# In silico modelling of the mechanical behaviour of bone and bone-implant systems


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Indian Institute of Science, Bangalore – 18 February 2016

# Exact evaluation of contact stress state in computational elasto-plasticity

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(*Received August 1988*)

INTRODUCTION

Various stress return algorithms in elastoplastic analyses using the finite element method require the

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Crisfield, MA (1991). Nonlinear Finite Element Analysis of Solids and Structures, Wiley.

[A3] Armen, H., Assumptions, models and computational methods for plasticity, *Computers & Structures*, **10**, 161–174 (1979).
[B1] Besseling, J. F., A theory of elastic, plastic, and creep deformations of an initially isotropic material showing anisotropic strain-hardening, creep recovery and secondary creep, *JAM*, **24**, 529–536 (1958).
[B2] Bicanic, N. P., Exact evaluation of contact stress state in computational elasto-plasticity, *Engineering Comp.*, **6**, 67–73 (1989).
[B3] Braudel, H. J., Abouaf, M. & Chenot, J. L., An implicit and incremental formulation for the solution of elastoplastic problems by the finite element method, *Computers and Structures*, **22** (5), 801–814 (1986).

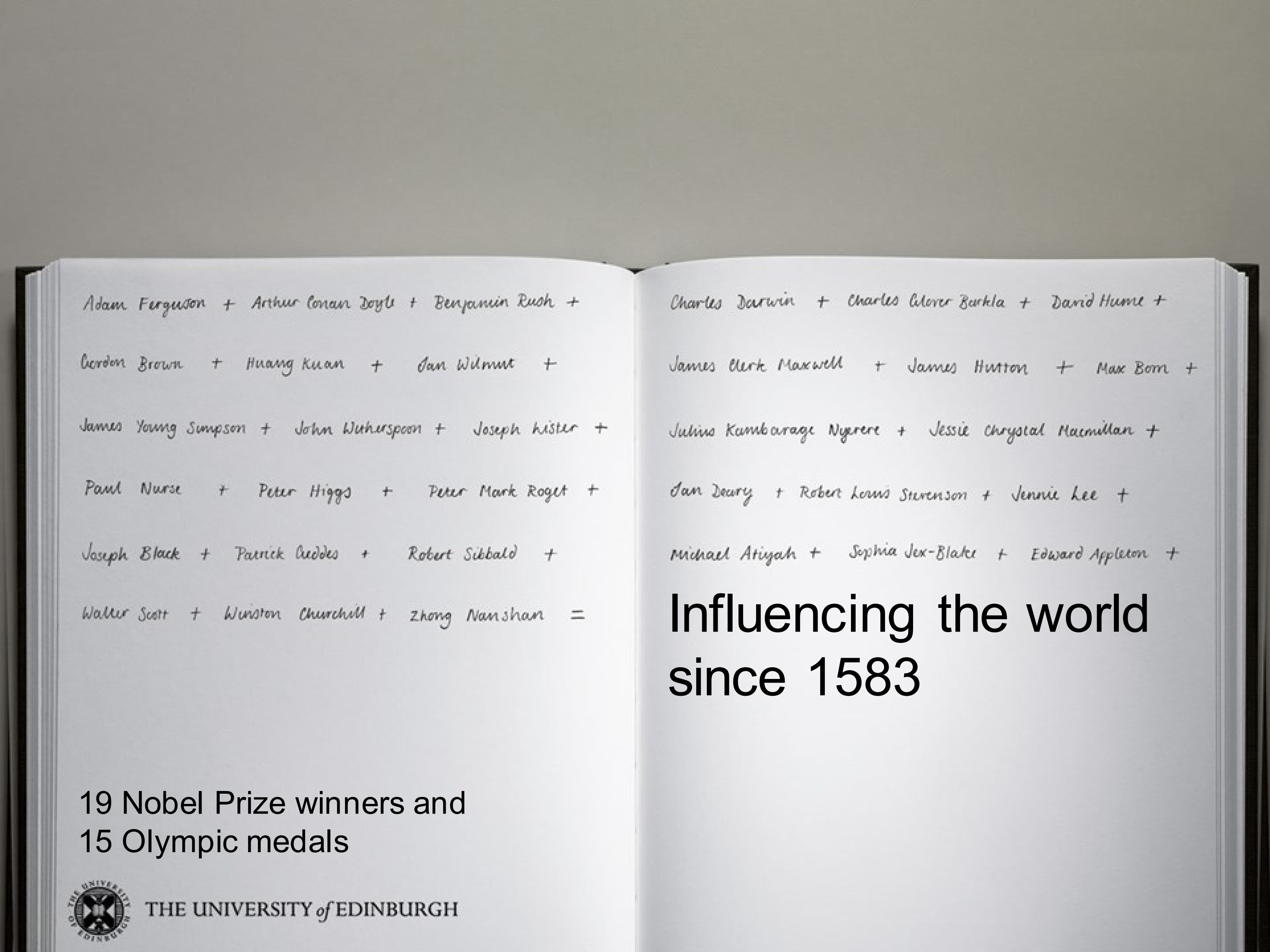
Founded in 1583,the sixth-oldest university in the English-speaking world

We are consistently ranked one of the top 50 universities in the world*

** QS, THES – Thomson Reuters, and Shanghai Jiao Tong Rankings 2015*

100% of our departments are conducting world leading research *

- *2014 UK-wide Research Excellence Framework*


Adam Ferguson + Arthur Conan Doyle + Benjamin Rush +
Gordon Brown + Huang Kuan + Ian Wilmut +
James Young Simpson + John Witherspoon + Joseph Lister +
Paul Nurse + Peter Higgs + Peter Mark Roget +
Joseph Black + Patrick Geddes + Robert Sibbald +
Walter Scott + Winston Churchill + Zhong Nanshan =
Charles Darwin + Charles Glover Barkla + David Hume +
James Clerk Maxwell + James Hutton + Max Born +
Julius Kambarage Nyerere + Jessie Chrystal Macmillan +
Ian Deary + Robert Louis Stevenson + Jennie Lee +
Michael Atiyah + Sophia Jex-Blake + Edward Appleton +
Influencing the world since 1583
19 Nobel Prize winners and
15 Olympic medals
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# Relationships

## 'Pop up campuses' / annual visits

India 2015

- 40 academics

India 2016

- Activities in Pune, Chennai, Mumbai, Delhi, Bengaluru, Vellore
- Participation in MII
- Interaction with industry
- Interaction with government
- Student participation

Strategy

- Partnerships
- Attracting best talent
- Student mobility

# Motivation

- Ageing population – fractures and mortality, implant suitability
- Bone structure/behaviour of interest to pharmaceutical industry
- Implants need to last longer
- Patients expect to remain active
- Potential to replace expensive clinical trials

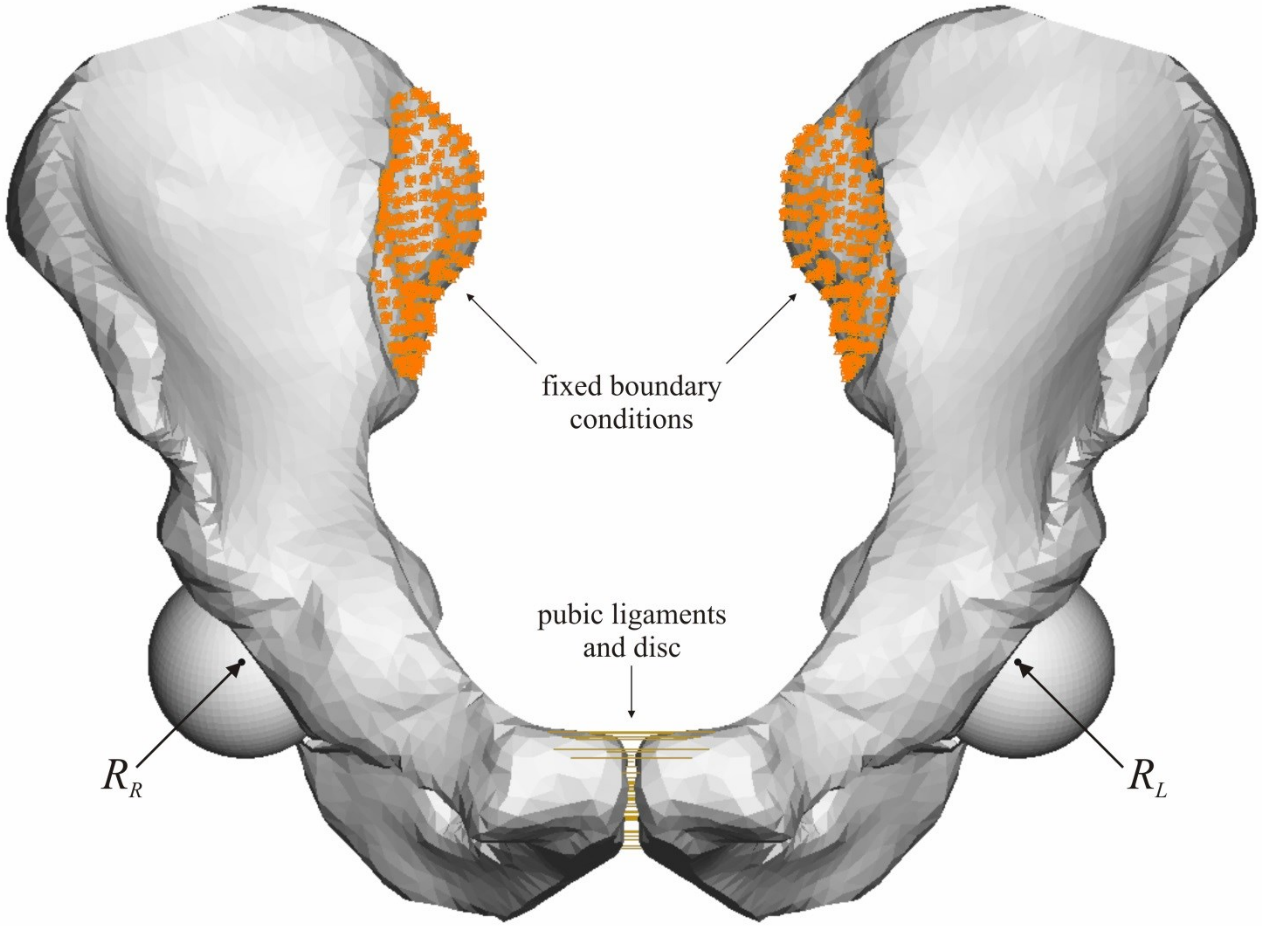
# Modelling – Information required

- Geometry: subdivided into elements – 1/2/3D
- Boundary conditions and interactions
- Material properties: linear/nonlinear, isotropic/anisotropic, time dependent/ independent
- Loads: static/dynamic

# Boundary conditions

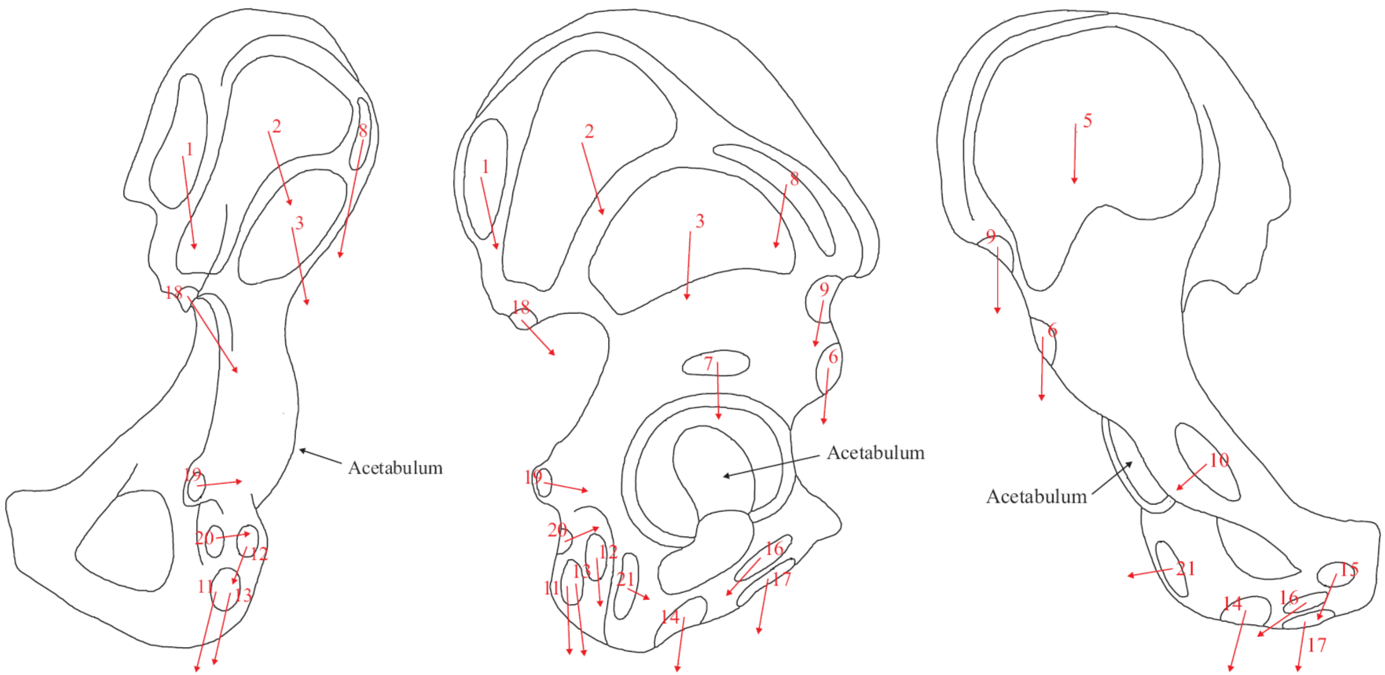
# Boundary conditions – stresses in the pelvis

Constrained at the sacro-iliac joints



# Boundary conditions – stresses in the pelvis

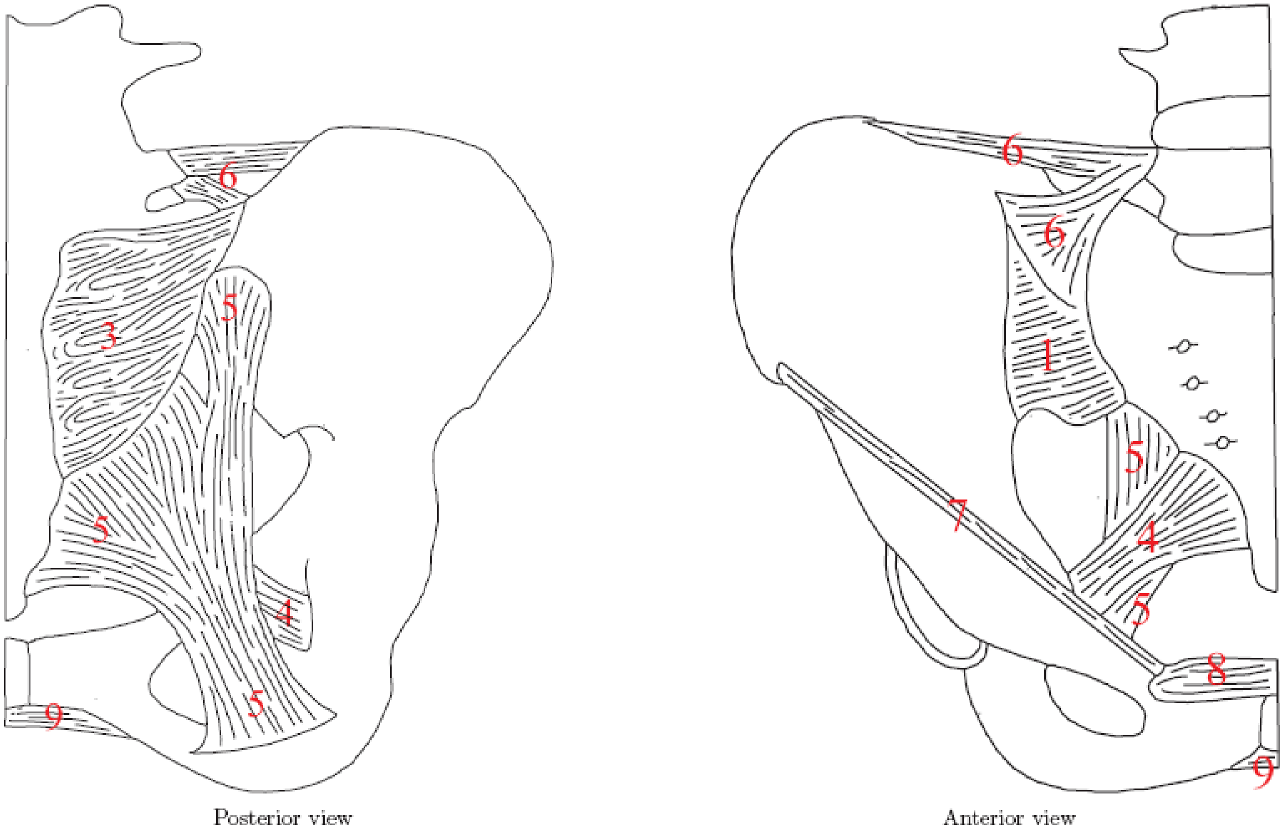
## Muscles



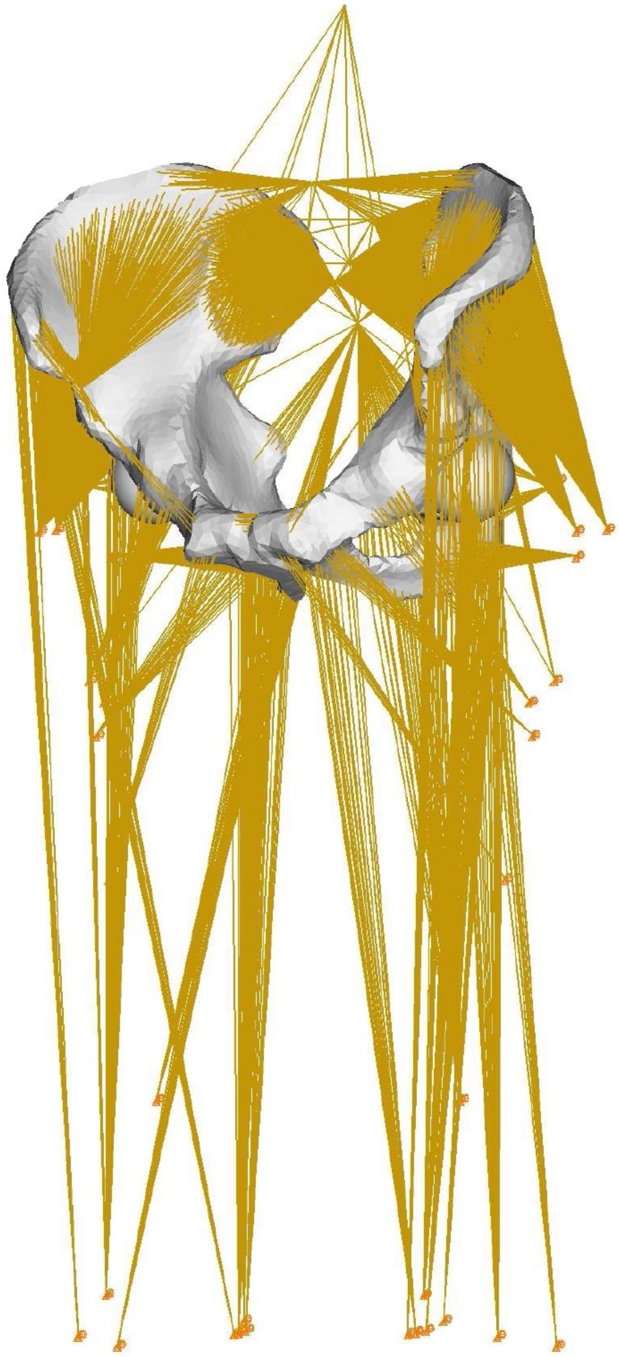

1. Gluteus maximus; 2. Gluteus medius; 3. Gluteus minimus; 4. Psoas (not shown); 5. Iliacus; 6. Rectus femoris (straight head); 7. Rectus femorus (reflected head); 8. Tensor fasciae latae; 9. Sartorius; 10. Pectineus; 11. Semitendinosus; 12. Semimembranosus; 13. Biceps femoris (long head); 14. Adductor magnus; 15. Adductor longus; 16. Adductor brevis; 17. Gracilis; 18. Piriformis; 19. Gemellus superior; 20. Gemellus inferior; 21. Quadratus femoris

# Boundary conditions – stresses in the pelvis

## Ligaments

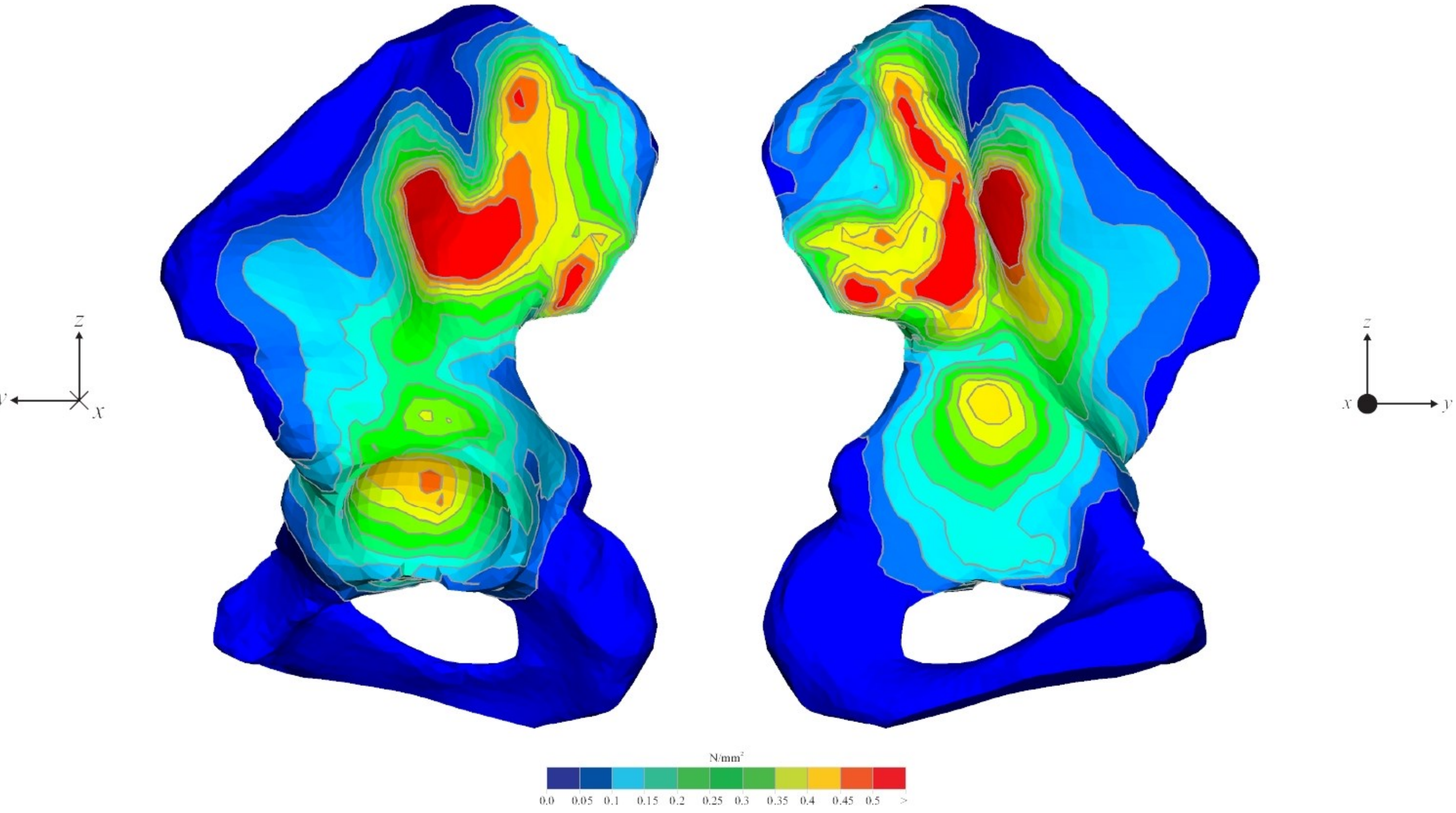



1. Anterior sacroliliac; 2. Interosseus sacroiliac (hidden); 3. Posterior sacroliliac; 4. Sacrospinous; 5. Sacrotuberous; 6. Iliolumbar; 7. Inguinal; 8. Superior pubic; 9. Arcuate pubic



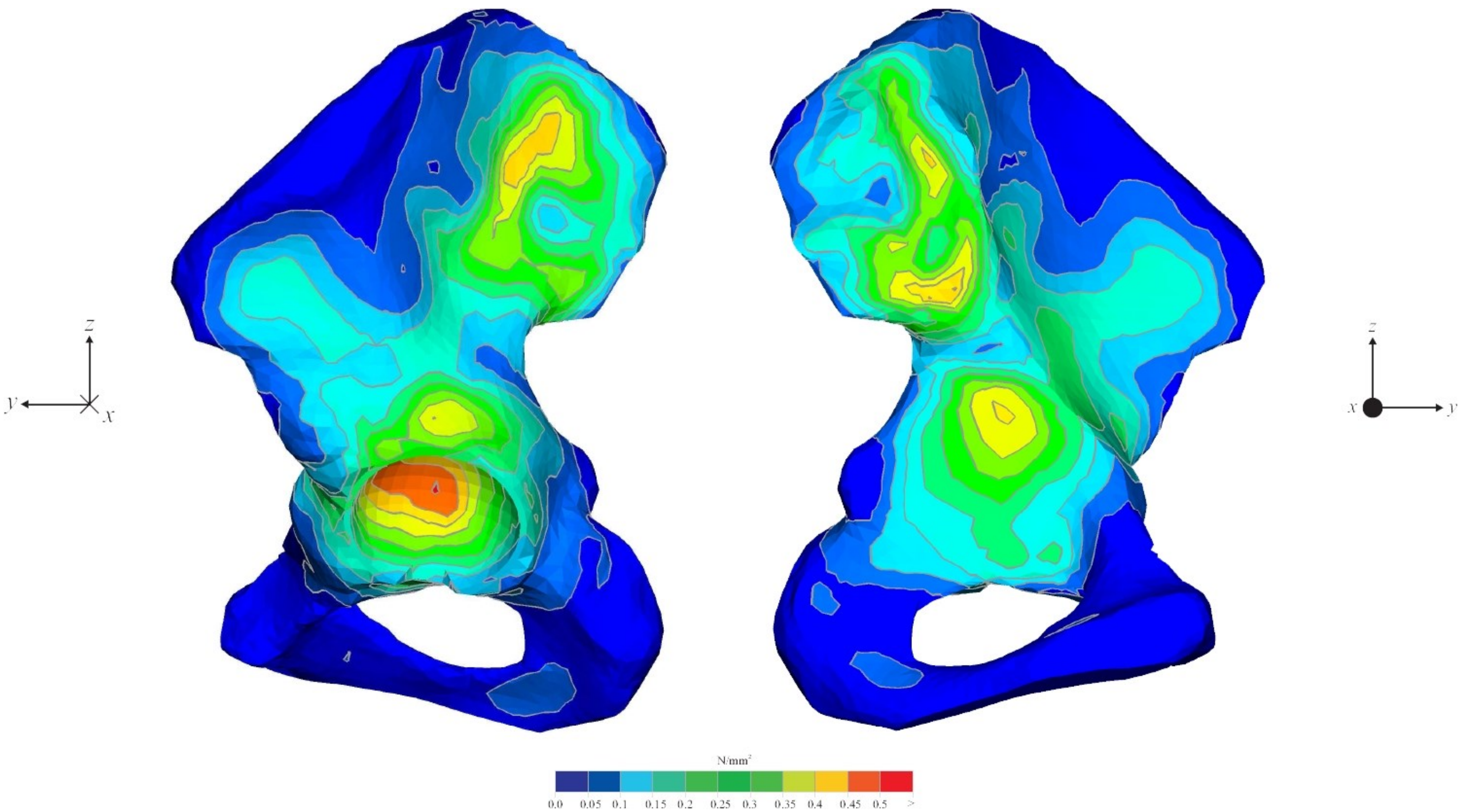
**Phillips, Pankaj, Howie, Usmani, Simpson — *J Med Eng & Phy,* 2007**

