A Numerical Study on the Effects of Laser Refractive Surgery: SMILE vs PRK

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Abstract

In the last two decades, corneal laser surgery has become a common procedure to correct medium-low refractive defects. It consists of reshaping the corneal geometry by means of a laser in order to correct the present refractive error. In this work, we compare the opto-mechanical performance of two laser surgery procedures: Photorefractive Keratectomy (PRK) and Small Incision Lenticule Extraction (SMILE).

Introduction

Laser refractive surgeries have become widely employed for correction of medium-low refractive defects. There exist different surgery procedures, that affect the biomechanics of the cornea in different ways: in this work we compare Photorefractive Keratectomy (PRK) and Small Incision Lenticule Extraction (SMILE). PRK consists in reshaping the anterior surface of the cornea, by removing a portion of tissue with a laser ablation. In SMILE procedure, a lenticule inside the corneal thickness is created with the laser and removed through a small incision, preserving the integrity of the anterior surface and, thus, causing less post-surgical discomfort. In both cases, the removal of a portion of corneal tissue causes geometrical changes, also due to the action of the intraocular pressure (IOP) inside the eye cavity, affecting the biomechanics of the structure in terms of stress and strain distributions on the tissue. In this work, we perform a mechanical and optical analysis of the two procedures, underlying advantages and disadvantages of both surgeries.

Material and methods

Two 3D conicoid finite element (FE) models of the cornea were built, one for each surgery procedure, using geometrical measurements of a healthy patient. 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 fibers dispersion parameters [1]. A pre-stretch iterative algorithm was used to recover the stress-free configuration, before performing the surgery simulations. Subsequently, the surgery simulation is performed in two steps: in the first step, a physiological IOP of 15 mmHg is applied to the posterior surface of the cornea; in the second step, the laser surgery is simulated. In both surgeries, the portion of the corneal tissue to be removed was determined in order to obtain a myopic correction of -4D [2]. PRK surgery simulation consisted of removing the previously determined ablation portion from the anterior surface. In SMILE simulation, the lenticule was created at a 20% depth of the corneal thickness, moving from the anterior surface, with the same shape as in PRK. All simulation were performed using ABAQUS 6.13.1. Subsequently, an opto-mechanical analysis was performed to compare the outcomes of the two surgery simulations. Corneal optics was determined using an in-house developed algorithm, that computes sagittal curvature plots, defined as the inverse of the distance of each point of the anterior surface with respect to the optical axis, that, for sake of simplicity, coincides with the z-axis.

Results

The results of the mechanical analysis of the comparison between the two surgeries are shown in Figure 1. The difference in terms of displacements, stresses, and strains between the pressurization step and the surgery step has been computed in order to highlight the effects of the surgeries onto the corneal geometry. By looking at the displacement maps, we can notice that SMILE surgery reaches higher displacement values and, consequently, higher strains with respect to PRK. This can be explained with the fact that the removal of a portion of corneal tissue from its thickness causes a lowering of the central zone of anterior surface, while PRK causes an upward deformation. This observation is confirmed by the optical analysis (Figure 2) of the post-surgical anterior surfaces. As expected, the sagittal curvature plots for the pre-surgical configuration of both models coincide; once the simulations are performed, we can notice a difference in the curvatures contour plot, due to the fact that the applanation that characterizes SMILE surgery causes a local increase of the curvature around the apical zone (green ring in post-surgical curvature plot of the SMILE, Figure 2). PRK surgery, instead, maintains the curvature anterior surface of the cornea more regular. Coming back to Figure 1, we can also notice that PRK causes a concentration of stresses at the anterior surface, while SMILE surgery maintains it completely unloaded. Even if the final optical outcome is similar in the two surgery procedures, the mechanical effects of stress and strain distribution affect very differently the corneal geometry in the two models.

