A FIBRIL-REINFORCED POROMECHANICAL MODEL OF ARTICULAR CARTILAGE UNDERGOING LARGE DEFORMATION

Mojtaba Kazemi, LePing Li
Department of Mechanical and Manufacturing Engineering, University of Calgary, Canada
LePing.Li@ucalgary.ca

INTRODUCTION
Fluid pressurization in articular cartilage and meniscus has been successfully modelled in recent 3D knee models. Due to computational cost and convergence difficulties, these studies were limited to small deformations. The long term goal of the current study is to investigate the fluid pressurization under physiological loading and boundary conditions. Our small deformation results suggested that the cartilaginous tissues should be modeled as fibril-reinforced porous materials. Therefore, in the present work, the quasi-linear viscoleasticity (QLV) theory is used to define the constitutive behaviour of the fibers undergoing large deformation. A user defined FORTRAN subroutine, UMAT, was incorporated in ABAQUS for this purpose.

METHODS
The fibrillar stress can be expressed by the QLV model as:

$$
S'(t) = S'(0) + \int_0^t G(t - \tau) \frac{\partial S''(E^g)}{\partial \tau} d\tau
$$

(1)

where $S'$ is the second Piola-Kirchhoff stress, $G$ is the reduced relaxation function and $S''$ is the elastic stress. $E^g$ is the Green strain:

$$
E^g = \frac{1}{2} [F^T F - I]
$$

(2)

and $F$ is the deformation gradient. An exponential form was used for the elastic stress response, $S''$. The non-fibrillar matrix was assumed as Kirchhoff material:

$$
S''' = \lambda tr(E^g) + 2\mu E^g
$$

(3)

where $S'''$ is the second Piola-Kirchhoff stress in the non-fibrillar matrix and $\lambda$ and $\mu$ are the Lame's constants. The numerical form of the tissue stress was implemented in a user subroutine UMAT using FORTRAN. As the first step, a 3D finite element (FE) model of the knee including the femur, tibia, femoral cartilage and tibial cartilages was considered. The FE software ABAQUS v6.11-1 was used for the simulations. Four layers of hexahedral quadratic elements were used to mesh the femoral and tibial cartilages. The tibial cartilages were tied to the femoral cartilage. Fluid exudation was permitted from the free surfaces of the femoral cartilage and through the thickness of the tibial and femoral cartilages. The geometrical nonlinearities were considered using the NLGEOM option in ABAQUS. A relaxation protocol of 0.3mm compression was applied to the femur in one second. Four different models were considered: 1) porous cartilages with no fibril-reinforcement, 2) fibril-reinforced porous cartilages, 3) non-porous (elastic) cartilages with no fibril-reinforcement with an equivalent modulus and nearly incompressible, and 4) fibril-reinforced, elastic cartilages.

RESULTS
The maximum of the First Principal Stress (Fig. 1a) in the porous model without fibril-reinforcement decreased very slowly: about 2.8% after 50s. The fibril-reinforced porous model, however, exhibited a strong relaxation: about 35% decrease in stress. As expected, the elastic model with no fibril-reinforcement yielded a constant stress during the relaxation. The fibril-reinforced elastic model showed a moderate relaxation when the whole viscoelastic terms of eq. (1) were considered (Fig. 2). The relaxation phenomenon was clearly seen in the obtained fluid pressure in the fibril-reinforced model, while the model without fibers showed a very slow relaxation (Fig. 1b).

DISCUSSION
The large deformation viscoelasticity of collagen fibers was implemented into a 3D knee model using UMAT in ABAQUS. The comparison between the four different models demonstrated that a fibril-reinforced porous model predicts the stress relaxation phenomenon much better than the other models. This confirms our previous results using small deformation theory. The predicted fluid pressure using a fibril-reinforced model was considerably higher than the porous model without fibers (Fig. 1b), which further supports the role of collagen fibers in a knee model. The presented model can be used to predict the time-dependent response of the knee, which cannot be obtained using the available elastic models.

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