Computational Bone Mechanics

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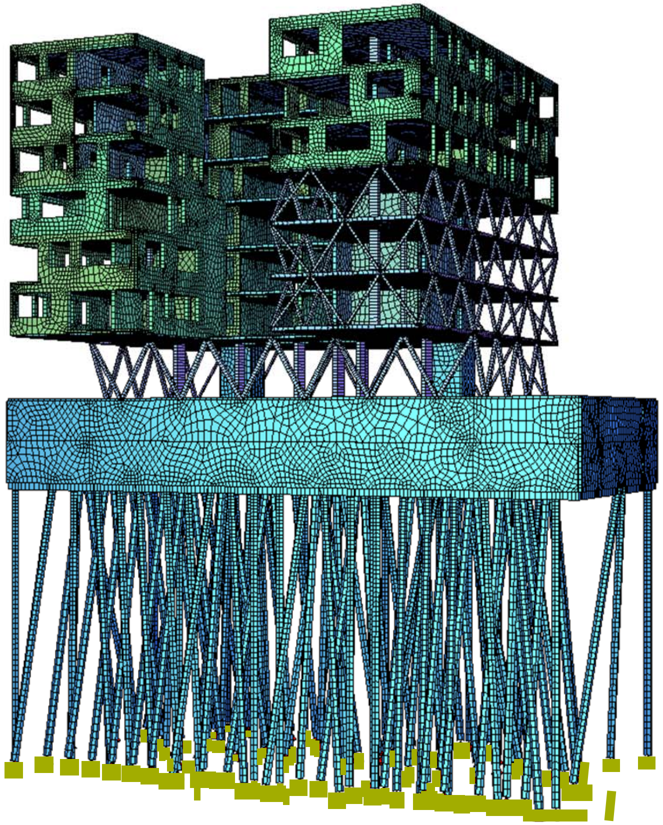
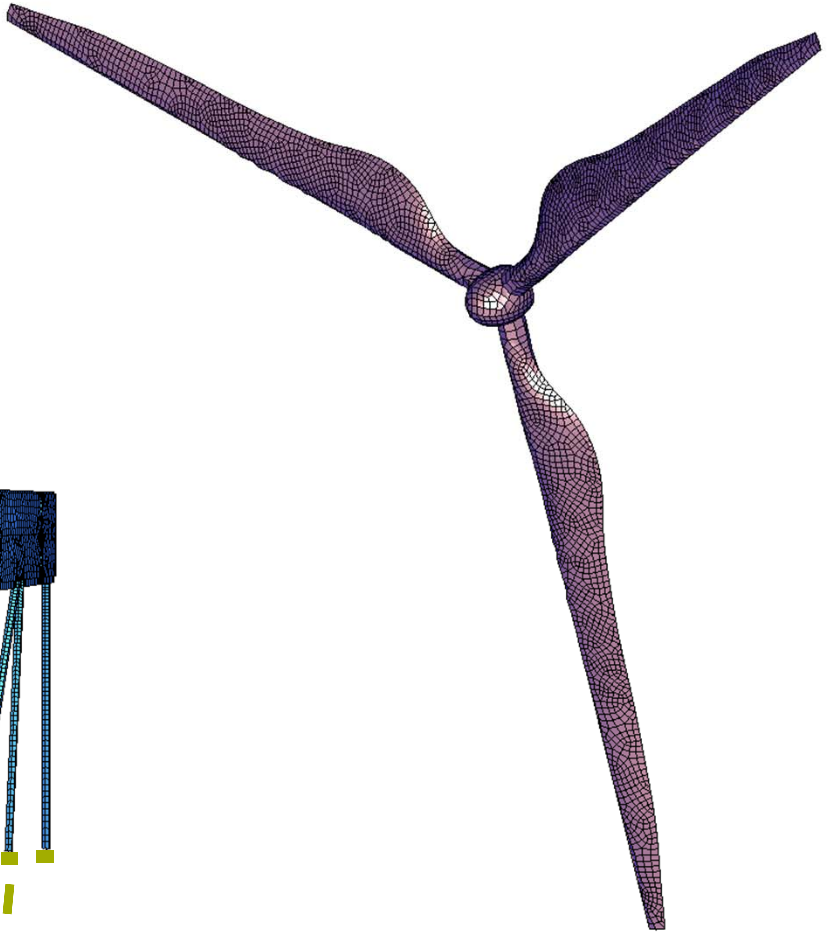
Computational Engineering



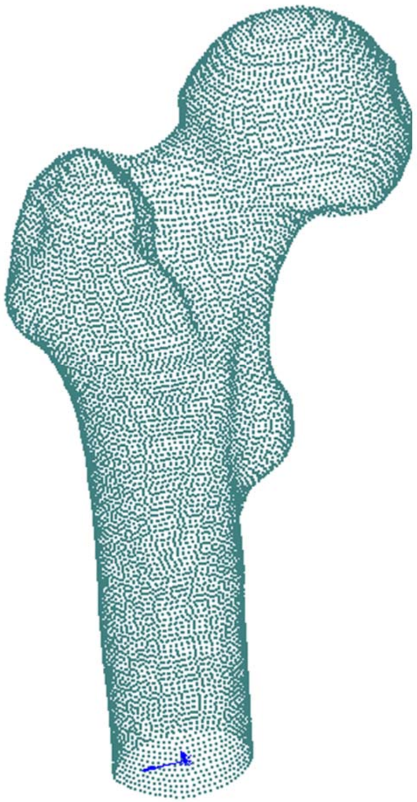


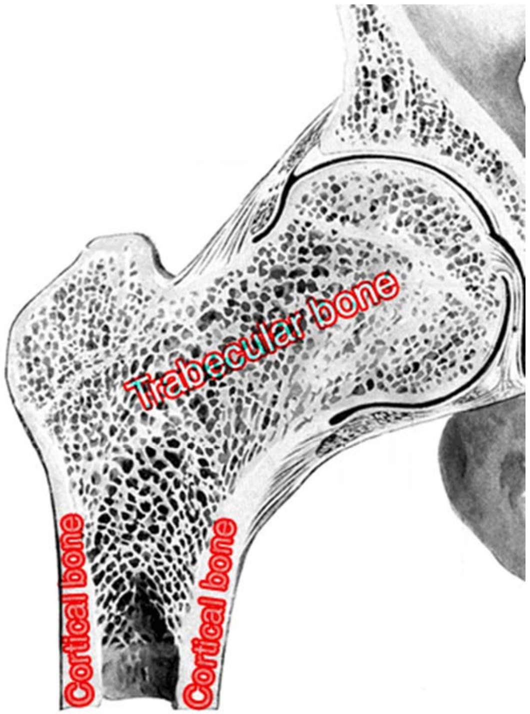
Multiscale problems in Computational Engineering

