Journal of the Korean Physical Society (2021) 79:874–881
https://doi.org/10.1007/s40042-021-00279-9

Online ISSN 1976-8524
Print ISSN 0374-4884

ORIGINAL PAPER - CROSS-DISCIPLINARY PHYSICS AND RELATED AREAS OF SCIENCE AND TECHNOLOGY

Application of computational modeling to improve cornea transplant surgery

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Received: 15 March 2021 / Accepted: 26 July 2021 / Published online: 8 September 2021

Abstract
Cornea transplant involving applanation results in a deformation of the cornea. This deformation combined with a mismatch of dimensional and mechanical properties between donor and recipient corneas gives rise to tension on the transplanted cornea, astigmatism and vision difficulties. Therefore, accurate prediction of deformation of the incision plant during such operations is necessary to minimize complications. In this work, we employed a finite element simulation on a cornea with measured geometry and hyperelastic Mooney–Rivlin mechanical properties to analyze the intended incision plane's change during corneal applanation. A simulation of the cornea transplant procedure assuming two different geometries to be the same was performed, and the transplanted cornea showed a 5.1% change in the exterior radius. When the proposed method was applied, no change in the radius after transplant was observed. Moreover, a precise matching of the incision plane can be selected for the corneas, and the corneal deformation after an IntraLase-Enabled Keratoplasty (ILEK) corneal transplant procedure is expected to be minimal.

Keywords Cornea transplant · Cornea deformation · Cornea modeling · Finite element modeling

1 Introduction

Advances in laser technology have brought dramatic advances in ophthalmologic surgical methods such as LASIK and LASEK, as well as improvement in the cornea transplant procedure [1–4]. The IntraLase®-Enabled Keratoplasty (ILEK) method enables accurate incision of the cornea on the order of 1 μm [5–7]. However, whether the ILEK allows significant improvement over previous incision methods is controversial; while post-operative astigmatism is reduced, visual acuity is lower compared to that after a conventional penetrating keratoplasty [8]. In the ILEK procedure, the eye is clamped using a rigid ring structure around the corneal boundary, and then applanated prior to incision. Although the fixation and applanation ensures stability of the cornea during incision, when the applanated cornea returns to its original state, the incision plane is expected to be different in aspect of angle and depth. Furthermore, individual corneas have different geometric and mechanical properties; therefore, applanating and cutting them using the same incision parameters results in a geometric mismatch of the different corneas post-applanation. This gives rise to a deformation of the transplanted cornea, which results in a change of eyesight and vision difficulties. Other devices such as Femtec (Technolas Perfect Vision GmbH, Munich, Germany) and Visumax (Carl Zeiss Meditec, Inc., California, USA) place a curved glass structure, which reduces the deformation of the target cornea during incision, over the cornea. However, the gently placed glass cannot fix the cornea as firmly as clamping and applanation as in the ILEK method. Therefore, understanding how the intended incision

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plane changes during corneal applanation and knowledge of how the incision parameters differs between donor and recipient corneas of different geometry is necessary. In this research, a computer simulation was performed using ANSYS Workbench 11.0 (ANSYS Inc., Canonsburg, USA). It was used to observe the incision plane's change for finite element models of the donor and the recipient corneas. Also, corneal incision in the conventional ILEK method was simulated to observe the geometric mismatch between donor and recipient corneas and the resulting deformation of the transplanted eye. The results for the transplant simulation using incision parameters specified to each cornea were compared with those from conventional ILEK simulation, suggesting that our method will enhance the ILEK method's incision accuracy.

2 Methods

2.1 ILEK incision

The ILEK incision procedure consists of three deformation stages of the cornea (Fig. 1). First, the eye is clamped surrounding the corneal boundaries so as to limit eye motion during the applanation procedure. Next, the cornea is applanated using a glass flat to firmly stabilize and applanate the cornea. Then, using a femtosecond laser, the applanated cornea is cut according to the input incision radius and incision shape. Of the various incision shapes available in ILEK, the straight cut method is chosen for simulation for a straightforward verification of the relationship between corneal applanation and resulting incision plane's deformation. If the corneal deformation is to be simulated, the geometries of the donor and the recipient corneas are needed. Also, the material characteristics of the cornea and the surrounding tissues should be set for the finite element model. The simulation conditions for cornea deformation, such as the structural support and the applanation method, need to be clarified.

