Experimental characterisation of cancellous bone:
from 2D measurements to 3D identification

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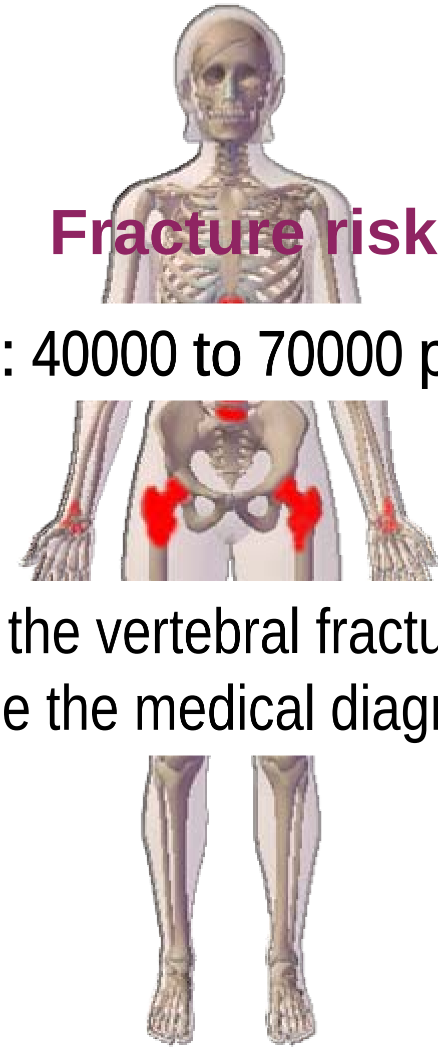
Experimental Mechanics in Biological Tissue, BSSM,
Loughborough University, 23rd June 2009

Osteoporosis and fracture risk prediction



Fracture risk

Vertebrae: 40000 to 70000 per year

2/3 of the vertebral fractures
escape the medical diagnosis*

Decreasing of
bone quantity

Micro-architecture
alteration

*From: * Cummings et al., The Lancet, 2002.*

Consequences of vertebral fracture

Picture : International Osteoporosis Foundation

Morbidity:

severe kyphosis,
back pain,
loss of height,
loss of function and independence,
risk for additional fracture

Cost:

2000: 31.7 billions €
2050: 76.7 billions €

Needs for improving diagnosis and treatment

Data from: Lips P et coll. Osteoporosis Int. 1999. Gold DT Rheum. Dis. Clin. North. Am. 2001. Hall SE et coll. Osteoporosis Int. 1999. Adachi JD et coll. Musculoskelet. Disord. 2002

Needs for non destructive bone characterization

- Bone mineral density (DXA):

  ☹ only predict 45% to 65% of the vertebral strength
  (Cheng et coll, Spine 1997, Singer et coll, Bone, 1995)

dual energy X-ray absorptiometry (DXA)

- Personalized Finite Element Models with tomodensitometry

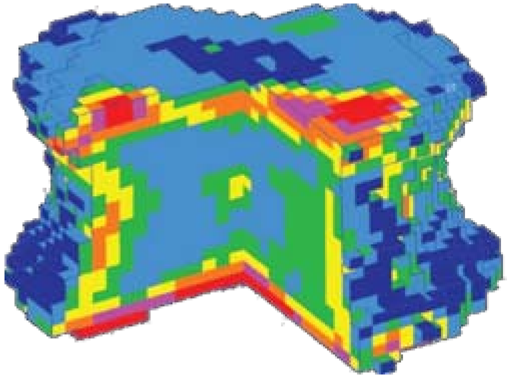


Image : Buckley et coll.,
J. Biomech. Engineering, 2006

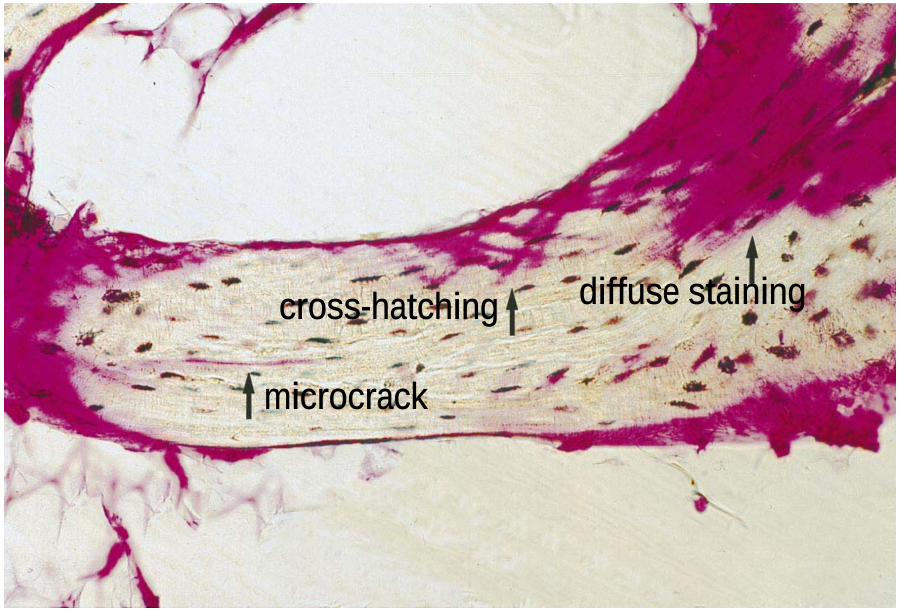
☺ **Good prediction of vertebral strength**
(r^2 = 0.85 à 0.95)
Crawford et coll., 2003 ;
Buckley et coll., 2007

