Finite Element Analysis of Cornea and Lid Wiper During Blink, With and Without Contact Lens

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Abstract

Contact Lens-related Discomfort (CLD) is one of the major problems in about 50% of contact lens users. It is a symptom of a variety of conditions such as Lid Wiper Epitheliopathy (LWE), Superior Epithelial Arcuate Lesion (SEAL), Limbal Stem Cell Deficiency (LSCD), Superior Limbic Keratoconjunctivitis (SLK) and dry eye disease; which affect the quality of life. Hence, it is essential to investigate the underlying cause of CLD. During a blink, the under surface of the eyelid tends to interact with the cornea and the conjunctiva. The presence of a contact lens can add to the biomechanical changes on these surfaces. To estimate these changes with and without a contact lens, a Finite Element Model (FEM) of the eyelid wiper, eyeball and contact lens was developed using COMSOL Multiphysics®. Biomechanical properties such as von Mises stress and displacement were calculated. Our study concluded that large stress formed in the lid wiper could be the reason for the occurrence of LWE and SLK without contact lens in the eye. When the contact lens was in situ, large stress was found in the superior 1.3mm of the cornea which could be responsible for the development of SEAL and superior LSCD.

Introduction

It is estimated that currently there are more than 140 million contact lens (CL) wearers worldwide¹. Previous literatures have stated that about 21%–64% of CL wearers discontinue CL use, while others are able to continue wearing their CLs well into their presbyopic years^{2,3,4}. Contact Lens-related Discomfort (CLD)⁵ is one of the major reasons for dropout rates in about 50% of CL users followed by dry eye (19.9%)⁶, ocular redness (6.8%)⁶, cost of CL (6.8%)⁶ and handling issues (6.3%)⁶. Other factors include age, gender, presence of systemic disease, CL solution and care regimen, design, material, the modality of the contact lens^{1,7}

During a blink, the under surface of the eyelid interacts with the cornea and the conjunctiva⁸. This transforms the human eye into a complex tribological system consisting of two sliding surfaces (eyelid and corneo-conjunctival complex) moving relative to each other; with the tear film as a lubricant⁹. With the CL in situ, there results in two sets of sliding surfaces. In the anterior aspect, it is formed by the under surface of the eyelid and anterior surface of the contact lens; while in the posterior aspect, it is formed by the posterior surface of contact lens, anterior surface of the cornea and bulbar conjunctiva¹⁰. This tribological system is influenced by varying tear film characteristics that may result from the, presence of dry eye disease in the wearer.

A substantial amount of research has been carried out in CL users with dry eye and it has been found that the prevalence rate is 37-73%, globally^{11,12}. Deficiency of tear fluid or excessive evaporation of tears may lead to dry eye disease¹³ which in turn may harm the ocular surface due to friction¹⁴. Cornea and the lid wiper are more prone to frictional damage than tarsal and bulbar conjunctiva^{15,13}. Frictional damage to the ocular surface causes Blink Associated Disorder (BAD) such as Lid Wiper Epitheliopathy (LWE), Superior Limbic Keratoconjunctivitis (SLK)¹⁷, Superior Epithelial Arcuate Lesion (SEAL)¹⁸ and Limbal

Stem Cell Deficiency (LSCD)¹⁹. These conditions cause a variety of symptoms such as foreign-body sensation during blink, discomfort and visual loss; thereby decreasing the quality of life¹⁷.

Friction is usually quantified using Coefficient of Friction (CoF) which is the ratio between the frictional force and the normal force. The most commonly used in vitro methods to measure CoF is through the use of an instrument called Microtribometer^{20,21} and Atomic force microscopy^{22,23}. In case of CL, CoF can vary depending on its material properties, thickness and modulus. But in general, a CL having low CoF reduces friction and improves comfort^{21,24–26}. The CoF values ranges from 0.011 to 0.562 across various studies^{20,21,27}. This wide variation noted, is due to the difference in the material used to measure the CoF. For example, instead of cornea and eyelid, studies have used Borosilicate glass slab²¹ and Mucin coated glass slab²⁰ where only the curvature was considered whereas the exact material properties such as modulus, Poisson's ratio and density of the ocular structures were not considered. In other case an in-vivo experiment done on animal models using microtribometer has led to epithelial damage because of the rubbing of the cantilever against the cornea while estimating CoF²⁸.

