Friction Measurements on Contact Lenses in Their Operating Environment

M. Roba · E. G. Duncan · G. A. Hill · N. D. Spencer · S. G. P. Tosatti

Abstract An important issue concerning the use of soft contact lenses is comfort, which, among other factors, has been related to the level of friction between the anterior side of the lens and the inner eyelid. Although several studies have been carried out to investigate the frictional properties of contact lenses, these have not taken the physiological environment of the eye into account. In use, lenses are in contact with proteins present in tears, with corneal cells and with the palpebral conjunctiva (clear membrane on inner eyelid). The focus of this study was to establish a biologically relevant measurement protocol for the investigation of friction of contact lenses that would mimic the eye’s physiological environment. By optimizing parameters such as the composition of the friction counter surface, the lubricant solution, the normal load and the velocity, an ideal protocol and setup for microtribological testing could be established and used to perform a comparative study of various commercially available soft contact lenses.

Keywords Contact lens · Microtribometer · Mucin · Friction · Hydrogel

1 Introduction

The use of soft contact lenses is extremely widespread [1]. However, issues concerning end-of-day comfort still exist [2]. Discomfort caused by contact lenses has been related to several factors such as dryness, protein adsorption, physiological factors and friction occurring during the blinking process, especially between the anterior side of the lens and the inner eyelid [3–8]. Clinical tests have been performed to understand and improve comfort, and have centered on the trial of different lens materials and ophthalmic solutions [9–13]. The dryness issue has been investigated by studies of the incorporation of wetting agents into contact lenses [8] and on the effect of water content of the lens [14]. A few studies have been carried out to investigate friction of the lens [4–7]. Blinking is the primary physiological contributor to the forces exerted on contact lenses and their consequent motion. Typical values of contact pressure are in the range of 3–5 kPa, sliding speed being around 12 cm/s [15, 16]. The friction studies carried out to date have been based on these reported values, despite the practical difficulties in achieving them because of resolution limits of the microtribometers used. However, the physiological environment has never been taken into account. Rennie et al. [4] investigated the friction between glass and a contact lens by positioning the lens taken from borate buffer on a special holder, without additional lubricant being added. Nairn and Jiang [5] looked at friction, for both the anterior and posterior side of contact lenses, against polymethylmethacrylate (pMMA) and polyhydroxyethylmethacrylate (pHEMA) counter...
surfaces, using ophthalmic solutions as lubricants. Dunn et al. [7] carried out studies on friction between the anterior side of a contact lens and corneal epithelial cells, while Dong and Haugstad [17] looked at friction and adhesion of polyvinylalcohol (PVA) contact lenses by scanning probe microscopy (SPM). Lydon et al. [18] studied the coefficient of friction (CoF) for contact lens versus glass and polyethylene (PE) and, lastly, Ngai et al. [6] investigated friction for a contact lens versus glass system in the presence of saline solution. Interestingly, they also considered the possible effect of protein adsorption from the tear film by incubating some of their lenses in a lysozyme and albumin solution. Apart from the work performed by Ngai et al., these studies generally did not take physiological aspects, such as the eyelid counter surface and the presence of a tear film, into account. Under the physiological conditions on the eye surface, the contact lens is in contact with proteins present in tears and the anterior side of the palpebral conjunctiva (inner eyelid) [7].

This study has shown that measuring contact lens frictional properties without taking the physiological environment into account can lead to misleading results. It is, therefore, important to perform such measurements under biologically relevant conditions. Friction tests on a glass versus contact lens system were performed by means of a microtribometer. The measurement protocol was optimized by varying the functionalization of the glass counter surface, with the aim of mimicking the on-eye environment. A comparative study was carried out by measuring the coefficient of friction of several commercially available contact lenses using the newly developed measurement protocol.

