Abstract: Contact lenses have a special effect on the treatment of some eye diseases. The tribological behaviour of soft contact lenses considerably influences their clinical performance. Improper wearing of contact lenses can lead to mechanical damage of the contact interface, which can lead to pathological changes in the eyeball. In this study, the sliding friction of two kinds of typical contact lens materials (hilaficon-B and lotrafilcon-B) in three lubricants (distilled water, care solution, and eye drop) and tribological parameters are studied, using PMMA as a control. Hydrogels have high water content but the dehydration rate is high. Silicone hydrogels have low initial water content but low dehydration rates. The friction test in distilled water gives the highest coefficient of friction value. The care solution and eye drop significantly reduce the friction coefficient of the lens due to the formation of tribofilm.

1 Introduction

The contact lens, which has special characteristics of optics and physics, is used as a third-class medical device and has achieved great progress in vision correction and ophthalmic treatment. The most popular materials of soft contact lenses (SCLs) are hydrogel and silicone hydrogel: the primary material, hydrogel, is soft, moist, and flexible. When wearing the hydrogel contact lens, the wearer’s subjective comfort is reduced by absorbing protein from the tear film [1]. The silicone hydrogel with high oxygen permeability has advantages, particularly in terms of oxygen permeability, over traditional hydrogels as SCLs given that the medium of oxygen transport in the former is siloxane-based polymer rather than water in the latter [2]. Figs. 1a and b show the contact lenses and it may cause eye damage by improper usage of lenses, as shown in Figs. 1c and d. Microbial keratitis, a sight-threatening condition that rapidly progresses, is the most serious corneal complication associated with wearing contact lenses [3, 4]. Some researchers have investigated care solutions that could remove the biofilm from the lenses [5–7]. Some studies have shown that the use of higher viscosity lubrication, compared to saline or water, is related to the comfort of the lens. Ozkan et al. have studied the effect of three different viscosity lubricants on the comfort after 6 h of wearing. It was found that a more viscous lubricant is more comfortable for the user and reduces lens wear [8]. Some researchers have focused on research and development of contact lenses and care solutions by using different biological materials to improve the comfort of the wearer [5, 9–12]. Few studies have reported new biomaterials, such as composite hydrogels, that have excellent antibacterial properties [13]. These materials are used to inhibit the adsorption of biofilm on the lenses to reduce the adverse reactions [14, 15]. Also, adding polymer materials to hydrogels or silicone hydrogels can improve their hydrophilicity [2]. However, there is no clear conclusion on the long-term assessment of biocompatibility and bio-floculation of these biomaterials. Thus, in-depth studies of the biocompatibility and biodegradability of hydrogels should be conducted before clinical application.

Some clinically observed phenomena, such as eyelid epithelial lesions and dry eye correlation, may be related to the friction between the lens and the conjunctiva [11]. Such phenomena may lead to contact lens-related giant papillary conjunctivitis due to the increased friction between the contact lens surface and the conjunctiva [12]. The changes in the surface properties of lenses caused by the deposition of proteins and lipids may alter the friction between the outer surface of the contact lens and the inner surface of the eyelid [16]. The boundary lubrication state of the lenses during blinking and the slow functional eye movement may have a significant influence on the comfort of the wearer; in this regard, careful friction measurement and clinical observation should be conducted [17]. The tear film is an actively controlled lubrication system that continuously adds lipids and mucin to the sliding interface. Tear film dysfunction causes pain and enhanced immune activity, which may interfere with vision [18]. Some studies have shown that the coefficient of friction (COF) of silicone hydrogels may be changed due to long-term reaction with the tear film components, indicating that last-longing moist lens is favourable for maintaining a low COF in a long time [19], and some research studies related to the design of novel highly weTable contact lens materials have been done already [20–22]. Blinking and eye rotation are the most important physiological processes for lens and lens friction, which can lead to various corneal infections, corneal ulcers, decreased vision, and other symptoms [23]. Roba et al. [24] studied the friction values of contact lenses with different friction-pair surfaces, loads, sliding speeds, and lubricating fluid conditions under physiological conditions of the eye and compared the performance of contact lenses provided by different commercial brands. Zhou et al. [25] studied the friction properties of stainless-steel balls and contact lenses in physiological saline environment and compared the curves of different loads, friction forces, sliding speeds, and COF. Wilson et al. [26] found the COF value of the cornea in four different liquid environments varied between 0.006 and 0.015. Hofmann et al. [27] studied the friction between five silicone hydrogels and two p-HEMA contact lenses and human corneal epithelial tissue and found that the COF changed in the scale of 0.04–0.07. However, the existing research has several shortcomings. The tribological behaviour of typical contact lens materials is not very clear, causing difficulties in the follow-up development of new products, solving medical problems, and guiding proper wearing of lenses.