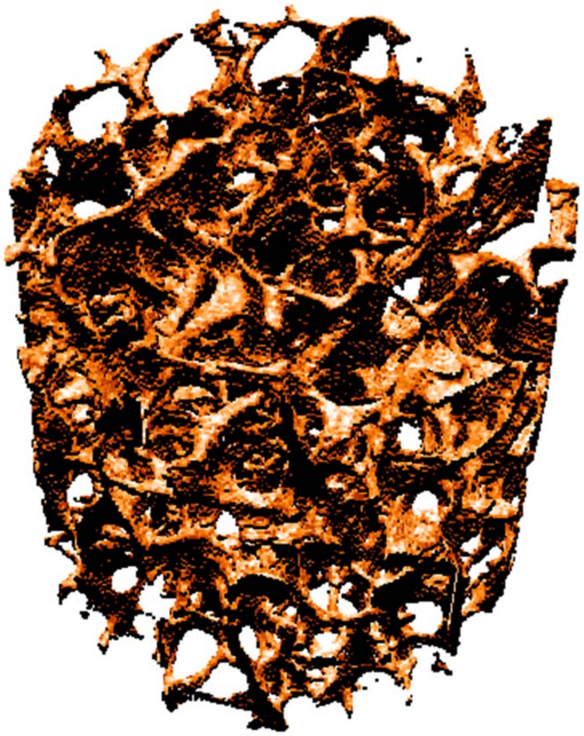


Images from:Wikipedia

A multiscale problem in bone mechanics







Internal structure of a human femur

- leightweight composite “structure”
- adaptive load bearing capacity
- heterogeneous on all scales

Trabecular bone
“soft”
porous
orthotropic

Cortical bone
“hard”
dense
transversal isotropic

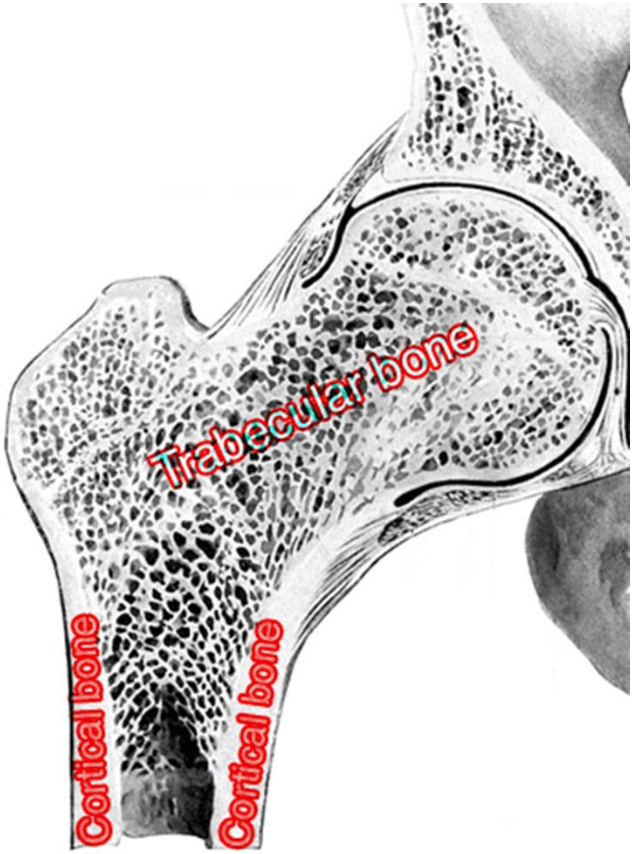


Illustration of a cross-section of the femur - abdn.ac.uk

Predicting the mechanical behavior of human femurs

Background

Orthopedic surgeons lack quantitative information on the mechanical behavior of bones (strains, deformations, stresses, etc.)

Accurate predictions of the mechanical behavior would allow to

- optimize implants and fixation devices
- estimate the strength of bones with defects
- virtualy plan surgeries

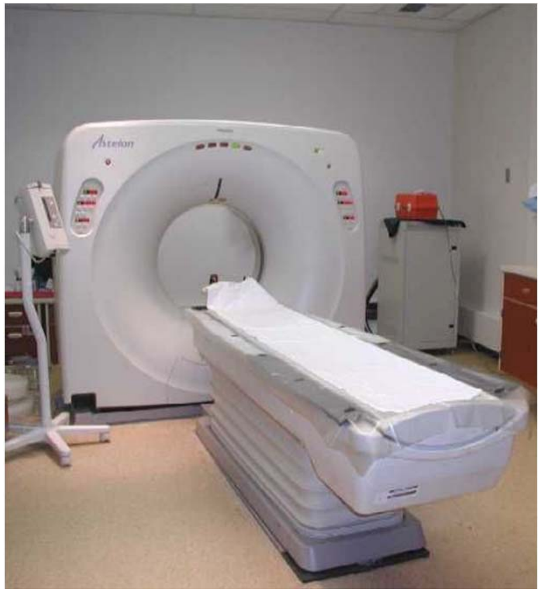
No templates anymore!

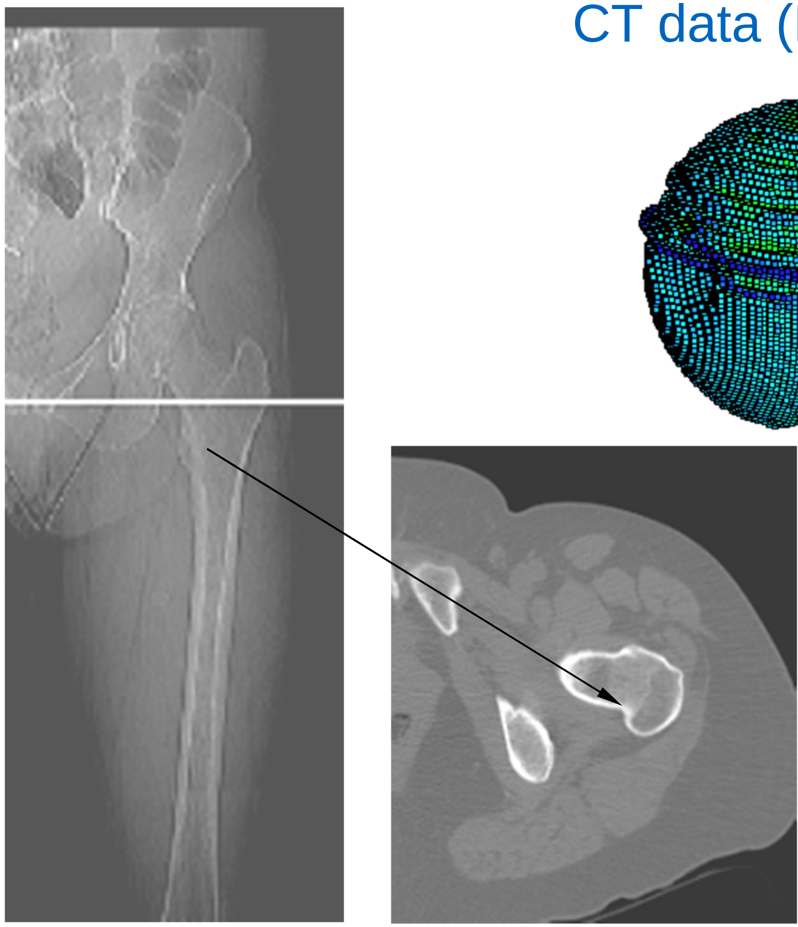
Research goal

A simulation tool that predicts the mechanical response of a patient's bone under physiological loading scenarios