# Boundary conditions - constrained




von Mises stress in the trabecular bone for the constrained BC model

# Boundary conditions – muscles and ligaments

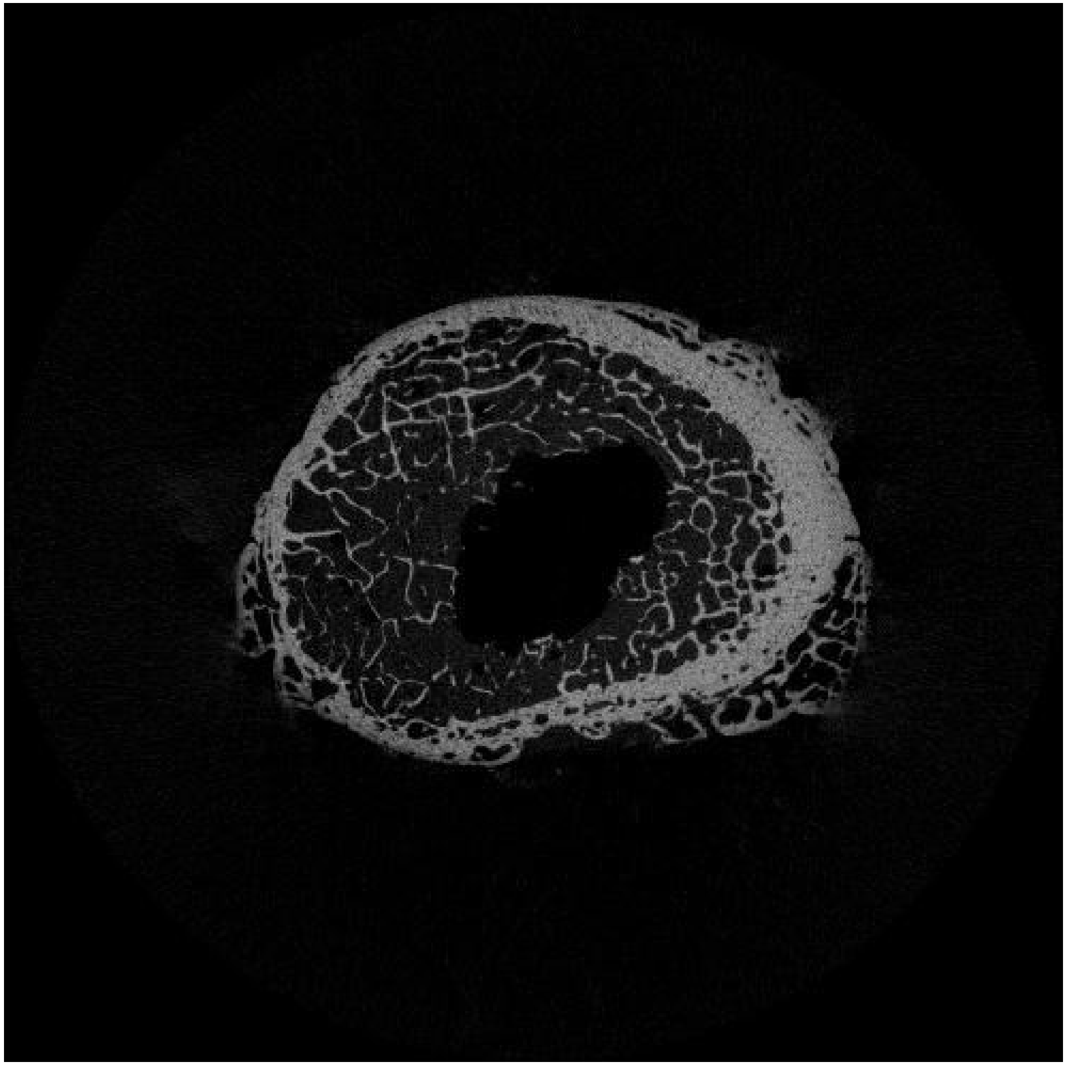



von Mises stress in the trabecular bone for the ML BC model

**Phillips, Pankaj, Howie, Usmani, Simpson — *J Med Eng & Phy*, 2007**

# Bone microstructure

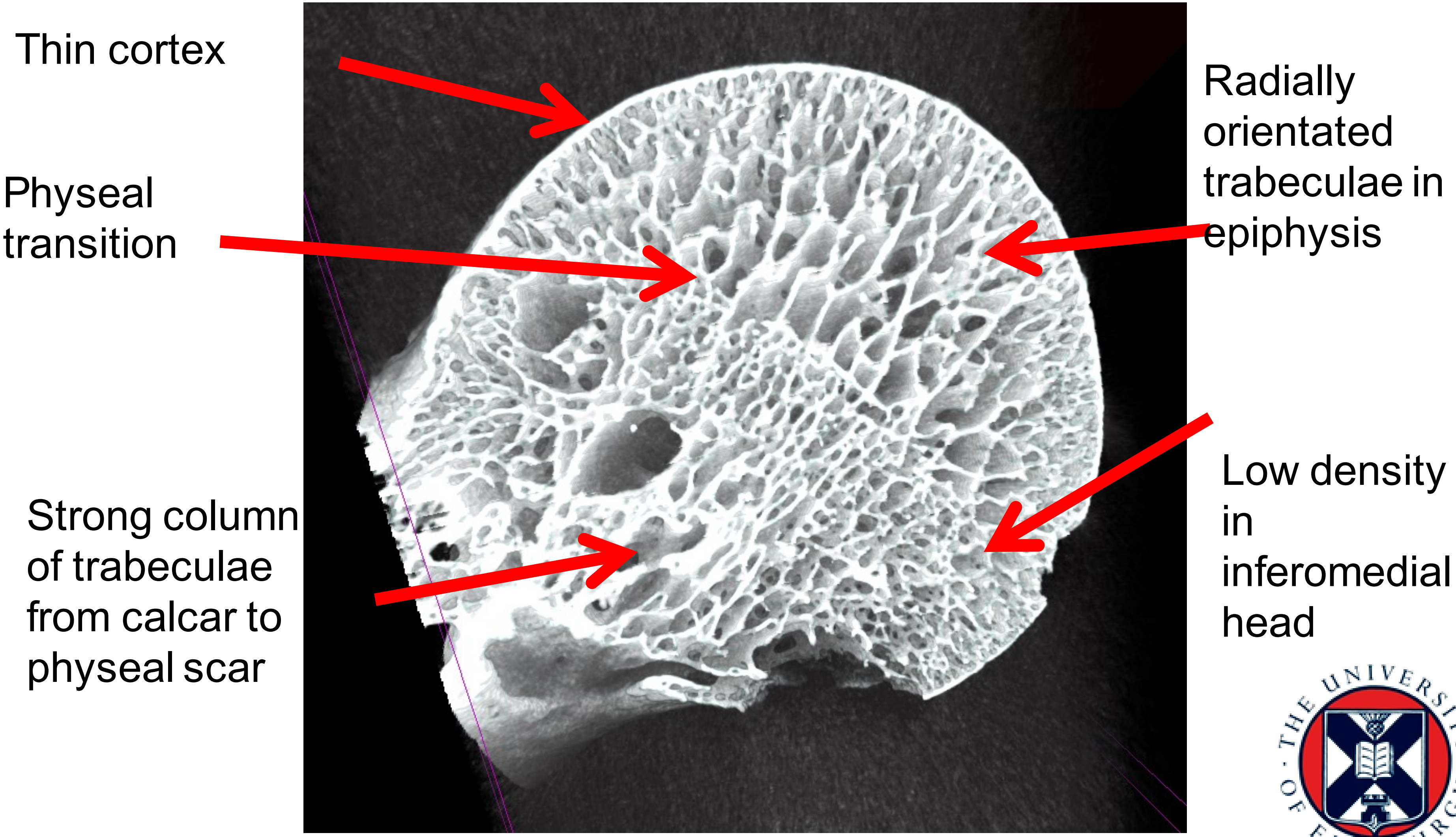
# Microarchitecture of the femoral head



# Morphometrical Parameters

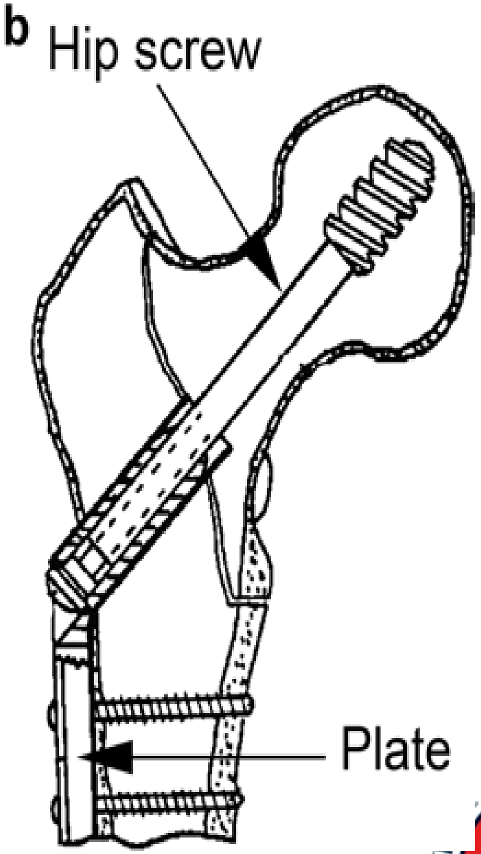
- BV/TV
- Trabecular thickness (Tr. Th.)
- Structural model thickness (SMI)
- Degree of anisotropy (DA)

# Results

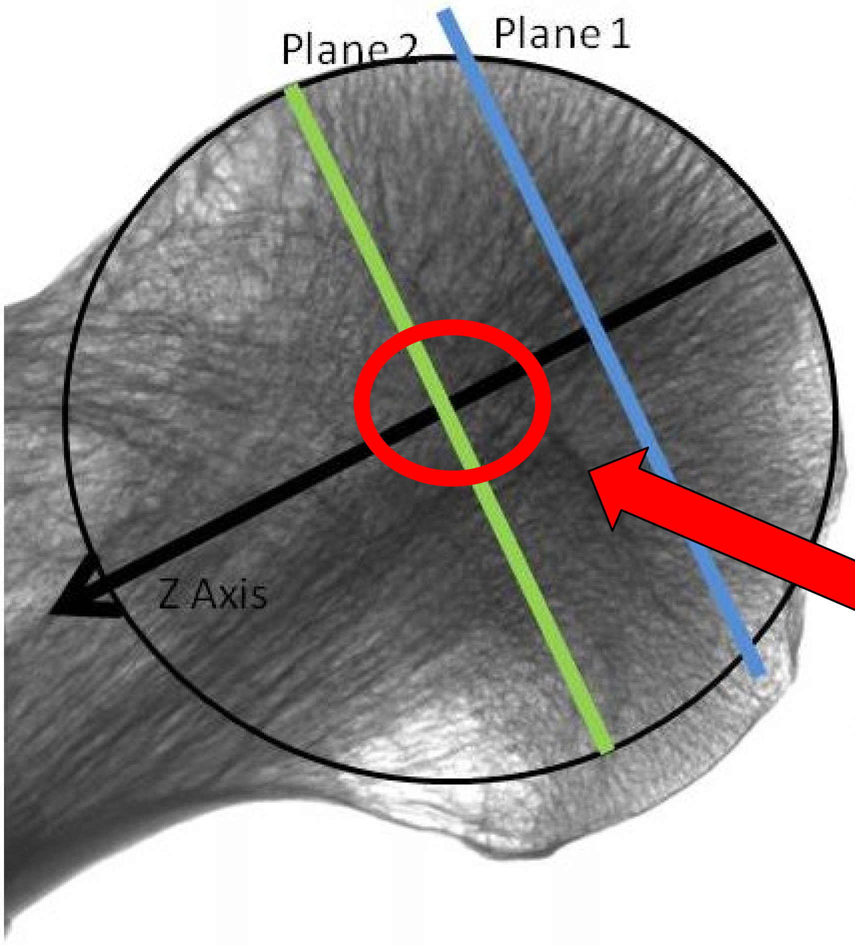


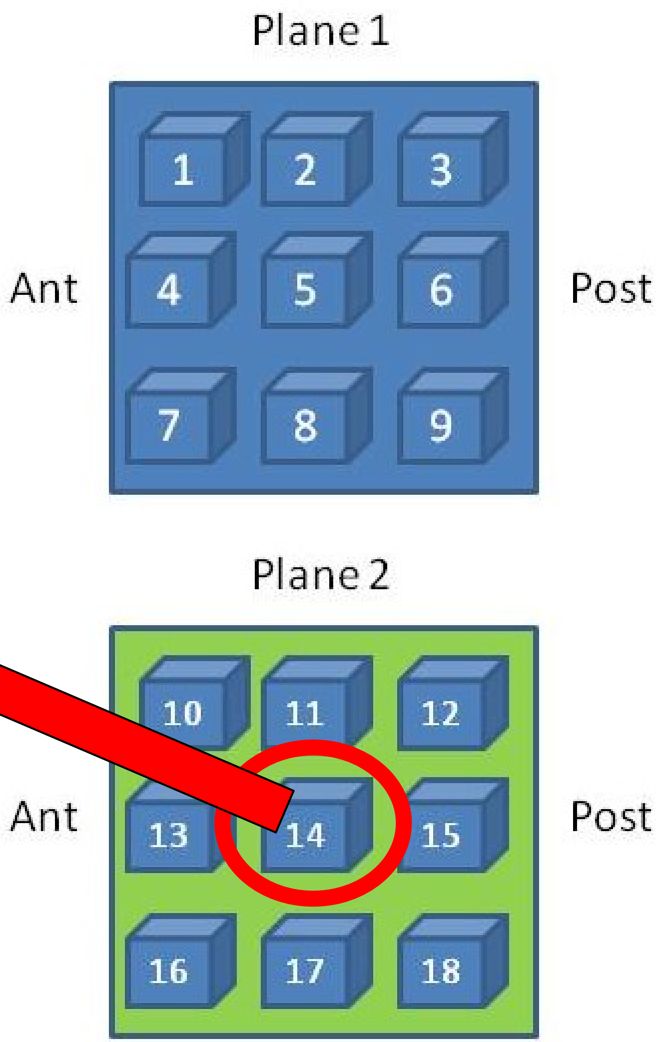
Thin cortex
Physeal transition
Strong column of trabeculae from calcar to physeal scar
Radially orientated trabeculae in epiphysis
Low density in inferomedial head

# Hip Fracture Fixation

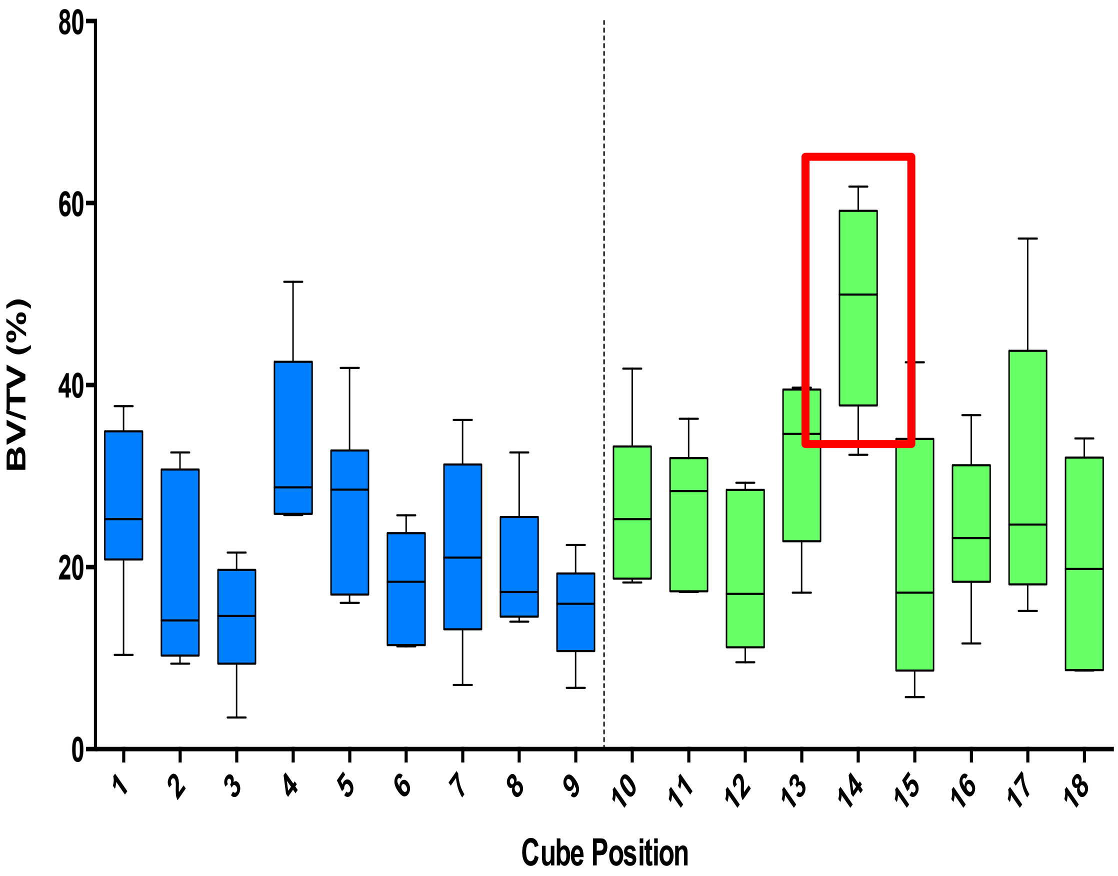


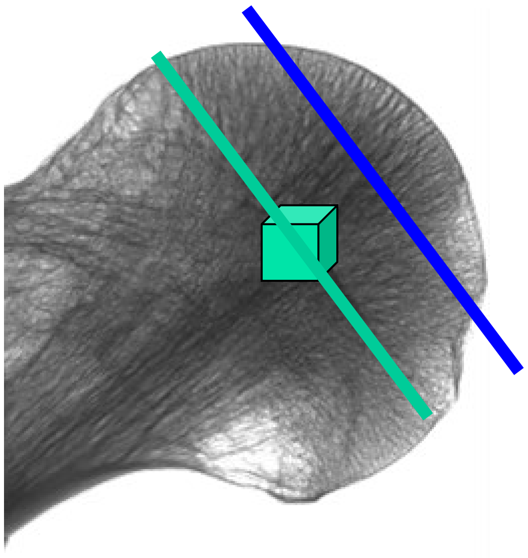
# Femoral Scans



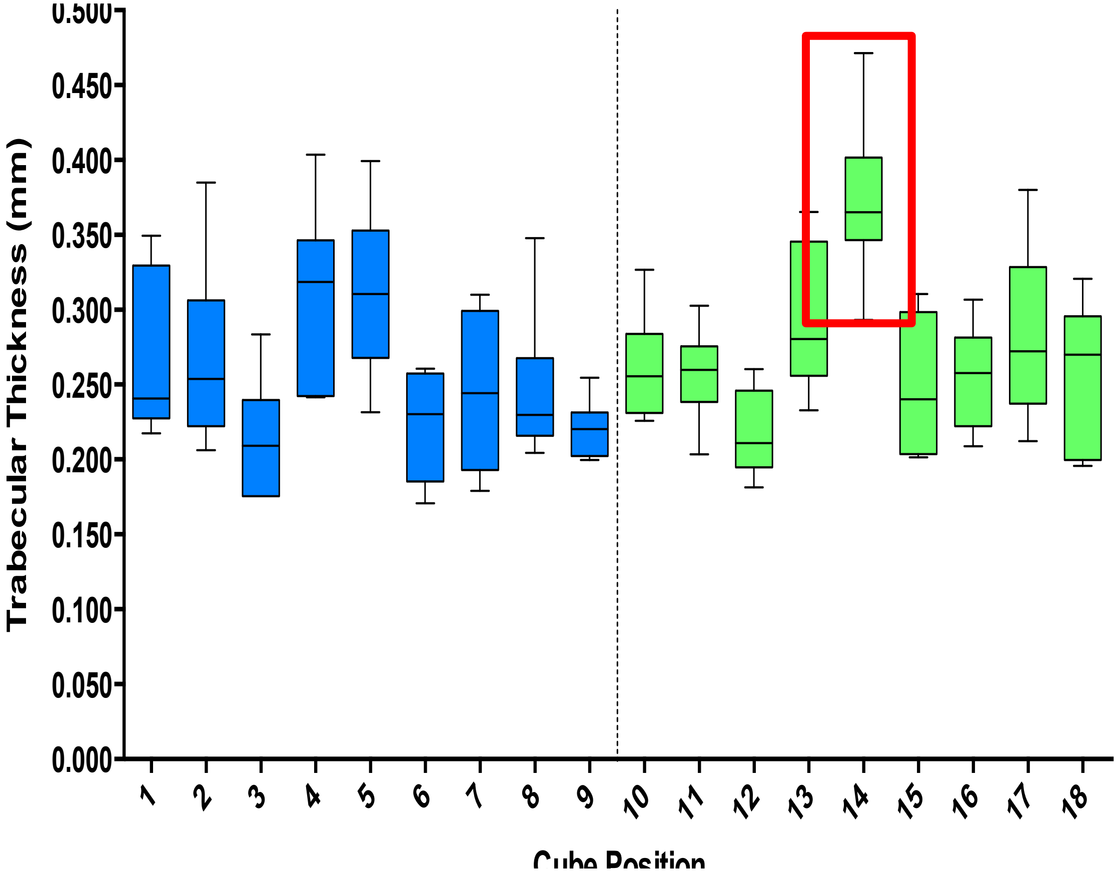



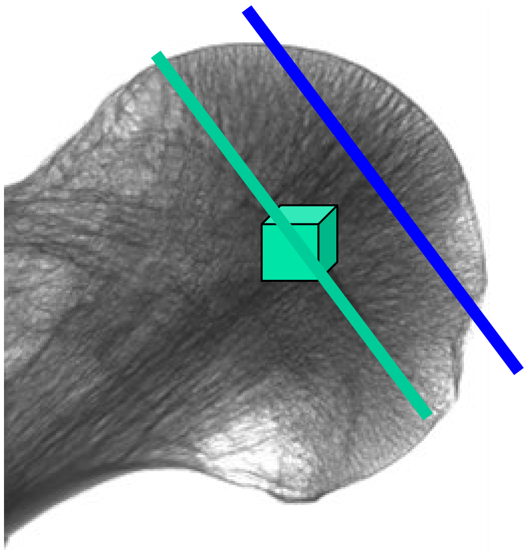
# 3D: BV:TV (Density)



# Trabecular Thickness (Tb. Th.)



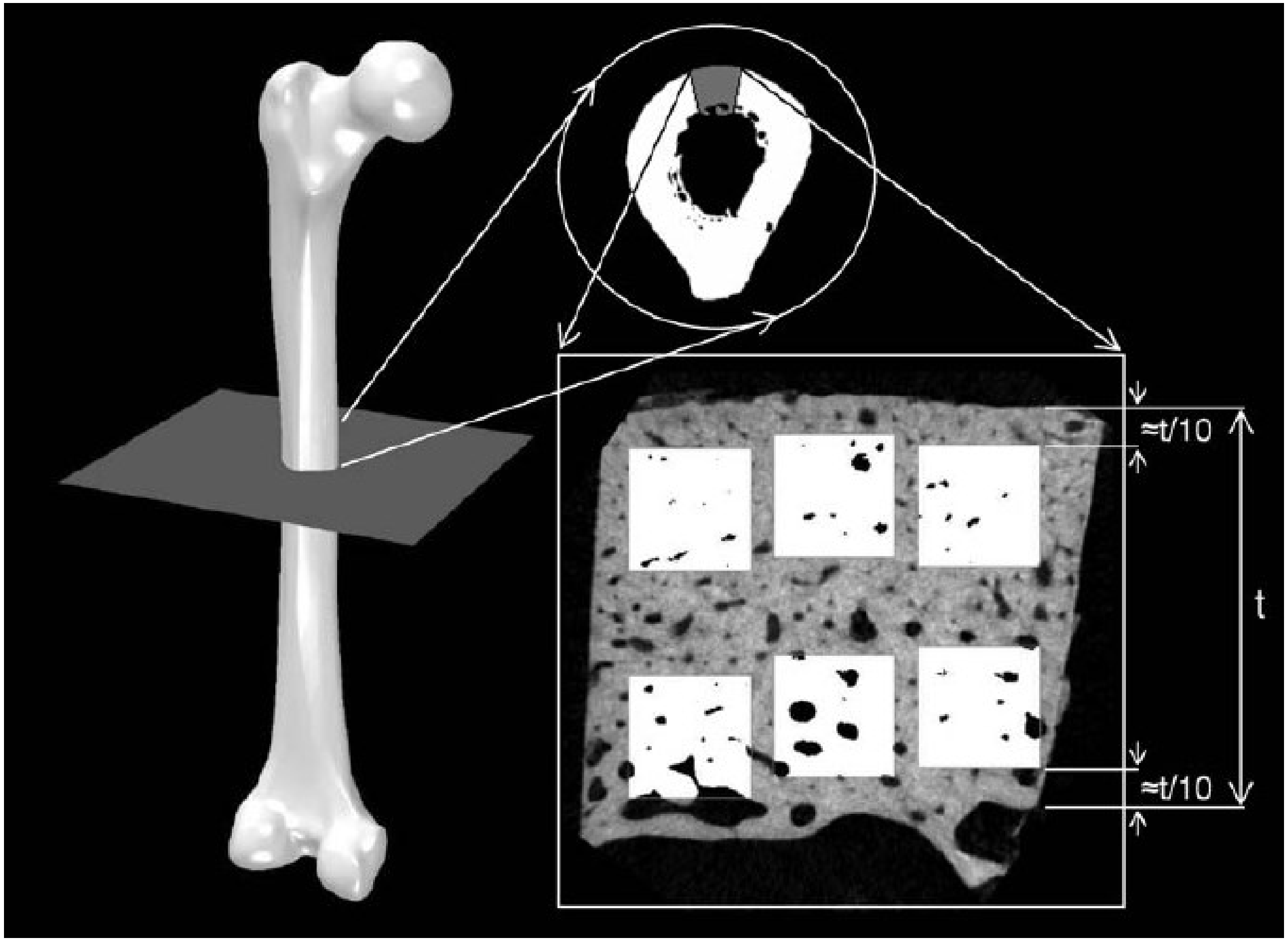
# Material properties:

