rate

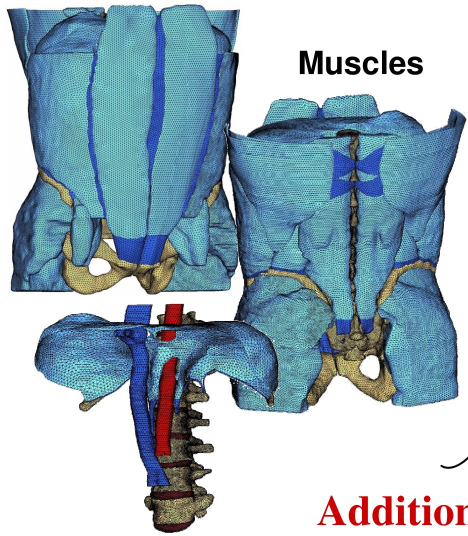
Foie, reins et colon



La vessie



Muscles

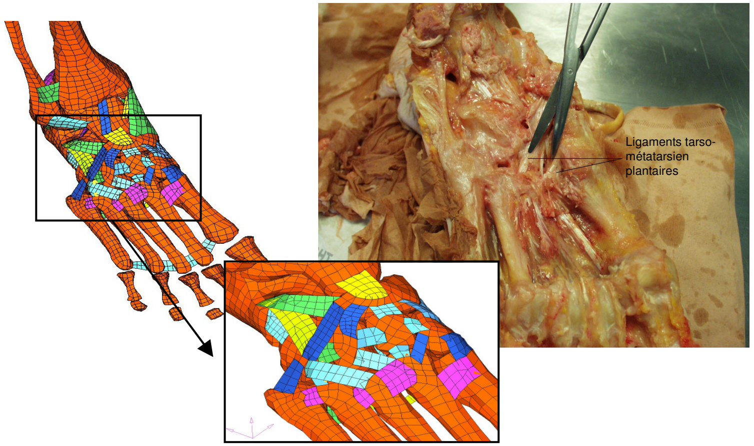


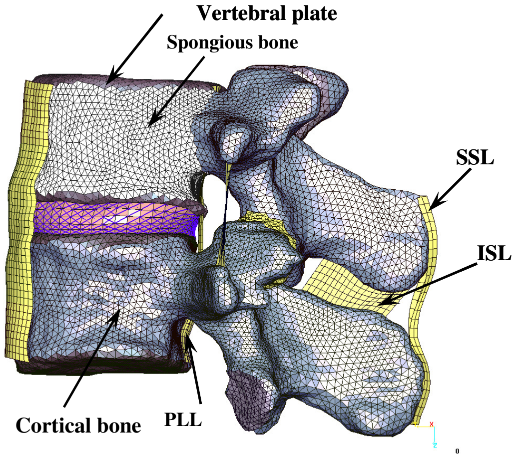
Additionnal strength
Modulate pressure…

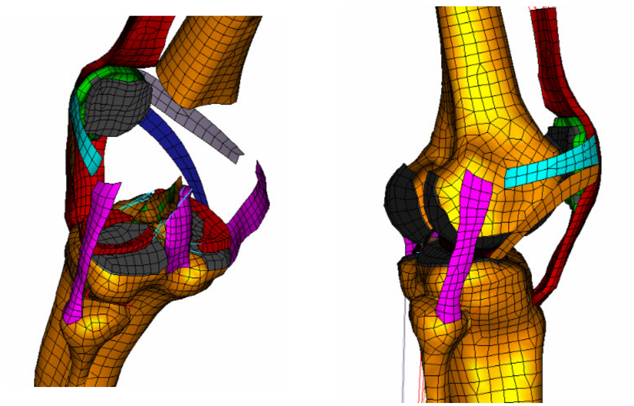
The challenge of joint modeling

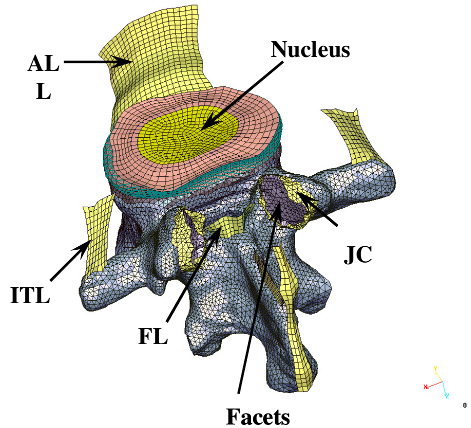
Joint modelling combine :

Contact conditions (hard-hard, hard-soft tissues)
Mobilities (physiological kinematics)
Mechanical (& numerical) stability

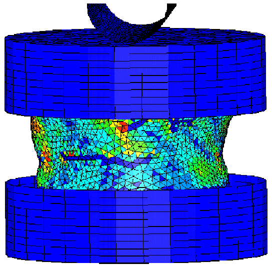




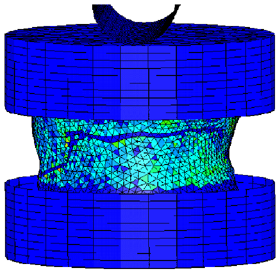




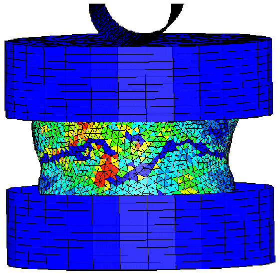
On the variability of properties distributions