In order to overcome this variability, Finite Element Analysis (FEA) is used as a tool to analyse the biomechanical changes¹⁷. FEA is the simulation of any given physical phenomenon using the numerical technique called Finite Element Method (FEM). Using FEA a study has estimated, the deformation and shearing stress between the eyelid and the corneo-conjunctival complex considering it as a flat surface¹⁷.

In-vitro studies are not reliable because of the difference noted in methodology across various studies and in-vivo studies were not safe enough to perform on the eyes as it may cause epithelial defect²⁸. When compared to in-vitro studies done using microtribometer, atomic force microscope, etc., FEA helps to understand the biomechanical changes (deformation, displacement and stress) which take place during blinking. But there are no studies that estimate the biomechanical parameters during blinking by considering the actual anatomy and material properties of the eye.

Therefore, this study aims to develop a Finite Element Model (FEM) of the lid wiper, eyeball and contact lens to estimate the biomechanical changes during blink in the cornea and lid wiper, with and without contact lens.

Results

The three-dimensional model of the eyeball (**Figure 1**) was created using the COMSOL tool.

The biomechanical changes due to the blink were simulated using the FEM and the results were obtained as von Mises stress and displacement. Initially, the blink was simulated by displacing the lid wiper for every 10⁰ (1.3mm) using the parametric sweep.

I. Without contact lens:

Figure 2 shows the von Mises stress (kPa) of the lid wiper and cornea at different position of lid wiper during blink without contact lens. Lid wiper undergoes large stress (32kPa) when it interacts with the superior 1.3mm of the cornea (**Figure 3**). The large stress is seen in the central 1.3mm of the cornea (23 kPa) than the rest of the peripheral cornea during blink (**Figure 4**). The maximum stress is noted in the lid wiper (32kPa) than the cornea (23kPa) during the interaction between them (**Figure 2**).

The displacement of the lid wiper is maximum when the lid wiper interacts with the central cornea. Displacement caused by the lid wiper on the cornea during blink is shown in **Figure 5**. It can be seen clearly that the central 1.3mm of the cornea (120µm) has displaced more than the peripheral 2.6mm of the cornea during blink (**Figure 6**).

II. With contact lens:

Figure 2 shows the von Mises stress (kPa) of the lid wiper and cornea at different position of lid wiper during blink with contact lens. Lid wiper undergoes large stress (10kPa) when it interacts with the superior 1.3mm of the cornea (**Figure 3**). The large stress is seen in the superior 1.3mm of the cornea (15kPa) than the central 1.3mm of the cornea (11kPa) during blink (**Figure 4**). Maximum stress is noted in the cornea (15kPa) than the lid wiper (10kPa) during the interaction between them when contact lens is in situ (**Figure 2**).

The displacement of the lid wiper is maximum when the lid wiper interacts with the central 1.3mm of the cornea. Displacement caused by the lid wiper on the cornea during blink is shown in **Figure 5**. It can be seen clearly that the central cornea (30µm) has displaced more than the peripheral cornea during blink (**Figure 6**).

Discussion

The three-dimensional model of the eyeball was created. The construction of the three-dimensional model of the eyeball used the retrospective data from FEA studies^{29–33}.

I. Von Mises stress and displacement – without contact lens:

The current study, aimed at quantifying the biomechanical changes such as stress and displacement in the eye during blink. In this study the von Mises stress was found to be higher in the lid wiper than in the cornea. This large stress on the lid wiper could be the reason for lid wiper epitheliopathy seen in many patients with ocular dryness and discomfort^{9,17,34,35}. This also suggests that the lid wiper would be the first structure to get affected in any ocular surface diseases even before a change is noticed in the cornea^{34,35}. Hence the stress developed during the rubbing could be the reason behind the formation of LWE especially in patients with dry eye disease^{9,36}.

Von Mises stress was found to be larger in the central 1.3mm of the cornea, than the peripheral cornea. Which makes it susceptible to injury¹⁷. This is in accordance with the study done by Ousler et al., where

they've reported that the ocular surface discomfort was more severe in patients with central corneal damage³⁷.

Displacement is more in the central 1.3mm of the cornea than the peripheral cornea. This suggests that the force produced by the eyelid because of its body load displaces the cornea by 120μ posteriorly. This finding is in good accordance with the study by Masterton et al., in which they've found out that during blink, the lid wiper pushes the cornea back thereby causing thinning of the tear film, under this compressed area³⁸. During blink, the rubbing may cause shear forces on the cornea. This combination of shear forces and displacement caused by the eyelid on the cornea can harm the health of the cornea³⁸.

