Tribological behavior of soft contact lenses

Relevant for: Nano Tribometer, Bioindenter, Contact lenses

The frictional properties of contact lenses are extremely important for proper application in everyday life. Several attempts have been made to characterize the tribological properties of contact lenses but there is no general conclusion as to how these properties should be tested. This application report presents the results of a tribological study using the Anton Paar Nanotribometer for characterization of soft contact lenses. The measurement methodology is presented and the influence of load and sliding speed on the coefficient of friction is discussed.

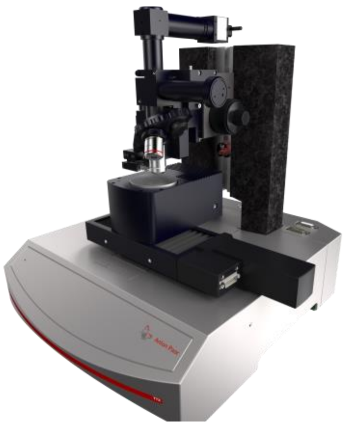

Figure 1 – The Anton Paar Nano Tribometer.

1 Introduction

Hydrogels have been used for many years as the primary material in the fabrication of contact lenses. A hydrogel is a cross-linked hydrophilic polymer network filled with liquid. Hydrogel behaves both like solid and liquid under applied stress. When the mechanical stress is released, the hydrogel recovers as it supports diffusion of the liquid through the pores in the solid meshwork (1). Hydrogels contain typically 30-70% of water in the polymeric matrix (1, 2).

A contact lens, in its in vivo environment, is subjected to the movement of the eyelid, which is commonly believed to be the primary force and motion contribution onto the ocular surface. The contact pressure induced by the eyelid during blinking was estimated to be in the range of 1 to 7 kPa and the blinking average speed was estimated to 12 cm/s (3, 4).

This paper summarizes a complete study on two commercially available contact lenses named L1 and L2 respectively. The determination of coefficient of friction and its evolution depending on normal load and sliding speed was done by the Anton Paar Nano Tribometer. The outcomes of this study contribute to further research of new types of soft contact lenses and their optimization for the best wear comfort.

1.1 Experimental setup

Two different p(HEMA) contact lenses were selected for the nanotribology experiments. The tribological properties of the contact lenses were determined using a Nano Tribometer device (NTR^3). This tribological device achieves low contact pressures and ensures accurate measurements of very low forces (both normal and tangential). Figure 2 shows the Nano Tribometer during measurement; the 2 mm diameter ruby ball (counter-body) is approaching the contact lens which is immersed in saline solution (PBS) or tear-like fluid (TLF).

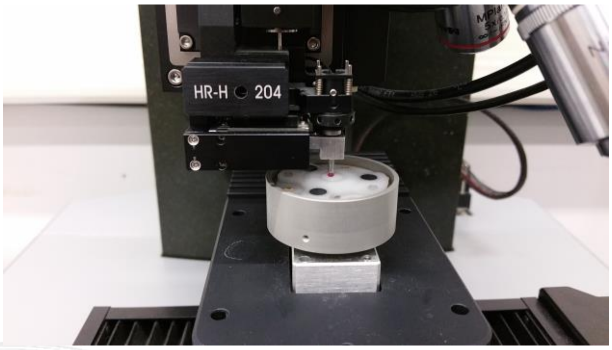

Figure 2 - Nano Tribometer setup with contact lens placed ind special sample holder and immersed in saline solution.

1.1.1 Sample mounting

In the tribological tests, the contact lenses were mounted onto a sample holder specially designed to match the internal curvature of the lens. The lens was then clamped with the upper part to be held in place. Three magnetic pegs are embedded in the clamping (upper) part and in the support (lower) part of the contact lens holder in order to safely and firmly hold the contact lens during the testing (see Figure 3).

Figure 3 - Clamping parts of the sample holder: lower support (left) and upper clamp (right). Note three magnetic pegs for firm holding between the two parts.

