

Finite element modeling of nanoindentation of plastic embedded trabecular bone

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Introduction

Nanoindentation is a technique by which highly localized surface mechanical properties are measured within a material sample. Owing to the heterogeneous properties of bone at the lamellar level, more researchers are using nanoindentation to study its stiffness and hardness properties at high spatial resolution (<1 μ m). Trabecular bone specimens are embedded such that a flat surface can be obtained, a requirement for nanoindentation. Poly (methyl methacrylate), or PMMA, is a common embedding plastic. However, material properties of PMMA are significantly different from that of bone. In general, it is assumed that the plastic does not contribute significantly to the measured stiffness properties of a bone sample, since indentation depth and indenter radii are small in relation to the dimension of a trabeculae and the embedded sample (typically in the hundreds and tens of nanometers, respectively). The effect of PMMA properties on the apparent bone stiffness measurements has not been quantified previously. In this study, we employ a finite element model to simulate nanoindentation testing on a 3-D trabecular bone sample. We hypothesize that the mechanical properties of embedding material can significantly affect measured bone stiffness obtained via nanoindentation, and the effect will vary depending on the ratio of actual plastic modulus to actual bone modulus.

Methods

A 100x100x100 pixel cube was isolated from a previously obtained μ CT image of trabecular bone. Custom finite element (FE) modeling software was used to generate a mesh with element size of 50 μ m to match the voxel size of the image. The image contained two distinct regions: white space (material code 255) which represents the bone trabeculae, and gray space (material code 128) which represents a surrounding medium such as PMMA. Elastic modulus was then defined for each material, with the modulus of the “bone” set to 10,000 MPa and the modulus of the “plastic” set to 3,000 MPa, a reasonable estimation for the elastic modulus of PMMA. The bottom plane was constrained to zero displacement and a single node of the FE mesh located on the top plane (Figure 1) was displaced 0.0005 mm (500 nm) in the positive (+) z-direction.

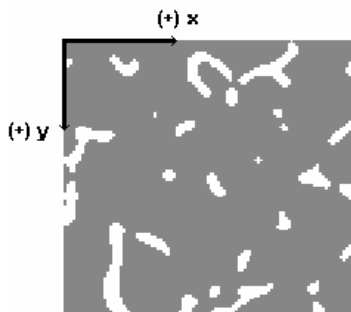


Figure 1: 2D plane image (top) taken from 3D image of trabecular bone. The positive z-axis is directed into the page.

There was no constraint on the remaining elements within the mesh. Post processing software was used to sum the total reactive force in the z-direction on the displaced node. Stiffness of the material was then calculated by dividing this reactive force by the set displacement.

Results

The results of the FE simulations indicate that the apparent stiffness changes with the ratio of plastic to bone modulus. The change is non-linear, as seen in Figure 2. For higher ratios of plastic to bone moduli, variations in plastic moduli have a smaller effect on the apparent stiffness, as indicated by a decreasing slope with increasing moduli ratio.

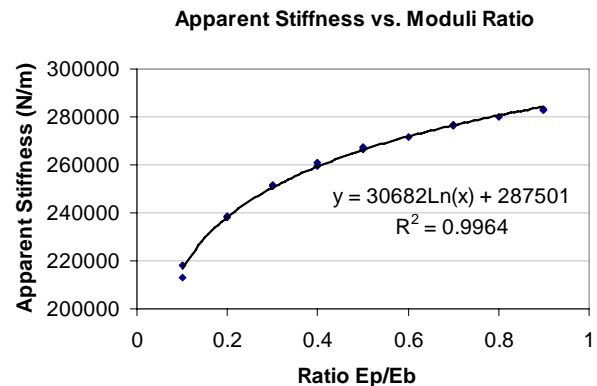


Figure 2: Apparent stiffness as a function of plastic to bone moduli ratio.

Discussion

PMMA is a commonly used embedding material, but its properties can differ depending on method of preparation, polymer batch, and age. Our data shows a significant variation in apparent stiffness with the ratio of plastic to bone moduli, which suggests that bone samples prepared at different times and/or by different people will yield varying apparent stiffness measurements if plastic modulus varies between preparations. Our ultimate goal is to determine the relationship between apparent bone stiffness and true bone stiffness, and correct for variation in the plastic modulus.

References

- [1] Testworks® 4 Software for Nanoindentation Systems, Manual ver 16, MTS Systems Corp (2002).
- [2] Oliver, Pharr. J Mater Res. 1992; 7:1564-1583.