MFEM Community Workshop

μ-FEA of a Rabbit Femur

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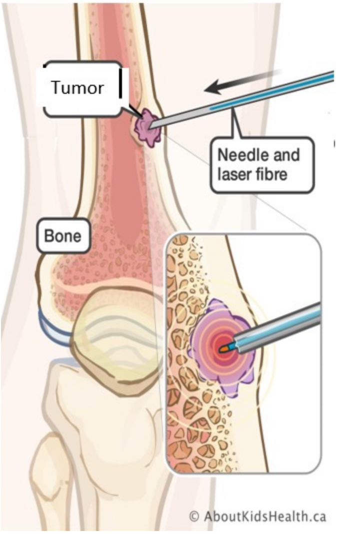
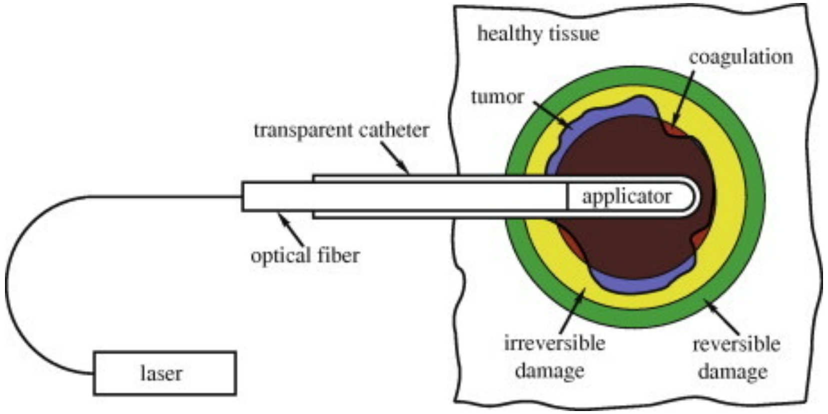
Motivation.

- Global bone cancer treatment market[1]: $1.2B in 2021
- Laser-induced thermotherapy (LITT) is used to destroy metastatic bone tumors by high localized temperature.
- Holes created for the optic fiber may weaken the bone and induce fracture.
- Predicting risk of bone fracture following LITT.

x-ray demonstration of lytic lesions in the left femur



Laser fiber passes through a needle to induce heat and destroy the tumor.



Sketch of laser-induced thermotherapy

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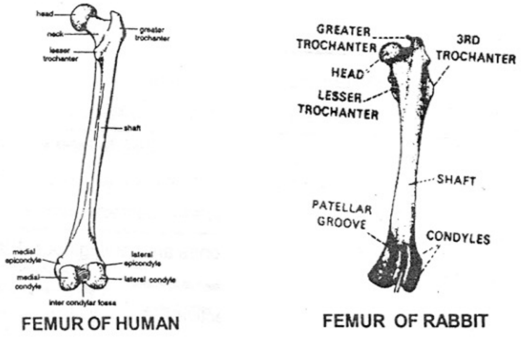


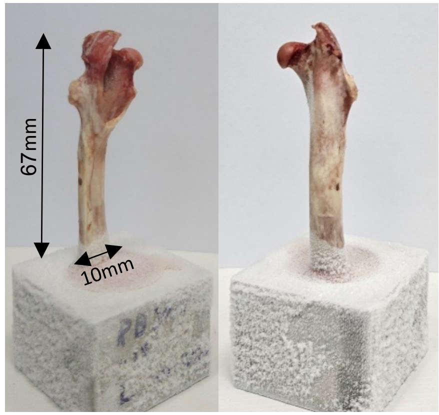
- Due to ethical limitations we use New Zealand White (NZW) rabbits as models for treatment validation.
- Main goal: **μ-FEMs based on μCT may predict patient-specific risk to fracture**.

[1] Market Research Future (MRFR)

µFEA from a µCT scan.