2 Materials and Methods

2.1 Instrument and Setup

Friction tests were performed with a microtribometer (Basalt®, Must, Tetra®, Germany). Cantilevers (Tetra®, Germany) with different ranges of spring stiffness (N/m) were used: \( k_n = 23 \), \( k_t = 23 \), ±10% and \( k_n = 15 \), \( k_t = 15 \), ±10% (\( k_n \) is the normal force spring constant and \( k_t \) is the tangential force spring constant). The contact lens was placed inside a Teflon® chamber on top of a sand-blasted rounded plastic holder (cyclo olefin polymer, Johnson & Johnson Vision Care Inc., USA), matching the internal radius of curvature of the lens, and was held in position by a cast silicone-rubber cover (polyvinylsiloxane, Provil Novo, Germany) and plastic ring (poly(methyl methacrylate), PMMA) (Figs. 1 and 2). Silicone cover and PMMA ring were screwed to the Teflon® chamber by two screws placed at 180° to one another. The anterior surface of the lens was facing upward. The counter surface consisted of a functionalized 5-mm diameter glass disk (cover glass, Thermo Scientific, Germany). Functionalization protocols are described in the following. A 6-mm long glass rod was glued onto the tip of the tribometer cantilever. In turn, the functionalized glass disk was glued to the glass rod, being the latter as centered as possible (Fig. 3). Gluing was
performed using a cyanoacrylate-based glue (UHU GmbH & Co. KG, Germany). The cantilever was then mounted in the tribometer. Just before the test, the cantilever was slowly lowered so that the glass disk approaches the center of the contact lens surface (determined by eye) (Fig. 4). The contact lens was covered with lubricant solution during the friction test. Figure 5 shows an example of contact lens and counter surface mounted in the microtribometer. Contact area and pressure between the flat glass counter surface and the soft contact lens (Table 1) were estimated using the Hertzian contact model as described by Chaudhri and Yoffe [19]. They related the radius of the contact area \( a_h \) to the mechanical properties of the materials by

\[
a_h = R P \left[ \frac{(1 - v_1^2)}{E_1} + \frac{(1 - v_2^2)}{E_2} \right]^{\frac{1}{2}}
\]

\( R \) being the radius of the contact lens, \( P \) the load, \( v_i \) Poisson’s ratio and \( E_i \) Young’s modulus.

French reported the Young’s modulus for a series of contact lenses materials [20]. For the purposes of this publication, values of contact area and pressure were estimated for the contact lens materials with the highest and lowest moduli. These materials are:

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACUVUE®</td>
<td>0.3 MPa</td>
</tr>
<tr>
<td>NIGHT &amp; DAY®</td>
<td>1.5 MPa</td>
</tr>
</tbody>
</table>

ACUVUE® brand contact lens is a cast-molded polyHEMA contact lens manufactured by VISTAKON, a division of Johnson & Johnson Vision Care Inc., Jacksonville, FL, USA. The water content is around 58%. Focus Night & Day is a cast-molded silicone hydrogel contact lens manufactured by CIBA VISION®. It has a water content of about 24% and has a plasma-treated surface. Poisson’s ratio has not been reported for these materials. A value of 0.3 was used in the calculations. The values for the glass counter surface are not important for this analysis. The Young’s modulus is much greater than that of the contact lenses; therefore, \( 1/E \) becomes negligible in Eq. 1.

### 2.1.1 Sample Preparation

Contact lenses were removed from their packaging immediately before the test and installed on the sample holder, which had previously been cleaned with water and

