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A Virtual Reality Simulation of Corneal Cutting Process during Cataract Surgery Operation

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ABSTRACT

A haptic simulation of the corneal incision is implemented based on a validated mathematical model of the corneal cutting process. The experimental setup measures force in three phases of pre-cutting, cutting, and relaxation. The mechanical behavior of the corneal incision is modeled mathematically from the experiments. The haptic model is characterized by the behavior of the ovine corneal tissue in sequential phases. In the pre-cutting phase, the force increases until the instrument tip penetrates into the cornea. Then, a reduction in the force indicates the onset of the cutting phase after which the force remains constant. At the relaxation phase, the force returns to zero. The numerical results of the haptic simulation show that the maximum force error predicted by the model is 0.016 N for the keratome velocity of 2 mm/s and the root mean square of the error is 0.004 N.

1. Introduction

Virtual reality simulators are used in medical surgery training to reduce the training duration and error rates. Surgical simulators have been developed for various surgeries, including endoscopic surgery [1], endovascular surgery [2], laparoscopic surgery [3], breast cancer diagnosis [4], bone surgery [5], and also cataract surgery [6].

Cataract surgery is the most common eye surgery throughout the world [7][8]. The traditional master-apprentice surgical training on a live patient and the wet-lab training on animal cadavers suffer from several drawbacks, including heterogeneity of anatomic situations [9]. Cataract surgery is an error-prone operation. In [10], 33 cataract surgery operations, which had been carried out by 33 ophthalmic surgeons with different skill levels, were studied. 330 constituent steps of the cataract surgery were analyzed and 228 errors were recorded including 151 (66.2%) executional and 77 (33.8%) procedural errors. Surgical errors, complications and traumas during an actual cataract surgery can be mimicked in a three-dimensional virtual environment to increase the awareness of surgeons and medical residents.

Virtual reality can be used to simulate the corneal cutting process. Agus et al. [6] simulated the corneal cutting process during cataract surgery operation. In that research, the corneal cutting was simulated without considering the interaction between the keratome and the corneal tissue. El-Far et al. [11] modeled the corneal surface by triangular meshes and telementored the cataract surgery operation. In their study, the cutting of the corneal tissue was simulated by deleting the meshes that are in contact with tool. Also, the surrounding areas of the cutting point on the corneal surface was highlighted to be distinguished from other areas. Perez et al. [12] simulated the corneal tissue cutting process by the paracentesis technique, which is used in modern cataract surgery operations. Choi et al. [13] simulated the cutting of the corneal surface using the subdividing algorithm. In their research, triangle meshes along the cut direction, were divided into sub-triangle meshes. Lam et al. [14] carried out a cataract surgery simulation in four main steps, and used visual guidance system and performance parameters to enhance the user's experience. In the above-mentioned research works, the performed simulations were not validated by the experimental results of the mechanical behavior of the corneal tissue during the cutting process.

There are two main commercial cataract surgery simulators, EYESi® and PhacoVision®, which are focused on capsulorhexis and phacoemulsification procedures [15][16]. EYESi® was developed to evaluate the progress of the user's wet-lab performance by a virtual reality simulator as a training method [17]. PhacoVision® was developed in order to increase the monitoring and characterizing of the trainee surgical proficiency by virtual phacoemulsification procedures [18].

This paper presents a virtual reality simulation of the corneal cutting process based on the mathematical model of corneal tissue material properties during incision, which is extracted from experiments. First, an experimental setup for simulating the first step of cataract surgery operation is constructed, which records the cutting force of the ovine corneal tissue for the first time. Then, the haptic simulation of this procedure is implemented.

The remainder of the paper is organized as follows. In the experimental setup section, we describe the corneal incision measurement setup. Then, the force-displacement relationship is formulated mathematically to describe the corneal tissue mechanical behavior. In the haptic simulation section, the virtual reality simulation of the cataract surgery operation is explained. Finally, in the results section, the corneal haptic results are compared with the experimental and mathematical simulation results.