2 Test parameters and results

The presence of liquid on the surface of the hydrogel is known to affect dramatically its friction properties (4). Therefore, in order to avoid the dehydration, the contact lenses were tested completely immersed in saline solution. This solution (usually PBS) is also often replaced by tear-like fluid (TLF), which simulates better the in-vivo conditions. The amount of liquid was monitored during the tests to ensure permanent hydration of the lens. If necessary, the liquid was added between measurements.

Two sets of experimental conditions were applied for all tribological tests (Figure 4). During the first set of experimental conditions the normal load was gradually increased in 50 steps from 0.4 mN to 5.0 mN whereas the linear sliding speed was kept constant at 0.2 cm/s. During the second set of experimental conditions the sliding speed was gradually increased in 50 steps from 0.03 cm/s to 1.0 cm/s whereas the normal load was kept constant at 1.0 mN.

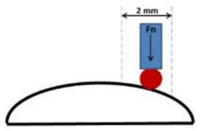

Figure 4 - Schematic drawing of the Nano Tribometer test setup.

The following table (Table 1) summarizes both sets of experimental conditions:

	Load variation	Speed variation
Normal load	0.4 to 5.0 mN (50 sequences)	1 mN
Movement amplitude	2 mm	2 mm
Cycles per sequence	30	30
Max linear speed	0.2 cm/s	0.03 to 1.0 cm/s (50 sequences)
Environment	Saline solution, 24°C	Saline solution, 24°C
Ruby ball diameter	2 mm	2 mm

Table 1 Summary of experimental conditions.

The contact pressure ***P*** was calculated using Hertz solution for spherical contact with a flat (5, 6) (it was assumed that the radius of the contact lens is much larger than the contact of the ruby sphere).

$$P = \frac{F}{\pi a^2} \qquad (1)$$

$$a^3 = \frac{3FR}{4E} \qquad (2)$$

where ***F*** is the normal applied load, ***a*** is the contact radius, ***R*** is the radius of the hemispherical counter-body and ***E*** is the Young's modulus of the contact lens. The elastic modulus of the lenses was determined using nanoindentation testing using the Anton Paar Bioindenter (more details about indentation measurements of contact lenses will be published later). Table 2 shows the values of the contact pressure induced by the applied normal load from 0.4 mN to 5.0 mN using a ruby ball with diameter of 2 mm.

F [mN]	P_{L1} [kPa] (E~40 kPa) – O&P	P_{L2} [kPa] (E~106 kPa) – O&P
0.4	3.3	6.4
2.0	5.7	10.9
3.5	6.9	13.1
5.0	7.8	14.8
F [mN]	P_{L1} [kPa] (E~19 kPa) – Creep	P_{L2} [kPa] (E~42 kPa) – Creep
0.4	2.0	3.4
2.0	3.4	5.8
3.5	4.1	7.0
5.0	4.7	7.9
F [mN]	P_{L1} [kPa] (E~23 kPa) – Hertz	P_{L2} [kPa] (E~64 kPa) – Hertz
0.4	2.3	4.6
2.0	3.9	7.8
3.5	4.7	9.4
5.0	5.3	10.6

Table 2 Contact pressures reached during the tribology tests. The elastic modulus values determined by the three methods were employed in the calculations. The counter-body was a 2 mm diameter ruby ball.

The contact pressures reached during the tribology tests were in the same order of magnitude as the *in vivo* contact pressure (1 to 7 kPa) but the sliding speed (12 cm/s) proved to be challenging to reach. The maximum linear speed during the tests was set to 1 cm/s. The proper control of the normal load would be difficult at higher speeds due to the spherical shape of the lens. Additionally, the vibrations caused by the requested speed could lead to errors in the measurement of the coefficient of friction. The chosen parameters, even if inferior to the *in vivo* sliding speed, however lead to a detailed study of the effect of the sliding speed on the coefficient of friction.

The following figures show the evolution of the coefficient of friction with normal applied load and sliding speed.

