Proceedings of ANTEC `95, Boston, MA, May 7-11, 1995.

MEASUREMENT OF THE FRICTION AND LUBRICITY PROPERTIES OF CONTACT LENSES

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Introduction

During blinking, there is sliding motion between the eyelid and the surface of the eye. When a contact lens is placed on the eye, the surfaces of the contact lens might influence the frictional forces during blinking and therefore change the "feel" of the blinking process. To study the effect that contact lenses have on the blinking process and any subsequent role in patient comfort, it is useful to study the friction and lubricity properties of contact lenses.

A contact lens sits on the corneal surface of the eye. After a short period of time in the eye, the front surface of the lens will be coated with tear fluid. During blinking, there is some motion of the lens with respect to the corneal surface and more motion of the eyelid with respect to the lens surface. We were thus interested in the kinetic coefficients of friction of both surfaces of contact lenses and of the effects of lubricants, such as tear fluid, on the sliding motion.

This paper describes a custom-built friction and lubrication apparatus that was optimized for studying contact lenses. Typical blinking speeds are 12 cm/sec [1]. Typical pressures during blinking are 0.35 to 0.40 N/cm^2 (35-40 g/cm^2) [1,2]. Our apparatus was developed to work at a range of speeds and pressures in a window around these typical eyelid conditions. After describing the apparatus, we give some typical results for coefficient of friction. The results include the lubrication effectiveness of some commercially available opthalmic solutions, the difference between the front and back surfaces of a contact lens, and the effect of varying from the typical eyelid speeds and pressures.

Friction and Lubricity Apparatus

We measured kinetic friction, with and without lubricants, using a pad-on-disk apparatus. The heart of the instrument is shown in Figure 1. The pad is attached to a cantilever arm that is made from two crossed cantilever beams. The position of the cantilever can be adjusted vertically and the vertical position determines the normal force (N). The disk is attached to a rotating stage. As the disk rotates, the sliding motion exerts a frictional force (F) on the pad.

The normal and frictional forces cause deflections of the relatively compliant beam. These deflections are detected optically. The tips of each of the crossed beams are coated with a reflective coating. Laser 1 reflects in the tangential direction off beam 1 and is used to monitor tangential deflections. A change in surface angle of beam 1 of $\Delta\theta_1$ adds to both the angle of incidence and the angle of reflection of laser 1. The reflected light is thus rotated by $2\Delta\theta_1$. The spot on the position-sensitive detector shifts by $\Delta x_1 = 2r_1\Delta\theta_1$ where r_1 is the distance from the beam to the detector. Similarly laser 2 reflects in the normal direction off beam 2. The spot in its detector shifts by $\Delta x_2 = 2r_2\Delta\theta_2$.

Assuming linear responses of the beams and the position sensitive detectors, $\Delta\theta_1$ will be proportional to F, $\Delta\theta_2$ will be proportional to N, and $\Delta x_i = k_i\Delta v_i$, where k_i is the calibration constant for detector i and Δv_i is the voltage signal at detector i. Combining all effects, the system calibration can be reduced to

$$F = \alpha_F \Delta v_1 \qquad (1)$$

$$N = \alpha_N \Delta v_2 \qquad (2)$$

$$\mu = \frac{F}{N} = \alpha \frac{\Delta v_1}{\Delta v_2} \qquad (3)$$

where α_F is the frictional-force calibration constant, α_N is the normal-force calibration constant, and α is the overall system, or coefficient of friction calibration constant. Using beam theory, the calibration constants have the following forms:

$$\alpha_F = \frac{E d_1 h_1^3 k_1}{12 r_1 \left[(l_1+l_2)^2 - l_2^2\right]} \qquad (4)$$

$$\alpha_N = \frac{E d_2 h_2^3 k_2}{12 r_2 \left[l_2^2 + \frac{d_2 h_2^3}{d_1^3 h_1}\left((l_1+l_2)^2 - l_2^2\right)\right]} \qquad (5)$$

$$\alpha = \frac{d_1 h_1^3 k_1 r_2}{d_2 h_2^3 k_2 r_1}\left[\frac{l_2^2}{(l_1+l_2)^2 - l_2^2} + \frac{d_2 h_2^3}{d_1^3 h_1}\right] \qquad (6)$$

