BONE MECHANICS FROM FINITE ELEMENT MODELING AND MICRO-COMPUTED TOMOGRAPHY: VALIDATION OF AN ORTHOTROPIC MATERIAL MODEL WITH FUSED DEPOSITION MODELING

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INTRODUCTION

Bone diseases such as osteoporosis result in bone loss and weakened bone micro-structure and could lead to spontaneous fractures. Detection of bone micro-structural changes and their impact on bone mechanics is important for the successful treatment of bone diseases and progression of joint injuries.

It is commonly postulated that local mechanics (tissue stress or strain) is related to stimuli for bone remodeling [1]. A micro finite element (μFE) solver was developed in our lab to numerically predict the local stress and strain in bone structure [2,3]. Micro-computed tomography (μCT) can provide high resolution image data suitable to the μFE solver and allows non-destructive, three-dimensional morphological and mechanical analysis of bone. With newly developed in vivo μCT, μFE simulation of bone mechanics can be evaluated over time. However, it is important that μFE models be validated for numerical accuracy. This is problematic because it is difficult to perform experiments on 1:1 scaled bone.

A method has been developed to validate μFE models using rapid prototyping: fused deposition modeling (FDM). FDM prototypes can be built based on μCT image data and scaled up so that local stress values can be measured in an experimental setup using strain gauges for comparison with μFE models to estimate accuracy.

METHODS

Five identical FDM prototypes were manufactured (FDM Titan, Stratasys, Minnesota, U.S.A) based on a 1.7x1.7x1.7mm^3 volume of trabecular bone scaled to 30:1. Two rosette strain gauges were mounted on each prototype: one on a flat and one on a curved surface. Uniaxial compression (1%ε) was performed on the five prototypes. Two data acquisition systems were used for recording. Apparent stress (E_{app}) and local 1st principal stresses calculated from rosette readings were obtained experimentally.

The μFE model is based on the same trabecular bone image data used for the prototypes, and boundary and loading conditions mimicked the experiments. The material properties used were the orthotropic properties of FDM material which were previously determined experimentally [4]. Our in-house μFE solver was upgraded to solve this orthotropic model. Results from μFE (stress results in elements in a 3x3 region corresponding to each gauge were averaged) were compared to experimentally measured strains.

RESULTS AND DISCUSSION

The FDM Titan machine was tested for volumetric reproducibility (five models; 0.1% error), and the FDM prototype volumes were matched to the μFE mesh volumes. The μFE model predicted E_{app} measured experimentally within <1% (Fig. 1). The local 1st principal stress calculated by μFE was within 9% of experimental data on the flat surface and 56% on the curved surface (Fig. 1). The accuracy of our in-house μFE model at the apparent level (1%) indicates that global orthotropic material properties can be predicted well based on digital FE models. The error of prediction on the curved surface was largest due to the jagged hexahedron mesh used, as well as due to the problems of attaching strain gauges to curved surfaces. The reduced error in local stress measurements on the flat surface is due to the reduced effect of jagged surfaces in that region of the μFE model.

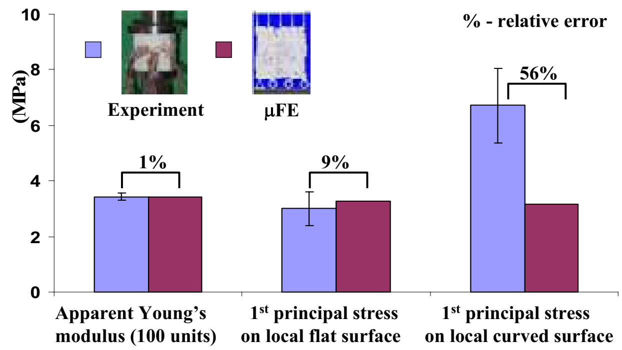

Figure 1: Comparison of experiment and μFE results at both global (left) and local levels (middle/right) on a trabecular bone model.

CONCLUSIONS

The prediction of trabecular bone mechanical properties by our in-house μFE solver is more accurate at the apparent level than local level. This result is expected, and smoothing these μFE models may reduce these local errors (work in progress). The results presented here reinforce that μFE models used to predict bone remodelling based on local stress/strain should account for the large errors that may occur on the model surface.

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ACKNOWLEDGEMENTS

Research funded by NSERC.