lubricants

MDPI

Article

Experimental Evaluation of the Tribological Properties of Rigid Gas-Permeable Contact Lens Under Different Lubricants

Chen-Ying Su [1,2,†], Hsu-Wei Fang [1,2,3,†], Mousa Nimatallah [4], Zain Qatmera [4] and Haytam Kasem [4,*,†]

[1] Department of Chemical Engineering and Biotechnology, National Taipei University of Technology, No. 1, Sec. 3, Zhongxiao E. Rd., Taipei 10608, Taiwan; chenying.su@mail.ntut.edu.tw (C.-Y.S.); hwfang@ntut.edu.tw (H.-W.F.)
[2] High-Value Biomaterials Research and Commercialization Center, National Taipei University of Technology, No. 1, Sec. 3, Zhongxiao E. Rd., Taipei 10608, Taiwan
[3] Institute of Biomedical Engineering and Nanomedicine, National Health Research Institutes, No. 35, Keyan Road, Zhunan Town, Miaoli 35053, Taiwan
[4] Tribology and Microstructure Laboratory, Department of Mechanical Engineering, Azrieli College of Engineering, Jerusalem 9103501, Israel; mousa.nimatallah@gmail.com (M.N.); zainkatmera@gmail.com (Z.Q.)
* Correspondence: haytamka@jce.ac.il
† These authors contributed equally to this work.

Abstract: Myopia patients wear rigid gas-permeable contact lenses during the day to achieve normal vision, but they might feel uncomfortable, since they are made of hard materials that can cause inappropriate friction and adhesion. These forces affect the biological tissues of the cornea and eyelid. In this study, an in vitro rigid gas-permeable contact lens friction testing method was established to mimic the friction between the eyelid and the rigid contact lens. The lens was rubbed against a gelatin membrane to investigate the tribological properties of artificial tear, saline, and two kinds of care solutions using a dedicated experimental setup. The viscosity, pH value, and surface tension of each lubricant was also analyzed. The friction coefficient of the artificial tear solution was the highest: 0.18 for its static friction and 0.09 for its dynamic friction. In contrast, polysaccharide-containing care solution demonstrated the lowest friction coefficient. The viscosity of artificial tear solutions ranged from 0.97 ± 00 to 1.15 ± 0.16 mPa·s, when the shear rate was increased from 19.2 to 192 1/s, while it ranged from 2.26 ± 1.12 to 2.91 ± 0.00 for polysaccharide-containing care solution. Although the physical–chemical properties of various lubricants could not explain the distinct tribological outcomes, the in vitro tribological testing method for rigid gas-permeable lenses was successfully established in this study.

Keywords: bio-tribology; rigid gas-permeable contact lenses; lubrication; friction

check for updates

Received: 16 April 2025
Revised: 3 June 2025
Accepted: 5 June 2025
Published: 11 June 2025

Citation: Su, C.-Y.; Fang, H.-W.; Nimatallah, M.; Qatmera, Z.; Kasem, H. Experimental Evaluation of the Tribological Properties of Rigid Gas-Permeable Contact Lens Under Different Lubricants. *Lubricants* **2025**, *13*, 256. https://doi.org/10.3390/lubricants13060256

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Myopia is defined as a spherical equivalent refraction of −0.50 diopter or less, and it is increasingly a global problem [1]. Myopia has already affected around 23% of the world population in 2020, and researchers have predicted that by 2025 there will be 50% of the world population affected by myopia [2]. There are many ways to treat myopia, such as wearing single-vision spectacles or contact lenses [3]. To conform with fashion or for convenience during sports or outdoors activities, many myopic people wear contact lenses. The majority of contact lens wearers use hydrogel or silicone hydrogel contact lenses [4], which are soft with various ranges of oxygen permeabilities and water content. In contrast, rigid gas-permeable (RGP) contact lens are mainly made by polymethylmethacrylate (PMMA), which is a hard material. Fewer myopia wearers are willing to wear these due

to the discomfort [4]. However, an increasing number of schoolchildren prefer to wear orthokeratology (ortho-k) lenses that are modified RGP lenses with a reverse geometry design. By wearing ortho-k lenses overnight, myopia patients do not need to wear glasses the following day [5]. Therefore, how to make RGP or ortho-k lens wearers to feel comfortable has become a critical issue.

Researchers have proposed that the in vitro friction coefficient of contact lenses corresponds to the degree of comfort in vivo, although the direct correlation has not yet been made [6,7]. Thus, some methods for measuring the in vitro friction coefficient of hydrogel or/and silicone hydrogel contact lenses have been established. Roba et al. propose that the physiological environment of the contact lenses should be considered when measuring the friction coefficient of contact lenses. An effective commercial soft contact lens friction measurement method was established by using a sliding speed of 0.1 mm/s with a microtribometer, a glass disc coated with mucin as a counterface, and using a lubricating solution of lysozyme and serum that simulates tears as the optimal testing conditions [7]. The literature [8] points out that friction between the eyelids and contact lenses is the main factor affecting comfort. The eyelids and the surface of the contact lenses, or the surface of the cornea, create brush-to-brush friction. Friction behavior is seen in an environment filled with tear fluid. A spontaneous blink is a movement of the upper and lower eyelids against the surface of the cornea, lubricated by the tear film. The friction between the cornea and the eyelids, or the contact lens surface and the sliding eyelids, is at a high speed under the fluid-filled mechanism and at a low speed under the brush-to-brush mechanism. The rubbing behavior does not cause eye damage due to the lubrication of the tear film in healthy eyes. Therefore, the viscosity properties of the liquid layer between the eyelid and the contact lens or cornea are very important. Although several friction measurement methods have been established and investigated for hydrogel/silicone hydrogel contact lenses, there has not yet been any measuring method to evaluate the tribological properties of RGP lenses.

Understanding which factors affect friction coefficient of contact lenses might be critical to making contact lens wearers feel comfortable. Previous studies show that deposition of tear film proteins can affect the friction coefficient of certain hydrogel or silicone hydrogel contact lenses, whether the friction coefficient is increased or decreased, depending on the materials of contact lenses [7,9–11]. It has been shown that the several properties of soft contact lenses, such as hydrophobicity, surface charges, water contents, pore sizes, etc., are critical factors in reducing protein deposition [12–15]. In addition to protein deposition, protein structures on the surface of soft contact lenses are important, since denatured proteins have been demonstrated to increase the friction coefficient of contact lenses [16]. Therefore, either reducing protein deposition or preventing protein denaturing from the surface of contact lenses becomes critical for soft contact lens manufacturers. A commonly used method to reduce protein deposition is to clean soft contact lenses with protein removal agents containing a care solution [17]. Coating a wetting or lubricating agent onto the surface of soft contact lens prevents protein deposition or denaturing, resulting in a reduction of the friction coefficient [18,19]. Studies show that the presence of tear lipids is the main reason for tear protein deposition on the surface of RGP lenses due to the hydrophobic nature of PMMA [20]. The accumulation of protein deposition has been observed even after a lens is cleansed daily with a commercial care solution [21]. Similarly, with the treatments of soft contact lenses, wetting agents are often incorporated into RGP lens manufacture or coated on the surface of RGP lenses, resulting in resistance to deposits and wettability [22]. Since an in vitro RGP lens friction testing method has not yet been established, it is unclear whether wetting agents for RGP lenses can provide lubrication to result in a more comfortable feeling for wearers.

In this study, an in vitro RGP lens friction testing method was first established to mimic the friction between the eyelid and the RGP lens, and the tribological properties of various lubricants were investigated. A lens was rubbed with a rigid glass, soft polyvinylsiloxane, or soft gelatin counterface. A gelatin membrane was selected for further testing. The friction coefficient was investigated when rubbing the lens with different lubricants, including an artificial tear solution, a polysaccharide-containing care solution, normal saline, and a commercial care solution. The static and dynamic friction coefficient of different lubricants was then analyzed and evaluated.

2. Materials and Methods

This study utilized a friction pair consisting of a rigid spherical contact lenses (Optimum Extreme final product lenses) rubbed against a flat gelatin membrane affixed on a rigid glass substrate. Friction tests were performed using various liquid lubricants. This study aimed to simulate the contact between a rigid lens and the eyelid, rather than the eye itself. The contact configuration consisted of a rigid sphere in contact with a soft gelatin counterface, which was expected to undergo slight deformation under vertical loading, resulting in a small, approximately spherical contact area.