☹ **Irradiating for the use on a whole spine**

Needs for non destructive bone characterization

- Microcracks accumulation increases fracture risk (Burr*, Zioupos**)

- Quantitative measurement of microcracks would be helpful for fracture risk diagnosis



Fazzalari et coll. Bone 1998

** Burr, Osteo. Int, 2003, **Zioupos, J. Microsc, 2001*

Needs for non destructive bone characterization

– Ultrasound method :

Available to assess elastic parameters

Non linear ultrasound can detect accumulated damage in human bone*

⇒ Needs for objectivising damage

⇒ Needs for inducing a controlled damage in a trabecular bone sample

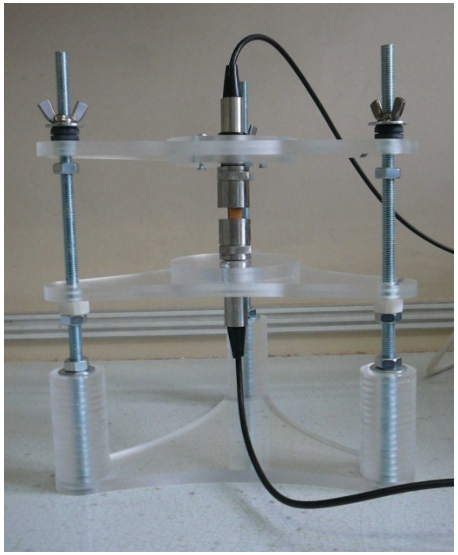


Image : Laboratoire d'imagerie Paramétrique, CNRS UMR7623

*Müller M et coll, J. Biomechs, 2008

Mechanical characterization of trabecular bone

- 2D characterization: uni-axial compression test on human trabecular bone sample

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- 3D kinematic fields: uni-axial compression test on bovine trabecular bone sample

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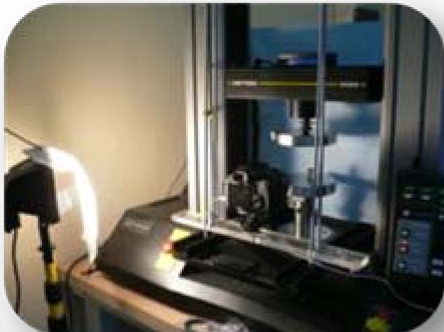
2D characterization of human trabecular bone