In clinical practice, using inappropriate contact lenses over wear and tear can lead to harmful effects. The tribological behaviour of
The tribological properties of contact lens materials is not very clear, causing troubles in the follow-up development of new products, solving medical problems, and guiding proper wearing of lenses. The tribological properties of contact lens materials can directly or indirectly affect their service performance, whether optical functionality or biocompatibility. This work investigated lubricants that improve the friction and wear of certain types of contact lenses in three lubricant environments.

2 Materials and test method

Tribology performance test with a ball-to-flat contact model was held in UMT-2 testing machine in three lubricant environments: distilled water, care solution (water rhyme contact lens multi-function care solution of Horien), and eyedrop (sodium hyaluronate eye drops of Hycosan). As shown in Table 1, two kinds of commercially available contact lenses, hydrogel (Bausch & Lomb® hilaficon-B) and silicone hydrogel (Alcon® lotrafilcon-B), were selected and tested with PMMA. PMMA has a smooth texture and low hardness. It is suitable for the friction experiment. However, PMMA is harder than the cornea of humans. So, in theory, the wear scar will be bigger than expected. In addition, without lubricating the material produced by the cornea, the COF obtained may be different from the actual one. The main compositions of the three solutions are shown in Table 2. The contact stress during the sliding of the contact lens is 10–100 kPa, corresponding to the Hertz contact stress of 78 kPa, so a constant normal load of 0.2 N was set in the tribology test. Six sliding speeds (0.1, 0.5, 1, 5, 10, and 20 mm/s) were selected, and the sliding friction test for each lens lasts 1 h. The displacement amplitude of PMMA is 10 mm. Each test was repeated three times.

The materials were analysed by different characterisation methods. Infrared spectroscopy of Fourier transform (IF, Nicolet 5700), based on the principle of Fourier transform of the infrared light after interference, to analyse the characteristic transmission peaks of hydrogels by KBr tableting and test the polar bonds of the lens, through two background subtraction, at a spectral resolution of 2 cm⁻¹, by recording 16 scans with a spectral width ranging from 550 to 4000 cm⁻¹. Raman spectrum (Lab Ram HR), analysis of the scattering spectrum different from the incident light frequency to obtain molecular vibration and rotation information, to test the polar bonds of the lens by using 532 nm laser light source, a low excitation power of 5 mW. X-ray diffraction (XRD, Panalytical), optical radiation generated by the transition of atomic inner electrons under the impact of high-speed moving electrons, to obtain information on the composition and structure of the lens. The XRD analysis of hydrogels and silicone hydrogels was performed by using CuKα radiation with a wavelength of 0.154 nm at 30 kV and 20 mA, and scanned within 10–80°. Mass change (MC, Electronic scale) was used to measure changes in the water content in contact lenses made of hydrogel and silicone hydrogel under air-dried condition. Two kinds of contact lenses were soaked in the three lubricants for 24 h and then naturally air dried. The weight of the two contact lenses was measured at 10, 20, 30, 40, and 50 min as well as 1, 2, 4, 8, 12, and 24 h. The water content was calculated and used super-depth microscope (SDM, VHX-5000) to obtain the wear scar of the lens.

