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Evaluation of the Lubricating Effect of Hyaluronic Acid on Contact Lenses Using a Pendulum-Type Friction Tester Under Mimicking Physiological Conditions

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Objective: To evaluate the lubricating effect of hyaluronic acid (HA) on soft contact lenses (SCLs) measured using a pendulum-type friction tester.

Methods: We measured the coefficient of friction (CoF) of narafilcon A, delefilcon A, and etafilcon A with polyvinylpyrrolidone (PVP), daily disposable SCL material, using a modified pendulum-type friction tester. Sample SCLs were set on an acrylic plastic half-ball and placed into the polyethylene terephthalate hemisphere cup filled with 0.4 mL of test lubricants that included saline and 0.05%, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% (wt/vol) HA (molecular weight, 850 kDa). The viscosities of saline and HA were measured using an Ubbelohde viscometer.

Results: The CoF of the SCL under a low concentration (0.05%) of HA was the lowest and significantly lower than saline in narafilcon A and delefilcon A ($P<0.05$, Steel multiple comparison test). Under higher HA concentrations (0.3%, 0.4%, and 0.5%), the CoF was significantly higher than that of saline ($P<0.01$, Steel' multiple comparison test) in all three SCLs. There were no significant differences of CoF among three SCLs in saline and all concentrations of HA. The HA viscosities increased exponentially with the concentration ($Y=1.2829e^{9.286X}$).

Conclusion: The viscosity of a high concentration of HA may increase the friction of SCLs, which may have a deleterious effect on the ocular surface.

Key Words: Friction—Contact lens—Hyaluronic acid—Lubricant—Viscosity.

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As the use of soft contact lens (SCL) becomes increasingly more common, the number of cases of ocular surface damage and/or dry eye symptoms among CL wearers have been increasing globally.[1,2] Contact lens discomfort (CLD) is a condition that leads to decrease wearing time and discontinuation of contact lens wear resulting from reduced compatibility between the CL and ocular environment.[3] Two major factors result in CLD: the CL and environmental factors.[3] Friction and wettability between the CLs and the surface of the eye or eyelids seem to be highly related to CLD.[4] Even under normal conditions, the presence of the CL on the ocular surface disrupts the tear film by dividing it into the prelens and postlens tear film, which could increase the friction and decrease the wettability on the ocular surface.[5] To reduce the friction between the CL and ocular surface, many researchers have developed CL materials and eye drops as lubricants.[6–9]

Hyaluronic acid (HA) is effective for moisturizing[10] and healing the ocular surface damage[11] and is expected to remain on the ocular surface for an extended period because of its viscosity.[12] Although HA is a commonly used lubricant for patients with dry eye or CLD, no studies have reported any in vivo or clinical studies designed to directly improve comfort during CL wear.[4] We reported previously that the contact angles (CAs) of the 0.1% HA ophthalmic solution on daily disposable silicone hydrogel lenses in vitro were significantly higher than saline and artificial tears,[13] possibly because of the effect of the HA viscosity with its high molecular weight and non-Newtonian fluid.[13–15] We hypothesized that HA also increases the friction between the CL and the ocular surface because of its viscosity.

Several studies have measured the friction of CLs.[6,7,16,17] We recently developed a pendulum-type friction tester for CLs, which is a modification of a friction tester for artificial joints.[18] In the current study, we measured the friction of a commercially available silicone hydrogel SCL using a range of HA concentrations to evaluate the effect of its lubrication property using the newly modified pendulum-type friction tester.

METHODS

Sample Preparation

The commercially available, two daily disposable silicone hydrogel SCL, narafilcon A (1-Day Acuvue TruEye, Johnson and Johnson, New Brunswick, NJ) and delefilcon A (DAILIES TOTAL①, Alcon, Inc, Switzerland), and one daily disposable hydrogel SCL, etafilcon A with polyvinylpyrrolidone (PVP)

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(1-Day Acuvue Moist, Johnson and Johnson, New Brunswick, NJ) were used in this study. All CLs used had a −3.00-diopter sphere. All samples were soaked in saline for 48 hr before measuring the friction to eliminate the effect of the packing solution.

Lubricants

We used saline (Otsuka Normal Saline, Otsuka Pharmaceutical Co, Tokyo, Japan) and HA (Denka HA 170209-090, Denka, Tokyo, Japan) (molecular weight, 850 KDa) for measuring the friction on the CLs. The HA was diluted with distilled water to obtain 0.05%, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% concentrations (wt/vol).