2.2 Geometry of the model cornea and finite element modeling

The measured geometries from optical coherence tomography (OCT) images [9–11] were used for designing finite element models of the donor and the recipient human corneas to be used in the simulation. The post-incision geometry is not easily observable even in OCT; therefore, a half-depth incision was conducted to confirm our initial hypothesis of the geometric difference between applanated incision and the resulting incision plane, mainly the incision angle. To prevent from wasting a perfectly good human cornea, we used a sample porcine cornea (Fig. 2) to confirm the aforementioned geometrical difference. Figure 3 shows the geometric information for the human cornea and its surrounding tissue. The cornea dimension is expressed using the following parameters: central corneal thickness *D*, external corneal curvature Cext, internal corneal curvature Cint, and radius of the cornea around the *y* axis (Rcornea). Using OCT we measured the parameters *D*, Cext and Cint for each individual cornea. For the finite element model simulation, tetrahedral meshing was

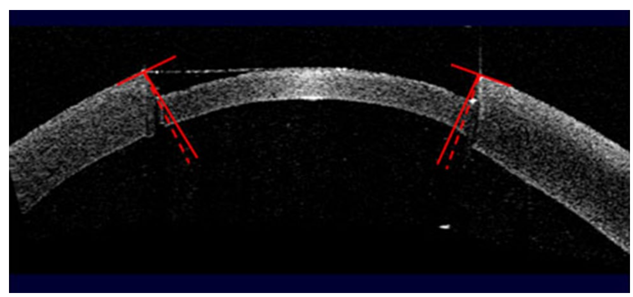

Fig. 2 Anterior OCT image of porcine cadaveric eyes. Incision of porcine cornea was done perpendicular to the flattened surface. The intended incision plane (perpendicular to the external corneal curvature) is denoted as dotted lines while the resulting incision plane (solid lines) shows angular differences from the intended incision settings. The incision was made for half the cornea to suppress the intraocular pressure's effect that causes corneal curvature changes on the incised region

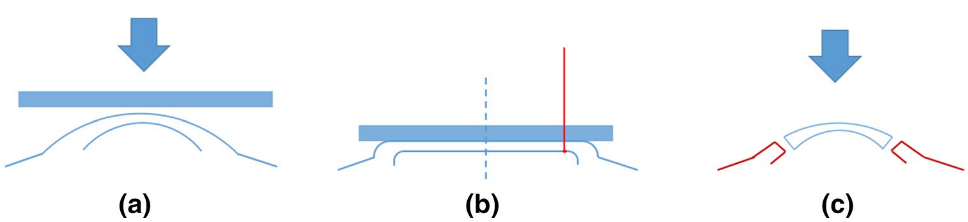

Fig. 1 Description of the ILEK femtosecond laser procedure: **a** A healthy donor cornea is placed under a flat glass cone and then applanated to a flattened state. **b** Then, it is cut with a symmetric incision radius and angle. **c** The cut-out cornea is then sutured to the recipient's remaining eye after removal of the dysfunctional cornea

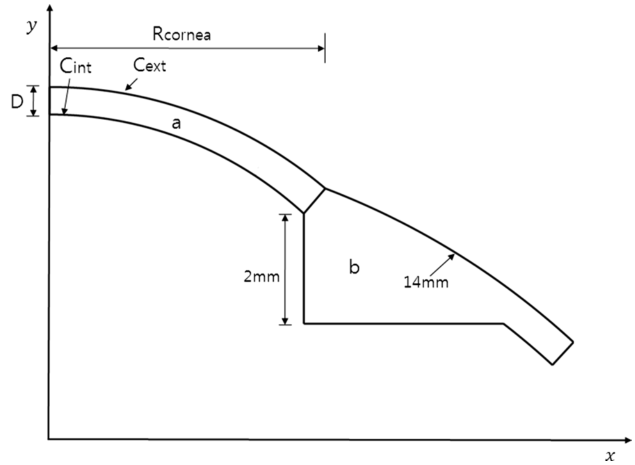

Fig. 3 Geometric information for the human cornea and the surrounding region shown as half of the sliced plane symmetric around the y axis. Part **a** refers to the corneal region, and part **b** is the sclera along with the ciliary muscle. The intended incision line is perpendicular to the external corneal curvature Cext

applied to the eye model while adaptive meshing method was used to increase the resolution of the cornea model. The resulting resolution of the model sclera was 0.8 mm, while the cornea resolution was 0.16 mm.

