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Ultra-low friction in Soft Contact Lenses: Analysis of Dynamic Free Responses Measured by the Dynamic Oscillating Tribometer

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ABSTRACT

Friction coefficient is considered as a measurement for clinical comfort of soft contact lenses. One of the main challenges in the tribology field is to evaluate the friction in soft materials such as soft contact lenses. In this work, we aim to evaluate the friction at the eyelid-lens contact using a new technique. This technique is based on a single-degree-of-freedom (SDOF) mass-spring system having a sliding contact. The experimental technique measures the free responses of the mechanical system. The friction is then evaluated from the damped free responses with a high accuracy. A variety of soft contact lenses are tested with some lubricants under many physiological conditions. The results are discussed and compared with those in the literature.

Keywords: Soft Contact Lenses (SCL), friction, free response, dynamic oscillating tribometer, damping

1. Introduction

The use of soft contact lenses is widely prevalent [1]. Comfort is the most significant factor for soft contact lenses (SCL) wearers. Feinbloom [2] recognized its significance in 1938. Then, in 1995, Nairn and Jiang [3] found that the frictional force affects the comfort factor of the SCL during eye blinking with a contact lens. Thus the friction coefficient is considered to be a measurement for clinical comfort of soft contact lenses. Indeed, one of the common challenges in the field of tribology is evaluating the friction of soft materials including soft contact lenses.

Several clinical tests have been carried out in order to analyze and enhance the comfort of contact lenses [4, 5]. The comfort of SCL is affected by many factors, including those related to the patients and to contact lens material [6]. Previous studies have investigated the influence of lubricants on CL wearers [7]. Moreover, the dryness factor has been investigated by studying the wettability [8] as well as the water content of contact lenses [7]. Moreover, the type of the contact lens material is important for the wearers comfort. Recently, Haworth et al. [9] carried out clinical trials in order to compare the effectiveness and safety between hydrogel and silicon hydrogel SCLs. Their study was based on wearers comfort, eye dryness, and adverse events during wearing the SCL. They did not examine a clear difference in the comfort between the materials. The blinking phenomenon is considered also as a significant criterion in the physiological behavior of the contact between the eyelid and the contact lenses. This phenomenon defines the pressure exerted on the SCL as well as the sliding

velocity [10]. The contact pressure of the eyelid on the cornea has been reported in [11, 12] to be in the range of 3 to 8 KPa. Moreover, the contact lens can support a maximum pressure in the range of 10 to 20 KPa [12]. In 1980, Doane [13] measured and plotted the motion profile of a human blink. The latter is related to the eyelid's sliding speed, which depends on some factors such as age, gender, and eye health as well as the blinking position. The sliding velocity between the eyelid and lenses can attain a maximum value of the range 100 to 200 mm/s [14]. More precisely, Kwon et al. have found that the blinking speed is 243 ± 9 mm/s when closing the eye and 157 ± 5 mm/s when opening the eye [15]. Thus, the friction test of contact lenses focuses on mimicking the eyelid and the contact lens lubricated contact, low contact pressure, and a sliding velocity inferior to 250 mm/s.

Although the operating conditions applied on the contact lenses have significant influence on the frictional behavior, many scholars have showed the importance of lubricant constituents and their interaction in improving the frictional behavior of SCLs. In 2005, Ngai et al. [16] measured the friction force for silicon hydrogel and conventional hydrogel contact lenses using a reciprocating pin-on-plate tribometer. Each lens was measured in saline solution. For half of the experiments, the lenses were doped with living proteins. They found that the friction force increases with increasing applied normal load. They also showed that the doped contact lenses have lower friction than those undoped. In [17] An et al. have reported the significance of the studied mucins and how the friction is positively influenced. They carried out friction tests using the atomic force

microscopy in order to study poly-methyl-methacrylate (PMMA) surfaces coated with two different types of mucin. Later Kaya et al. [18] showed that hyaluronic acid (HA) may increase the tear film for a maximum of 30 minutes. Later, Sterner et al. [19] reported that polyvinylpyrrolidone (PVP) plays an important role as a boundary lubricant. In 2021, some authors [20] studied the friction coefficient for hyaluronic acid (HA and HA2-C12) in saline and trehalose buffers. They showed that HA in saline solution gives the lowest friction coefficient.

Mucin is defined as a glycoprotein with high molecular weight (MW), it is shown in many research studies that mucin reduces the friction between biological surfaces [21, 22, 23]. In a recent research, Nečas et al. [24] both Senofilcon A and Comfilcon A soft contact lenses using 12 different eye drops. They performed their experiments on a linear reciprocating pin-on-plate tribometer in order to evaluate the friction coefficient and study the lubricant film at the eye/contact lens/lid interface. In their work, they focused on the importance of the mucin presence, buffer type, and MW of the hyaluronic acid (HA). They showed for Senofilcon A SCL that by adding mucin to Fluoresceinylamino hyaluronan (HA-FA) in borate and HEPES buffers decrease the friction coefficient except for HA-FA337 in HEPES buffer. However, by changing the SCL to Comfilcon A, more complex and different frictional behavior may occur by adding mucin to HA-FA in borate and HEPES buffers.