Material and methods

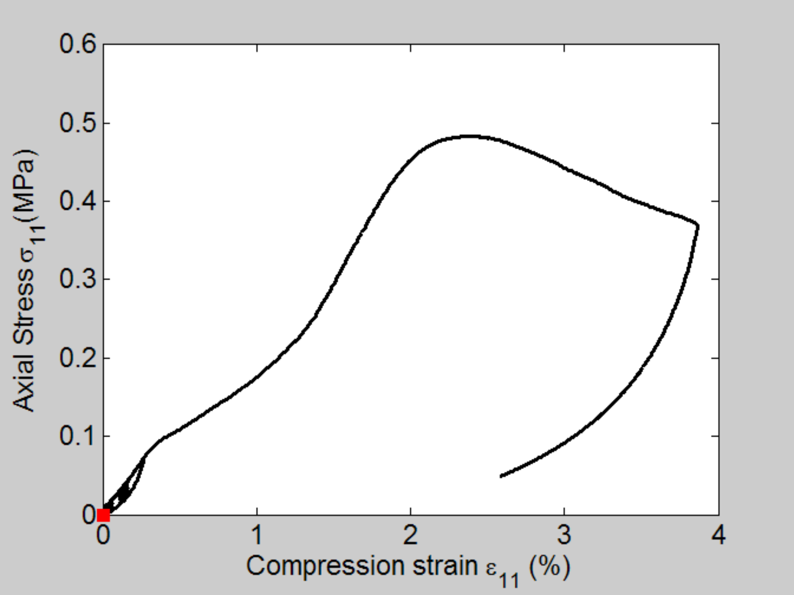


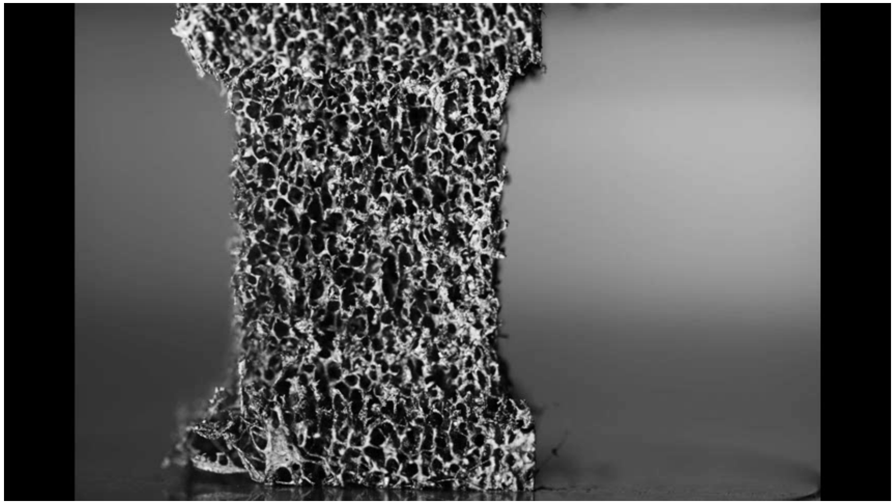
- Sample cut
- Alizarin coloration
- Ultrasound measurement
- Uni-axial compression test
- DIC analysis
- Calcein coloration
- Ultrasound measurement
- Histology