One of the most accepted theories proposed by Wright et al., is that the primary factor which causes the development of SLK is constant friction caused by the lid wiper on the conjunctiva and cornea due to excessive laxity of the lid wiper³⁹. This is also proved by one more study where they have found out that in cases of SLK there was an upregulation of transforming growth factor-beta 2 (TGF-β2) and the tenascin 13. These are the factors that are induced by mechanical trauma, thereby proving that mechanical trauma is one of the crucial factors in the development of SLK⁴⁰. This can be attributed to the mechanism of the formation of SLK, where the large friction was caused by the lid wiper on the superior 1.3mm of the cornea during blink⁴¹.

II. Von Mises stress and displacement – with contact lens:

Studies^{9,38} have proven that the introduction of contact lenses in the eye many disrupt the tear film thereby dividing the tear film into pre and post lens tear film⁴². In some cases, the long-term use of the contact lens can result in the meibomian gland blockage and reduced tear film thickness thereby causing more friction^{43,44}. This may also lead to damage of ocular surface, lid wiper in some patients^{9,45}. The current study has found that the von Mises stress is larger in the superior 1.3mm of the cornea than the central cornea when the contact lens is placed. This can be attributed to the formation of contact lens-induced SEAL and LSCD, where the friction is caused by the lid wiper on the superior cornea during blink. In some cases, the inadequate lens flexure creates an area of misalignment in the superior epithelial cornea where pressure from the lid forces the lens against the cornea⁴⁶⁻⁴⁹. This produces greater frictional forces on the cornea in the superior region^{18,50}. This is how SEAL occurs in the cornea due to the friction caused by the contact lens wear¹⁸. Mechanical trauma caused by the rubbing of the contact lens plays a central role in the etiology of LSCD^{19,51}. This rubbing is induced by the movement of the soft contact lens during blink⁵².

In this study, it is found that the effect of the lid wiper during blink displaced the cornea posteriorly by 30μm. During blink, the lid wiper pushes the contact lens against the ocular surface, moving the tears away, causing the dryness in the surface, thereby creating friction¹⁸. Hence during blink, the contact lens slides over the high-pressure areas i.e. the superior cornea, superior limbus. This can induce chronic trauma to the ocular surfaces^{19,53-57}. As noted in this study, during blink, the lid wiper pressure is less

when it reaches the inferior cornea, which is why the contact lens less often induces mechanical trauma at the inferior cornea/limbus¹⁹. Hence the occurrence of LSCD is also uncommon in the inferior areas.

This study explores the mechanism behind the occurrence of few ocular conditions such as SLK, LWE, SEAL and LSCD in lens wearers and non-lens wearers using FEA. Due to the complexity in the modeling of the tear film and its dynamics, it has not been incorporated in our study. Involving the effect of the tear film could give us a concrete conclusion about the effect of the blink on our ocular surface. A deep scan OCT or 3D optical profilometer can give exact dimensions of the eyeball which can be helpful in constructing a proper eye model that closely resembles the human eye. Overall, FEA is a useful simulation tool that helps us to understand the effect of blink on a normal and diseased eye. This can be extended to other wider areas of research including simulation of surgery, trauma, etc.

Methods

FEA is a popular method to analyze complex systems. The benefits of using an FEA on complex problems are that geometry can be precisely defined⁵⁸. It is very sensitive to measure even a subtle change in geometry, which is otherwise difficult to pick up with the current instruments⁵⁹. Since FEA uses the static equilibrium and theories of elasticity, it is possible to assess a physical system subjected to multiple external forces with regard to stresses, deformation and strain⁶⁰. Hence FEA was chosen as the analytical tool.

A computer with 2.80GHz CPU and 8GB RAM was used for this experimental study. COMSOL Multiphysics® (v5.2, COMSOL AB, Stockholm, Sweden), an FEA tool was used for the construction and analysis of the human eye model. The COMSOL Multiphysics® was used for the FEA because of its ability to provide accurate FE simulation results. The flow of procedure for the FEA includes,

- Modeling of the geometry
- Assigning the material properties
- Meshing
- Setting boundary conditions
- Parametric sweep analysis
- Post-processing of the results

Ocular parameters of various structures and their material properties were obtained from previous works of literature done on Indian eyes. Linear static analysis was carried out ignoring gravity.