Furthermore, Mabuchi et al. [25] developed a pendulum tribometer to measure the friction coefficient at the contact between a soft contact lens and a polyethylene terephthalate (PET) hemispherical surface, by measuring the angular free response at the contact. They tested the contact between narafilcon A SCL-PET surface at dry and lubricated conditions. They used pure saline solution (SS) as well as saline solution with 0.1 and 0.3% of HA. Results showed that the SCL lubricated with pure saline solution provides the lowest friction coefficient among the other cases. They also showed that the friction coefficient increases with increasing sliding speed. Later, Iwashita et al. [26] used the same pendulum tribometer to measure friction between three commercial soft contact lenses and the PET surface lubricated with saline solution as well as saline solution with different percentages of HA (0.05%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%). They showed that the lowest friction coefficient is determined for the saline with 0.05% of HA for the 3 tested SCLs.

In literature, many scholars have measured the friction coefficient in SCL and have found a range 0.0001 and 0.64 [3, 8, 10, 27 - 34]. These measurements have been performed using conventional tribometers with a maximum sliding velocity of 50 mm/s. It can be concluded that the sliding velocity is very low compared to the values defined in the physiological conditions. Using a conventional tribometer, low friction coefficient values cannot be measured. Moreover, these friction coefficient values are defined by a simple law, known as Coulomb's law, which does not depend on the sliding velocity.

In 2010, a non-conventional oscillating dynamic tribometer was developed at the Laboratory of Tribology and Systems Dynamics [35 - 39, 40, 41], allowing to measure ultra-low friction that depends on the sliding velocity. Recently, Carvalho et al. [42] used a similar innovative method as in [35 - 39, 40, 41] in order to measure the friction of soft contact lenses. In [28], two contact lenses have been used, Somofilcon A and Nelfilcon A. The normal load varies from 21 to 63 mN with a maximum sliding speed of 200 mm/s.

In this study, we aim to measure the friction at the eyelid-lens contact using the original technique, called "Dynamic Oscillating Tribometer" [35 - 39]. Section 2 represents the materials and methods of this study. In this section, the experimental setup and the friction law used are presented. Then, the tribological contacts are illustrated with a variety of lens materials and lubricants. Finally, the different operating conditions will be introduced. In section 3, the experimental results are presented and discussed. The results are compared qualitatively with those in the literature. At the end, a summary and some perspectives conclude this research.

2. Experimental Setup and Analytical Analysis

Friction tests were run using an original tribometer, known as "Dynamic Oscillating Tribometer" [35 - 39], described in the following section.

2.1. The dynamic oscillating tribometer

The experimental apparatus is described by a pure sliding contact between spherical pin and a flat surface. A schematic representation of the tribometer is shown in Figure 1. The spherical pin is clamped to a moving mass, connected to the extremities of a pair of elastic steel cantilever beams. The electromagnet is used to initiate the motion of the bi-cantilever beams. The material used for the bi-cantilever beams as well as the linkages between the mechanical parts are chosen to reduce the internal damping of the system. The damping ratio has been measured without any lubricant meniscus and it is found to be 0.0013.

A rotational knob allows the application of a micrometric vertical position that stays constant during each oscillatory test. As a result, a normal load is applied on the contact. The vertical position can have a range of 0 to 0.5 mm, which is equivalent to a normal load varying from 0 to 500 mN. The apparatus is designed in a way to ensure that the upper surface is perfectly parallel to the lower plane surface in order to minimize the normal load variation.

The friction test is launched by setting out the head of the equilibrium position, allowing a deviation parallel to the sliding direction. As the head is released, the elastic energy, stored in the beams, is released as well. As a result, the velocity free response is obtained. The oscillating dynamic response is identified using a laser vibrometer Polytec OFV-5000 based on Doppler principle, measuring back-scattered laser light from the

vibrating structure. This permits to accurately measure the velocity free response with a resolution of $0.015\mu\text{m/s}$.

This experimental apparatus is shown to be performant in measuring low friction coefficients with high precision [35 - 39].

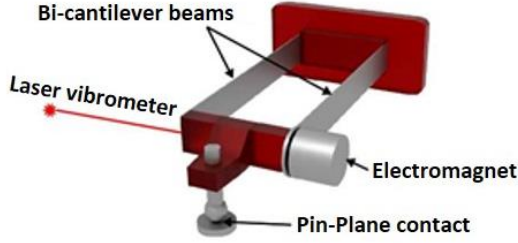


Figure 1. Schematic representation of the Dynamic Oscillating Tribometer.

