communications
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https://doi.org/10.1038/s43246-022-00317-4 OPEN

Effect of grip-enhancing agents on sliding friction between a fingertip and a baseball

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Friction between a pitcher's fingers and the leather surface of a baseball is a key factor that influences ball delivery, causing Major League Baseball in the United States to recently enhance enforcement of rules banning the unauthorized use of friction-enhancing agents or sticky substances. Here, we examine how the application of rosin powder and sticky substances alters the friction coefficient between a fingertip and the leather of a baseball. We find that sticky substances increase friction which can positively affect ball spin rate, while rosin has the advantage of keeping friction consistent within and between individuals. Additionally, we find that baseballs used by the Nippon Professional Baseball Organization in Japan are less slippery compared with the ones used in Major League Baseball, suggesting that grip-enhancers may have a larger impact on friction for baseballs used in the United States compared to Japan. Furthermore, our results indicate that changing the characteristics of the leather the baseball is made from may increase friction, reducing the unauthorized use of sticky substances.

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On June 15, 2021, Major League Baseball (MLB) announced enhanced enforcement of the rules that prohibit the use of foreign substances (i.e., sticky substances) to baseballs, except for rosin, a mixture of magnesium powder and pine resin[1]. Enforcement of the ban on grip-enhancing agents had a significant impact on pitching performance, e.g., spin rates on fastballs subsequently dropped by approximately 4%[2]. However, it is currently unclear how applied substances alter the friction coefficients and the potential effects of these changes on baseball pitching.

In baseball pitching, the friction between the finger and the baseball ensures the grip of the ball during the pitching motion and at the moment of the release when tangential force increases drastically with the rolling of the ball causing ball spin[3]. The resultant force determines the translational direction of the baseball and friction at the release can affect the accuracy of ball control. Thus, friction can play a key role in affecting pitching performance, such as ball spin and ball control.

Yamaguchi et al.[4] investigated the effect of rosin application on the sliding friction between the finger and baseball leather sheet used in Nippon Professional Baseball (NPB) in Japan. They found that rosin application to baseball leather increased the friction under wet conditions compared with no application condition[4]. Additionally, they found that the variation in friction within and between individuals was significantly reduced after rosin application, suggesting that rosin acts as a friction stabilizer[4]. Therefore, the use of rosin is advantageous for pitchers to maintain constant friction. Currently, no studies have investigated the effects of sticky substances on the friction between fingers and baseballs. One reason why MLB pitchers are willing to risk using sticky substances is the slipperiness of currently used baseballs in MLB. For example, Yu Darvish, a pitcher in San Diego Padres, mentioned that balls in MLB are slippery and claimed that the slipperiness of MLB balls is a factor causing the use of unauthorized foreign sticky substances by MLB pitchers[5]. Baseball texture is a topic of debate when pitchers move to teams in other countries or at international competitions. For example, many Japanese pitchers commented that balls used in MLB are more slippery than ones used in Nippon Professional Baseball (NPB)[5], and those who moved to MLB teams from NPB have struggled to adjust to the slippery MLB balls[6]. However, there is currently no study that has compared the friction coefficients for MLB and NPB balls when contacting human fingers.

In this study, we investigated the effects of applying rosin and sticky substances on the friction coefficient between fingertips and MLB balls (Fig. 1). We also compared the friction coefficient between MLB and NPB baseballs. In fact, MLB balls are rubbed with mud and NPB balls are rubbed with sand before games to remove gloss, slimy materials, and wax around the seam, thereby improving the finger–ball grip. However, the mudding and sanding are not necessarily intended to increase friction, and no study has investigated their effects on friction coefficients. Thus, we additionally investigated the effects of mudding and sanding on friction. The goal of the study was to better understand how grip-enhancing agents impact friction between the ball and fingers during pitching. As there are no regulations on ball friction in the official baseball rules in MLB or NPB, the results of the current study could be used as a reference for discussions regarding the impact of friction-altering agents in pitching.

Results

Effects of rosin and sticky substance application on the friction coefficient for MLB ball. The relationship between the horizontal force ($F_{y\_\mu max}$) and normal force ($F_{z\_\mu max}$) was less varied among participants with rosin or sticky substance application compared with the no application condition (Fig. 2a–f). In particular, for the rosin application on the ball without seams, the gradient is most consistent among participants (Fig. 2e). Variation in the relationship between frictional coefficient (μ_{max}) and normal force ($F_{z\_\mu max}$) was reduced by applying rosin powder instead of any sticky substance or not applying anything at all (Fig. 2g–l). The sticky substance application increased μ_{max} with decreasing normal force regardless of the presence of a seam and showed the largest values at low normal force (Fig. 2i, l). Thus, the within-participant variation was larger with sticky substance application compared with other conditions.

