Computational Bone Mechanics

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Computational Engineering
Multiscale problems in Computational Engineering
A multiscale problem in bone mechanics
Internal structure of a human femur

- lightweight 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
- virtually plan surgeries

**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 *validated simulation* 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)

CT scan

Density

Material assignment

Finite Element analysis

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  

![Image of in vitro experiment](image1.png)

approximated by  

Simulation

![Image of simulation](image2.png)

Measurements (EXP)  

Agreement?  

Predictions (FEA)

EXP = 1.003 FEA + 28.15

$R^2 = 0.978$
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
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 – 20³ sub-cells

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The finite cell method for bone simulations: Verification and validation
**FCM** – p = 4 – 40 x 40 x 10 voxel/cell

**p-FEM** – p = 5 – tetrahedral mesh

- point data
  - $R^2 = 0.975$ (FCM)
  - $R^2 = 0.981$ (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

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

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... micro CT scanned specimen

p-degree = 6 -- # dof 52761

von Mises stress distribution

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Interactive numerical simulation
Joint project with:
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