where E is the modulus of the beam material, and l_i, d_i, and h_i are the length, depth, and thickness of beam i, respectively (see Figure 1). Notice that α depends only on geometry and is independent of the modulus of the beam material. A typical setup for contact lens experiments has l_1 = 3.0 cm, l_2 = 2.89 cm, d_1 = 0.23 cm, d_2 = 0.28 cm, h_1 = h_2 = 0.0127 cm, r_1 = 14.5 cm, r_2 = 10.8 cm, k_1 = 0.161 cm/v, and k_2 = 0.152 cm/v. The beams were made from molybdenum which has E = 315 GPa. These constants result in $\alpha_F = 2.508 \times 10^{-3}$ N/v, $\alpha_N = 5.213 \times 10^{-3}$ N/v, and $\alpha = 0.208$.

For the friction system to work properly, the cantilever beams must remain linear. We must therefore assure no yielding of the molybdenum. Using beam theory, it is simple to calculate the maximum stresses in the beams as a function of normal and frictional loads. Comparing these stresses to the yield strength of molybdenum of 565 MPa, the typical system mentioned above is limited to normal loads of 147 mN. Our typical pad is 0.06 cm^2 which translates to a normal force of 21 mN when using eyelid conditions of 0.35 N/cm^2. We are thus comfortably within the linear range of molybdenum. The current apparatus could easily be modified to work at higher loads simply by changing the dimensions of the crossed cantilever beams.

Normal force is controlled by positioning the cantilever beam at a fixed position. This method of setting normal forces requires the disk position to remain the same while rotating and therefore necessitates careful alignment. First we needed a rotation motor with low axial run out. Any imprecision in the motor bearings can translate into oscillations in normal force. Second, we mounted the disk on an adjustable stage. Three fine-thread screws could be adjusted to optimize the alignment of the disk relative to the cantilever beam holder. By using a dial indicator or by monitoring normal force while the disk was rotating we could achieve disk flatness within ±10 μm. At least this level of flatness is required for getting good results.

For lubrication experiments, we added a short wall to the disk to contain the lubricant. If too much lubricant was added, it could add hydrodynamic drag forces to the side of the pad that would influence the measurement of the coefficient of friction. For each lubricant system, we did experiments as a function of lubricant volume to insure the hydrodynamic drag effects were negligible. No humidity control was required for lubrication experiments because the samples were immersed in water.

Results

Some raw experimental results are given in Figure 2. The normal force has slight oscillations which were due to residual misalignment in the disk and to resonance of the beam. Converting the magnitude of the oscillations to beam deflections, the residual misalignment was less than ±10 μm. The frictional force has more oscillations which are a consequence of real surface effects (*i.e.*, slip-stick motion). The ratio of the frictional force to the normal force gives the kinetic coefficient of friction. The kinetic coefficients of friction reported here were all averaged over about 100 sec of stable sliding motion.

Table 1 gives some results for lubrication of a Bausch & Lomb SeeQuence® contact lens sliding on a polycarbonate disk. The lubrication was provided by various, commercially available opthalmic solutions. With no lubricant the coefficient of friction was 0.640. All solutions provided some lubrication. The lubrication effectiveness ranked in the order Bausch & Lomb Artificial Tears > ReNu® > Allergen Complete > Alcon Opti-Free > Bausch & Lomb Saline where higher ranking indicates a lower coefficient of friction (*i.e.*, more lubrication). The viscosity of each opthalmic solution is also listed in Table 1. The ranking of the viscosities is nearly identical to the ranking of the lubrication effect with higher viscosity providing more lubrication. A useful goal for developing improved opthalmic solution is to either get higher viscosity, without affecting other properties, or to find new solutions that provide better lubrication even with low viscosities.

The processing of contact lenses can lead to differences between the anterior and posterior surfaces. The posterior surface is the surface that rests on the cornea; the anterior surface is the one exposed to the tear fluid and the one that contacts the eyelid during blinking. Table 2 lists the coefficient of friction for Bausch & Lomb SeeQuence® and SeeQuence® 2 lenses while sliding on either a poly-methyl-methacrylate (PMMA) disk or a poly-hydroxy-ethyl-methacrylate (PHEMA) disk. The sliding motion was lubricated by a saline solution. There were reproducible differences between the two surfaces with the coefficient of friction for the anterior surface always being higher than for the posterior surface. We also noticed significantly more slip-stick motion while sliding on the anterior surface than on the posterior surface. In the eye, there is more sliding motion on the anterior surface than on the posterior surface. The coefficient of friction for the anterior surface is probably the more important one for determining contact lens comfort. The results in Table 2 suggest there is potential for reducing the coefficient of friction of the anterior surface. By varying processing methods, it could, perhaps, be made as low as the coefficient of friction on the posterior surface.