Fig. 2 shows the structure of the fixture of the wear test. The fixture supporting the contact lens was designed into three parts: upper splint, lower splint, and ball support crown. The upper splint is a PMMA board with a length of 36 mm, a width of 24 mm, and a height of 4 mm. The centre position is the ball crown space and the lower splint height is 2 mm and made of stainless steel. The dimensions of the ball crown support are 20 mm in diameter and 5 mm in height. The upper splint, lower splint, and test box were connected by screws, and the contact lens was fixed in the test box containing the experimental medium. The PMMA plate was held by the upper sample holder and slowly approached the contact lens. Applying a load of 0.2 N and moving back and forth were conducted to achieve the experimental conditions.

3 Results and discussion

Fig. 3 shows the Fourier Transform infrared spectroscopy (FTIR) spectra of the hydrogel and silicone hydrogel after soaking for 24 h in care solution and eye drop. The transmission spectra of the
lenses were recorded. No significant difference of hydrogel was observed after soaking for 24 h in the care solution and the eye drop as shown in Fig. 3a. Fig. 3b shows that the peak at 3440 cm\(^{-1}\) after soaking in the care solution is stronger than that after soaking in the eye drop. The peak at 3440 cm\(^{-1}\) is the –OH of the water in the background and the peak at 1650 cm\(^{-1}\) is the –RCONH\(_2\) in the cross-linking agent. The peak at 1050 cm\(^{-1}\) is due to primary alcohol and that at 720 cm\(^{-1}\) is assigned to substituted benzene. When the test was carried out, the hydrogen bond association peak broadened due to a large amount of water. The peak of amide I with carbonyl stretching vibration shifted to a low wave number of about 1650 cm\(^{-1}\), indicating the presence of hydrogen bond among gel factor molecules. Hydrogel contains hydroxyl functional groups and amide groups in the cross-linking agent. The hydroxyl group is a typical polar group, which can form a hydrogen bond with water and has hydrophilicity. The amide group is also hydrophilic and can adsorb water or aqueous solutions equivalent to 10–100 or even 1000 times their mass [25]. Silicone hydrogels contain primary alcohols and substituted benzenes.

The Raman spectra of the hydrogel and silicone hydrogel after soaking in the care solution and eye drop for 24 h are shown in Fig. 4. Some new peaks appeared and some old peaks were masked or changed. However, two distinct peaks of the Raman spectra of the silicone hydrogels appear at 489 and 637 cm\(^{-1}\). In the eye drop, the peak near 2906 cm\(^{-1}\) in the Raman spectrum is also prominent. A comparison of the material composition among the hydrogel, the silicone hydrogel, and the standard card indicated that the prominent peak could be attributed to the siloxane-based polymer. In the silicone hydrogels, the siloxane-based polymers provide numerous channels for oxygen transport, rather than relying solely on moisture.

**Fig. 2** Schematic and real photos of the experimental fixture of wear test

*Fig. 3** FTIR spectra of

*a* Hydrogel  
*b* Silicone hydrogel

IR transmission spectra after soaking for 24 h in the care solution and the eye drop

**Fig. 3** FTIR spectra of

*a* Hydrogel  
*b* Silicone hydrogel

**Fig. 4** Raman spectra after soaking for 24 h in care solution and eye drop

*a* Hydrogel  
*b* Silicone hydrogel
The XRD patterns of hydrogels and silicone hydrogels within 2θ range of 10–80° after soaking in the eye drop and care solution for 24 h are shown in Fig. 5. The hydrogel shows peaks at 27.8° and 40.1°, while the silicone hydrogels show peaks at 12.5° and 26.5°. No significant difference was found in the diffraction patterns of both hydrogels and silicone hydrogels as is shown in Figs. 5a and b. Hence, the two solutions had no significant effect on the composition of the hydrogel and the silicone hydrogel as well as on the internal atoms and molecules.