Figure 3a shows the group mean values of mean μ_{max} for MLB balls with and without seams under three different application conditions, calculated as the gradients of the relation between $F_{z\_\mu max}$ and $F_{y\_\mu max}$ (Fig. 2a–f). Two-way repeated measures analysis of variance (ANOVA) indicated that mean μ_{max} value was significantly affected by application condition ($F[2,16] = 26.103$, $p < 0.001$, $\eta_p^2 = 0.765$) and seams ($F[1,8] = 20.285$, $p = 0.002$, $\eta_p^2 = 0.717$) but unaffected by application-seam interaction ($F[2,16] = 0.717$, $p > 0.05$, $\eta_p^2 = 0.082$). A post hoc paired t-test with Bonferroni correction revealed that the mean μ_{max} value for rosin application (95% CI: 1.028–1.186, 27.0% increase, $p = 0.002$, Cohen's $d = 1.449$) and sticky substance application (95% CI: 1.243 − 1.458, 54.9% increase, $p = 0.002$, Cohen's $d = 2.730$) was significantly larger than that for the no application condition (95% CI: 0.714–1.029) for the MLB ball with seam. For the MLB ball without seams, the mean μ_{max} value for rosin application (95% CI: 0.923–1.007, 23.9% increase, $p = 0.014$, Cohen's $d = 1.466$) and sticky substance application (95% CI: 1.128–1.380, 61.0% increase, $p = 0.004$, Cohen's $d = 2.832$) was also significantly larger than that for the no application condition (95% CI: 0.647–0.910). Except for sticky substance application conditions, the mean μ_{max} value increased with the presence of seams for no application (12.0% increase, $p = 0.007$, Cohen's $d = 0.493$) and rosin application conditions (14.7% increase, $p = 0.002$, Cohen's $d = 1.721$).

Figure 3b shows the group mean coefficient of variance (CV) of μ_{max} within participants (under different normal force conditions). Two-way repeated measures ANOVA indicated that the mean within-participant CV of μ_{max} was significantly affected by application condition ($F[2,16] = 30.915$, $p < 0.001$, $\eta_p^2 = 0.794$) but unaffected by seams ($F[1,8] = 0.291$, $p > 0.05$, $\eta_p^2 = 0.035$) and seam-application interaction ($F[2,16] = 1.942$, $p > 0.05$, $\eta_p^2 = 0.195$). A post hoc paired t-test with Bonferroni correction revealed that the mean within-participant CV of μ_{max} for the sticky substance application (95% CI: 0.166–0.289) was significantly larger than that for no application (95% CI: 0.085–0.135, $p = 0.008$, Cohen's $d = 1.912$) and rosin powder application (95% CI: 0.062–0.091, $p = 0.002$, Cohen's $d = 2.585$) for the MLB ball with seams. For the MLB ball without seams, the mean within-participant CV of μ_{max} for rosin application (95% CI: 0.034–0.057) was significantly smaller than that for no application (95% CI: 0.077–0.146, $p = 0.014$, Cohen's $d = 1.960$) and sticky substance application (95% CI: 0.167–0.310, $p = 0.003$, Cohen's $d = 2.897$). The mean within-participant CV of μ_{max} increased with seams for rosin application conditions ($p = 0.017$, Cohen's $d = 1.777$).

Figure 3c shows the mean CV of mean μ_{max} between participants. The between-participant CV of mean μ_{max} under the no application condition (0.235 with seam and 0.220 without seam) was considerably larger than that of rosin application (0.093 with seam and 0.056 without seam) and sticky substance application (0.103 with seam and 0.131 without seam).

As shown in Fig. 4, the mean μ_{max} and moisture level of the finger showed a strong positive correlation in the no application