Tribologic Experiment

All friction tests were performed on a pendulum-type friction tester (Fig. 1A–C)[18] made by modifying the friction tester for measuring artificial joints.[19] The sliding area was a complete CL itself set at the fulcrum of the pendulum (Fig. 1B). The CLs were attached to an acrylic plastic hemisphere with a small amount of silicon resin that was only applied only at the center of contact lens (Bathcaulk, Cemedine Co, Ltd, Tokyo, Japan) and placed into a polyethylene terephthalate (PET) cup (internal radius, 10 mm) filled with 0.4 mL of the test lubricant (Fig. 1C). All friction tests were conducted with the CLs fully submerged in the lubricants.

The motion of the pendulum was started from a 30-degree inclination and video recorded until the motion stopped.[18] During the free motion, the position of the marker on the protractor scale was recorded by the video camera (Fig. 1B). After the measurement, the amplitude was obtained from the video by replaying each cycle of the pendulum motion. The decay in amplitude $\Delta\theta$ in one cycle (Fig. 2) was calculated from the regression curve of change in the peak angle.[18] The measurements were performed 10 times with each lubricant, and the CL was renewed for every measurement (n=10). The coefficient of friction (CoF) was calculated using the following formula giving the frictional coefficient f which reported previously.[18,19]

$$f = l \cdot \Delta\theta / (4\mathrm{r})$$

f is the friction coefficient, $\Delta\theta$ is delay in amplitude per cycle, l is the distance between the center of gravity and the center of the fulcrum of the pendulum, and r is the radius of the sliding surface.

All experiments were performed in a room with a temperature maintained at 25.3±0.6°C; the humidity of 56±3.5% in the measurement room was maintained at a constant level.

To mimic the physiologic environment of the eye, we considered the eyelid pressure and the velocity of blinking.[18] Shaw et al.[20] reported that the static upper eyelid pressure was about 8.0 mm Hg (= 1.067 kPa) measured using a piezo resistive pressure sensor attached to a rigid CL. Because the area of the SCL used was 158.3 mm^2, the force was calculated to be 0.1689 N. Therefore, we set the weight of the load at 17.2 g.[18] Regarding the blinking speed, Navascues-Cornago et al.[21] reported closing (129.3 and 140.8 mm/sec) and opening (48.6 and 58.0 mm/sec) blink speeds measured using infrared illumination and white light illumination methods, respectively. The length from the fulcrum center to a gravity center in this tester was set to 27 mm.[18] The sliding velocity of the tester was calculated from the previously reported formula.[18] In this study, the estimated maximal sliding velocity was set to 90.0 mm/s[18]

The lubrication using saline and HA was measured using an Ubbelohde viscometer (Sibata Scientific Technology, Ltd, Tokyo, Japan).

