

Image-guided failure assessment of human trabecular bone – Inverse finite element modelling for characterization of elastic properties

Alexander Zwahlen¹, David Christen¹, Davide Ruffoni¹, Philipp Schneider¹, Werner Schmölz², Ralph Müller¹

¹Institute for Biomechanics, ETH Zurich, Switzerland

²Universitätsklinik für Unfallchirurgie, Medizinische Universität Innsbruck, Austria

azwahlen@ethz.ch

Abstract: Local interpretation of micro finite element (μ FE) simulations has become important in different fields of bone biomechanics. Although on an apparent level μ FE has successfully been validated against experiments, local validations are sparse and limited by imaging resolution. At the tissue level heterogeneity of Young's modulus has been reported. Although non-uniform material distribution have been shown to only have a minor influence on the apparent material properties, its impact on local material behaviour is largely unknown. By combining image-guided failure assessment (IGFA) using synchrotron-based-micro-computed tomography, strain mapping and inverse μ FE modelling, we present an experimental and computational framework which will allow studying local effects of intratrabecular heterogeneity of the Young's modulus.

Keywords: Image-guided failure assessment, strain mapping, synchrotron radiation μ CT, inverse μ FE modeling

Introduction

Local interpretation of micro finite element (μ FE) analysis has become important in bone structure-function relationships, stress concentrations around osteocyte lacunae, crack initiation and failure studies. μ FE simulations based on micro-computed tomography (μ CT) images have successfully been validated with experimental measures such as apparent stress and strain. Unfortunately local validations of strains are sparse and the resulting low correlations with experiments were explained by limited image resolution affecting the experimental and simulated strains [1]. Experimental nano-indentation studies have reported intratrabecular heterogeneity of Young's modulus. Including the variation in Young's modulus based on measured mineral density only marginally influenced apparent level properties of μ FE simulations [2]. Nevertheless intratrabecular heterogeneity may further explain the low local accuracy of μ FE simulations.

Improvement of the local accuracy of μ FE could be achieved by investigating different local distributions of elastic moduli. Here, we propose to calculate an optimal modulus distribution that produces locally accurate μ FE simulations. For this we performed image guided failure assessment (IGFA) [3] to measure experimental displacement fields and local strain maps using a deformable image registration algorithm [4]. Combining displacement and strain measurements with inverse μ FE modelling [5]

will allow the investigation of the local heterogeneity of the Young's modulus.

Methods

Materials and specimen preparation

Forty trabecular bone specimens (\varnothing 6 mm x 9 mm) were excised from fresh frozen thoracic vertebral (Th 9-12) bodies. The age of the 11 donors (5 females, 6 males) ranged from 27 to 83 years (median 76 years, mean 68.1 ± 16.7 years). Using a diamond core drill (Breu Diamantwerkzeug GmbH, Arbon, Switzerland) samples were drilled out in cranial-caudal direction and bone marrow was washed out subsequently. Using a precision saw (IsoMet 5000, Buehler, Lake Bluff, IL, USA) specimen ends were cut parallel to each other to ensure a precise length (9 mm). Prior to IGFA testing all 40 specimens were analyzed for bone volume density (BV/TV) and heterogeneity based on standard μ CT imaging (μ CT 40, Scanco Medical AG, Brüttisellen, Switzerland) at a nominal resolution of $12\mu\text{m}$, a voltage of 70 kVp and a current of $114\mu\text{A}$.

For the IGFA experiments 12 specimens spanning a range of BV/TV from 4.8% to 21.8% (mean $9.86\% \pm 4.84\%$) were selected. The chosen specimens originated from 8 human donors (4 females, 4 males) aged from 27 up to 82 years (median 74 years, mean 64.0 ± 17.8 years). Stainless steel end plates were glued on the specimens top and bottom end using commercially available cyanoacrylate glue. Apart from the gluing procedure the specimens were stored in phosphate buffered saline (PBS) or frozen in PBS-soaked gauze to ensure wet conditions during testing.

Image-guided failure assessment (IGFA)

Using a previously published micro-compression device [6], the IGFA experiments were performed as follows: First the specimens were loaded with a preload of 3N before an alternating sequence of micro-compression tests (uniaxial strain) and SR μ CT imaging was repeated in steps of 0.5% strain until failure. Finally, the specimens were unloaded and imaged again by SR μ CT. The strain-rate was set to 0.01% per second and a relaxation time of 20 min was allowed before imaging in order to prevent movement artifacts. Mechanical strain was applied by a plunger with a spherical tip acting on the top endplate while the bottom endplate was fixed. SR μ CT imaging was performed at the TOMCAT beam-line of the Swiss Light Source (Paul Scherrer Institute, Villigen, Switzerland) using a beam energy of 17.5 keV and 1081 projections. The entire specimens were scanned at a nominal

image resolution of $7.4\mu\text{m}$ resulting in roughly $1200 \times 1000 \times 1000$ voxels or $8.9 \times 7.4 \times 7.4 \text{ mm}^3$.