## Elasticity

# Material properties

- Variations – inhomogeneity
- Linear elastic – isotropic or transtropic or orthotropic or anisotropic
- Time dependent – e.g. viscoelasticity
- Inelasticity – e.g. plasticity
- Etc

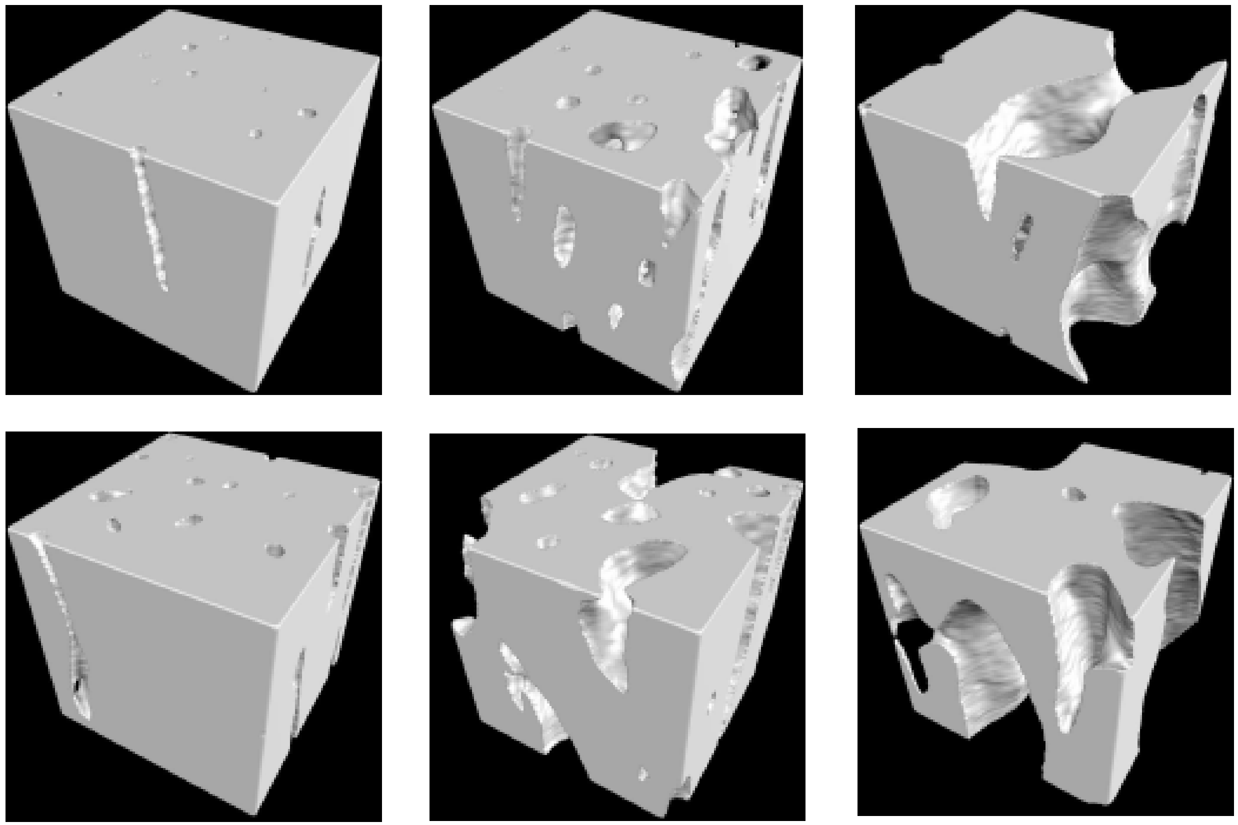
# Cortical bone data



# Cortical bone

Periosteal

Endosteal



Female 20-year-old

Female 61-year-old

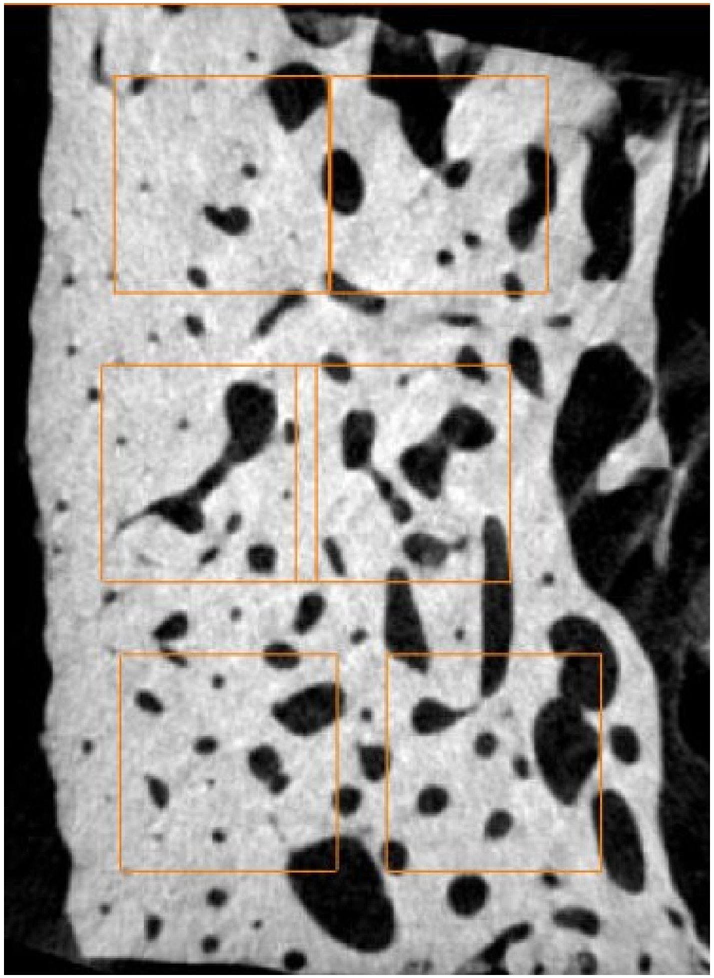
Female 84-year-old

# Cortical bone – elastic properties with patient-specific parameters

- μCT scans of cortices from the anterior femoral midshaft, (Melbourne Femur Collection)
  - 27 females, 50 males
  - 7μm isotropic scanning resolution
- Scanning and micro-architecture analysis – Cooper et al. 2007
- This study – variation of mechanical properties with micro-architecture

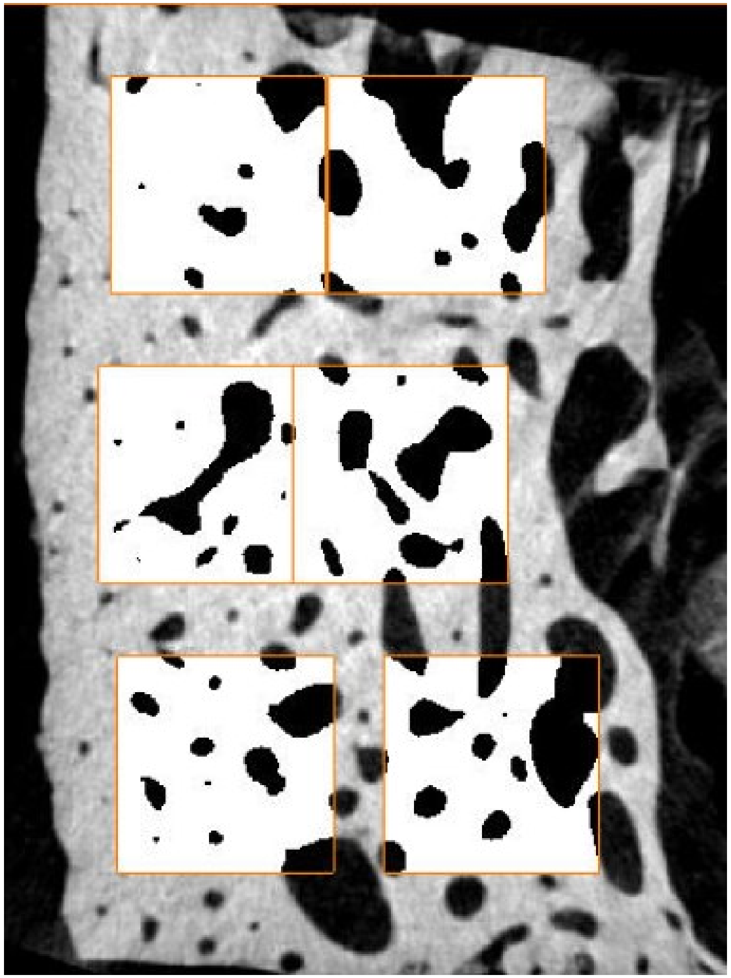
# Cortical bone – elastic properties with patient-specific parameters

- Select sub-samples



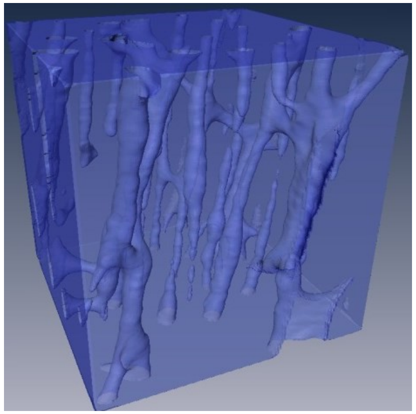
# Cortical bone – elastic properties with patient-specific parameters

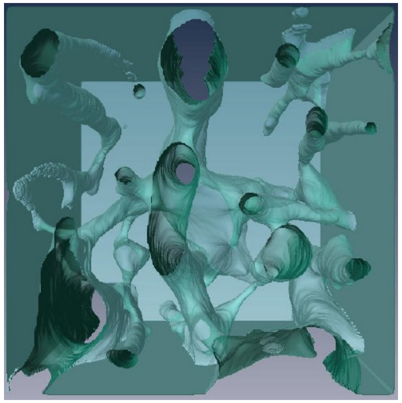
- Label solid/void

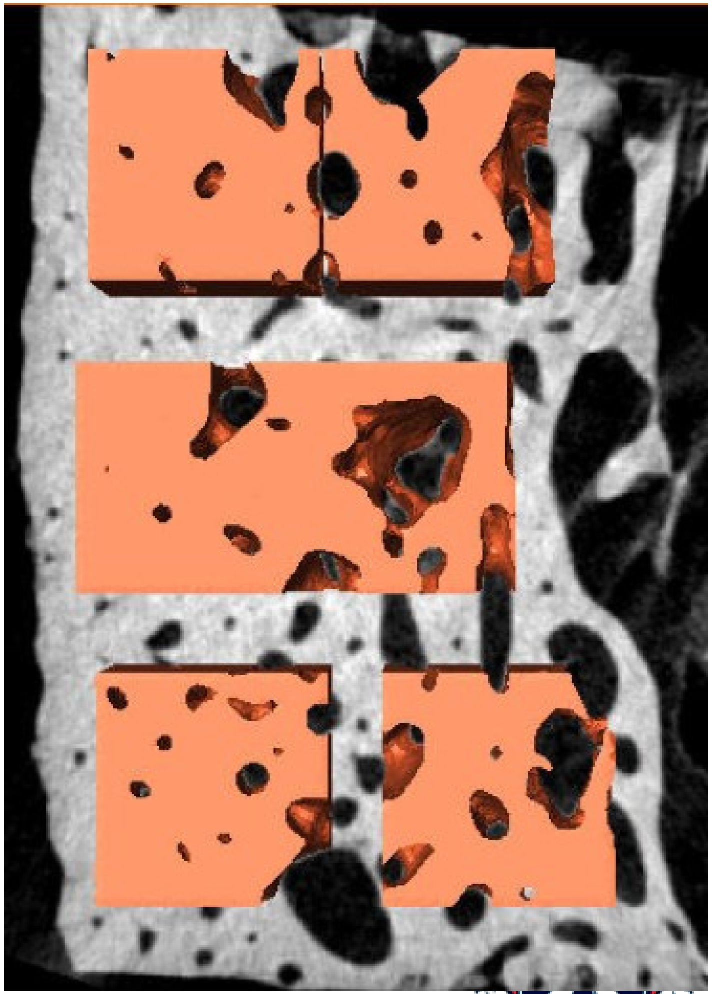


# Cortical bone – elastic properties with patient-specific parameters

- Generate triangular surface. Approx. 20,000 triangles per surface



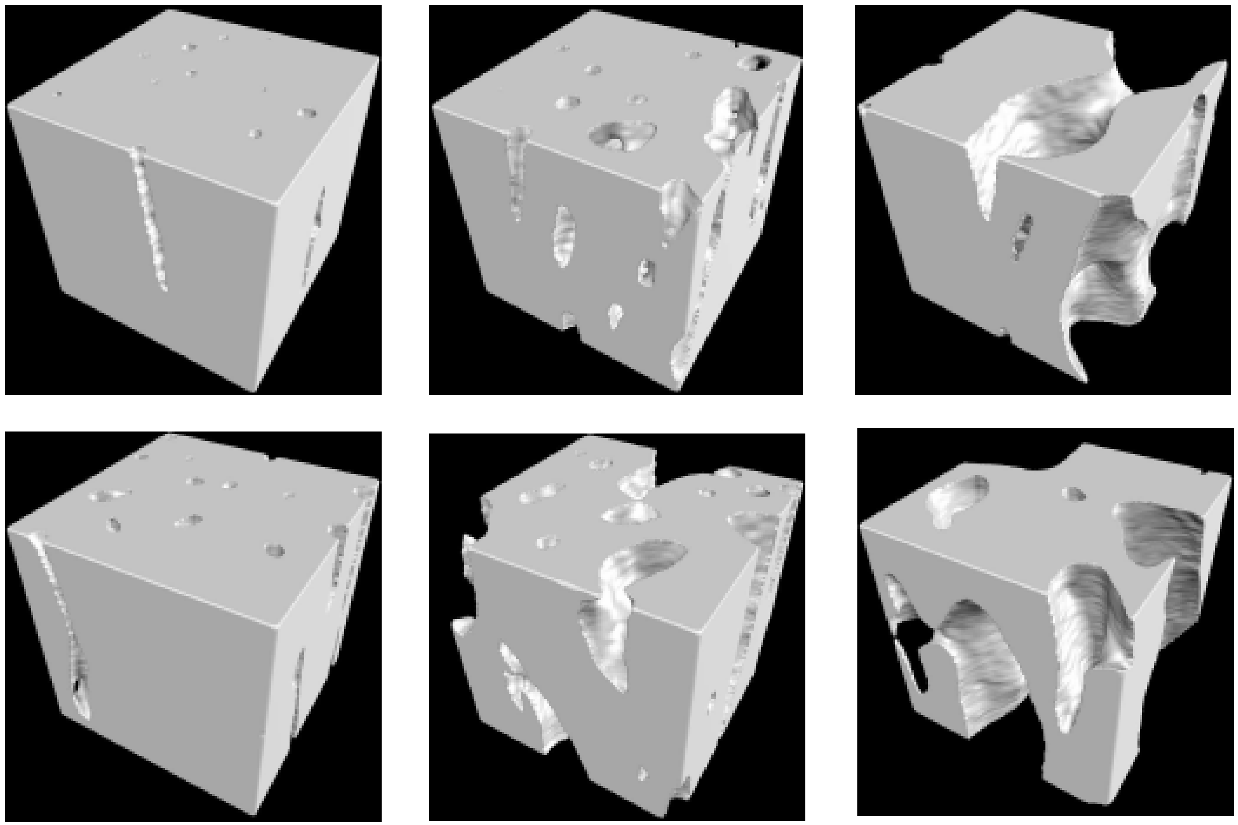




# Cortical bone – elastic properties with patient-specific parameters

Periosteal

Endosteal



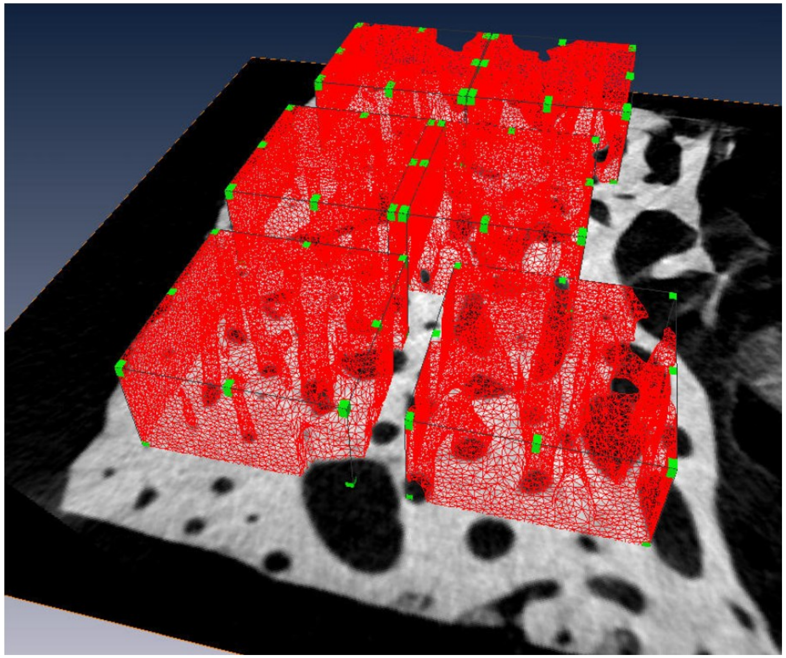
Female 20-year-old

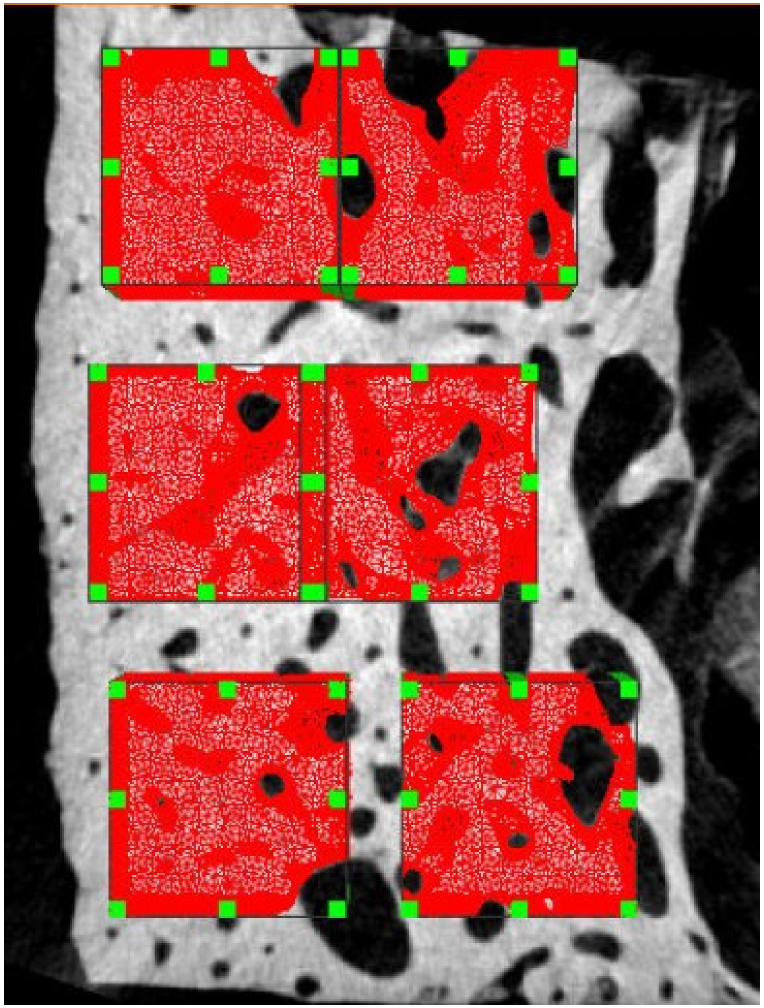
Female 61-year-old

Female 84-year-old

# Cortical bone – elastic properties with patient-specific parameters

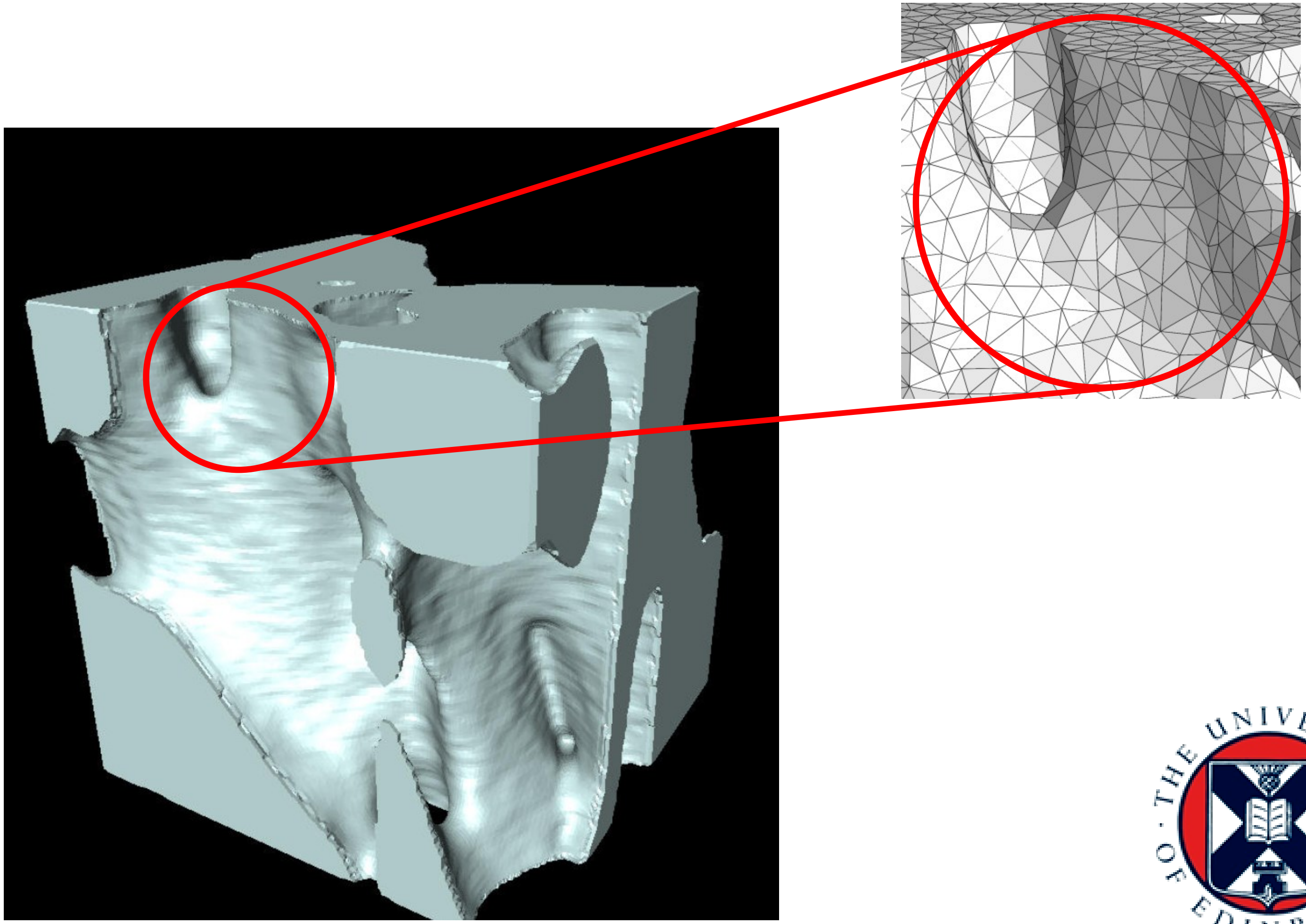
- Generate mesh
- Approx 250k elements





# Cortical bone – elastic properties with patient-specific parameters

- Constructed 3D image and mesh



# Cortical bone – elastic properties with patient-specific parameters

- Six numerical strain states computationally applied
- Full elasticity tensor evaluated
- Tensor reoriented to best fit orthotropy assumption

# Cortical bone – elastic properties with patient-specific parameters

Q1: Is cortical bone in femoral midshaft orthotropic?