To induce and measure damage at a macroscopic scale

2D characterisation of human trabecular bone

Results and discussion

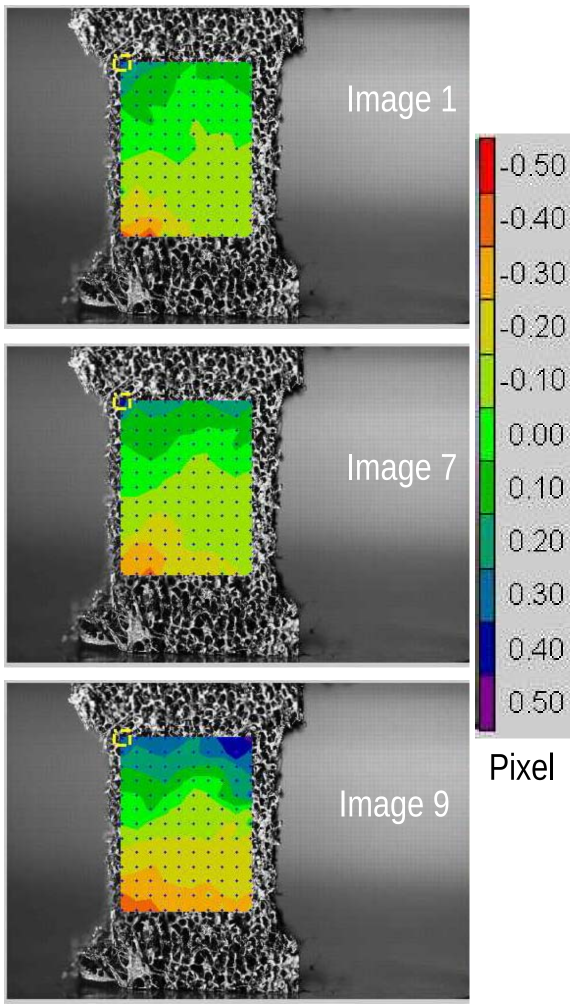


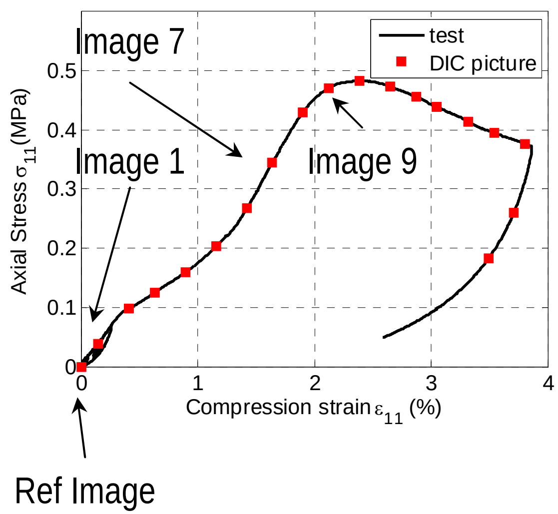


2D characterisation of human trabecular bone

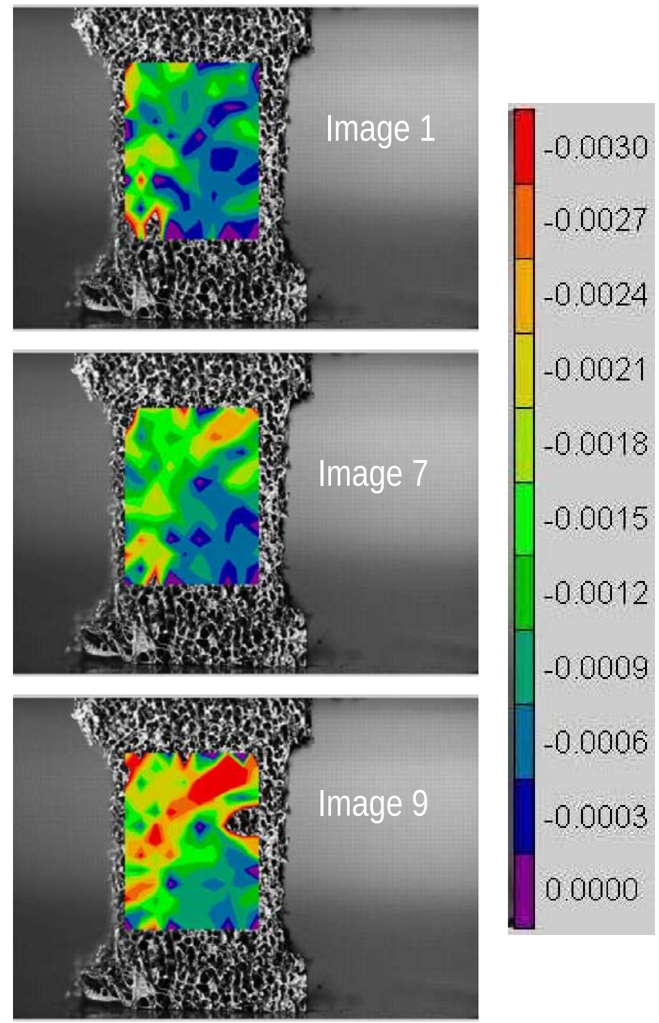
Results and discussion

Displacement field (pixel)



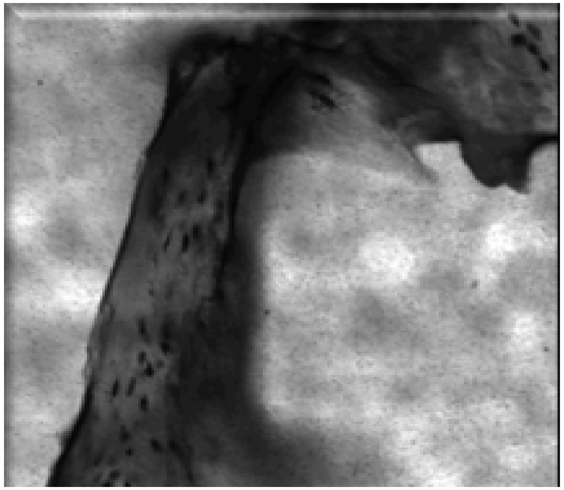


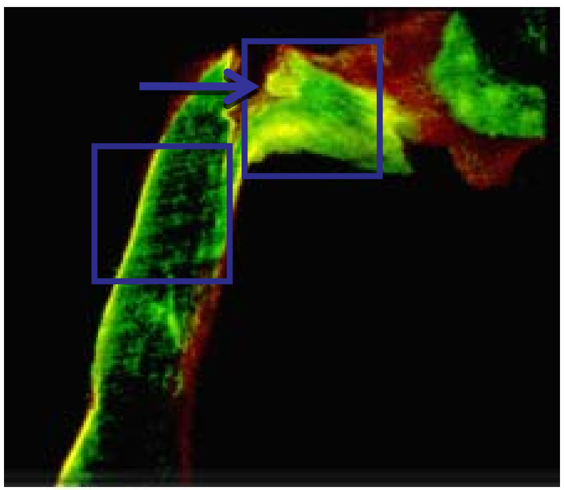
Strain field (pixel/pixel)



2D characterisation of human trabecular bone

Results

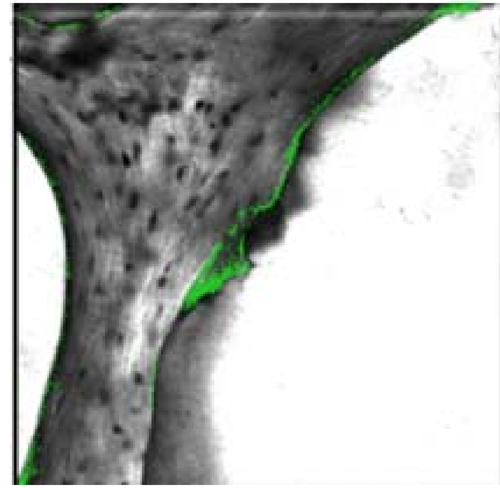


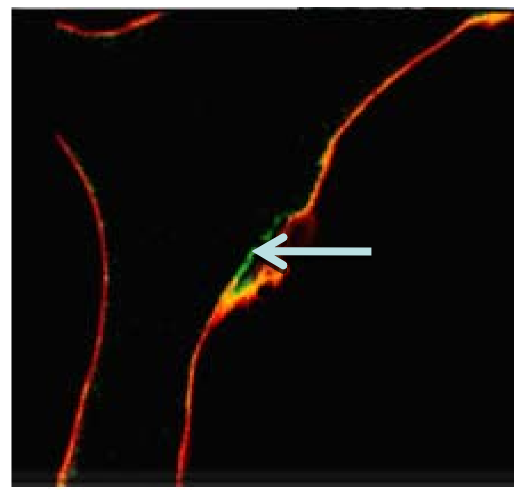


Broken trabecula

Increasing of the size of microcracks

Stained microdamage





Existing damage: red and yellow
Created damage: green

2D characterisation of human trabecular bone

Conclusions

- Coupling 2D DIC and histology to assess bone damage
- 2D DIC and histology are local measurement
- Only surface measurement
- Extension to 3D evaluation of trabecular bone behaviour ?