I. Modeling

It is unrealistic to consider a single eye geometry since the dimensions of the human eye vary from person to person. Here we have used the average value of each of the ocular parameters of the Indian eyes obtained through a thorough literature search.

The human eye model, which closely resembles the dimensions of the actual human eye, was constructed in 2D (**Figure 7A**) and was converted into a solid 3D model (**Figure 7B**). For simplicity, the human eye was assumed to be rotationally symmetrical along the optic axis. The eye model comprises of the following structures: Lid wiper, cornea, anterior chamber, vitreous cavity, sclera, optic nerve and optic nerve head. The anteroposterior (transverse) diameter of the eye model is approximately 24 mm, and the vertical (sagittal) diameter is approximately 23 mm⁶¹.

The asymmetrical nature of the optic nerve was ignored. The dimensions used in the construction of each structure of the human eye are as shown in **Table 1**.

Table 1: Dimensions of ocular structures and contact lens used in the finite element modeling

Part of the eye	Value (mm)
Lid wiper thickness	0.8
Corneal thickness	0.5
Corneal diameter	12
Anterior corneal curvature	7.8
Posterior corneal curvature	6.5
Scleral thickness	0.5
Scleral radius	11.5
Diameter of the contact lens	15
Base curve of the contact lens	8.6
Thickness of the contact lens	0.08

Since eyelid, conforms to the curvature of the ocular surface while blinking, we have assumed the curvature of the inner lid wiper to be the curvature of the anterior cornea. The thickness of the lid wiper was considered to be as 0.8mm with reference to the literatures⁶². The contact width between the lid wiper and cornea was 1mm⁶³. The entire simulated model consisting of the eyeball and the lid wiper can be seen in **Figure 7C**.

Different soft CL geometries have been explored, in the previous research^{64–66}. Complete specifics of the exact contact lens geometries were not available in the literature. The center thickness, base curve and the diameter of the CL were made to be available in the literatures⁶⁷. In general, a CL is thicker at the center than in the periphery and this ranges from 0.05-0.9mm. The radius of curvature of the back

surface of the lens i.e. the base curve generally ranges from 7-9 mm and also the diameter of the CL ranges from 13.00 to 14.50mm.

In this study, based on the eye geometry the contact lens of 15 mm diameter (2-3mm greater than Corneal diameter) and 8.6mm base curve (0.8-1.0mm flatter than Corneal curvature) was fitted in the eye (**Figure 7D**). Contact lens parameters used in this study can be found as mentioned in **Table 1**.

Young's modulus, Poisson's ratio and Density were the important material properties considered. Human ocular tissues are generally viscoelastic and exhibit nonlinear material properties²⁹. This nonlinear material property of the human eye ranges widely due to its complex nature. Hence, the material properties were assumed to be homogenous, isotropic and linearly elastic. As shown in **Table 2** the material properties of the ocular structures were obtained from the previous works of literature. Young's modulus of the human eyelid has not yet been investigated⁴⁵. Hence a value of 0.42MPa which is the young's modulus of the human skin was assumed^{45,68}. The Poisson's ratio of the aqueous humor, vitreous humor, retina, zonules, and optic nerve have not yet been investigated. Since soft biological tissues hold more amount of moisture, Poisson's ratio was set to be less than 0.5 for these ocular structures^{29,69}.

Table 2: Material properties of the ocular structures and contact lens used in the finite element modeling

Part of the eye	Young's modulus (MPa)	Poisson's ratio	Density (Kg/m ³)
Lid wiper ^{68, 70}	0.42	0.49	999
Cornea ^{60, 71,72}	0.4	0.42	1400
Aqueous humor ^{60,73}	0.037	0.49	999
Vitreous humor ^{60,73}	0.042	0.49	999
Retina ^{68,74,69,75}	0.03	0.49	999
Optic nerve ^{69,75,76}	0.03	0.49	999
Comfilcon A contact lens ^{59,77}	0.82	0.49	1040

The material properties used for the contact lens are as shown in **Table 2**. Contact lens is a rubbery polymer and it is highly hydrated. Hence a Poisson's ratio of 0.49 was set which makes it incompressible. Density of the contact lenses was not directly available in the literature. But specific gravity was available

for the contact lenses. Hence using the following formula, we have calculated the density of these contact lenses.