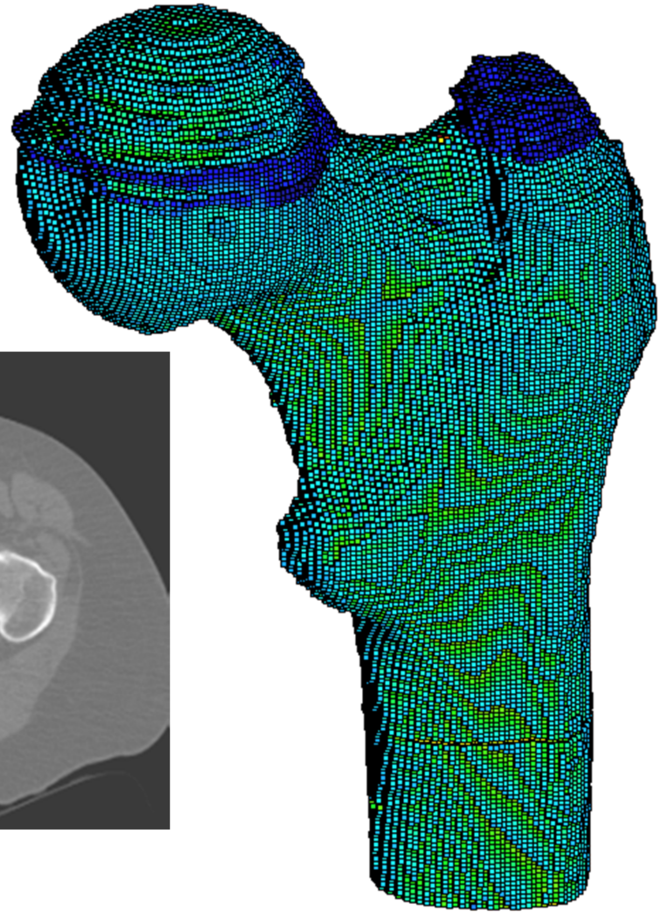
→ clinical practice requires a fast, *interactive* and <u>*validated simulation*</u> tool

CT scans



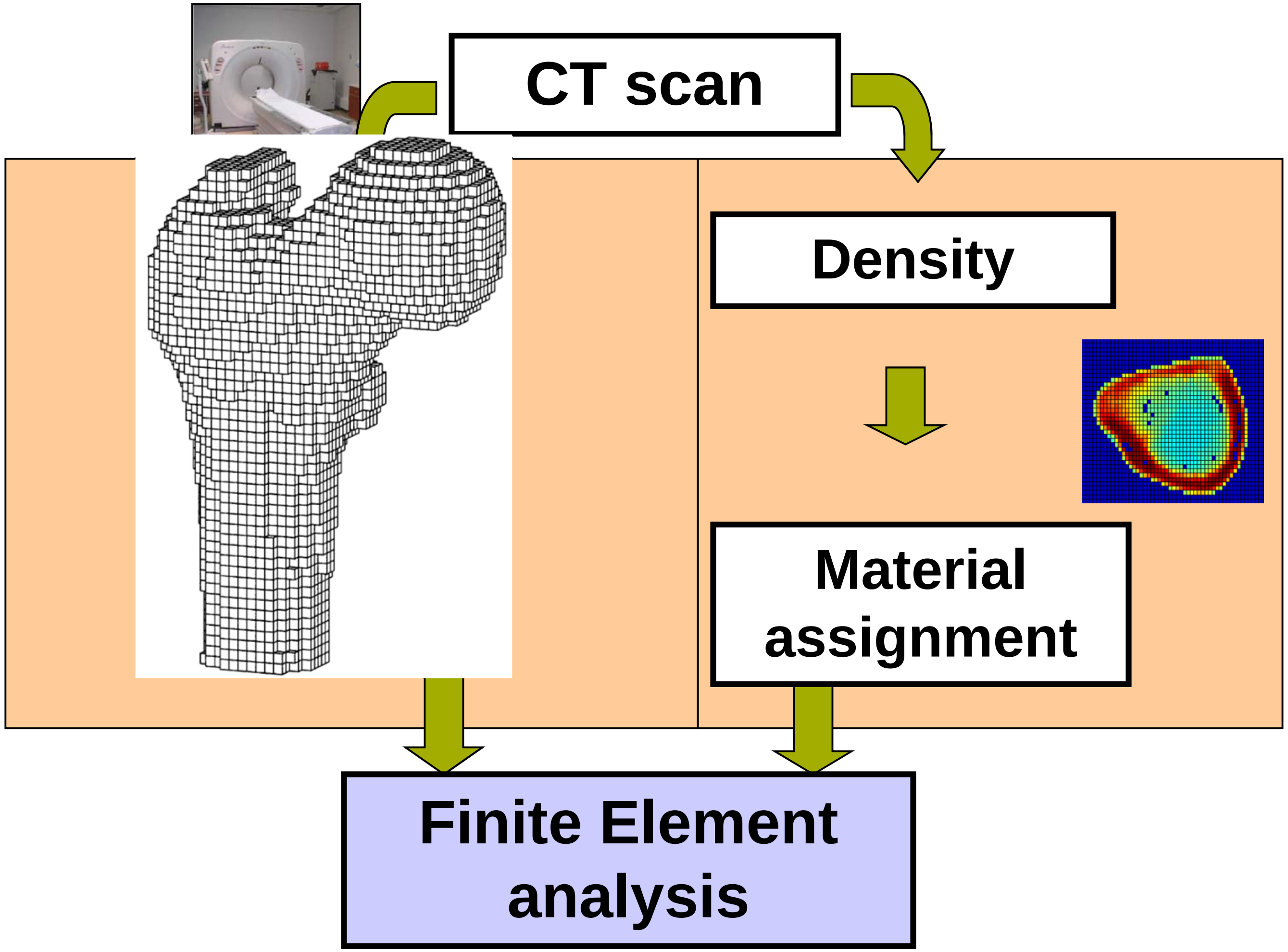


CT data (Hounsfield Unit)



Aim: predict mechanical behaviour based on patient specific data

Voxel-based Finite Element method (e.g. Keyak et al. 1990)