2.2. The Mechanical System

This tribometer is characterized by a single-degree-of-freedom (SDOF) mass-spring oscillator mechanical system supporting the sliding contact. As shown in Figure 2, the mechanical system consists of a mass m attached to a linear spring of stiffness K . The mass m slides freely on a fixed rigid frame. A normal load N is applied at the contact, resulting in a friction force T . The friction force T is opposite to the direction of motion. A second order equation of motion defines the mechanical system. The equation of motion is written as follows:

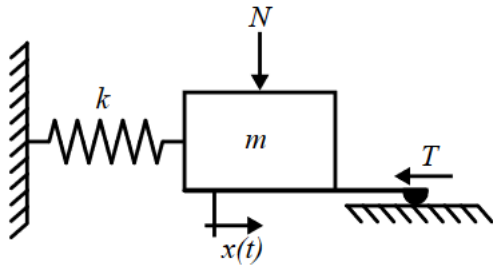
$$m\ddot{x} + kx = -T = -\mu_k(\dot{x})N \quad (1)$$


Figure 2. Mass-Spring-Damper Oscillator System.

x is the displacement of the mass, \dot{x} is the sliding velocity, and \ddot{x} is the corresponding acceleration. The friction force is T includes the damping behavior of the system. It is proportional to the normal load N through the kinetic friction $\mu_k(\dot{x})$. The friction coefficient depends on the sliding velocity \dot{x} and is defined as an odd function of \dot{x} , where $\mu_k(-\dot{x}) = -\mu_k(\dot{x})$. The friction coefficient has the same sign as the sliding velocity due to the dissipative nature of the friction.

In order to model the friction $\mu_k(\dot{x})$, a friction law is defined as a pseudo-polynomial velocity-dependent model with different friction contributions μ_{2j} and μ_{2j+1} is used [39]. The general friction law is represented as:

$$\mu_k(\dot{x}) = \sum_{j=0}^n [\mu_{2j}\dot{x}^{2j} \text{sgn}(\dot{x}) + \mu_{2j+1}\dot{x}^{2j+1}] \quad (2)$$

In this study, a first order-polynomial friction model is sufficient to use in order to model the dissipated energy from our experimental free responses, simplified as:

$$\mu_k(\dot{x}) = \mu_0 \text{sgn}(\dot{x}) + \mu_1 \dot{x} \quad (3)$$

The parameters, μ_0 and μ_1 , correspond respectively to the Coulomb and viscous-like friction contributions [43]. The sign function, $\text{sgn}(\dot{x})$, preserves the odd property of the friction coefficient. The analytical method for identifying the friction coefficients from the experimental velocity free responses is explicitly explained in [36, 39]. As mentioned previously, $\mu_k(\dot{x})$ considers not only the friction but also the internal damping of the system. This friction model is shown in Figure 3. This friction law depends linearly on the sliding velocity, which represents the eyelid speed during blinking. μ_0 is the friction at a speed tending to zero and μ_1 is a slope due to a viscous-like friction contribution.

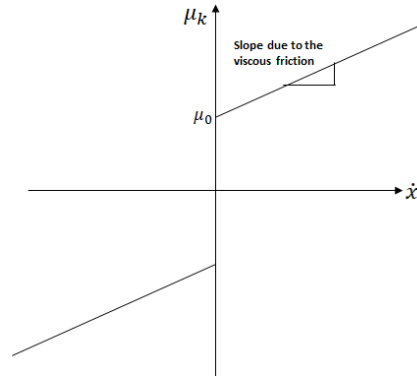


Figure 3. Coulomb and viscous-type friction model.

2.3. Tribological Contact

As shown in Figure 1, the tribometer consists of pin-on-plane contact. The upper pin surface, shown in Figure 4, is modeled using resin material using a 3D-printer. The pin is described by a hemi-spherical geometry, having a diameter of 20 mm and a radius of curvature of 8.5 mm . These dimensions are taken according to that of the cornea in order for the contact lens to be perfectly placed on it. The contact lens is placed on the hemi-spherical upper surface and then clamped by a ring in a way to avoid the slipping between the contact lens and the hemi-sphere. Each friction test is repeated 4 times to check accuracy of the results as well as to confirm that there is no slip between the lens and the hemi-sphere. Moreover, resin is used as the material of the pin surface due to its smoothness in order not to destroy the contact lens material during the friction test. The condition of the contact lenses have been checked after each test and they have not been torn.

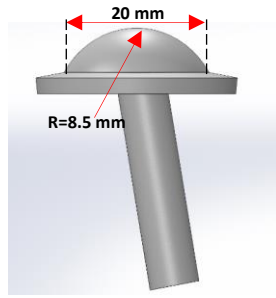


Figure 4. The geometric configuration of the upper surface.

The counter surface is made of polyethylene terephthalate (PET) material, having a square plane surface of 25 mm-side. The PET surface is glued in a cup of 55 mm-diameter and 5 mm-depth as shown in Figure 5. The PET surface has a roughness of 0.312 μm . The counter-surface is selected herein as polyethylene terephthalate since PET is defined as a polymer close to the cell membranes according to Mabuchi and his colleague [25]. The cup has a depth in order to have lubricant bath between the pin and the plane. The lubricant bath keeps the contact lubricated to mimic the eye conditions, where tears fluid is always lubricating the eye.