A1: Yes

$$Error^{ORT} = \max_{\varepsilon \neq 0} \frac{\left\| \varepsilon - \varepsilon^{ORT} \right\|}{\left\| \varepsilon \right\|}$$

Periosteal: 0.16% median, 3.86% max

Endosteal: 2.16% median, 11.48% max

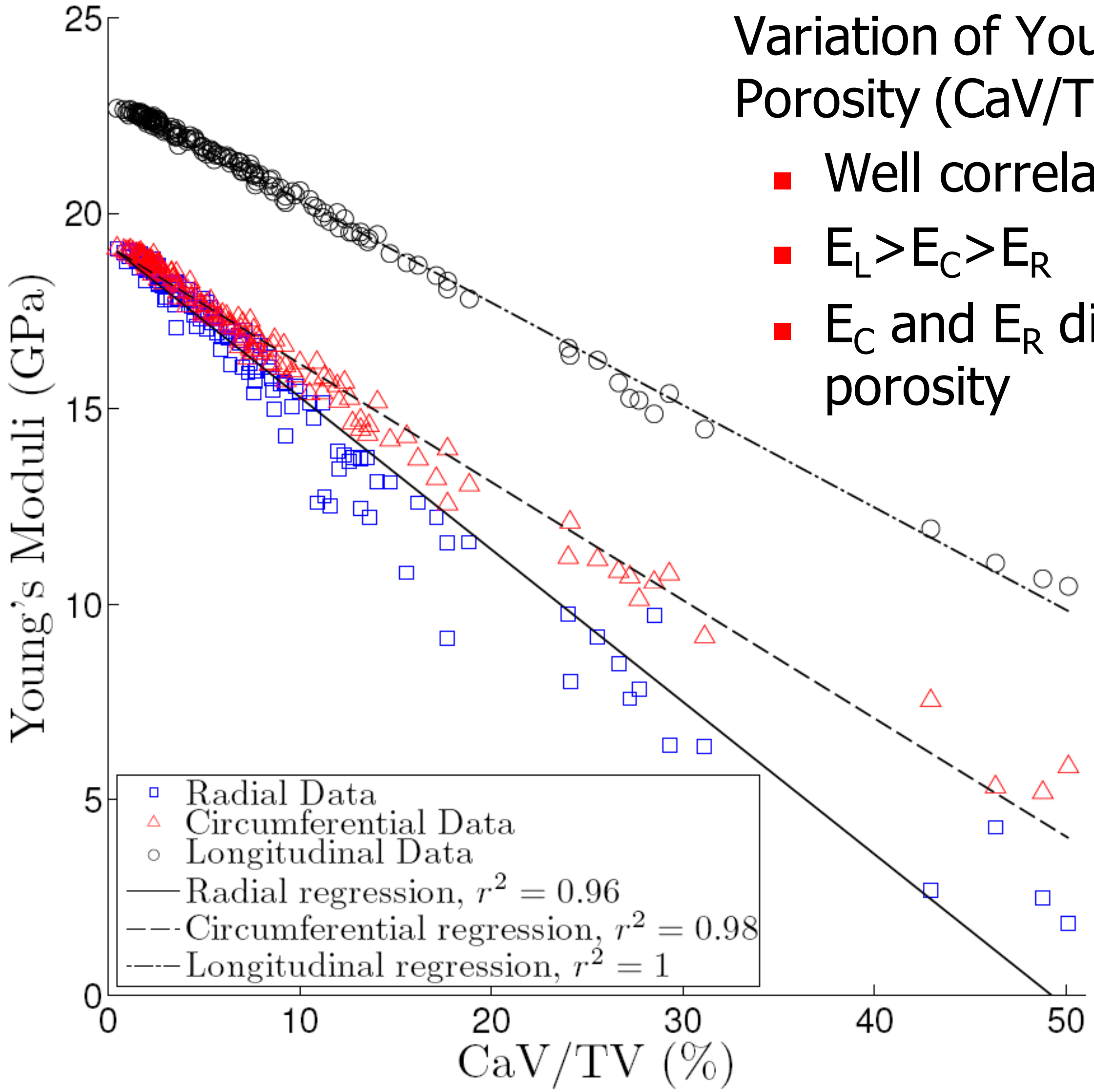
# Cortical bone – elastic properties with patient-specific parameters

Q2: Which indices of micro-architecture correlate best with elastic constants?

A2: Ca.V/TV

We also considered Ca.S/TV, Ca.Dm/TV, DA

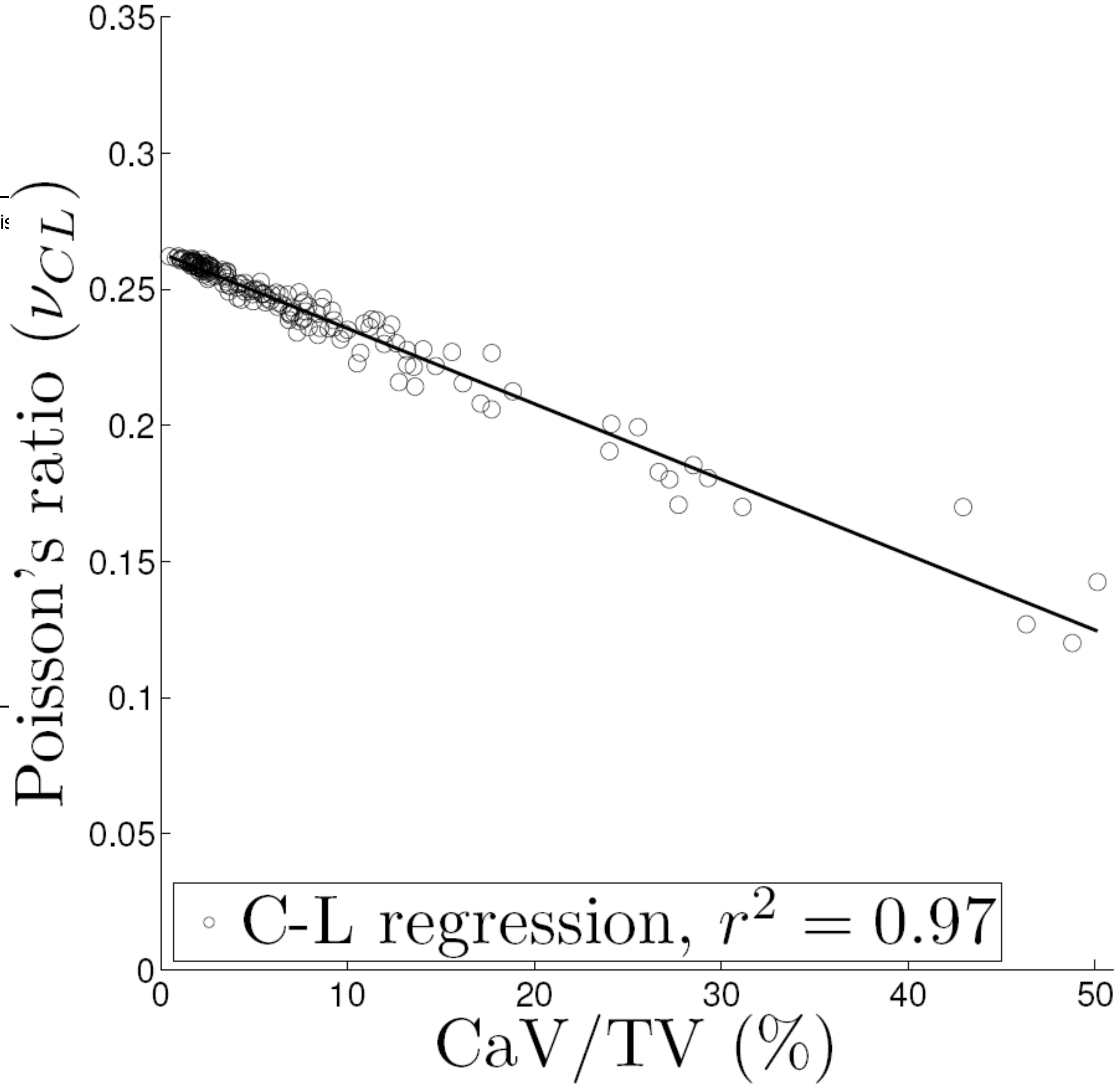
# Results – *E*



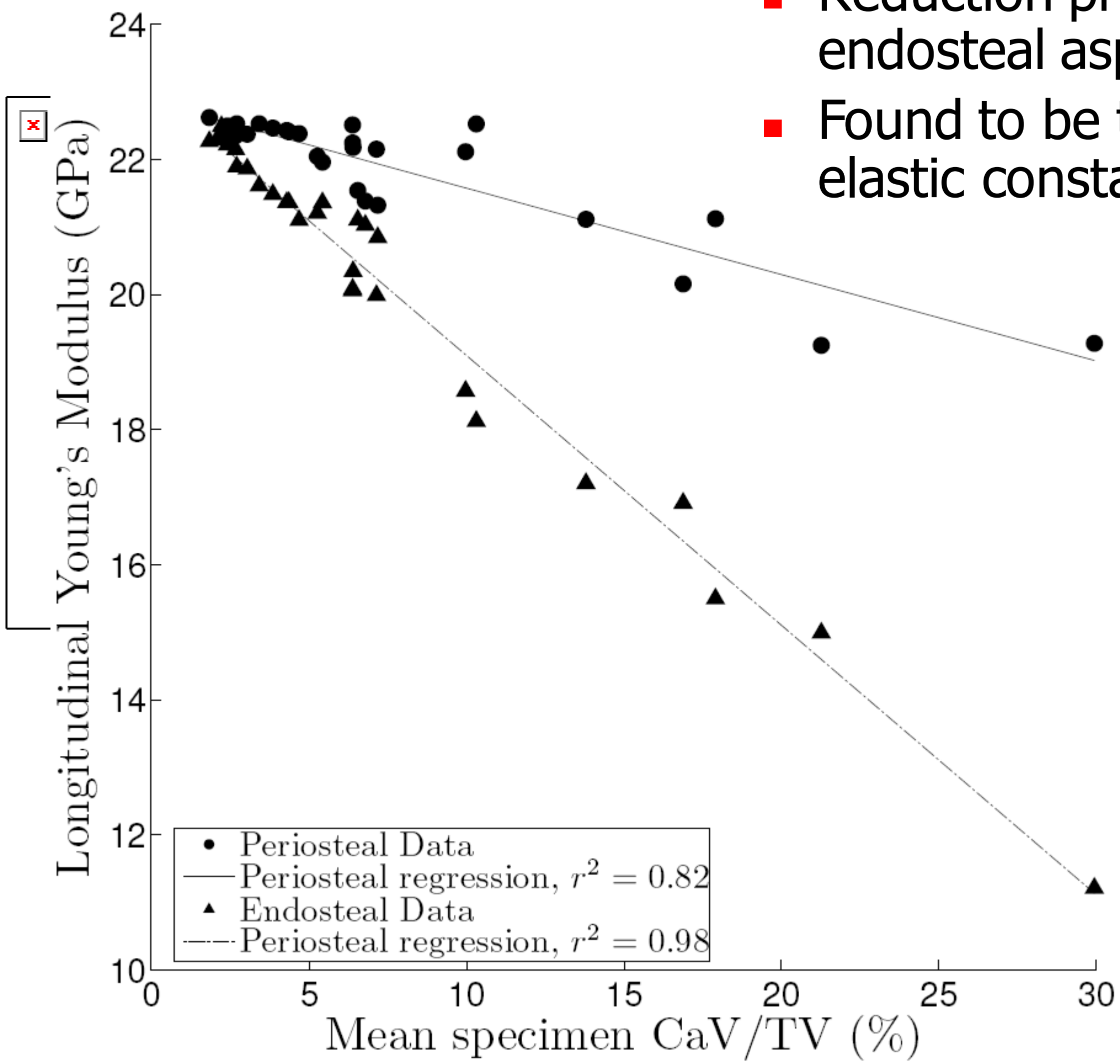

Variation of Young's moduli vs Porosity (CaV/TV)

- Well correlated
- $E_L > E_C > E_R$
- $E_C$ and $E_R$ divergent with porosity

# Results – $\nu_{CL}$



# Results – periosteal-endosteal variation




- E decreases with Ca.V/TV
- Reduction prnounced at endosteal aspect
- Found to be true for all elastic constants

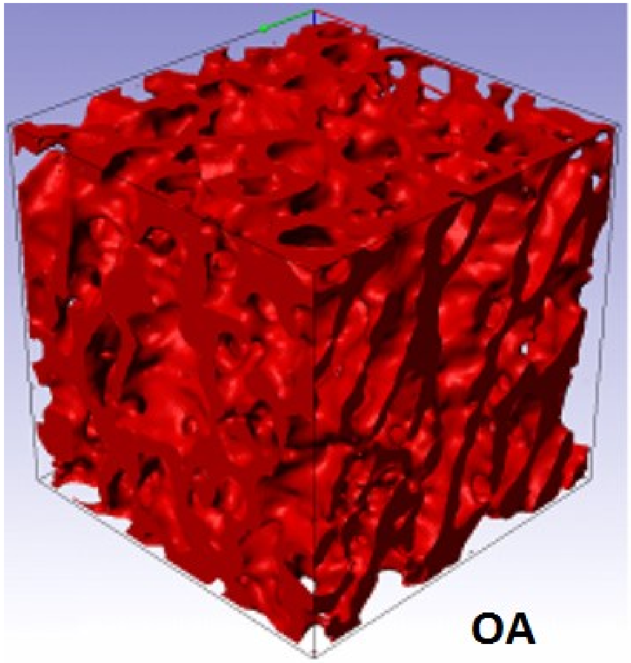
# Conclusions

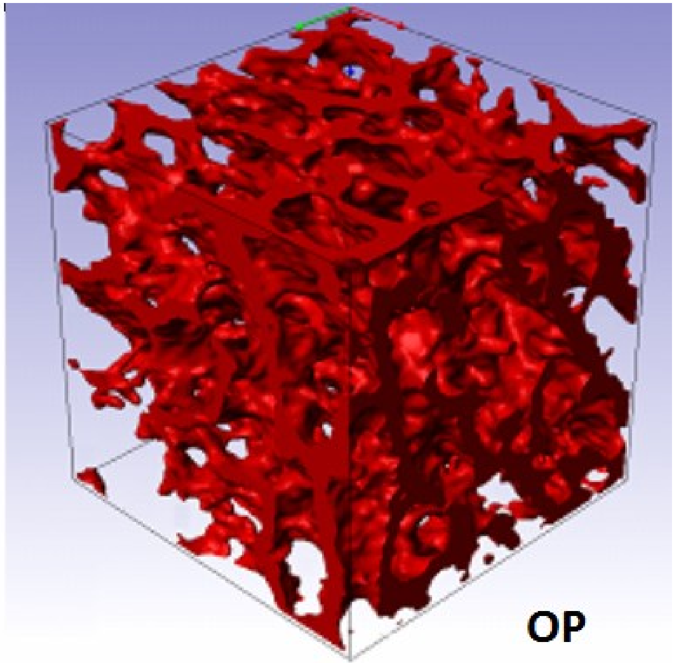
- It providess all orthotropic constants
- Ca.V/TV is best (and only required) predictor
- All constants reduce with increasing porosity

Donaldson et al., 2011, IMechE, H

# Trabecular bone – elastic properties

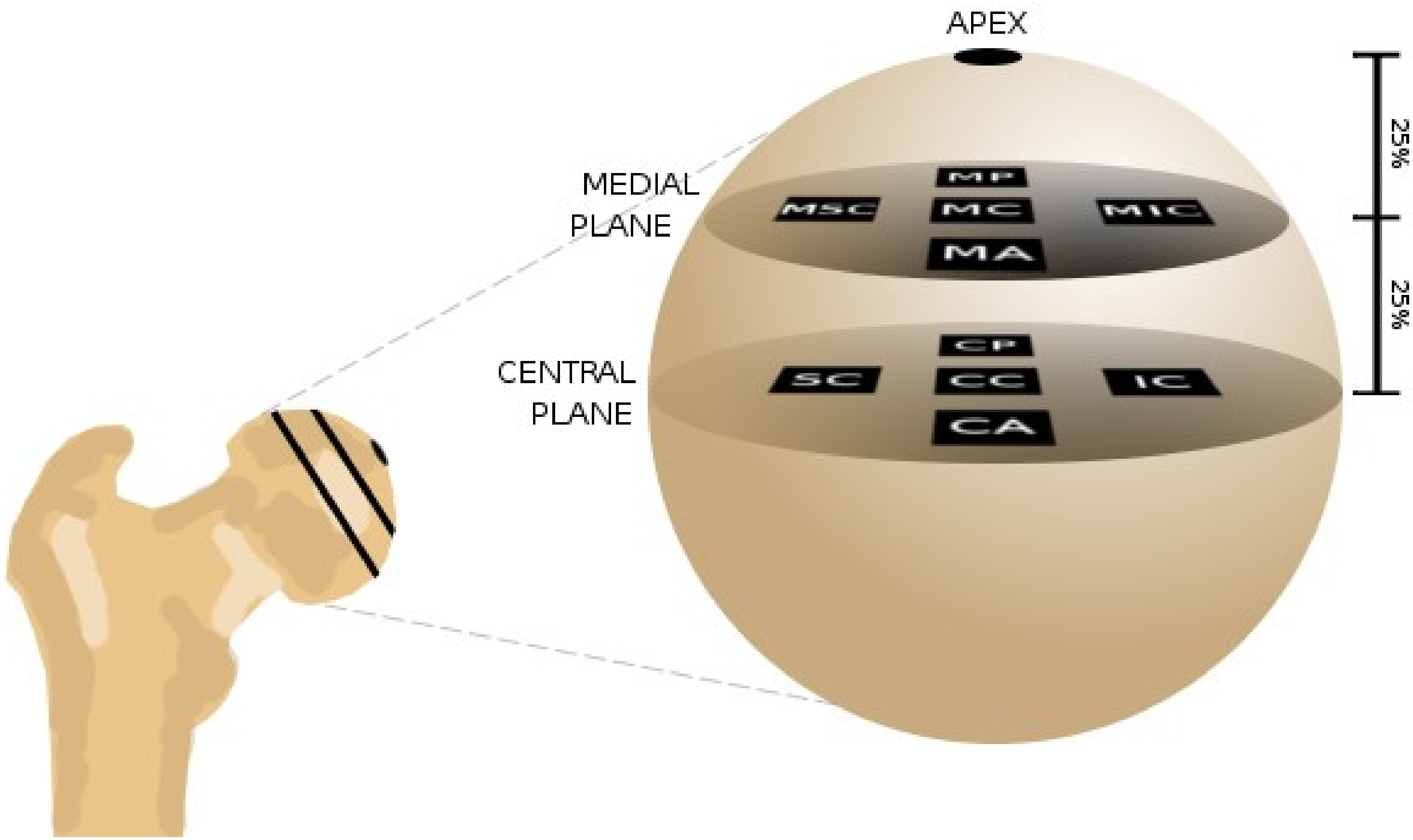
- µCT scans of trabecular bone from the femoral head (Tissue Bank of the Scottish National Blood Transfusion service)
  - 10 female, 2 male (age 71.3 ± 7.6 years)
  - 6 OA and 6 OP
  - 30µm isotropic scanning resolution



# Methodology – µCT scan data

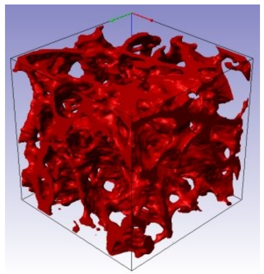
- 5mm cubic regions extracted from 10 locations for each head



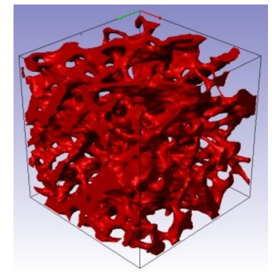
# Methodology - µCT scan data

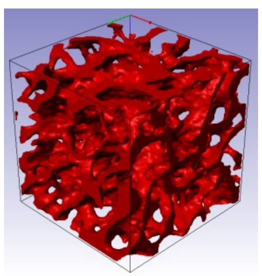
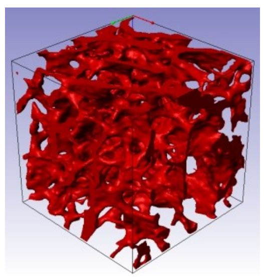
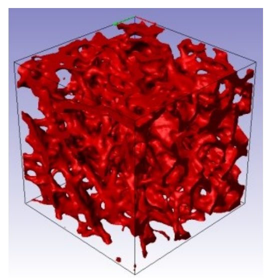
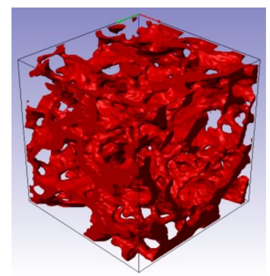
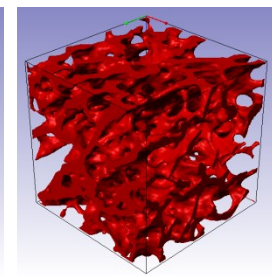
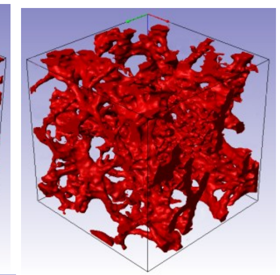
- 10 scans for each of head = 120 scans

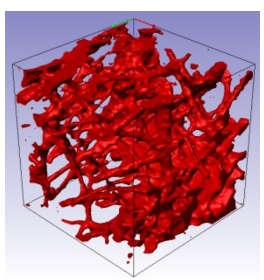
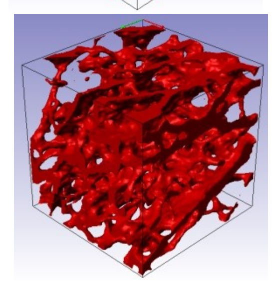
Medial plane



Central plane

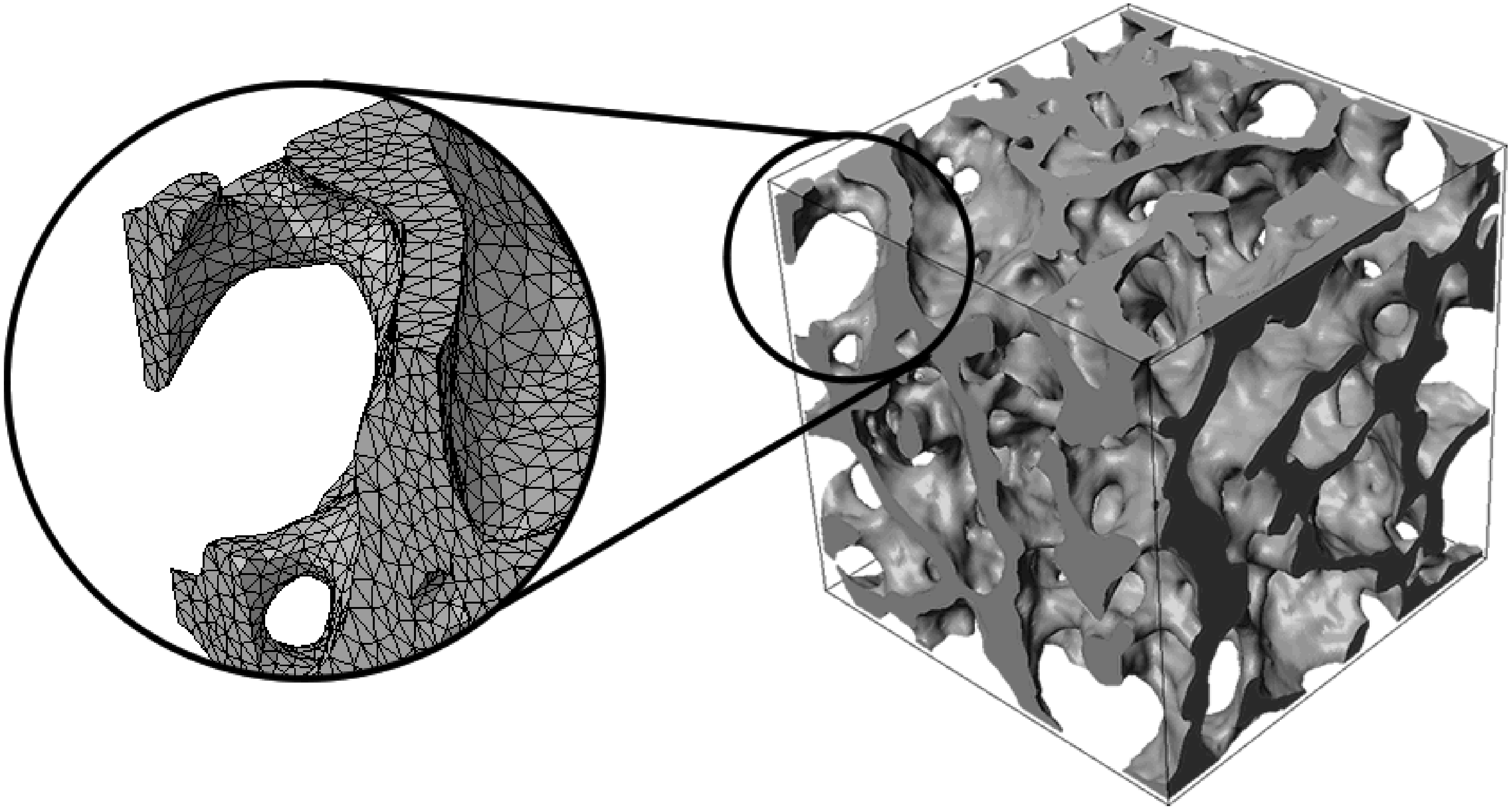


# Methodology

- Constructed 3D image and mesh

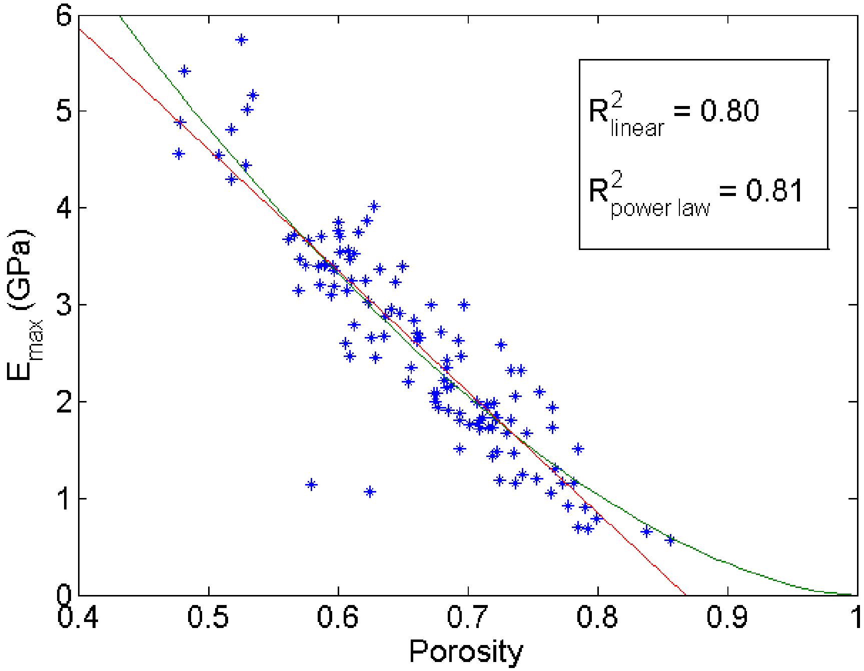


# Results – regression analysis

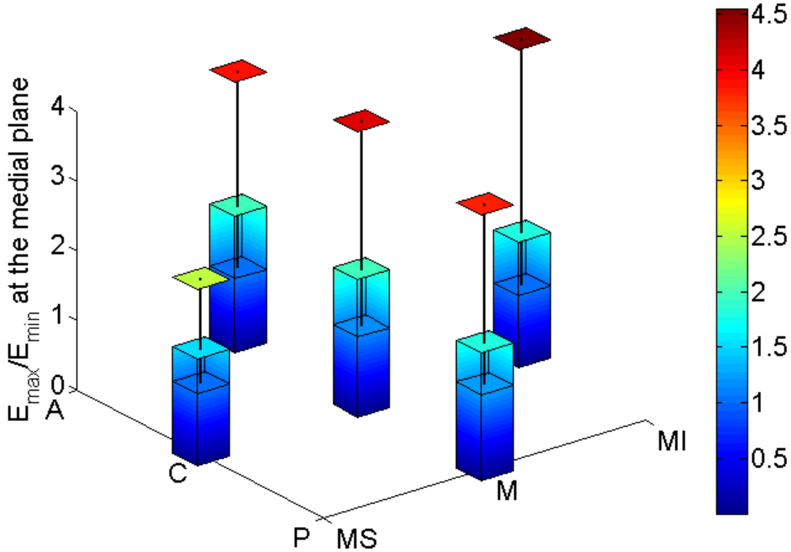
Q2: Which indices of micro-architecture correlate best with elastic constants?