2. Experimental setup

The test apparatus measures position, velocity, and force of the corneal tissue during the cutting process as shown in figure 1. The setup adjusts the intraocular pressure during the cutting process. The keratome cuts the soft tissue with a constant velocity while recording the cutting force exerted on the keratome.

The experimental setup includes a keratome incision instrument, a data-acquisition card, a high-speed camera, a force sensor, and a linear potentiometer, and an actuator. The incision mechanism stands on a base and moves on vertical guides. A lead screw is attached to a DC motor to move the incision mechanism. The keratome is fixed to the load cell.

Experiments were carried out to measure the incision forces applied to the surgeon's hand during the cutting process. Experiments consisted of 16 tests on ovine eyes, because of their similarity to the human eyes. Eyes were tested within 4 hours of post-mortem. Finally, the tests were carried out 4 times for each intraocular pressure.

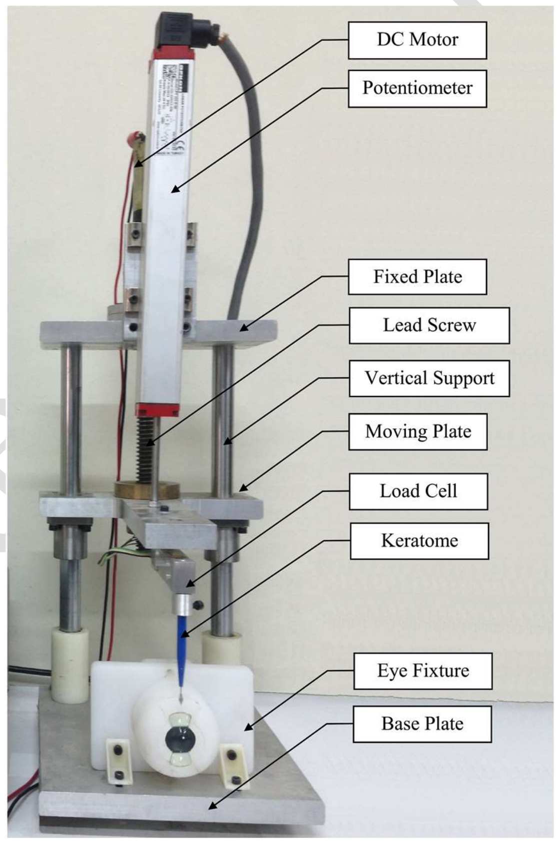

Figure 1. The test apparatus of the corneal cutting process.

Figure 2 shows the incision of keratome into the corneal surface. Figure 2(A) shows the position of the keratome before penetration and figure 2(B) shows the position after penetration. The yellow lines highlight the keratome edge before penetrating into the cornea and the red line indicates the cutting width after incision.

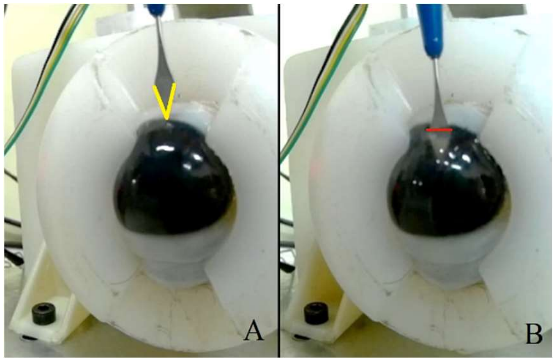

Figure 2. Keratome penetration into the cornea; A: before incision; B: after incision.

3. Force-displacement relationship

Experiments were performed for 2 mm/s of keratome velocity, at four intraocular pressures ranging between 15 mm-Hg and 18 mm-Hg. Figure 3 shows the test results when the keratome penetrated into the corneal tissue. Increasing the force values continues until it reaches to the maximum as shown in figure 3. The corneal tissue is deformed as a result of the increased force. Quickly after the peak, the force decreases because of the initial incision. Then, the edges of the keratome cuts the corneal tissue while penetrating into the cornea. Accordingly, the force fluctuates around the constant value during the cutting process. Finally, the keratome moves deeper into the corneal tissue until the force become negligible.