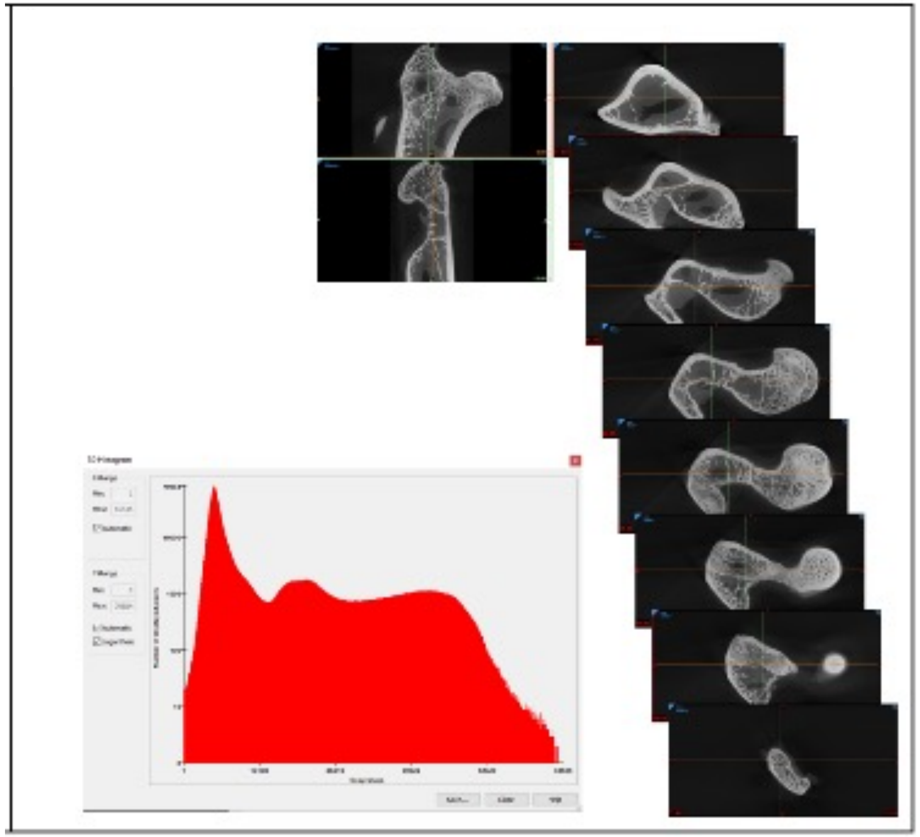
1. An intact NZW rabbit femur with bone tumors (~ø1.2 mm drilled hole for optic fiber).

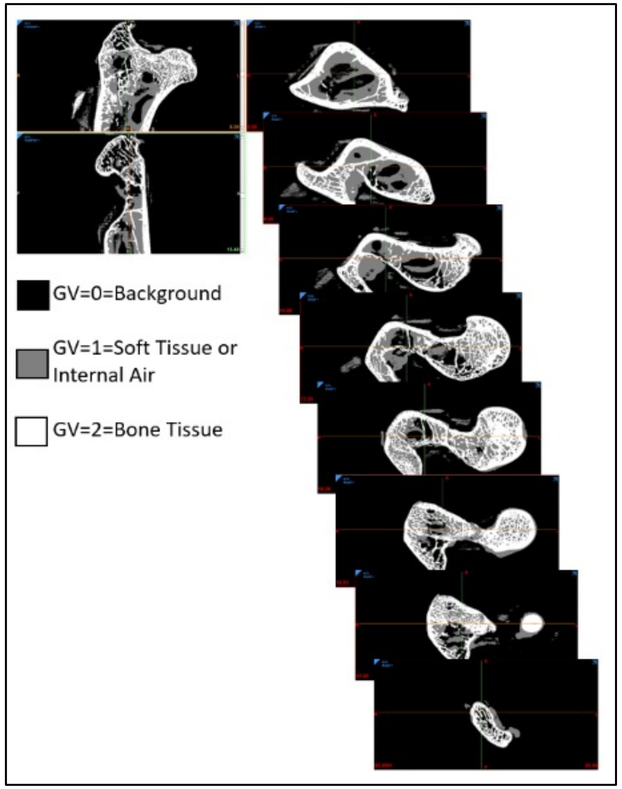
2. µCT: Nikon XT H 225 ST, voxel size: 40 µm³



NZW rabbit femur sample

3. Segmentation: Subtract bone tissue from the background via Medical Image Analysis (MIA) [2]. MIA semi-automated segmentation method based on iterative clustering algorithms.