3D kinematic fields on bovine trabecular sample

Introduction

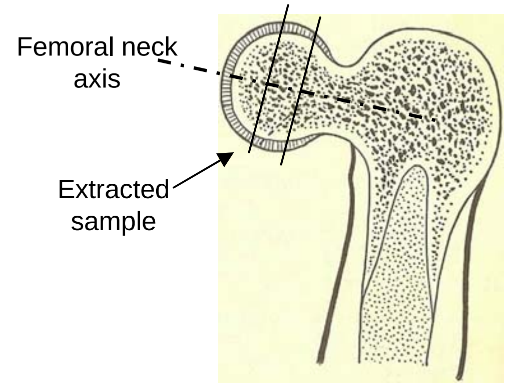
- The alternative of ultrasounds is medical imaging
- Two possibilities:
  - Micro-SCAN (Verhulp*, Thurner**):
    ☺ Resolution good enough to assess macroscopic properties and local strain field
    ☹ Temperature rise: can't be used *in vivo* (tissue damage)
  - Micro-MRI:
    ☺ No irradiation: can be used *in vivo*
    ☹ Long time of exposure to increase spatial resolution
- Question: is the spatial resolution good enough to allow for 3D DIC measurements ?

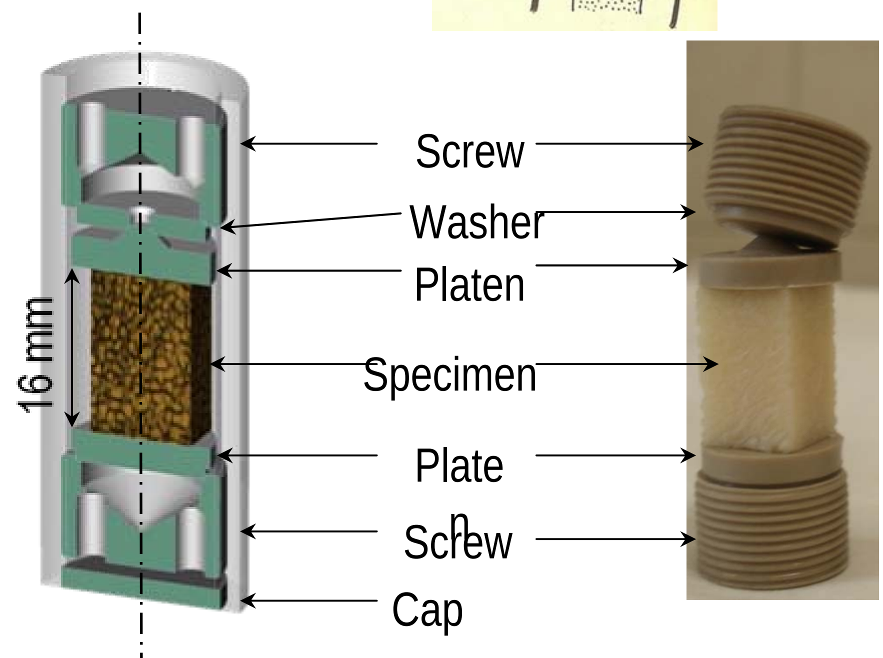
**Verhulp et coll. J Biomech, 2004, **Thurner et coll., Bone 2006*

3D kinematic fields on bovine trabecular sample

Material and methods

- Samples extracted from bovine femoral head
- 16-mm long, 100-mm2 square cross-section parallelepiped
- MRI-compatible mini-compression jig





3D kinematic fields on bovine trabecular sample

Material and methods

- The sample in the compression device is placed into the MRI antenna
- 2 compression levels applied on the samples
- 20minutes relaxation prior to image acquisition*

MRI

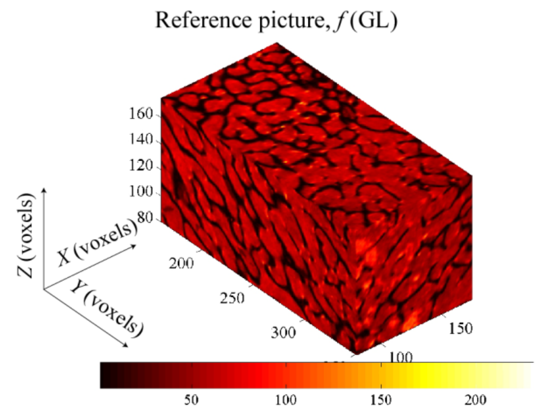
MRI antenna and experimental device

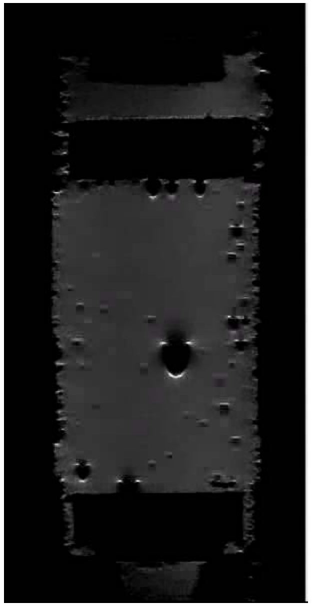
*Nagaraja et coll. J Biomech, 2005, Nazarian et coll., J Biomech 2004