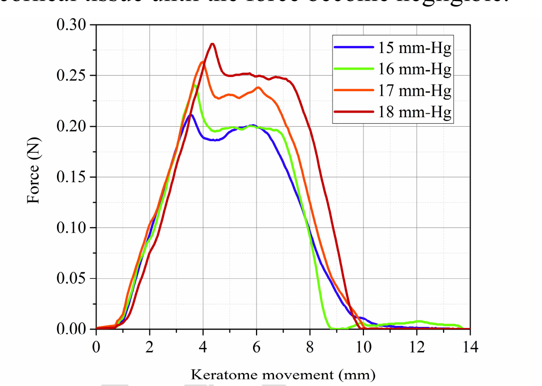

Figure 3. Experimental results for the 2 mm/s velocity and different pressure values.

Corneal tissue pre-tearing, tearing and relaxation phase are modeled mathematically from experimental results. This force-displacement relationship is useful to characterize cutting properties of corneal tissue in virtual reality simulation. Experiments on the corneal tissue can greatly help researchers understand the mechanics of deformation and cutting process during cataract surgery to develop mathematical models. The corneal tissue force-displacement relationship for 2 mm/s keratome velocity developed as Eq.1.

$$\begin{cases} ax & 0 \le x \le 0.75 \\ bx - c & 0.75 \le x \le x_{pi} \\ d \times (ln(x-e) - fx) + \mathrm{g}P & x_{pi} \le x \le 6.89 \\ hx + m + nP & 6.89 \le x \le x_{pf} \\ 0 & x_{pf} \le x \le 14 \end{cases} \quad (1)$$

The parameters of *a, b, c, d, e, f, g, h, k, m,* and *n* are equal to 0.0066, 0.078, -0.053, -0.004, 3.282, -0.495, 0.02, -0.08, 0.659, and 0.02, respectively. x_{pi} and x_{pf} depend on pressure values. All possible values for different intraocular pressures have been presented in the following table 1.

Table 1. $x_{pi}(mm)$ and $x_{pf}(mm)$ for 2 mm/s in different intraocular pressure values

Intraocular Pressure (mm-Hg)	$x_{pi}(mm)$	$x_{pf}(mm)$
15	3.55	9.35
16	3.75	9.55
17	3.96	9.83
18	4.30	10.03

The mathematical model of the corneal tissue cutting process during cataract surgery operation was developed for four intraocular pressures ranging between 15 mm-Hg and 18 mm-Hg. The keratome velocity was set to 2 mm/s as the most common velocity during corneal tissue cutting in cataract surgery operation. Based on experimental test results, a suitable formulation was fitted for four intraocular pressures. This mathematical model can be broken down into 5 parts, which describe the behavior of the cornea as a function of force and keratome movement. The first and the second parts of the formulation present the linear part of material behavior, which neatly ties in with the experimental tests and describes the deformation of the cornea prior to incision. The third part of the formulation presents the tearing behavior of the corneal tissue during the cutting process; this section is the most important part of force-displacement relationship in terms of surgery side effects. We simplified this section using the Stribeck formulation [19] because its overall trend is similar to that of the experimental results. The fourth part of the formulation, which constitutes the unloading section, presents the keratome that penetrates further into the corneal tissue. Finally, the fifth part of the formulation constitutes the relaxing part where the force values reach zero without any major variation. Figure 4 presents the mathematical modeling results for the 2 mm/s velocity of the keratome motion for 4 intraocular pressures. In this figure, a pattern similar to the experimental results is observed.

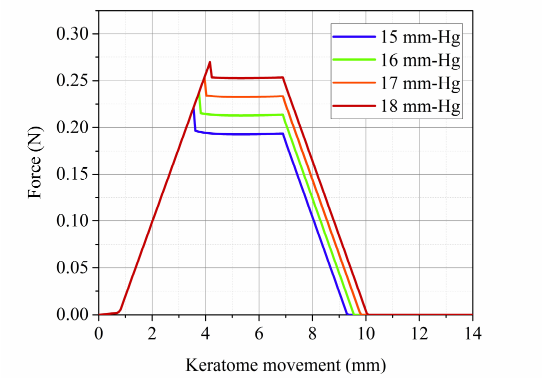

Figure 4. Mathematical results for the 2 mm/s velocity and 4 pressure values.