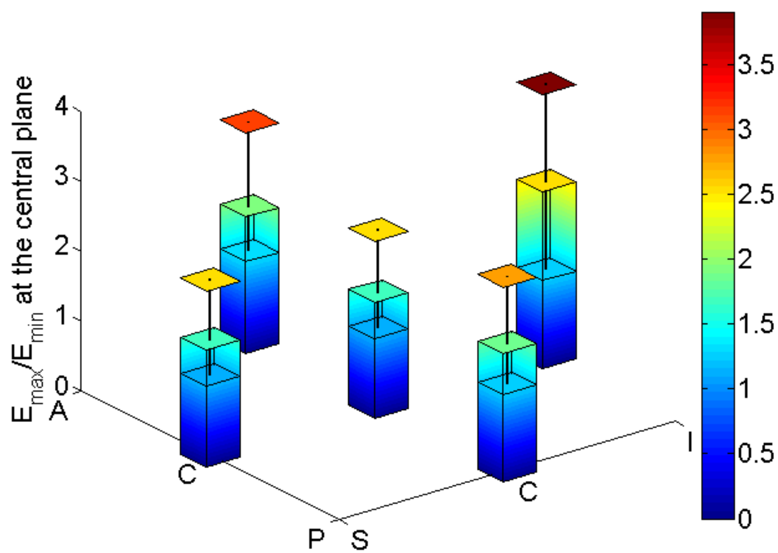
A2: Porosity

We also considered Ca.S/TV, Ca.Dm/TV, DA



# Results – *Anisotropy*

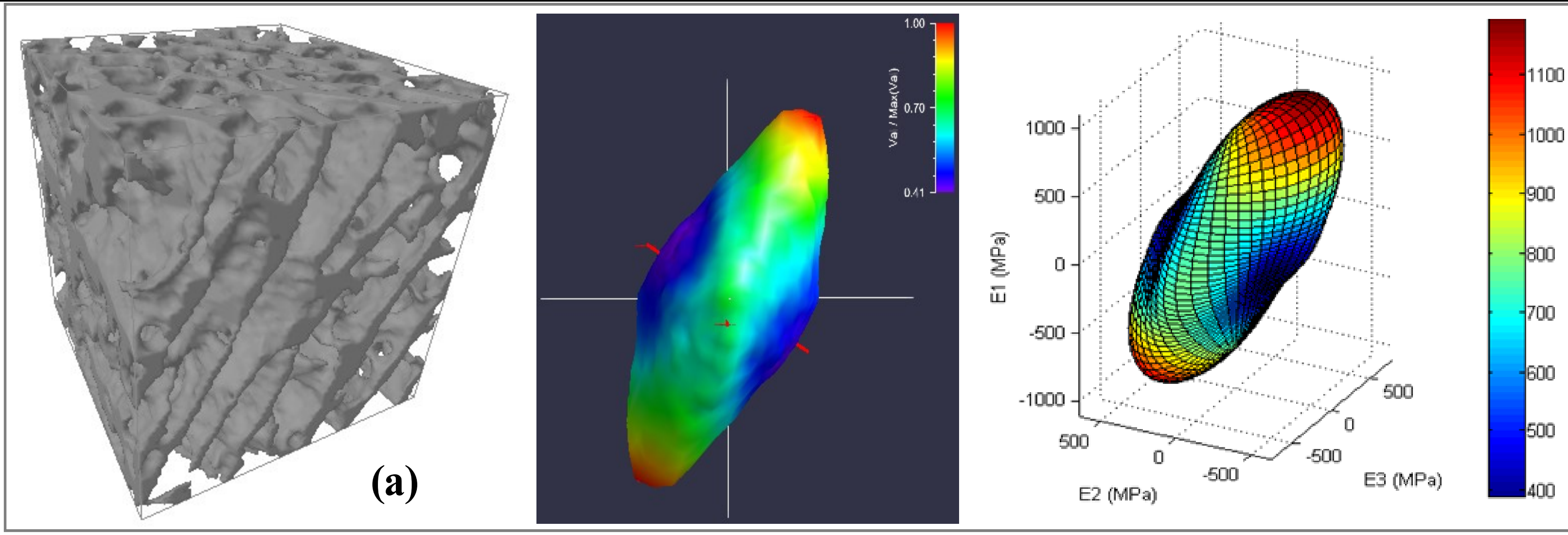


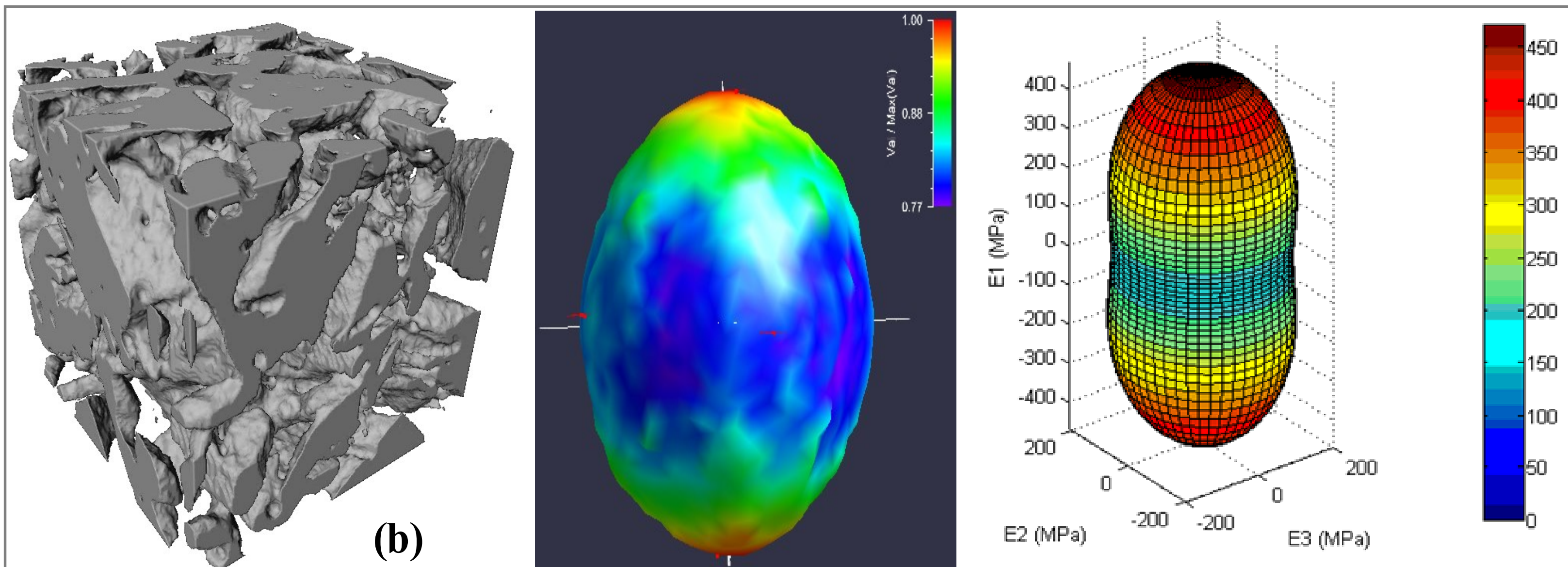

Variation of E_max/E_min vs location

- Large range on both planes :
  - 3.52 on central plane
  - 2.75 on medial plane
- Mean = 1.87
- Wider range at medial plane
- Mean OP = 1.95
- Mean OA = 1.80

# Trabecular bone and snow

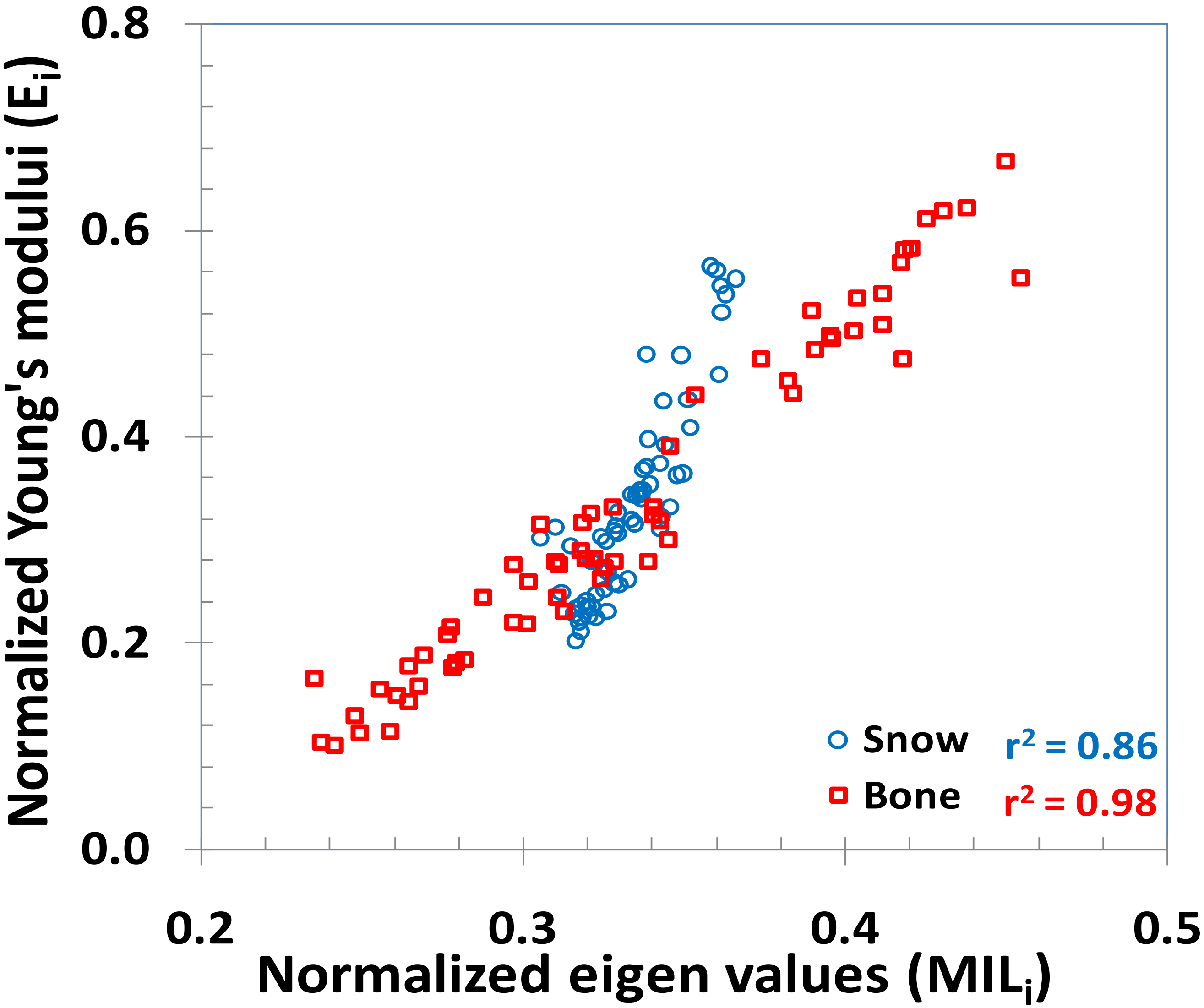



(a)




(b)

# Trabecular bone and snow




Srivastava et al., Cold Region Sc., In press

# Material properties:

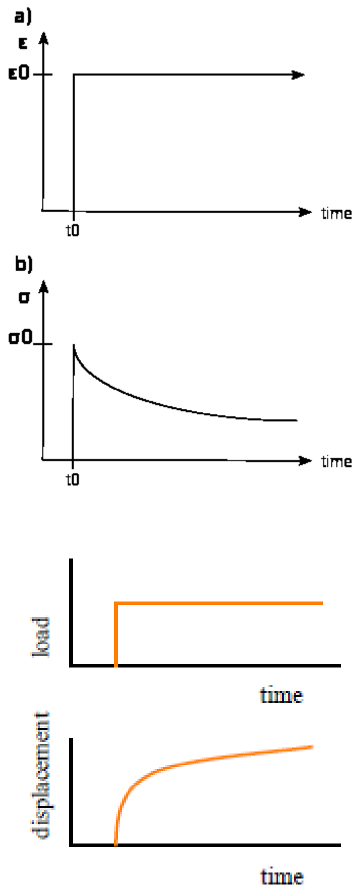
## Time-dependent

# Motivation

- Trabecular bone exhibits time-dependent behaviour
- Time dependent nature needs to be explored to predict
  - Orthopaedic implant loosening
  - The response to traumatic events - sudden dynamic loads
  - Age related non-traumatic fractures

# How to measure time-dependent behaviour – viscoelasticity?

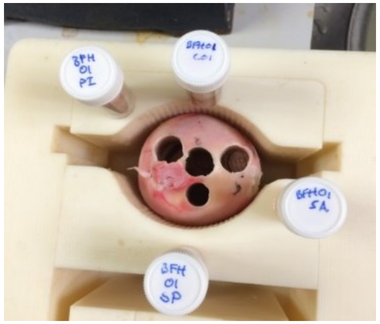
- Creep/Relaxation/Dynamic
- Need inter-conversion methods
- Creep may contain irrecoverable strains
- Need loading and unloading experiments



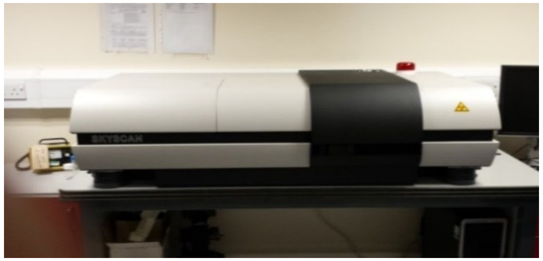
# Creep-recovery experiments


Bovine femoral head

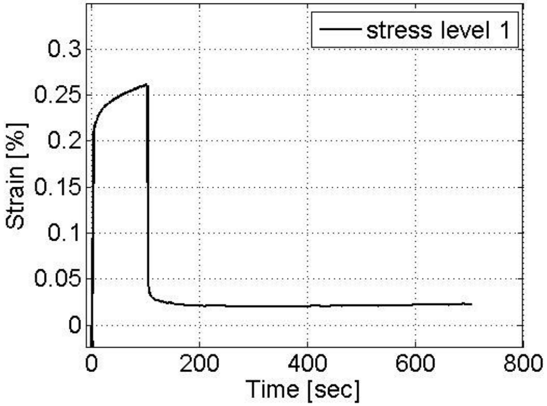

Machining cores


Samples cored out


Sample with end-caps, hydrated

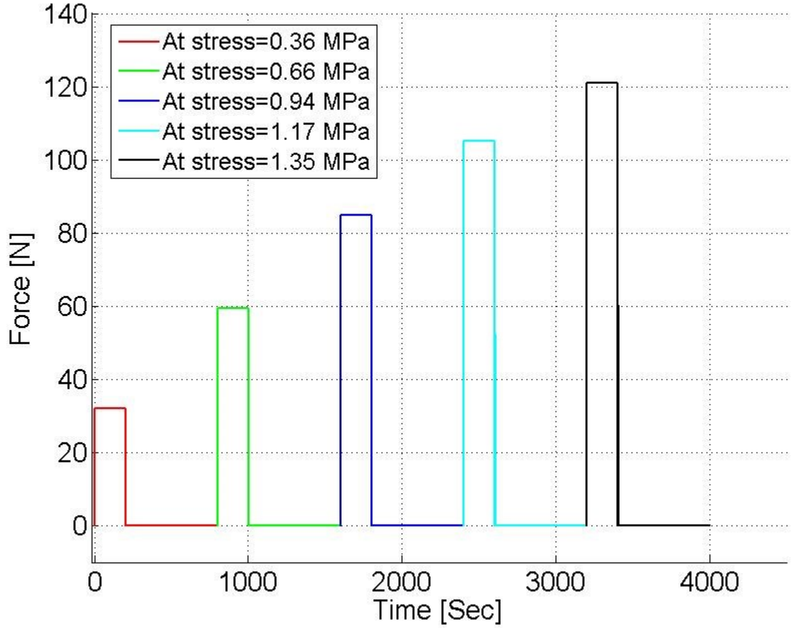

μCT scanning (Skyscanner 1172)

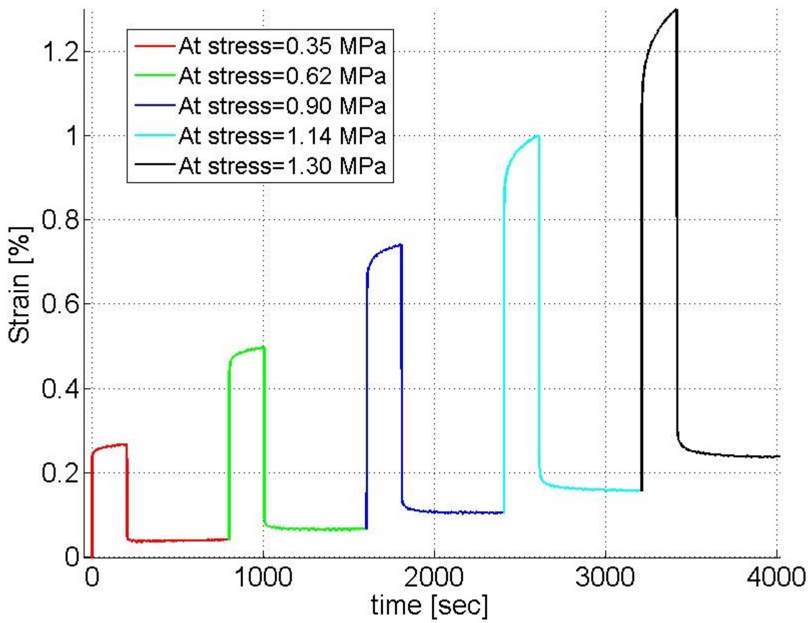

Creep-recovery experiments, Zwick



Creep-recovery response

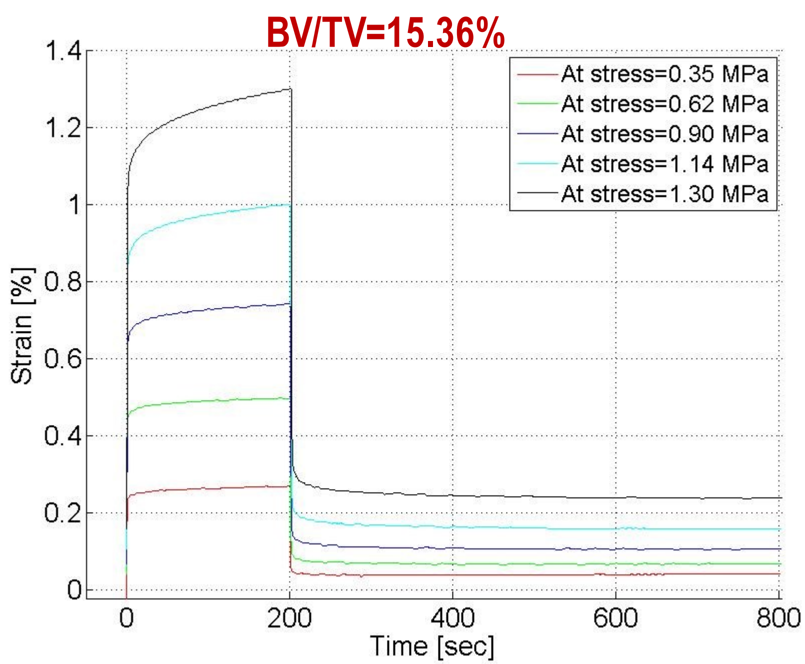
# Creep-recovery experiments…

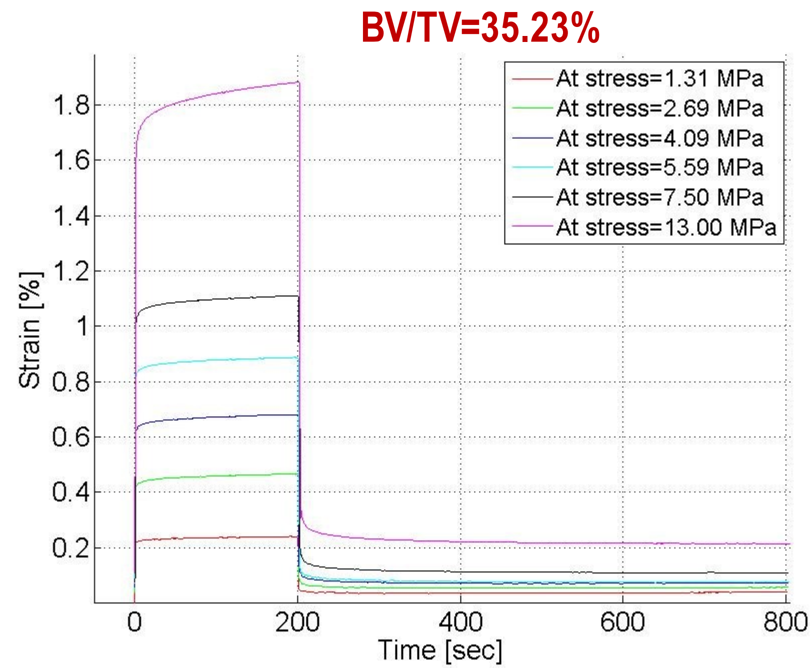



- 20 cylindrical bovine samples (5 from trochanter, 15 from femoral head) with marrow
- Force for 200 sec; recovery for 600 sec for each cycle
- Stresses corresponding to: 0.25, 0.4%, 0.6%, 0.85, 1%, 1.5% strain

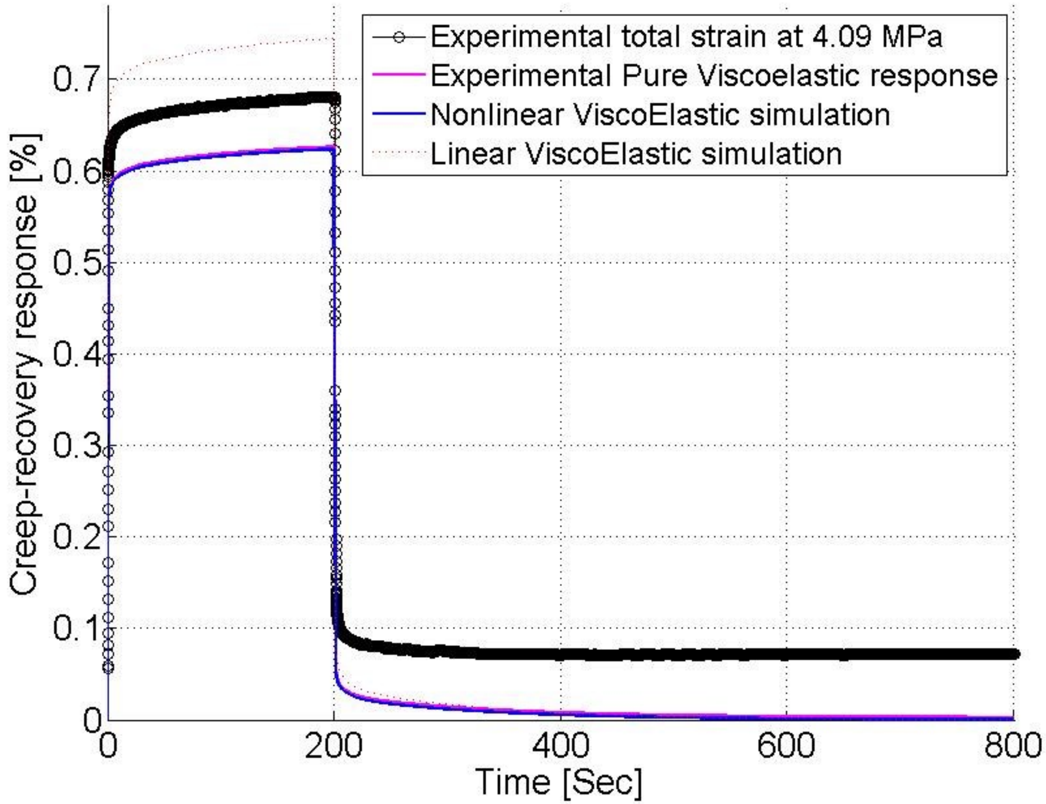
# Creep-recovery curves




- Creep rate is higher with lower BV/TV
- Creep behaviour changes with stress levels
- Irrecoverable strains exist at the end of each at cycles
- Creep part of the curve may contain plastic and residual strains

# Results: Dense sample, BVTV=35%

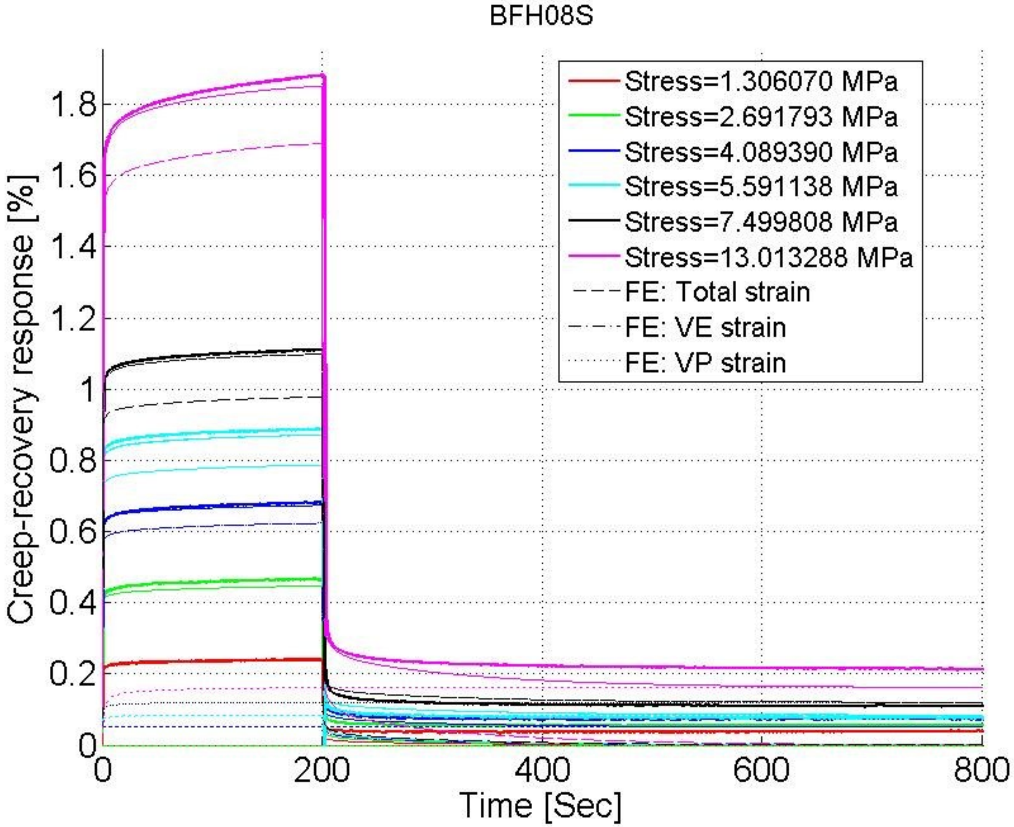



Linear VE models do not predict well the VE response even at very lower strains

Nonlinear VE  models predict well

# Results

| Parameter | Value |
|---|---|
| $N$ | 3.00E+00 |
| $\alpha$ | 3.50E-01 |
| $\beta$ | 3.00E-01 |
| $k_0$ | 4.77E+00 |
| $k_1$ | 7.99E+00 |
| $k_2$ | 8.48E+02 |
| $\sigma_0$ | 6.62E+00 |
| $\eta$ | 2.85E-03 |




