THE EFFECT OF COLLAGEN FIBRES
ON PERMEABILITY OF ARTICULAR CARTILAGE

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INTRODUCTION

The proteoglycan meshwork is deemed to be the main source of resistance to fluid flow in articular cartilage. Maroudas (1968) showed that the decrease in proteoglycan volumetric fraction from the tidemark (bone-cartilage interface) to the articular surface corresponds to an increase in permeability from tidemark to surface, which is consistent with the well accepted "proteoglycan paradigm". However, Maroudas and Bullough (1968) also found that, in the upper layers of the superficial zone, permeability decreased instead of the expected increase. They ascribed this to the fact that, in the superficial zone, the collagen fibres are parallel to the surface, and have a higher volumetric fraction.

Nevertheless, there are no microstructural models of cartilage permeability in which the effect of the arrangement of the collagen fibres or the inhomogeneity caused by the depth-dependent proteoglycan content, were considered. Based on the perfect analogy between the laws of fluid filtration in porous media (Darcy's law) and the electric induction in dielectric media, we recently proposed a model for the permeability of fibre-reinforced porous materials (Federico and Herzog, 2007), exploiting results for dielectrics reported by Landau and Lifshitz (1960). Here, we use this model to verify whether the collagen fibres cause the anisotropy, and affect the inhomogeneity of articular cartilage permeability.

METHODS

Articular cartilage is considered as a composite comprised of a porous matrix (the proteoglycans), with volumetric fraction ϕ_0 and isotropic intrinsic permeability k_0, a phase of impermeable fibres ($k_1 = 0$), with fraction $\phi_1 = \phi$, and the fluid phase with fraction $\phi_f = 1 - (\phi_0 + \phi)$. A "unit cell" describing the *local* properties of this composite material is comprised of a segment of a fibre, together with its cylindrical neighbourhood, filled with the mixture of matrix and fluid. The volume Ω of the embedding cylinder is such that the ratio between the volume Ω_1 occupied by the fibre and Ω equals the fibre volumetric fraction, ϕ (Fig. 1).

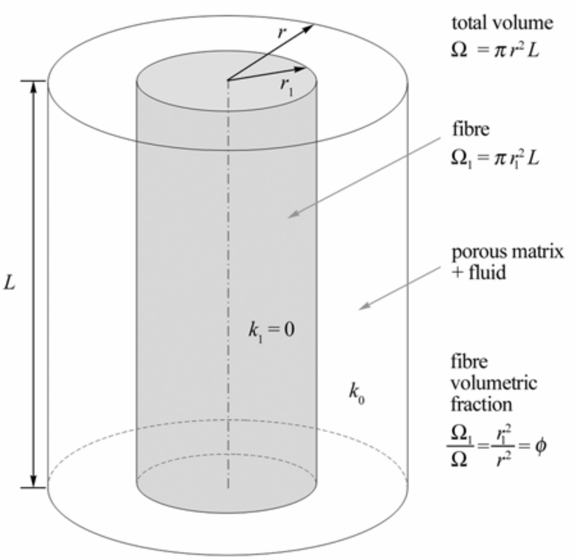

Figure 1: Unit cell, with an impermeable fibre embedded in the porous matrix

According to our model (Federico and Herzog, 2007), the *local* permeability tensor is given by

$$\boldsymbol{k} = \begin{bmatrix} (1-\phi) & 0 & 0 \\ 0 & (1-\phi)^2 & 0 \\ 0 & 0 & (1-\phi)^2 \end{bmatrix} k_0 . \quad (1)$$

The overall permeability, $\boldsymbol{K}$, at a given normalised depth ξ (such that $\xi = 0$ at the tidemark and $\xi = 1$ at the surface) is then obtained through the directional averaging integral

$$\boldsymbol{K}(\xi) = \int_{\mathbb{S}^2} \psi(\boldsymbol{w};\xi)\ \boldsymbol{k}(\boldsymbol{w};\xi)\ dS(\boldsymbol{w}) , \quad (2)$$

where $\mathbb{S}^2 = \{\boldsymbol{w} \in \mathbb{R}^3 : \|\boldsymbol{w}\| = 1\}$ is the set of all directions in space, $\boldsymbol{k}(\boldsymbol{w},\xi)$ is the permeability of the unit cell oriented in the direction $\boldsymbol{w}$, which depends on ξ through the proteoglycan permeability k_0, and $\psi(\boldsymbol{w},\xi)$ is the probability to find, at depth ξ, a unit cell oriented in the direction $\boldsymbol{w}$.

RESULTS AND DISCUSSION

In order to compare our theoretical predictions to the experimental results obtained by Maroudas and Bullough (1968), we assumed a linear increase of the proteoglycan permeability and the collagen volumetric fraction from the tidemark to the articular surface. The probability distribution, ψ, describing the arrangement of the collagen fibres, was constructed from the X-ray diffraction measurements of Mollenhauer et al. (2003) which showed that the fibres were oriented parallel to the surface in the surface zone, randomly oriented in the middle zone, and perpendicular to the tidemark in the deep zone. Our model was able to catch the decrease in permeability in the superficial zone that is associated with the parallel-to-the-surface fibre orientation, and gave good agreement with the experiments by Maroudas and Bullough (1968) (Fig. 2). We demonstrated that the structural arrangement of the collagen fibres plays a crucial role in the depth-dependent permeability of articular cartilage, and causes anisotropy. Unfortunately, there are no experimental data to compare the predicted anisotropy in cartilage permeability, although such experiments seem possible and should be performed in the near future.

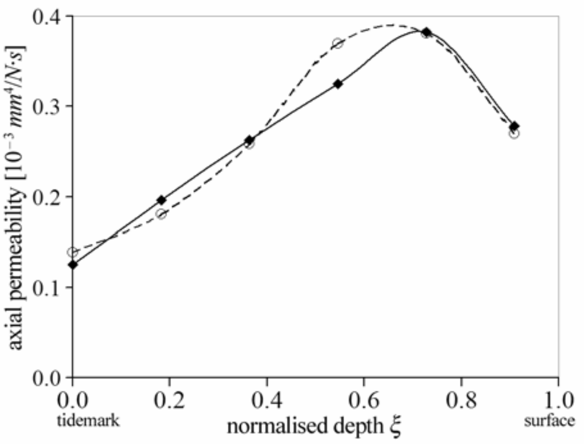

Figure 2: Axial permeability measured by Maroudas and Bullough (1968) (dashed line with open circles) and model predictions (solid line with solid diamonds)

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ACKNOWLEDGEMENTS

The Canada Research Chair Programme, the Canadian Institute of Health Research (CIHR), the Alberta Heritage Foundation for Medical Research (AHFMR, Canada)