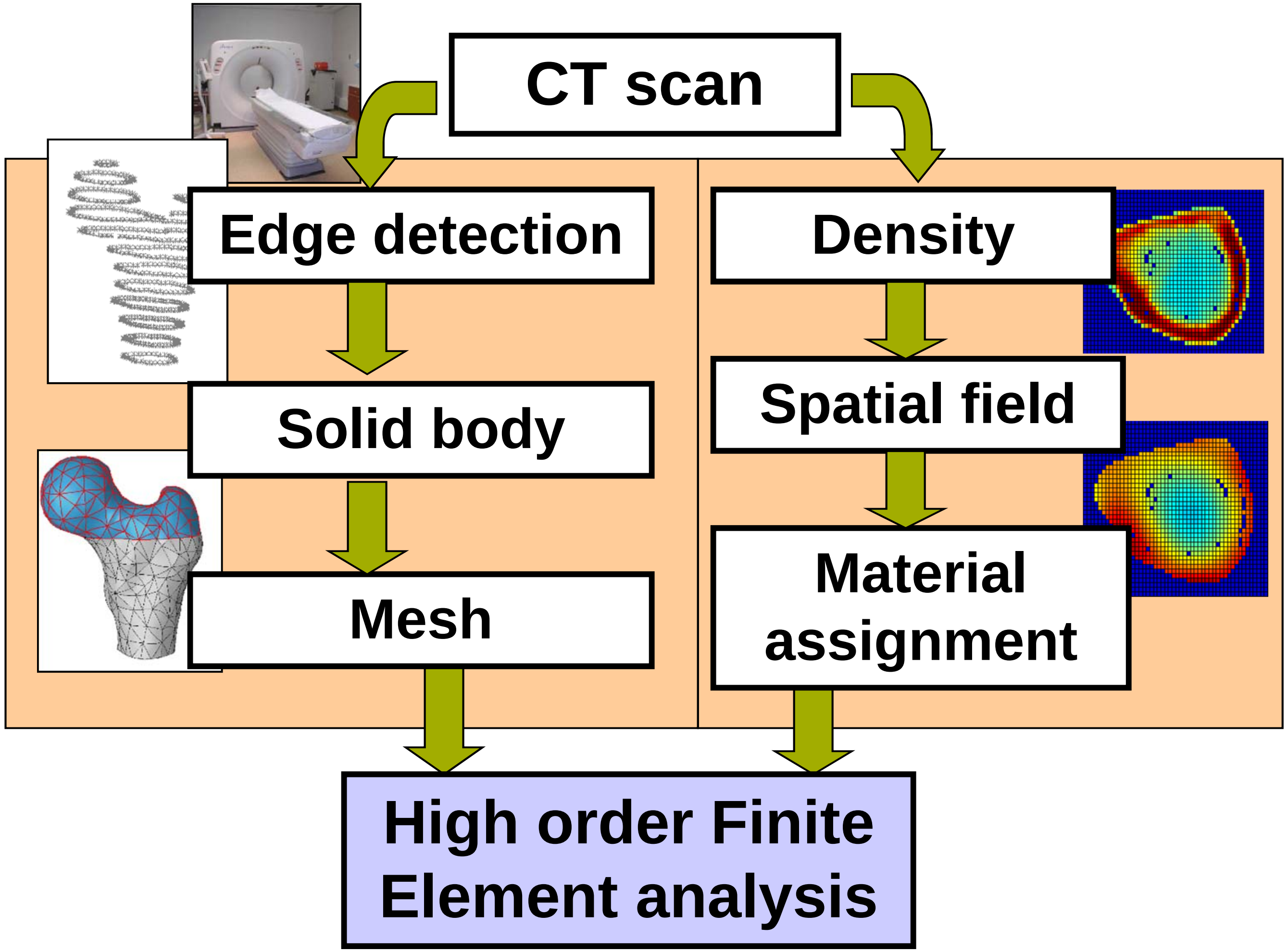


Advantage:
Can largely be automated

Drawback:
(Very) low accuracy

(High order) structure-based method

(e.g. Marom 1990, Müller-Karger et al. 2001 …, Yosibash et al. 2007)



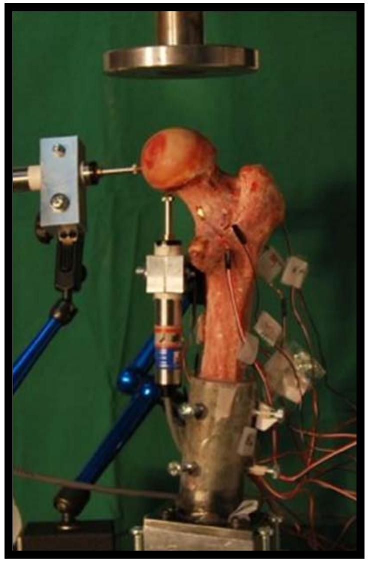
Advantage:
Accurate

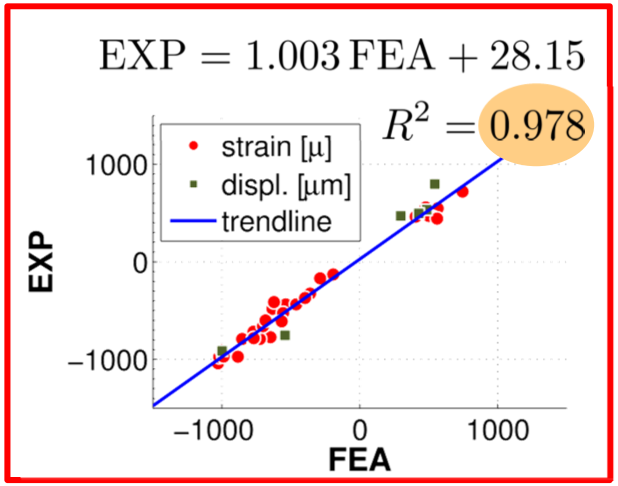
Drawback:
Time consuming model definition

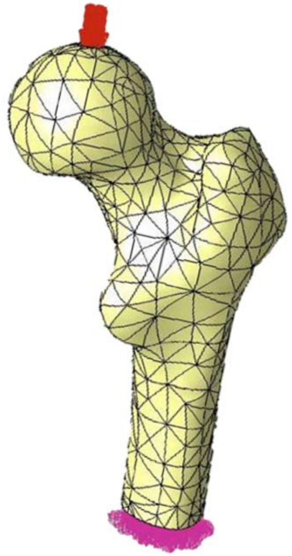
State of the art in computational biomechanics

High-order finite element analysis validated by experimental observations
(Prof. Zohar Yosibash et al. – Ben Gurion University, Israel)

In vitro experiment —— approximated by ——→ Simulation







Measurements (EXP) ←—— Agreement? ——→ Predictions (FEA)

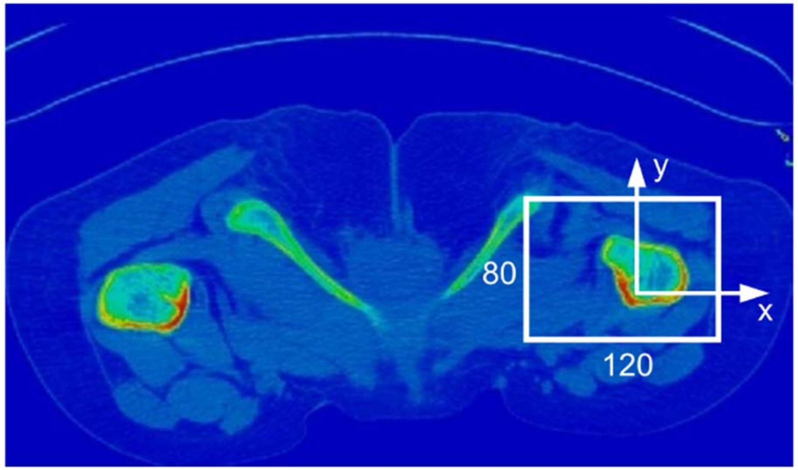
Our goal: Combine the best of two worlds