- Total strain is composed of viscoelastic and viscoplastic strains
- Coupled viscoelastic-viscoplastic model predicted strains accurately

# Conclusions

- Time-dependent response varies nonlinearly with stress levels and comprises recoverable (viscoelastic) and irrecoverable (viscoplastic) strains
- Nonlinear VE-VP model predicts the behaviour well at apparent level

# Material properties:

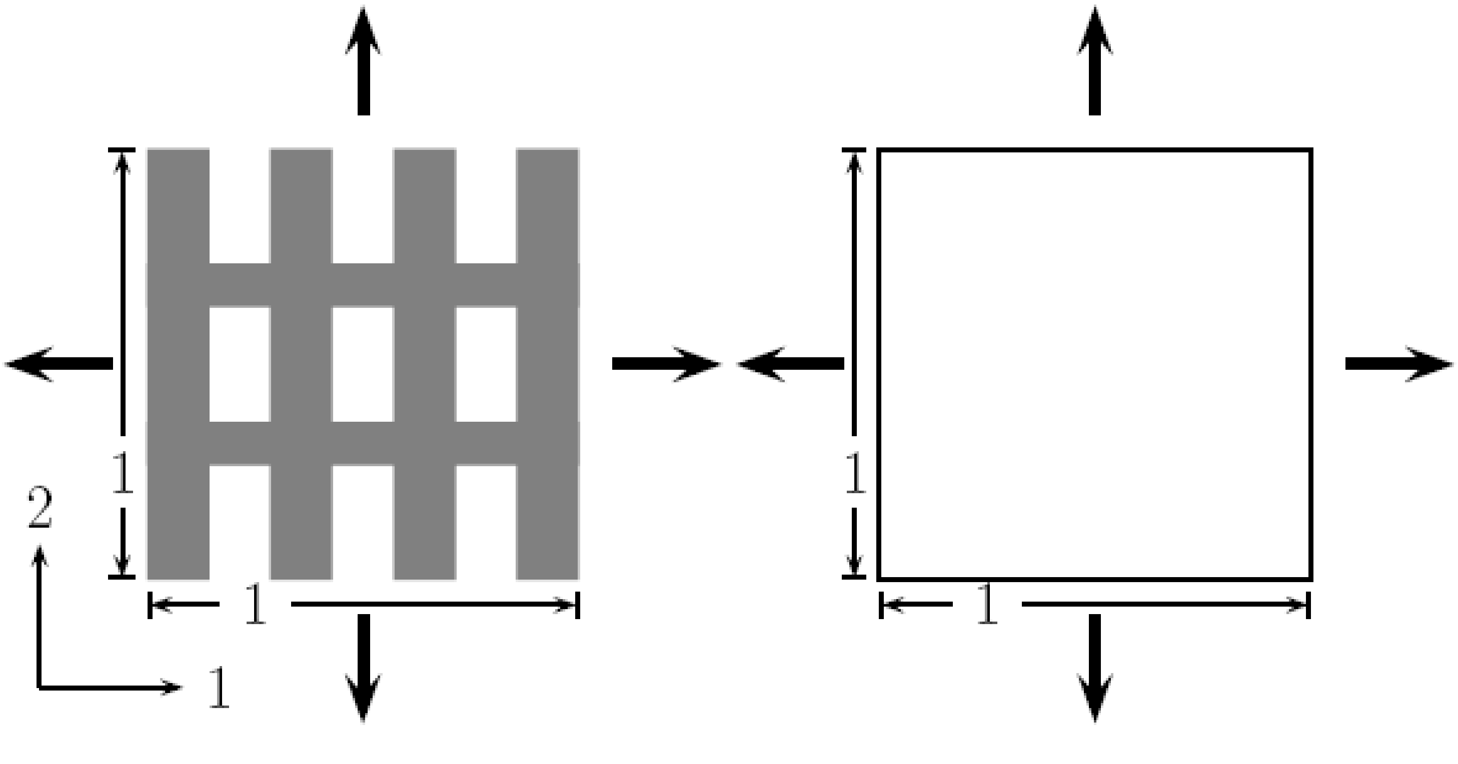
## Strain-based plasticity

# Material properties – post-elastic modelling

- Stress based criteria require too many parameters
- Bone yield anisotropic in stress space isotropic in strain space
- Experimental evidence to suggest that yielding of bone is based on strain rather than stress

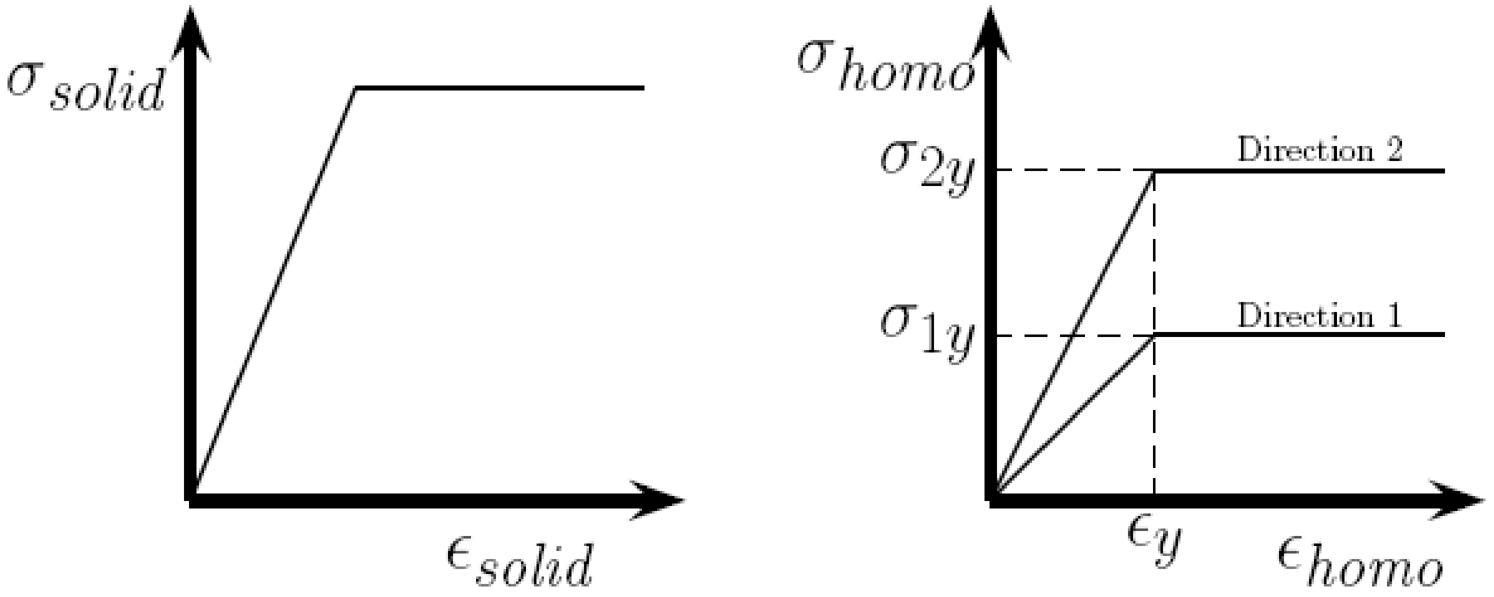
# Material properties – post-elastic modelling

Strain-based criterion concept



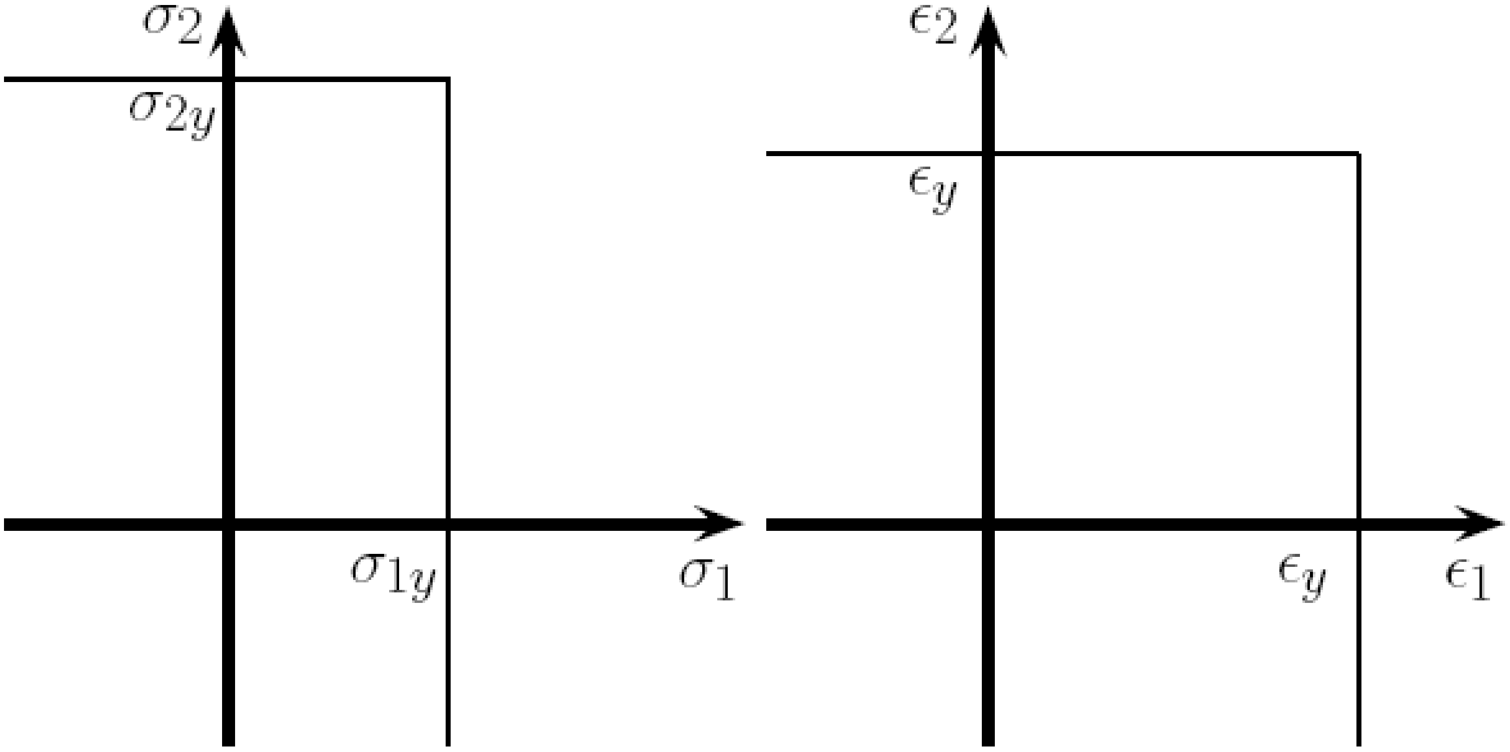
# Material properties – post-elastic modelling

Strain-based criterion concept

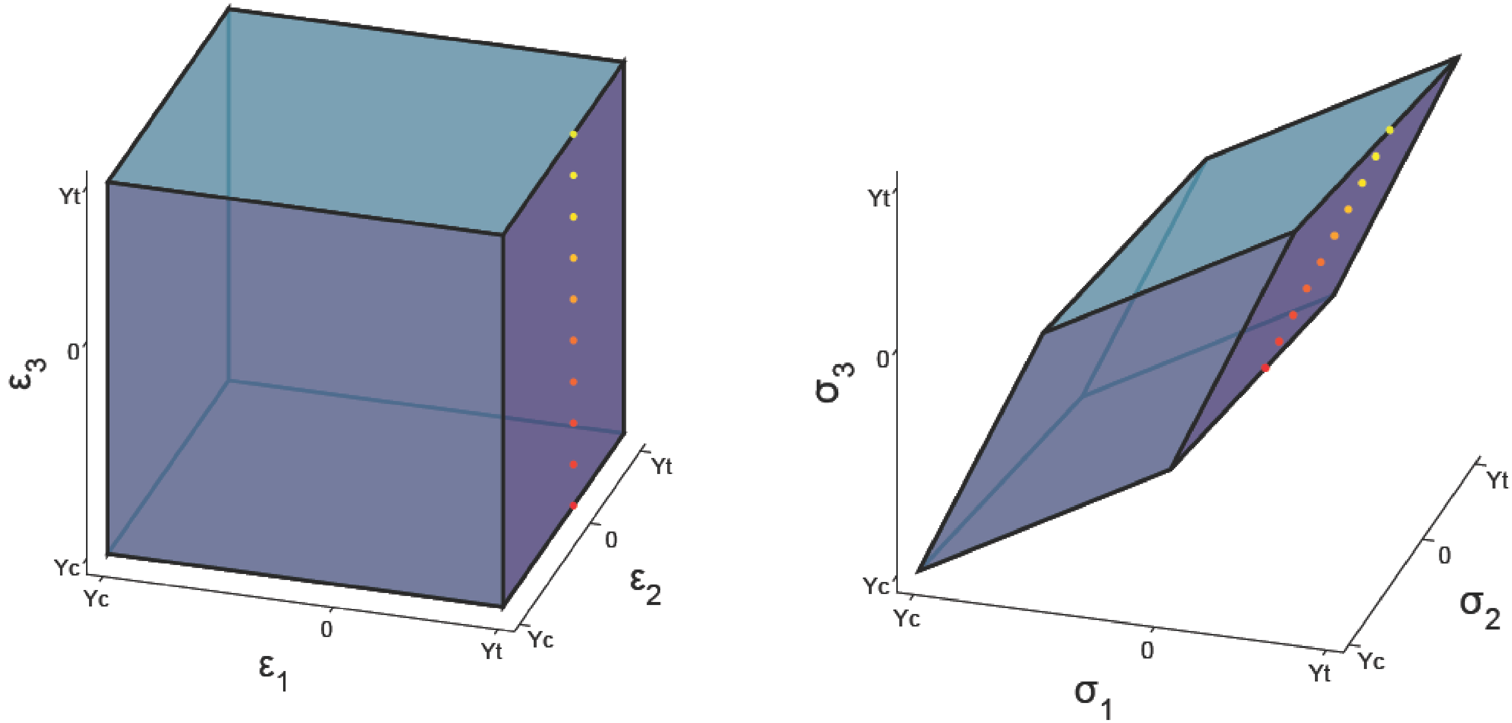


# Material properties – post-elastic modelling

Strain-based criterion concept



# Material properties – post-elastic modelling



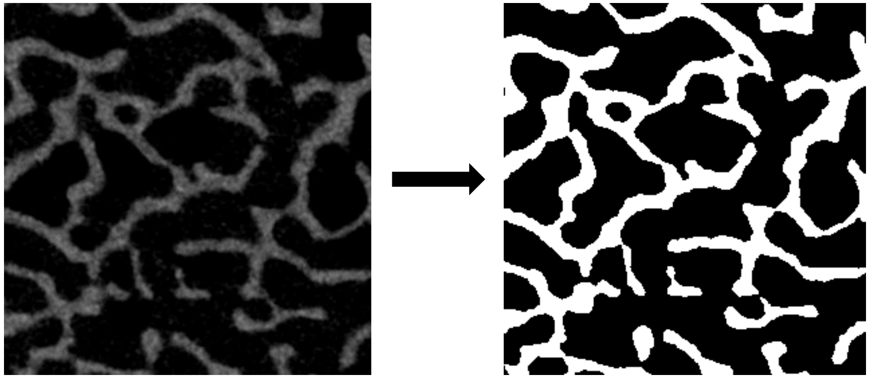

Pankaj and Donaldson, 2013, IJNMBE

# Material properties:
## Plasticity – nonlinear homogenisation

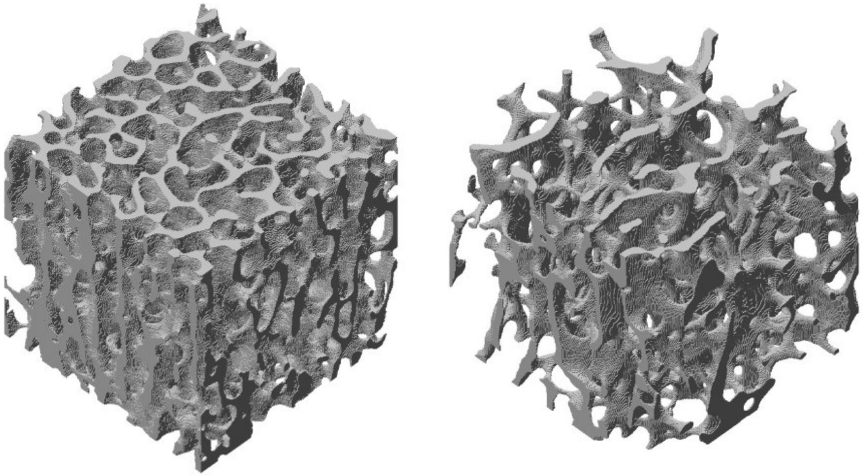
# Motivation

- Use FE to evaluate yield behaviour of trabecular bone – nonlinear homogenisation
- Assess how properties translate from microscale to macroscale when using different constitutive laws for the bone tissue
- To relate apparent level yield surfaces to micro-architectural indices

# Methods



**Right –** Reconstructed scan. **Left –** Binarised image



FE meshes. **Left –** 26.9% BV/TV. **Right –** 12.3% BV/TV.

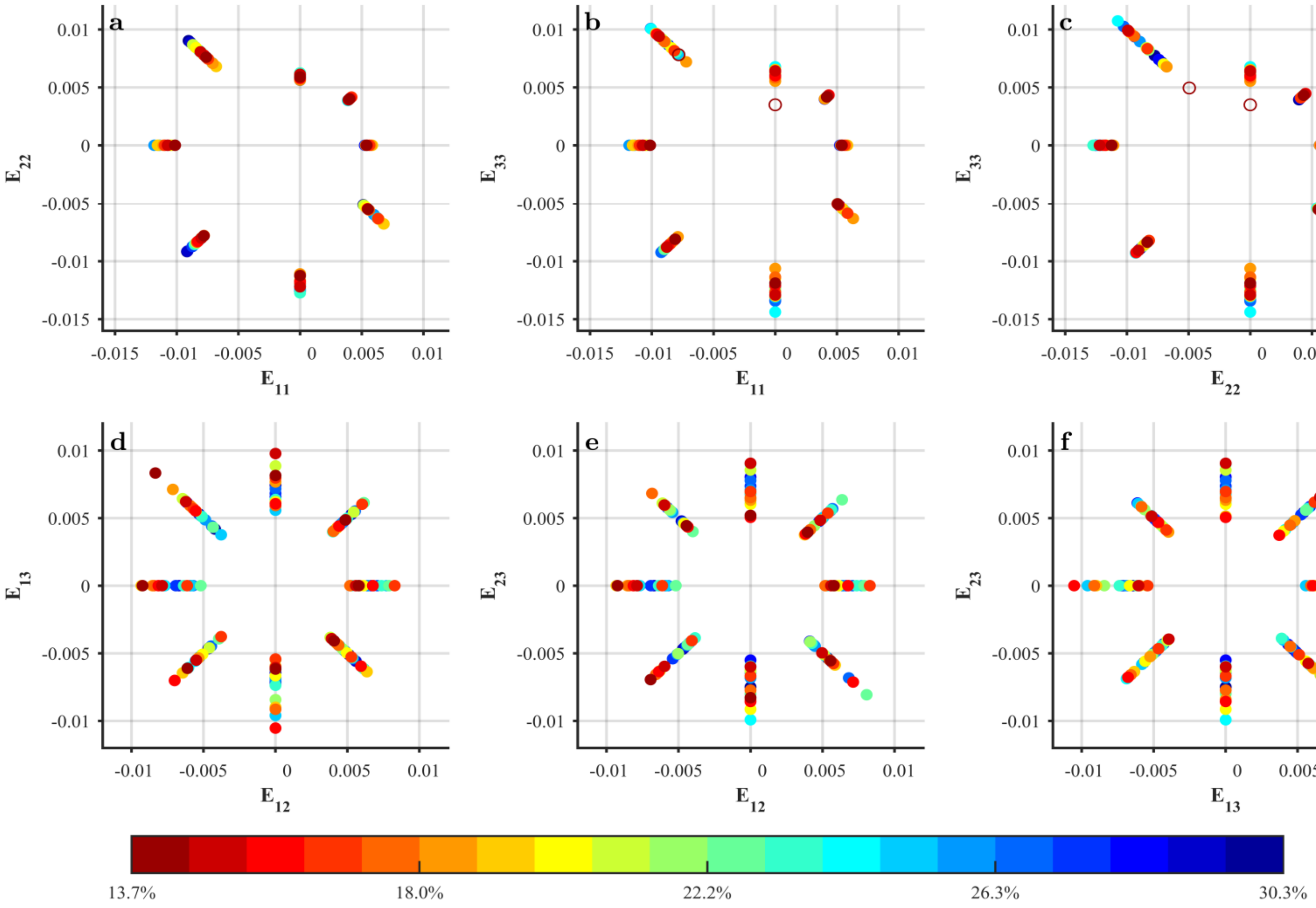
- Two sample with very different morphologies, scanned at 17 μm on a μCT system
- Binary segmentation using Gomez *et al.* approach*
- Coordinate axes of the stack of images were aligned to MIL axes
- Scans transformed to voxelised FE meshes through an *in-house* developed Message Passing Interface (MPI) script
- The dense and porous models have 29M and 13M degrees of freedom, respectively.
- 5 mm cubes used
- Used the approach with 20 samples

* Gomez *et al.* A comparative study of automatic thresholding approaches for 3D x=ray tomography of trabecular bone. *Med Phys* (2013).

# Load cases

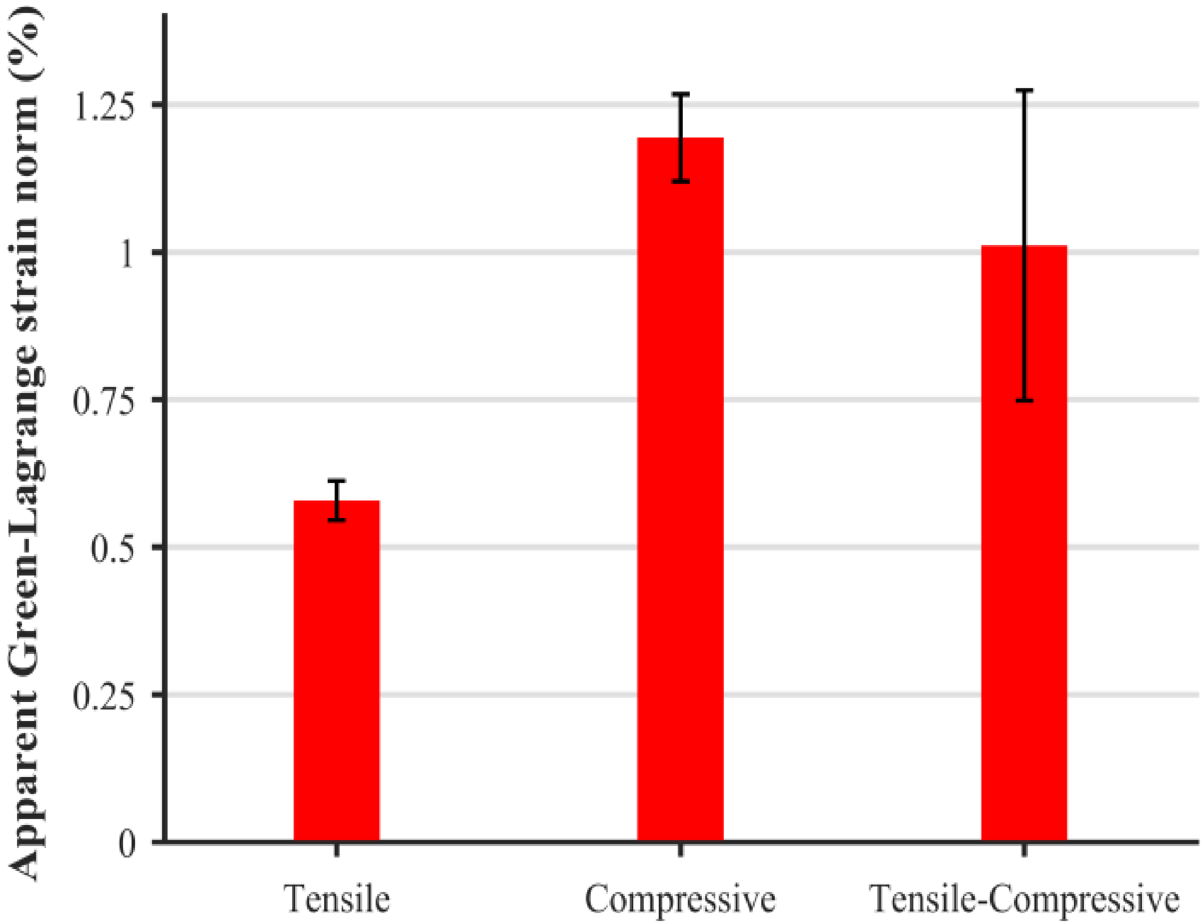
- Elastic homogenisation requires 6 uniaxial loading cases
- Nonlinear homogenisation requires “infinite” load cases
- 171 load cases applied to each sample with linear boundary displacements.
  - Same ratios
    - 3 uniaxial normal tension
    - 3 uniaxial normal compression
    - 12 biaxial normal
    - 8 triaxial normal
    - 3 uniaxial shear
    - 3 biaxial shear
    - 1 triaxial shear
    - 18 biaxial normal-shear
  - Different ratios
    - 24 biaxial normal
    - 48 triaxial normal
    - 6 biaxial shear
    - 6 triaxial shear
    - 36 biaxial normal-shear