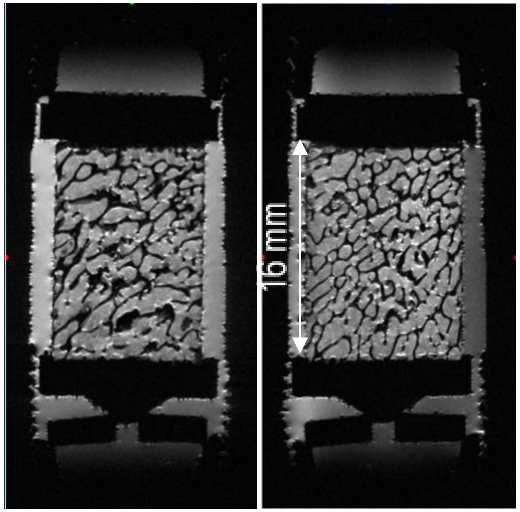
3D kinematic fields on bovine trabecular sample

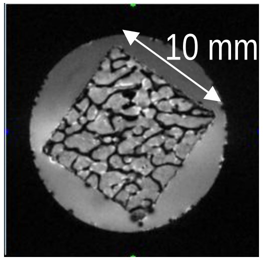
Results and discussion

- Isotropic 78-µm resolution (scan time 9h)
- Displacement measurements by image correlation** and strain evaluation







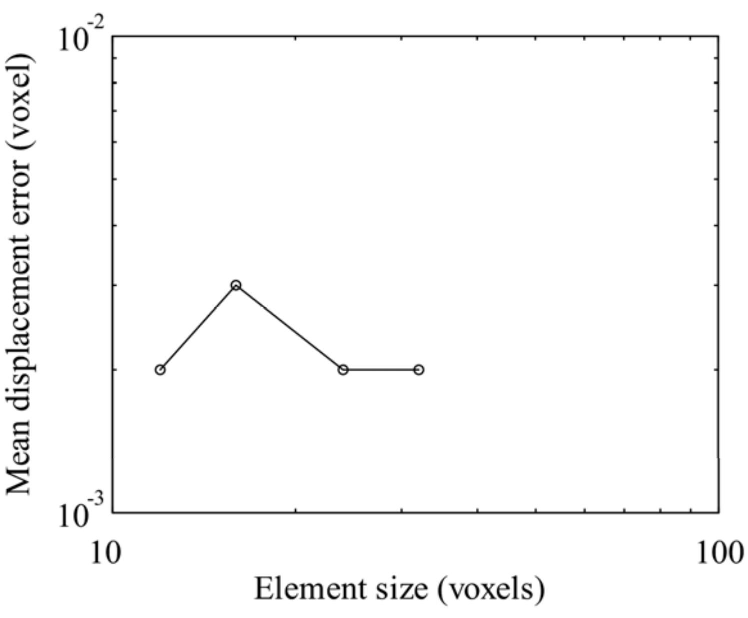


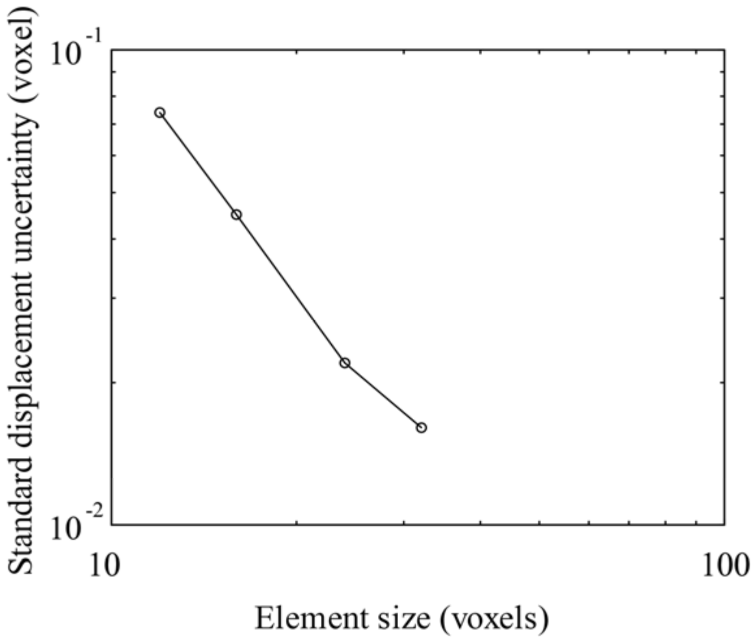
**Roux et coll. Comp. Part A, 2008*

3D kinematic fields on bovine trabecular sample

Results and discussion

- Mean displacement error as function of the element size
- Standard uncertainty as function of the element size

