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

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Osteoporosis and fracture risk prediction

Vertebræ: 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

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


Picture: International Osteoporosis Foundation
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)

- **Personalized Finite Element Models with tomodensitometry**

  😃 **Good prediction of vertebral strength**
  \[
  r^2 = 0.85 \text{ à } 0.95
  \]
  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
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

* 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

Histology

Ultrasound measurement

Calcein coloration

DIC analysis

Uni-axial compression test

Ultrasound measurement

Alizarin coloration

Sample cut

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)

Axial Stress $\sigma_{11}$ (MPa)

Image 1

Image 7

Image 9

Strain field (pixel/pixel)

Compression strain $\varepsilon_{11}$ (%)

Ref Image

Image 7

Image 9

DIC picture

Image 1

Image 9

Image 9

Image 1
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
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?
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*
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
- 20 minutes relaxation prior to image acquisition*

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

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

![Images of strain fields and gray level pictures for different loading steps]
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?