The coefficient of friction during lubrication is potentially influenced by sliding speed (v), normal force (N), and solution viscosity (η). In lubrication theory, these three quantities often appear in a single quantity called the Sommerfeld number

$$S = \frac{\eta v}{NL} \tag{7}$$

where L is a sample dimension. Experiments on lubrication of metal surfaces as a function of Sommerfeld number often reduce to the Stribeck curve shown in Figure 3 [3]. At high Sommerfeld number, the surfaces are lubricated by hydrodynamic lubrication and there is no contact between the surfaces. As Sommerfeld number reduces the surfaces get closer and the coefficient of friction increases. If the lubricant is capable of adsorbing on the surfaces or has additives that adsorb on the surface, the Stribeck curve makes a transition to boundary lubrication. In boundary lubrication, the coefficient of friction is lower than for dry friction and the lubrication is provided by molecular monolayers adsorbed to the surfaces.

Lubrication of contact lens surfaces may not conform to the Stribeck curves of metal-metal lubrication, but experiments as a function of Sommerfeld number are still a convenient method for examining the effect of the important variables of sliding speed and normal force. Figure 4 shows coefficient of friction as a function of Sommerfeld number for a Bausch & Lomb SeeQuence® 2 lens sliding on a PMMA disk while lubricated by a saline solution. The four curves are for four different levels of normal force. The data on each curve were obtained by varying the sliding velocity. The results did not conform to a unique curve as a function of Sommerfeld number; thus there is no master curve for lubrication of contact lenses. All curves, however, decreased with increasing Sommerfeld number. We suggest that contact lens lubrication is boundary lubrication that is possible near the transition to hydrodynamic lubrication.

Similar results for sliding of a Johnson & Johnson NueVue® lens on a PMMA disk while lubricated by a saline solution are given in Figure 5. Compared to the results in Figure 4, these results are less sensitive to normal force and have a stronger indication of a transition to hydrodynamic lubrication at high Sommerfeld number.

Conclusions

We built a pad-on-disk friction apparatus for studying the friction and lubrication properties of contact lenses. A key distinguishing feature of our apparatus is that it was optimized for typical conditions of contact lenses in an eye. We can measure dry friction and the effect of lubricants. The only requirements of the system are that the contact lens can be attached to the pad and that the surface of interest can be obtained as a sufficiently flat two-inch diameter disk (flatness to within ±10 μm).

Lubrication of contact lenses by various opthalmic solutions was observed to be in the boundary lubrication regime. In this regime there is contact between the sliding surfaces and thus the coefficient of friction is influenced by both the lubricant properties and the contact lens surface properties. A good example of the contact lens surface properties is the significant difference between the coefficients of friction of the anterior and posterior surfaces of Bausch & Lomb SeeQuence® and SeeQuence® 2 lenses.

Acknowledgments

This work was supported by a gift from Bausch & Lomb. The work was monitored by Dr. Paul Valint.

References

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Table 1: Viscosity (η) in centipoise and coefficient of friction (μ) for a SeeQuence® lens sliding on a polycarbonate disk while lubricated by various commercial opthalmic solutions.

Solution	η	μ
None	-	0.640
B&L Tear Drop	2.396	0.158
ReNu®	1.198	0.245
Allergen Complete	1.060	0.245
Alcon Opti-Free	0.839	0.273
B&L Saline	0.959	0.308

Table 2: The coefficients of friction for sliding of the anterior or posterior surfaces of SeeQuence® or SeeQuence® 2 on PMMA or PHEMA disks while lubricated by a saline solution.

