Influence of Mechanical Properties on Photorefractive Keratectomy Outcome

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Abstract

In the 90's, excimer lasers were introduced in refractive eye surgery for correcting vision errors by reshaping the corneal surface. However, the post-surgical mechanical consequences of removing the tissue have not been analyzed to date. To address this issue, a finite element (FE) model has been developed to reproduce Photorefractive Keratectomy (PRK), in order to investigate surgery's outcomes depending on mechanical parameters.

Introduction

Laser refractive surgeries have become widely used in correction of vision defects such as myopia and hyperopia. Among different procedures, PRK is the most common: it consists of reshaping the anterior corneal surface with a laser, by following a pre-established profile, in order to achieve the spectacle independence (desired diopters correction). The removal of the ablation tissue affects the biomechanics of the cornea, causing geometrical changes and, consequentely, deformations and stresses on the tissue, due to the action of the intraocular pressure (IOP) inside the eye cavity.

FE models are a useful tool that allows us to accurately reproduce the surgery and to analyze the mechanical effects on the final visual performance of the patient. In this work, a FE model of the cornea has been developed to address the influence of geometrical, physiological and material parameters on the final outcome of PRK surgery simulation.

Materials and Methods

A 3D conicoid finite element (FE) model of the cornea (Figure 1) was built using average geometrical parameters [1]. A non-linear anisotropic Holzapfel-Gasser-Ogden constitutive model was chosen to model the behavior of corneal tissue, including in-plane and out-of-plane dispersion of the corneal collagen fibers [2]. A pre-stretch iterative algorithm was applied to introduce stromal stresses related to intraocular pressure (IOP), before performing the PRK simulation. The PRK surgery simulation consisted of removing corneal tissue from the anterior surface following a specific ablation profile. The ablation depth was calculated using a conic ablation profile [3], in order to obtain a correction of 4 D. All mechanical simulations were calculated using ABAQUS.

To study the effect of the corneal mechanical properties on the PRK surgery's outcome, a 2^k full factorial design was conducted, considering as key factors of the FE simulation the following variables: the materials constants of the constitutive model (C_{10}, k_1, k_2), the IOP and the thickness of the cornea (with k = 5, resulting in 32 simulations, see Table 1). The material constant C_{10} represents the isotropic behavior of the constitutive model, while k_1 (fibers' stiffness) and k_2 (fibers' non-linearity) are related to the anisotropic contribution. The IOP and the thickness of the cornea are two physiological and geometrical parameters, respectively, that can affect the mechanical response of the tissue.

The material constants were considered within a 50% variation with respect to the reference values [2] ($C_{10\text{-Ref}}$ = 30 kPa, $k_{1\text{-Ref}}$ = 20 kPa, $k_{2\text{-Ref}}$ = 400 [-]), whilst IOP and corneal thickness were changed within average physiological values.

The simulations' outcomes were analyzed by considering the diopters corrected with the PRK and the apex displacement of anterior corneal surface. An ANOVA statistical analysis was performed to interpret the results of the full factorial design.

Table 1. Parameters tested in the sensitivity analysis

	C_{10} [kPa]	*k_1 [kPa]*	*k_2 [-]*	*IOP [mmHg]*	*Thickness [μm]*
Min	15	10	200	13	490
Max	45	30	600	18	550

Results

The results obtained from the statistical analysis are shown in Figures 2-3. The statistical model used to describe the results included up to third-order terms;

consequentely, also the interaction among the parameters was taken into account.

The constant k_2 turned out to be the most influential factor for both the corrected diopters and the apical displacement (Figure 2). This underlines the highly non-linear contribution of the anisotropic component of the material to the behavior of the FE model and, therefore, the need of incorporating the collagen fibers when modeling the corneal tissue, as previously demonstrated in [4].

Both C_{10} and k_1 also have shown high influence (Figure 3), implying the influence of both isotropic and anisotropic components in the model response.

Although the IOP and the corneal thickness gave a statistically significant contribution, their effect is lower with respect to the other parameters.

In general, the material constants and their interactions have shown the major influence in determining the behavior of the corneal model and must be set properly, in order to take into account post-surgery mechanical deformations.