2.3 Mechanical properties of the cornea and the neighboring tissue

In ILEK, the cornea goes under a large deformation caused by the applanation process with a flat glass cone. Materials undergoing deformations with large strains can be described using nonlinear elasticity theory. For human tissues, hyperelasticity is commonly used for an analysis of its stress–strain relationship [12]. The stress in the human tissue due to its deformation can be expressed as

$$P = \frac{\delta W(\mathbf{F})}{\delta \mathbf{F}},$$

where W is the strain energy density function, P is the first Piola–Kirchhoff stress tensor and $\mathbf{F}$ is the deformation gradient tensor. The Cauchy stress tensor and the first Piola–Kirchhoff stress tensors have the following relation:

$$\mathbf{P}\mathbf{F}^T = J\sigma,$$

where $J = \det(\mathbf{F})$. The Mooney–Rivlin strain energy density strain model is an accurate formulation for representing biological tissues [13]. A generalized form of the volume-preserving Mooney–Rivlin strain energy density W can be written as follows:

$$W = \sum_{p,q=0}^{N} C_{pq}(\overline{I_1} - 3)^p(\overline{I_2} - 3)^q + \sum_{m=1}^{M} D_m(J - 1)^{2m},$$

where C_{pq} are material constants related to the distortional response, N is infinite to enable double infinite series of generating deformation material constants, $\overline{I_1}$ and $\overline{I_2}$ are the first and the second invariants of the deviatoric component of the deformation gradient tensor $\mathbf{F}$, and D_m are material constants related to the volumetric response. A 3-parameter Mooney–Rivlin strain energy density function can be simplified from the above function as

$$W = C_{10}\left(\overline{I_1} - 3\right) + C_{01}\left(\overline{I_2} - 3\right) + C_{11}\left(\overline{I_1} - 3\right)\left(\overline{I_2} - 3\right) + D_m(J - 1)^2.$$

Previously conducted experiments [14–17]show a hyperelastic stress–strain relationship for strips of the human cornea. The same material constants were used for both the donor and the recipient corneas. Cubic spline interpolation was performed on the stress–strain curve to select the material constants C_{10}, C_{01} and C_{11} to best fit the curve. D_m is the bulk modulus of the human cornea, and a value of 5.5 MPa was used for all calculations [12]. The clamping procedure for the corneal boundary during ILEK provided rigid structural support to the model during applanation, and mechanical properties of the sclera were chosen to have a linear elastic modulus of 2.35×10^6(N m^{-2}) [18].

2.4 Simulation conditions of cornea deformation

The conditions of corneal deformation were considered for the simulation. Because the sclera and other tissues neighboring the cornea are positioned within the eye socket, deep regions of the eye are fixed. In ILEK, the cornea is clamped around its boundaries to fix the eye prior to applanation. Therefore, the region connecting the cornea and the sclera is assumed to be rigid during the applanation procedure. Applanation of the modeled cornea was simulated using a rigid cylindrical structure pressing the cornea down. Figure 4 depicts the desired incision radius and angle, which are the parameters to be observed during corneal applanation to derive the actual incision conditions on a flattened cornea.