2.1. Rigid Gas-Permeable (RGP) Contact Lens Samples

This work investigated the influence of different liquid lubricants on the frictional behavior of rigid contact lenses. Boston XO^{TM} lenses were used here, made from material with the generic name Hexafocon A, which is composed of PMMA, silicon, and fluorine (Brighten Optix Co., Taipei, Taiwan) with oxygen permeability of 100×10^{-11} (cm^3O_2/cm^2s), and a captive bubble wetting angle of 49° that is relatively hydrophobic [23]. A custom holder was designed and fabricated using a high-resolution 3D printer (Asiga, Alexandria NSW, Australia) to enable evaluation of the tribological properties of these lenses on a customized tribometer. Figure 1 gives a cross section of the used lens holder that incorporated three key parts: (1) a main casing open on its bottom side to allow the tested lens to protrude in such a way as to expose the exterior lens surface for the friction tests; (2) a cylindrical soft polyvinylsiloxane (PVS) filler with a spherical bottom surface used to provide compliant mechanical support for the tested lens (PVS was chosen due to its mechanical similarity to ocular tissue, with a Young's modulus of approximately 3 MPa and a density of around 1.1 g/cm^3); and (3) a top cover that closed the main casing and maintained the PVS filler under pre-pressure during the test to avoid any unwanted clearance, and in addition allowed attachment of the holder to the top part of the used tribometer.

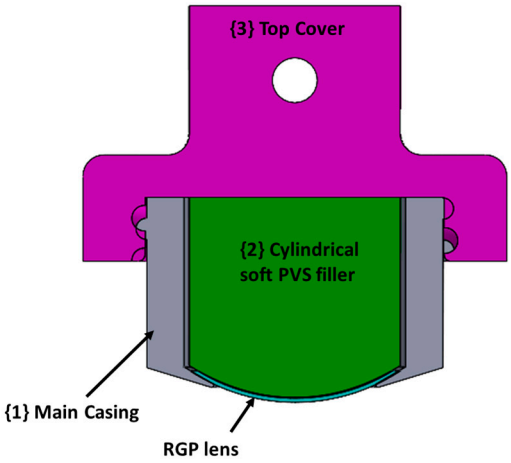


Figure 1. Cross section illustrating the assembly of the mechanical holder for the tested lenses.

2.2. Counter Surface

A gelatin membrane was selected and considered as the suitable counterface material after evaluating the tribological responses of three different materials, one rigid and two soft (i.e., rigid glass, soft PVS membrane, and soft gelatin membrane). The rigid, flat, and smooth counterface was made of a glass plate of 76 × 26 × 1 mm, purchased from (Paul Marienfeld GmbH & Co KG, Lauda-Königshofen, Germany). The glass plate featured a smooth surface with an average roughness of approximately 30 nm, measured using a Wyko NT1100 3D optical profilometer (Tucson, AZ, USA). Glasses are often used as counter surfaces when investigating the frictional behavior of soft contact lenses [7,24,25], because the surface of glass does not exhibit any adsorption. Thus, it is an effective material to investigate the interaction between soft contact lens and different lubricant liquids.

PVS and gelatin membranes of 0.3 mm thickness were flattened and affixed on a rigid glass plate using cyanoacrylate adhesive. A very thin film of cyanoacrylate adhesive was applied to the glass counterface before affixing the gelatin or PVS membranes. This procedure helped to limit the penetration depth of the adhesive into the membranes—particularly the gelatin—thereby minimizing its influence on the tribological response. The same procedure was applied to all specimens to ensure reproducibility and uniformity of the initial experimental conditions. Both soft materials were used as an ocular impression of the eye or applied in many ocular tissues [26,27]. Pre-evaluation tests of the frictional behaviors were conducted under a normal load of 250 mN and a sliding velocity of 1 mm/s. The results of the three materials are presented in Figure 2. Although a glass counterface rubbed against the contact lens presents relatively low friction, its mechanical properties, especially hardness and stiffness, are too high compared to those of biological tissues such as a cornea or an eyelid [9]. As for the other soft counterface (PVS and gelatin membranes), observations showed that PVS led to very high friction. Hence, it was excluded from this study, while a gelatin membrane presented relatively low friction (comparable to that obtained with glass) and was, therefore, included. Taking into consideration that gelatin's mechanical properties are closer to those of biological tissues, gelatin turned out to be the most suitable counterface among the three preliminary tested materials. In addition, gelatin is commonly used as an artificial material to simulate biological tissue in in vitro friction tests, particularly for ocular applications. Its soft, hydrated, and viscoelastic properties make it suitable for mimicking the mechanical behavior of tissues like the cornea [28].

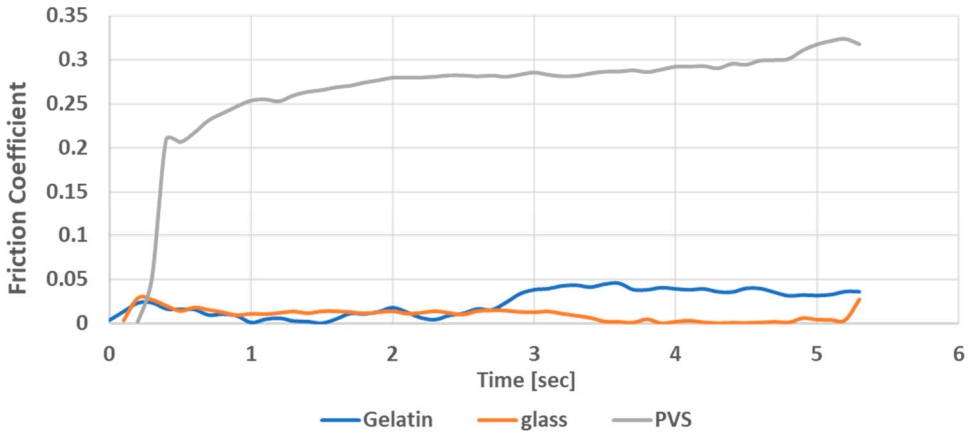


Figure 2. Friction results obtained for the pre-evaluation of three counterface materials rubbed against contact lens under lubricated contact with artificial tear solution.

2.3. Lubricants

As mentioned above, this study aimed to evaluate and compare the properties of different liquids used as lubricants for rigid contact lenses. To achieve this, friction tests were

conducted on a customized linear two-axis tribometer to accurately assess the tribological behavior of lubricated contact lens rubbed against a flat gelatin membrane under linear cyclic friction. This allowed us to objectively classify resolution of lubrication performance in repeated experiments of the tested different lubricants. Four different lubricants were considered in this study:

- Artificial tear solution contains lipids, salts, and proteins. In general, a complex of salt solution was made, containing 5.26 mg/mL of sodium chloride, 1.19 mg/mL of potassium chloride, 0.44 mg/mL of sodium citrate, 0.036 mg/mL of glucose, 0.072 mg/mL of urea, 0.07 mg/mL of calcium chloride, 1.27 mg/mL of sodium carbonate, 0.3 mg/mL of potassium hydrogen carbonate, 3.41 mg/mL of sodium phosphate dibasic, 0.94 mg/mL of hydrochloric acid, and 200 µl of ProClin 300 per one liter of solution. Then, a stock lipid solution including 3.6 mg/mL of oleic acid, 24.0 mg/mL of oleic acid methyl ester, 32.0 mg/mL of triolein, 3.6 mg/mL of cholesterol, 48.0 mg/mL if cholesteryl oleate, and 1.0 mg/mL of phosphatidylcholine was dissolved in a solution of 1 hexane: 1 ether. The detailed preparation of lipid–salt mixed solution has been previously published [21,29]. We added 2 mg/ml of lysozyme and 0.2 mg/ml of albumin into the mixed solution for further experiments. The tear film proteins in healthy human eyes contain on average 1.9 mg/mL of lysozyme, 0.2 mg/mL of albumin, 0.15 mg/mL of mucin, 1.8 mg/mL of lactoferrin, and 0.02 mg/mL of immunoglobulin G [30]. Since lysozyme is the most abundant tear film protein, and the concentration of albumin is similar when eyes are closed or wearing ortho-k lenses [31,32], only these two proteins were added into the artificial tear solution. All the chemicals were purchased from Sigma-Aldrich (St. Louis, MO, USA).
- Polysaccharides containing care solution included 0.45 g of alginate acid (AA, Sigma-Aldrich), 0.45 g of lambda-carrageenan (CRG, Sigma-Aldrich), 0.75 g of poloxamer-407 (Wei Ming Pharmaceutical Mfg. Co., Ltd., Taipei, Taiwan), 0.2 g of ethylenediaminetetraacetic acid (Sigma-Aldrich), 0.015 g of calcium chloride (Sigma-Aldrich), 0.15 g of potassium chloride (Sigma-Aldrich), 0.45 g of sodium chloride (Sigma-Aldrich), 0.4 g of sodium phosphate dibasic (Sigma-Aldrich), and double distilled water in a final volume of 100 mL and pH of 7.4.
- Normal saline solution contained 0.9 g of sodium chloride in 100 mL of double distilled water (Taiwan Biotech Co., Ltd., Taoyuan, Taiwan).
- The commercial care solution used was Menicon Care Plus multipurpose solution for all rigid gas-permeable lenses (Menicon, Nagoya, Japan). The main ingredients are 0.5% poloxamer, 0.0005% polyhexamethylene biguanide, and 0.275% hypromellose, according to manufacturer's manual. The reason for selecting this commercial care solution was the presence of hypromellose, which is also a kind of polysaccharide.

