VALIDATION OF ARTICULAR CARTILAGE TENSILE MODULI FROM TRANSVERSELY ISOTROPIC BIPHASIC INDENTATION FEM ANALYSIS

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INTRODUCTION

Indentation testing has frequently been used as a method to obtain the material properties of articular cartilage in compression [1]. To account for the well-established anisotropic nature of cartilage [2] previous studies have modeled the cartilage as a transversely isotropic biphasic material using optimized FEM curve-fitting techniques to obtain the material properties of the tissue in compression. Average tensile moduli obtained from these studies have compared well with average tensile moduli obtained from direct measurements of similar material [3]. This study is unique in that it compares the tensile moduli obtained from direct measurements to those obtained from FEM curve-fits of indentation tests of the same material.

MATERIALS AND METHODS

Experimental Data

Biphasic indentation tests were performed at 4 locations for two fresh-frozen, grossly normal human shoulders (18 and 34 years), for at total of 8 tests using the protocol of Mow [4]. The tests were 2500 seconds in duration to ensure equilibrium. Two full-thickness, 1 cm x 0.2 cm tensile strips, parallel and perpendicular to the split line orientation directly adjacent to each indentation test site, as shown in Figure 1, were harvested from the joint surfaces immediately following the indentation tests. Each strip was subjected to a series of stress-relaxation loadings following the protocol of Akizuki [5]. The tensile modulus for each strip was computed from an exponential curve-fit of the equilibrium stresses for strains between 0.02 and 0.16.

FEM Curve-fitting

The nonlinear optimization formulation of Cohen [6] of the transversely isotropic axisymmetric biphasic indentation FE program of Spilker and Suh [7] was used to curve-fit the displacement-time histories of the cartilage surface under the indenter tip. A new fine mesh of 1197 elements found to be numerically convergent was used to model the cartilage and indenter tip. The material properties obtained from the FEM curve-fit were the in-plane elastic modulus E_1, the out-of-plane elastic modulus, E_3, (aligned with the axis of the indenter tip and perpendicular to the cartilage surface), the out-of-plane shear modulus μ, the in-plane Poisson's ratio $\nu_{21,}$ and the permeability of the tissue k, (assumed to be the same in both the axial and transverse directions). Following Cohen [6] the out-of plane Poisson's ratio, ν_{31}, was fixed at zero. The boundary conditions consisted of an adhesive, free-draining interface between the indenter tip and cartilage surface, and an impermeable, rigid substrate to which the cartilage was rigidly attached, represented the cartilage-subchondral bone interface.

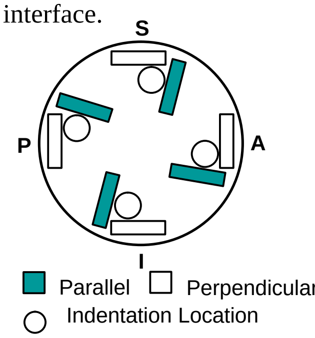

Figure 1. Specimen locations on the humeral head.

Analysis

A one-way ANOVA with repeated measures on test type was used to determine if a statistical difference existed between the experimentally measured tensile modulus and the tensile modulus obtained from the curve-fit. A p value of 0.05 was used to signify statistical significance.

RESULTS

No significant difference (p=0.3005) was found between the tensile modulus as measured directly and the tensile modulus obtained from the FEM curve-fits, as shown in Figure 2. All material properties resulting from the FEM curve-fits provided in Table 1. All curve-fits had an excellent agreement with the experimental data for both

Material Property	Mean ± S.D. (n=8)
E_3 [MPa], axial	0.899 ± 0.602
E_1[MPa], transverse	9.802 ± 4.075
ν_{21}(in-plane)	0.013 ± 0.023
μ [MPa]	0.793 ± 0.823
k [x10^{-15}m^4/N-s]	2.610 ± 1.273

Table 1. Biphasic transversely isotropic material properties of the human humeral head.

DISCUSSION

In general the values for E_3, μ, k, ν_{21} obtained from the transversely isotropic curve-fit were consistent with the corresponding values obtained previously using the transversely isotropic curve-fitting technique [3]. The aggregate modulus, represented here as E_3, was somewhat higher than the previously reported values, but well within normal values. The similarity of the tensile moduli from FEM curve-fits to those experimentally measured from the same tissue supports the validity of using the transversely isotropic biphasic FEM curve-fitting method to provide accurate material properties in both the transverse and axial directions from nondestructive and potentially *in vivo* indentation testing.

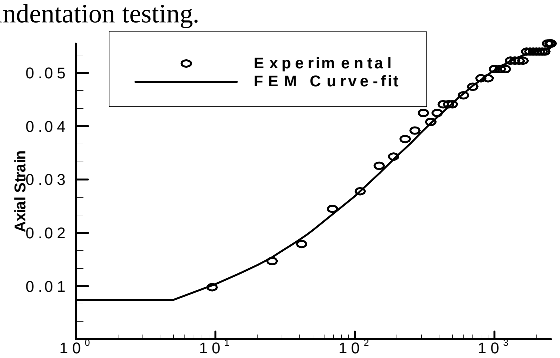

Figure 3. Typical FEM curve-fit of superior humeral head.

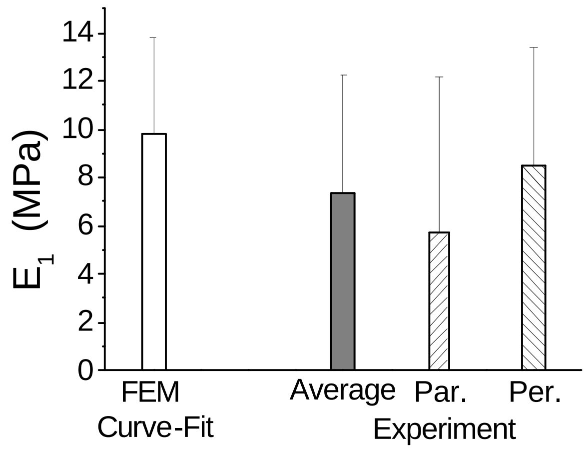

Figure 2. Tensile moduli by method and direction.

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