3 Results and discussion

The geometric changes in the desired incision planes of the donor and the recipient corneas were observed during applanation. Additionally, equal incision parameters on flattened donor and recipient corneas for the transplant were applied to confirm the transplanted cornea's geometric mismatch in

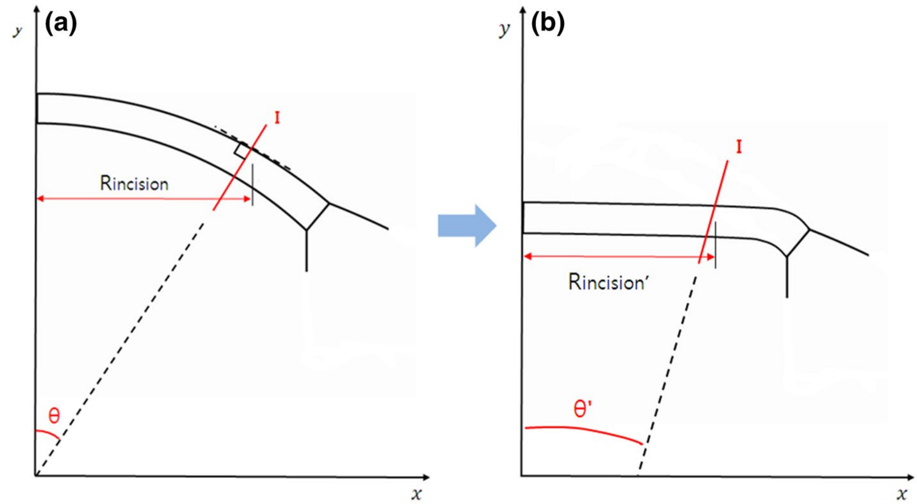

Fig. 4 Description of the corneal incision line change. **a** The red line running through the undeformed cornea shows the intended angle (θ) and incision radius ($R_{incision}$). **b** When the cornea is applanated, the incision angle and the radius changes accordingly. The changed incision parameters (θ', $R_{incision}$') during the applanated state are the values to be used for optimal removal of the cornea

Table 1 Geometric parameters of the donor and the recipient corneas

Geometry parameters	Donor cornea	Recipient cornea
Cext	7.42 mm	7.60 mm
Cint	6.06 mm	6.80 mm
D	0.55 mm	0.5 mm
Rcornea	5.50 mm	
Sclera ext. curvature	14.0 mm	
Sclera int. curvature	13.4 mm	
Ciliary muscle thickness	2.00 mm	

During corneal applanation, the sclera region experiences minimal deformation; therefore, the sclera and the ciliary muscle geometry used simplified parameters

a conventional ILEK procedure. Results from this mismatch using the same incision parameters were compared with transplant results for different incision parameters according to each cornea's deformation simulation.

3.1 Donor and recipient cornea deformation simulation

Deformation simulations for the donor and the recipient corneas using the previously measured parameters in Table 1 were conducted. The optimal incision of the cornea was chosen to be perpendicular to the external corneal curvature. Changes to the incision radius $R_{incision}$ and angle θ were acquired for varying degrees of corneal applanation, and the parametric changes in the donor and the recipient corneas were compared to observe the differences between the two.

Incision angle changes of the corneas are plotted in Fig. 5. The incision radius and the corneal applanation depth were varied. Simulation results show that the incision line is not perpendicular to the flat exterior surface and that the incision angle θ' is different between the donor and recipient due to the geometric parameter difference between the two corneas. Figure 6 shows the incision radius changes for an applanated corneas. Results show that the incision radius also changes more as the radius increases and that cutting the actual incision point at the exterior surface of the cornea differs from the actual intended region.

From the simulation results, the difference between the donor and the recipient corneas' parametric values (θ' and $R_{incision}$') increased as the incision radius was increased (Fig. 7). This suggests that when a corneal transplant with a wider incision radius uses the same incision parameters for both the donor and the recipient corneas at applanation, a larger geometric mismatch occurs. Therefore, if the corneas are cut out according to each cornea's changed parameters θ' and $R_{incision}$' acquired from the applanation simulation, their actual parameters at the recovered state are the same.