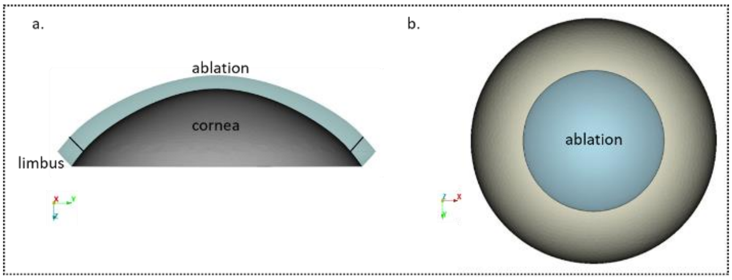

Figure 1: 3D FE model

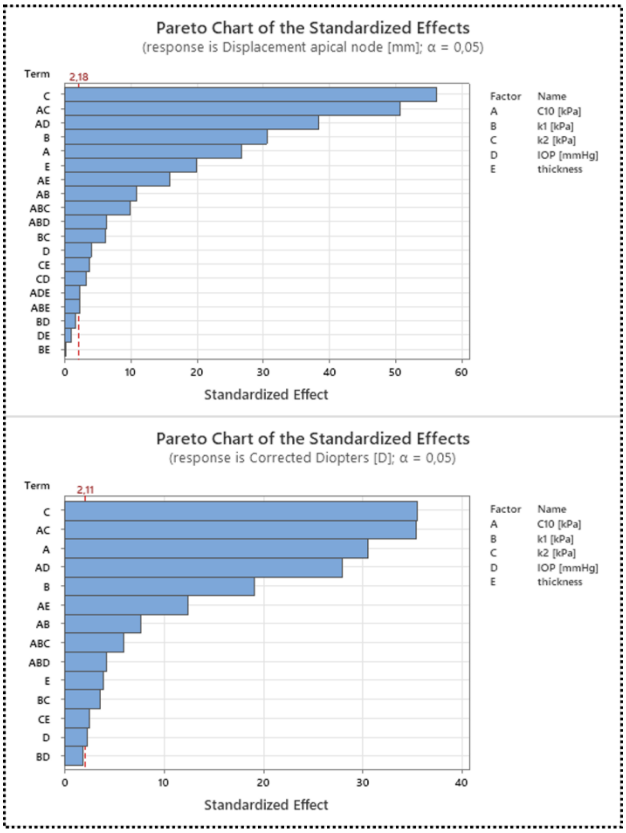

Figure 2: up: Pareto chart of the variables with respect to the apex displacement and to the corrected diopters

Conclusions

This work aimed to enlight the influence of the mechanical parameters on the PRK simulation’s outcome. From the statistical analysis it turned out that the material constants do play a role on the final result of the PRK FE simulations, while the IOP and the thickness contribute in a minor way. Consequentely, it is of major importance to set the correct material constants in order to perform an accurate and reliable PRK simulation, having as final goal the post-surgical optical quality of the patient. To achieve this goal, post-surgery mechanical deformations cannot be neglected.

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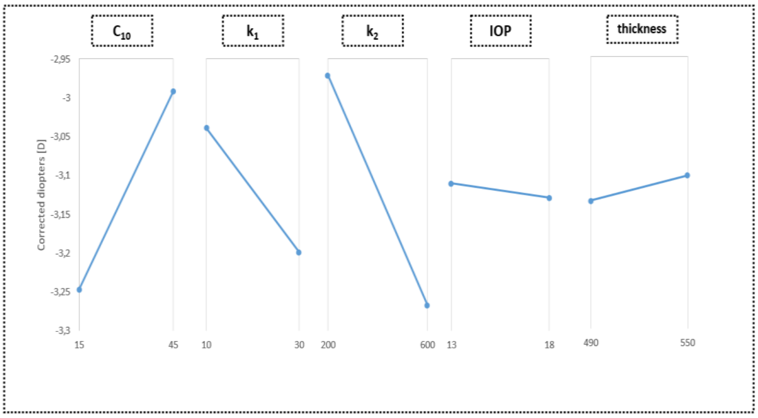

Figure 2. Factorial Plots for Corrected Diopters

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