Surface/Disk	SeeQuence®	SeeQuence® 2
Anterior/PMMA	0.297	0.308
Anterior/PHEMA	0.121	0.115
Posterior/PMMA	0.051	0.046
Posterior/PHEMA	0.045	0.060

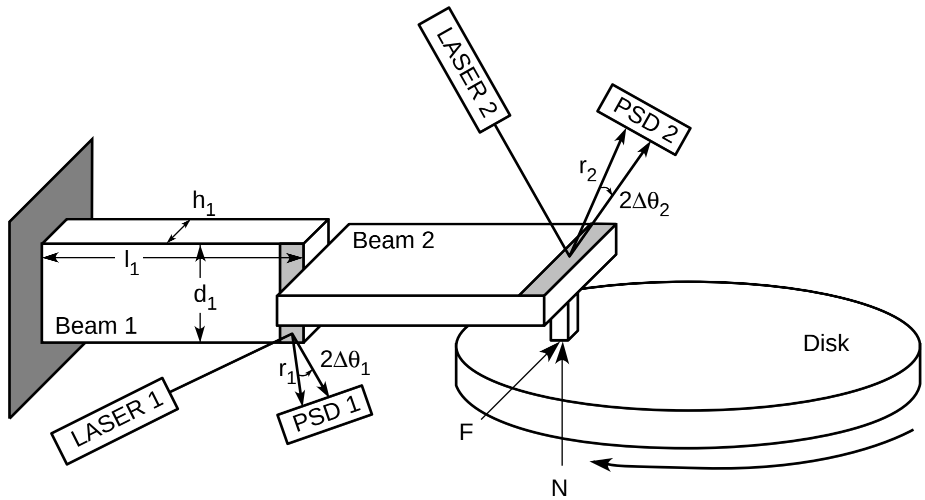

Figure 1: Schematic drawing of the main features of the pad-on-disk friction apparatus. The pad is attached to crossed cantilever beams. Laser 1 detects tangential deflections which are converted into the frictional force. Laser 2 detects normal deflections which are converted into the normal force.

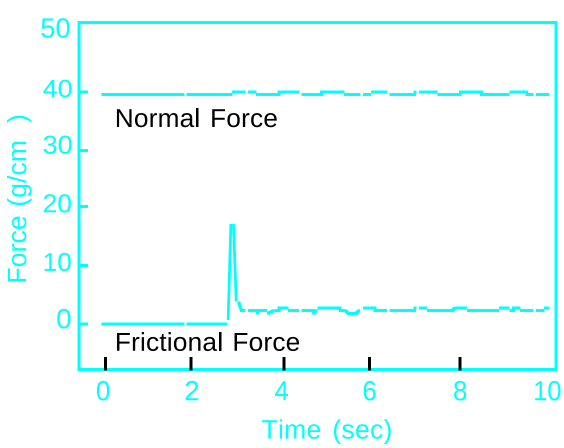

Figure 2: Typical raw data for normal force and frictional force as a function of time

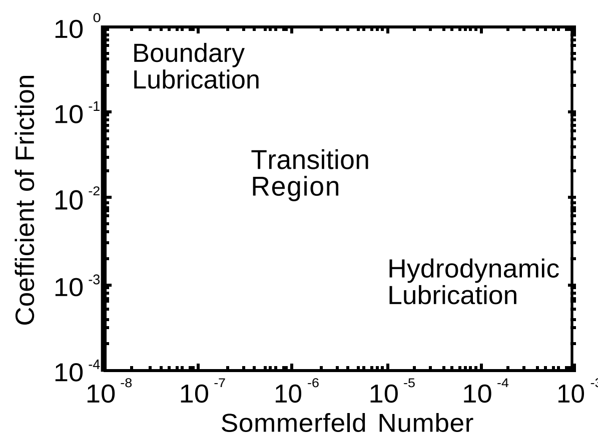

Figure 3: Typical Stribeck curve for coefficient of friction under lubrication conditions as a function of Sommerfeld number