3.2 Cornea transplant simulation

A corneal transplant procedure where the donor and the recipient corneas are cut using the same incision parameters was simulated. Because a simulation from the applanated geometry back to the pre-applanated state is not possible, an iterative method for determining the incision parameters by searching for the pre-applanation $R_{incision}$ and θ that results in the wanted incision parameters at applanation is applied. The differences between the intended and the actual incision parameters are listed in Table 2. From the simulation results, cutting the cornea at its applanated state does not guarantee its dimensions in its original state. Attachment of the donor cornea onto the remainder of the recipient's eye was simulated to verify the geometric change induced in the transplanted cornea (Fig. 8a). The transplanted donor cornea's curvature decreases from 7.4192 to 7.0407 mm (a 5.1% decrease in cornea curvature). The curvature change occurs due to the tension on the incision/attachment surface, and

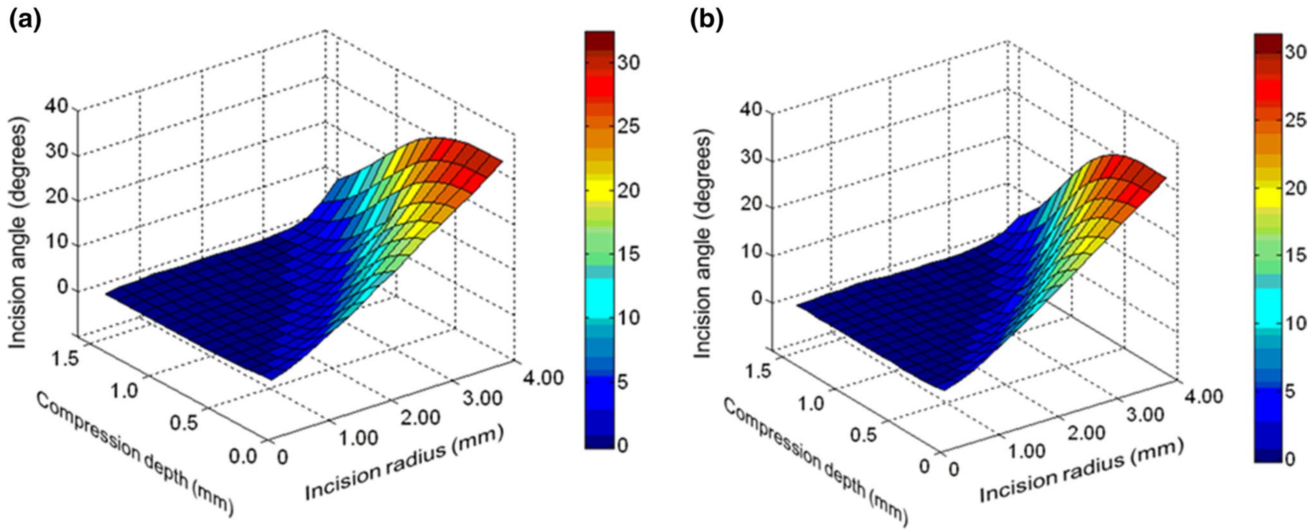

Fig. 5 Incision angle change of the donor (**a**) and the recipient (**b**) corneas versus corneal applanation depth and the incision radius. Slope tendencies of the two corneas seem similar, but their absolute values vary