Homogenous properties,

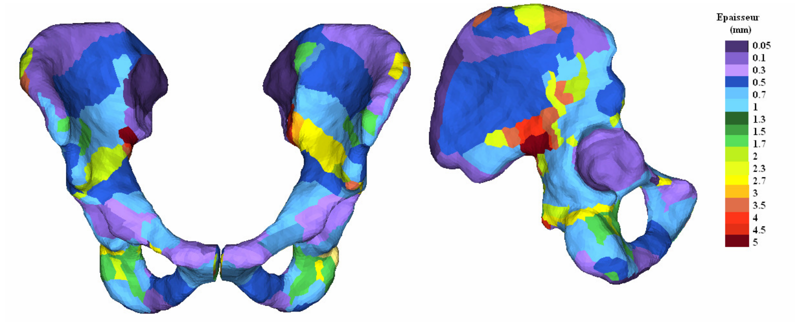


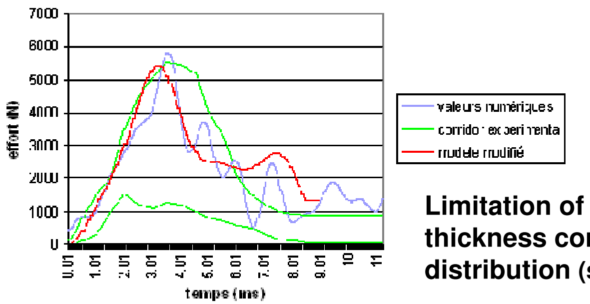
heterogenous random properties,



Full personnalisation

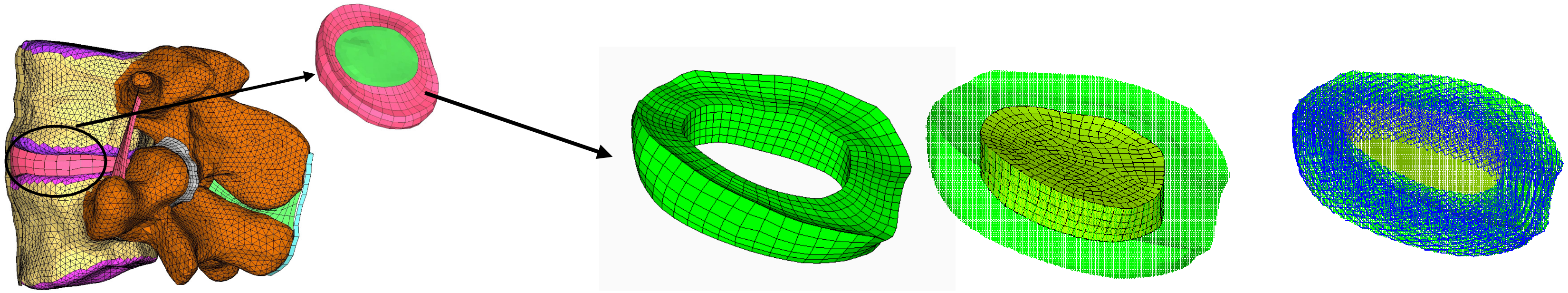
Integration of thickness distributions





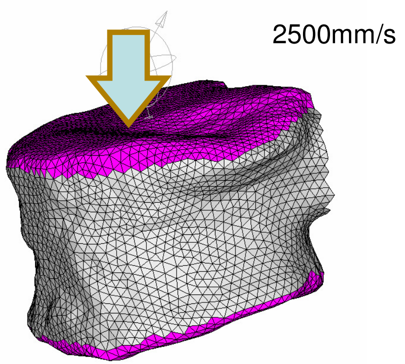
Limitation of vibrations with geometrical thickness cortical bone thickness distribution (side impact for pelvis)

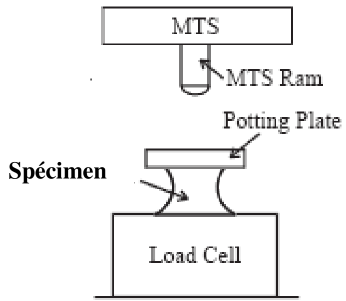
Links between structure specificities modelling choices

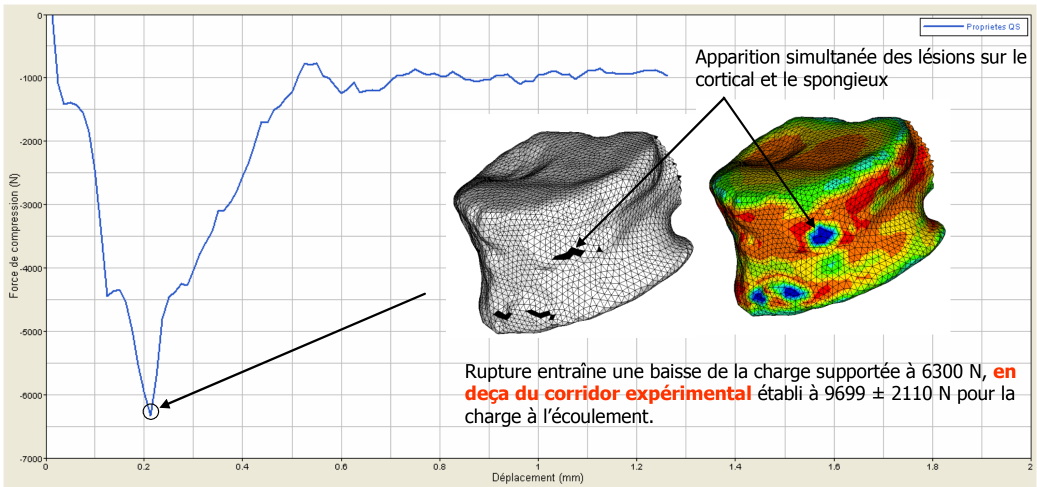


Spine functional unit : Viscoelasticity – Incompressibility – <u>Fibrous reinforcements</u>

