Spontaneous Blinking from a Tribological Viewpoint

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ABSTRACT The mechanical forces between the lid wiper and the ocular surface, and between a contact lens and the lid wiper, are reported to be related to dry eye symptoms. Furthermore, the mechanical forces between these sliding partners are assumed to be related to the ocular signs of lid-wiper epitheliopathy (LWE) and lid-parallel conjunctival folds (LIPCOF). Recent literature provides some evidence that a contact lens with a low coefficient of friction (CoF) improves wearing comfort by reducing the mechanical forces between the contact lens surface and the lid wiper. This review discusses the mechanical forces during spontaneous blinks from a tribological perspective, at both low and high sliding velocities, in a healthy subject. It concludes that the coefficient of friction of the ocular surfaces appears to be strongly comparable to that of hydrophilic polymer brushes at low sliding velocity, and that, with increased sliding velocity, there is no wear at the sliding partners' surfaces thanks to the presence of a fluid film between the two sliding partners. In contrast, in the case of dry eye, the failure to maintain a full fluid film lubrication regime at high blinking speeds may lead to increased shear rates, resulting in deformation and wear of the sliding pairs. These shear rates are most likely related to tear film viscosity.

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I. INTRODUCTION

When two surfaces are in contact and move relative to each other, friction is observed. This phenomenon is studied by tribologists and has a critical impact on everyone's daily life. Without friction, it would not be possible to drive a car on the road or ignite a lighter. On the other hand, a friction value that is too high will not allow a snowboarder to slide downhill, or it will make it impossible to slide a heavy cardboard box from one corner of a room to another. In addition to the two sliding surfaces, one other component often participates in the tribological system: lubricant. For example, synthetic oil is used to lubricate the pistons inside an engine, and shaving foam and water facilitate a razor sliding over the skin, reducing wear and friction, and minimizing skin irritation, respectively. (*Wear* is a term used to describe the removal and deformation of material on a surface, as a result of mechanical action by the opposite surface.)

In the eye, during a spontaneous complete blink, the upper and lower eyelids move with respect to the ocular globe and the corneal surface, while being lubricated by the tear film. The speed of eyelid movement during a blink varies between patients, with an average speed reported to be between 17 and 28 $cm.s^{-1}$, and a maximum blink speed of around 40 $cm.s^{-1}$.[1,2] A spontaneous blink does not result in a significant demonstration of Bell's movement, but the downward movement of the upper lid will still cause the eyeball to move backward (posteriorly) by around 0.9 mm.[2,3] At the same time, and based on a hydrodynamic model of the human eyelid wiper model, the upper lid slightly lifts off the cornea by 1.1 µm (*h*, Figures 1 and 2) in the closing phase.[4,5] This ensures that the force the eyelid applies to the ocular surface during the closing phase of the blink is significantly higher than that during the opening phase of the blink[4] and allows the tears to flow from under the upper eyelid during the blink, assisting in tear drainage. The lower lid, as well as moving vertically upward, moves both inward (nasal direction, 4.5±0.9 mm)[6] and tilts slightly inward.[2,7] At the same time as the upper lid moves

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downward, it also constricts horizontally (3.1±1.0 mm).[6] In contrast to the lower lid, the upper lid does not tilt inward, but follows the corneal shape, with the lid margin remaining perpendicular to the tangent of the cornea.[7] This was observed from a side view from the fully opened lid position to just before lids closed.[7] As a result of these movements, the upper lid, when closed, slightly overlaps the lower eyelid, producing an "over-blink."[6,7]

The action of blinking is important for the eye and for good visual performance, since the action of blinking serves to produce a smooth optical surface by re-forming the tear film, which undergoes a destabilization process during the interblink interval. It also acts to remove unwanted debris or foreign bodies that become trapped in the tear film, helping them to be removed through tear drainage.[8,9] However, even though blinking is vital for maintaining optical performance, ocular surface health, and tear film drainage, in the presence of an insufficient tear film, the mechanical forces involved in blinking can damage the lid wiper and/or the ocular surface.[10-12] (The lid wiper is that portion of the central, posterior eyelid in apposition to the ocular surface).

Contact lenses are optical devices made from biocompatible polymers that rest on the corneal and ocular surface, and which are lubricated by the tear film. The lenses have limited movement on the surface, which is important for optical stability, but interact with the movement of the eyelids during blinking. It is important, therefore, that among the physical and chemical properties that contact lenses should possess, there should be a low coefficient of friction between the upper lid and the contact lens surface. This may have a particular influence on contact lens wearing comfort.[13-15] Consequently, new soft contact lens materials have been developed to reduce friction between the contact lens surface and the lid-wiper. Such "comfort-enhancing" contact lenses show a reduced coefficient of friction when measured under eye-simulating conditions in vitro.[16]

We hypothesize that, with increased sliding velocity, there is no wear at the sliding partners' surfaces, thanks to the presence of a fluid film between the two sliding partners. Due to the ocular surfaces being strongly comparable to those of hydrophilic polymer brushes, no wear between sliding partners in low sliding velocity can be assumed. This may be different in dry eye, due to insufficient brush-to-brush lubrication and altered tear film viscosity. Dry eye symptoms at high sliding velocity, both in the presence or absence of contact lenses, may be more likely related to the tear film than the surfaces. In contrast, in the case of low sliding velocity, dry eye symptoms in both groups may be more likely related to the surfaces of the sliding partners.

In this paper, we discuss friction between the upper eyelid and the cornea or contact lens surfaces during spontaneous, complete blinks, according to the most widespread tribological theories.

II. TRIBOLOGICAL MODELS

In classical tribology, the relationship between coefficient of friction, load, relative speed, and lubricious fluid properties — in particular viscosity — has been described in the well-known Stribeck curve[17] (Figure 3). In this model, three different regimes have been identified: boundary lubrication, dominated by the close contact of the solid surfaces; the mixed regime, where occasional contact between the solid surfaces occurs; and the hydrodynamic regime, where a full lubricant film is present between the two surfaces moving relative to each other. In boundary friction, the material surface quality mainly influences friction, where as in hydrodynamic friction, where both surfaces are fully separated, friction depends on the viscosity of the fluids between the surfaces. Using this model and applying it to the non-contact lens blink cycle, the hydrodynamic regime is reported to be dominant, and, as such, the cycle has low friction.[18]

Furthermore, one can observe that at the beginning, end, and return points of the blinking cycle, boundary lubrication may be expected to be predominant, due to the low lid velocities and the constant load that should squeeze the tear film apart. So, according to the theory behind the Stribeck curve, under this condition an increase in the coefficient of friction is to be expected. However, this is not the case for the eye, or for other biological systems that are known to be highly lubricious under a wide variety of conditions.[19,20] Also, according to the Stribeck curve, the coefficient of friction is expected to significantly decrease when transitioning from boundary friction to hydrodynamic friction. Such behavior, to the best of the authors' knowledge, has been widely described for various hard-hard tribopairs, but not for contact lenses or for the ocular surface.[17]

Indeed, when comparing different lubricious systems found in nature, e.g., the propulsion of snails, food transport through the digestive system, the articulation movement or, as in this case, eyelid blinking, a common component can be identified, i.e., the presence of so-called surface brushes that consist of hydrophilic, surface-tethered, sugar-containing biomolecules.[20,21]

Molecules that are placed in a "good solvent" tend to disperse in order to maximize their entropy. However, upon being tethered to a surface, the molecules are