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Arthroscopic evaluation of cartilage degeneration using indentation testing—Influence of indenter geometry

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Abstract

Background. It has been suggested that the early onset of cartilage degeneration might be detected with a handheld indentation probe during knee arthroscopy, prior to any visible change on the articular surface. Collagen degradation has been considered as the first sign of cartilage degeneration. Therefore, it is important to consider the collagen network as a distinct constituent in the study of arthroscopic evaluation of cartilage degeneration.

Methods. The tip of an arthroscopic probe (indenter) was modeled as rigid and in contact with a cartilage/bone disk of sufficiently large radius to simulate an indentation in a joint. A fibril-reinforced model of cartilage, including streaming potentials and distinct constitutive laws for the proteoglycan matrix and collagen network, was used to determine the contact mechanics of indenter and cartilage. The finite element package ABAQUS was employed to obtain numerical solutions.

Findings. A spherical indenter produces a relatively uniform deformation in cartilage, but can easily slide on the articular surface. In contrast, a cylindrical indenter produces great deformation gradients for quick compression rates, but does not slide as easily on the articular surface as the spherical indenter. Small porous and large solid indenters should be used to evaluate the properties of the proteoglycan matrix and collagen network, respectively, in order to minimize or maximize the fluid pressure in the corresponding case. When the collagen network is substantially degraded, the gradients of fluid pressure and deformation are greatly reduced regardless of indenter geometry.

Interpretation. The indenter geometry including its porosity is important to the material safety of articular cartilage in indentation and precise evaluation of cartilage degeneration.

Keywords: Arthroscopic probe; Arthritis diagnosis; Articular cartilage mechanics; Cartilage degeneration; Fibril-reinforced model; Indentation testing

1. Introduction

Indentation testing has been widely used to determine the mechanical properties of articular cartilage (Hayes et al., 1972; Kempson et al., 1971), including Poisson's ratios (Jin and Lewis, 2004), anisotropic properties (Bischoff, 2004), and electrochemical properties (Lu et al., 2004). Recently, it has been suggested that the early onset of cartilage degeneration may be detected with a handheld indentation probe during knee arthroscopy (Duda et al., 2004; Lyyra et al., 1995; Niederauer et al., 2004), prior to any visible signs of damage on the articular surface. Using manual compression with an arthroscopic probe to the articular surface of the knee, the load response and/or streaming potentials produced by the fluid pressure gradients have been measured (Garon et al., 2002, 2003). The corresponding results were associated with the Mankin score, a clinical

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indicator of the degree of cartilage degeneration (Franz et al., 2001; Mankin et al., 1971; van der Sluijs et al., 1992). In some applications, an ultrasound transducer was also integrated into the probe to obtain additional data (Hattori et al., 2003; Suh et al., 2001). Such arthroscopic probes have also been used to evaluate cartilage repair (Vasara et al., 2005).

An essential step of arthroscopic evaluation is to estimate the material properties of cartilage from the measured forces, pressures, strains or streaming potentials. Such estimates are possible with a theoretical model of contact between arthroscopic probe and cartilage surface. Typically, the results from indentation testing were interpreted using elastic or biphasic models in which material properties were not defined separately for the proteoglycan matrix and collagen network. Given the distinct roles of these two constituents in the load response and degeneration of articular cartilage (Aigner and Stöve, 2003; Mizrahi et al., 1986), we modeled the interaction between the arthroscopic indenter and articular cartilage using a fibril-reinforced model in which the proteoglycan matrix and collagen network were represented with different material properties (Li et al., 1999). This model allows for differentiation between proteoglycan depletion and collagen digestion (Korhonen et al., 2003), and may give a better description of the strain-rate dependent load response observed in experiments (Li and Herzog, 2004). Streaming potentials were also incorporated into the fibril-reinforced model (Li and Herzog, 2005), because of their relevance in evaluating the integrity of articular cartilage (Grodzinsky et al., 1981; Gu et al., 1999; Kim et al., 1995; Légaré et al., 2002).

Fluid pressurization is a basic response of articular cartilage to loading. In arthroscopic indentation, the geometry of the indenter affects the pore fluid pressure in the contact region and the contact stresses. The objective of the present study was to explore the relevance of indenter shape, size and porosity in arthroscopic evaluation of articular cartilage using a fibril-reinforced model. Differences in slip properties of spherical and cylindrical indenters were quantified, and the effect of indenter size and porosity on fluid pressurization was investigated.

2. Methods

The tip of the arthroscopic probe was considered rigid (porous or non-porous), and in contact with a cartilage/bone disk of sufficiently large radius to simulate an arthroscopic indentation in a joint. Preliminary calculations showed that deformation and stresses for the loading conditions and indention geometry considered here were confined to the vicinity of the contact region, and thus a radius of 6 mm was sufficient to cover the loaded region. Axisymmetry was assumed in all analyses, and the effects of bone deformation on the load response were found to be negligible. Therefore, the tissue disk was modeled as a cartilage layer of 1.13 mm bonded to a rigid substrate. The maximum compression applied by the indenters was limited to 200 μm. The loading speed was 200 μm/s except for one case in which a lower compression speed was simulated for evaluation of rate effects.

Spherical and cylindrical indenter geometries were simulated. Cylindrical, plane-ended indenters are commonly used in experiments (Mow et al., 1989; Suh and Spilker, 1994; Zhang et al., 1997). We also considered a spherical indenter with the same geometry as the Arthro-BST™ probe (Biosyntech Inc., Montreal, Canada) which is instrumented with microelectrodes for detection of streaming potentials. The spherical indenter was modeled with a radius of 4.20 mm, the cylindrical indenter with a radius of 1.25 mm (default) or 0.50 mm for evaluation of size effects.

Finite element solutions were obtained using the surface-based contact approach formulated in ABAQUS/Standard (ABAQUS Inc., Providence, USA). The problem was defined by the contact between a rigid master surface (tip of probe) and a deformable slave surface (articular surface). The nodes of the slave surface were constrained not to penetrate into the master surface, which was enforced by Lagrange multiplier techniques. Sufficient nodes were meshed to obtain a smooth surface deformation (Figs. 1, 2 and 7, nodes of the 8-node elements). The "small sliding" option was used for rapid convergence, which was justified as it was assumed that the probe did not slide on the articular surface (i.e. no rigid movement of the probe on the articular surface was simulated). The geometrical non-linearity option was activated for all analyses.

The coefficient of friction (*f*) between indenter and articular surface was varied from 0 to 0.15, in reference to the measured macroscale coefficients ranging from 0.004 at transient to 0.138 at equilibrium (Park et al., 2004). However, larger coefficients of friction were also considered for cases in which fibril reinforcement was absent, representing the theoretical limit of collagen degeneration (Fig. 6 only).

Articular cartilage was modeled with strain and direction dependent collagen fibrillar moduli, Young's modulus (0.26 MPa) and Poisson's ratio (0.36) of the non-fibrillar proteoglycan matrix, as well as permeability (0.003 $\text{mm}^4/\text{N s}$), conductivity and the electrokinetic coupling parameters (Li and Herzog, 2005). Streaming potentials were not investigated in the present study, and thus the values for conductivity and coupling parameters were not required. The fibrillar moduli in the radial and axial directions were, respectively, $(3 + 1600\varepsilon_r)$ and $(1.5 + 800\varepsilon_z)$ MPa, with the exception of Fig. 6, where the fibrillar stiffness was neglected to