The goodness of fit has been calculated by Matlab for the force-displacement relationship. For the first section of formulation, the parameters of sum squared error (SSE), R-square, and root mean square error (RMSE) are equal to 9e-7 N, 0.92 N, and 2e-4 N, respectively. In the second part of the equation, the parameters of SSE, R-square, and RMSE are equal to 0.004 N, 0.97 N, and 0.009 N, consequently. The third part of the equation has the maximum deviation from experimental because of simplifying. The parameters of SSE, R-square, and RMSE in the third part of the formulation are equal to 0.002 N, 0.031 N, and 0.007 N, respectively. R-square value in this section is in minimum values, it happens because of the horizontal trend of diagram in this part. The parameters of SSE, R-square, and RMSE for the fourth part of equation are equal to 0.005 N, 0.93 N, and 0.012 N, respectively.

4. Haptic simulation

The simulation of a corneal incision during cataract surgery operation was implemented by using a personal computer with an Intel Core i5 Duo 4GHz CPU and 8GB RAM and Phantom Omni as a haptic device. This simulation was developed with C++ using OpenGL as a graphical library and OpenHaptics as a haptic library. The overall simulation of corneal cutting during cataract surgery operation is presented in figure 5.

Figure 5. Virtual environment of corneal cutting.

Moreover, a haptic simulation of the corneal cutting process includes a haptic robot which allows the trainee to interact with the virtual simulation of corneal tissue and feel the force of cutting; and a graphical device for visual display to the trainee is shown in figure 6.

The diagnosis of collision is the most important part of every medical virtual reality simulation. By changing the haptic tool position, the position of simulated keratome starts to change in a graphical environment and also, updates its features in haptic simulation. When the keratome tip reaches to the corneal tissue surface, collision detection diagnosis algorithm is used to determine contact and by continuing the movement of keratome into the cornea, a force-displacement relationship which is validated by experiments update graphical simulation and also calculate force feedback. Finally, the calculated force feedback is applied to the user's hand by the haptic device. Moreover, the graphical changes displayed on the monitor.

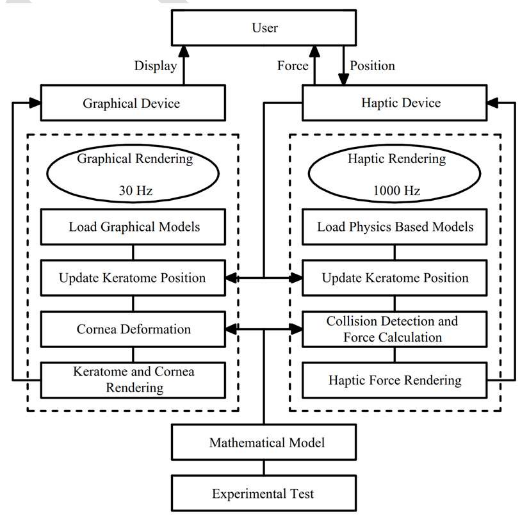

Figure 6. Overview of corneal cutting haptic simulation framework.

The frequency rate of 1000 Hz is sufficient for fidelity in the perception of users, so we use this range to render haptic simulation, and also the range of graphical simulation rendering frequency to seem continuous is between 20 to 30 Hz, so we rendered by sampling rate of 30 Hz.

The calculation of the exact position of virtual keratome, a geometric model of the eye and their movement, collision detection between virtual keratome, and corneal tissue deformation during corneal incision was developed in C++ code by using mathematical methods. Surgical trainee by using haptic device able to move virtual keratome in a graphical environment. Also by reaching the keratome tip to the corneal tissue surface, the collision detection algorithm determine the initial contact. Quickly after the contact, corneal tissue deform by moving virtual keratome into the cornea and update its position by using keratome tip position. Corneal surface deformation in a virtual environment during cutting is equal to values where presented mathematical formulation. Moreover, during virtual operation, the equivalent force of corneal cutting act on trainee as a haptic response were calculated based on corneal tissue deformation.