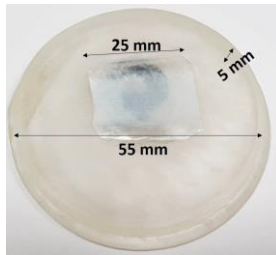


Figure 5. The geometrical configurations of the counter-lower contact: PET plane glued on resin cup.

A variety of commercial soft contact lenses has been tested. Table 1 presents the used contact lenses as well as their corresponding material and percentage of water content. The latter aims to study the effect of SCLs material type and water content on the friction of these lenses. The friction test is carried out at the contact between the lens and a flat surface made of polyethylene terephthalate (PET). Some eye drop lubricants are added to mimic tears. A physiological saline solution is used as a lubricant. Furthermore, the effect of hyaluronic acid in the saline solution on the comfort of the SCL wearers is studied.

Soft contact lenses	Material	Water content (%)
Senofilcon A	Silicon hydrogel	38
Etafilcon A	Hydrogel	58
Somofilcon A	Silicon hydrogel	56
Nelfilcon A	Hydrogel	69
Delefilcon A	Silicon hydrogel	33 at the center 80 at the surface

Table 1. List of soft contact lenses tested.

2.4. Operating Conditions

Blinking is the primary physiological contributor to the forces exerted on contact lenses. In this process, eye movements occur under mainly hydrodynamic lubrication regime. Thus, during the majority of a blink

cycle, the sliding resistance is governed by the viscous shear of the lubricant [37]. According to the literature [11-15], the tribological SCLs measurements in the human eye focus on lubricated contact, low pressures and speeds lower than 250 mm/s.

Therefore, the conditions for SCLs friction tests are defined by the blinking physiological conditions. In this context, the tribological operating conditions consist of lubricated contacts, sliding velocities higher than 100 mm/s, and low applied contact pressures. The experiments are performed at room temperature with different applied normal loads and sliding velocities as shown in Table 2.

Normal load (mN)	50-250
Sliding speed (mm/s)	0-230

Table 2. Tribological operating conditions of the friction test.

The lubricated contacts are defined by hydrodynamic lubrication regime in which there is no asperities between the contact lens and the PET surface. A maximum sliding speed of 230 mm/s is applied which corresponds to the maximum blinking speed while opening the eyelid [14, 15]. The contact pressure is related to the normal load as well as the elastic deformation of the lens. Thus, in order to be close to the range of 3-8 KPa applied during muscle contractions [12], a normal load varying between 50 mN and 250 mN is applied to the soft contact lenses – PET surface.

For thin soft materials on hard substrates, Hertzian theory is not suitable anymore to evaluate the contact pressure between two surfaces. However, the elastic-foundation model (EFM) is valid for this kind of soft materials, described by the soft contact lenses in our study [44]. A relationship between the normal load and the contact area, solved using the elastic-foundation model, is proposed by [29] as:

$$A_{EFM} = \pi \sqrt{\frac{4 \times N \times R \times t}{\pi \times E^*}} \quad (4)$$

The parameters in the above equation are defined as follows:

N : Applied normal load.

R : Radius of curvature of the spherical pin = 8.5 mm.

t : Thickness of the soft contact lens (depends on the type of the SCL used).

E^* : Reduced modulus of elasticity of the contact.

The reduced modulus of elasticity is computed as:

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \quad (5)$$

where:

ν_1, ν_2 : Poisson ratios of the soft contact lens and PET surface respectively.

E_1, E_2 : Moduli of elasticity of the soft contact lens and PET surface respectively.

3. Results and discussion

The friction is determined from the analysis of the decaying envelope of the free response [27]. The friction law defined in this paper permits us to evaluate both the Coulomb friction contribution at zero speed, μ_0 , and the viscous damping friction contribution, μ_1 . The analysis of the free responses of a single degree-of-freedom damped oscillator is performed with unrivaled accuracy and precision.

During the experiments, different types of soft contact lenses are tested in order to study the effect of the lenses materials on the comfort of the wearers. Moreover, different lubricants are used in order to determine the effect of viscosity on the friction of contact lenses. Furthermore, a range of sliding velocities and normal loads, similar to the physiological conditions of the eye, allow the observation of the friction evolution as a function of these conditions.

Before testing the contact lenses, an experiment is carried out without any contact or lubricant meniscus in order to determine the damping effect due to the apparatus. Figure 6 demonstrates the values of the friction coefficient corresponding to the experiment without any contact or lubricant meniscus. The friction coefficient due to the intrinsic damping of the apparatus is in the order of 10^{-4} .