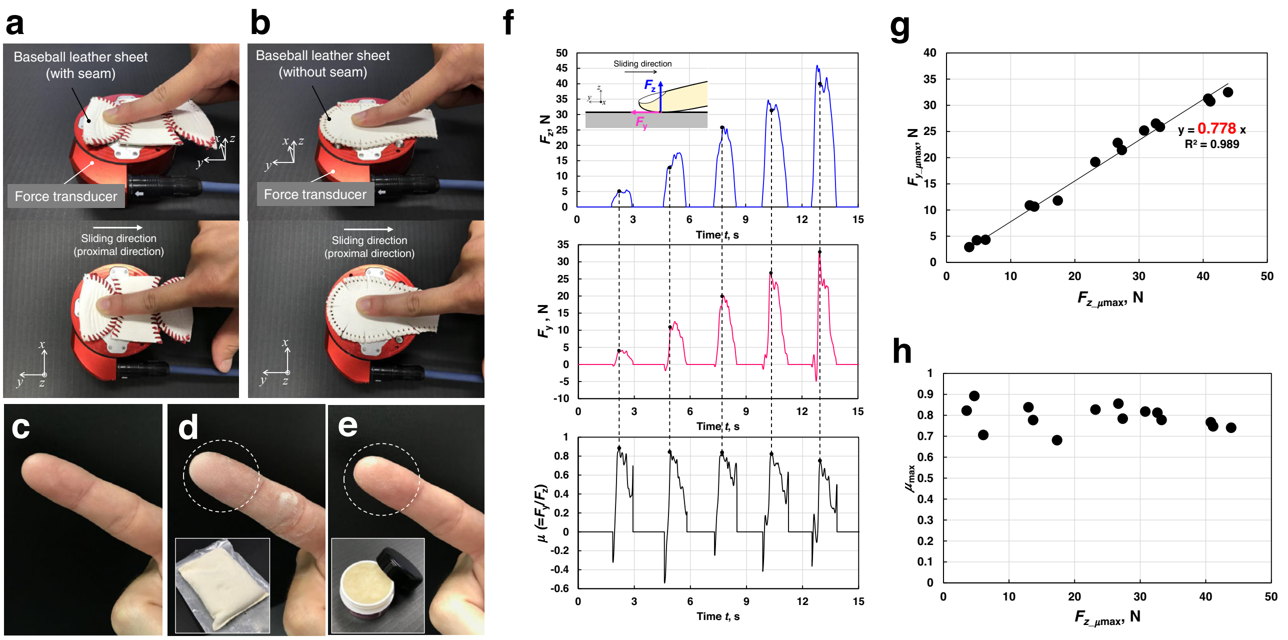

Fig. 1 Measurement of friction between fingertip and baseball leather sheet. **a**, **b** Experimental setup for MLB ball leather sheet with seam (**a**) and that for MLB ball without seam (**b**). **c**–**e** Finger conditions; no application (**c**), rosin application (**d**), and sticky substance application (**e**). **f** An example of time series of the normal force (F_z), the horizontal force (F_y), and the friction coefficient μ (F_y/F_z) during a single trial in which an index fingertip is slid with five different levels of the normal force. **g** The relation between horizontal ($F_{y\_\mu max}$) and normal forces ($F_{z\_\mu max}$) at the maximum friction coefficient μ_{max}. Using this plot, we calculated the mean μ_{max} as the slope of the least square regression square line (e.g., 0.778 in **g**). **h** The relation between the μ_{max} and $F_{z\_\mu max}$. Using this plot, we evaluated the dynamic change of friction across the applied normal force. The data in g and h were collected from three trials at five force levels (15 slides) under no application conditions for MLB ball without seam.

condition ($r = 0.827$ for MLB ball with seam, $p < 0.01$; $r = 0.685$ for MLB ball without seam, $p < 0.05$) (Fig. 4a, d); however, the correlation coefficient was smaller in rosin (Fig. 4b, e) and sticky substance application conditions (Fig. 4c, f).

Comparison of the friction coefficient between MLB and NPB balls. We investigated friction coefficients only under no application conditions for NPB balls and not under rosin and sticky substance application conditions. Note that Fig. 5a, c, e, g are the same as Fig. 2a, d, g, j, respectively, which compares the gradient between $F_{z\_\mu max}$ and $F_{y\_\mu max}$ and the distributions of μ_{max} as a function of $F_{z\_\mu max}$ between MLB and NPB balls. The relationship between the horizontal force ($F_{y\_\mu max}$) and normal force ($F_{z\_\mu max}$) varied among the participants for MLB and NPB balls under no application condition (Fig. 5a–d). Moreover, the relationship between frictional coefficient (μ_{max}) and normal force ($F_{z\_\mu max}$) variation varied among the participants (Fig. 5e–h).

Figure 6a shows the group mean values of mean μ_{max} for MLB and NPB balls with and without seam. The two-way repeated measures ANOVA indicated that mean μ_{max} value was significantly affected by ball type ($F[1,8] = 43.268$, $p < 0.001$, $\eta_p^2 = 0.844$) and seam ($F[1,8] = 7.849$, $p = 0.023$, $\eta_p^2 = 0.495$) but unaffected by ball-seam interaction ($F[1,8] = 0.539$, $p > 0.05$, $\eta_p^2 = 0.063$). A post hoc analysis revealed that mean μ_{max} value for NPB ball (95% CI: 0.876–1.157 without seam; 95% CI: 0.770–1.147 without seam) was significantly larger than that for MLB ball with (95% CI: 0.714–1.029, 16.6% increase, $p < 0.001$, Cohen's $d = 0.747$) and without seam (95% CI: 0.647–0.910, 23.1% increase, $p = 0.004$, Cohen's $d = 0.849$). For MLB ball, seam increased mean μ_{max} value by 12.0% compared to that without seam ($p = 0.007$, Cohen's $d = 0.493$). But there was no significant difference in the mean μ_{max} value for NPB ball by seam ($p > 0.05$, Cohen's $d = 0.271$). Two-way repeated measures ANOVA indicated that the group mean value of the within-participant CV of μ_{max} was not affected by ball type ($F[1,8] = 1.410$, $p > 0.05$, $\eta_p^2 = 0.150$), seam ($F[1,8] = 0.671$, $p > 0.05$, $\eta_p^2 = 0.077$), and ball type-seam interaction ($F[1,8] = 1.726$, $p > 0.05$, $\eta_p^2 = 0.177$) (Fig. 6b). As shown in Fig. 6c, the between-participant CV for MLB ball (0.235 with seam and 0.220 without seam) was not significantly different from that for NPB ball (0.179 with seam and 0.255 without seam).