Deformable image registration and strain mapping

From the IGFA experiments local displacements were calculated with a demons deformable registration algorithm as described in [4]. Local strains were then derived from the displacement fields in three dimensions.

Inverse micro finite element (μFE) analysis

In order to estimate the distribution of the local Young's modulus, the experimentally measured strain and displacement fields were combined with μFE . In Figure 1, a schematic of the inverse FE algorithm is shown. Starting with a homogenous modulus distribution a "simulated strain" was computed with μFE by imposing proper local boundary conditions (BC). The new modulus distribution was estimated proportionally to the ratio between "simulated" and "experimental" strain before starting the loop again.

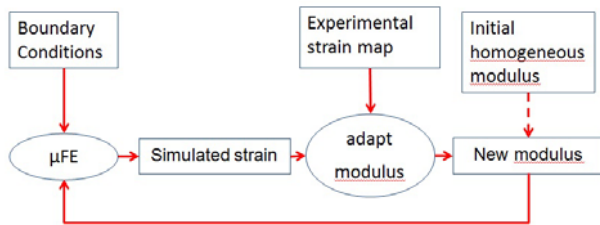


Figure 1: Flow chart of the proposed inverse μFE analysis

Results

For 10 out of 12 specimens IGFA experiments were successful and they allowed strain mapping for each loading step. The number of loading steps varied between specimens and 68 loading steps were measured in total. Strain mapping was performed for the entire specimens allowing global as well as local failure patterns to be visualized and animated (Figure 2a,b). Displacements from the strain maps allowed the application of experimental boundary conditions for μFE calculations of a subset (Figure 2 c).

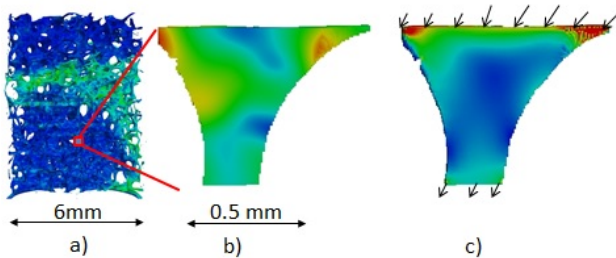


Figure 2: Strain map of a) specimen loaded at 3% apparent strain, b) of single trabeculae and c) μFE with experimental BC (note: different color scales for a, b and c)

For verification of the inverse μFE algorithm a random Young's modulus distribution in 2D was used to create a virtual experimental strain (Figure 3). For this virtual experimental strain, the inverse μFE algorithm was run for 10 iterations starting from an initial guess (iter=0) using a homogenous Young's modulus providing updated distributions of Young's modulus approaching the "real" distribution defined for the virtual case (Figure 3).

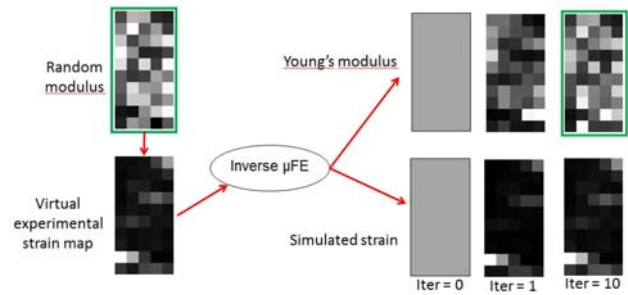


Figure 3: Inverse μFE applied to random modulus

Discussion

With 10 successfully measured samples we could show that IGFA using SR μCT was feasible for larger number of specimens, providing strain maps, visual inspection and quantitative analysis (Figure 2a and b). Furthermore, local strains were successfully derived and experimental boundary conditions imposed on μFE simulations based on IGFA experiments (Figure 2c). The μFE derived strain patterns using a homogenous Young's modulus differed from the experimental strain (Figure 2c vs. 2b) supporting the need of a heterogeneous modulus distribution for locally accurate μFE simulations. The presented experimental and computational framework allowed the inverse μFE algorithm to be applied to experimental IGFA data. The test case for the inverse μFE successfully converged towards the virtual modulus distribution (Figure 3, green box). From this we conclude that a Young's modulus distribution can be calculated that allows μFE simulations to be accurate. Currently, large scale inverse μFE simulations are running on all samples. From the resulting modulus distributions relations between density and Young's modulus as well as between location and modulus can be investigated. Incorporating such relations in μFE simulations will improve the local accuracy of μFE simulations.

Acknowledgement

The authors would like to thank Marco Hitz for technical support. Alina Levchuk and Sandro Badilatti are acknowledged for their support during the experiments.

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