Geometrical non linearity : an indicator for potential failure







III Applications to virtual trauma

About vulnerable road users

- Pedestrian & lower limb injuries
- Spine trauma : Motocyclists

III. Applications to virtual trauma

Aims and methodology with virtual trauma

Injury chronology analysis :
- *Injury mechanisms*
- *Injury criteria*

According to validated models

- Investigate new impact conditions
- Obtain data which can not recored during experiments

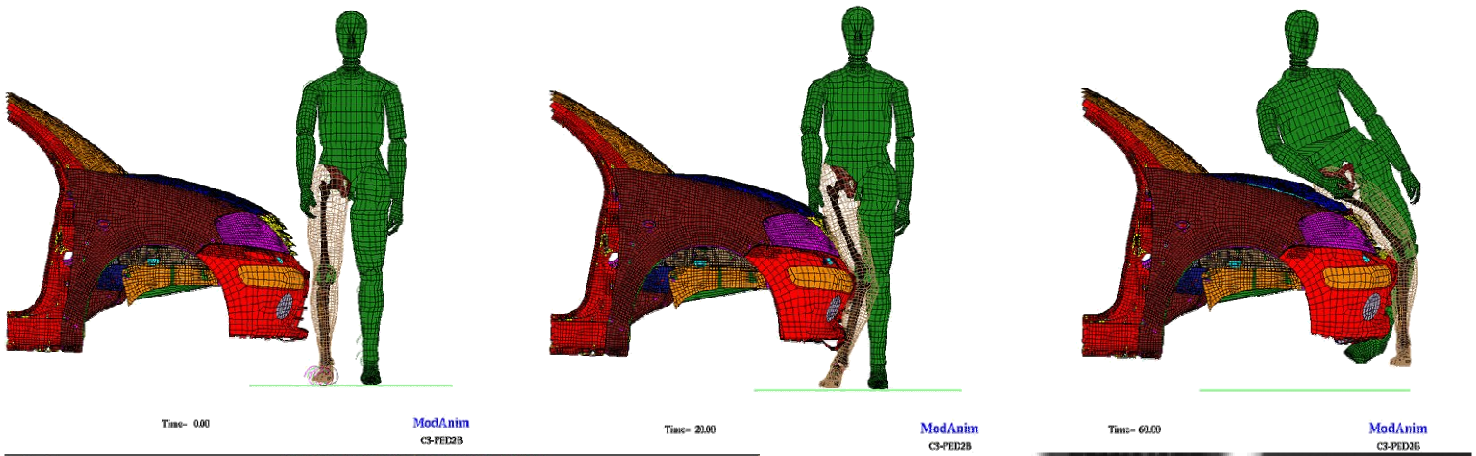
Methodology : *A combined clinical and mechanical analysis*

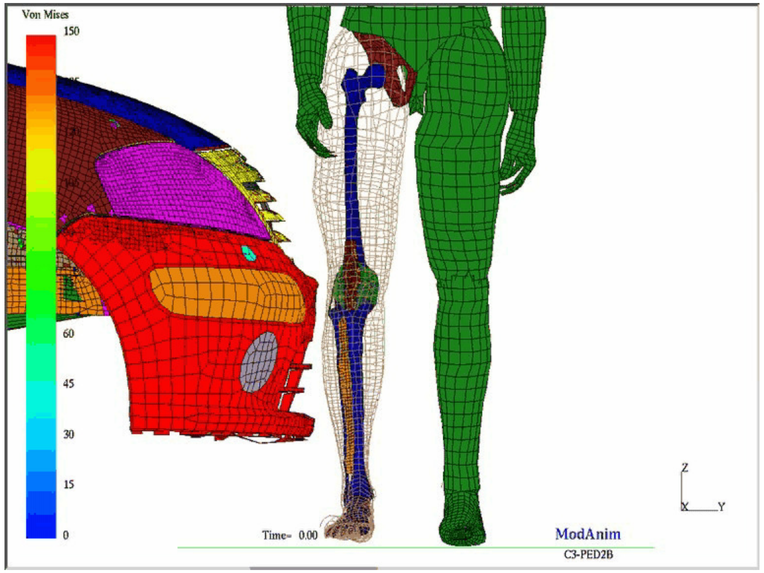
- ***Joint Kinematics***
- ***Strain and pressure on soft tissues***
- ***Forces & stress on bones***