A pipette was used to ensure precise application of the exact quantity of solutions to the contact area. A new friction pair (a RGP contact lens and a flat soft gelatin membrane) was used for each lubricant.

2.4. Experimental Setup for Measuring Tribological Property of RGP Lenses

Friction tests were performed on a specially designed biaxial tribometer, fully described in the reference [33]. The tribometer had a horizontal moving stage that was able to move in three directions to load and unload the mating surfaces in both vertical and tangential directions, and accurately evaluate the tribological performances of the different friction pairs under dry or wet contact conditions, according to needs.

The tribometer included two primary functional units designed for driving and measurement purposes (see Figure 3). (i) The drive unit, located at the bottom of the system, incorporated three translation stages allowing the movement of the horizontal counterface

(glass covered with gelatin membrane) in the three directions to adjust the location of the contact lens on the flat horizontal counterface, load the system, and conduct friction experiments. Movements in the vertical (z) and horizontal (x) directions are achieved thanks to ZABER motors X-LSM025A-E03 (Vancouver, BC, Canada) (25 mm total travel distance with 15 µm precision) and X-LHM050A-E03 (Vancouver, BC, Canada) (50 mm total travel distance and 75 µm precision) for normal and lateral displacement, respectively. Adjustment of the contact location between the lens and the gelatin counterface in the third (y) direction was obtained manually with a precise micrometric translation stage (ZABER model TSB28M-MH2, Vancouver, BC, Canada). (ii) The measurement unit located on the upper part of the tribometer consisted of two high-resolution (0.1 mN) load cells (FUTEK's FSH00092-LSB200, Irvine, CA, USA). This allowed for precise measurement of force variations in both vertical and lateral directions occurring at the interface during a friction experiment.

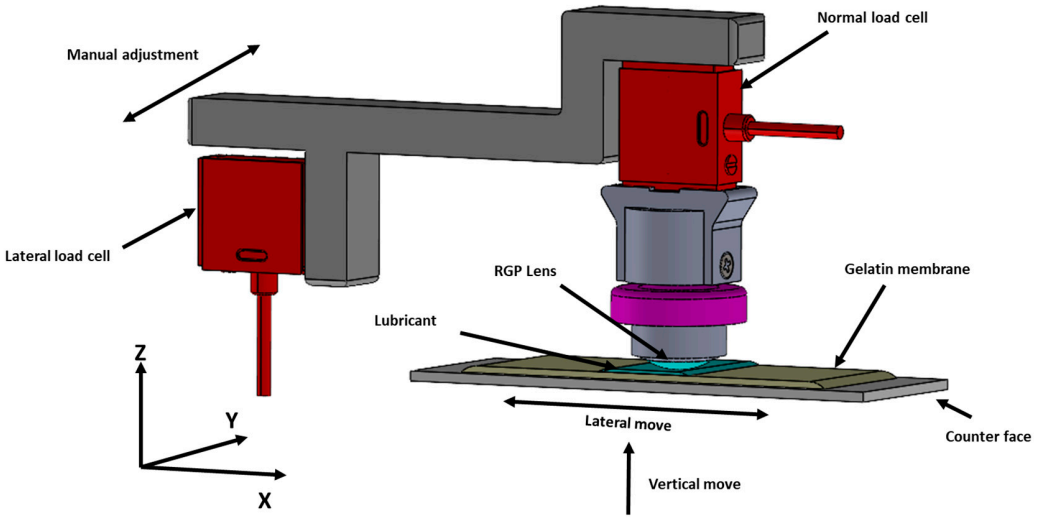


Figure 3. 3D model showing the functional moving and measurement units of the used customized test rig.

The measurements were collected using a multifunctional data acquisition board Lab-PC and NI USB-6211 (National Instruments Co., Austin, TX, USA) and treated using a LabVIEW 2017 software package (Version 20.0.1f1 (32-bit)) (National Instruments Corporation, 11,500 N. Mopac Expressway, Austin, TX, USA). The programmed LabVIEW interface permits setting the desired operational parameters, such as vertical and lateral velocities of the moving stage that holds the counterface specimen, total traveled sliding distance, waiting dwell time, etc. To reduce unwanted noise on the recorded data, the sampling rate of data acquisition was adjusted at 1000 samples per second, then averaged for every 10 points. Given that the present study considered sphere-on-flat contact, no parallelism between mating surfaces was relevant, and the self-aligning system was, thus, not used.

2.5. Tribological Experiment Procedure

First, the gelatin membrane, initially dry, was immersed into water for 30 min, then flattened and affixed on a clean glass plate using ab cyanoacrylate adhesive. It was then mounted on the bottom moving stage of the tribometer using specific mechanical fasteners (see Figure 4).

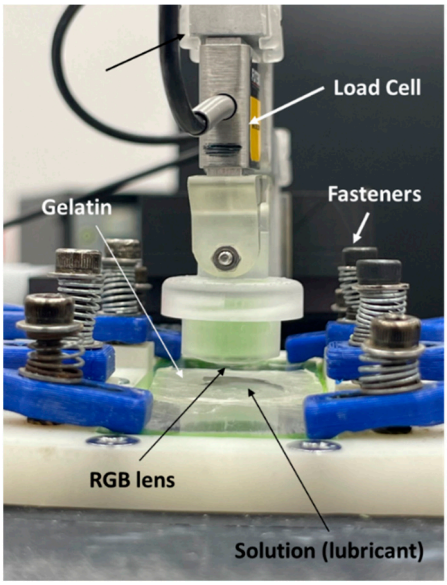


Figure 4. A close-up view of the interface of the rigid lens and flat gelatin with presence of a liquid prior to friction experiment.

The RGP lens was placed and centered in its holder, then the cylindrical PVS filler was inserted and the cover closed and mounted on the upon static part of the tribometer. Next, the RGP lens was cleaned with a delicate tissue soaked slightly to prevent any contamination on the surfaces. Then, using a micrometric stage, the contact position between the lens and the gelatin counterface was fine-tuned in the y-direction. Once specimens were mounted and adjusted on the tribometer, prior to friction experiment, to eliminate the effect of gravity, the load cells were reset as part of the measurement system calibration, which was repeated after every sample change. Then, a quantity of 50 µL of the desired solution to be tested was added carefully to cover the surface of the flat gelatin.

