DYNAMIC MECHANICAL RESPONSE OF CHONDROCYTES IN UNCONFINED COMPRESSION -- FINITE ELEMENT SIMULATION

*Wu, J. Z., +*Herzog, W., *Epstein, M.
*Faculties of Kinesiology and Engineering, The Univeristy of Calgary, 2500 University Dr. NW, Calgary, Alberta, Canada, T2N 1N4
+Tel: (403)220-3438, FAX (403)284-3553, walter@kin.ucalgary.ca

Relevance To Musculoskeletal Conditions*:* Experimental evidence suggests that cells are sensitive to their mechanical environment and react directly to mechanical stimuli. Therefore, a primary step to understanding the mechanism of articular cartilage adaptation and degeneration is to know the stress-strain states of chondrocytes during physiological loading in diarthrodial joints.

Introduction: It is well accepted that fluid pressure and stress-strain state in and around chondrocytes are important mechanical stimuli associated with remodeling, adaptation, and degeneration of articular cartilage. However, it is technically impossible to measure fluid pressure, stress, and strain in cells; the determination of time-dependent deformation of chondrocytes is also a technical challenge that has not been met to date. The purpose of the present study was to simulate numerically the location- and time-dependent stress-strain state and fluid pressure distribution in chondrocytes during cartilage deformation, in order to get a first glimpse at the likely mechanics of chondrocytes for simple loading conditions.

Methods: Because chondrocytes are numerous and are randomly distributed in the matrix, it is technically difficult to simulate the mechanical behaviour of cartilage including the effects of the distributed chondrocytes, and to simulate precisely the time-dependent stress and strain state of each individual cell within the cartilage. The technique used here involved three basic steps [1]: first, the cartilage was approximated as a macroscopically homogenized material having effective material properties; second, the mechanical behaviour of cartilage was obtained using the homogenized model; and third the solution of the time-dependent displacement and fluid pressure fields was used as the time-dependent boundary conditions for a microscopic sub-model, to obtain the average, time-dependent mechanical behaviour of cells in different locations within the cartilage. Cartilage was considered to be composed of extracellular matrix and small, spherical cells. Both matrix and cells were assumed to have linear biphasic material properties. Numerical tests using unconfined compression with similar configurations as in the experiments by Guilak [2] (Fig. 2) were performed. The indentation plate on top of the specimen was assumed to be perfectly permeable or impermeable. In both tests, the specimen was compressed by 15% at a constant rate during a ramp period of 30 s, and the deformation was then kept constant until t=1200 s. The values for the elastic modulus, Poisson's ratio, and the permeability of the matrix and cell were assumed according to [3,4]. The cartilage specimen was assumed to contain 5 % of chondrocytes in volume. The cells were located at four positions within the cartilage specimen (Fig. 1): A(r=0,z=0), B(r=0,z=0.4), C(r=0,z=-0.4), and D(r=2.9,z=0.0).

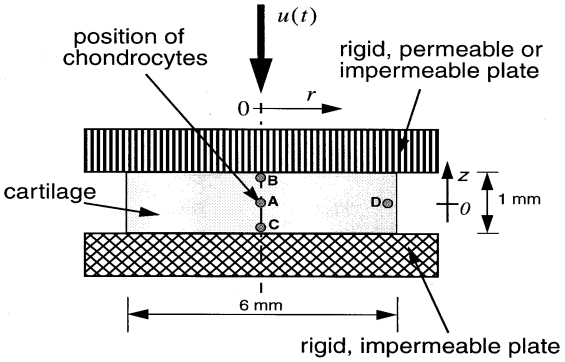

Figure 1: The Model of Numerical Tests.

Results and Discussion: The location- and time-dependent deformation of chondrocytes is illustrated in examples of the changes in height/width ratio (H/W) and the normalized cell volume (V/V_0) for a permeable and an impermeable indentation plate (Fig. 1). The fluid boundary conditions on the cartilage surface have a big influence on the deformation behaviour of the chondrocytes. We also analyzed the time-dependent distribution of strains, elastic stresses, elastic energy densities, and fluid velocity fields in the cells at different locations within the cartilage specimen for the whole deformation process (results are not shown). Our simulations agree with the experimental results by Guilak [3] who measured the shape and volume change of chondrocytes in the surface, middle, and deep layers of a cartilage specimen after a steady-state had been reached (t=1200 s). However, in addition to the experimental results by Guilak [3], our model also shows that the chondrocytes experienced large and fast deformations in the first 30 s of loading. These large, fast-rate deformations of chondrocytes may be much more important in triggering a biological response than the steady-state values reached almost 20 minutes later. But these transitional deformations of the chondrocytes cannot be measured experimentally at present in in situ or in vivo preparations, therefore the experimental approaches may miss the most crucial aspects of cell loading and deformation, and models like the one presented here may be the only means (in the near future, at least) to uncover the relationship that may exist between chondrocyte deformation and cartilage adaptation.

References:

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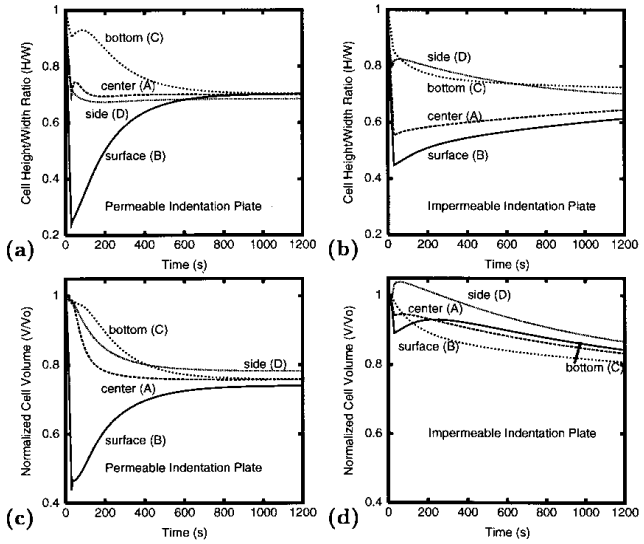

Figure 2: Model predictions of chondrocyte deformation as a function of location and time. (a)-(b): cell height/width ratio; (c)-(d): normalized cell volume.

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