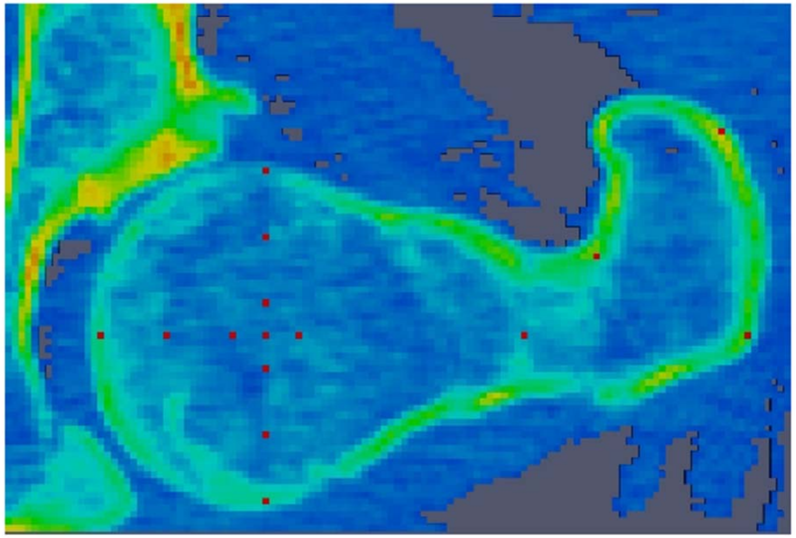
- fast and simple model definition like in voxel-FEM
- validated accuracy like in p-FEM

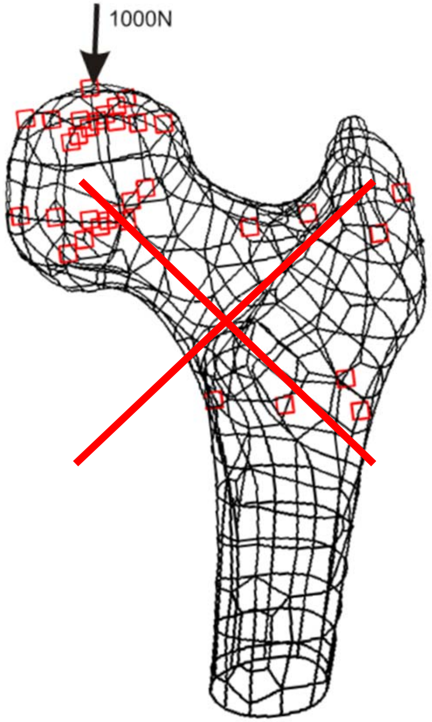
- … and much, much shorter computational time

→ **Finite Cell Method**

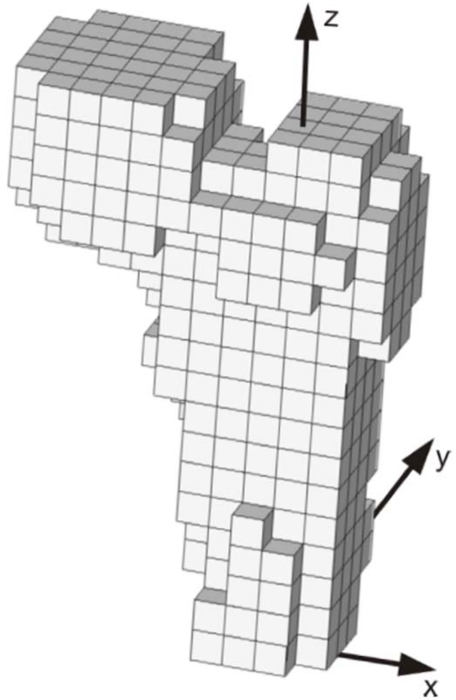
- high order embedded domain method
- uses large ‚super-voxels' (= ‚cells') for ‚ansatz-functions'
- represents (bone) material by precise, voxel-wise numerical integration







