Estimation of Material Parameters of a Fiber-Reinforced Constitutive Model of the Human and Porcine Cornea

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Introduction

It is predicted that the number of people suffering from myopia will increase to 5 billion by 2050 [1]. Myopia is one of the most common refractive errors treated by laser ablation, but suboptimal refractive outcomes remain in approximately 10% to 15% of patients. Mechanical deformation of the tissue after the procedure has been proposed as an explanation for these suboptimal results. Therefore, accurate characterization of tissue material properties may help ophthalmologists improve surgical planning. This work addresses the relevance of experimental multiaxial tensile data for estimating corneal stroma material. In this context, a testing protocol for biaxial tensile tests was investigated, and parameter estimation for human and porcine corneal tissue was improved based on existing research.

Materials and Methods

The corneal stroma is a complex material reinforced by a network of collagen fibers. Therefore, a constitutive model is required that can capture the effects of the ECM and collagen [2]. The first part of the model is the neo-Hookean contribution of the ECM, and the second part integrates the contribution of collagen fibers distributed over the unit sphere.

$$\Psi = \Psi_m + \int_0^{\pi} \int_0^{2\pi} \rho(\phi,\theta)\Psi_f \sin(\theta) d\theta d\phi$$

Fig. 1 Constitutive model used in the simulations.

Experimental data from porcine specimens and existing data from human DMEK strips [3] were used in various simulations to estimate the parameters of the constitutive model in an optimization algorithm. The algorithm iteratively compared results of numerical simulations with the experimental data to find an optimal set of parameters. Porcine corneal inflation data and experimental data from SMILE lenticules with patient-specific FE models were used to validate the identified parameters.

Results

Corneal inflation data were incorporated into the human material model to estimate the stiffness of the ECM. Optimizations for both the porcine and human models achieve good curve fits of the included experimental data by simulating the experiments with the appropriate parameters. Validation using patient-specific data from SMILE shows that the human model correctly reproduces corneal behavior, although it tends to underestimate collagen fiber tensions. In contrast, the porcine model exclusively relies on uniaxial tensile data and impressively mimics the experimental pressure-displacement curve of the inflation model used for validation.

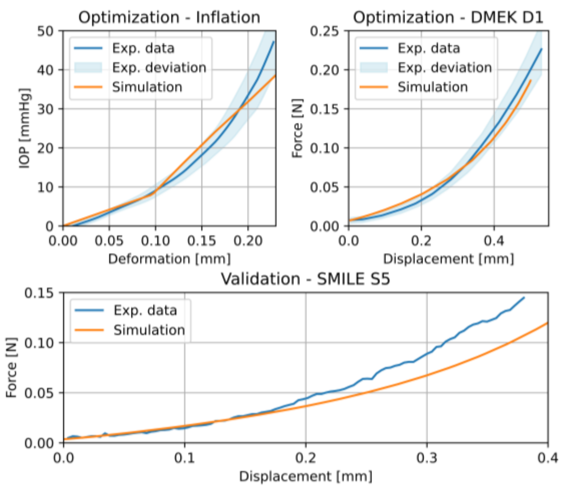

Fig. 2 Results of the optimization on human tissue and validation of the identified parameters against patient specific uniaxial tensile data on of the SMILE lenticules.

Discussion

The simulations and parameter validation provided valuable insight into the constitutive model. The results show that the selected material model can reproduce the experimental data well, although only three of the total six parameters were included in the optimizations. Further investigations are needed to improve the precision of the parameter estimates, especially with respect to depth-dependent fiber dispersion and crimp. In addition, an expansion of the number of loading cases is essential to accurately capture the physiological biaxial loading orientations to which the cornea is subjected. The transition from uniaxial to biaxial experiments that better capture the physiological loading of the cornea is complex, but initial testing has demonstrated the feasibility of a suitable testing protocol.

References

[1] BA Holden et al., Ophthalmology, 123(5), 2016
[2] GA Holzapfel et al., Journal of The Royal Society Interface, 12(106), 2015
[3] MH Nambiar et al., SSRN, 2023