Corneal deformation continues until the initial penetration occurs, at this stage keratome starts to cut the virtual corneal tissue and pass through the corneal surface. Geometric model of virtual eye is developed as 3D sphere. The texture is mapped on the geometrical model of the eye. By considering local deformation of corneal during the cutting procedure the sector of sphere where exposed to deformation has been modeled separately. This sector is involved in the cutting process of corneal tissue calculation to increase the calculation speed. Corneal tissue was developed by using mass-spring model where the vertices and edges of the triangles are regarded as mass and spring respectively. As a result of corneal surface deformation and spring length variation, force propagates on the springs around the incision.

In the proposed deformation approach, corneal tissues are modeled as a mass-spring system and tissue deformation is modeled as a result of force propagation among the mass points on a per-node basis. When an external force is applied to a node, the force propagates from the point of contact, namely the incision node, to its neighboring nodes via the interconnecting springs. The process proceeds in an ordered manner from the nearest neighbors to the farthest ones, until the maximum penetration of keratome and end of cutting process. The dynamics of the nodes in the mass-spring system is governed by Newton's law of motion. The displacement of node i which is defined by x_i due to an external force F_i is derived as follow:

$$m\ddot{r}_i + c\dot{r}_i + \sum_j k_{ij}(L_{ij} - l_{ij})\,\hat{r}_{ij} = F_i \qquad (2)$$

where m is the mass constant of the nodes and c is the damping constant of the nodes. L_{ij} is spring extension between node i and j. $\hat{r}_{ij}$ is the identical vector between node i and j.

The dynamic equation is simplified to the following equation because of small amounts of mass. So the effect of acceleration has vanished in the formulation.

$$c\dot{r}_i + \sum_j k_{ij}(L_{ij} - l_{ij})\,\hat{r}_{ij} = F_i \qquad (2)$$

The schematic model of mass-spring is presented in figure 7 and figure 8. The model consists of different types of springs in figure 7. The blue springs represents stretching ones, and the brown springs show shearing ones. Moreover, the red springs in figure 8 demonstrate bending ones. This pattern of mass-spring is developed for all the masses.

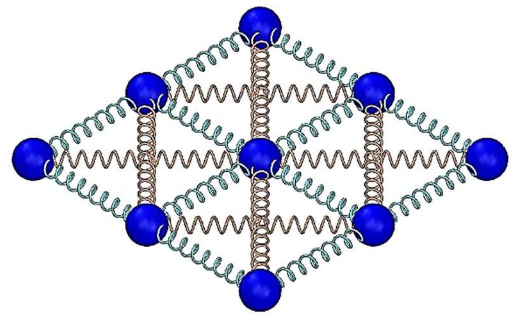

Figure 7. Schematic model of mass-spring system, consist of stretching and shearing springs

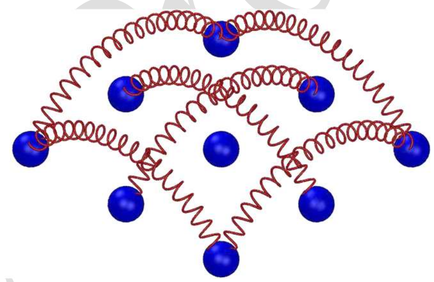

Figure 8. Schematic model of mass-spring system consist of bending springs

The graphical environment of the corneal incision simulation during cataract surgery operation was presented in figure 9. The area of keratome insertion modeled by using 169 vertexes and 886 springs. Figure 9(a) presented the initial contact of corneal tissue and keratome, in figure 9(b) the deformation of the corneal tissue is the maximum values before initial penetration. After the tip penetration, the keratome pass through the corneal tissue figure 9(c). Keratome completely penetrate into the corneal tissue when the corneal tissue cut open by the maximum width of surgical instrument figure 9(d). Also, the cutting process of corneal tissue simulation presented in figure 10 from the close-up view.