$$\text{Specific gravity} = \frac{\text{Density of the contact lens}}{\text{Density of the water at } 4^{\circ}\text{C}}$$

Where,

Density of the water at 4°C = 999.97⁷⁸

Specific gravity of the contact lens = 1.04⁷⁹

II. Analysis

Mesh convergence study was carried out to analyze the proper number of finite elements. **Figure 8** shows the result when a body load of 0.03N is applied on the surface of the lid wiper. It can be found that the von mises stress, barely change when the length of a side of the finite element is 0.259 mm or more. Hence, the value of 0.259 mm was used as the length of a side of the element during Finite Element Analysis.

All components of the FEM were meshed with the physics-controlled settings in the COMSOL Multiphysics®. The predefined size of each element was set as fine. **Figure 9** shows the mesh-divided model of the eyeball with lid wiper **(A)** and the contact lens **(B)**.

The outer surface of the sclera was fixed completely. During blink the lid wiper is in contact with the cornea. Hence a contact pair was created between these 2 surfaces. The dynamic friction coefficient of the contact surface between the cornea and the lid wiper was set to 0.1 with reference to the previous literatures⁸⁰. The eyelid itself exerts some amount of force over the cornea during blink⁹. Hence a body load of 0.03N was applied at the surface of the lid wiper⁴⁵.

Blink was simulated by making the lid wiper move over the cornea (**Figure 7C**). Parametric sweep analysis was carried out by displacing the lid wiper for every 10^0 i.e. from the superior to the inferior portion of the cornea. Linear static analysis dealing with the contact problem was carried out. The whole analysis along with the parametric sweep required approximately 12hrs to complete. Von Mises stress, deformation and displacement were obtained as the result of FEA. Stress is defined as “the ratio of internal force produced to the area over which the force acts”. In humans, it represents the feeling of pain. Displacement is the distance from which one object has moved from its original location when an external force is applied. These indicate the amount of biomechanical response in human tissues⁸¹. Surface plots were used to display the results of the analysis.

Declarations

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Figures

Figure 1

Three-dimensional model of the eyeball depicting the different ocular structures

Figure 1

Three-dimensional model of the eyeball depicting the different ocular structures

Figure 2

Von Mises stress (kPa) in the lid wiper and cornea during blink without and with CL (value of the data labels shows von Mises stress; unit: kPa)

Figure 2

Von Mises stress (kPa) in the lid wiper and cornea during blink without and with CL (value of the data labels shows von Mises stress; unit: kPa)

Figure 3

Von Mises stress in the lid wiper during blink without CL (A) and with CL (B) (value of the legend shows von Mises stress; unit: kPa)

Figure 3

Von Mises stress in the lid wiper during blink without CL (A) and with CL (B) (value of the legend shows von Mises stress; unit: kPa)

Figure 4

Von Mises stress in the cornea during blink without CL (A) and with CL (B) (value of the legend shows von Mises stress; unit: kPa)

Figure 4

Von Mises stress in the cornea during blink without CL (A) and with CL (B) (value of the legend shows von Mises stress; unit: kPa)

Figure 5

Displacement in the cornea during blink without CL (A) and with CL (B) (value of the legend shows displacement; unit: μm)

Figure 5

Displacement in the cornea during blink without CL (A) and with CL (B) (value of the legend shows displacement; unit: μm)

Figure 6

Displacement (μm) in the cornea during blink without and with CL (value of the data labels shows displacement; unit: μm)

Figure 6

Displacement (μm) in the cornea during blink without and with CL (value of the data labels shows displacement; unit: μm)

Figure 7

Two-dimensional (A), three-dimensional (B) model of the eyeball, three-dimensional model of the eyeball with lid wiper (C) and cross-section of the eyeball with soft contact lens (D)

A

B

C

D

Figure 7

Two-dimensional (A), three-dimensional (B) model of the eyeball, three-dimensional model of the eyeball with lid wiper (C) and cross-section of the eyeball with soft contact lens (D)

Figure 8

Mesh convergence study – proper No. of finite elements

Figure 8

Mesh convergence study – proper No. of finite elements

Figure 9

Meshing of the eye (A) and contact lens (B)

Figure 9

Meshing of the eye (A) and contact lens (B)