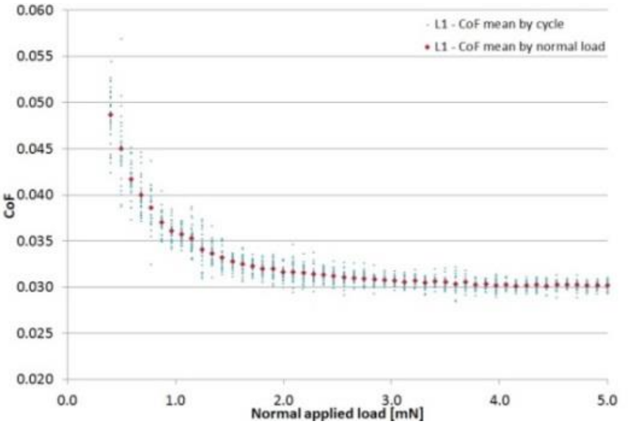

Figure 5 - Evolution of the CoF with normal applied load (50 sequences of load between 0.4 mN and 5.0 mN). The red dots represent the average CoF value of the 30 cycles (in blue) performed under the same applied load.

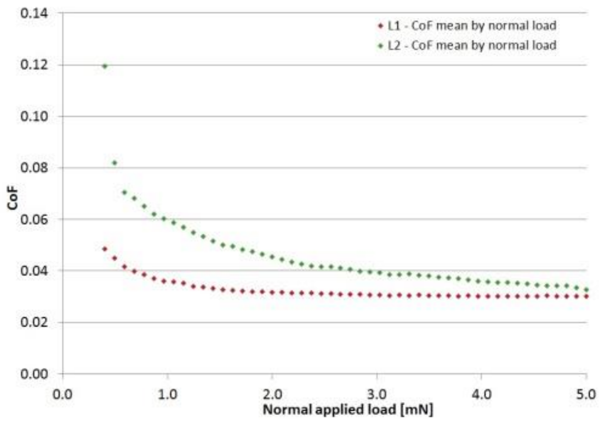

Figure 6 - Comparison of the evolution of the CoF with normal applied load (50 sequences of load between 0.4 mN and 5.0 mN) of the two types of tested lenses (L1 and L2). Each point represents the average of the 30 cycles performed under the same applied load.

2.1 Influence of load

A decrease of the CoF was observed with the increase of the applied load for both tested contact lenses. This tendency is in agreement with the results of previous studies on the dependence of the coefficient of friction of different hydrogels on load, available in literature (1, 7). This phenomenon is attributed to the crosslink nature of hydrogels with high content of water. With the increase of normal pressure, the crosslinks are more easily lost/dissolved and the contribution of the solid-solid contact is reduced. As the load increases, more liquid diffuses to the surface resulting in a decrease of friction. The contribution of this phenomenon to the overall friction is amplified with higher load.

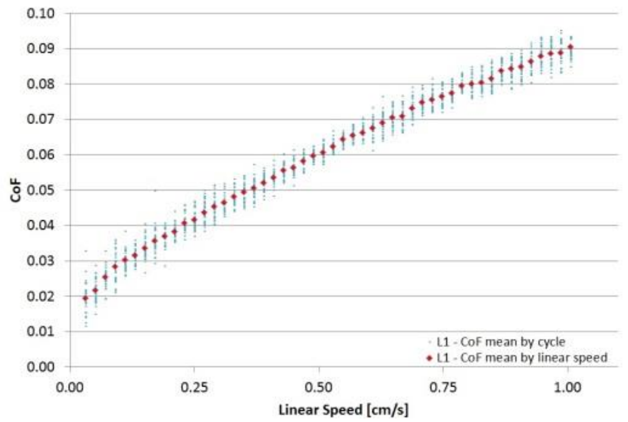

Figure 7 - Evolution of the CoF with linear speed (50 sequences of linear speed between 0.03 cm/s and 1.0 cm/s). The red dot represents the average CoF value of the 30 cycles (in blue) performed for the same linear speed.