The tests of water loss of the two materials were carried out under air-dried condition, as shown in Fig. 6. Some researchers have found that a persistent wetting agent is beneficial in maintaining a low COF after prolonged simulated wearing [19]. Some other researchers have also discovered that determining the change in water content helps study the changing trend of COF when using lenses. Water molecules exhibit a bipolar structure and bind to the surface of the phosphoryl choline in the contact lens, thereby inhibiting the binding of other molecules and decreasing the friction coefficient of the lens [28]. In addition, from a physiological point of view, the oxygen permeability coefficient is the most important parameter characterising the contact lens. Also, water content is an important parameter used to characterise the oxygen permeability coefficient of hydrogels, but have a little effect on that of silicone hydrogels because of the siloxane groups. The more oxygen that reaches the eyes through the lens, the healthier the eyes are. Figs. 6a–c show the MC of the hydrogel and silicone hydrogel under the air-dried condition after soaking in three lubricants for 24 h. The different solutions did not significantly affect the MC curve of the hydrogel and the silicone hydrogel. In the test, the initial value of water content of hydrogel is higher than that of silicone hydrogel, as shown in Table 1. Hydrogels mainly rely on water molecules to transport oxygen, while silicone hydrogels primarily rely on silane-based molecules to transport oxygen. Therefore, with the increase of test time, the oxygen permeability of the hydrogel is significantly reduced. However, in the long-term use, the silicone hydrogel retains moisture better than the hydrogel. In this test, the initial oxygen permeability coefficient of the selected hydrogel was lower than that of the silicone hydrogel. Therefore, it is speculated that in the two types of contact lenses involved in this test, the silicone hydrogel has better performance in oxygen permeability and moisture retention.

Fig. 7 shows the line chart of the COF of the hydrogel and silicone hydrogel as a function of speed. The figure shows the COF curve at the speed of 0.1, 1, and 10 mm/s, respectively, through lubricants with distilled water, care solution, and eye drop. As shown in Fig. 7, it can be seen that the eye drops and the care solution have
a significant effect on improving the friction of the lens. Both hydrogel and silicone hydrogel lenses obtained maximum COF values when lubricated with distilled water. Also, the hydrogels and silicone hydrogels have the lowest COF when lubricated with the care solution. As a result, from this point of view, the care solution exhibits the best lubrication effect.

Fig. 8 shows the COF curves, changed with speed, of the two materials in the test, and the value of COF is indicated by the average value of friction over a period of time when the friction is relatively stable. The sliding speeds are 0.1, 0.5, 1, 5, 10, and 20 mm/s. Fig. 8a shows the COF as a function of sliding speed when the hydrogel is subjected to the friction test in three liquid environments: distilled water, care solution, and eye drop. In addition, Fig. 8b shows the COF of the silicone hydrogel. The general trend of the friction coefficient of the hydrogel and silicone hydrogel is as follows: first decreases with increasing friction speed and then increases thereafter. Zhou et al. [25] found that the COF of contact lenses in the saline environment increases with increasing speed (0.1–50 mm/s). At very low sliding speeds (0.1 mm/s or even 0.3 mm/s), the surface properties of the viscoelastic material become less important in terms of friction and wear [26]. At low sliding speeds, the COF is not only affected by the sliding complex and the lubricating medium (if any) but also by the measurement conditions (speed and contact pressure) [19, 29–31]. Therefore, the present results cannot be easily validated. When the speed is low (0.1 mm/s), the elastic deformation of the viscoelastic object increases during relative sliding and the tendency of the two surfaces to remain relatively stationary is greater; thus, the COF had higher value, as the figure shows. When the sliding speed ranges from 0.1 to 5 mm/s, the downward trend is mainly due to the fact that speed has a more pronounced effect on the COF under low load conditions. When
the sliding speed increases (10 mm/s), the COF values of the two materials are basically similar but the COF of the hydrogel is relatively low. Under the condition of constant load of 0.2 N in this test, the COF decreases when the sliding speed changes from 0.1 to 5 mm/s. When the sliding speed is 5–20 mm/s, the COF tends to increase as the speed increases. In this test, the COF of the hydrogel varies from 0.01 to 0.21, while the COF of the silicone hydrogel varies from 0.01 to 0.11.