<table>
<thead>
<tr>
<th>Normal force (mN)</th>
<th>Contact area (mm²)</th>
<th>Contact pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACUVUE®</td>
<td>NIGHT &amp; DAY®</td>
</tr>
<tr>
<td>2.50E - 01</td>
<td>0.093</td>
<td>0.032</td>
</tr>
<tr>
<td>5.00E - 01</td>
<td>0.15</td>
<td>0.057</td>
</tr>
<tr>
<td>1.00E + 00</td>
<td>0.24</td>
<td>0.081</td>
</tr>
<tr>
<td>2.00E + 00</td>
<td>0.37</td>
<td>0.13</td>
</tr>
<tr>
<td>3.00E + 00</td>
<td>0.49</td>
<td>0.17</td>
</tr>
<tr>
<td>4.00E + 00</td>
<td>0.59</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 1 Contact area and contact pressure estimated values for ACUVUE® and NIGHT & DAY® pressing against a flat glass surface
detergent (1:1) (hydrochloric acid 300 mmol/L, detergent 1%, Cobas Integra, Roche, Switzerland) and wetted with lubricant solution. Excess storage solution (from lens packet) trapped between the lens and the holder was avoided by gently tapping the edge of the lens on a clean surface. The contact lens was immediately covered with lubricant solution to avoid drying.

2.1.2 Counter Surface Preparation

Before fixation onto the cantilevers, glass disks were oxygen plasma cleaned for 2 min (Diener Electronic, Germany) and hydrophobized with hexamethyldisilazane (Alfa Aesar®, Germany) from the gas phase for 30 min in a vacuum desiccator. To assess successful hydrophobization, the dynamic water contact angle (>75°) was measured on hydrophobized glass model surfaces. Contact angle (advancing \(\theta_{\text{advancing}}\)) measurements were performed with a Krüss contact angle–measuring system (G2/G40 2.05-D, Krüss GmbH, Germany) with a drop speed of 15 \(\mu\)L/min. A movie with 100 images was recorded for the advancing contact angle and the analysis was carried out by means of the tangent method 2 routine of the Krüss Drop-Shape Analysis program (DSA version 1.80.0.2 for Windows 9x/NT4/2000, 1997-2002 KRUESS). Hydrophobized glass disks were mounted on the cantilever as previously described. Immediately before the friction tests, the glass disk mounted on the cantilever was incubated in a 1 mg/mL mucin solution (from bovine submaxillary glands type I–S, Sigma-Aldrich®, Germany) in HEPES 1 (10-mM \(N\)-2-hydroxyethylpiperazine-\(N\)-2 ethanesulfonic acid, pH 7.4, BDH™, UK) for 30 min and rinsed with ultra-pure water to remove any non-adsorbed species. Additionally, hexamethyldisilazane and mucin layer thickness in the dry state were evaluated by ellipsometry (J.A. Woollam Co., Inc., Ellipsometry Solutions, USA) on oxidized silicon wafer model surfaces. The surface modification protocol applied to the silicon wafers was the same as for glass model surfaces, with additional initial pre-cleaning with toluene and isopropanol. Adlayer thickness measurements were conducted under ambient conditions at an angle of incidence of 70° with respect to the surface normal, averaging 50 measurements at each point. The spectral range was 370–995 nm. Data were fitted with the WVASE32 analysis software using a three-layer model (Si/SiO_2/Cauchy), where Si was assumed to be constant for all wafers (1 nm). The SiO_2 layer was fitted with the SiO_2 model before hydrophobization with silanes and mucin adsorption; the silane and mucin layers were fitted using the Cauchy (organic) layer model. The dry film thickness of the silane layer and of the mucin layer was assumed to have a refractive index of 1.45. Characterization results are shown in Table 2.

To mimic the surface of the eyelid, glass disks with different functionalizations were evaluated: oxygen plasma cleaning (hydrophilic), silanization (hydrophobic) and protein or polymer attachment. Proteins used were fibrinogen (from bovine plasma, fraction I type I–S, Sigma-Aldrich®, Germany) and lysozyme (AppliChem, Germany), whereas poly(L-lysine)-graft-poly(ethylene glycol) (PLL(20)-g[3.5]-PEG(2), SuSoS AG, Switzerland) was used for polymer coating. Plasma cleaning and silanization were carried out as described above. Fibrinogen and lysozyme coatings were achieved by immersing plasma-cleaned glass disks, already glued onto the cantilevers, in 1.5 mg/mL fibrinogen in phosphate-buffered saline (PBS) or 1 mg/mL lysozyme in HEPES 1 for 30 min. Finally, PLL-g-PEG functionalization was performed by immersing plasma-cleaned cantilever-mounted glass disks into 0.1 mg/mL PLL-g-PEG solution in HEPES 1 for 30 min. After incubation, the disks were rinsed with ultra-pure water and dried with nitrogen. Results are discussed in Sect. 3.