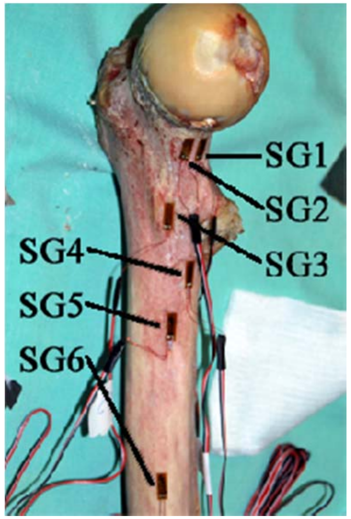
p-FEM mesh

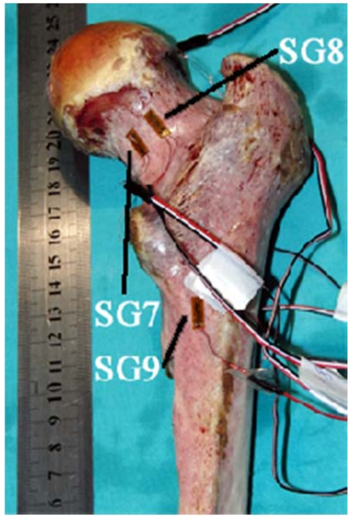


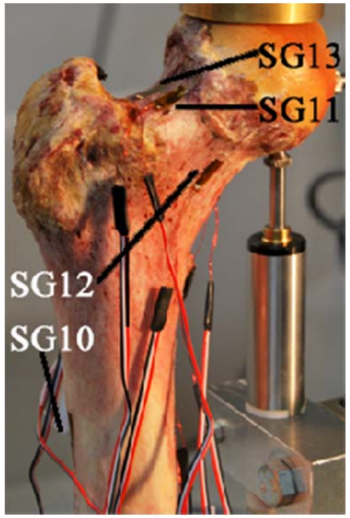
Finite Cell mesh

Time for definition of a numerical model reduced from *hours* to a few *seconds*

Verification and validation for the *Finite Cell Method*

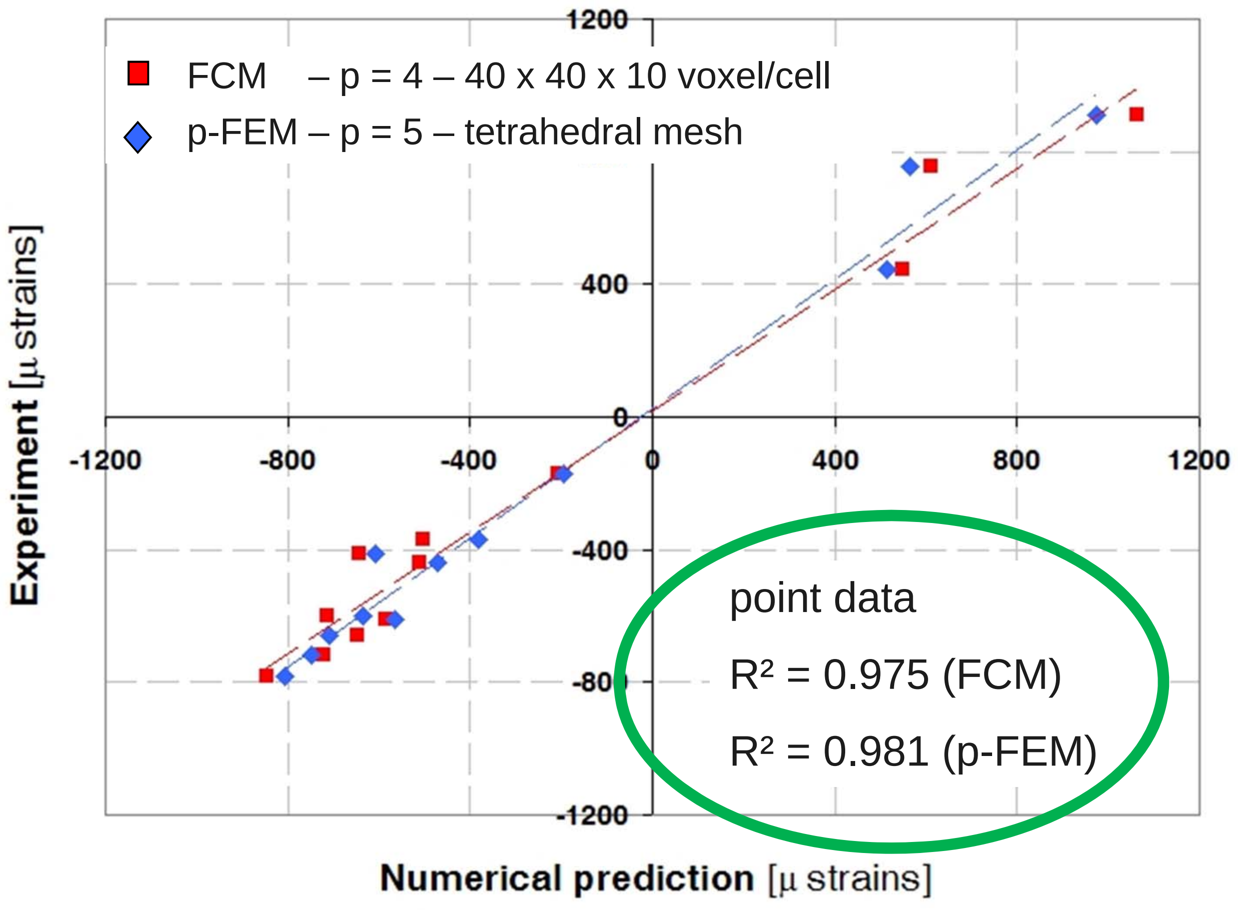






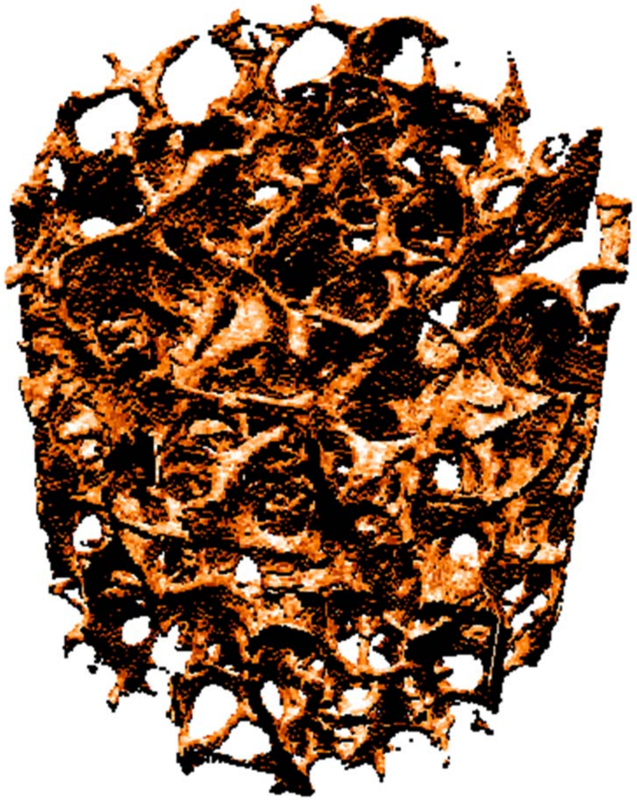
- fresh frozen femur – 63 year old male
- load controlled pressure   1000 N
- model size 1024 x 1024 x 185 voxel – 40 x 40 x 10 voxel/cell
- 678 finite cells – 20^3 sub-cells

M. Ruess, D. Tal, N. Trabelsi, Z. Yosibash, E. Rank
The finite cell method for bone simulations: Verification and validation
DOI: 10.1007/s10237-011-0322-2, *Biomechanics and Modeling in Mechanobiology*, 2011.


FCM – p = 4 – 40 x 40 x 10 voxel/cell
p-FEM – p = 5 – tetrahedral mesh
Experiment [µ strains]
Numerical prediction [µ strains]
1200
400
0
-400
-800
-1200
-1200
-800
-400
0
400
800
1200
point data
R² = 0.975 (FCM)
R² = 0.981 (p-FEM)

Microscale simulation

- basis for bone remodelling (healing, bone ingrowth, ...)
  - basis for stability prognoses of osteoporotic bone



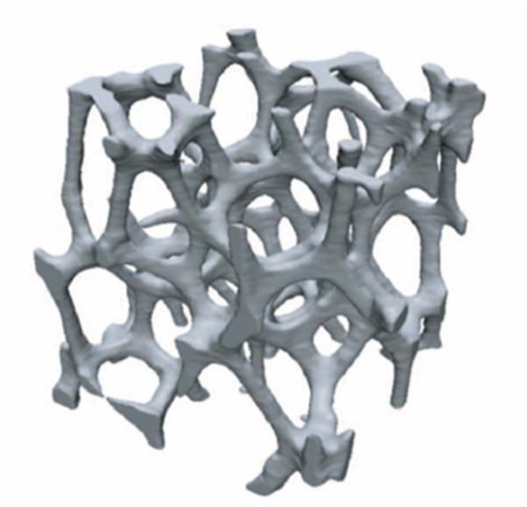
MICRO CT Model

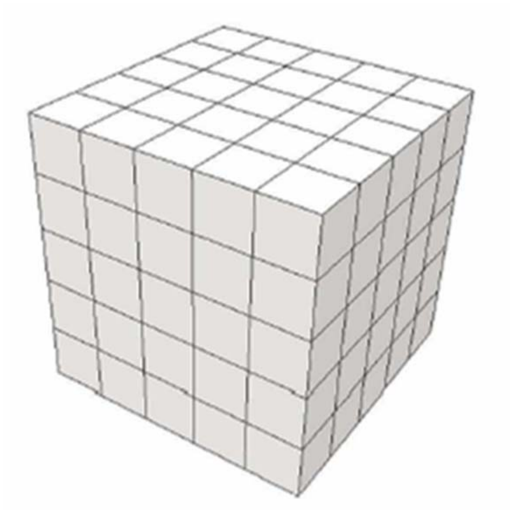
- second lumbar vertebra
- 5% formalin embalmed human cadaver

- diameter: 6mm
- height : 14mm

- resolution: 26 µm isotropic
- scan time: 4.1 h
- top loaded 100 N/mm²
- bottom clamped

