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Anisotropy nanoindentation properties of human cortical bone

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Preferences and Keywords

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ANISOTROPY NANOINDENTATION PROPERTIES OF HUMAN CORTICAL BONE

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INTRODUCTION

Cortical bone is an anisotropic material, and its mechanical properties are determined by its composition as well as its microstructure. On the microstructure level (a few microns), cortical bone is composed primarily of single osteons and interstitial lamellae. Nanoindentation has been shown to be an effective technique to probe mechanical properties of microstructures at the micron scale. However, for anisotropic materials, the indentation modulus obtained by nanoindentation in a specific direction is a composite quantity that depends on all of the elastic constants [1,3]. The purpose of this study is to investigate the effects of elastic anisotropy to nanoindentation measurements in cortical bone.

MATERIALS AND METHODS

A specimen was obtained from one human tibia (52 years old). After being dehydrated in a series of alcohol baths, 12 specimens were cut based on various surface orientations in order to assess the anisotropy of cortical bone. An orthogonal coordinate system was chosen, where directions 1, 2, and 3 were the radial, circumferential and axial directions, respectively. Nanoindentation was conducted in twelve different directions in the principal planes. After cutting, the specimens were embedded in epoxy resin at room temperature and pressure. Silicon carbide abrasive papers with decreased grit size (600, 800, and 1200 grit) were used to grind surfaces of specimens, then the specimens were polished on microcloths with 0.05 μm grit alumina powder. All nanoindentation tests (Nano Indenter II) were performed in single osteons or interstitial lamellae for each specimen. The position of each indent was carefully selected based on microscopy observations. A total of 216 indentions were conducted in three tests to minimize experimental errors. For anisotropic materials, the indentation modulus (M) can be defined by Eq. 1 [2], where s is contact stiffness and A is the projected area of contact.
Based on a recently developed analysis of indentation of anisotropic

$$s = \frac{2}{\sqrt{\pi}} M\sqrt{A} \quad ......(1)$$

$$M = \frac{4\pi}{\int_0^{2\pi} \frac{a_3 B_{ij}^{-1}(\gamma) a_{3j}}{\sqrt{\frac{a_1}{a_2}\cos^2\gamma + \frac{a_2}{a_1}\sin^2\gamma}} d\gamma} \quad ......(2)$$

materials [3], for indentation by cones, the value of M is given by Eq. 2, where, a_1/a_2 (ratio of elliptical axes of the projected area of contact) can be determined numerically. B_{ij} are the components of the first Barnett-Lothe tensor, which are derived from the elastic stiffness matrix, and a_{3i} and a_{3j} are the direction cosines of the angles made between the indentation direction and the directions used to define the coefficients of the elastic stiffness matrix. In order to evaluate the nanoindentation experimental results, Eq. 2 was utilized to calculate the theoretical indentation modulus (M) by using the stiffness matrix of human tibial cortical bone, which was determined by earlier ultrasonic velocity measurement [4].

RESULTS

Nanoindentation experiments were conducted at the microstructure level (data obtained from single osteons and interstitial lamellae), while ultrasonic experiments were performed at the macrostructure level. A rule-of-mixture that takes into account the structural properties was used to calculate experimental M values from nanoindentation measurement data. Table 1 shows the experimental M values and predicted M values by using Eq. 2 at all orientations.

Table 1. Experimental and predicted M values for various orientations (Θ is the angle measured from direction 1 in the 1-2 plane, and φ is the angle measured from the 1-2 plane).

Θ (Degrees)	φ (Degrees)	Experimental (GPa)	Predicted (GPa)
0	0	17.15	14.02
90	0	16.77	14.52
0	90	24.66	19.66
30	0	17.02	14.11
45	0	17.55	14.23
60	0	17.81	14.36
0	30	18.14	15.03
0	45	19.28	16.25
0	60	22.02	17.76
90	30	17.77	15.5
90	45	18.85	16.65
90	60	22.25	18.02

DISCUSSION

For isotropic materials, the Oliver-Pharr method [5] can predict intrinsic material properties, such as Young's modulus, within 4% of literature values. However, for anisotropic materials, since the formation of the contact impression involves deformation in many directions, the indentation modulus represents a weighted average quantity, which is not easy to be interpreted by conventional methods. However, based on Eq. 2, when all effects of elastic constants are considered, the predicted M values exhibit the same trend as experimental results in all orientations. The larger experimental M values can be attributed to different conditions of the specimens. After taking into account that dehydration increases indentation modulus by 15% [6], the corrected experimental M values are not statistically significant from the predicted M values. Therefore, the above analysis describes the anisotropic indentation properties of cortical bone. This study shows that the nanoindentation can be used to quantitatively evaluate cortical bone anisotropy. Combined with the indentation analysis method of anisotropic materials, it is possible not only to predict the indentation modulus from elastic constants, but also to potentially compute the elastic constants through an iterative approach.

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