Table 2 Advancing contact angle measurements for treated glass surfaces and ellipsometry thickness measurements for SiO_2 model surfaces

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Contact angle (°)</th>
<th>Adlayer thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma</td>
<td>&lt;10</td>
<td>n/a (substrate base)</td>
</tr>
<tr>
<td>Hexamethyldisilazane</td>
<td>&gt;75</td>
<td>0.25 (±0.04)</td>
</tr>
<tr>
<td>Mucin</td>
<td>&lt;45</td>
<td>1.2 (±0.1)</td>
</tr>
</tbody>
</table>

Adlayer thickness measurements were performed on two separate occasions with a total of six measurements.
2.1.3 Lubricant Solution

A 0.9% sodium chloride solution with a borate buffer (pH = 7.4) was used as a control (packing solution [PS] supplied by Johnson & Johnson Vision Care Inc. [JJVCI]). As a lubricant solution, a tear-mimicking solution containing PS plus serum (Precinorm U, Roche, Germany) (20:1) plus lysozyme (5 mg/mL) was used to perform comparative friction tests described in Sect. 3.

2.1.4 Experimental Conditions

All experiments for the optimization step were carried out using 1•DAY ACUVUE® and 1•DAY ACUVUE® MOIST™ brand contact lenses. In particular, the influence of sliding cycles and velocity was determined using tear-mimicking solution as a lubricant and mucin-coated silanized glass disks as counter surfaces. The effect of glass disk functionalization to mimic the eyelid was evaluated using packing solution as lubricant. The comparative study was performed when a model to mimic the natural eye environment was established: All contact lenses were tested in tear-mimicking solution against mucin-coated silanized glass disks.

2.1.5 Measurement Program

The measurement program used for the optimization step and the comparative friction tests involved applying three sets of seven normal forces varying from 0.25 to 5 mN. Two cycles, backward and forward, were recorded for each target normal force value. Only data points obtained from the second cycle were recorded and subsequently analyzed. Ageing was simulated by performing 50 additional cycles at 2-mN normal force between each set of seven normal forces. In detail, the measurement protocol consisted of the following steps: measurement of coefficient of friction (CoF) with seven normal forces, 50 ageing cycles, measurement of CoF with seven normal forces, 50 ageing cycles to give a total of 100 ageing cycles and again a final CoF determination. The measured stroke length was 1 mm and the sliding speed was 0.1 mm/s. During optimization of the measurement protocol, 1 and 10 mm/s sliding speeds were also investigated. For data processing, lateral and experimentally determined normal force values were calculated by averaging 20 data points at around 0.5-mm distance, and then plotted in a graph. Trace and retrace curves obtained in this way were averaged and a coefficient of friction was determined from the slope.

2.1.6 Contact Lenses

The lenses used in this study are listed in Table 3. The lenses were supplied by JJVCI.

3 Results

3.1 Optimization Measurements

3.1.1 Effect of Number of Sliding Cycles

Preliminary tests run on 1•DAY ACUVUE® and 1•DAY ACUVUE® MOIST™ brand contact lenses to investigate the influence of ageing on friction revealed that CoF at 100 cycles at a normal load of 2 mN (maximum ageing) is equal to or not significantly different than CoF at 0 cycles (no ageing) (Fig. 6), indicating that there is no change in the coefficient of friction for either lens type within the limits of this experimental protocol. 1•DAY ACUVUE® MOIST™ contact lenses exhibited significantly lower CoF than 1•DAY ACUVUE® contact lenses. Significant differences in the results were evaluated by means of statistical analysis (p value <0.05).

