Depth-dependent compressible equilibrium properties of articular cartilage explained by its composition

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Introduction

The compressive equilibrium stiffness of articular cartilage (AC) increases with distance from the articular surface [1,2]. While the stiffness of the surface layers increased with increasing strain, the stiffness of the deep layers decreased with increasing strain [1,2]. This depth and strain-dependent behavior has so far unexplained.

Hypothesis: The depth-dependent compressive properties of AC are the consequence of the depth-dependent composition alone.

Material and methods

To test this hypothesis our composition based fibril-reinforced poroviscoelastic swelling model [3] was used. In this model the following features were included:

- Distinction between intra- and extra-fibrillar fluid
- Solid fraction dependent compressibility
- Fraction dependent contribution of the proteoglycan and collagen matrix
- Depth-dependent composition and collagen structure
- Strain-dependent fibril stiffness
- Osmotic swelling

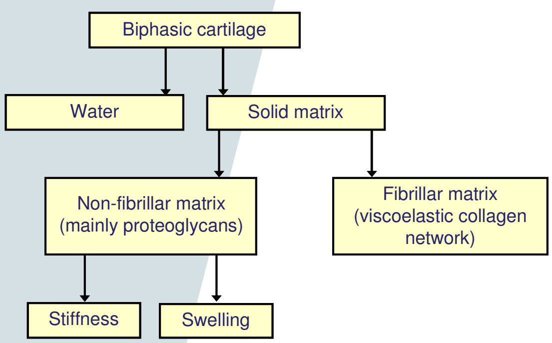

Figure 1: Schematic of fibril-reinforced poroelastic swelling model

The model was axially compressed in a confined compression setup in a stepwise manner (Fig. 3, left). After each step the model was left to equilibrate and the applied pressure and the local strains were recorded. The model results were compared with the experimental data [1]. The depth- dependent composition was taken from literature (Fig. 2) [2, 5-7].

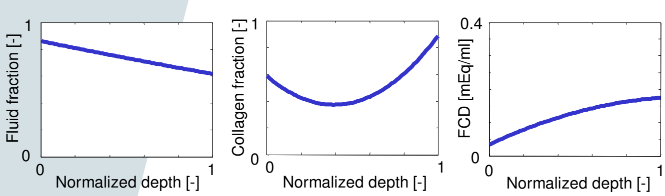

Figure 2: Depth-dependent compostion of articular cartilage

Results

The stress-strain curves of the simulations and the experiments correspond well (Fig. 3, right). Due to the high osmotic pressure in the deep zone the tissue is initially in tension (Fig. 4). Only when the external compressive load exceeds the internal osmotic pressure the tissue becomes compressed. Hence, for low external pressures the measured properties are tensile properties (mainly fibril properties) and for high external pressures the compressive properties.

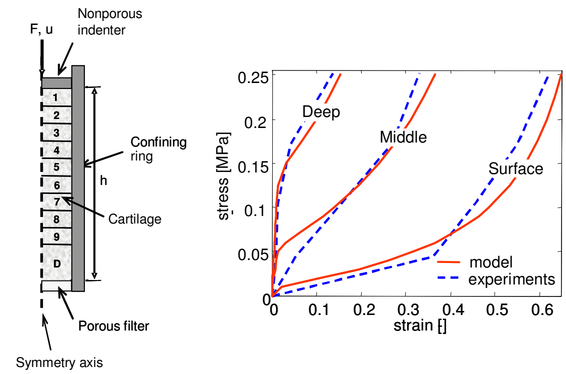

Figure 3: (left) Confined compression mesh (h=1.38 mm). (right) Depth-dependent stress-strain behavior of AC measured during confined compression [1] along with FEA-model results.

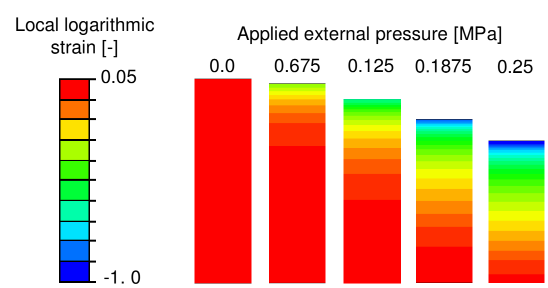

Figure 4: Depth-dependent strain in AC as a function of the externally applied pressure as computed with the finite element model.

Discussion

The depth-dependent compressive behavior of AC is explained based solely on its composition, and is highly dependent on the local proteoglycan and collagen content. The softening behavior of the AC during compression is caused by the combined effect of compression-tension non-linearity of collagen fibrils and osmotic prestressing.

References

[1] Schinagl et al., JOR (1997)
[2] Chen et al. OA & cart (2001)
[3] Wilson et al., J Biomech (2005)
[4] Maroudas et al. Biochim Biophys Acta (1991)
[5] Rieppo, proc ORS (2005)
[6] Shapiro et al., OA & cart (2001)
[7] Maroudas et al., Biorheology (1981)

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