Unpublished: Martin Ruess TU Delft/TUM



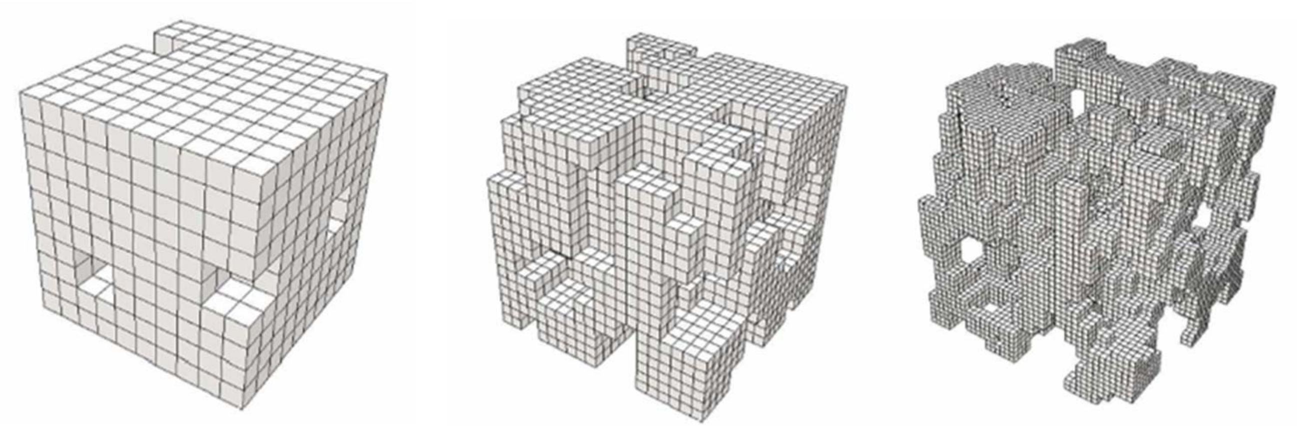


1. Basis:

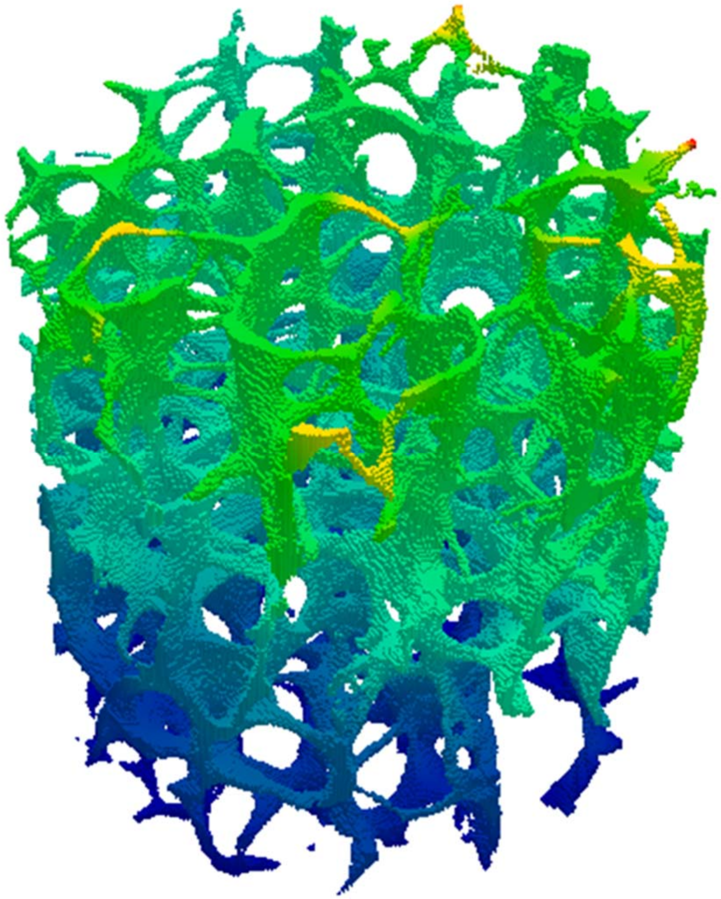
Structured grid of high-order finite cells

2. Accurate integration:

Adaptive sub-cells along geometric boundaries



… micro CT scanned specimen



displacements

Analysis Model

- data size: 15.2 m voxel
- finite cells: 408
- 32 x 32 x 29 voxel / cell

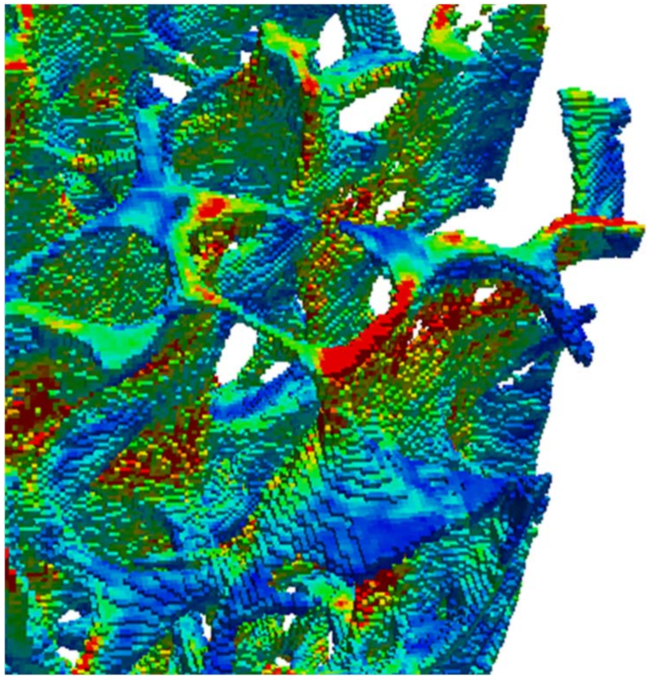
bottom clamped (weak bc)