3.1.2 Effect of Sliding Velocity

CoF was shown to significantly increase (p value <0.05) with sliding velocity for both 1•DAY ACUVUE® and 1•DAY ACUVUE® MOIST™ brand contact lenses (Fig. 7). Above 1 mm/s, distinguishing between the two lenses investigated was difficult because of high and overlapping standard deviations.

3.1.3 Choice of Counter Surface

The CoF was measured for different counter surfaces in packing solution. Results show that the lowest CoF was obtained for PLL-g-PEG-coated glass disks, whereas higher CoF values were obtained for hydrophilic and lysozyme-coated glass disks (Fig. 8). In the case of hydrophilic glass disks, CoF for 1•DAY ACUVUE® MOIST™ was significantly higher than for 1•DAY ACUVUE®. In all other cases where there is a significant difference, 1•DAY ACUVUE® MOIST™ contact lenses exhibited lower CoF than 1•DAY ACUVUE®. No post measurement testing was performed on the mucin-coated counter surface. As the coefficient of friction did not change between the first ramp (0 cycles) and the final ramp (after 100 cycles), the lens surface and counter surface were deemed unchanged during the experiment.

3.2 Comparative Study

Various commercially available daily disposable and reusable contact lenses were tested using the optimized protocol, tear-mimicking solution as lubricant and mucin-coated silanized glass as counter surface. Friction
coefficient was evaluated before (0 cycles) and after ageing (50 and 100 cycles) (Tables 4 and 5; Figs. 9 and 10).

4 Discussion

The goal in the development of a model is to be able to use the in vitro data to predict in vivo performance. To correlate clinical contact lens performance with the model results and to evaluate potential sources of comfort-driven performance, possible lens discontinuation and adverse effects to the coefficient of friction, it is desirable to measure the CoF of contact lenses in the most biologically relevant conditions.

In the physiological environment, contact lenses are in contact with proteins present in tears, with corneal cells (on the posterior side) and with the palpebral conjunctiva (on the anterior side). Most studies carried out so far on the tribology of contact lenses have not taken such physiological conditions into account [4–6, 18]. The coefficient of friction is a property of the sliding pair; therefore, the determination of the coefficient of friction using different counter surfaces would be expected to produce different results. When comparing the results found in this study
with those from previous studies, the following observations can be made. Rennie et al. [4] evaluated Etafilcon A using an untreated spherical glass counter surface at normal forces of 3–20 mN. They report that the coefficient of friction obeys a sliding speed–dependent power law. Using their data, a coefficient of friction of about 0.15 would be predicted for Etafilcon A. Our results, on the other hand, show a coefficient of friction of 0.02–0.09 that was invariant with normal force. Nairn and Jiang [5] evaluated the coefficient of friction for SeeQuence (Polymacon) brand contact lenses using a pin-on-disk tribometer. They report coefficients of friction of 0.05–0.3 in saline. Our results for Optima™ 38, a Polymacon lens produced by the same manufacture, were 0.55. Finally, Ngai et al. [6] reported the coefficients of friction for Lotrafilcon A and Polymacon A to be 0.27 (calculated from normal and tangential forces in their study). Our results were 0.38 and 0.55, respectively. These variations show the need for a standardized method for the measurement of the coefficient of friction for contact lenses. Protein adsorption on contact lenses was investigated by Garrett and Milthorpe [21] and by Ngai et al. [6], who also performed friction tests. The major finding was that CoF decreased at an early stage of protein deposition, but it was hypothesized to increase in time because of protein denaturation. Protein deposition on contact lenses was also found to be related to comfort, vision and increased inflammatory responses, as reviewed by Jones [22]. In this study, the physiology of the eye was taken into account by establishing a measuring protocol that mimics the natural environment. For this optimization step, not only parameters such as ageing and sliding speed were considered but also the role of eyelid and tears. The eyelid surface was mimicked by the counter surface, which was required to meet several conditions. It had to be hard and flat so that any lens deformation would be accommodated on contact. This would yield a constant contact area and eliminate the modeling required when using a spherical counter surface [4]. For this study, a hard–soft contact pair was chosen rather than the soft–soft contact pair found in the ocular environment. The hard–soft pair was chosen because the goal of this study was to provide a method to conveniently compare materials rather than to mimic the eye’s mechanics exactly. It was felt that the hard glass surface would produce more reproducible results and has less experimental difficulty than a soft counter surface. Additionally, it was required not to adhere components from the contact lens and to provide a surface representative on the ocular environment. The various glass functionalization procedures that were investigated were deliberately chosen with the aim of mimicking the eyelid. PLL-g-PEG, well known for its lubricating properties in an aqueous environment [23], gave rise to the lowest CoF,
Table 4 Coefficients of friction measured on daily disposable contact lenses at 0.1 mm/s, arranged in ascending order of CoF at 100 cycles