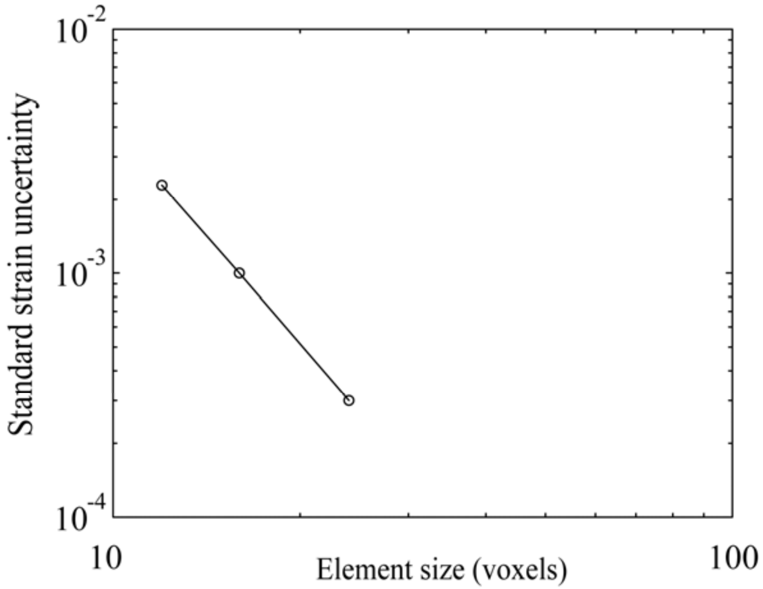




3D kinematic fields on bovine trabecular sample

Results and discussion

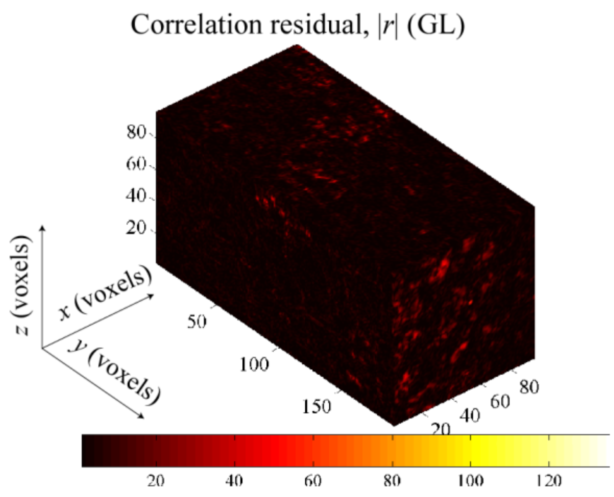
- Strain uncertainties also evaluated by using the previously displacement field



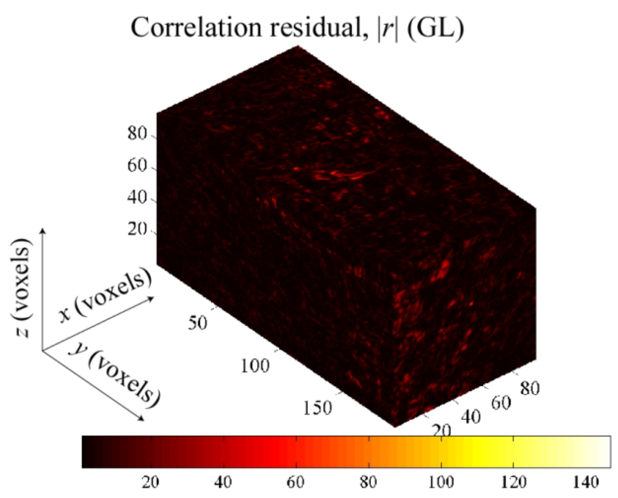
3D kinematic fields on bovine trabecular sample

Results and discussion

- The residual maps show that correlation residuals are not only very small on average, but also locally for the two loading steps



