INTRODUCTION:

Trabecular bone can resist considerable forces even when it is loaded in the post-yield range [1]. Such post-yield behavior is due to both its micro-architecture and tissue properties, but what each of these factors contributes is unknown. A better understanding of this behavior is important for estimates of mechanical integrity in collapsed vertebrae, a condition commonly found in osteoporosis. Nonlinear micro-finite element (µFE) analysis, a novel computational tool, was used successfully to predict trabecular yield properties [2] and to demonstrate geometric nonlinear behavior in post-yield simulations [3]. In this study we evaluated the contribution of failure behavior in trabecular bone tissue itself.

We used nonlinear µFE analysis to test two bone-tissue failure models that might predict apparent failure behavior. Predicted results were compared to experimental results by evaluating load-displacement curves and, at the local level, trabecular deformations.

MATERIALS AND METHODS:

A 5 mm cylindrical trabecular bone specimen with a diameter of 5.35 mm was extracted from the proximal part of a bovine tibia. Following scanning of the structure with a µCT scanner (µCT-80, Scanco Medical AG) the specimen was compressed in a micro-compression device (MCD) [4] to a strain of 5 %. After testing, another µCT scan was made with the sample still in the deformed state.

The initial µCT scan was used to create a µFE mesh with 156,007 brick elements measuring 60 µm on a side. First, a linear analysis was performed to extract the tissue effective elastic modulus and to see if elements were loaded in tension or compression. Geometrically nonlinear analyses were performed using Marc (MSC.Software Corporation) with two different isotropic material models: (1) Hill plasticity and (2) von Mises plasticity. In a first set of analyses, the tissue material properties were represented by a bilinear curve with parameters based on experimental data for cortical bone [5-7]. For the first model the elements were divided into tension and compression groups, and the effective stress was determined accordingly [6]. Post-yield moduli were set to 0.0 GPa [5] or 0.98 GPa [7] for elements loaded in compression and tension, respectively. The second model did not differentiate between tension and compression and used the tissue compressive properties only.

In a second set of analyses, the tissue material properties were represented by curves built of multiple linear segments, thus introducing additional failure parameters that cannot be taken from the literature. The initial linear analysis showed that a tissue modulus of 9.28 GPa was represented by curves built of multiple linear segments, thus introducing additional failure parameters that cannot be taken from the literature. In order to determine these additional trabecular tissue failure properties, the yield and post-yield parameters of the models were adjusted to fit predicted and experimentally obtained load-displacement curves.

Virtual µCT scans were created from the deformed µFE meshes and superimposed over the CT scans of the deformed specimen. The simulated and measured load-displacement curves, and the percentage of bone voxels shared by the measured and predicted images were used as a local and global accuracy measure respectively.

RESULTS:

The linear analysis showed that a tissue modulus of 9.28 GPa was required to describe the elastic behavior of the specimen and that only 7.5 % of the tissue was loaded in tension. The apparent failure behavior of the specimen (Fig. 1) could only be reproduced when the tissue properties were changed from a bilinear model based on cortical bone to models implementing softening behavior (Fig. 2). After fitting of the yield and post-yield parameters, a good correlation between experimental and predicted load-displacement curves was obtained. Local deformations (Fig. 3) were improved as well with the mean percentage of shared bone voxels increasing from 74 % to 77 % (Fig. 1).

DISCUSSION:

The results demonstrate that simple bilinear models for tissue failure properties with parameters based on cortical bone were unable to produce realistic results for the specimen failure behavior. In particular the decent in the load-displacement curve was not reproduced. This suggests that this decent is not due to large (local) deformations, which are accounted for in the µFE model, but to changes in tissue material properties. When bone tissue softening is accounted for, very good agreement between experimental and predicted results could be obtained after fitting. The fitting procedure, in fact, provides a new method for the determination of such failure parameters for bone tissue in-situ in an indirect way.

This study demonstrates that the determination of tissue properties by applying such a fitting procedure is feasible. It is expected that, once applied to more specimens, this approach can be used to accurately determine post-yield bone-tissue failure parameters.


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