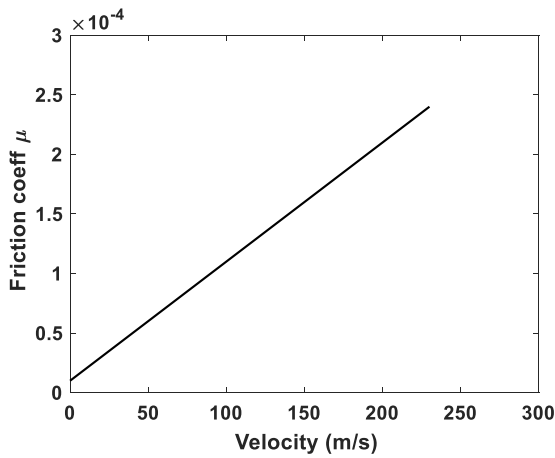


Figure 6. Friction coefficient without any contact or lubricant meniscus.

3.1 Effect of the Contact Lens Material

Four soft contact lenses (Senofilcon A, Etafilcon A, Somofilcon A, and Nelfilcon A) are tested on a flat surface made of polyethylene terephthalate (PET) under a normal load of 50 mN lubricated by a physiological saline solution. Figure 7 presents the velocity free responses measured from the friction test for the four contact lenses. Figure 8 demonstrates the friction coefficient values of the four SCLs as a function of the sliding velocity. The values of the Coulomb's and viscous friction coefficient values, μ_0 and μ_1 , of the four tested SCLs are represented in Table 3. The free responses in Figure 7 shows that the loss of dissipated energy due to friction is faster for Etafilcon A than that of Senofilcon A.

In other words, it can be observed from the measured free responses that the velocity amplitude loss is greater for Etafilcon A compared to Senofilcon A. This may be explained by the fact that Senofilcon A is made of silicon hydrogel; however, Etafilcon A is made of hydrogel. These results are in agreement with the study of Sterner et al. [45], showing that the friction coefficient is lower for Senofilcon A compared to Etafilcon A (Figure 8), as well as the survey done by Pritchard et al. [46] that shows that Senofilcon A are more comfortable than Etafilcon A. It is shown from Table 3 that Coulomb's friction coefficient is more dominant than the viscous one. μ_0 is in the range of 10^{-3} ; however, μ_1 is in the range of 10^{-5} for both Senofilcon A and Etafilcon A contact lenses.

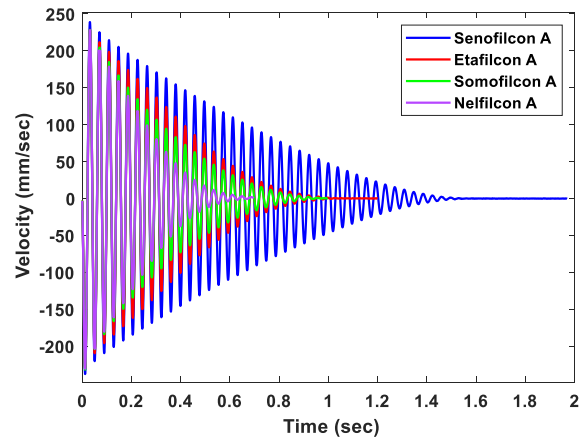


Figure 7. Velocity free responses of a contact lens (Senofilcon A/Etafilcon A/Somofilcon A/Nelfilcon A) on a PET flat surface under a normal load of 50 mN lubricated by a physiological saline solution.

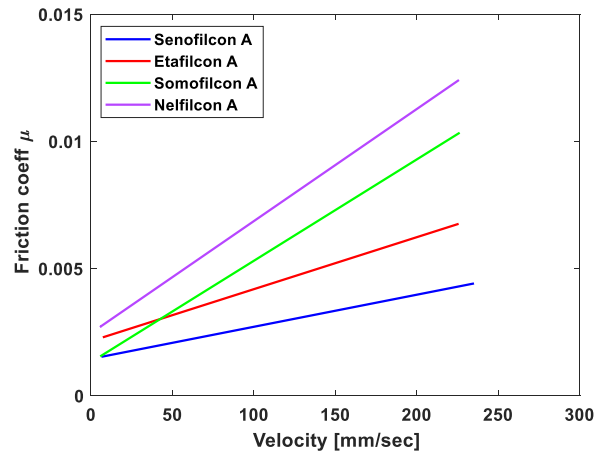


Figure 8. Friction coefficient values at the contact between CLs (Senofilcon A/Etafilcon A/Somofilcon A/Nelfilcon A) and a PET flat surface under a normal load of 50 mN lubricated by a physiological saline solution.

Contact lens	μ_0	μ_1
Senofilcon A	1.4×10^{-3}	1.3×10^{-5}
Etafilcon A	2.1×10^{-3}	2.0×10^{-5}
Somofilcon A	1.3×10^{-3}	4.0×10^{-5}
Nelfilcon A	2.4×10^{-3}	4.4×10^{-5}

Table 3. Coulomb and viscous contributions of the friction model at the contact between CLs (Senofilcon A/Etafilcon A/Somofilcon A/Nelfilcon A) and a PET flat surface under a normal load of 50 mN lubricated by a physiological saline solution.