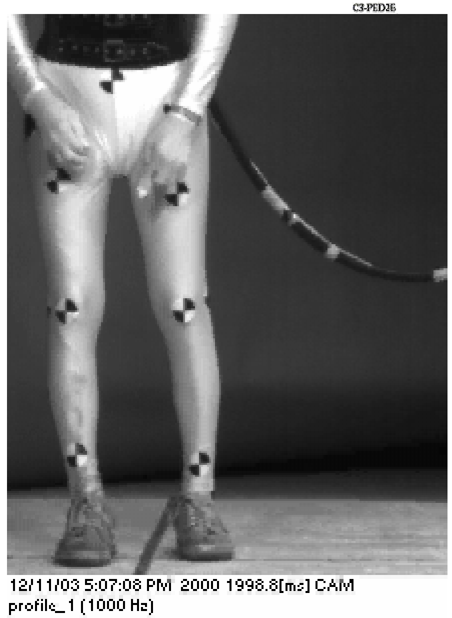
→ ***Detailed analysis of injury***

III. Applications to virtual trauma

On pedestrian lower limb safety





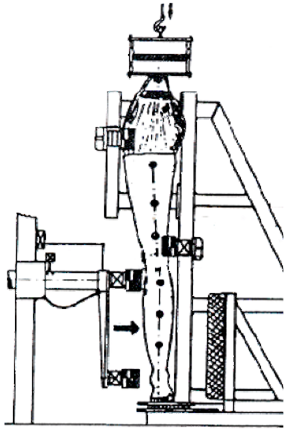


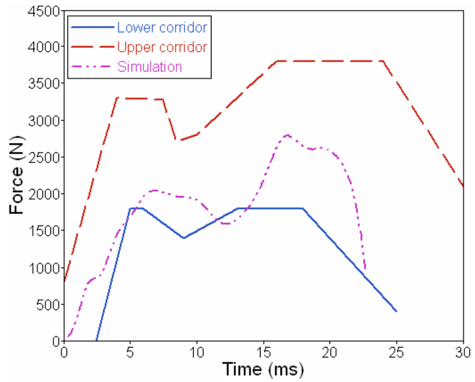
Lateral shearing and bending govern knee injuries

III. Applications to virtual trauma

On pedestrian lower limb safety

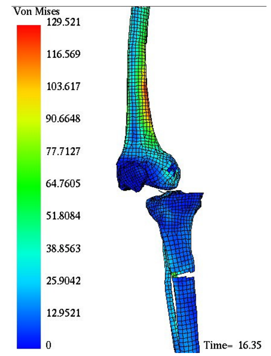
Case of pure shearing



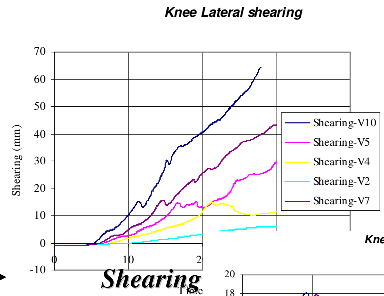


Kajzer (5.55m/s)