1st loading step

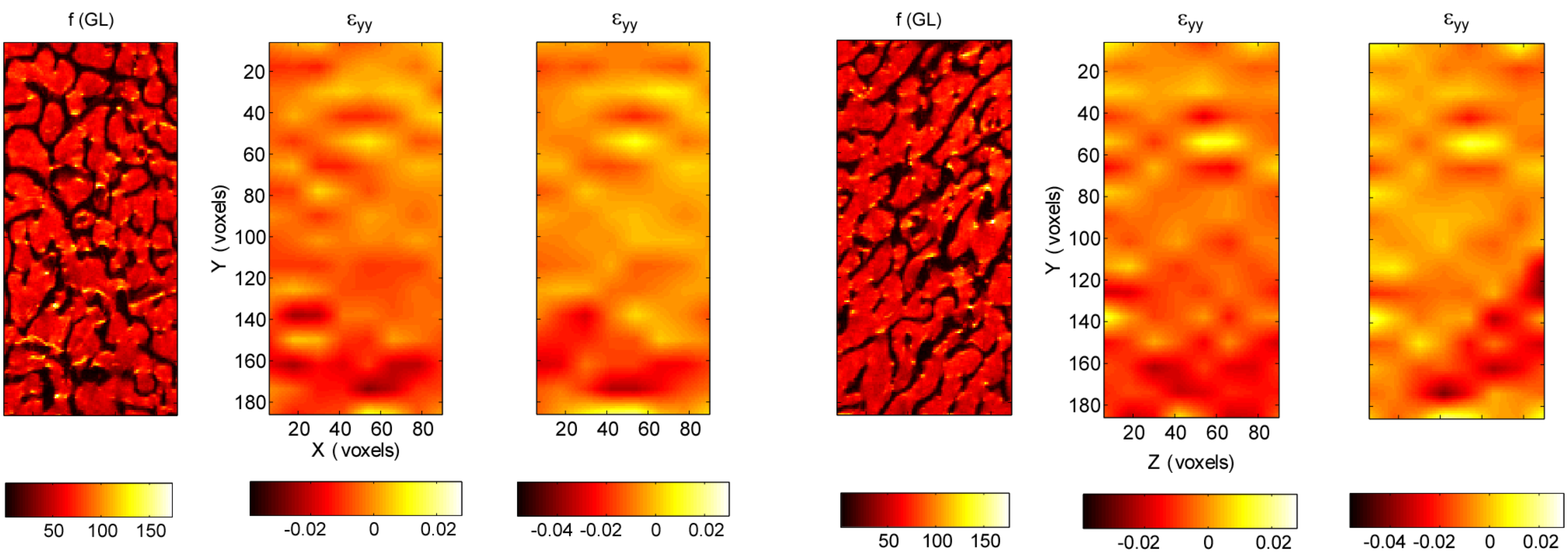


2nd loading step

3D kinematic fields on bovine trabecular sample

Results and discussion

- Cuts along two planes containing the longitudinal axis of the region of interest
- Longitudinal strain fields corresponding to the two loading steps

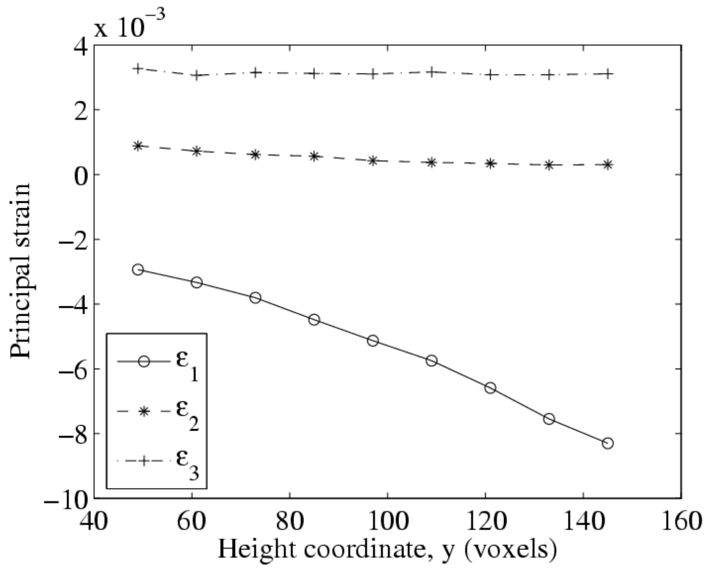


Gray level picture | 1st loading step | 2nd loading step | Gray level picture | 1st loading step | 2nd loading step

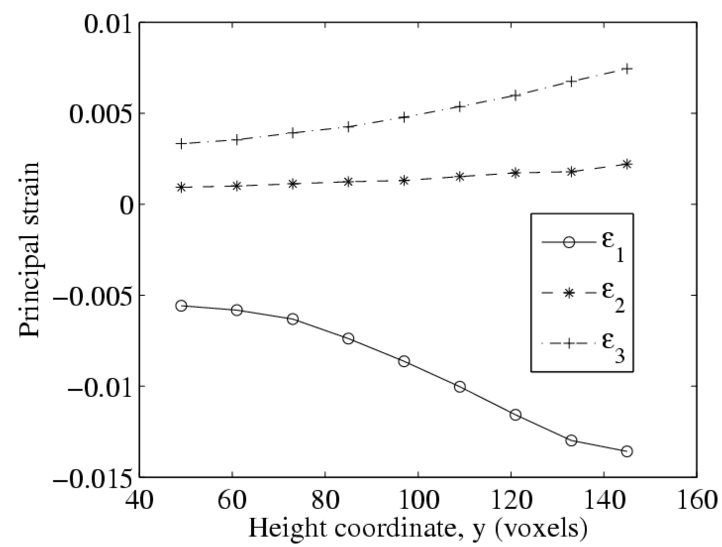
3D kinematic fields on bovine trabecular sample

Results and discussion

- Macroscopic principal strains as functions of the longitudinal position of the gauge volume for the two loading steps



1st loading step



2nd loading step

3D kinematic fields on bovine trabecular sample

Results and discussion

- No uniformity in terms of mesoscopic and macroscopic strains
- The material response is not that expected from a homogeneous medium
- Effect of the microstructure: even if elasticity can be assumed, the elastic properties cannot be inferred from the present observations

3D kinematic fields on bovine trabecular sample

Conclusions

- Uni-axial compression test realized on bovine trabecular bone
- Displacement and strain fields assessed using a DIC technique
- Feasibility of the technique has been demonstrated
- Possibility to measure macroscopic damage on soft tissues such as cartilages or ligaments ?