Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

A biphasic finite element study on the role of the articular cartilage superficial zone in confined compression

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ARTICLE INFO

Article history:
Accepted 6 November 2014

Keywords:
Articular cartilage
Superficial zone
Biphasic
Finite element analysis
Confined compression

ABSTRACT

The aim of this study was to investigate the role of the superficial zone on the mechanical behavior of articular cartilage. Confined compression of articular cartilage was modeled using a biphasic finite element analysis to calculate the one-dimensional deformation of the extracellular matrix (ECM) and movement of the interstitial fluid through the ECM and articular surface. The articular cartilage was modeled as an inhomogeneous, nonlinear hyperelastic biphasic material with depth and strain-dependent material properties. Two loading conditions were simulated, one where the superficial zone was loaded with a porous platen (normal test) and the other where the deep zone was loaded with the porous platen (upside down test). Compressing the intact articular cartilage with 0.2 MPa stress reduced the surface permeability by 88%. Removing the superficial zone increased the rate of change for all mechanical parameters and decreased the fluid support ratio of the tissue, resulting in increased tissue deformation. Apparent permeability linearly increased after superficial removal in the normal test, yet it did not change in the upside down test. Orientation of the specimen affected the time-dependent biomechanical behavior of the articular cartilage, but not equilibrium behavior. The two tests with different specimen orientations resulted in very different apparent permeabilities, suggesting that in an experimental study which quantifies material properties of an inhomogeneous material, the specimen orientation should be stated along with the permeability result. The current study provides new insights into the role of the superficial zone on mechanical behavior of the articular cartilage.

1. Introduction

Articular cartilage is a connective tissue serving as a low-friction, load-bearing material in diarthrodial joints. Mature articular cartilage has a depth-dependent heterogeneous composition and is usually divided into three zones: superficial, middle and deep zones (Mow et al., 2005). Collagen fibers are oriented parallel to the cartilage surface in the superficial zone (SZ), becoming more randomly oriented in the middle zone and perpendicular to the articular surface in the deep zone, where they are imbedded into calcified cartilage and subchondral bone (Clark, 1985; Jeffery et al., 1991). The equilibrium aggregate modulus (H_A) of mature articular cartilage increases with depth (Schinagl et al., 1997) while the tensile modulus decreases with depth (Krishnan et al., 2003). The SZ represents about 20% of the total thickness and has a critical role in the normal function of the articular cartilage, including load-distribution and viscoelastic response (Flannery et al., 1999; Gannon et al., 2012; Hosseini et al., 2014; Korhonen et al., 2002; Owen and Wayne, 2006; Setton et al., 1993). Breakdown and loss of the SZ is an early sign of osteoarthritis (Heinegård and Saxne, 2011; Hollander et al., 1995). Collapse of the SZ is believed to be responsible for controlling interstitial fluid transport across the articular surface (exudation and imbibition), and more important, the overall mechanical response of the articular cartilage (Torzilli et al., 1983; Torzilli, 1984). While there is experimental evidence to support this hypothesis, computational validation of this mechanism is lacking.

The aim of this study was to use a hyperelastic biphasic finite element analysis to investigate the role of the SZ on the mechanical behavior of articular cartilage in two different confined compression creep test configurations, one in which the articular surface was loaded with a porous platen (normal test) and the other with the cartilage inverted to load the deep zone with the porous platen (upside down test). Depth and strain-dependent material properties of the articular cartilage were included. Different amounts of superficial tissue were removed in both test configurations to investigate whether the deformation (collapse) of the SZ had a significant influence on the mechanical behavior of the articular cartilage.

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http://dx.doi.org/10.1016/j.jbiomech.2014.11.007
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2. Method

2.1. Hyperelastic biphasic theory

The hyperelastic biphasic theory proposed by Holmes and Mow (Holmes and Mow, 1990) was used in the current study. The governing equations are

$$\nabla \cdot (\sigma_E^s - pI) = 0 \tag{1}$$

$$\nabla \cdot (\nu^s - \kappa \nabla p) = 0 \tag{2}$$

where p is the fluid pressure, I the identity tensor, $v^s = du/dt$ the solid phase velocity, k the permeability, and σ_E^s the effective stress of the solid matrix defined as

$$\sigma_E^s = \frac{1}{J} F \cdot \frac{\partial \Psi^s}{\partial \varepsilon} \cdot F^T \tag{3}$$

where J is the volume ratio defined as $J = \det(F)$, F the Jacobian determinant of the deformation gradient, and $\varepsilon = 1/2\left(\nabla u + (\nabla u)^T + \nabla u (\nabla u)^T\right)$ (Bonet and Wood, 1997) the Green–Lagrangian strain tensor. The strain energy density function is defined by (Holmes and Mow, 1990)

$$\Psi^s = \alpha_0 \frac{e^{\alpha_1 (I_1 - 3) + \alpha_2 (I_2 - 3)}}{I_3^{\beta}} \tag{4}$$

where I_1, I_2, and I_3 are the invariants of the right Cauchy–Green deformation tensor, C, defined as $C = F^T F$, the dimensionless nonlinear stiffening coefficient $\beta = \alpha_1 + 2\alpha_2$, and α_0, α_1 and α_2 positive material parameters. α_0, α_1, and α_2 are related to β, aggregate modulus, H_A, and Poisson's ratio, ν, by

$$\alpha_0 = \frac{H_A}{\beta}, \alpha_1 = \frac{1 - 3\nu}{1 - \nu} \beta, \alpha_2 = \frac{\nu \beta}{1 - \nu} \tag{5}$$

The deformation-dependent permeability (Lai and Mow, 1980) is defined as

$$k = k_0 J^m \tag{6}$$

where k_0 is the initial permeability and m a material parameter.