$V_0 \geq 10$ m/s

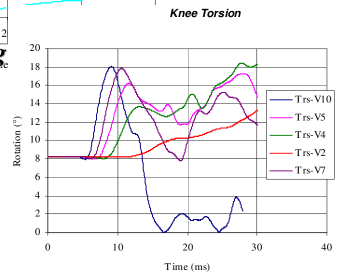


Tibia fracture



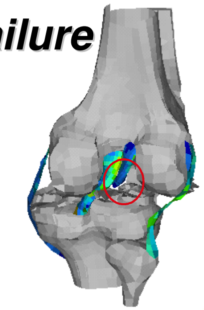
Shearing

$9m/s \geq V_0 \geq 4$ m/s

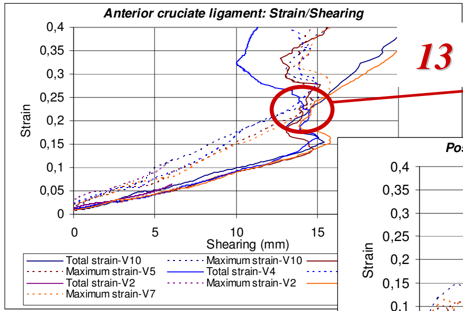


Axial Torsion

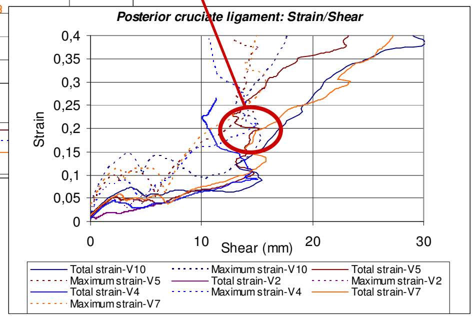
Ligaments failure



Relationship between ligaments strain and global shearing



13 mm lateral shearing



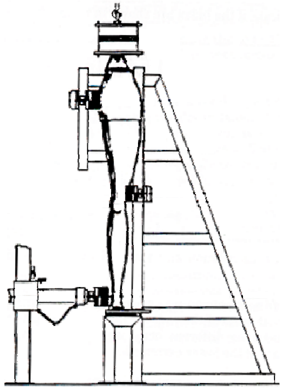
Strain vs shearing
ACL & PCL

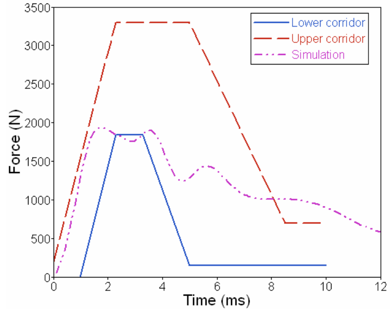
13 mm lateral shearing injury criteria

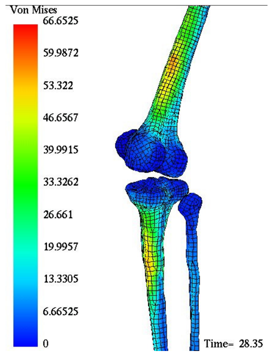
III. Applications to virtual trauma

On pedestrian lower limb safety

Case of pure bending



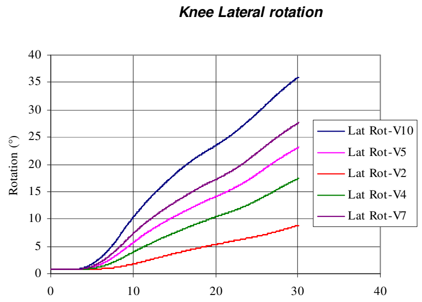




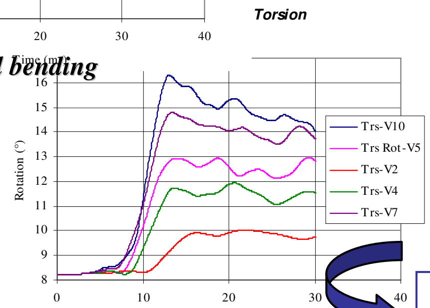
Kajzer (5.55m/s):

$10m/s \geq V_0 \geq 4$ m/s

Ligaments failure

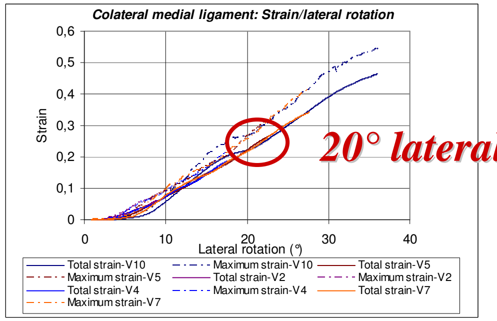


Lateral bending



Axial Torsion

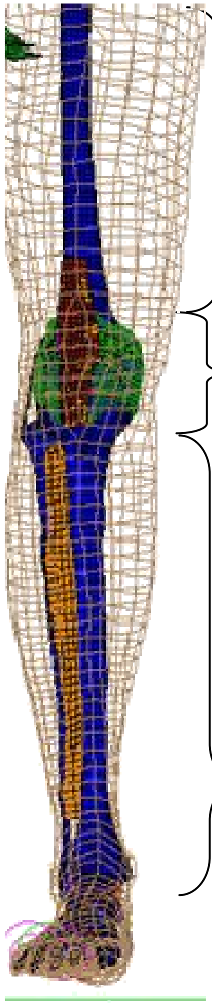
Relationship between ligaments strain and global bending



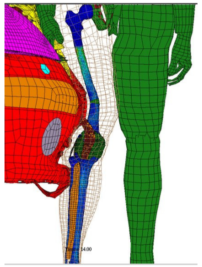
Strain vs lateral bending on MCL

20° lateral bending injury criteria

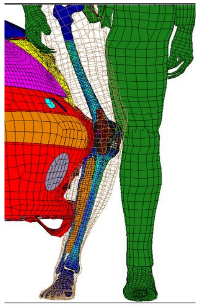
On pedestrian lower limb safety



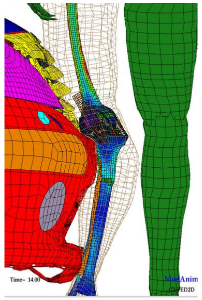
Impact on femur
- **dominant shearing + bending**
- Primary risk for bones
- Ligament injury delayed



Impact on knee joint
- **Combinaison de cisaillement et flexion**
- Primay risk for ligaments
- delayed risk for bones



Impact on Tibia
- **Cisaillement dominant**
- Primary risk for ligaments
- Secondary risk for bones