µCT output DICOM files



MIA segmentation: input DICOM µCT files, 3 clusters (colors), 15 voxel grid, default local threshold value (0.02), output .raw file.

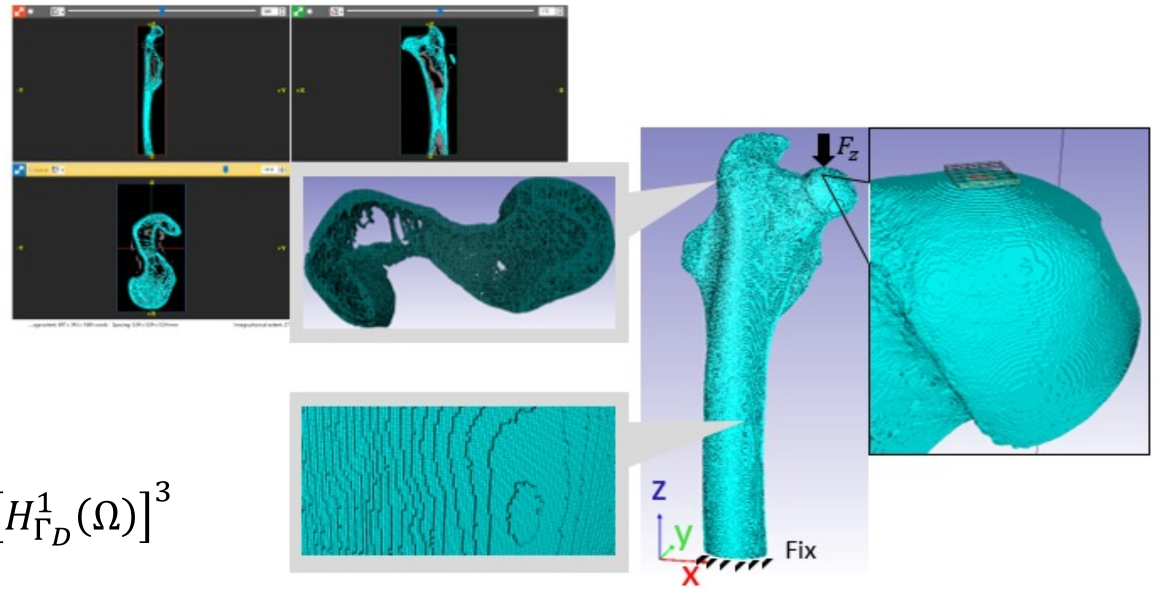
[2] Wollny G, Kellman P, Ledesma-Carbayo M-J, Skinner MM, Hublin J-J, Hierl Th, "MIA - A Free and Open Source Software for Gray Scale Medical Image Analysis", Source Code for Biology and Medicine, 2013, 8:20

μFE MODEL

- Mesh: Each μCT bone voxel is converted into a hexahedral element using Simpleware ScanIP[3].
- Boundary Conditions:
  I. Bottom surface fixed;
  II. Surface traction on the femur's head:
  $\mathrm{T_z} = -235\ \mathrm{MPa\ on\ A} = 0.4256\ \mathrm{mm}^2 \rightarrow \mathrm{F_z} = -100\ \mathrm{N}.$
- Homogenous isotropic material properties (assumed):
  $\lambda = 3846\ \mathrm{MPa}\,, \mu = 5769\ \mathrm{MPa}.$
- Linear elastic problem: Find $\mathbf{u} \in \left[H^1_{\Gamma_D}(\Omega)\right]^3$ such that,

$$\int_\Omega [2\mu\varepsilon(\mathbf{u}):\varepsilon(\mathbf{v}) + \lambda\, \mathrm{div}\mathbf{u}\ \mathrm{div}\mathbf{v}]\, d\Omega = \int_\Omega \mathbf{f}^T\mathbf{v}\, d\Omega + \int_{\Gamma_N} \mathbf{T}^T\,\mathbf{v}\, d\Gamma \quad \text{for all } \mathbf{v} \in \left[H^1_{\Gamma_D}(\Omega)\right]^3$$