Friction experiments were carried out in six sequential stages (refer to the schematic illustration in Figure 5). In Stage (1) the gelatin membrane counterface was covered with the desired lubricant to be tested, then moved in Stage (2) in the vertical direction, hence contacting the rigid spherical lens at a constant loading speed of 1 mm/s, resulting in a gradual increase of the vertical load P, until the predefined load of 250 mN was achieved. Then, the system was held in this loaded state for a dwell time of five seconds, during which the normal load P remained constant. After the five-second dwell time was completed, the tangential load cell was reset to eliminate residual forces, and in Stage (3), the translation stage initiated lateral motion at a steady sliding speed of 1 mm/s, traversing a total distance of 5 mm. The normal load was regulated throughout this stage via a closed-loop control system with a 2% force error margin, while the friction force resisting the sample's movement was measured. A relatively low sliding speed (1 mm/s) was imposed by the limitations of the tribometer used in this study, which employed a motorized translation stage with restricted velocity capabilities. In Stage (4), after completing the 5 mm of lateral sliding, a dwell time of 0.5 s followed. Next, Stage (5) began with the translation stage moving upward at a constant velocity of 5 mm/s, retracting over a total distance of 10 mm. Stage (6) entailed lateral movement in the opposite direction at a constant velocity of 5 mm/s, bringing the specimens back to their starting point and marking the end of the friction test cycle. Then, a new test cycle was started. In the present study, each friction experiment was repeated 13 times (friction cycles), whereby the first three cycles were considered as running-in without recording, while the last ten cycles were recorded and saved for analysis. All friction experiments in this study were conducted at room temperature of 25 °C ± 1 and a relative humidity of 43% ± 2, using a constant vertical

load of 250 mN. While it is well established that load plays a central role in determining frictional behavior—and according to the Stribeck curve, increasing the load typically leads to higher friction in the boundary and mixed lubrication regimes—a constant load was applied in the present study. This decision was made to minimize the number of varying parameters and to focus on refining the experimental procedure. The selected load of 250 mN was expected to generate an average contact pressure in the range of 30 to 70 kPa, based on the contact area formed between the lens and the gelatin substrate. This value was slightly higher than the estimated physiological contact pressure between the human eyelid and the eye, typically reported to be between 5 and 10 kPa. The elevated pressure in this study was intended to reduce surface waviness of the gelatin and ensure consistent and reproducible contact conditions.

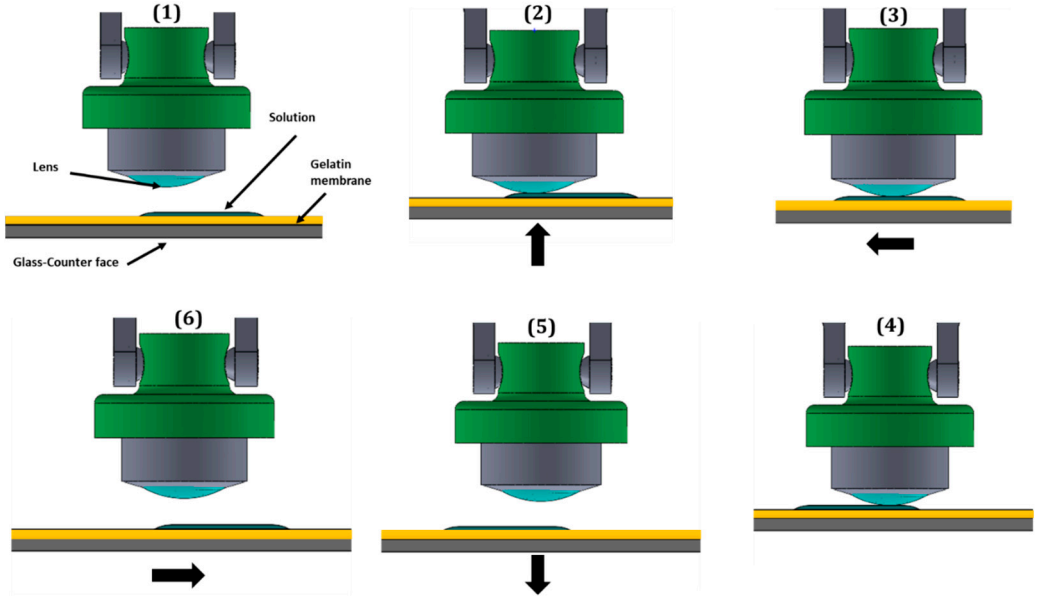


Figure 5. Schematic illustration of the different successive steps followed during a single friction test cycle.

Each liquid was tested three times, each time on a new area of the gelatin surface, and consisting of 13 friction cycles, as mentioned above. The friction experiments were conducted with the four solutions mentioned in Section 2.3. Operational conditions remained consistent across all solutions, an essential condition for the accuracy and reproducibility of results.

2.6. Analysis of Physical–Chemical Properties of Different Lubricants

The viscosity of each lubricant was measured using a programmable rheometer (DV-III ultra, Brookfield, Middleboro, MA, USA) with a cone-on-plate fixture in the steady-shear mode. The measured lubricants were 0.5 mL of artificial tear solution, polysaccharide-containing care solution, normal saline, and commercial care solution. Each solution was tested three times at 25 °C. A rotation speed of 5, 20, and 50 revolutions per minute (rpm) was performed, and the viscosity of each lubricant at 19.2, 76.8, and 192 1/s shear rate was recorded. A previous study showed that shear rates in the human eye are less than 0.14 1/s during eye tremor, ranging from 20 to 115 1/s during microsaccades, and from 475 to 5400 1/s during smooth pursuit [34]. Therefore, three different shear rates that would represent different eye movements were used here.

The pH value of each lubricant was measured using a pH meter (Eutech pH meter 510). The surface tension of each lubricant was measured using the pendant drop method and the FTA 100B instrument (First Ten Angstrom, Newark, CA, USA). Data obtained of physical–

chemical properties are given in Table 1. Differences between viscosity, pH value, and surface tension of different lubricants were analyzed via two-tailed t-tests using Microsoft Excel. A value of $p < 0.05$ was considered significant.

Table 1. The viscosity, pH value, and surface tension of each lubricant. The value means average ± standard deviation, and * $p < 0.05$, ** $p < 0.01$, or *** $p < 0.001$ when comparing viscosity, pH value, or surface tension of each solutions versus commercial care solution.

Group	Artificial Tear Solution	Polysaccharide-Containing Care Solution	Normal Saline Solution	Commercial Care Solution
Viscosity (mPa·s) at 19.2 1/s	0.97 ± 0.00	2.26 ± 1.12	0.97 ± 0.00	1.29 ± 0.56
Viscosity (mPa·s) at 76.8 1/s	0.89 ± 0.28 **	2.26 ± 0.37	0.24 ± 0.00 **	2.51 ± 0.37
Viscosity (mPa·s) at 192 1/s	1.15 ± 0.16 ***	2.91 ± 0.00 ***	1.26 ± 0.06 ***	7.08 ± 0.09
pH value	7.40 ± 0.02	7.40 ± 0.01	5.82 ± 0.26 **	7.03 ± 0.21
Surface tension (mN/m)	43.23 ± 0.55 *	41.71 ± 0.45 **	73.00 ± 1.00 ***	44.47 ± 0.22

3. Results and Discussion

3.1. Comparison of Tribological Properties of Each Lubricant During Whole Friction Cycles

As mentioned above, each lubricant liquid was tested three times (three friction experiments), and each test was conducted on a new gelatin surface. Figure 6 shows the typical frictional behavior observed during a single friction cycle, representing one of the 10 recorded repetitions. From this curve, both static and dynamic friction coefficients (μs and μd) can be determined. On the one hand, the static friction coefficient μs was computed by dividing the friction force recorded at the sliding inception point (see (1) in the Figure 6) by the applied vertical force P. On the other hand, the dynamic friction coefficient μd was calculated as the average friction force recorded in the stabilized zone (average friction force recorded in 80% of the middle sliding stock (see (3) in the Figure 6) divided by the applied vertical force P. This approach intentionally excludes potential instabilities that may occur during the initial 10% of stroke (sliding onset) and the final 10% (deceleration phase). The fluctuations of the friction force during sliding are mostly related to the wavy topography of the gelatin membrane counterface.