→ **Need to define combined cirteria**

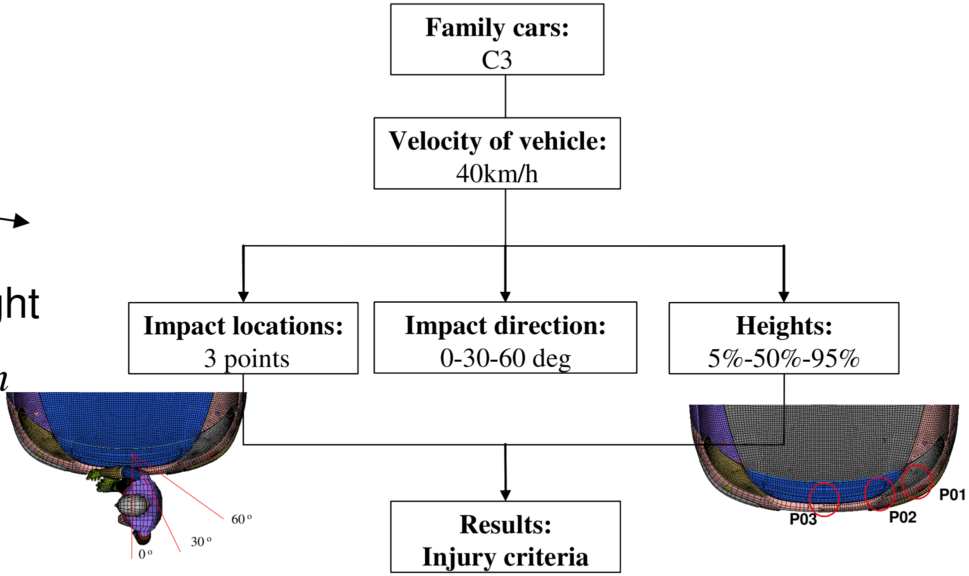
On pedestrian lower limb safety

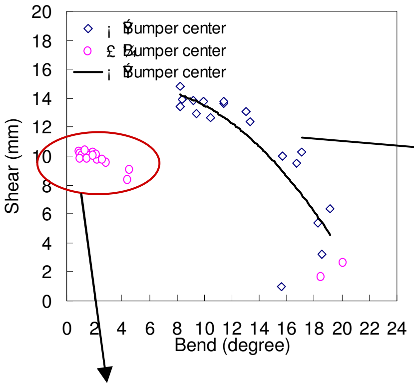
A two step sensitivity analysis

1: 27 runs on impact variability

2: 36 additional runs focusing on impact height

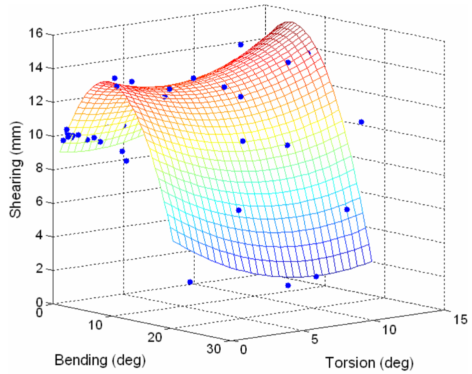
12 height levels from 5% to 95% pedestrian





A shearing criteria for femur and tibia impact

An injury risk surface for knee joint impact combining shearing, bending & torsion



Injury function
$d_s = 7.992 + 1.313\alpha_b - 0.111\beta_t - 0.027\alpha_b\beta_t - 0.073\alpha_b^2 + 0.031\beta_t^2$
R^2
69%