<table>
<thead>
<tr>
<th>Name of contact lens</th>
<th>0 Cycles</th>
<th>Standard deviation (±)</th>
<th>50 Cycles</th>
<th>Standard deviation (±)</th>
<th>100 Cycles</th>
<th>Standard deviation (±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLARITI™ 1 day</td>
<td>0.017</td>
<td>0.001</td>
<td>0.014</td>
<td>0.002</td>
<td>0.017</td>
<td>0.004</td>
</tr>
<tr>
<td>1•DAY ACUVUE® MOIST™</td>
<td>0.022</td>
<td>0.010</td>
<td>0.019</td>
<td>0.006</td>
<td>0.024</td>
<td>0.003</td>
</tr>
<tr>
<td>1•DAY ACUVUE® TruEye (narafilcon B)</td>
<td>0.032</td>
<td>0.013</td>
<td>0.030</td>
<td>0.006</td>
<td>0.034</td>
<td>0.009</td>
</tr>
<tr>
<td>1•DAY ACUVUE® TruEye (narafilcon A)</td>
<td>0.031</td>
<td>0.028</td>
<td>0.035</td>
<td>0.021</td>
<td>0.037</td>
<td>0.019</td>
</tr>
<tr>
<td>1•DAY ACUVUE®</td>
<td>0.046</td>
<td>0.023</td>
<td>0.024</td>
<td>0.004</td>
<td>0.047</td>
<td>0.029</td>
</tr>
<tr>
<td>Focus™ DAILIES® All day comfort™</td>
<td>0.122</td>
<td>0.021</td>
<td>0.113</td>
<td>0.016</td>
<td>0.091</td>
<td>0.009</td>
</tr>
<tr>
<td>Proclear® 1 day</td>
<td>0.090</td>
<td>0.033</td>
<td>0.081</td>
<td>0.039</td>
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<tr>
<td>ClearSight™ 1 Day</td>
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<td>0.181</td>
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<tr>
<td>DAILIES® AquaComfort Plus®</td>
<td>0.344</td>
<td>0.000</td>
<td>0.474</td>
<td>0.012</td>
<td>0.424</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Table 5 Coefficients of friction measured on reusable contact lenses at 0.1 mm/s, arranged in ascending order of CoF at 100 cycles