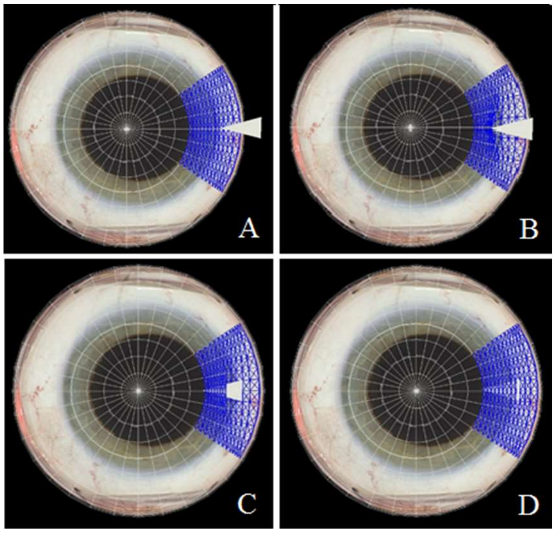

Figure 9. Virtual reality simulation of Keratome penetration into the cornea. A: Initial contact. B: deformation. C: cutting process, D: complete pass of Keratome.

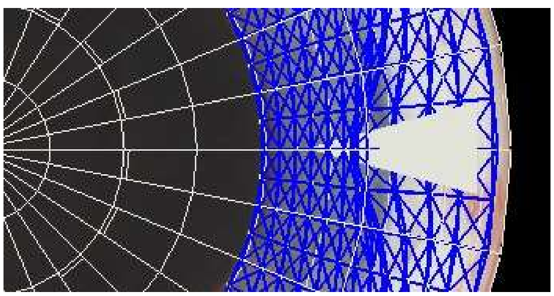

Figure 10. Virtual reality simulation of Keratome penetration into the cornea. A: Initial contact.

5. Results

The haptic simulation of the cataract surgery operation was developed for the corneal tissue cutting process for intraocular pressures between 15 mm-Hg and 18 mm-Hg with the keratome velocity of 2 mm/s. Figure 11 presents the haptic simulation results for different intraocular pressures and the 2 mm/s velocity of the keratome movement.

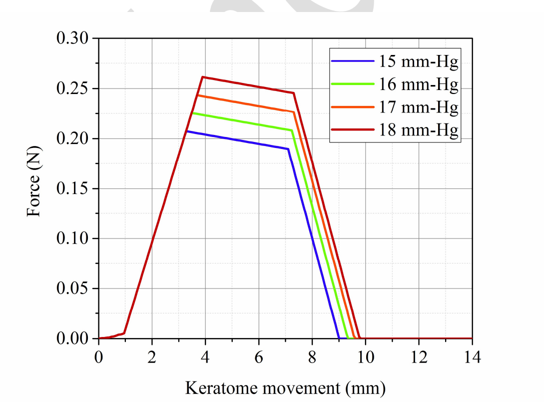

Figure 11. Haptic results for the 2 mm/s velocity and different pressure values.

The results of the experiments and the haptic simulation are compared for the keratome velocity of 2 mm/s and intraocular pressures of 15 mm-Hg as shown in figures 12. This pressure value is chosen because it is the best common pressure used during cataract surgery operation by most surgeons. The overall pattern of the experimental results and the haptic simulation are similar.

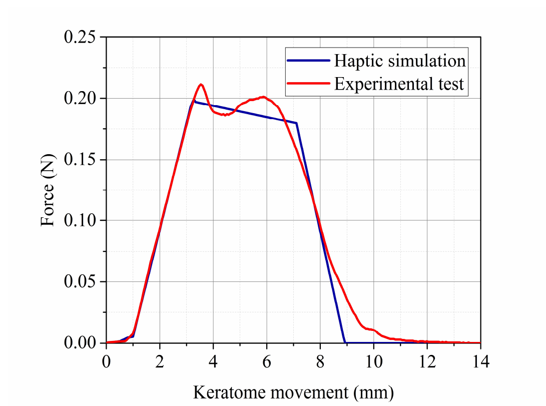

Figure 12. Experimental and haptic simulation results for the 15-mm-Hg pressure and the 2-mm/s velocity.