The effect of rubbing with mud/sand on the friction coefficients of MLB and NPB balls. Figure 7 shows the group mean μ_{max} of MLB and NPB balls rubbed with and without mud and sand, respectively. Two-way repeated measures ANOVA revealed that the mean μ_{max} of balls with seam (Fig. 7a) tended to be affected by the type of ball ($F[1,4] = 6.588$, $p = 0.062$, $\eta_p^2 = 0.622$) but was unaffected by rubbing with mud/sand ($F[1,4] = 0.333$, $p = 0.595$, $\eta_p^2 = 0.077$) and ball-rubbing interactions ($F[1,4] = 0.706$, $p = 0.448$, $\eta_p^2 = 0.150$). A post hoc t-test with Bonferroni correction revealed that the mean μ_{max} of MLB balls with seam (95% CI: 0.672–1.081 without rubbing; 95% CI: 0.675–1.074 with rubbing with mud) was smaller than that of NPB balls both with (95% CI: 0.770–1.267, $p = 0.115$, Cohen's $d = 0.793$) and without (95% CI: 0.753–1.182, $p = 0.047$, Cohen's $d = 0.573$) rubbing with sand. For balls without seam (Fig. 7b), two-way repeated measures ANOVA revealed that the mean μ_{max} was significantly affected by the type of ball ($F[1,4] = 10.043$, $p = 0.016$, $\eta_p^2 = 0.715$) but was unaffected by rubbing with mud/sand ($F[1,4] = 1.853$, $p = 0.245$, $\eta_p^2 = 0.317$) and ball-rubbing interactions ($F[1,4] = 0.101$, $p = 0.767$, $\eta_p^2 = 0.025$). Furthermore, post hoc t-test with Bonferroni correction revealed that the mean μ_{max} of MLB balls without seam (95% CI: 0.568–0.880 without rubbing; 95% CI: 0.610–0.875 with rubbing with mud) was smaller than that of NPB balls both with (95% CI: 0.692–1.214, $p = 0.083$, Cohen's $d = 1.259$) and without (95% CI: 0.658–1.163, $p = 0.016$, Cohen's $d = 1.105$) rubbing with sand.