<table>
<thead>
<tr>
<th>Name of contact lens</th>
<th>0 Cycles</th>
<th>Standard deviation (±)</th>
<th>50 Cycles</th>
<th>Standard deviation (±)</th>
<th>100 Cycles</th>
<th>Standard deviation (±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVAIRA®</td>
<td>0.011</td>
<td>0.002</td>
<td>0.018</td>
<td>0.003</td>
<td>0.018</td>
<td>0.001</td>
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<tr>
<td>ACUVUE® OASYS™</td>
<td>0.016</td>
<td>0.014</td>
<td>0.024</td>
<td>0.018</td>
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<td>CLARITY™</td>
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<td>ACUVUE® ADVANCE™ PLUS</td>
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<td>0.005</td>
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<td>0.002</td>
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<td>0.090</td>
<td>0.010</td>
</tr>
<tr>
<td>[AIR OPTIX®] NIGHT &amp; DAY® AQUA</td>
<td>0.108</td>
<td>0.051</td>
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<td>0.166</td>
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<td>0.187</td>
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<td>0.048</td>
<td>0.292</td>
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<tr>
<td>NIGHT &amp; DAY®</td>
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<td>0.081</td>
<td>0.394</td>
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<td>0.443</td>
<td>0.041</td>
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<td>Optima™ 38</td>
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<td>0.587</td>
<td>0.010</td>
<td>0.551</td>
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<td>SOFLENS®</td>
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<td>0.542</td>
<td>0.033</td>
<td>0.513</td>
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</tbody>
</table>

whereas hydrophilic glass led to an unusual behavior (Fig. 8). Against a hydrophilic counter surface, 1•DAY ACUVUE® MOIST™ brand contact lenses exhibited a higher friction coefficient than 1•DAY ACUVUE® despite the presence of polyvinylpyrrolidone (PVP). This is inconsistent with the tactile sensation felt when rubbing 1•DAY ACUVUE® MOIST™ lens surface between the fingers. 1•DAY ACUVUE® brand does not feel as slippery. Belyakova et al. [24] reported a strong attraction between PVP and silicon dioxide. The higher coefficient of friction observed for 1•DAY ACUVUE® MOIST™ brand lens is attributed to an attractive interaction between PVP in the 1•DAY ACUVUE® MOIST™ brand lens matrix and hydrophilic glass surface. Therefore, the high tangential force results from adsorption of the PVP on the counter surface rather than from an intrinsically high coefficient of friction for 1•DAY ACUVUE® MOIST™ brand. In the case of PLL-g-PEG, no difference in terms of friction could be observed between 1•DAY ACUVUE® and 1•DAY ACUVUE® MOIST™ brand, most likely masked by the excellent lubricating properties of PEG. For these reasons, the first two functionalization protocols were discarded. All other protocols gave rise to the opposite trend, as expected. Fibrinogen was chosen to have a more biologically oriented counter surface and because it readily adsorbs on glass. The use of lysozyme went one step further, as it is the major component of tears. Both proteins lead to a clearly distinguishable behavior of 1•DAY ACUVUE® and 1•DAY ACUVUE® MOIST™ brand, although friction coefficients were relatively high. Mucin, a natural lubricant additive, became the surface coating of choice for performing friction tests on glass. It was chosen as it is a glycoprotein found in the mucous membrane that constitutes the palpebral conjunctiva, and is therefore in contact with lenses in their operating environment. In particular, mucin from bovine submaxillary glands was used as it is a
readily available mucin that functions at pH 7, as do mucins in the eye. Hydrophobization of glass disks before incubation in mucin solution was performed to enhance mucin adsorption. The major finding with these experiments is that the CoF can significantly vary according to the measuring protocol.

Another important aspect of the physiology of the eye is the presence of tears, which play a fundamental role in lubrication. For the evaluation of different contact lens materials, the use of a lubrication solution that is closely related to human tears is preferred. Human tears contain a protein array that is similar to serum but is lacking lactoferrin, lysozyme and tear-specific prealbumin [25]. Yoon et al. [26] reported the use of diluted antilogous serum as eye drops for severely diseased patients. In their studies, they diluted the serum 1:20 with saline, and did not add any of the tear-specific proteins. Hill et al. [27] described a synthetic tear fluid of 5% blood plasma supplemented with lysozyme at 4.5 g/L and lactoferrin at 1.7 g/L. The tear-mimicking fluid used in this study was modified increasing the lysozyme to 5 g/L and eliminating the lactoferrin.