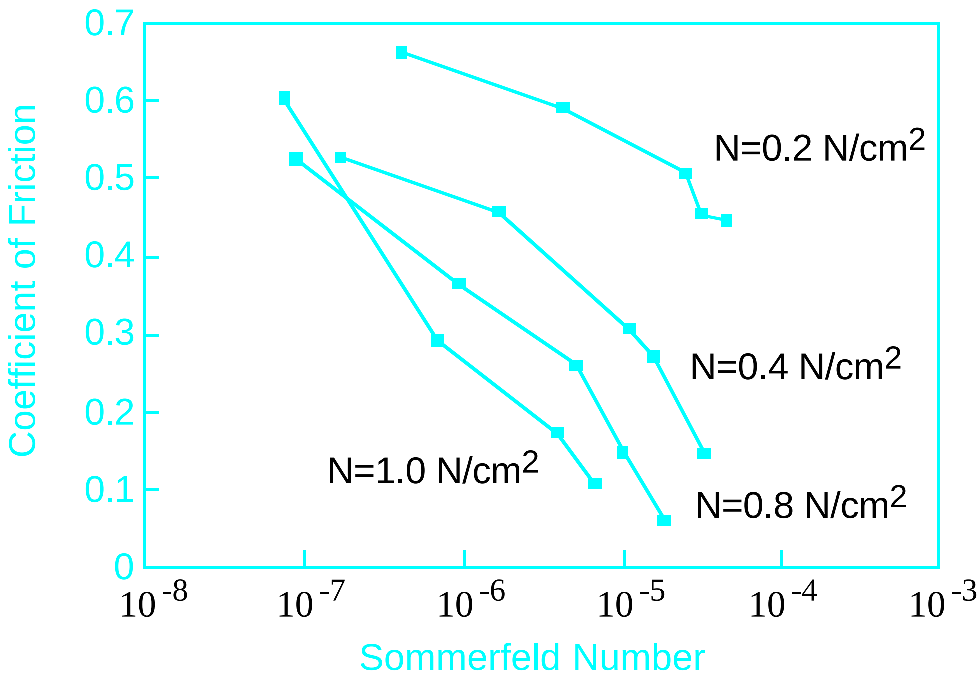

Figure 4: Coefficient of friction as a function of Sommerfeld number for a Bausch & Lomb SeeQuence® 2 Lens sliding on a PMMA disk while lubricated by a saline solution.

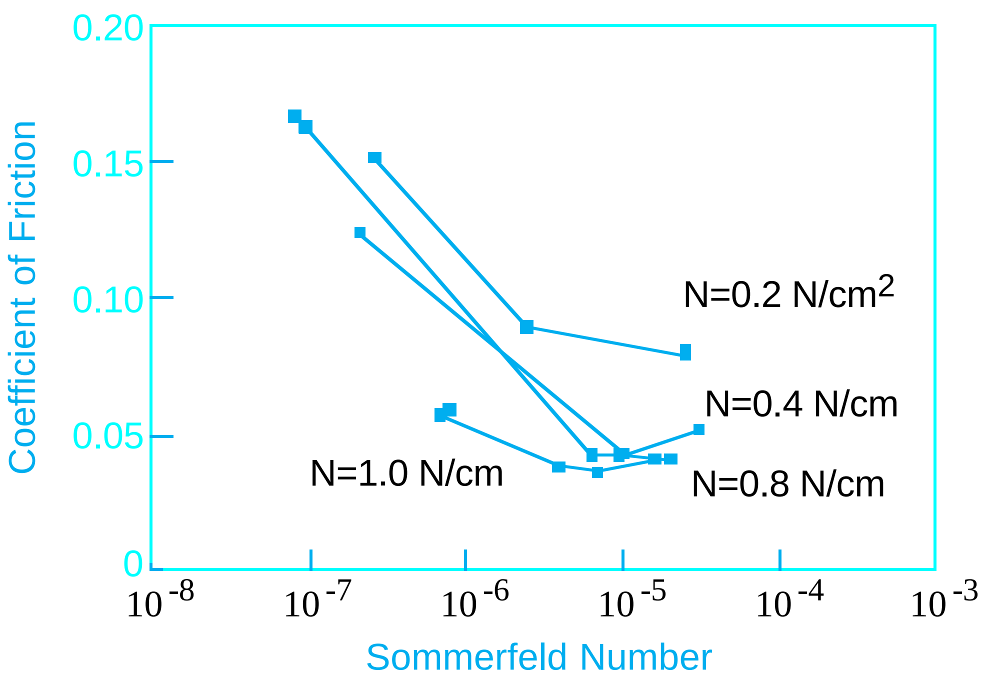

Figure 5: Coefficient of friction as a function of Sommerfeld number for a Johnson & Johnson NueVue® Lens sliding on a PMMA disk while lubricated by a saline solution.

Key Word/Phrase Index

Friction, Lubricity, Contract Lenses, Lubrication