According to the characterisation results, the silicone hydrogel has lower and more stable COF under the conditions of this test. Therefore, the wear scar of the silicone hydrogel at a specific speed was analysed. Fig. 9 shows the SDM image of the silicone hydrogel after testing in the three lubricants, distilled water, care solution and eye drop, with sliding speeds of 0.1 and 10 mm/s. As shown in Fig. 9a, the silicone hydrogel subjected to the sliding friction test in distilled water presented visible wear scar under the low-magnification mirror. When the speed is 0.1 mm/s, the wear of the lens surface is deeper, but the wear debris is less. When the speed is 10 mm/s, the wear scar on the surface of the lens deepens, and the wear debris is severely peeled off. As shown in Fig. 9b, the wear marks are shallow. At a speed of 0.1 mm/s, the furrow is extremely shallow and the wear debris is less. When the speed is 10 mm/s, the wear debris is more peeled off but the wear scar is shallower than that in the experiment in distilled water. Hence, the lubricating substance in the care solution could act as a lubricant at the friction interface (Fig. 10), thereby slowing down the friction of the lens and reducing its wear. As shown in Fig. 9c, in the eye drops, the surface of the lens has abrasive debris. When the sliding speed is 10 mm/s, the furrow is mainly worn and some fine lines are visible on the edge. As such, the eye drop solution has a certain lubricating effect on the contact lens in comparison with distilled water, thereby reducing the peeling of the surface of the material and the wear condition. The care solution has a more effective lubrication effect on wear and greatly

Fig. 8 Average COFs in three lubricants and varied sliding speed
a Hydrogel
b Silicone hydrogel

Fig. 9 SDM of silicone hydrogels tested in different liquid media
a Distilled water
b Care solution
c Eye drop
reduces the generation of wear debris. The lubricating effect of the care solution is more pronounced, as confirmed by the test results of the COF (Fig. 8). In the test in distilled water, the wear mechanism is mainly abrasive wear and material spalling. The wear mechanism in the care solution is mainly spalling of the material. The wear mechanism in the eye drops is mainly abrasive wear.

Through experiments and characterisation of the results, it was found that the lubricants have a great influence on the tribological behaviour of the two contact lenses involved in this test. Testing in different lubricants indicated that they have a great influence on the COF of lenses. The COF obtained in the sliding friction test in distilled water is higher than that in the two other media and varies between 0.01 and 0.15. This finding is due to the fact that the contact lens and PMMA are directly contacted and no lubrication medium is accessed to the friction interface (Fig. 10a). Hence, the contact lens shows high damage. In addition, compared with distilled water, both the care solution and the eye drop can reduce the COF value when the lens slides, and improve the wear of the lens surface. Comparison among the three liquid media showed that the COF in the care solution is low and stable, and basically maintained between 0.01 and 0.04. The care solution has a better friction lubrication effect on the contact lens. The lubrication medium could form a tribofilm at the friction interface between the contact lens and the PMMA, reducing direct contact (Fig. 10b). As a result, the damage of the contact lens decreases and the friction state of the contact lens and the cornea improve.

4 Conclusions

The tribological behaviour of contact lenses made of hydrogel and silicone hydrogen in different lubricants was investigated:

(a) Under 0.2 N load and sliding speed of 0.1–20 mm/s, the COF of the hydrogel varies from 0.01 to 0.21, while the COF of the silicone hydrogel varies from 0.01 to 0.11.

(b) The care solution and eye drops can reduce the friction coefficient of the contact lens. The substance in the solutions presumably forms a tribofilm at the friction interface. The care solution shows a better lubrication effect than the eye drops.

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6 References

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Fig. 10 Damage mechanism of contact lens materials under different liquid lubrication conditions

a Distilled water
b Care solution
c Eye drop
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