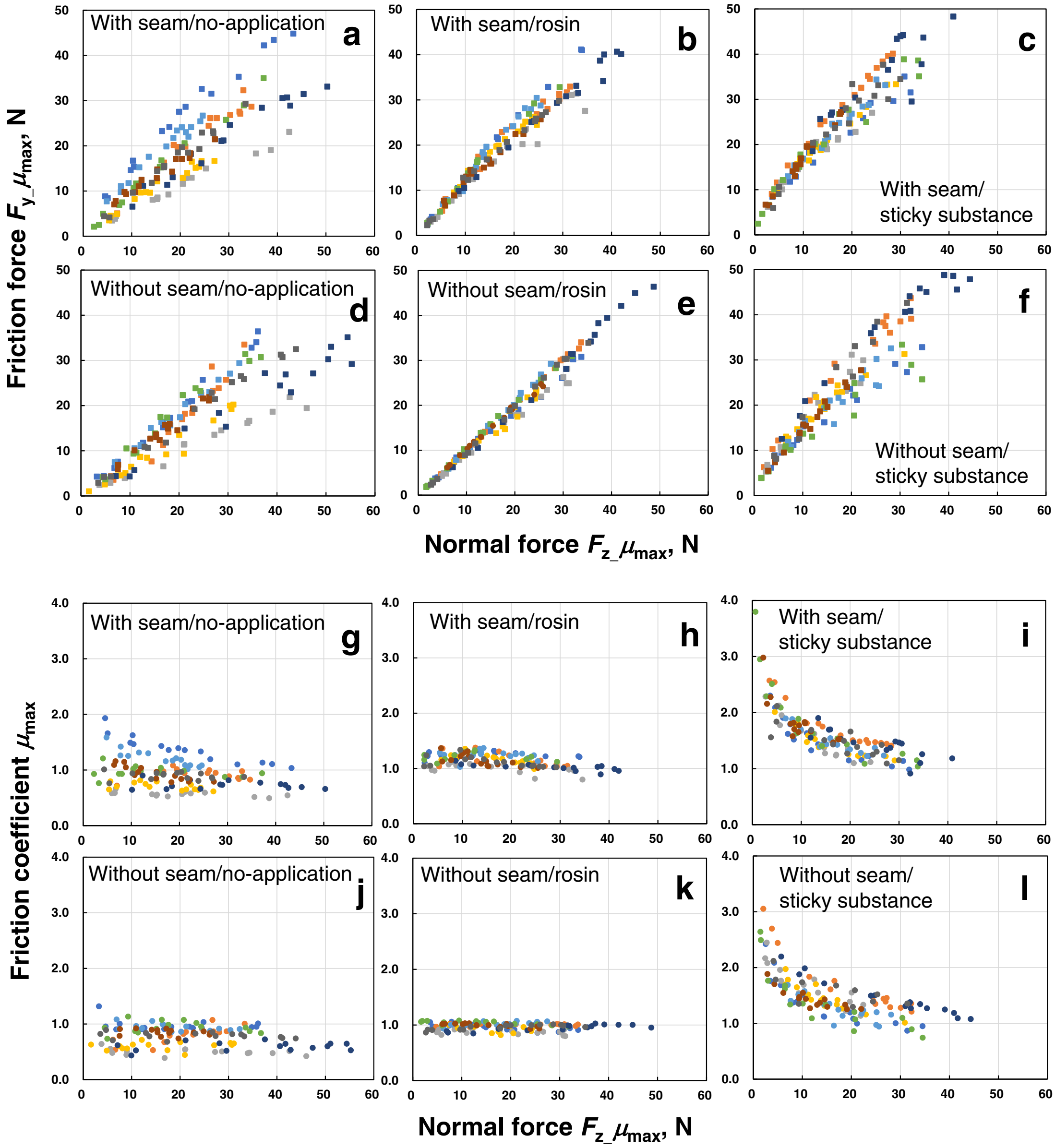

Fig. 2 Frictional characteristics for MLB ball under each application condition. a–f Relation between the horizontal force $F_{y\_\mu max}$ and normal force $F_{z\_\mu max}$ at the instant of each maximum value of the friction coefficient μ_{max} for each participant (with different plot color) under each application condition for MLB ball. No application with seam (**a**), rosin application with seam (**b**), sticky substance application with seam (**c**), no application without seam (**d**), rosin application without seam (**e**), and sticky substance application without seam (**f**). **g–l** Relation between μ_{max} and normal force at μ_{max} under each application condition for MLB ball. No application with seam (**g**), rosin application with seam (**h**), sticky substance application with seam (**i**), no application without seam (**j**), rosin application without seam (**k**), and sticky substance application without seam (**l**).

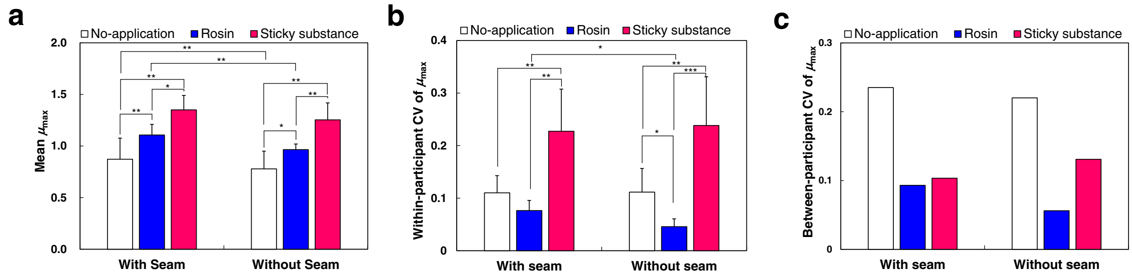

Fig. 3 Comparison of mean and CV values of friction coefficient for MLB ball among application conditions. a Mean μ_{max} value under each application condition for MLB ball. **b** CV values of μ_{max} within participants under each application condition for MLB ball. **c** CV values of mean μ_{max} between participants under each application condition for MLB ball. The error bar indicates the standard deviation. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