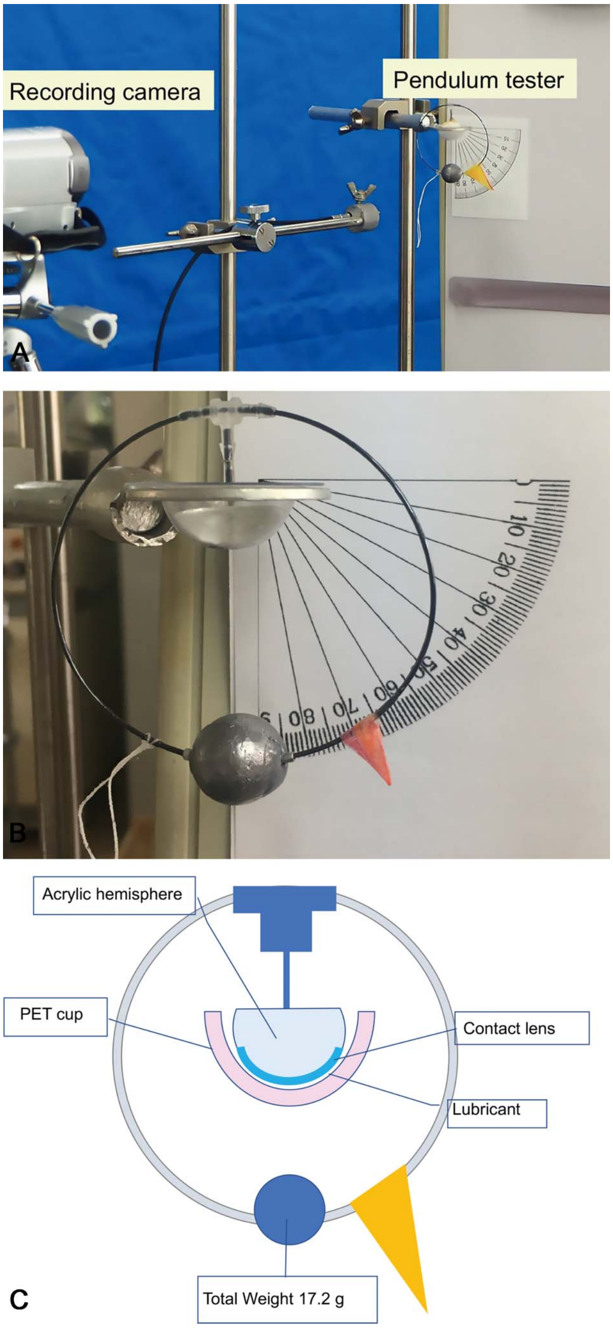

FIG. 1. Pendulum-type friction tester. (A) The motion of the pendulum tester is recorded by a video camera. (B) The sliding area is a complete contact lens itself set at the fulcrum of the pendulum. (C) The counter surface is a cup of polyethylene terephthalate (PET) with an internal radius of 10 mm. The soft contact lens is attached to the acrylic hemisphere and placed into the PET cup filled with 0.4 mL of test lubricant.

Statistical Analysis

All analyses were conducted using the JMP version 14 statistical analysis software (SAS Institute, Inc, Cary, NC). The Steel multiple comparison test was used to compare saline and each HA concentration. To compare the differences among SCLs of each lubricant, the Steel–Dwass test was used.

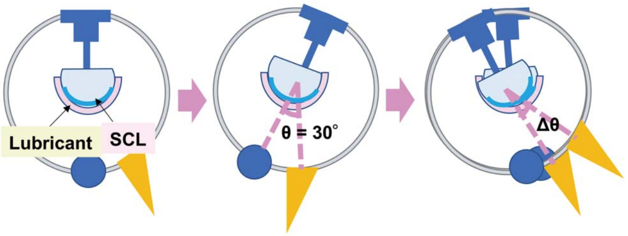

FIG. 2. The measuring system of the pendulum-type friction tester. The decay in amplitude $\Delta\theta$ in one cycle is calculated from the regression curve of change in the peak angle. SCL, soft contact lens.

RESULTS

Table 1 shows the CoF of each SCL and viscosities of saline and each HA concentration. The viscosity of each HA concentration increased exponentially from 1.831 mPa·s at the 0.05% concentration to 125.4 mPa·s at the 0.5% HA concentration ($Y=1.2829e^{9.286X}$, $R^2=0.9904$, Table 1). The increase in the HA viscosity increased the friction of the SCLs (Fig. 3A–C). The CoFs of the silicone hydrogel SCLs, narafilcon A and delefilcon A with a low concentration (0.05%) of HA (0.032±0.003 and 0.032±0.002, respectively) were significantly lower than with saline (0.037±0.02 and 0.038±0.004, respectively, $P<0.05$, Steel multiple comparison test, Fig. 3A and B). The CoF of the hydrogel SCL, etafilcon A with PVP, with a low concentration (0.05%) of HA was lower than with saline, but no significant difference (Fig. 3C). On the other hand, with higher HA concentrations (0.3%, 0.4%, and 0.5%), the CoFs were significantly higher than with saline in all three SCLs ($P<0.01$, Steel multiple comparison test, Fig. 3A–C). We compared the CoF among three different SCLs; however, there were no significant differences of CoF among them in saline and all the concentration of HA ($P>0.05$).

DISCUSSION

The current study measured the CoF of two silicon hydrogel and one hydrogel SCLs with various HA concentrations using a newly developed pendulum-type friction tester. The friction of the SCL with HA was significantly lower than with saline at a low concentration (0.05%) and significantly higher at high HA concentrations (0.3%, 0.4%, and 0.5%) in silicon hydrogel SCLs, narafilcon A and delefilcon A. In hydrogel SCL, etafilcon A with PVP, although the similar tendency was observed, there was no significant difference of CoF between saline and 0.05% HA. The viscosity of HA increased exponentially as the concentrations increased. These results indicated that the viscosity of a high HA concentration may increase the friction on the CL.

