NONLINEAR ELASTIC PARAMETERS OF ARTICULAR CARTILAGE

Ravi Namani (1), Narendra K. Simha (1) and Jack L. Lewis (2)

(1) Department of Mechanical Engineering
University of Miami
Coral Gables, FL 33124

(2) Department of Orthopaedic Surgery and
Mechanical Engineering
University of Minnesota
Minneapolis, MN 55455

INTRODUCTION

The primary function of Articular Cartilage (AC) is to facilitate the transfer of loads between the bones in a joint. Mechanical properties such as elastic parameters characterize the load carrying ability of materials. Hence elastic parameters provide a functional characterization of AC. Also, diseases such as Osteoarthritis are accompanied with deterioration in the mechanical properties of AC. Consequently; elastic parameters can be used as markers to study the progression of disease processes. Currently, there is a strong focus on the development of engineered tissues that can replace diseased AC. In addition to satisfying biochemical and physiological requirements, such tissue will have to withstand the in vivo mechanical loads in a joint. Elastic parameters can be used to establish such functional criterion. For instance, a simple criterion is to require the engineered tissue to have values comparable to that of natural tissue.

AC can be viewed as a composite structure consisting of collagen fibrils embedded in a hydrated proteoglycan gel. The distribution and orientation of the collagen fibrils varies considerably and hence AC is highly inhomogeneous. Consequently it will be advantageous to use a method that can quantify mechanical properties with sufficient spatial resolution. Microindentation, can measure elastic parameters with a spatial resolution of about 10 μm. In addition, it requires minimal specimen preparation and can use small specimens. Thus, this poster will demonstrate the advantages of evaluating nonlinear elastic parameters using microindentation.

The method is a modification of conventional hardness testing. Typically, the indenter displacement (d) and applied force (p) are measured continuously as the indenter pushes into a specimen. Existing semi-empirical methods assume linear elastic theories, use solutions for blunt punches indenting a half-space, and extract the Elastic modulus from the unloading part of the p-d curve [1,2]. These methods have successfully characterized bulk and thin films of hard materials like metallic alloys and ceramics. However, they cannot be trivially extended to soft tissues such as AC.

AC undergoes large deformations; hence it cannot be modeled as a linear elastic material with small deformation theories. The sample has a finite thickness hence infinite half space assumptions [3] do not work. Although, Yin and Costa [4] have studied such finite layer issues for soft tissues, they do not provide methods for complete material parameter identification. A model-based simulation approach, where parameters are extracted by minimizing the error between simulated and measured p-d curves, has been proposed in a companion abstract [5]. This paper will describe the application of this method to extract the nonlinear material parameters of bovine AC from microindentation tests.

METHODS

Microindentation tests on bovine AC were performed using a Nanoindenter XP (MTS Inc). The indenter was a conical diamond tip with an included angle of 57.5^0 and tests were performed under load control. Bovine patellar cartilage was frozen at -80°C soon after harvesting and preparation. Specimens were cut to have a thickness of ~2mm and surface area of ~1cm^2 and a thin layer of subchondral bone was left behind. The specimen was attached by bonding the bone to a holder with cyanoacrylate cement. The holder was rotated to make the indenter tip motion perpendicular to the cartilage surface. Phosphate buffered saline (PBS) was placed on the specimen surface to prevent drying. The load was increased at a constant rate until the displacement reached maximum. Indentation tests were performed on five specimens, (from the same patella).

The microindentation experiment is simulated using the Finite Element Analysis (FEA) package ABAQUS (Hibbit-Karlson, Inc.). The indenter is assumed to be rigid as the stiffness of cartilage is much less compared to the indenter tip. The cartilage is a 2mm thick layer lying on a rigid substrate. Frictionless boundary conditions were considered between the indenter and cartilage as well as between cartilage and substrate. The mesh density was adjusted to obtain a reasonable resolution of solution variables like displacement and strain energy under the indenter. Cartilage is treated as an incompressible nonlinear hyperelastic material, and the following strain energy density functions are used:

Mooney-Rivlin: $W_{MR}=C_1(I_1-3) + C_2(I_2-3)$ (1)

Exponential: $W_{EXP} = B_1 [\exp(B_2(I_1-3)) -1]$ (2)

Here W is the stored energy per unit volume, and I_1, I_2 are invariants of the Cauchy-Green Stretch tensor. The material parameters are C_1 and C_2 for the MR material and B1 and B2 for the EXP. An asymptotic relation between the indentation force p and indenter displacement d is [3, 4]

$$p= (4/\pi) E \tan \alpha \, d^2 \quad (3)$$

where α is the indenter half-angle and the elastic modulus is given by

$$E_{MR}=4(C_1+C_2);\ E_{EXP}=4B_1B_2 \quad (4)$$

These relations are valid only for small deformations, and are used here mainly for organizing experimental data and to guide parameter extraction. For brevity, the rest of the abstract will discuss only the MR material. However, the poster will describe both the MR and EXP models.