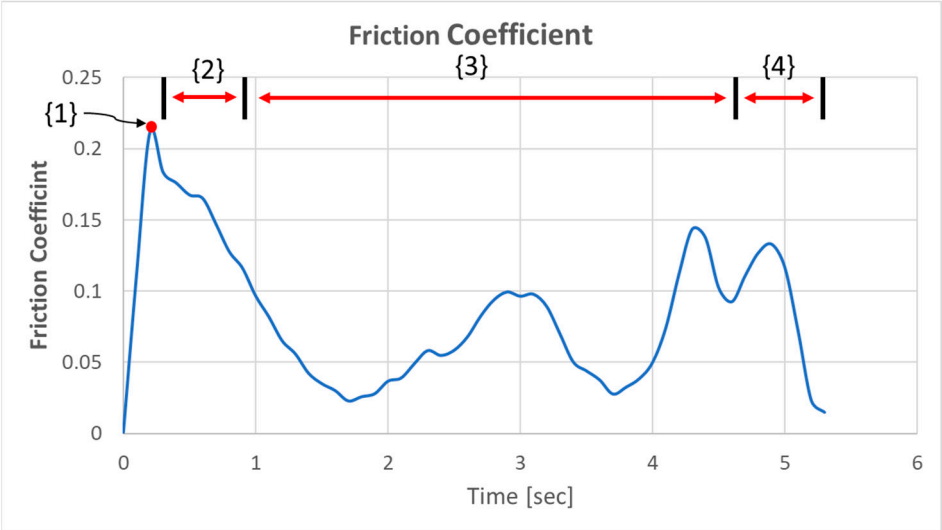


Figure 6. Typical frictional characteristics seen in a single friction cycle: (1) static coefficient of friction (μs); (2) initial 10% of dynamic friction; (3) 80% of the dynamic friction force used to calculate the average dynamic value; and (4) last 10% of dynamic friction.

Figure 7 shows the overlay of all ten friction cycles, repeated three times at different locations on the gelatin counterface, resulting in a total of 30 friction cycles for each liquid. As observed, the successive friction cycle repetitions exhibited excellent, almost perfect, reproducibility when tests were performed with the same lubricant under identical operational conditions and at the same location on the gelatin counterface. The difference in frictional behavior between different repetitions (same liquid but different locations on the gelatin counterface) was likely due to the different topography of the gelatin; slight variation between one given location and another is expected.

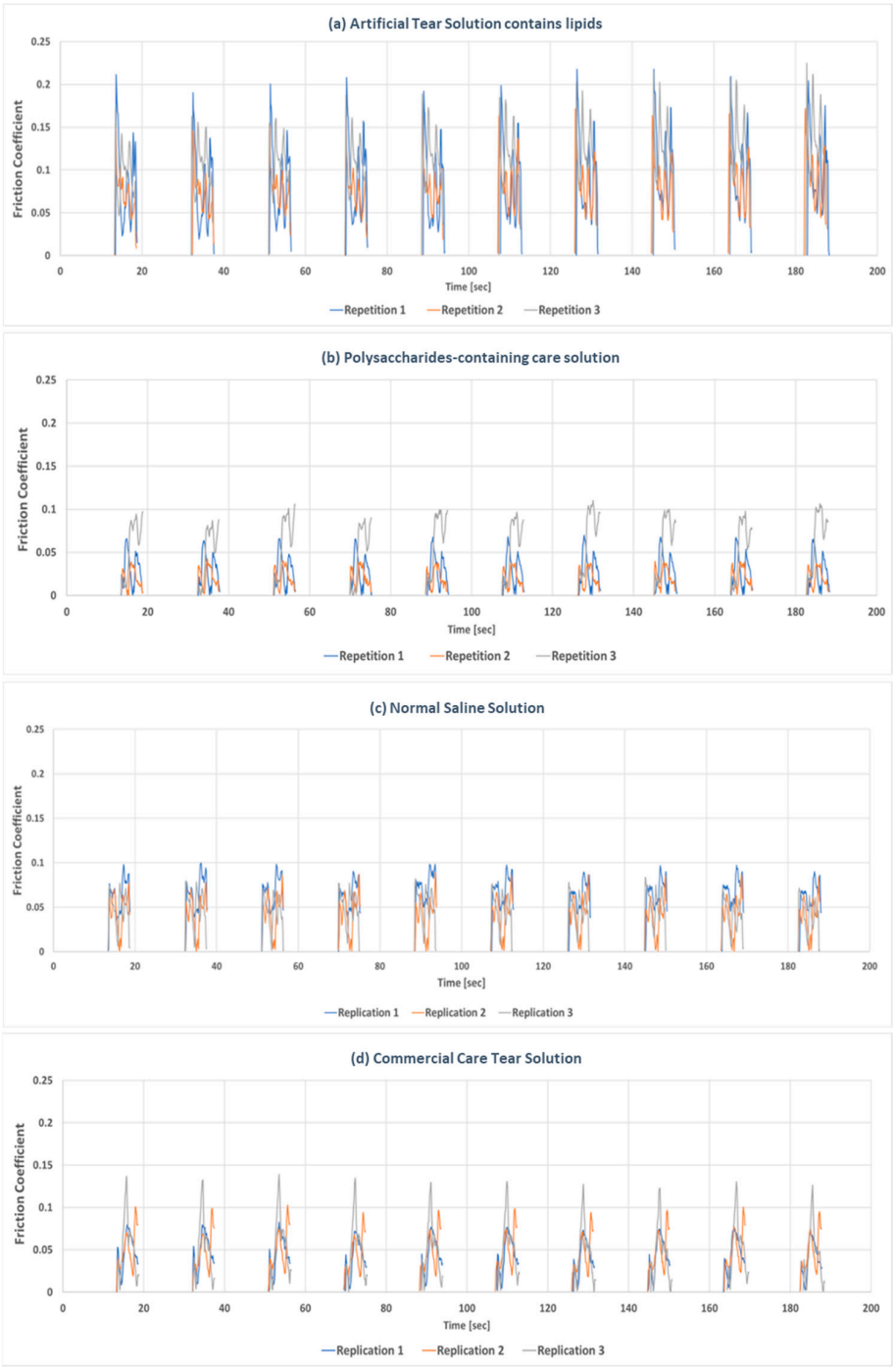


Figure 7. The friction coefficient behavior over time across successive friction cycles for different lubricants: (**a**) artificial tear solution, (**b**) polysaccharide-containing care solution, (**c**) normal saline solution, and (**d**) commercial care solution.

The maximum static friction coefficient, μs, and the average dynamic friction coefficient, μd, recorded after stabilization (steady state) were computed for each friction experiment or repetition. The average values and relative standard deviations, derived from 10 repetitions at the same location on the gelatin, were then calculated for the four liquids and are presented in Figure 8. The average values of the friction coefficients, both static and dynamic, for the same liquid tested on different locations on the gelatin counterface were mostly close to each other. However, these friction coefficients differed sufficiently between the various liquids, a finding that tends to indicate that the adopted experimental methodology was suitable for the evaluation and comparison of the lubrication capacity of the tested liquids.