Hyaluronic acid is a natural high–molecular weight biopolymer. Because of its advantageous characteristics, that is, high water retention, high biocompatibility, and viscoelasticity, HA has a wide range of applications in medicine such as in ophthalmic eye drops to treat dry eye.[22] To date, several kinds of HA eye drops have become commercially available, and many researchers have reported the effectiveness of HA to treat dry eye.[23,24] The concentrations of commercially available HA eye drops generally range from 0.1% to 0.4%. Park et al.[25] reported in a randomized multicenter study that there was no significant difference in the effectiveness among 0.1%, 0.15%, and 0.3% HA concentrations to treat the dry eye. The current study found that the CoFs of SCLs decreased with a low HA concentration but increased with higher HA concentrations. If there are no differences in the effectiveness among the HA concentrations for treating dry eye, it may be better to use an eye drop with a low HA concentration for CL wearers to relieve the dry eye symptoms of CLD.

The current study also found that the viscosity of HA increased exponentially as the concentration increased. The solution of HA could be highly viscous with non-Newtonian flow properties.[15] The viscosity of HA can increase its retention time on the ocular surface and enhance its effectiveness for treating the dry eye.[12] Snibson et al.[12] reported that a 0.2% HA eye drop had a significant longer ocular surface retention time in patients with dry eye than other eye drops including hydroxypropyl methylcellulose or polyvinyl alcohol and concluded that this was because of its non-Newtonian rheology with high viscosities at low shear rates. Tiffany[26] reported that the viscosity of tears of subjects without dry eye ranged from 4.4 to 8.3 mPa and that of subjects with dry eye ranged from 27.1 to 31.1 mPa. In the current study, the viscosities of the higher HA concentrations (0.3%, 0.4%, and 0.5%) were similar or much higher (27.66, 45.23, and 125.4 mPa, respectively) compared with the tears of patients with dry eye.[26]

We used a newly developed pendulum-type friction tester to measure the CoFs on the SCL.[18] The instrument was a modification of a friction tester used to measure the friction in artificial joints.[19] To mimic the movement of human eye blinks and eyelid pressure, we calculated and set the weight of the load and length of the pendulum and the initial inclination angle.[18] The CoF of narafilcon A under saline measured in this study was 0.037±0.003. Previously, Roba et al.[6] established a friction measurement system for CLs using a microtribometer and reported that the CoFs of narafilcon A ranged from 0.031±0.028 to 0.037±0.019 under a tear-mimicking solution. Therefore, the current results were similar to the previous report.

The current study had several limitations. First, we measured only two types of silicone hydrogel and one type of hydrogel SCL material. Further study using other types of SCLs should be performed in the future. Second, we used a PET hemisphere cup as

TABLE 1. *Mean±SD of the CoF and the Viscosities of Saline and Each HA Concentration*

CoF	Saline	0.05% HA	0.1% HA	0.2% HA	0.3% HA	0.4% HA	0.5% HA
Narafilcon A	0.037±0.002	0.032±0.003	0.033±0.002	0.038±0.002	0.048±0.004	0.053±0.003	0.062±0.004
Delefilcon A	0.038±0.004	0.0032±0.002	0.038±0.002	0.043±0.004	0.051±0.003	0.058±0.004	0.062±0.005
Etafilcon A with PVP	0.035±0.005	0.033±0.002	0.039±0.003	0.047±0.002	0.052±0.003	0.060±0.004	0.075±0.008
Viscosity (mPas)	Saline	0.05% HA	0.1% HA	0.2% HA	0.3% HA	0.4% HA	0.5% HA
	0.9152	1.831	3.128	8.841	27.66	45.23	125.4

CoF, coefficient of friction; HA, hyaluronic acid; PVP, polyvinylpyrrolidone.