Shearing- d_s

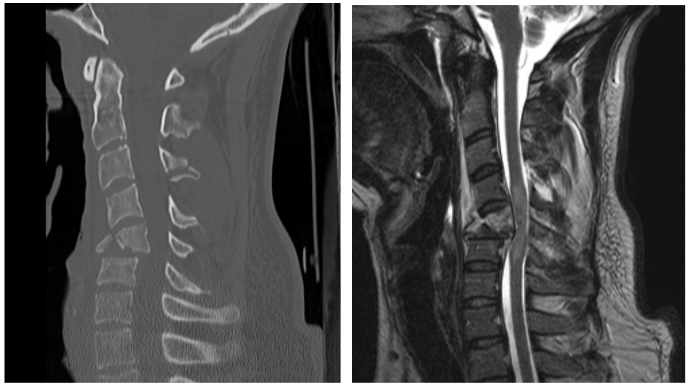
Bending- α_b

Torsion- β_t

III. Applications to virtual trauma

On Spine trauma current investigations

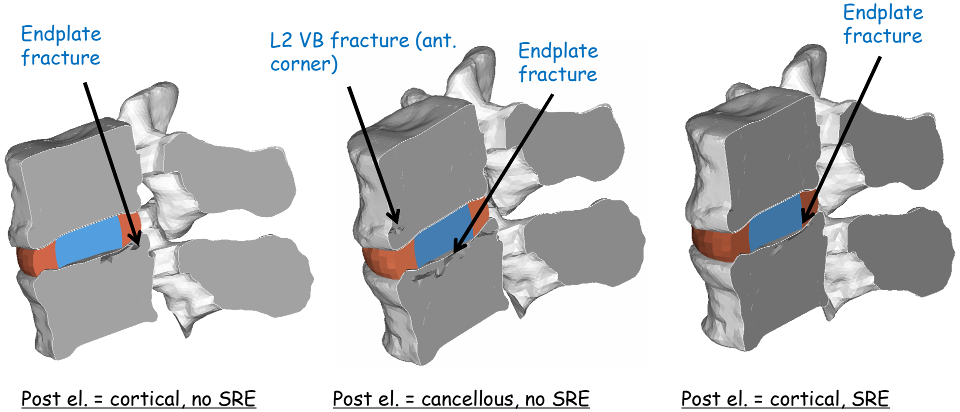
Spine fracture with instability



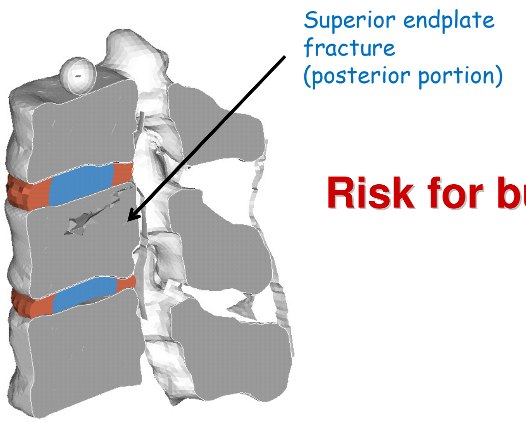
→ Flexion - Extension
Axial compression

- Vulnerability changes according to spine location

Endplate bone fracture on L2-L3



Endplate bone fracture on T12-L5

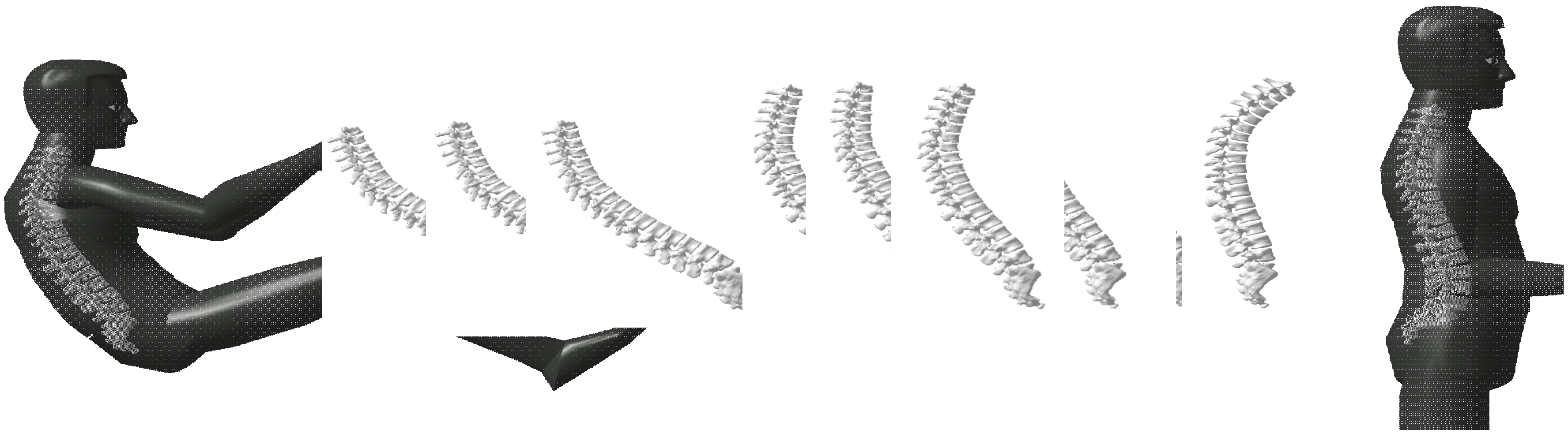


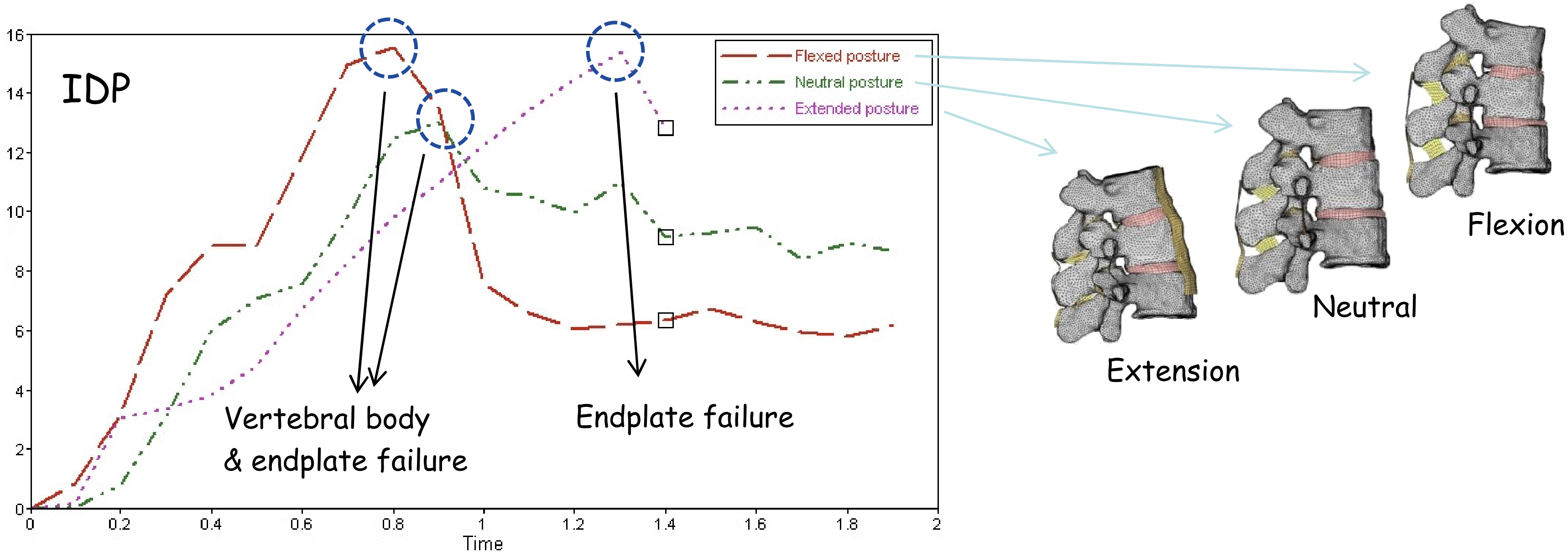
Risk for burst fracture

III. Applications to virtual trauma

On Spine trauma current investigations

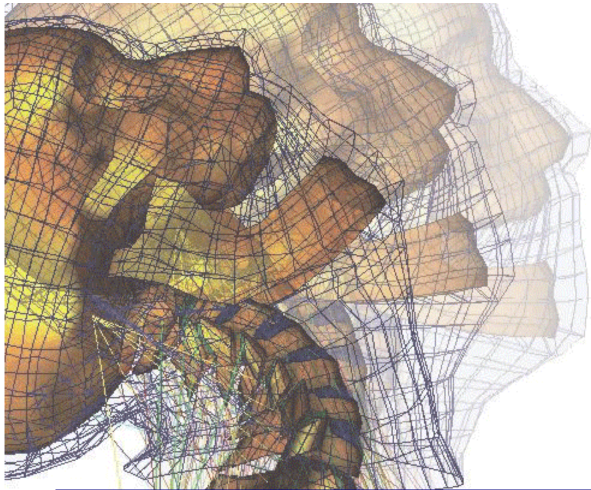
- Vulnerability changes according to spine curvature