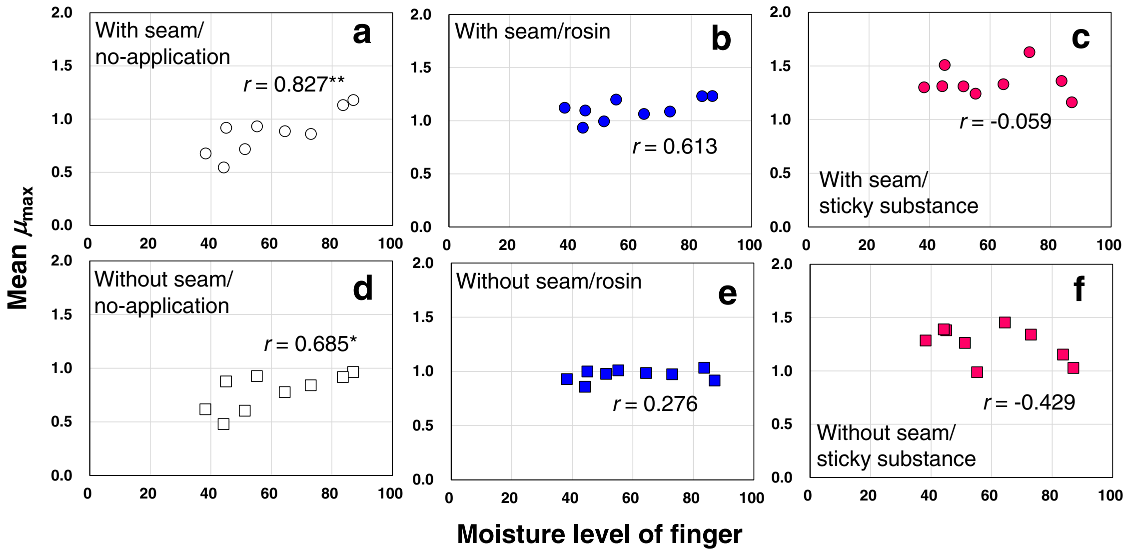

Fig. 4 Relation between the moisture level of the finger and friction coefficient. **a** No application with seam. **b** Rosin application with seam. **c** Sticky substance application with seam. **d** No application without seam. **e** Rosin application without seam. **f** Sticky substance application without seam. $^{*}p < 0.05$, $^{**}p < 0.01$.

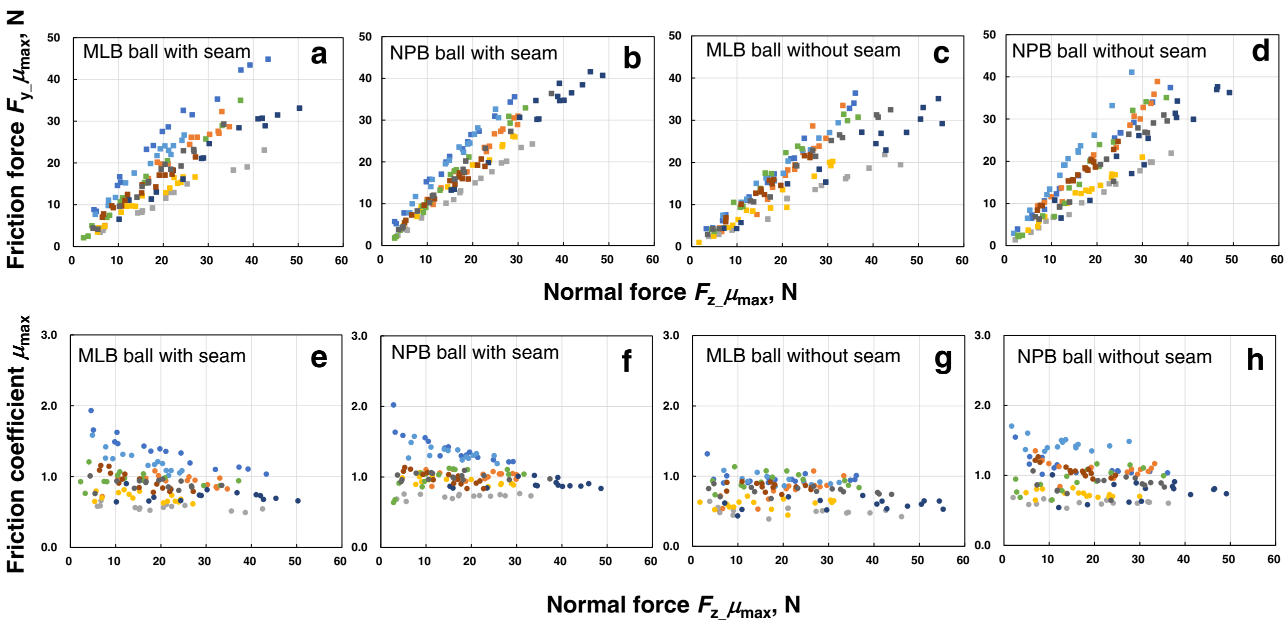

Fig. 5 Frictional characteristics for MLB and NPB balls. a–d Relation between the horizontal force $F_{y\_\mu max}$ and normal force $F_{z\_\mu max}$ at the instant of each maximum value of the friction coefficient μ_{max} for each participant (with different plot color) under no application condition for MLB ball with seam (the same graph as Fig. 2a) (**a**), NPB ball with seam (**b**), MLB ball without seam (the same graph as Fig. 2d) (**c**), and NPB ball with seam (**d**). **e–h** Relation between μ_{max} and normal force at μ_{max} under no application condition for each participant (with different plot color) under no application condition for MLB ball with seam (the same graph as Fig. 2g) (**e**), NPB ball with seam (**f**), MLB ball without seam (the same graph as Fig. 2j) (**g**), and NPB ball with seam (**h**).

Discussion

Under no application condition, the friction coefficient showed variation among participants (Fig. 3c), which may be due to variation in the moisture levels of finger skin among participants (Fig. 4a, d). Previous studies have suggested that moisture reduces skin elastic modulu[7], resulting in the increased contact area and increased adhesion friction[8–13]. The application of rosin increased the friction between finger skin and ball surface by more than 20% (Fig. 3a). Additionally, the application of rosin drastically reduced the variation in the friction coefficient among participants (Fig. 3c). The reduction in variation of friction is possibly due to the occurrence of shear within the rosin powder layers, which minimizes the effect of skin conditions such as moisture. Thus, rosin application increases finger–ball friction and potentially keeps friction consistent across pitchers. This could be beneficial for building a fair environment in baseball pitching.