Nelfilcon A contact lenses are made of only hydrogels; however, Somofilcon A lenses are made of hydrogel silicone. From the velocity free responses in Figure 7, one can conclude that Nelfilcon A is described by a higher friction compared to Somofilcon A. This is observed from the fact that the velocity amplitude loss is lower for Somofilcon A. Thus, it can be concluded that silicone hydrogel lenses are described by a low friction and more comfortable to wear (Figure 8). These results confirm those obtained by Roba et al. [10], Mann and Tighe [30], and Carvalho et al. [42]. This is due to the fact that increasing the hydrophilicity in silicone hydrogel lenses is essential in reducing the friction compared to hydrogel lenses. One of the effective methods used to increase the hydrophilicity of silicone hydrogel lenses is the incorporation of monomers or polymers with lubricating properties [42]. This results in reducing friction of silicon hydrogel lenses compared to hydrogel lenses. Table 3 shows that also for both Somofilcon A and Nelfilcon A soft contact lenses that the Coulomb's friction coefficient is more dominant than the viscous one. μ_0 is in the range of 10^{-3} ; however, μ_1 is in the range of 10^{-5} .

By comparing the four SCLs tested in this study (Senofilcon A, Etafilcon A, Somofilcon A, and Nelfilcon A.), results show that Nelfilcon A lens has the highest friction coefficient values among the four tested contact lenses. These results are consistent with those of Sterner and his colleagues [45]. They have showed that the friction coefficient of Nelfilcon A, defined as hydrogel contact lenses, have a significant high friction coefficient compared to Etafilcon A and Senofilcon A. By comparing both Etafilcon A and Senofilcon A on one side and Somofilcon A and Nelfilcon A, it can be concluded that Etafilcon A is more comfortable than Senofilcon A and Somofilcon A is more comfortable than Nelfilcon A. However, it is difficult to conclude that silicon hydrogel soft contact lenses are more comfortable to wear compared to the hydrogel ones. It is concluded in [47] that hydrogel SCLs are more practical for daily wearing compared to silicon hydrogel lenses. Etafilcon remains widely worn as hydrogel SCLs due to that fact that hydrogel SCLs maintain a physiological stability for the wearers. It is demonstrated that hydrogel lenses are able to offer low inflammation and infection risk for daily wearers, which is the case of Etafilcon A. This is due to its low modulus of elasticity, and lysozyme and lactoferrin absorbed into the lens from the tear fluid [48, 49]. Furthermore, in the study of Haworth et al. [9], two trials showed that silicon hydrogel SCLs may have adverse risk of 2.03 times more than hydrogel SCLs.

By comparing Senofilcon A and Somofilcon A, both defined as silicon hydrogel SCLs, as well as Etafilcon A and Nelfilcon A, both defined as hydrogel SCLs, one can observe that the values of the friction coefficient are lower for those with lower water content for contact lenses of the same material. In [50], Wild and his colleagues have stated that low water content lenses are more often found in market because they are more durable and easier to handle compared to high water

content lenses. In fact, the water content enriches the soft contact lenses with oxygen for hydrogel contact lenses [51]. In other words, the higher the water content, the greater the oxygen permeability of the contact lenses for hydrogel contact lenses [52]. On the other hands, it is concluded that there is an inverse relationship between the water content and oxygen permeability for silicone hydrogel lenses. This is due to the type of material where water is the limiting factor in oxygen permeation [52]. Therefore, one cannot conclude a general relation dependency of friction and oxygen permeability. This depends on the type of the CLs material. Thus, in this type of lenses, the higher the water content, the greater the difficulty for oxygen to move through the material.

It has been concluded in [53] that SCLs with high water content are not comfortable for wearers suffering from dry eyes since this type of lenses absorbs the eye's natural tear film. It is also shown that the friction coefficient values corresponding to the tested four contact lenses are very low, varying between 0.001 and 0.013, as a function of the sliding velocity. Meanwhile, these values are much higher from the friction coefficient values for the experiment without contact shown in Figure 6. The results demonstrate that the experimental dynamic tribometer used can accurately evaluate the low values of friction coefficient corresponding to the contact lenses.

3.2 Effect of Lubrication and Hyaluronic Acid

Two different concentrations of hyaluronic acid (0.3% and 0.5%) are used with the saline solution in order to compare the friction coefficient of the contact between a SCL (Delefilcon A, Etafilcon A, and Senofilcon A) and a PET surface plat with an applied load of 50 mN lubricated with saline solution. Table 4 shows the coefficients of friction of each SCL with 100% saline solution, saline solution with 0.3% of HA, and saline solution with 0.5% of HA. Results show that the addition of HA to the saline solution increases the friction. Moreover, as the concentration of HA is added, the friction coefficient is higher. This confirms the results presented in [26], which concluded that the friction of the SCL is increased significantly at high HA concentrations (0.3%, 0.4%, and 0.5%). Hyaluronic acid is used in different drop eye pharmaceutical solutions. This is due to its biomedical characteristics, i.e. high water retention, which is used to treat dry eyes and retain moisture. In fact, low concentration of HA is used in the pharmaceutical eye drops. In this context, we have chosen the commercial Bio True which contains a certain amount of HA, in order to examine its effect on friction.