- Huge FE model: over 125 million DOFs
- MFEM with modified ex2p.cpp code on 10 processors, enabling Hypre-bigint, CPU clock time = ~272 minutes.
- ex2p.cpp modifications:
  I. No mesh refinement
  II. Output: Displacements, strain tensor and the principal strains.

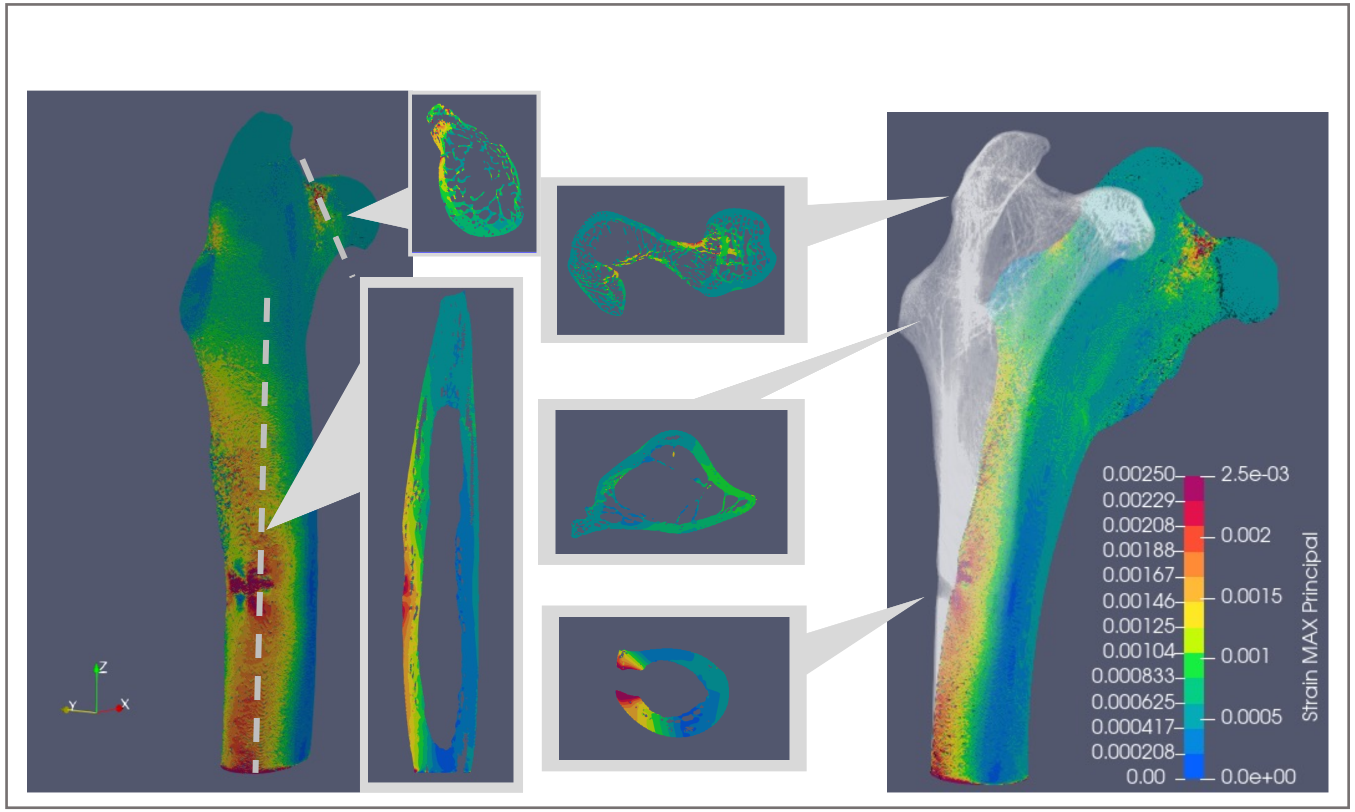


μFEM in Simpleware ScanIP

[3] Simpleware™ software (U-2022.12-SP1; Synopsys, Inc., Mountain View, USA) with the Simpleware FE module