The rosin application also reduced the variation of friction within-participant (Fig. 3b). Thus, the friction coefficient was quite constant across the normal force, indicating that the friction force between a fingertip and a baseball surface is highly proportional to the normal force, i.e., Amontons' first law[14]. This linear relationship between the normal force and the friction force must be advantageous for pitching performance. That is, this

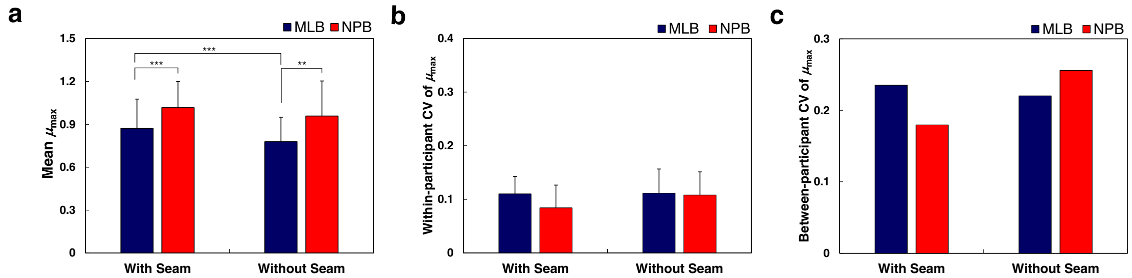

Fig. 6 Comparison of mean and CV values of the friction coefficient between MLB and NPB balls. a Mean μ_{max} values for MLB and NPB ball with and without seam. **b** Mean CV values of μ_{max} within participants for MLB and NPB balls with and without seam. **c** CV values of μ_{max} between participants for MLB and NPB ball with and without seam. Error bar indicates standard deviation. $^{**}p < 0.01$, $^{***}p < 0.001$.

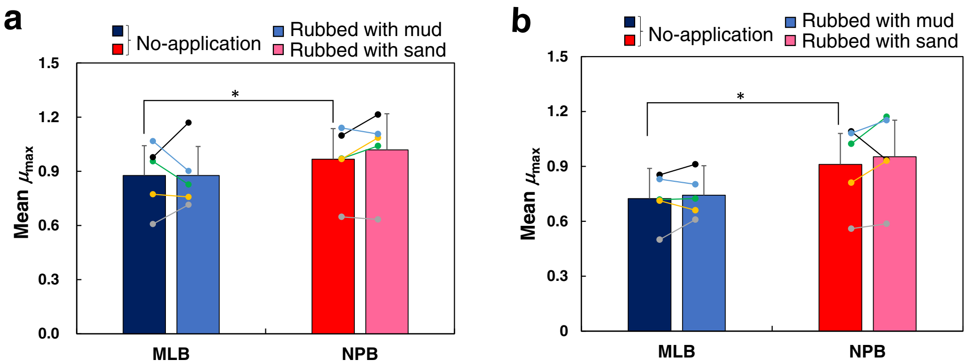

Fig. 7 Effect of rubbing with mud/sand on the friction coefficient. a Mean μ_{max} of seamed MLB and NPB balls with and without rubbing with mud/sand. **b** Mean μ_{max} of seamless MLB and NPB balls with and without rubbing with mud/sand. Each plot indicates the mean μ_{max} for each subject, while the error bar indicates standard deviation. $^{*}p < 0.05$.

constant friction coefficient can facilitate precise control of the friction force between a fingertip and the ball by controlling the normal force during a pitching motion and across multiple pitches, which must dominate the maximum tangential force that highly affects ball spin rate. Also, as the resultant force determines the translational direction of baseball, the friction at the release can affect the accuracy of ball control. These results suggest that the rosin application has the advantage of keeping the friction consistent during pitching, a benefit to improve the repeatability of ball spin and potentially increase ball control.

The individual's moisture level of fingers can affect the friction in no application, as mentioned above (Fig. 4a, d), which causes the large between-participant variation of friction coefficient in no application. This lets us think that pitchers with dry fingers may prefer to use foreign substances to compensate for their less friction on the finger compared with others.