Contact lens	Saline	Saline +0.3% HA	Saline +0.5% HA
Delefilcon A	4.2×10^{-3}	4.3×10^{-3}	4.5×10^{-3}
Etafilcon A	4.6×10^{-3}	5.2×10^{-3}	1.9×10^{-2}
Senofilcon A	4.0×10^{-3}	4.7×10^{-3}	1.0×10^{-2}

Table 4. Friction coefficients at the contact between SCLs (Delefilcon A/ Etafilcon A/ Senofilcon A) and a PET flat surface under a normal load of 50mN lubricated with saline solution, saline solution + 0.3% hyaluronic acid (HA), saline solution + 0.5% HA.

Pure physiological saline solution and a commercial

solution (Bio True) containing a certain amount of Hyaluronic acid (HA) has been tested at the contact between both hydrogel and silicone hydrogel contact lenses.

Figure 9 presents the measured friction coefficient as a function of the sliding speed corresponding to a hydrogel contact lens (Etafilcon A) on a PET surface lubricated by both saline solution and a commercial solution containing an unknown percentage of HA (Bio True HA). Results show that the friction of the hydrogel SCL (Etafilcon A) lubricated with a solution containing hyaluronic acid is lower than with saline. These latter results are coherent with Iwashita et al. [26]. This may be explained by the fact that saline contains more water than the solution with HA. This conclusion is related to the results discussed in the previous section where hydrogel SCLs with more water content are described with higher friction coefficient.

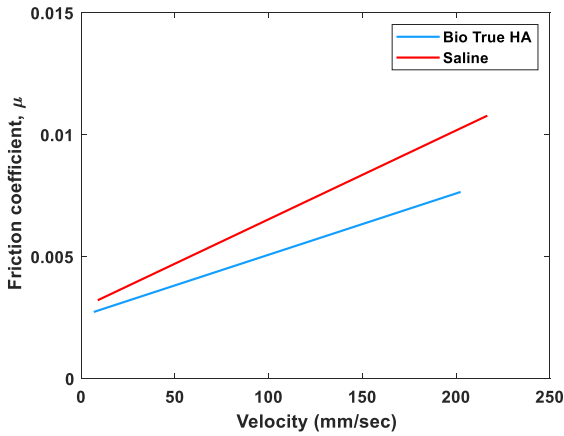


Figure 9. Comparison of the friction coefficient values at the contact between Etafilcon A SCL and a PET flat surface under a normal load of 100 mN lubricated with a physiological saline solution and a commercial solution with a certain amount of hyaluronic acid.

The friction coefficient is measured at the contact of Senofilcon A on a flat PET plane lubricated with saline solution and a commercial solution (Bio True) containing hyaluronic acid. Figure 10 shows the friction coefficient as a function of the sliding speed at the contact between Senofilcon A SCL and PET surface. Three physiological lubricant samples are used: saline solution, commercial solution (Bio True), and a mixture of 50% of saline solution and 50% of Bio True solution. It is shown that the friction coefficient of silicone hydrogel SCLs is lower with a solution containing a certain percentage of HA than with saline. However, when the percentage of hyaluronic acid increases (100% Bio True), the friction is higher than the solution with lower percentage of HA (50 % Bio True). At a sliding velocity greater than 175 mm/s, one can observe that the friction coefficient corresponding to 100% of Bio True solution is very close to that with only saline solution. For a sliding speed greater than 210 mm/s, the friction coefficient corresponding to 100% of Bio True solution is slightly higher than that with only saline solution. These results are in a good agreement with those presented in [26]. It can be noticed from Table 5 that Coulomb's friction

contribution decreases as the percentage of hyaluronic acid is increased. In [54], it has been demonstrated that Hyaluronic acid is effective for moisturizing the ocular surface damage. Hyaluronic acid (HA) is a natural viscoelastic hydrophilic polymer used to lower ocular damage in patients suffering from dry eyes [55]. It can be probably treated by enhancing corneal hydration and decreasing surface friction. This is due to the fact that HA has its own lubrication properties [54] and thus, modifies that of the eyes drops when added to it. Some clinical trials [56] have shown that eye drops containing 0.1% HA increase tear film break-up time and improve symptoms of ocular irritation associated with dry eye. In our present results, we have observed that in the presence of HA, Coulomb's friction contribution, μ_0 , which describes the dry friction contribution, is decreased.