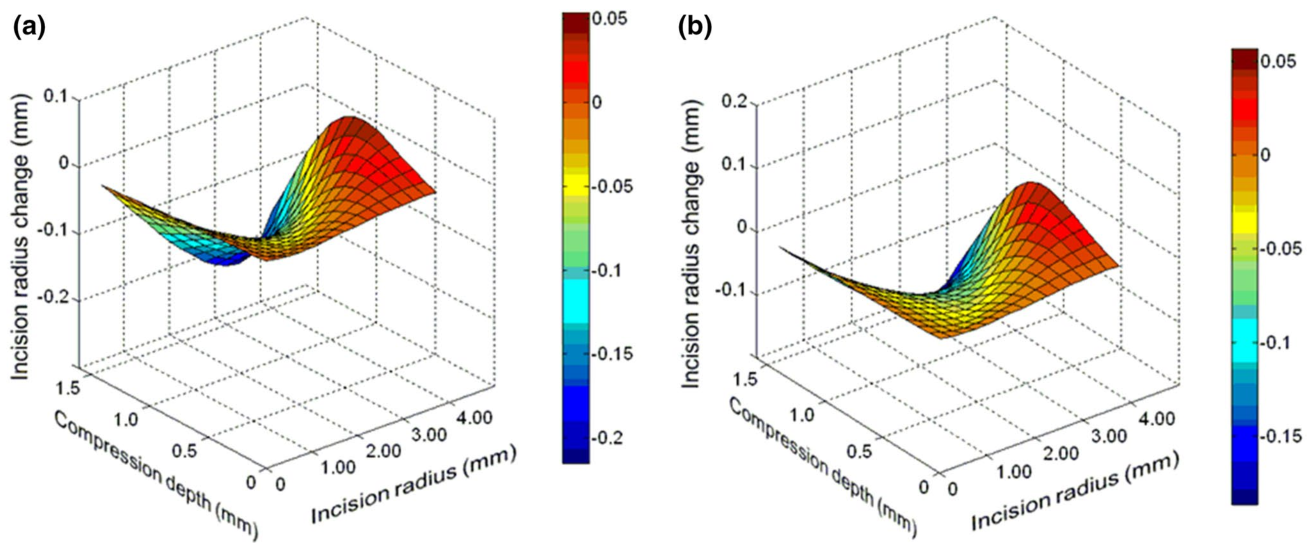

Fig. 6 Incision radius change of the **a** donor and the **b** recipient cornea versus applanation depth and the initial intended incision radius

due to this tension, an uneven suture will lead to distorted vision for the recipient. A simulation of corneal transplant using the parametric changes observed in Sect. 3.1 was conducted to verify our method. Because the incision angle and the radius are the same for the corneas, deformation of the transplanted cornea does not occur (Fig. 8b).

4 Conclusions

The ILEK applanates and fixes the target cornea during incision so as to stabilize the cornea. However, due to the nature of applanation, when the cut-out cornea returns to its pre-applanation state, the incision plane undergoes deformation as well. Also, the geometric difference between the donor and the recipient corneas is not considered in ILEK, leading to a deformation of the transplanted cornea. In this work, the ILEK corneal transplant procedure was simulated using a finite element analysis,

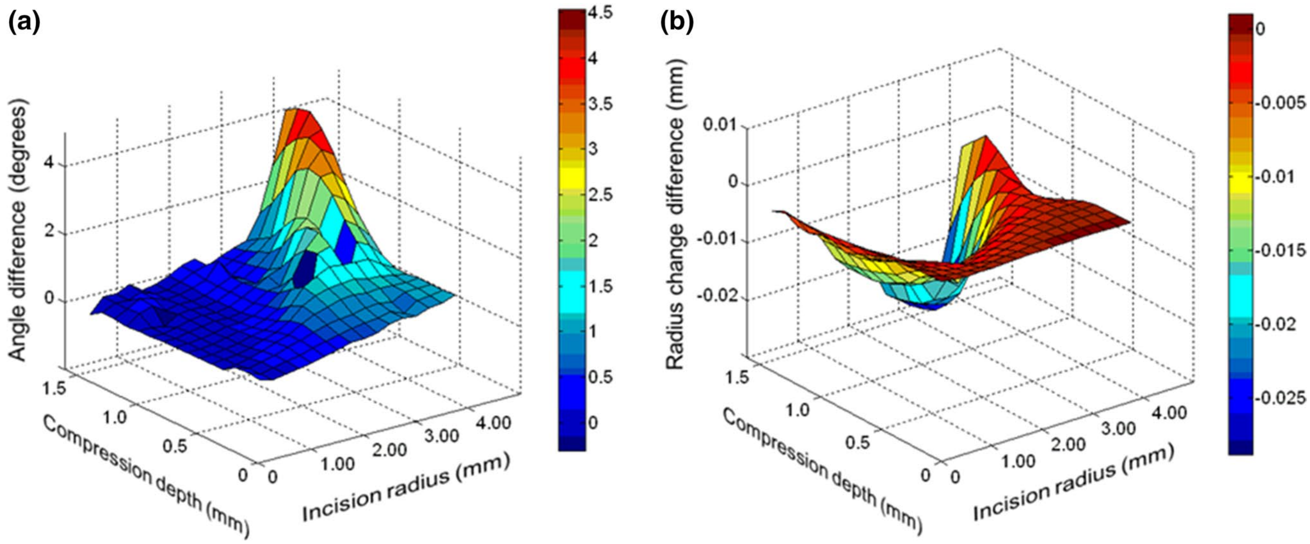

Fig. 7 Plot of parametric differences between donor/recipient cornea versus corneal applanation depth and incision radius. **a** Depicts the angular difference, while **b** refers to the incision radius change

