A COUPLED MULTISCALE MODEL OF THE HUMAN CORNEA ACCOUNTING FOR THE COLLAGENOUS MICROSTRUCTURE AND THE EXTRACELLULAR MATRIX

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ABSTRACT

The human cornea is a complex, highly specialized structure necessary for the vision function of the Eye. The cornea, due to its shape and transparency, refracts and transmits the light to the retina. Cornea's mechanical properties, critical for maintaining corneal shape and function under intraocular pressure, arise from the composition of a hydrated proteoglycan-rich extracellular matrix (ECM) reinforced by an intricate network of collagen fibrils organized into lamellae. Despite extensive research, existing biomechanical models often fall short of capturing the coupled interplay between the ECM and collagen reinforcements, especially under physiological and pathological conditions. This work seeks to address this gap by proposing a novel computational model that integrates a continuum representation of the ECM with a discrete collagen-crosslinking network. The continuum approach for the ECM is chosen to represent its viscoelastic behavior and interaction with fluid flow, critical for corneal hydration and load transmission. Conversely, the collagen network is modeled as a discrete, anisotropic reinforcement system, capturing the directional stiffness imparted by the collagen fibrils and their crosslinking. The model is developed to account for the influence of enzymatic degradation, age-related changes, and disease processes such as keratoconus, where alterations in the ECM-collagen coupling are known to drive structural instability.

The innovation of this approach lies in its multiscale integration, bridging the molecular mechanics of collagen crosslinking with macroscopic corneal behavior. By explicitly linking the continuum matrix with a collagen-reinforced network, the model offers some possibility to deepen our understanding of corneal mechanics.

The inclusion of experimentally derived parameters for collagen alignment, crosslink density, and ECM properties, will make the model predictive in the simulation of physiological responses to intraocular pressure and external mechanical perturbations.