MECHANICAL MODELING OF ARTICULAR CARTILAGE CONSIDERING ANISOTROPIC/INHOMOGENEOUS MICROSTRUCTURE OF COLLAGEN NETWORK

T. Osawa, H. Naito, T. Matsumoto and M. Tanaka

Osaka University, Dept. Mechanical Science and Bioeng., Machikaneyama, Toyonaka, Osaka, Japan

tk-osawa@mbox.me.es.osaka-u.ac.jp

Introduction

Articular cartilage has an important role in diarthrodial joints function, and the dysfunctions of cartilage harms daily living qualify seriously. The destruction of articular cartilage caused by degenerative disease such as osteoarthritis is accompanied by the change of microstructure in cartilage. Cartilage is a multi-phasic material of permeable composite comprised of a solid matrix mainly composed of collagen fibres and an interstitial fluid[1], and the mechanical behaviour as cartilage depends on its microstructure of cartilage. Collagen fibres constitute a three-dimensional anisotropic network exhibiting the cartilage depth dependency. In this study, the influence of the depth-dependent anisotropic/inhomogeneous microstructure of collagen fibres is examined based on extended model submitted by Federico *et al.* [2].

TITH model

The transversely isotropic, transversely homogeneous (TITH) model assumes that cartilage is the composite of isotropic proteoglycan(PG)-matrix and ellipsoidal inclusion of chondrocytes and collagen fibres [2]. Both the solid phase and the fluid phase are assumed to be incompressible and undergo infinitesimal deformation. The fluid is assumed to be isotropic and inviscid. Depth-dependent microstructure is considered for the orientation and volume fraction of collagen fibre and the chondrocytes cell shape. The fibre orientation is given by a Gaussian probability distribution, and the cell shape is characterized in terms of its aspect ratio. Transverse homogeneity is coming from the depth-dependent volume fraction of fibre and cell in solid phase. Uniform volume fraction, perfectly sphere cell shape, and random orientation reduce the TITH model to the isotropic/homogeneous one. The finite element formulation was carried out by Galerkin weighted residual method[3]. The PG-matrix, cells and fibres are assumed to be isotropic, an their material properties were determined from published experimental data (Table 1). Permeability was set to $k=0.76 \times 10^{-14} [\text{m}^4/\text{N}\cdot\text{s}]$ and solidity to $\phi^s=0.2[3]$.

Unconfined compression

To examine the effect of collagen microstructure on the macroscopic properties, unconfined compression analyses were conducted for a cylindrical cartilage specimen of $r = 1\text{mm}$ in radius and $h = 1.4\text{mm}$ in thickness discretized by eight-node hexahedron elements of seven layers. The bottom of the specimen was fixed in plane without friction, and the top of the specimen was compressed by a porous platen perfectly adhesive to the specimen. The rate of compression was $1\mu\text{m/s}$ for the initial 100s, and then the displacement was kept constant up to 500s.

Four cases of different microstructure were examined (Table 2). First, examined was the effect of the volume fraction of the fibre on mechanical properties as the cartilage in case 1. The volume fraction of fibre was ranged 15-50% in solid matrix with 5% volume fraction of cell. Next, examined was the effect of the anisotropy and inhomogeneity. The

fibre volume fraction of 30% was assumed for all cases. When inhomogeneity was assumed, fibre volume distributes linearly from the bottom of fibre-rich bone-cartilage interface to the articular surface.

The force relaxation curves were illustrated in Figure 1, where the reaction force was normalised between the peak and relaxed forces. It was confirmed that the volume fraction of collagen fibre has a profound effect on force-relaxation (Figure 1(a)), and that the orientation of collagen fibre exhibited a significant effect on the force-relaxation as well (Figure 1(b)). It was also demonstrated that the depth-dependent anisotropic orientation of fibre showed much influence on the microscopic cartilage properties than its depth-dependent volumetric distribution. These results indicated the importance of microstructure of collagen fibres to understand the mechanical behavior of cartilage.

Table 1 Material properties. [4][5][6]

	Young's modulus E (MPa)	Poisson's ratio ν
PG-matrix	0.2	0.05
Cells	10^{-3}	0.4
Fibres	10	0.3

Table 2 Different microstructure cases.

	homogeneous	isotropic	volume fraction	orientation
case 1	yes	yes	constant	random
case 2	no	yes	linear	random
case 3	yes	no	constant	*
case 4	no	no	linear	*

(* fibre orientation horizontal at surface and vertical at bottom in average)

(a) Effect of fibre volume fraction

(b) Effect of anisotropy and inhomogeneity

Figure 1 Reaction force in confined compression.

References

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