The hyperelastic biphasic theory was implemented in COMSOL Multiphysics (Burlington, MA). Solid mechanics in the Structural Mechanics Module and Darcy's Law in the Earth Science Module were used (Guo et al., 2013; Guo et al., 2012; Guo and Spilker, 2011; Guo and Spilker, 2014). The user defined strain energy density function in COMSOL was used to input the strain energy density function (Eq. (4)) (Guo et al., 2014b).

2.2. Confined compression of the articular cartilage

Confined compression test is widely used to measure the material properties of articular cartilage (Lu and Mow, 2008). Test is normally performed by confining a full-depth cartilage within a nonporous chamber and loading the articular surface with a rigid porous platen, resulting in one-dimensional interstitial fluid exudation through the articular surface and tissue. To evaluate the role of the SZ, two loading configurations were simulated using our hyperelastic biphasic finite element (HBFE) model: loading the articular surface (Fig. 1, normal) and inverting the cartilage to load the deep zone (Fig. 1, upside down). Four conditions were simulated for each test configuration: intact and after removal of 100, 200, and 300 μm of the superficial zone. The thickness of the intact cartilage was $h_o = 1.5$ mm. A stress of 0.2 MPa was linearly applied on the articular cartilage in 100 s and thereafter held constant for additional 2900 s. The magnitude of the applied stress was chosen to limit the equilibrium strain to ~25%. The nonlinear depth-dependent aggregate modulus and initial permeability of the articular cartilage were obtained from published experimental measurements (Chen et al., 2001; Maroudas, 1968; Schinagl et al., 1997; Wang et al., 2001) (Fig. 2). Material parameters ν, β and m were 0.1, 0.35 and 2.2 (Wang et al., 2001), respectively.

Overall strain was defined as the tissue deformation (displacement of the porous platen) divided by the initial tissue thickness, while the apparent aggregate modulus and initial permeability were extracted by curve-fitting the HBFE model to the overall strain. The local peak strain, permeability and maximum principal shear stress, compressive stress and compressive strain were calculated at $z = 1.2$ mm for all test conditions. Fluid support ratio, defined as ratio of average fluid pressure to average total normal stress, was also computed.

3. Results

For both types of confined compression tests (normal and upside-down orientations), removal of the SZ resulted in greater overall strain than the intact tissue at early times (< 500 s) and smaller overall strain at larger times (Fig. 3a). The overall strain at equilibrium (3000 s) decreased with increasing superficial removal. For the normal test, peak strain occurred at the surface of the SZ and remained constant once the applied force was constant (Fig. 3b). In the upside-down test, the peak strain initially occurred at the bone surface of the deep zone (< 100 s), then shifted to the surface of the SZ (100–150 s), and increased thereafter until equilibrium was reached. Removal of the SZ increased the apparent aggregate modulus of the tissue in both types of tests (Fig. 4a) and the apparent permeability in the normal test, however, SZ removal did not affect the apparent permeability in

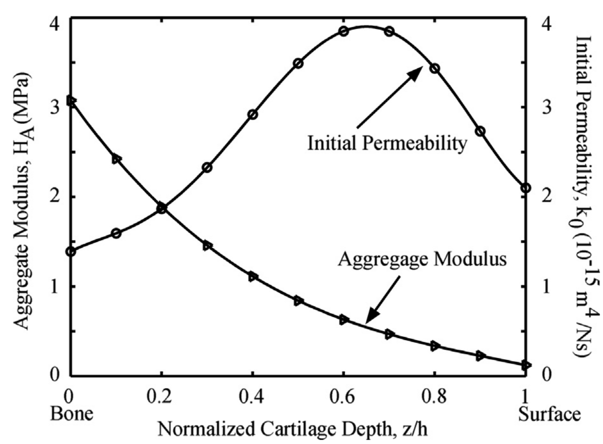

Fig. 2. Depth-dependent aggregate modulus (Chen et al., 2001; Schinagl et al., 1997; Wang et al., 2001) and initial permeability (Maroudas, 1968) of the articular cartilage used in the models.

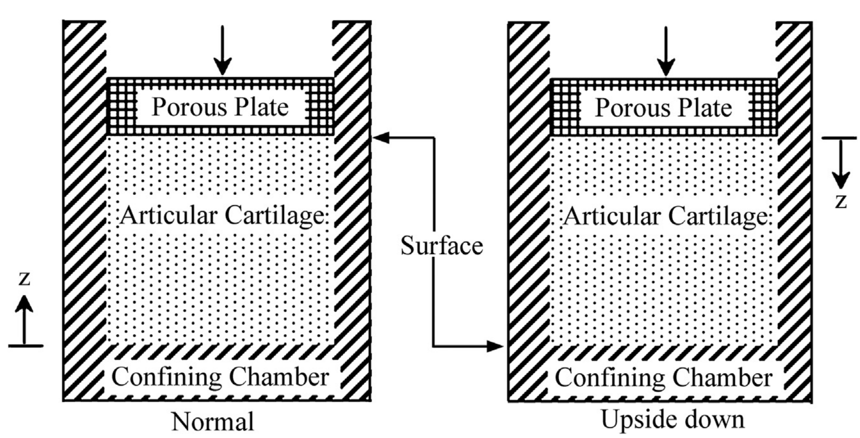

Fig. 1. Schematic diagram of the confined compression tests modeled where the cartilage is orientated normal (left) and upside down (right).

Please cite this article as: Guo, H., et al., A biphasic finite element study on the role of the articular cartilage superficial zone in confined compression. Journal of Biomechanics (2014), http://dx.doi.org/10.1016/j.jbiomech.2014.11.007