Table 2 Incision parameter differences of the corneas back from the applanated state

Incision parameters	Donor cornea	Recipient cornea
$R_{incision}$' (applanated)	3.75 mm	
θ' (applanated)	0°	
$R_{incision}$ difference	0.173 mm	0.161 mm
θ difference	8.03°	3.6°

Incision radius and angle of the donor and the recipient corneas show significant differences in their original geometries

and deformations of incision angle and incision radius were acquired for different applanation depths at different radii. The measured geometries of the corneas were used for the finite element model of the donor and the recipient corneas, and unobtainable geometry information, such as sclera curvature, ciliary muscle thickness and cornea radius, was equally set for the donor and the recipient. Mechanical properties of the donor and the recipient cornea, as well as the sclera, were set according to previously obtained stress–strain curves [12–14]. Incision parameters were found to depend heavily on the cornea's original unapplanated geometric parameter rather than the material characteristics of the cornea (Fig. 9). Therefore, when the incision parameters are chosen for the donor and the recipient corneas, geometric measurements prior to corneal transplant allow us to select the optimal incision parameters necessary to match the dimensions of both corneas. The simulation, however, does not take into consideration several conditions of the human eye, which, when taken into account, would result in a more accurate simulation of the transplant procedure [19]. One, the deformation effect of intraocular pressure (IOP) is not considered in the current model, which is due to the fact that any realistic measurement of the sample cornea is done on eyes with IOP already applied. Furthermore, abnormal geometric structures of the human cornea, such as keratoconus, result in material characteristic changes over the corneal dimension, which by itself has been a subject of research [20]. With a full understanding of the effect of IOP on the cornea model's geometric changes, the transplant procedure could be modeled in a more accurate way [21, 30, 31]. The material characteristic of the human cornea can also be improved with further studies, and then be applied for a more accurate prediction of corneal deformation [22–29]. In conclusion, the proposed method suggests a means to predict the corneal deformation morphology in the ILEK system. The femtosecond laser technique enables a precise and stable incision of the human cornea during transplant, but the effect of applanation has not been considered during the procedure. From the simulation results, differences in the geometries of the donor and the recipient corneas lead to tension between sutured tissues and to deformation leading to distortion of the recipient's vision. A precise matching of the incision plane can be selected for the corneas, and minimization of the corneal deformation after transplant procedure can be achieved. Furthermore, our future work will focus on the acquisition of actual incision data for eye bank corneas to confirm that the simulation model can control the incision