Lipids are an important part of the dacruon [28] and have been shown to adsorb onto contact lenses [29]. Cher [28] has proposed dacruon as a new description of the tear film. The historical model describes the tear film as a lipid layer, an aqueous layer and a mucus layer. The dacruon model describes it as a continuous concentration gradient of mucin from the ocular surface to the lipid layer of the
tear film. Lipids are reported to be floating on the surface of the dacron [28], and therefore would not be involved in the lubrication of the lid on the contact lens unless a break in the tear film would occur, allowing lipids to adsorb on the surface of the lens. This eventuality can take place as a consequence of eye dryness, irritation and on insertion of the contact lens. Our model does not contemplate such situations, but rather focuses on mimicking the eyelid–contact lens system in standard conditions, where the tear film is intact and lipids are not adsorbing on the contact lens surface. Moreover, the inclusion of lipids into the tear-mimicking fluid results in a heterogeneous lubricating fluid, which could affect the reproducibility of measurements. For these reasons, lipids were not included in the described model.

For the determination of our eye-mimicking system, contact pressure and sliding speed were also taken into account. Typical in vivo pressure and speed values are reported to be around 3–5 kPa and 1.2 mm/s, respectively. We chose normal loads that allow our setup to be in the contact pressure and sliding speed range described in literature. Contact pressures for 1•DAY ACUVUE® were estimated by using the Hertzian contact model and were found to be in the range of 2.6–6.5 kPa for the normal loads used in this study.

The purpose of this model is to evaluate the coefficient of friction of contact lenses against a realistic counter surface. The data in Fig. 7 suggest that there is a convergence of the coefficients of friction as the sliding speed is increased. This is thought to be the result of an increased importance of hydrodynamic lubrication. However, the goal is to determine the materials properties, and this can be achieved by measuring the coefficient of friction in the boundary–lubrication regime. The sliding speed of 0.1 mm/s, which is one order of magnitude lower than literature values, was chosen to reduce the possibility of hydrodynamic effects and to ensure that measurements were made in the boundary–lubrication region.

Once optimization of the measurement protocol was achieved, with respect to the physiological environment, commercially available contact lenses were tested for frictional properties and compared with each other (Figs. 9 and 10). PVP-containing lenses exhibited the lowest friction coefficients, typically less than 0.050, whereas friction coefficient values for non-PVP-containing lenses ranged from 0.100 to 0.600. The exceptions are Sauflon CLARITI™, which contains the monomer N-vinylpyrrolidone (NVP), and AVAIRA®, which contains a monomer analogous to NVP. However, Sauflon (CLARITI™) claims that the N-vinylpyrrolidone in the formulation homopolymerizes to form PVP in situ [30]. In the United States Adopted Names Council (USAN) document for AVAIRA® (enflcon A), it is reported that the lens contains a homopolymer of N-ethenyl-N-methylacetamide, which can homopolymerize to produce a PVP analog in situ. This frictional behavior was expected because of the lubricating properties of PVP or its analogs and confirmed the validity of our measurement protocol, which proved to be successful in distinguishing between contact lens frictional properties.

5 Conclusion

Friction tests were run on commercially available contact lenses with a microtribometer. The measurement protocol was optimized according to sliding speed, counter surface and lubricant–solution composition, to achieve a set-up that mimics the physiological environment. The best combination was found to consist of 0.1 mm/s sliding speed, mucin-coated glass as a counter surface and a lubricant based on packing solution containing lysozyme and serum. Measuring contact lens frictional properties without taking physiological conditions into account was shown to lead to different and potentially misleading results, demonstrating the importance of establishing a broadly valid biologically relevant measurement protocol.

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