Failure in cartilaginous tissues.

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Summary: Cartilaginous tissues high load bearing capacity is explained by osmotic prestressing putting the collagen fiber reinforcement under tension and the proteoglycan gel under compression. The osmotic forces are boosted by a further 50% by the affinity of the collagen with the aqueous solution. The high osmolarity of the tissue provides a strong protection against crack propagation. Degeneration results in degradation of the prestressing and hence to internal damage. 3D visualisation of a discontinuity of the collagen strutction of the disc is achieved by confocal laser scanning microscopy. The collagen and the cells are visualised by means of a two fluorescent probes. The discontinuity is shown to open and close depending on the osmotic loading of the tissue. The process of internal degradation is presently modelled using Partition of Unity method in an osmotically prestressed fluid-solid mixture.

Introduction

Unlike most biological tissues, cartilaginous tissues tissues has no blood perfusion. The cells of the tissue obtain nutrition and removal of waste materials through diffusion only. This fact implies that cartilaginous tissues renew themselves at a much lower rate than any other tissue in the human body. The capacity of cartilaginous tissues to withstand relatively high loads of several MPa during a lifetime of up to 100 years, is a noteworthy achievement, especially in view of its low stiffness, low renewal rate and high water content. Cartilaginous tissues consists of a fluid-filled extra-cellular matrix, in which living cells are sparsely dispersed. The mechanical function is highly dependent on the composition of the extra-cellular matrix, which primary consists of collagen fibrils and negatively charged proteoglycans. Due to the fixed charges of the proteoglycans (PGs), the cation concentration inside the tissue is much higher in the intra-fibrillar space than if they were distributed uniformly throughout the entire matrix. Hence, the effective fixed charge density is higher than if computed from total tissue water content. Wilson et al. [6] predict the depth dependent stress-strain curve of articular cartilage solely from its composition and the inclusion of the intrafibrillar/extrafibrillar water compartments and their associated osmotic pressures. A corresponding analysis for intervertebral disc tissue (Fig. 1) demonstrates that intrafibrillar water affects pressure distribution, osmolarity and stress within the disc substantially [3]. Confined compression and swelling experiments on canine intervertebral disc samples were performed and fitted by Huyghe et al [1] using the concept of intrafibrillar water as well.

Fractures in the intervertebral disc

A peculiar observation in intervertebral disc degeneration is the finding that human intervertebral discs develop fractures with age virtually independently from load to which they are subjected (Fig. 2). Concomitantly, the osmotic prestressing is decreasing. Wognum et al. [7] studied the opening of a crack in a numerical and physical model of the degenerated intervertebral disc. Degeneration was modelled as a progressive decrease in osmotic prestressing. They demonstrate that, while the osmotic prestressing is decreasing, the overall fiber stress is decreasing as well, but the stress at the crack tip increases sharply, because the shrinking of the tissue induces opening of the crack. This phenomenon is intrinsically multiscale in nature and may explain the poor relationship between external loads and crack propagation. None of the models used by Wognum et al [7] considers the intrafibrillar water effect mentioned earlier, while experimental data suggest that 30% of the water contained in the annulus is grabbed by the collagen and is not seen by the charges fixed to the proteoglycan chains. This suggests...
that the protective effect of osmorality against failure is further enhanced by intrafibrillar water.

**In vitro observation of the tissue**

To observe the genuine tissue in 3D, a new method is created to visualize micromechanical swelling in the intervertebral disc annulus fibrosus. The deformations of the collagen fibers and the cells under osmotic loading are observed by fluorescent labelling under the confocal microscope (Fig. 3). A digital image correlation technique calculates displacements and finite strains. The results show the heterogeneous character of the tissue as well as the non-affine nature of the deformation (Fig. 4-5). A Partition of Unity formulation of fluid-solid mixture is presently developed to describe the osmotic failure mechanism.

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**References**