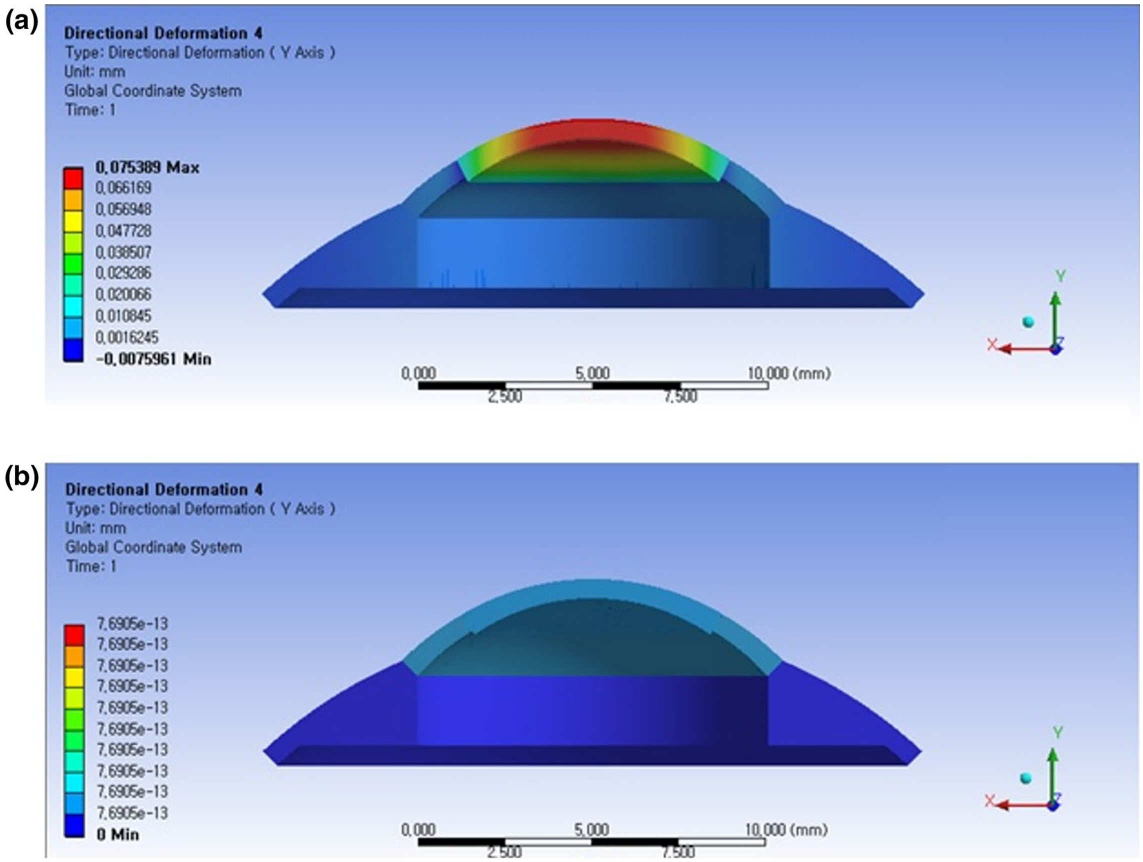

Fig. 8 Cornea transplant simulation. **a** Deformation of the donor cornea after a conventional incision of equal incision parameters. An elevation in the apex of 0.075 mm was observed. **b** On the contrary, when the incision parameters are chosen according to the deformation profiles of the donor and the recipient corneas, no deformation due to the transplant occurs

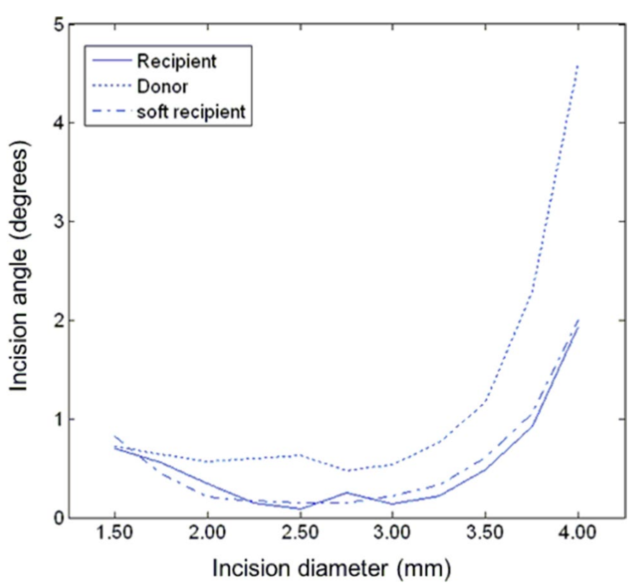

Fig. 9 Plot of the incision diameter vs. incision angle. A soft cornea material showing half of the stiffness was used to compare the effect of stiffness difference with the effect of geometric difference

parameter of the cornea according to its geometric parameters. Once our model has been confirmed from actual corneal transplant experiments, ILEK corneal transplant surgery will reach a more accurate level.

Acknowledgements This work was supported by the National Research Foundation of Korea (NRF) (NRF-2020R1A2C3010322 and NRF-2018M3A9D7079485).

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