Results

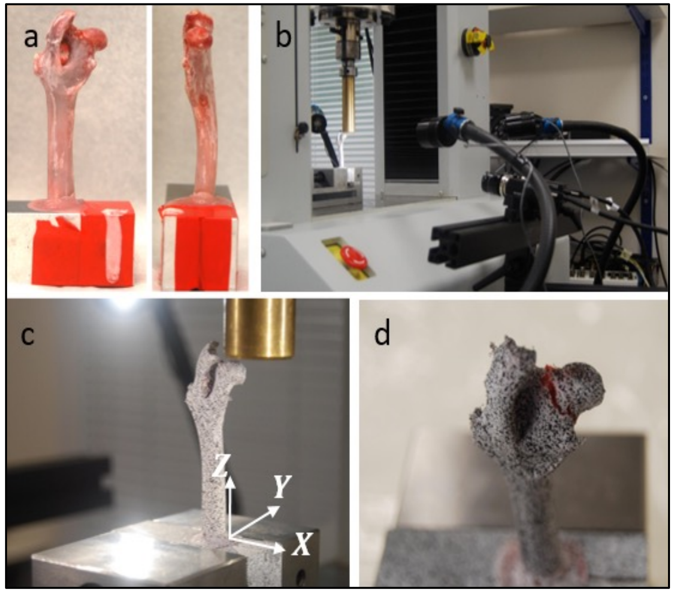
- Visualization using ParaView.
- Displacement magnitude (max 0.94mm) and maximum principal strain. To be compared with digital image coloration (DIC) and load cell results for experimental validation.
- Fracture prediction at areas with largest max principal strains: femur neck and fibers drilled hole.



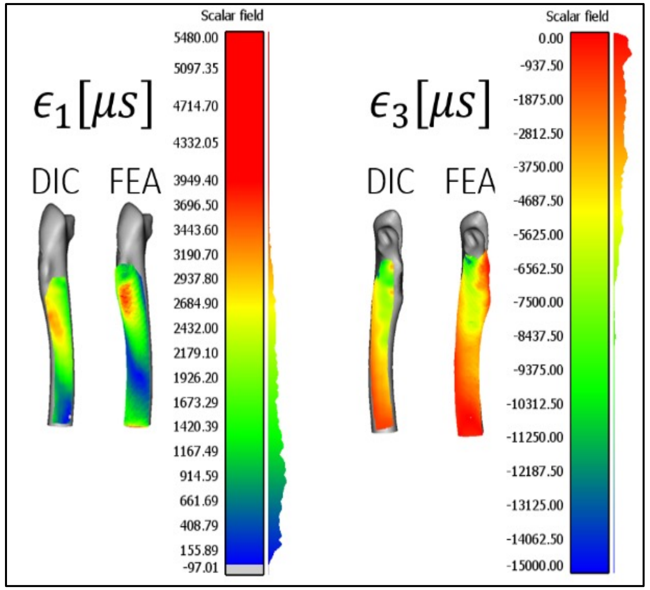
Maximum principal strains from μFEA .

Future work

- Solution convergence by using second and higher order hexahedral elements.
- Experimental validation, μFEA displacements/strains compared to DIC measurements.



Compression test with DIC apparatus and setup



From left to right, Max and min principal strain, FEA vs DIC .

- Material properties calibration, bone tissue material properties.
- μFE model of the human long bone/vertebrae (using HR-pQCT clinical scanners)?

Thank you for your attention