Figures 13 show the deviations of the haptic simulation from the experimental results. In this figure, the error root mean square and the maximum error are 0.005 N and 0.039 N, respectively.

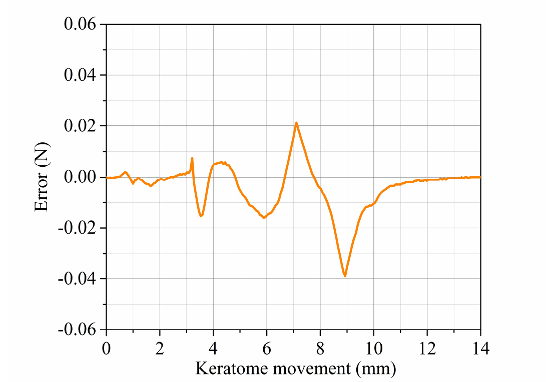

Figure 13. Haptic simulation deviation from the experimental results for the 15-mm-Hg pressure and the 2-mm/s velocity.

Also, the results of the mathematical formulation and the haptic simulation are compared for the keratome velocity of 2 mm/s and intraocular pressures of 15 mm-Hg as shown in figures 14. Figure 15 shows the errors of the haptic simulation from the mathematical results. In figure 15, the root mean square and the maximum of the error are 0.004 N and 0.016 N, respectively.

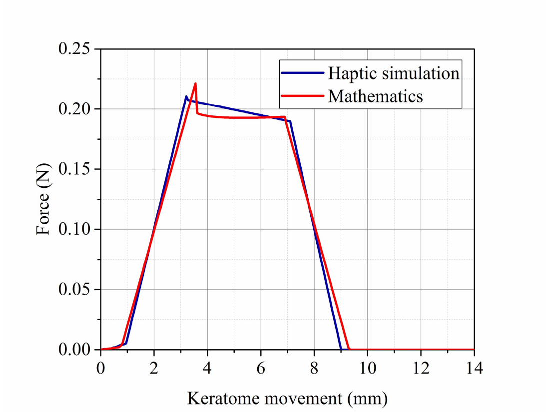

Figure 14. Haptic simulation and mathematical model for the 15-mm-Hg pressure and the 2-mm/s velocity.

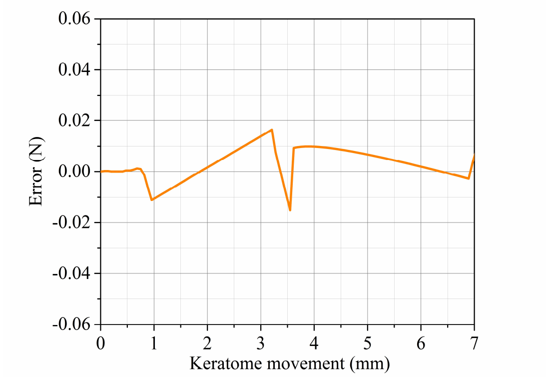

Figure 15. Haptic simulation difference from the mathematical model for the 15-mm-Hg pressure and the 2-mm/s velocity.

6. Conclusions

In this paper, a virtual reality simulation was presented for the corneal cutting process during cataract surgery operation. An important step in the cataract surgery operation is the corneal cutting process because of post-operation complications. The corneal tissue was modeled as a 3D surface using triangular meshes. This virtual simulation is based on the mathematical model of the corneal tissue behavior during the cutting process validated by experiments with the keratome velocity of 2 mm/s. This mathematical formulation derived from the corneal tissue behavior experiments can improve surgical training by increasing the fidelity of haptic simulators.

The experiments and the mathematical formulations were derived for the keratome velocity of 2 mm/s and four intraocular pressures ranging from 15 mm-Hg to 18 mm-Hg, and were subsequently used in the virtual reality simulations. New experiments would be needed for other keratome velocities and intraocular pressures to tune the parameters of the formulation.

In future, this system can be further improved to score the trainee and warn her/his mistakes in real-time. This system can be also used in real augmented reality surgery. For example, the onset of the rupture of the cornea can be magnified and displayed to the surgeon.

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Biography

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