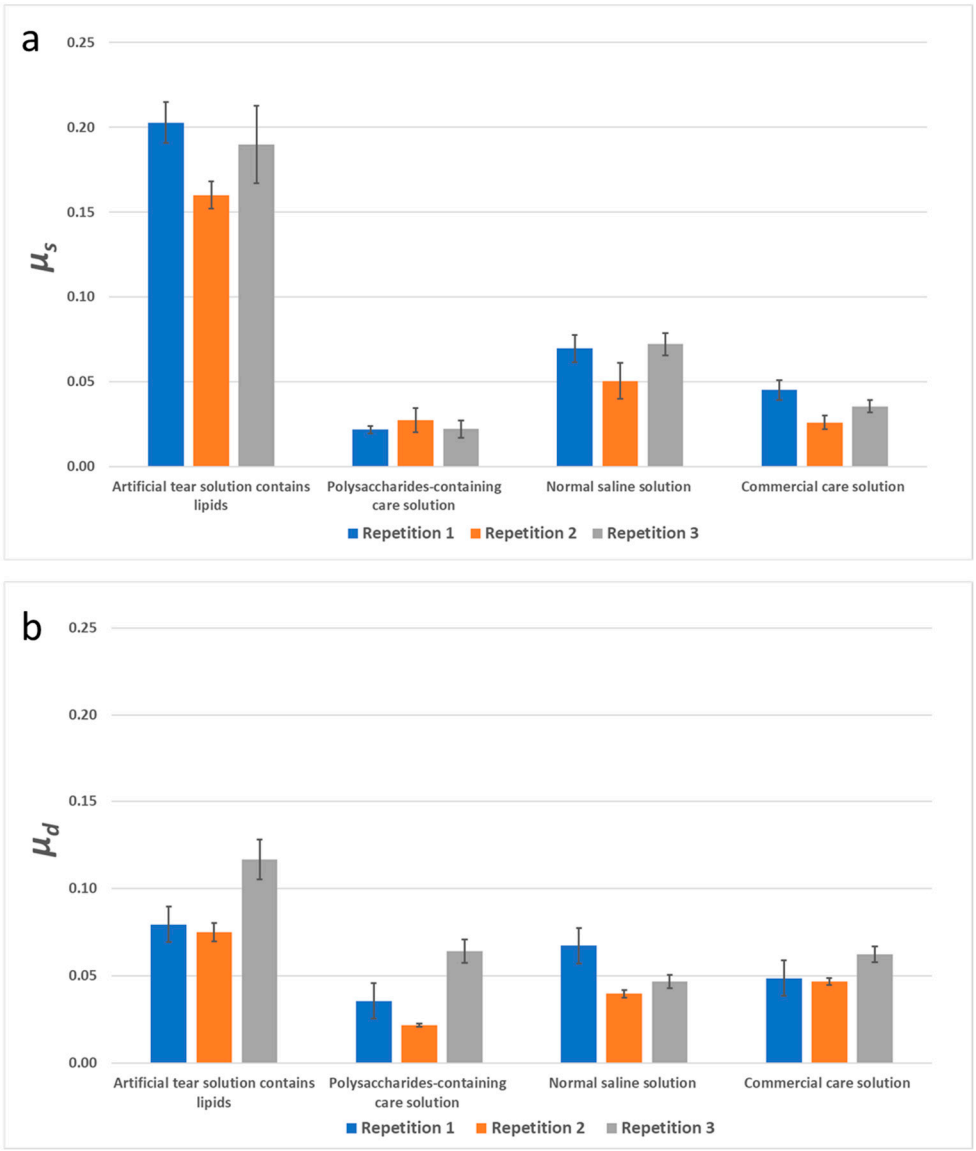


Figure 8. Average values of the (**a**) static friction coefficient μs, and (**b**) dynamic friction coefficient μd, obtained from 10 repetitions performed on the same location on the gelatin surface.

When comparing the performances of the different lubricants, we found the friction coefficient obtained for the artificial tear solutions was higher than that of other lubricants for both μs and μd (Figure 8).

In contrast, the friction coefficient of polysaccharide-containing solution tended to be lower than that of the others. Since the materials of RGP lenses and gelatin membranes were the same in all groups of friction pairs, the difference between physical–chemical properties of

lubricants on the two counter surfaces might have played a significant role in the tribological properties. When the shear rate was 19.2 1/s, the viscosity of artificial tear solution and normal saline solution was the same, while the viscosity of polysaccharide-containing and commercial care solutions was higher (Table 1). The differences, however, were not significant. When the shear rate was increased, the viscosity of each lubricant was also increased. At the shear rate of 192 1/s, the commercial care solution demonstrated the highest viscosity, which was significantly higher than viscosities of other lubricants (Table 1). It is important to recall that the sliding speed was 1 mm/s, and the RGP lens was brought into contact with the gelatin membrane. The friction pair was kept in this loaded static position for 3 s dwell time, likely resulting in the boundary lubrication according to the Stribeck curve [35]. The viscosity of each lubricant under 1 mm/s of sliding speed might be similar to the value when the shear rate was at 19.2 1/s; thus, the viscosities might not be the factor contributing to the differences in friction coefficient. Therefore, the other physical–chemical properties of lubricants might contribute to the friction coefficient results.

The surface tension of normal tear film is 43.6 mN/m [23]. The surface tension of the tested lubricants was also within the range of 41 and 45 mN/m, except for that of normal saline solution (Table 1). The pH value and surface tension of normal saline solution were distinct from the values of the other three solutions (Table 1), but the friction coefficient of normal saline solution was between that of artificial tear solution and polysaccharide-containing/commercial care solution, suggesting the physical–chemical properties of solutions were not the main influence. Polysaccharides are natural polymers, and can be applied as lubricants since they interact with water, resulting in changes of the viscosity [36]. AA has been incorporated into soft contact lenses, resulting in a reduction in contact angle and hydrophilicity, thus providing more lubrication [37,38]. Although lambda-carrageenan has not yet been applied as a lubricant, the friction of kappa-carrageenan hydrogel has been shown to be reduced in aqueous environment when sliding against a stainless-steel ball [39]. Here, the combination of AA and CRG was demonstrated as a good lubricant for RGP lenses for the first time. In addition, the types of hypromellose used in commercial care solutions are polysaccharides and hydrophilic polymers as well [40]. Therefore, the hydrophilicity of polysaccharides might be contributed to lower the friction coefficient.

The artificial tear solution used here contained two types of tear film proteins, lysozyme and albumin, and the concentration of proteins was exhibited in the normal tear film [32]. Both lysozyme and albumin are more likely to denature on a hydrophobic surface, and it is possible that both proteins underwent conformational changes resulting in an increased friction coefficient [20,41,42]. However, a short-term friction coefficient was only observed here. Previous studies show that lysozyme is adsorbed on the surface of RGP lenses, even after the lens is cleansed daily. The accumulation of lysozyme is saturated after 7 days and is maintained over 90 days in vitro [43]. It would be worthwhile to investigate the friction coefficient of RGP lenses in an artificial tear solution for a long period of time, or to immerse lenses into an artificial tear solution for several hours and then measure the friction coefficient to understand a long-term effect of protein deposition on the tribological properties of RGP lenses. In addition to proteins, the artificial tear solution also contained lipids and salts (ions). It is also possible that the interactions between lipids and proteins or lipids and the surface of RGP lenses created a more hydrophobic environment, resulting in an increased friction coefficient. Further investigations are required to understand the tribological characteristics of RGP lenses and their surrounding environment.

3.2. The Static and Dynamic Friction of Different Solutions

Finally, the average static and dynamic coefficients of friction, as well as relative standard deviations, obtained from all 30 repetitions for each solution were calculated and are displayed in Figure 9.

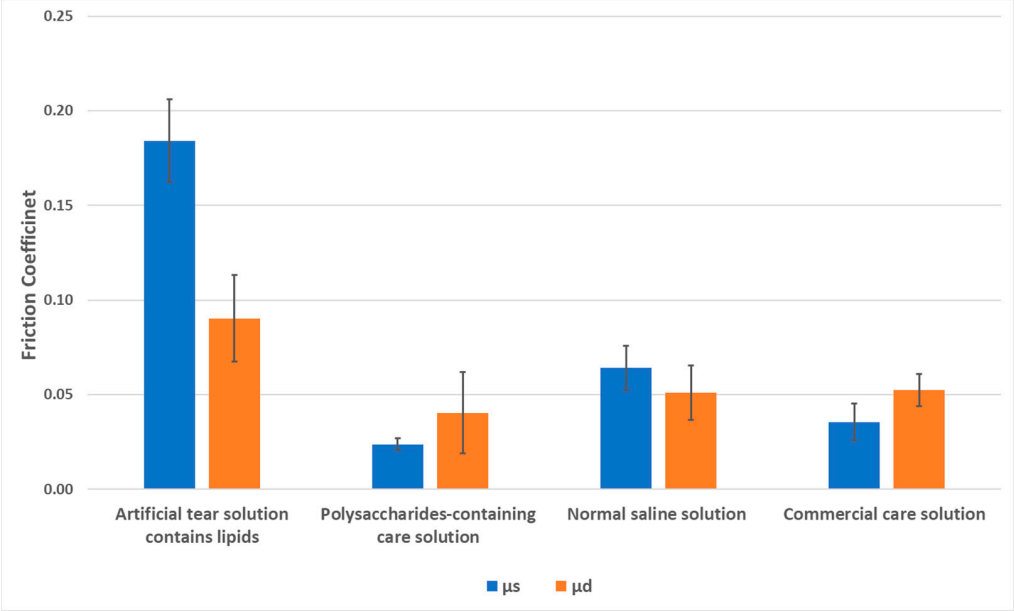


Figure 9. Average values of the static friction coefficient, μs, and dynamic friction coefficient, μd, obtained from the 30 repetitions for each liquid.

It can be clearly seen that the artificial tear solution exhibited the highest static friction, emphasizing its influence in resisting initial sliding between the lens and the gelatin membrane counterface. Conversely, the polysaccharide-containing care solution demonstrated the lowest static friction, indicating smoother interactions during the static shear loading. When considering dynamic friction, the artificial tear solution again recorded the highest values, signifying increased resistance during ongoing motion. In contrast, the polysaccharide-containing care solution displayed the lowest dynamic friction, suggesting reduced resistance during continuous sliding and smoother movement. Notably, the other two solutions, normal saline solution and the commercial care solution, presented slightly higher friction compared to the polysaccharide-containing care solution. Normal saline solution and the commercial care solution showed closely comparable results, indicating similar frictional behavior in both static and dynamic phases.