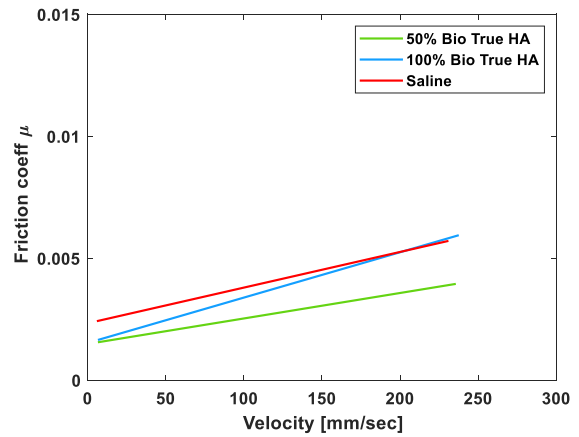


Figure 10. Comparison of the friction coefficient values at the contact between Senofilcon A SCL and a PET flat surface under a normal load of 100 mN lubricated with a physiological saline solution and a commercial solution with a certain amount of hyaluronic acid (Bio True HA) at different sliding velocities.

Lubricant	μ_0
100% saline solution	1.4×10^{-3}
50% Bio True HA + 50% Saline solution	1.3×10^{-3}
100% Bio True HA	9.0×10^{-4}

Table 5. Coulomb's friction contribution at the contact between Senofilcon A SCL and a PET flat surface under a normal load of 100 mN lubricated with different solutions.

3.3 Effect of the Physiological Conditions

A friction test is carried out using Senofilcon A contact lens on a PET flat surface lubricated by saline solution. The test is carried out at a range of applied normal loads varying from 50 to 250 mN and at different sliding speeds. The friction coefficient results are presented in Figure 11. The friction coefficient of Senofilcon A increases as either the normal load or the sliding velocity is increased. One can conclude that the friction coefficient of the contact lens-eyelid contact increases with a slight increase in the normal load as well as in the sliding velocity. These results agree with those in the literature. Roba et al. [10] showed for Etafilcon A that the friction coefficient increases as the sliding velocity increases. Moreover, Carvalho et al. [42] examined that the friction coefficients for Somofilcon A and Nelfilcon A SCLs get higher with increasing sliding speeds. On the

other hands, Carvalho showed in [57] that also the friction force increases with increasing normal load for the four SCLs: Somofilcon A, Nesoofilcon A, Nelfilcon A, and Delefilcon A.

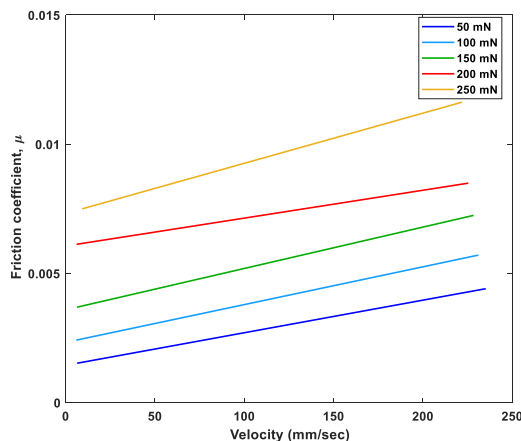


Figure 11. Friction coefficient values at the contact of Senofilcon A lens and a PET flat surface lubricated by a physiological saline solution as a function of a range of normal loads and sliding speeds.

4. Conclusion

This research study shows the feasibility of measuring friction at the eyelid-lens contact using the oscillating dynamic tribometer. The results have demonstrated that the precision is very high for low friction coefficient. In the present results, we show that millirange friction is currently identified, validating the use of the dynamic oscillating tribometer. The friction coefficient measurements of the different soft contact lenses at a range of physiological conditions are compared to the results found in literature.

By comparing the material type of soft contact lenses, it was hard to conclude which SCL is the most comfortable for wearers, since the comfort does not only depend on the material itself, but also on the physical interaction between the material and the tear film. Furthermore, it is shown that the contact lenses of the same material with a lower water content are comfortable. It has been concluded that using a physiological solution containing a very low percentage of hyaluronic acid reduces μ_0 , and thus enhances the comfort of the contact lenses especially for hydrogel lenses compared to silicon hydrogel lenses. The results of this work demonstrate that the comfort of all types of contact lenses, regardless of the physiological solution used, is reduced as either the contact pressure or the eyelid speed gets higher. As a conclusion, the results presented in this paper are in agreement with those shown in the literature. Moreover, it should be noted that our conclusions are limited to the types of commercial SCLs, studied in this paper as well for the defined operating conditions.

For future work, it is interesting to study the ageing effect of soft contact lenses on friction. The comprehension of the water properties of SCLs with respect to the friction measured is also significant to observe. Moreover, it is interesting to study and understand the chemical interaction between the different lubrication used as eye

drop and the SCLs surface as well as the effect of the SCL material and the lubrication on the tear film. As a perspective, a contact geometry arrangement, closer to the real contact between the lenses and eyelid, would be of high interest to be developed and applied to the dynamic oscillating tribometer used in this work.

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All the commercial names used in this paper, for SCLs and lubricants are registered brands.

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