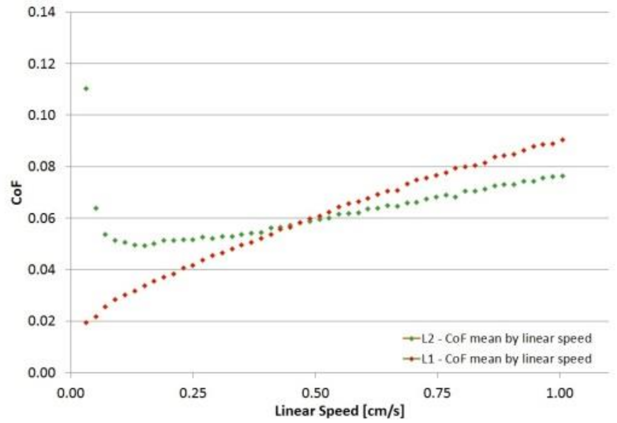

Figure 8 - Comparison of evolution of the CoF with linear speed (50 sequences of linear speed between 0.03 cm/s and 1.0 cm/s) of the two types of tested lenses (L1 and L2). Each point represents the average of the 30 cycles performed for the same linear speed.

2.2 Influence of sliding speed

The sliding speed dependence tests revealed an increase of the coefficient of friction with the linear speed for both tested lenses. This dependence can be explained by the repulsion-adsorption model proposed by Gong (8). According to this model, when a polymer or a cross-linked gel is in contact with a solid counter-face, the polymer chain can either be repelled from or adsorbed to the solid counter-face.

In the case of repulsion between the hydrogel and the solid, the solid-solid contact is minimized and the friction is dominated by the lubrication of a hydrated layer of polymer chains. The friction is expected to linearly increase with normal pressure and sliding velocity (for low normal applied loads). For the contact lenses studied in the current paper, the friction tests reveal low coefficients of friction (inferior to 0.1) which decrease with load and increase with sliding speed.

The friction is not dominated by the contribution of viscous flow – the test conditions do not seem to correspond to the repulsion regime.

In the case of attraction between the hydrogel and the solid, the friction is due to the elastic deformation of the adsorbing polymer chains and to the lubrication of the hydrated layer of the polymer network. Depending on the sliding velocity, the solid or the liquid contribution will be dominant, the transition velocity from elastic friction to lubrication depending on polymer chain dynamics. The transition velocity can be expressed in terms of elastic modulus of a gel as follows:

$$v_f = (T^{\frac{1}{3}} E^{\frac{2}{3}}) / \eta$$

where $\boldsymbol{T}$ is the absolute temperature in energy units, $\boldsymbol{\eta}$ is the liquid viscosity and $\boldsymbol{E}$ is the elastic modulus of the tested material (lens).

The transition velocities of the two lenses studied in the current report were of 11 cm/s and 19 cm/s respectively (using $\boldsymbol{E_{IT}}$ Creep for the calculations). In our friction tests the sliding velocity ranges varied between 0.03 and 1.0 cm/s which was much smaller that the calculated $\boldsymbol{v_f}$. Therefore, according to the repulsion-adsorption model, the contribution of viscous flow is negligible in the overall friction and the interaction between the hydrogel and the solid counter-face is of attractive nature which agrees with the experimental data (see Figure 6).

3 Conclusions

This application report presents the results of tribological experiments on soft contact lenses. The measurement protocol for such soft materials was successfully applied using the Nano Tribometer and dedicated contact lens holder.

The measurement protocol for the tribological tests consisted either in progressive increase of normal load under constant speed or in progressive increase of the sliding speed under constant load. These conditions were selected in order to reproduce the in-vivo environment conditions as closely as possible - without impacting the quality of the measured data. Even though the simulation of the natural process of blinking proved to be challenging, the test protocols demonstrated the dependence of the coefficient of friction on load and sliding speed:

- It was found that the coefficient of friction decreased with the increase of normal load because of the increasing contribution of viscous flow of saline solution to the overall friction.
- The increase of the coefficient of friction with sliding speed can be explained by a previously proposed “repulsion-adsorption” model describing the friction of polymer hydrogels where (in our case) the friction was controlled by the attractive regime.

Given the complexity of the frictional behavior of soft contact lenses and knowing that different parameters (applied load, sliding speed, type of liquid, state of surface, etc.) can have important impact on the results, explication of the frictional mechanisms are not always straightforward. Nevertheless, the above mentioned methodologies can significantly contribute in further research understanding of behavior and in improvement of clinical in vivo performances of contact lenses.

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