Steps involved in the parameter extraction are as follows:

1. Establish a correlation $E=h(\beta)$. Indentation simulations are performed for different values of E. The ranges considered were with $C_1 + C_2$ from 0.2MPa to 2MPa at a constant ratio of $C_2/C_1 =1/8$. Based on (3), quadratics of the form $p=\beta d^2$ are fit to p-d curves predicted by FEM for the displacement range $0<d<150\mu m$. Then a correlation between E and β is established.
2. Minimize using Golden Section Search. Choose an experimental p-d curve for Bovine AC and obtain the fit coefficient β. The correlation $E=h(\beta)$ provides an initial estimate $\hat{E}$. Fix $(C_1+C_2)= \hat{E}/4$ for MR. Minimize error ratio ε (area between predicted and measured p-d curves divided by area under measured p-d curve). This gives optimal parameter ratios C_2/C_1.
3. Minimize using Simplex method. Using optimal ratios and $\hat{E}$ obtain three initial points. Minimize error ratio e to obtain final values of (C_1, C_2).

RESULTS

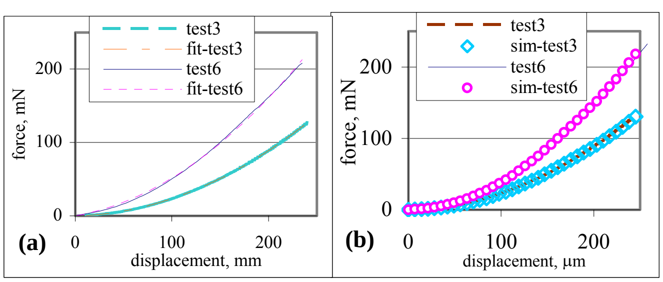

Figure 1 (a). Experimental (p-d) curves for Bovine AC. (b) Comparison of simulated and experimental (p-d) curves for two tests.

The measured force-displacement curves for three different specimens can all be well approximated by quadratic curve fits (Figure 1a). The variation in the measurements for all the tests are quantified by the quadratic fit coefficient β. This ranges from 2.106 to 4.715 (Table 1). Some of this variation is attributable to difference in the loading rate, since the loading rate for tests 1-4 and 8 was 4mN/s whereas it was 10 mN/s for the other tests. Although the measurements reveal a quadratic dependence of the force on the displacement, they do not strictly satisfy the asymptotic relations (3).

The results of the simulations revealed that there was a linear relationship between the Elastic modulus and the quadratic fit coefficient β. For MR materials, $E=0.837\beta$, (with fixed $C_1/C_2 =1/8$). Starting with a range $2\le C_1/C_2\le 80$, the Golden Section Search obtained the optimum parameter ratio C_1/C_2. There was little variation in this ratio for several tests and hence the average value of C1/C2=2.04 was chosen for this set of bovine patellar AC. The Simplex method was then applied to obtain the final values for C_1 and C_2.Results shown in Table 1 show that the values of C_1+C_2 range from 0.587 to 1.204 MPa.

DISCUSSION

Eight sets of experimental curves were analyzed. The area error was of the order of 10^{-5} indicating that the proposed methods are successful in extracting nonlinear elastic parameters. Also the negligible error suggests that the MR hyperelastic material model is a reasonable continuum description of AC, at least in the context of microindentation tests. The poster will also discuss the limitations of asymptotic small deformation relations (2) and thereby demonstrate that the extracted nonlinear parameters represent a more accurate characteristization of AC. However, it is well known that the hydrated nature of AC, results in significant rate-dependence. The focus of this preliminary work was to demonstrate that microindentation could characterize nonlinear elastic properties. Subsequent on going studies will incorporate rate dependence and obtain the viscoelastic parameters from creep data.

Test	Rate mN/s	βx10^3	**C1**	**C2**	C_1 +C_2	εx (10^{5})
1	4	3.451	**0.588**	**0.335**	0.923	3.00
2	4	2.709	**0.474**	**0.192**	0.666	5.30
3	4	2.288	**0.387**	**0.235**	0.622	1.97
4	4	2.106	**0.362**	**0.225**	0.587	2.79
5	10	4.331	**0.725**	**0.391**	1.116	2.88
6	10	4.715	**0.755**	**0.449**	1.204	1.84
7	10	3.630	**0.616**	**0.351**	0.967	3.39
8	4	2.122	**0.371**	**0.221**	0.639	2.02

Table 1. Details of parameter extraction from microindentation tests

REFERENCES

1. Doerner, M. F., and Nix. W. D., 1986, “A method for interpreting the data from depth-sensing indentation instruments”, J. Mater. Res., 1, pp. 601-609.
2. Oliver, V. C., and Phar, G. M., 1992, “An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation”, J. Mater. Res., 7, pp. 1564-1583.
3. Beatty, M. F., and Osmani, S. A., 1975, “On the indentation of a highly elastic half-space”, Quart. J. Mech. Appl. Math., 28, pp. 47-62.
4. Costa, K. D., and Yin, F. C. P., 1999, “Analysis of Indentation: Implications for Measuring Mechanical Properties With Atomic Force Microscopy”, ASME J. Biomech. Engineering, 121, pp. 462-471.
5. Simha, N. K., Namani, R., and Lewis, J. L., “Microindentation methods for evaluating nonlinear elastic properties of Articular Cartilage,” Abstract submitted to ASME 2003 Bioengineering Conference.