Conclusions

An in-silico study to compare the opto-mechanical effects of PRK and SMILE surgeries on corneal FE models has been presented. Both surgeries effectively lowered the refractive defect, but caused a quite different mechanical response of the corneal structure. While SMILE surgery preserves the integrity of the anterior surface of the cornea, causing less post-surgical pain, PRK seems to reach lower values of stress and strains. Further investigation on pathological corneas is required to determine which procedure is safer.

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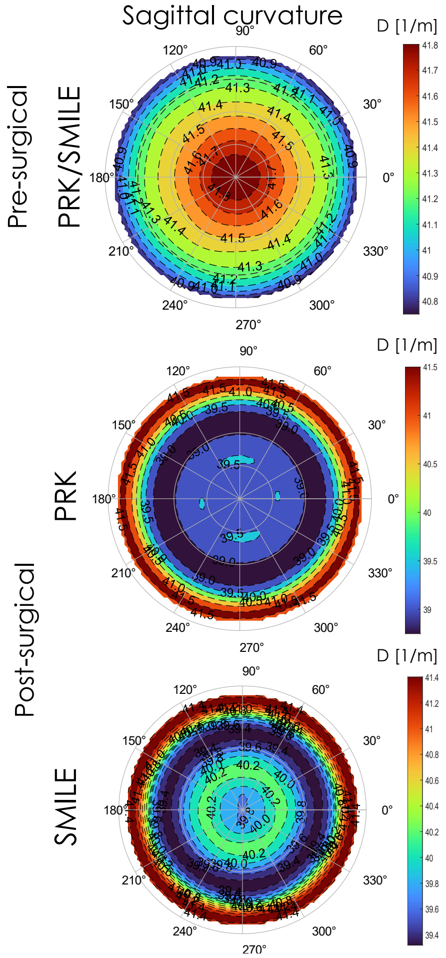

Figure 2. Pre- and post-surgical sagittal curvature maps of PRK and SMILE.

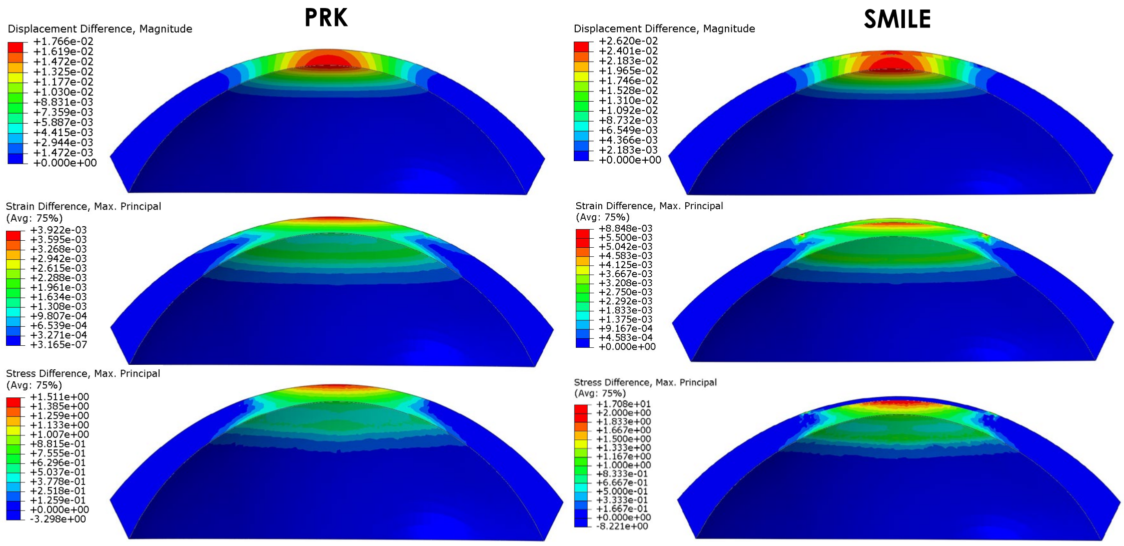

Figure 1. Mechanical analysis of PRK and SMILE surgery simulations: differences of displacement, stress and strain distributions due to the surgery step with respect to the pressurization step.