# Behaviour of different samples



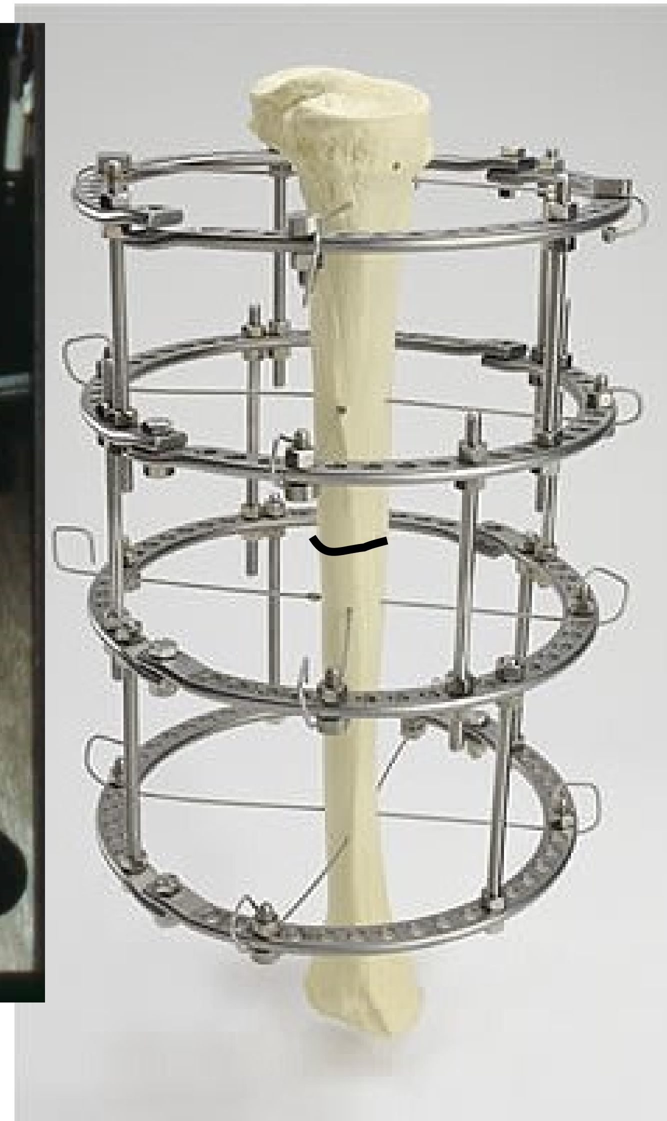

Florencio et al., submitted

# Behaviour of different samples

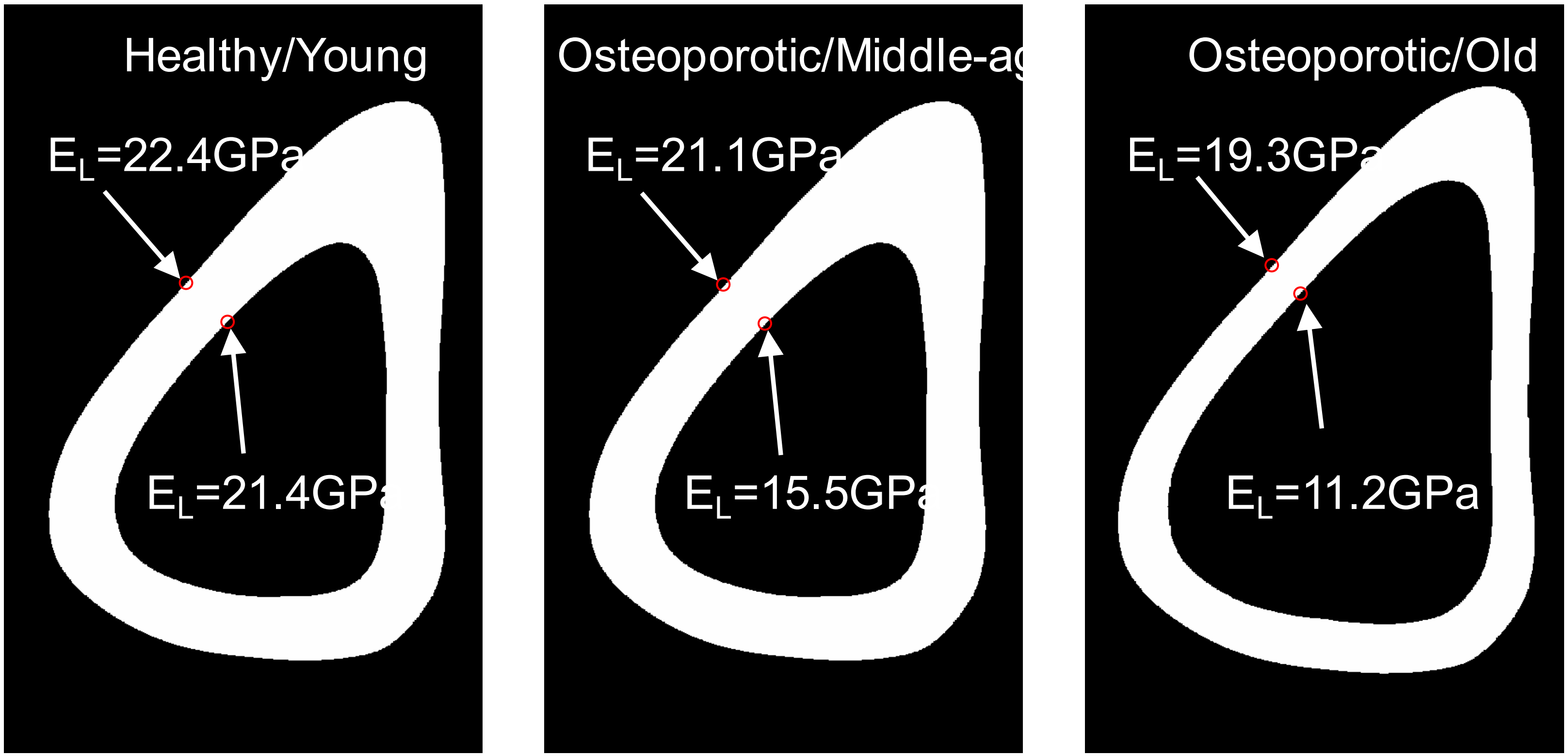



Florencio et al., JMBBM, submitted

# Application - Ilizarov fixation



# Geometry and material properties

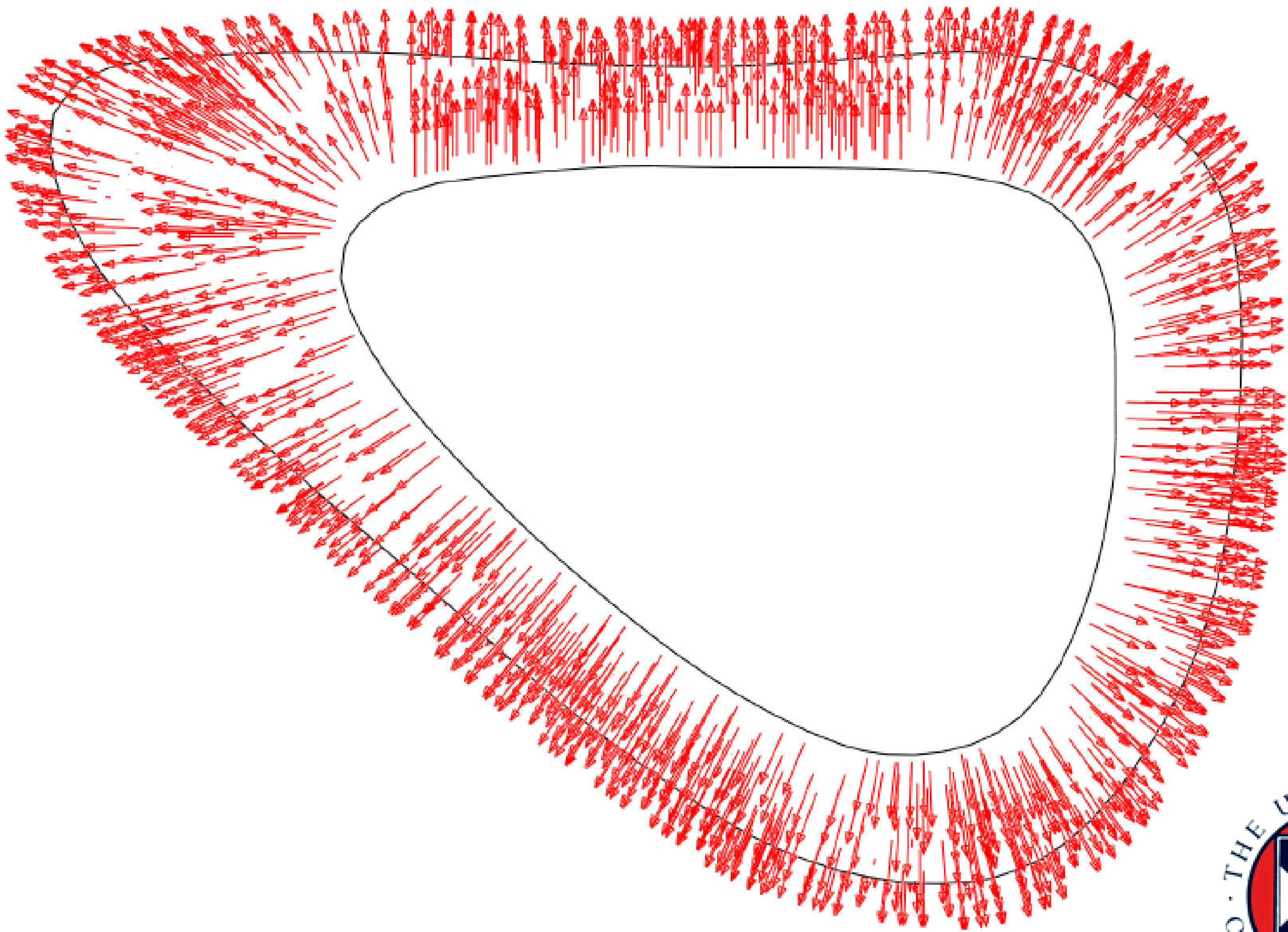



2.1% porosity
C.Area = 319.2mm$^2$
C.Th = 5.10mm

12.6% porosity
C.Area = 319.2mm$^2$
C.Th = 5.10mm

24.0% porosity
C.Area = 265.3mm$^2$
C.Th = 3.64mm

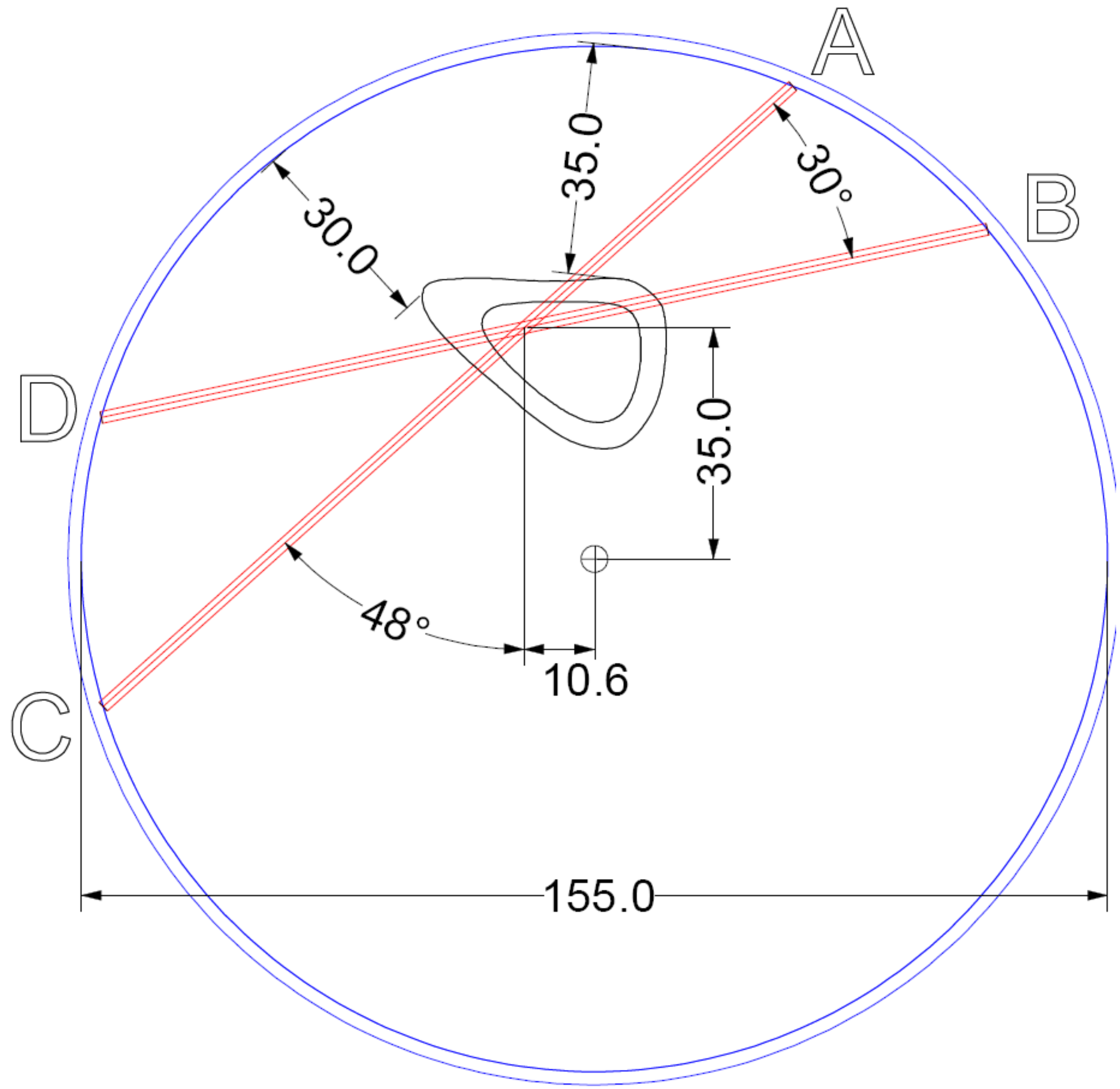
# Elastic properties - orthoptropy



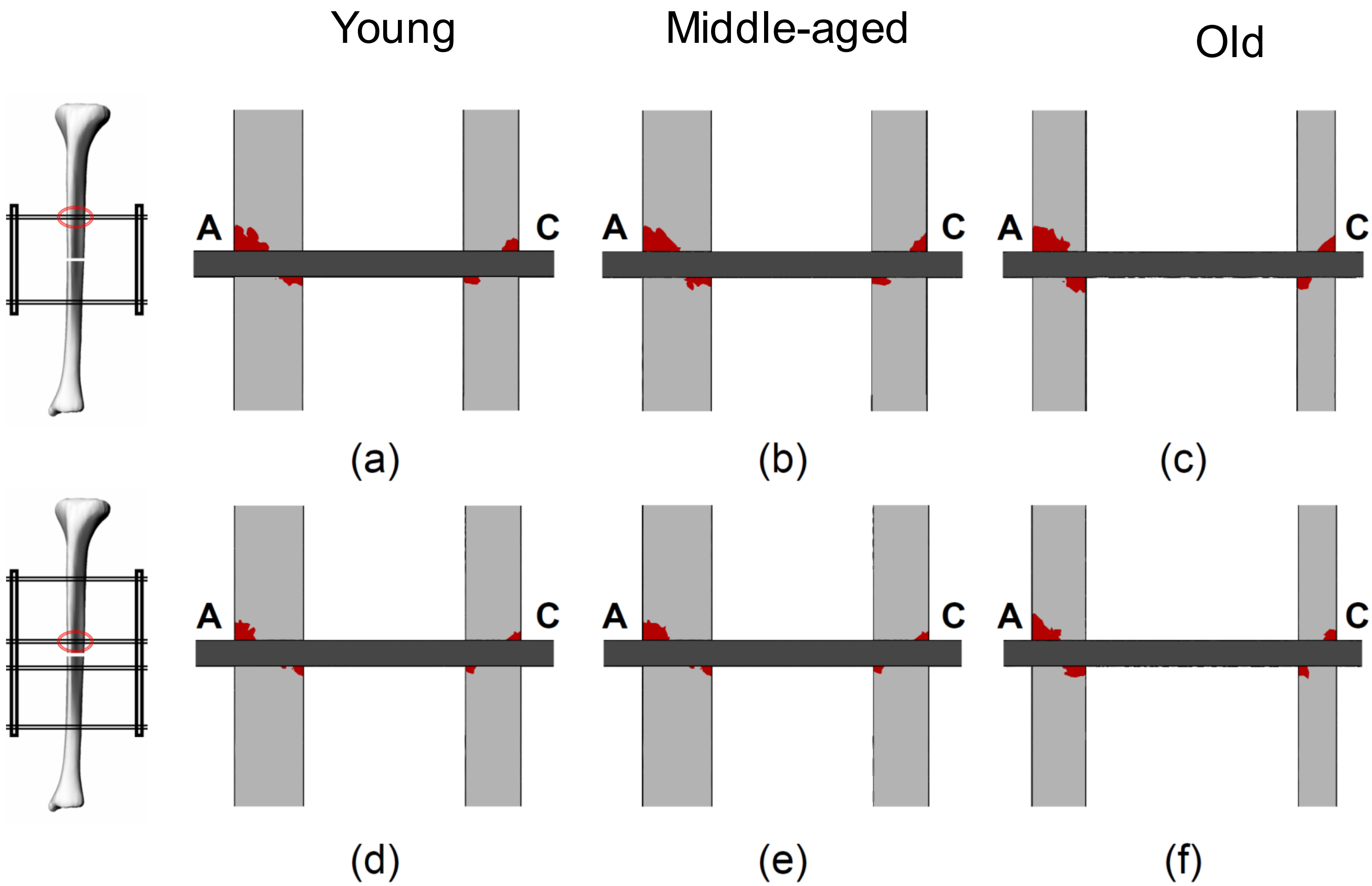
# Methodology – key features

- Elastic properties of bone
  - Orthotropic
  - Vary with "age"
  - Periosteum to endosteum variation
- Bone nonlinearity - strain-based plasticity
- Geometrical nonlinearity
- Contact interface (not tied)

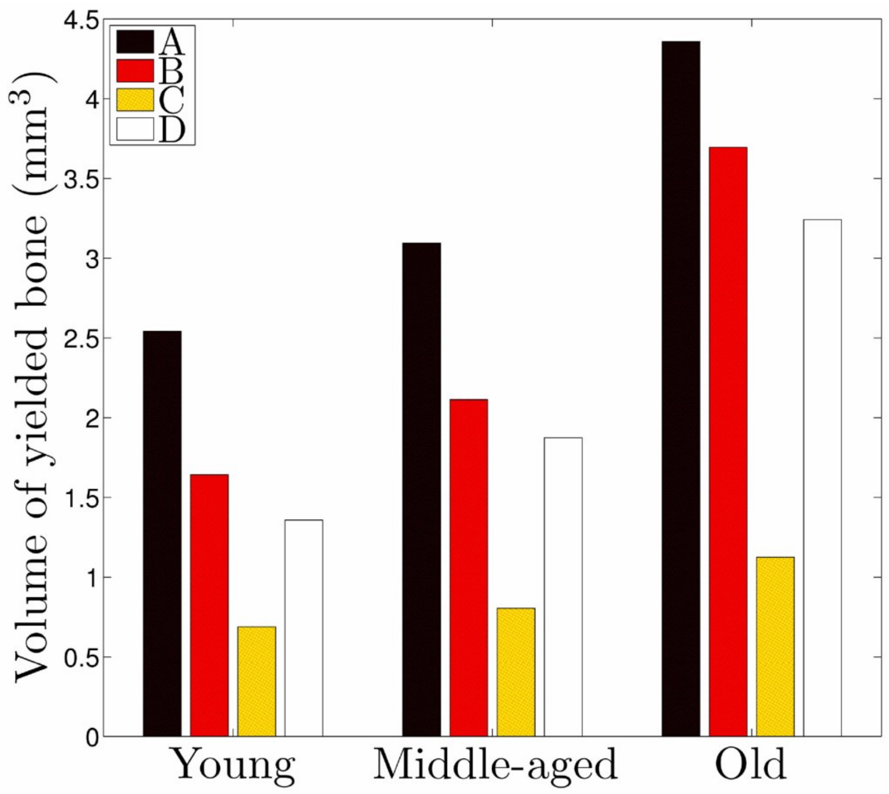
# Arrangement of wires

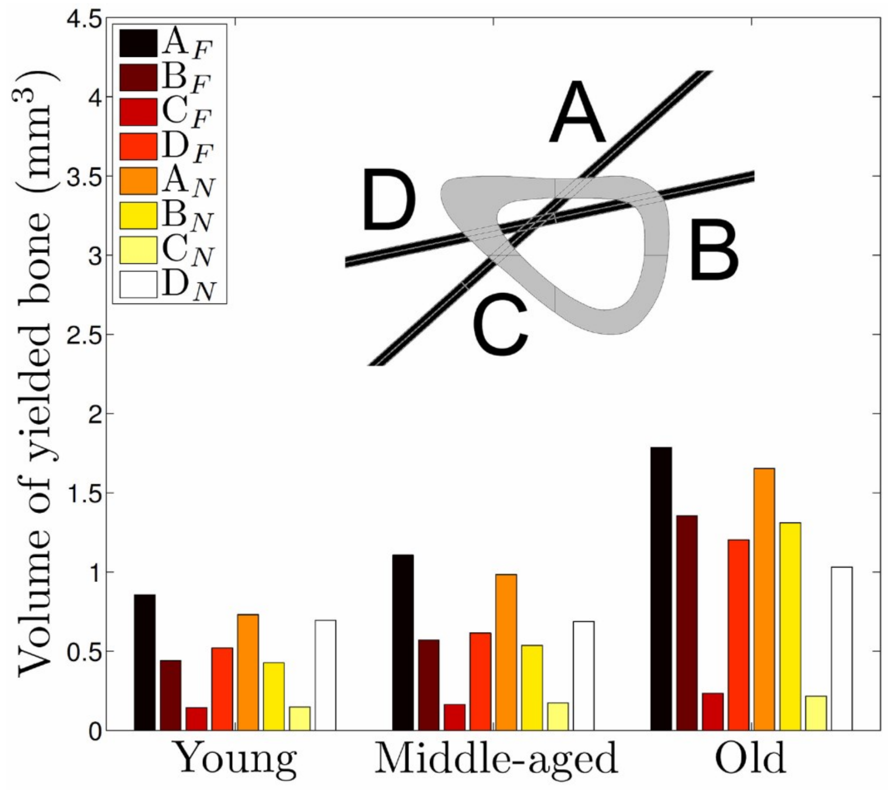


# Results – yielded bone



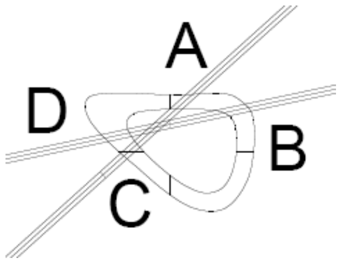
# Example 3: 2 and 4 wire fixation

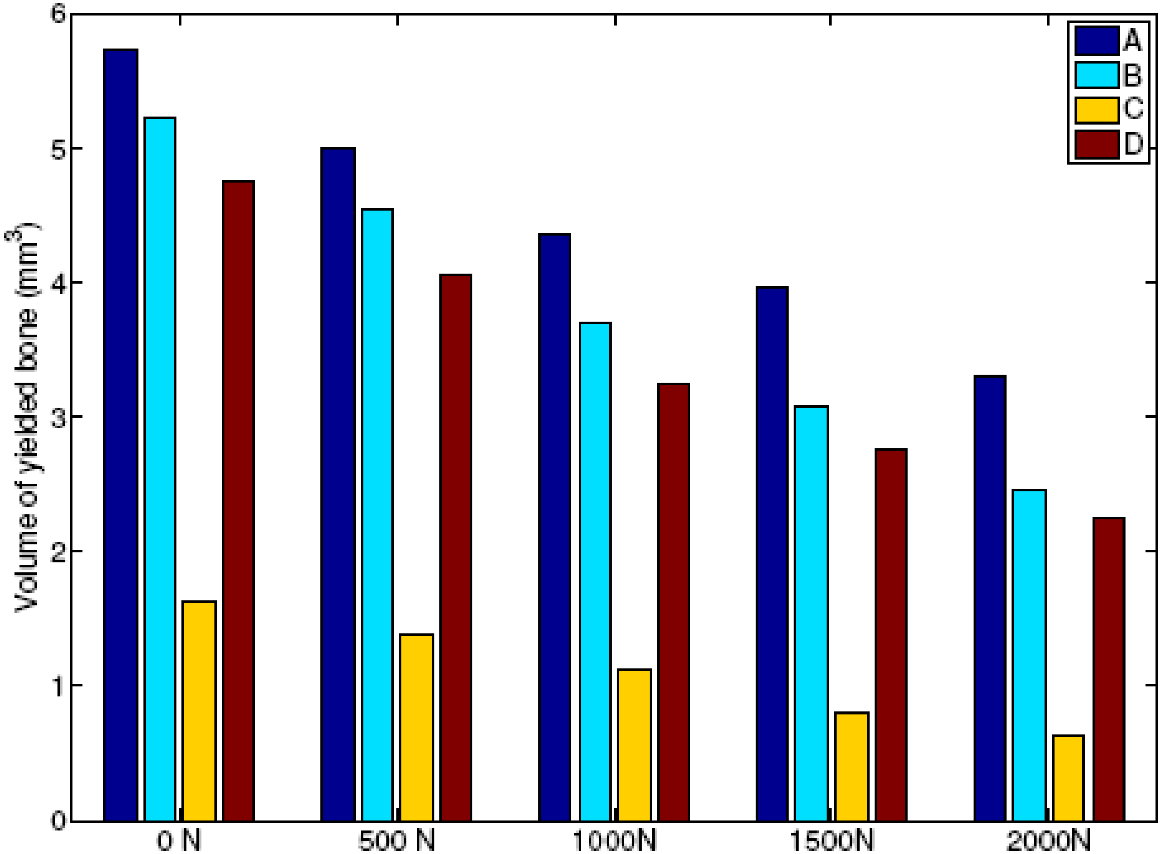


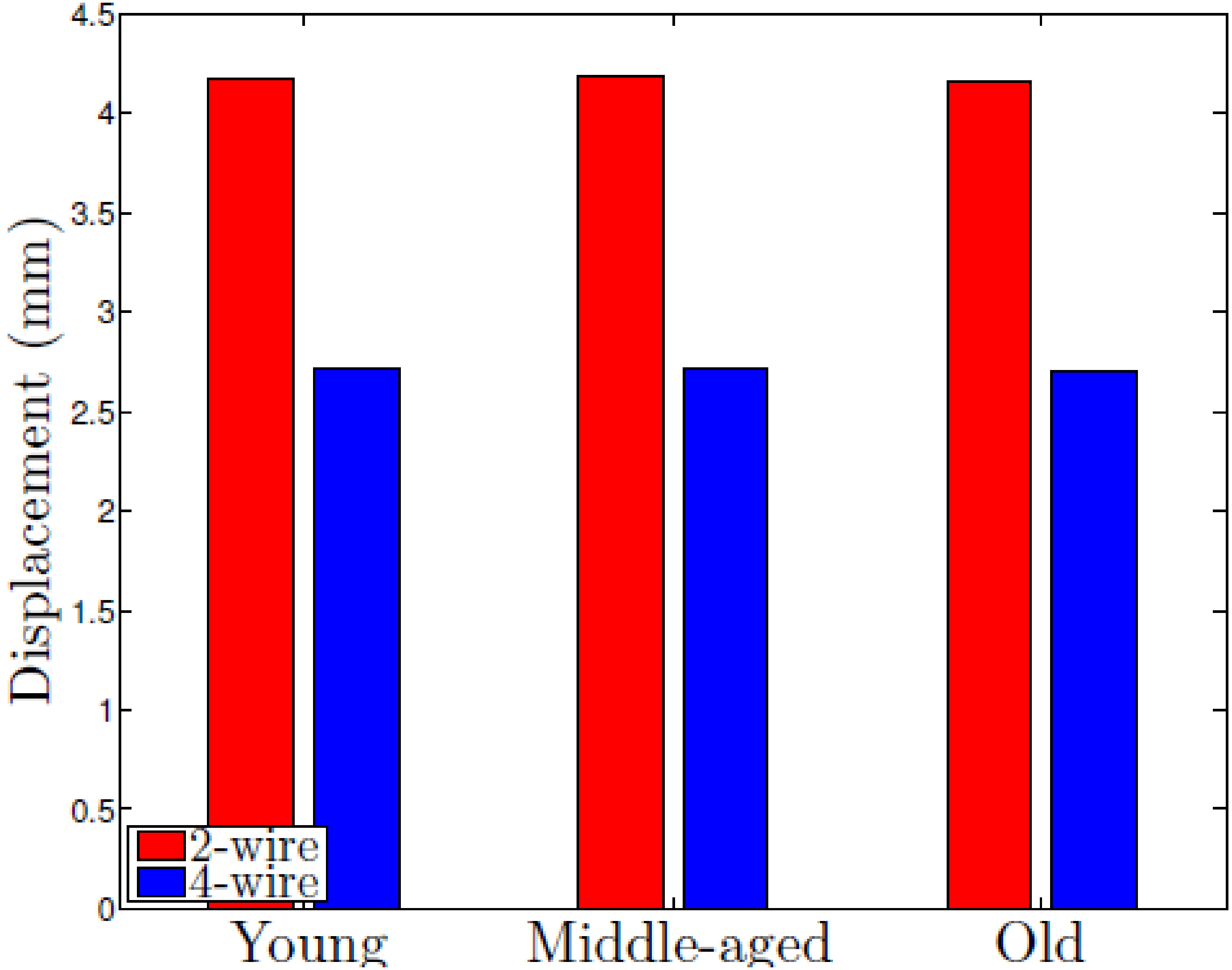
# Illizarov wire results

Effect of wire tension on volume of yielded bone:



# IFM in 2 and 4 wire fixation i.e. construct stiffness

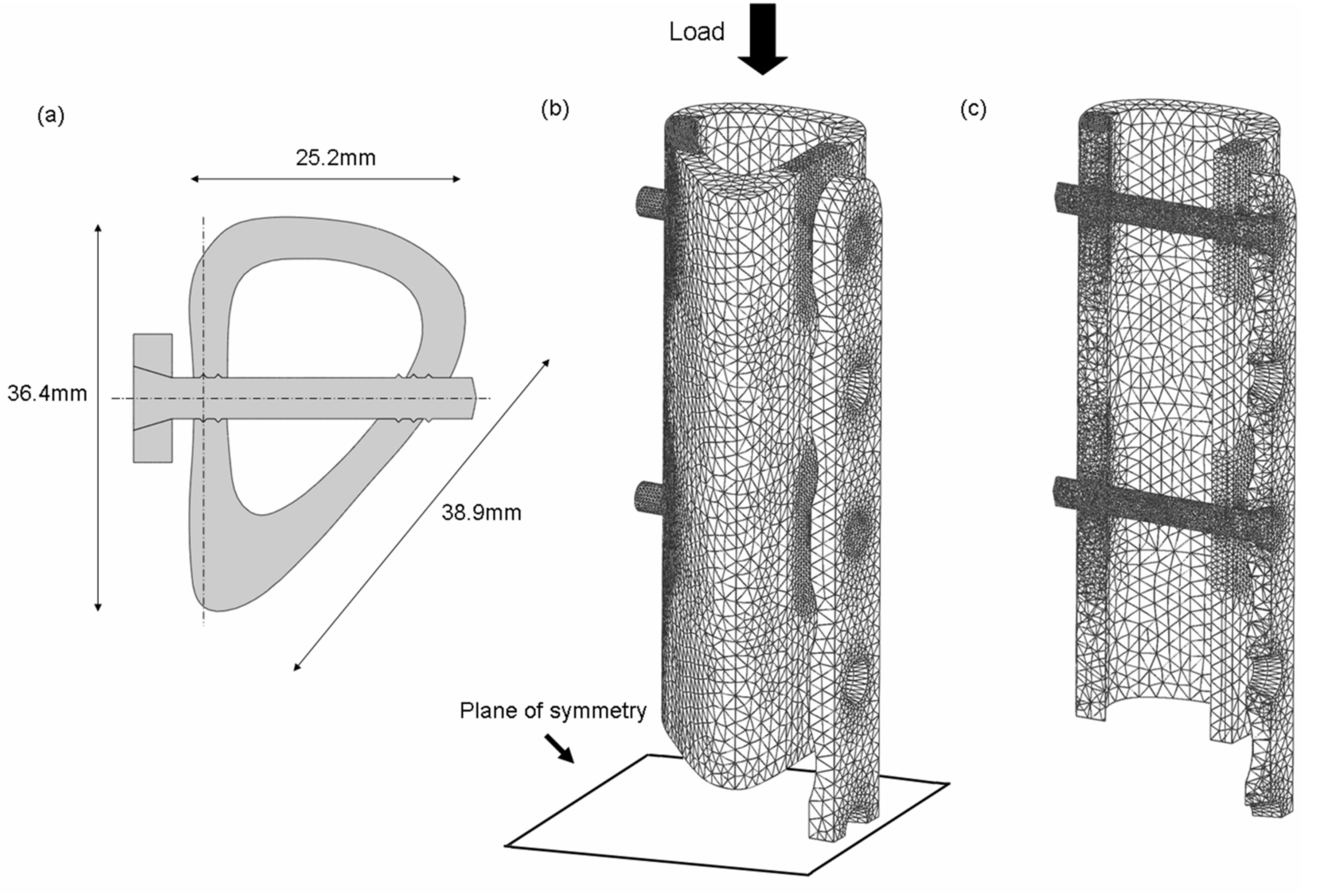


# Conclusions – Ilizarov fixators

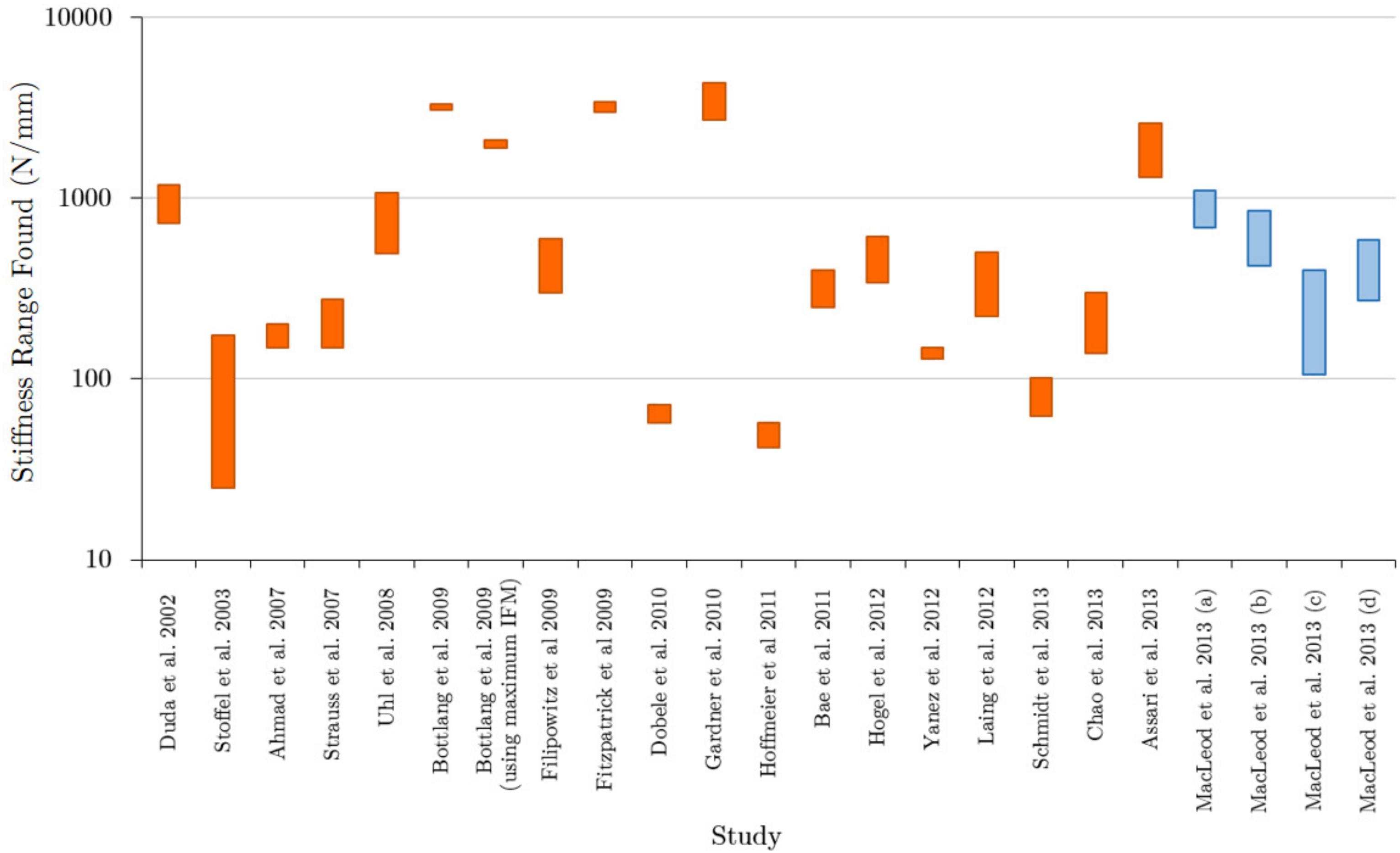
- Yielding never occurred through the entire cortical thickness
- Bone displacement is independent of age
- Increased yielding with ageing
- Increased wire tension reduces bone yielding

Donaldson, Pankaj, Simpson, 2012, J Orth Res

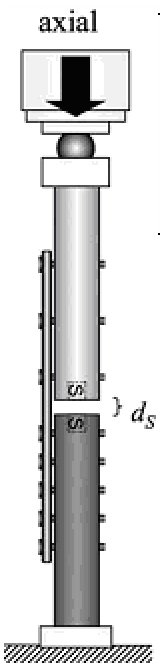
# Locking plates



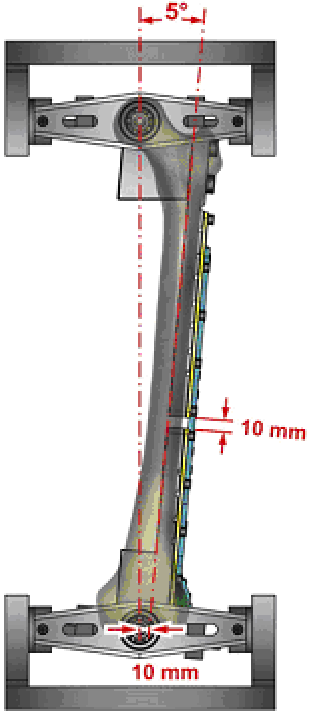
# Stiffness in literature



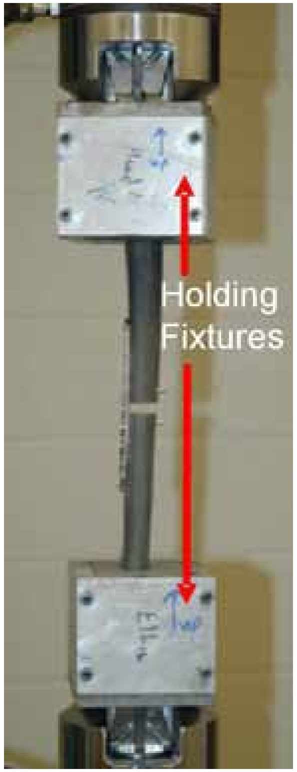
# Loading conditions



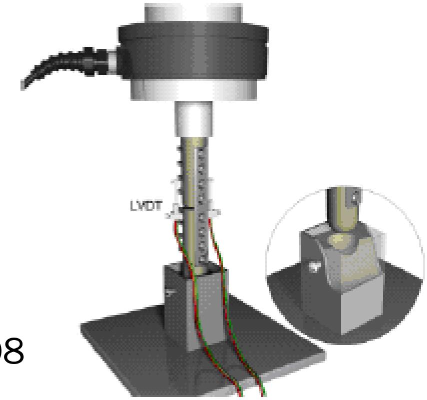

Ahmad et al. 2007




Hoffmeier et al. 2011

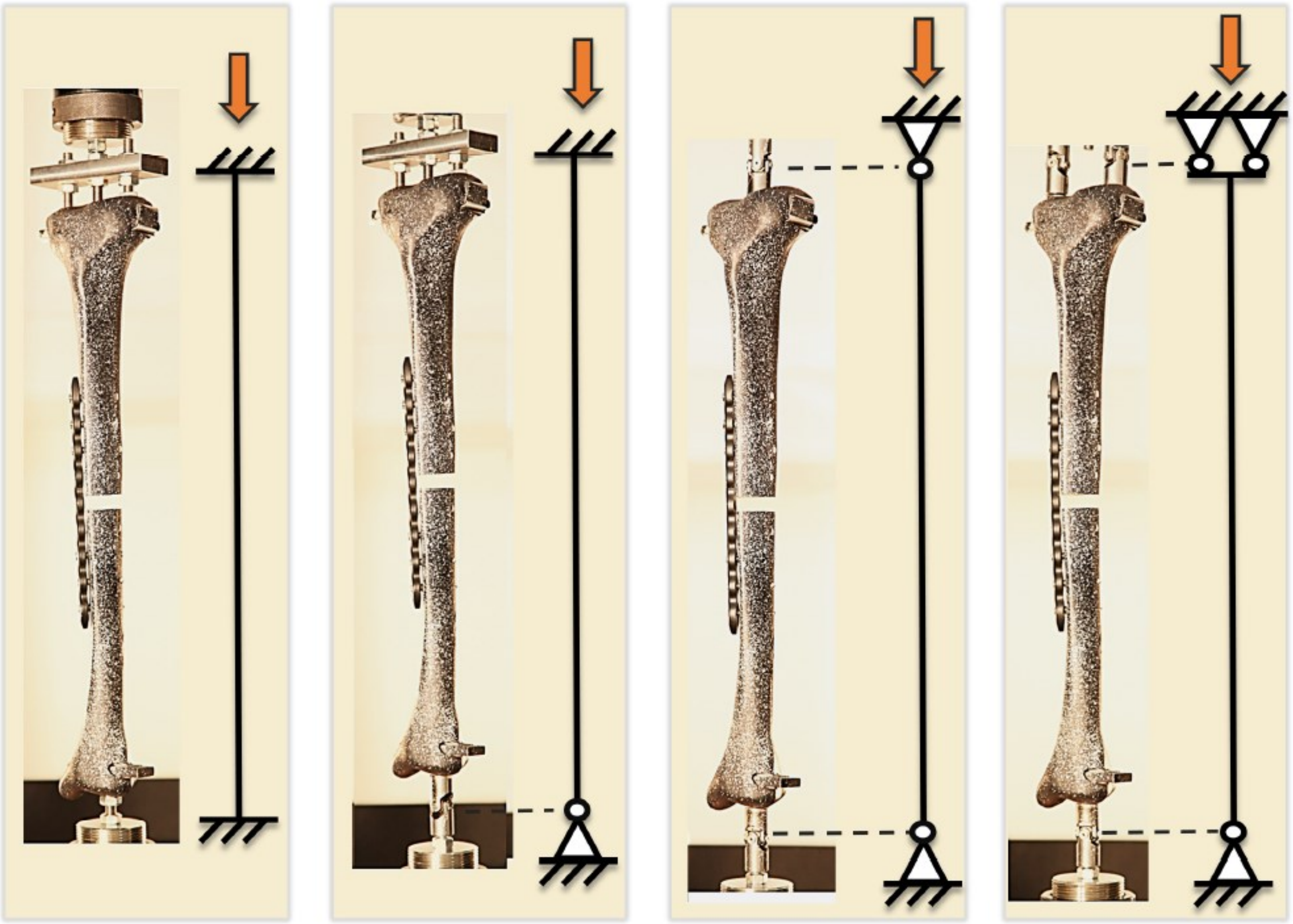



Dunlap et al. 2011



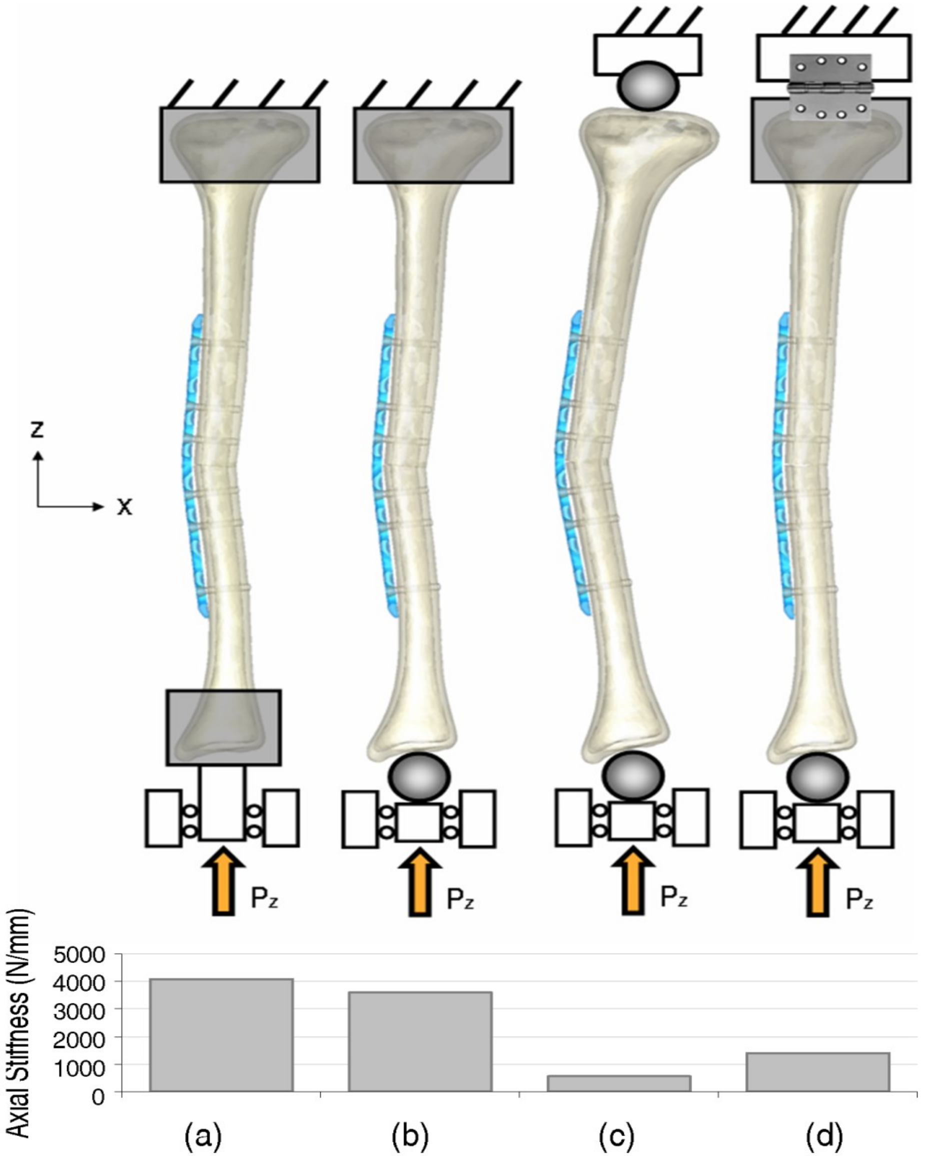

Uhl et al. 2008

# Our loading conditions

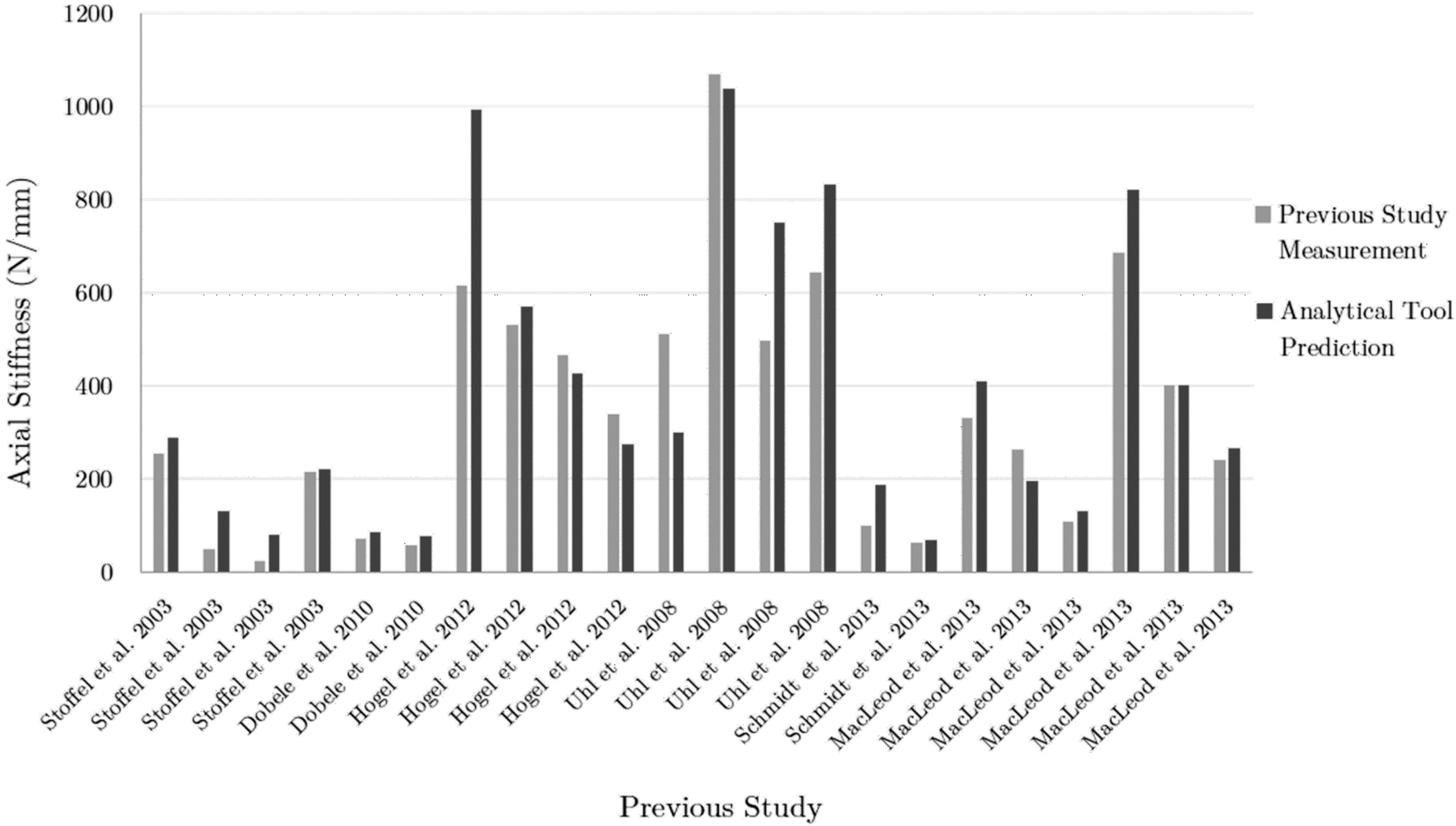


(a) (b) (c) (d)

# Loading conditions



# An analytical tool for locking plates




MacLeod and Pankaj – Poster M292 – Monday

# Conclusions

- IFM
  - Patient-specific material properties – small role
  - Implant-bone interface modelling – small role
  - Device configuration (placement, number, tension, materials) – major role
  - Nonlinear geometry – major role
  - Loading conditions – major role
- Device loosening
  - All above

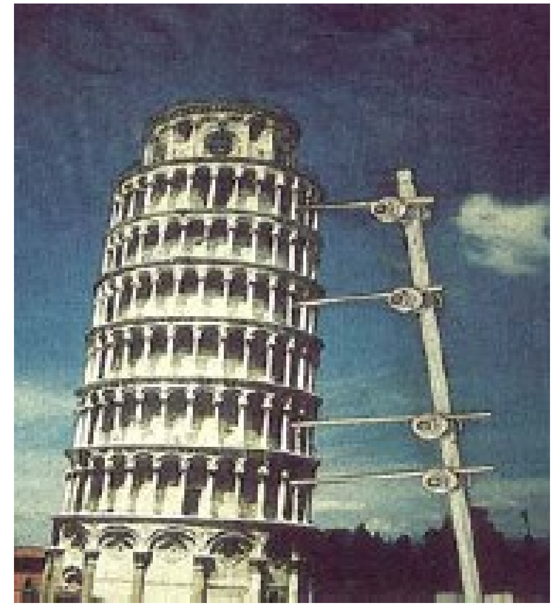
**MacLeod and Pankaj, 2014 — Comput Biomech Medicine, Springer**

EPSRC
orthopaedic research UK
stryker
CTC
UKIERI
UK-India Education and Research Initiative
British Orthopaedic Association

# Thank you

Francesc Levrero Florencio
Finn Donaldson*
Erica Sales
Krishna Manda
Rob Wallace
Paul Jenkins
Shuqiao Zhu
Noel Conlisk*
Andrew Phillips*
Alisdair MacLeod*
Chloe Scott
Jerome Goffin
Qing Ye
Adib Hamdani
Hamish Simpson
Colin Howie

Marco Viceconti
Enrico Dall'Ara
Yuan Chen
John Clement
David Thomas
Dave Cooper
Davide Ruffoni
Philipp Schneider
Alina Levchuk
Alexander Zwahlen
Puneet Mahajan
Ralph Muller
Praveen Srivastava
Chaman Chandel
Suhail Ahmad



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