It can be seen that the averaged static friction coefficient of artificial tear solution was two times higher than its averaged dynamic friction coefficient. In contrast, the averaged static friction coefficient values of polysaccharide-containing and commercial care solution were lower than those of their own averaged dynamic friction coefficient. The boundary lubrication of the human cornea-polydimethylsiloxane (PDMS, which mimics the upper eyelid) biointerface can be evaluated by static and kinetic friction [44]. During spontaneous blinking, the upper eyelid moves down and pressurizes the tear film, resulting in an increase in the thickness of the tear film [45]. Similar phenomena might have occurred here; the thickness of the artificial tear solution might have increased right after the RGP lens started to move. The friction of the lens subsequently switched to elasto-hydrodynamic or hydrodynamic lubrication regime, where viscous friction is expected to result in an increased coefficient of friction with increasing sliding speed. Once the RGP lens started to slide stably under a slow speed, the friction of the lens returned to the boundary lubrication, resulting in a lower dynamic friction coefficient and a reduction in the thickness of artificial

tear solution. Since AA, CRG, and hypromellose are highly hydrophilic polysaccharides, they may have interacted with the lens, resulting in increased resistance when the RGP lens slid under polysaccharide-containing and commercial care solution during stable friction period. Therefore, the μd of these two solutions was slightly higher than their own μs. Further investigations on the changes in the thickness of artificial tear solution or care solutions should be conducted to understand the mechanism behind the distinct μs and μd values of the different lubricants.

4. Conclusions

A customized biaxial tribometer was adapted to evaluate lubrication properties of different solutions used as lubricant for contact lenses. The friction pair was composed of a rigid spherical contact lens (Optimum Extreme final product lenses) rubbed against a flat gelatin membrane affixed on a rigid glass plate. The choice of gelatin as a counterface was justified due to it having mechanical properties close to those of biological tissues and its relatively low friction coefficient against rigid contact lenses under lubricated contact. Four different lubricants were tested: (i) artificial tear solution; (ii) polysaccharide-containing care solution; (iii) normal saline solution; and (iv) commercial care solution. The friction experiments were conducted under a normal load P of 250 mN and sliding velocity V of 1 mm/s. The following observations were made:

- Among the three counterface materials (gelatin, glass, and PVS), gelatin was the best candidate to simulate mechanical and tribological properties of biological tissues such as the cornea and eyelid.
- A very good reproducibility of frictional behavior was obtained with successive friction cycle repetitions when the tests were conducted with a given lubricant under the same operational conditions and on the same location on the gelatin counterface.
- The slight difference in frictional behavior at the different gelatin counterface locations is likely due to the different topography; such variations are expected between one given location and another on a gelatin surface.
- The adopted experimental methodology based on biaxial tribometer testing was suitable for the evaluation and comparison of lubrication capacity of lubricant used in contact lenses.
- Distinct outcomes were observed for the solutions. Higher static and dynamic coefficients of friction were obtained with the artificial tear solution, and the averaged static friction coefficient of artificial tear solution was twice as high as its averaged dynamic friction coefficient.
- Lower friction values were obtained with the polysaccharide-containing care solution, but the averaged static friction coefficient was lower than its averaged dynamic friction coefficient, which might result from its high hydrophilicity and lubricating properties.

Author Contributions: Conceptualization, C.-Y.S., H.-W.F. and H.K.; methodology, M.N., Z.Q. and H.K.; validation, M.N. and Z.Q.; formal analysis, M.N. and Z.Q.; investigation, C.-Y.S., H.-W.F. and H.K.; data curation, C.-Y.S., H.-W.F. and H.K.; writing—original draft preparation, C.-Y.S. and H.K.; writing—review and editing, H.K.; visualization, M.N., Z.Q. and H.K.; funding acquisition, H.-W.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science and Technology Council (NSTC), Taiwan under the grant number 111-2221-E-027-027.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sankaridurg, P.; Tahhan, N.; Kandel, H.; Naduvilath, T.; Zou, H.; Frick, K.D.; Marmamula, S.; Friedman, D.S.; Lamoureux, E.; Keeffe, J.; et al. Imi impact of myopia. *Investig. Ophthalmol. Vis. Sci.* **2021**, *62*, 2. [CrossRef] [PubMed]
2. Holden, B.A.; Fricke, T.R.; Wilson, D.A.; Jong, M.; Naidoo, K.S.; Sankaridurg, P.; Wong, T.Y.; Naduvilath, T.J.; Resnikoff, S. Global prevalence of myopia and high myopia and temporal trends from 2000 through 2050. *Ophthalmology* **2016**, *123*, 1036–1042. [CrossRef]
3. Gwiazda, J. Treatment options for myopia. *Optom. Vis. Sci.* **2009**, *86*, 624–628. [CrossRef]
4. Ezinne, N.E.; Bhattarai, D.; Ekemiri, K.K.; Harbajan, G.N.; Crooks, A.C.; Mashige, K.P.; Ilechie, A.A.; Zeried, F.M.; Osuagwu, U.L. Demographic profiles of contact lens wearers and their association with lens wear characteristics in trinidad and tobago: A retrospective study. *PLoS ONE* **2022**, *17*, e0264659. [CrossRef]
5. Bullimore, M.A.; Johnson, L.A. Overnight orthokeratology. *Contact Lens Anterior Eye* **2020**, *43*, 322–332. [CrossRef]
6. Jones, L.; Brennan, N.A.; Gonzalez-Meijome, J.; Lally, J.; Maldonado-Codina, C.; Schmidt, T.A.; Subbaraman, L.; Young, G.; Nichols, J.J. The tfos international workshop on contact lens discomfort: Report of the contact lens materials, design, and care subcommittee. *Investig. Ophthalmol. Vis. Sci.* **2013**, *54*, TFOS37-70. [CrossRef] [PubMed]
7. Roba, M.; Duncan, E.G.; Hill, G.A.; Spencer, N.D.; Tosatti, S.G.P. Friction measurements on contact lenses in their operating environment. *Tribol. Lett.* **2011**, *44*, 387–397. [CrossRef]
8. Pult, H.; Tosatti, S.G.; Spencer, N.D.; Asfour, J.M.; Ebenhoch, M.; Murphy, P.J. Spontaneous blinking from a tribological viewpoint. *Ocul. Surf.* **2015**, *13*, 236–249. [CrossRef]
9. Sterner, O.; Aeschlimann, R.; Zurcher, S.; Osborn Lorenz, K.; Kakkassery, J.; Spencer, N.D.; Tosatti, S.G. Friction measurements on contact lenses in a physiologically relevant environment: Effect of testing conditions on friction. *Investig. Ophthalmol. Vis. Sci.* **2016**, *57*, 5383–5392. [CrossRef]
10. Su, C.Y.; Lai, C.C.; Yeh, L.K.; Li, K.Y.; Shih, B.W.; Tseng, C.L.; Fang, H.W. The characteristics of a preservative-free contact lens care solution on lysozyme adsorption and interfacial friction behavior. *Colloids Surf. B Biointerfaces* **2018**, *171*, 538–543. [CrossRef]
11. Su, C.Y.; Yeh, L.K.; Fan, T.W.; Lai, C.C.; Fang, H.W. Albumin acts as a lubricant on the surface of hydrogel and silicone hydrogel contact lenses. *Polymers* **2021**, *13*, 2051. [CrossRef] [PubMed]
12. Chirila, T.V.; Constable, I.J.; Crawford, G.J.; Vijayasekaran, S.; Thompson, D.E.; Chen, Y.C.; Fletcher, W.A.; Griffin, B.J. Poly(2-hydroxyethyl methacrylate) sponges as implant materials: In vivo and in vitro evaluation of cellular invasion. *Biomaterials* **1993**, *14*, 26–38. [CrossRef] [PubMed]
13. Garrett, Q.; Laycock, B.; Garrett, R.W. Hydrogel lens monomer constituents modulate protein sorption. *Investig. Ophthalmol. Vis. Sci.* **2000**, *41*, 1687–1695.
14. Luensmann, D.; Jones, L. Albumin adsorption to contact lens materials: A review. *Contact Lens Anterior Eye* **2008**, *31*, 179–187. [CrossRef]
15. Vadgama, P. *Surfaces and Interfaces for Biomaterials*; CRC Press/Woodhead: Boca Ration, FL, USA, 2005.
16. Chang, Y.C.; Su, C.Y.; Chang, C.H.; Fang, H.W.; Wei, Y. Correlation between tribological properties and the quantified structural changes of lysozyme on poly (2-hydroxyethyl methacrylate) contact lens. *Polymers* **2020**, *12*, 1639. [CrossRef]
17. Efron, N.; Morgan, P.B. Soft contact lens care regimens in the uk. *Contact Lens Anterior Eye* **2008**, *31*, 283–284. [CrossRef]
18. Fahmy, M.; Long, B.; Giles, T.; Wang, C.H. Comfort-enhanced daily disposable contact lens reduces symptoms among weekly/monthly wear patients. *Eye Contact Lens* **2010**, *36*, 215–219. [CrossRef]
19. Hoteling, A.J.; Nichols, W.F.; Harmon, P.S.; Conlon, S.M.; Nunez, I.M.; Hoff, J.W.; Cabarcos, O.M.; Steffen, R.B.; Hook, D.J. Characterization and quantitation of pvp content in a silicone hydrogel contact lens produced by dual-phase polymerization processing. *J. Biomed. Mater. Res. B Appl. Biomater.* **2018**, *106*, 1064–1072. [CrossRef] [PubMed]
20. Bontempo, A.R.; Rapp, J. Protein-lipid interaction on the surface of a rigid gas-permeable contact lens in vitro. *Curr. Eye Res.* **1997**, *16*, 1258–1262. [CrossRef]
21. Su, C.Y.; Yeh, L.K.; Tsao, Y.F.; Lin, W.P.; Hou, C.H.; Huang, H.F.; Lai, C.C.; Fang, H.W. The effect of different cleaning methods on protein deposition and optical characteristics of orthokeratology lenses. *Polymers* **2021**, *13*, 4318. [CrossRef]
22. Sindt, C.W. Hydra-peg: A novel custom contact lens coating technology designed to improve patient comfort and satisfaction. In *Whitepaper*; Tangible Science LLC: Redwood City, CA, USA, 2016.
23. Wu, L.Y.; Lin, W.P.; Wu, R.; White, L.; Abass, A. Fea-based stress-strain barometers as forecasters for corneal refractive power change in orthokeratology. *Bioengineering* **2024**, *11*, 166. [CrossRef] [PubMed]
24. Ngai, V.; Medley, J.; Jones, L.; Forrest, J.; Teichroeb, J. *Friction of Contact Lenses: Silicone Hydrogel Versus Conventional Hydrogel*; Elsevier: Amsterdam, The Netherlands, 2005; Volume 48, pp. 371–379.
25. Rennie, A.C.; Dickrell, P.L.; Sawyer, W.G. Friction coefficient of soft contact lenses: Measurements and modeling. *Tribol. Lett.* **2005**, *18*, 499–504. [CrossRef]
26. Amornvit, P.; Rokaya, D.; Shrestha, B.; Srithavaj, T. Prosthetic rehabilitation of an ocular defect with post-enucleation socket syndrome: A case report. *Saudi Dent. J.* **2014**, *26*, 29–32. [CrossRef]