top load 100 N/mm²

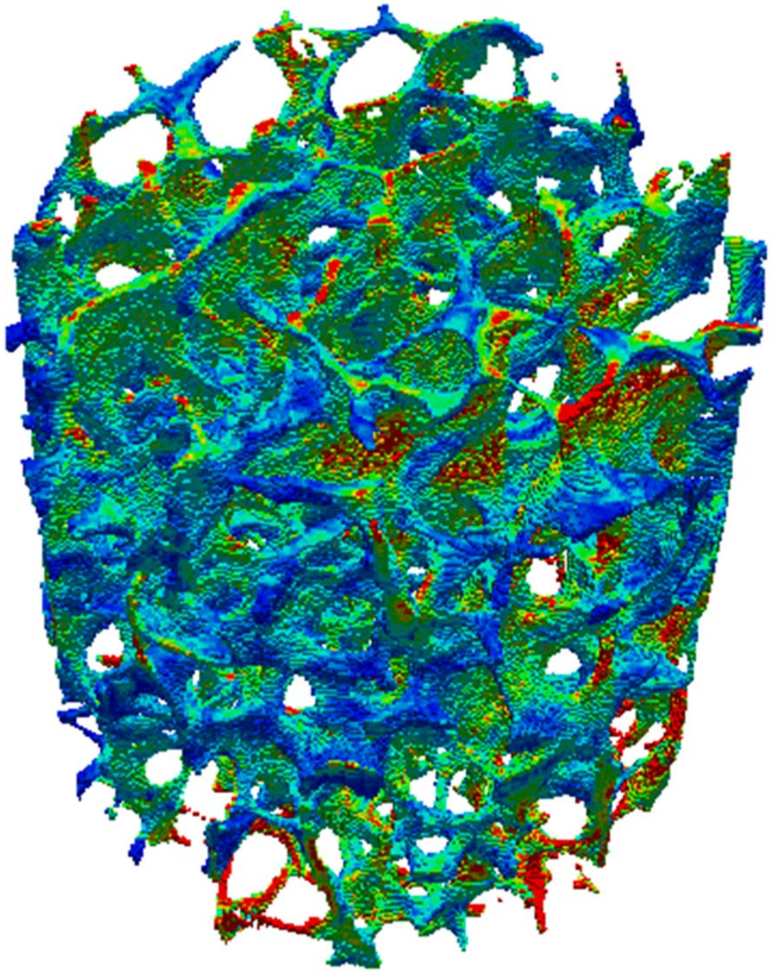
Unpublished: Martin Ruess TU Delft/TUM

… micro CT scanned specimen

p-degree = 6 -- # dof 52761



von Mises stress distribution



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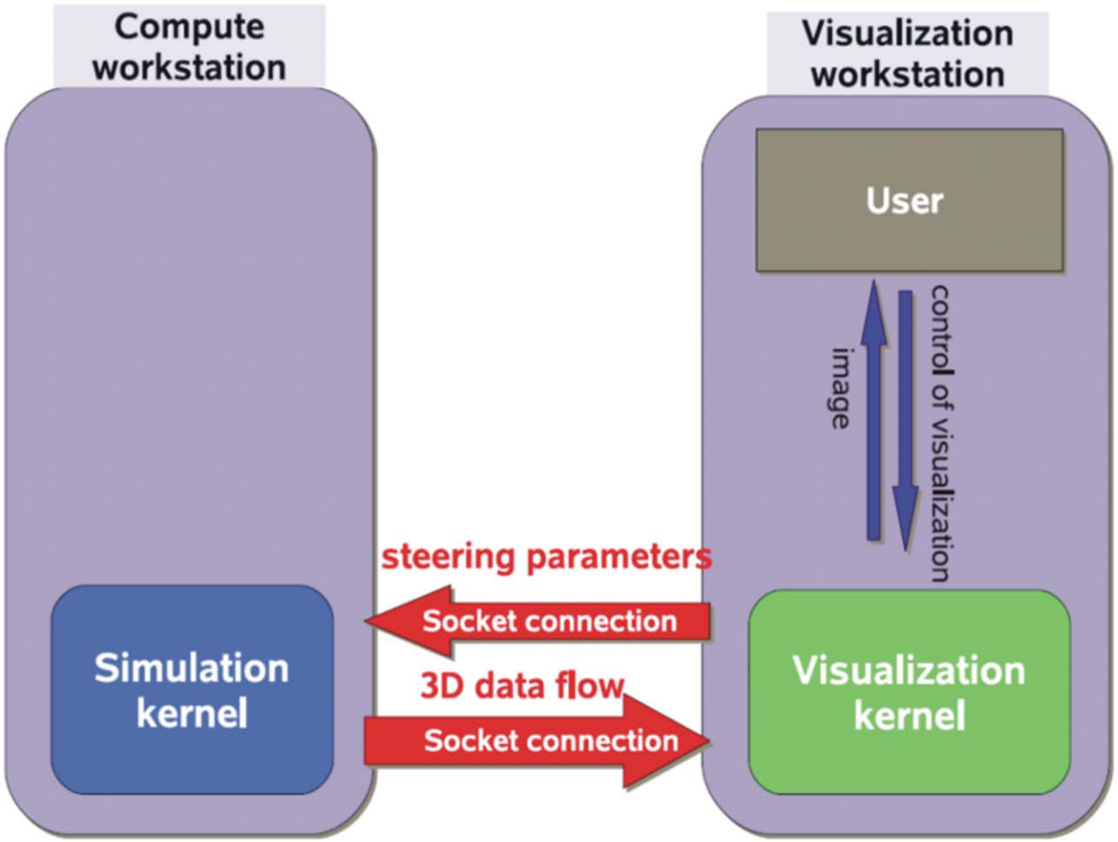
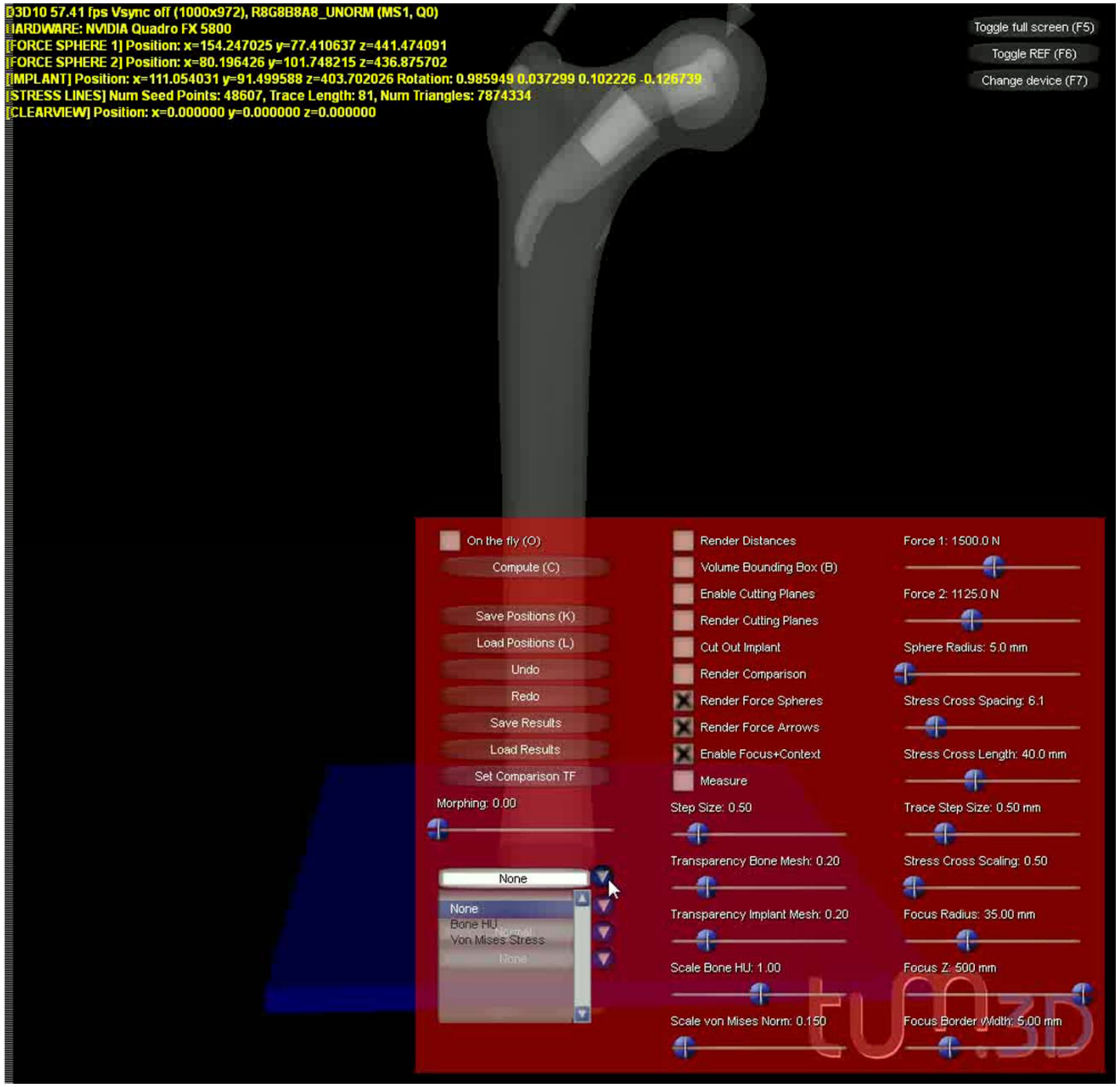
Interactive numerical simulation





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A.Düster (TUHH)

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Z. Yosibash (Univ. Beer Sheva)

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Thank you for your attention!