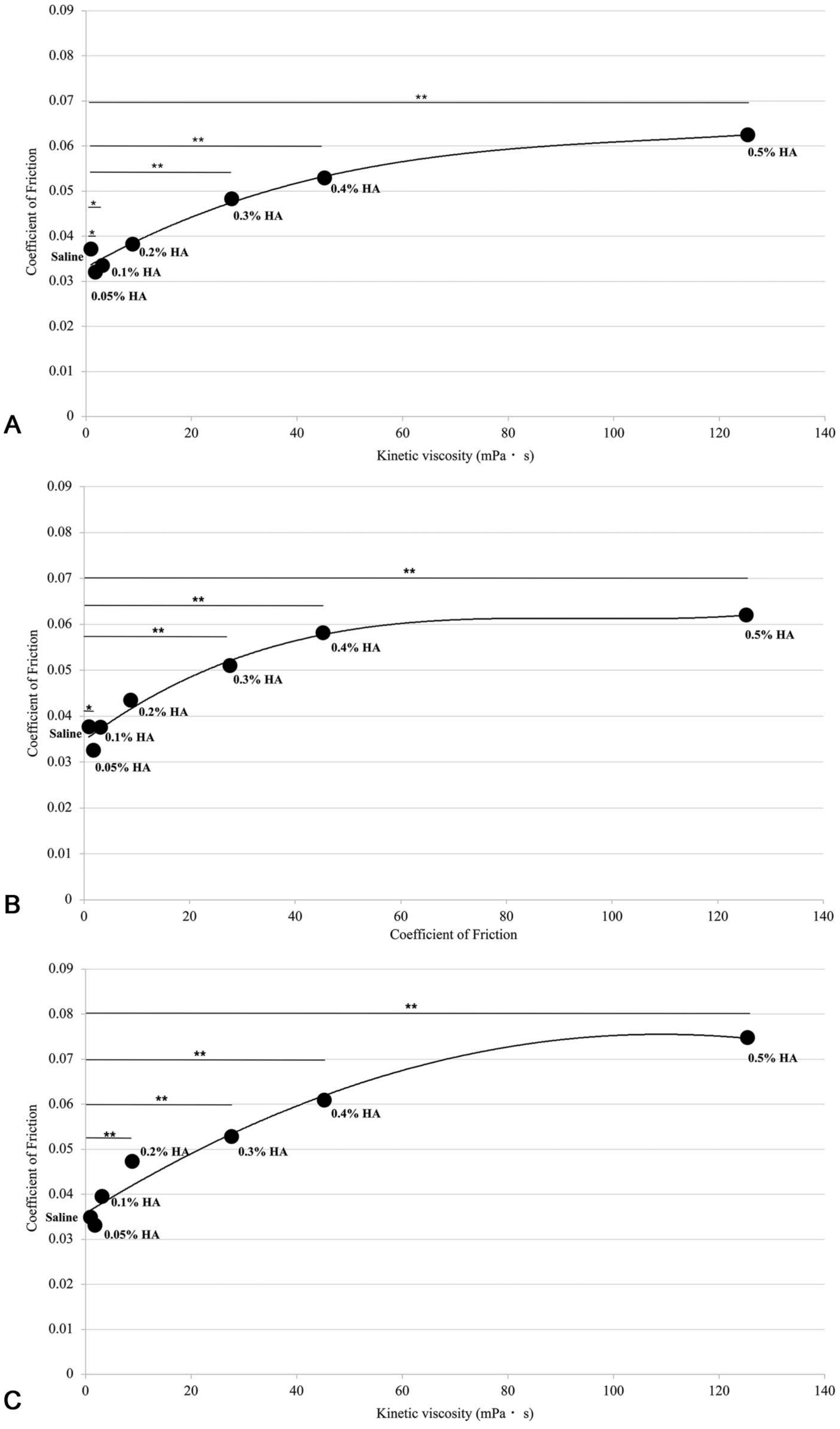

FIG. 3. The relationship between the friction and viscosity of the saline and hyaluronic acid (HA) on the three different SCLs, (A) narafilcon A, (B) delefilcon A, and (C) etafilcon with polyvinylpyrrolidone (PVP). The coefficient of friction (CoF) of the soft contact lens under a low hyaluronic acid concentration (0.05%) is significantly lower than saline in narafilcon A (A) and delefilcon A (B) (*$P<0.05$, Steel multiple comparison test). The CoF of etafilcon A with PVP with a low concentration (0.05%) of HA was lower than with saline, but no significant difference (C). Under higher HA concentrations (0.3, 0.4, and 0.5%), the CoFs are significantly higher than with saline (**$P<0.01$, Steel multiple comparison test) in all SCLs (A, B, and C). SCL, soft contact lens.

the counter surface for SCLs in this study. Several researchers have used a biologic mimicking surface such as mucin-coated glass disks.[6,7] Third, this pendulum-type friction tester is unsuitable for long-term measurements because the pendulum moves only with the potential energy of the initial position, so it stops after a while because of the friction on the SCL.

Hyaluronic acid eye drops are used widely by SCL wearers to relieve dry eye symptoms. To the best of our knowledge, the current study is the first to evaluate the effect of the HA concentration regarding the friction of the SCL. The viscosity of a high concentration of HA may increase the friction of SCLs, which may have a deleterious effect on the ocular surface. The newly developed pendulum-type friction tester is useful for assessing the lubricating ability of lubricant on a contact lens.

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