27. Rose, J.B.; Pacelli, S.; Haj, A.J.E.; Dua, H.S.; Hopkinson, A.; White, L.J.; Rose, F. Gelatin-based materials in ocular tissue engineering. *Materials* **2014**, *7*, 3106–3135. [CrossRef] [PubMed]
28. Baumberger, T.; Caroli, C.; Ronsin, O. Self-healing slip pulses and the friction of gelatin gels. *Eur. Phys. J. E Soft Matter* **2003**, *11*, 85–93. [CrossRef]
29. Omali, N.B.; Subbaraman, L.N.; Heynen, M.; Ng, A.; Coles-Brennan, C.; Fadli, Z.; Jones, L. Surface versus bulk activity of lysozyme deposited on hydrogel contact lens materials in vitro. *Contact Lens Anterior Eye* **2018**, *41*, 329–334. [CrossRef] [PubMed]
30. Lorentz, H.; Heynen, M.; Kay, L.M.; Dominici, C.Y.; Khan, W.; Ng, W.W.; Jones, L. Contact lens physical properties and lipid deposition in a novel characterized artificial tear solution. *Mol. Vis.* **2011**, *17*, 3392–3405.
31. Choy, C.K.; Cho, P.; Benzie, I.F.; Ng, V. Effect of one overnight wear of orthokeratology lenses on tear composition. *Optom. Vis. Sci.* **2004**, *81*, 414–420. [CrossRef]
32. Sack, R.A.; Tan, K.O.; Tan, A. Diurnal tear cycle: Evidence for a nocturnal inflammatory constitutive tear fluid. *Investig. Ophthalmol. Vis. Sci.* **1992**, *33*, 626–640.
33. Brdler, D.; Goltsberg, R.; Ammar, A.A.; Kasem, H. Experimental study of adhesion, friction, and peeling of biomimetic combined micro-mushroom and micro-spatulae textures. *Tribol. Int.* **2023**, *186*, 108609. [CrossRef]
34. Tiffany, J.M. The viscosity of human tears. *Int. Ophthalmol.* **1991**, *15*, 371–376. [CrossRef] [PubMed]
35. Robinson, J.W.; Zhou, Y.; Bhattacharya, P.; Erck, R.; Qu, J.; Bays, J.T.; Cosimbescu, L. Probing the molecular design of hyperbranched aryl polyesters towards lubricant applications. *Sci. Rep.* **2016**, *6*, 18624. [CrossRef] [PubMed]
36. Rhein-Knudsen, N.; Ale, M.T.; Meyer, A.S. Seaweed hydrocolloid production: An update on enzyme assisted extraction and modification technologies. *Mar. Drugs* **2015**, *13*, 3340–3359. [CrossRef]
37. Ko, N.Y.; Lee, K.M.; Lee, H.M. The effect of wettability and protein adsorption of contact lens by alginic acid. *J. Korean Chem. Soc.* **2017**, *61*, 352–388.
38. Park, H.J.; Lee, H.M. Effect of temperature on physical properties in the manufacture of porous contact lenses using natural polysaccharides. *J. Korean Ophthalmic Opt. Soc.* **2022**, *27*, 15–21. [CrossRef]
39. Kozbial, A.; Li, L. Study on the friction of kappa-carrageenan hydrogels in air and aqueous environments. *Mater. Sci. Eng. C Mater. Biol. Appl.* **2014**, *36*, 173–179. [CrossRef]
40. Kruk, K.; Szekalska, M.; Basa, A.; Winnicka, K. The impact of hypromellose on pharmaceutical properties of alginate microparticles as novel drug carriers for posaconazole. *Int. J. Mol. Sci.* **2023**, *24*, 10793. [CrossRef]
41. Garrett, Q.; Garrett, R.W.; Milthorpe, B.K. Lysozyme sorption in hydrogel contact lenses. *Investig. Ophthalmol. Vis. Sci.* **1999**, *40*, 897–903.
42. Garrett, Q.; Griesser, H.J.; Milthorpe, B.K.; Garrett, R.W. Irreversible adsorption of human serum albumin to hydrogel contact lenses: A study using electron spin resonance spectroscopy. *Biomaterials* **1999**, *20*, 1345–1356. [CrossRef]
43. Su, C.Y.; Yeh, L.K.; Huang, P.H.; Lin, W.P.; Huang, H.F.; Lai, C.C.; Fang, H.W. Long-term effects of tear film component deposition on the surface and optical properties of two different orthokeratology lenses. *Contact Lens Anterior Eye* **2023**, *46*, 101852. [CrossRef]
44. Morrison, S.; Sullivan, D.A.; Sullivan, B.D.; Sheardown, H.; Schmidt, T.A. Dose-dependent and synergistic effects of proteoglycan 4 on boundary lubrication at a human cornea-polydimethylsiloxane biointerface. *Eye Contact Lens* **2012**, *38*, 27–35. [CrossRef] [PubMed]
45. Dunn, A.C.; Tichy, J.A.; Uruena, J.M.; Sawyer, W.G. Lubrication regimes in contact lens wear during a blink. *Tribol. Int.* **2013**, *63*, 45–50. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.