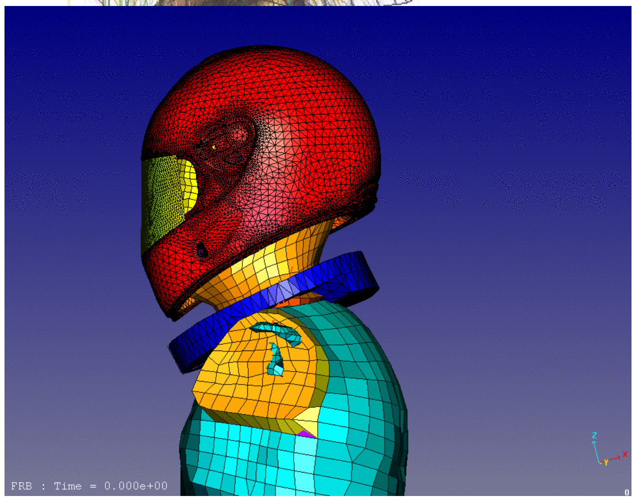


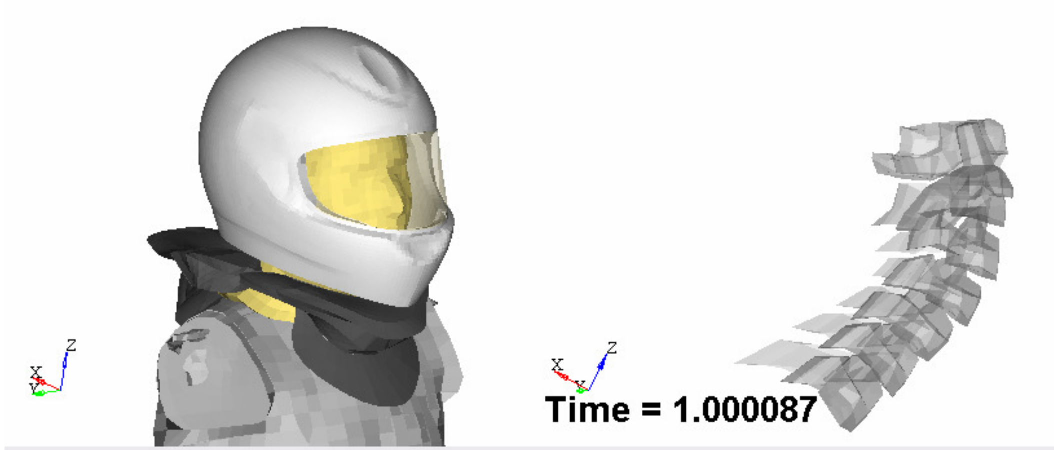


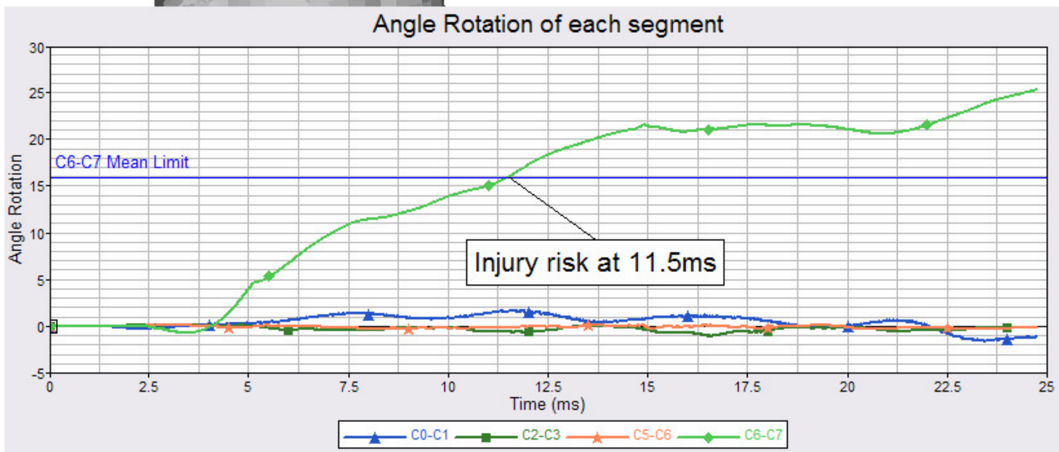
On Spine trauma current investigations

- From cervical spine vulnerability to safety systems evaluation









Discussion – Conclusion on biological tissues properties

Hard tissues | **Fibrous tissues** | **Soft Tissues**

- **Dedicated experiments for tissues identification**
  - Traction
  - Compression
- **Simple behaviour laws :**
  - The main physical properties
  - Dynamic loadings
- **Use recordable parameters in models :**
  - Closed to experiments
  - Introduction of human variability
- **A numerical environement**

Discussion – Conclusion on human modelling

The choice to define detailed FE models

On modeling tasks : des exigences et des questions

Meshing tasks
- Needs to optimise choice of elements
- Discontinuous mesh

Modelling
- All tissues should be investigated up to failure
- Human variability from ages, sexe, … – also from modelling choices
- Which interactions for organs, …

Validation
- A multi-level analysis

On Virtual trauma

Work on relationship between mechanical understanding and clinical features

A numerical model is tool, not a true ← **Which validity ? Which analysis ?**

Remerciements

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