The sticky substance application increased the friction coefficient by more than 50% compared to the no application condition (Fig. 3a). The relationship between the friction coefficient and normal force appears exponential (Fig. 2i, l) when the friction coefficient was large at the low normal force region. The friction coefficient can be expressed as a function of normal force F_z as follows[15,16].

$$\mu = \mu_0 + \frac{F_c}{F_z} \tag{1}$$

where μ_0 is constant, which is the Coulomb friction coefficient, and F_c is the adhesion force, which is determined by the intercept of the friction force-normal force relationship. This implies that the friction coefficient is sensitive to the adhesion force at lower normal forces, and the friction coefficient at the lower normal force region is determined by F_c. Thus, large F_c at low normal force region for the sticky substance due to its strong adhesiveness caused the drastically increased μ_{max} at low normal force conditions shown in Fig. 2i, l. Rosin has low adhesiveness at low normal force conditions; therefore, the friction coefficient appears to be insensitive to normal force and it approaches a constant, as shown in Fig. 2h, k.

The friction coefficient at the low normal force region must correspond to the friction coefficient at the time near ball release [3], where a much higher friction force is expected for the conditions of sticky substance application compared with the other two conditions. The ball spin rate ω_0 at ball release timing can be described in the following equation:

$$\omega_0 = \frac{R}{I}\int_{t0}^{t} F_t d\tau, \tag{2}$$

where R and I are the radius and moment of inertia of the ball, respectively; F_t is a tangential force applied to the ball; t_0 is the time when the ball starts to rotate; and t is the time when the ball is released from the finger. Therefore, using the sticky substance, pitchers can apply a larger tangential force to the ball during the release process, resulting in an increased ball spin rate compared with no application and rosin application conditions.

The exponential relation between the friction coefficient and the normal force results in a large variation in the friction coefficient within-participant (Fig. 3b). This implies that the friction may change drastically during a pitching motion, where the normal force must decrease to zero at the release. Therefore, pitchers may need to adapt this friction variation during the ball-releasing process compared to the other two conditions. This may be an unstable factor for the control of pitching and pitchers must adapt to it.

The presence of a seam increased the friction for MLB ball under no application and rosin application conditions. The friction coefficient for sticky substance applications also tended to increase by a seam ($p = 0.077$, Cohen's $d = 0.635$). In general, the friction force consists of the adhesion friction term and the deformation friction term. When the finger is slid over a baseball leather sheet without seam, the friction coefficient is mainly due to adhesion friction. However, when the finger is slid over a ball leather sheet with seam, a deformation friction term in addition to adhesion friction, i.e., deformation resistance of the finger pad due to the penetration of seam into the finger pad, cannot be neglected and should be considered. Thus, the seam tends to increase friction.

NPB balls showed larger friction coefficients than MLB balls at approximately 15–25% in no application condition, indicating that MLB balls are more slippery than NPB balls (Fig. 6a). The difference in the friction coefficient between MLB and NPB balls was larger when no seam was present (Fig. 6a). The cowhide leather sheet was used in MLB and NPB balls. The difference in the tanning process and chemicals between the cowhide leathers of MLB and NPB balls could affect the friction coefficient; however, the information regarding the tanning process for each balls is unclear. The thickness of the leather was significantly different ($p < 0.001$) between MLB (1.24 ± 0.08 mm) and NPB (1.39 ± 0.08 mm) balls, which could also alter the friction coefficient. The friction coefficient between the ball leather sheet and a fingertip could be expressed by the following equation based on the adhesion friction theory[14].

$$\mu = \frac{\tau A_r}{F_z}, \tag{3}$$

where τ is the interfacial shear strength and A_r is the real contact area. According to Eq. (3), the difference in the friction coefficient between MLB and NPB balls could be affected by τ and A_r at the identical normal force condition. The τ of the MLB and NPB ball leather surface may be different: τ for the NPB ball may be larger than that for the MLB ball. Furthermore, A_r for the NPB ball leather sheet could be larger than that for the MLB ball leather sheet because of its large thickness, which was less affected by the hardness of the base materials, resulting in increased adhesion friction.

These results suggest that the change of materials/structures can increase friction in MLB balls. Especially comparing Fig. 5g, h, when testing the leather without seams, some participants showed much higher friction coefficients with NPB balls compared to MLB balls. For two participants with high moisture levels of the finger, the mean friction coefficient for the NPB ball without a seam under no application condition (1.060 for a moisture level of 87.0 and 1.438 for a moisture level of 83.6) was higher than that for the MLB ball without a seam with sticky substance application (1.028 for moisture level of 87.0 and 1.154 for moisture level of 83.6). Thus, it is possible that when the skin moisture level is high, sticky substances are not advantageous.

Rubbing with mud/sand does not necessarily increase friction between the ball leather and fingertip, thus not improving the finger–ball grip (Fig. 7). Although the group mean value was not significantly different among balls with and without rubbing with mud or sand, as shown in Fig. 7, the effect of rubbing with mud or sand on the friction coefficient was different among subjects. Differences in the effect of rubbing with mud or sand between subjects may be due to variations in rubbing conditions, such as differences in the amount and area of mud or sand applied and drying duration. It has been pointed out that it is difficult for all balls to be mudded under the same conditions[17]. Further, another commentary pointed out that applying mud can make MLB balls more slippery, and the film of mud residue left on the ball can produce an inconsistent grip[18]. In addition, our results indicate that MLB balls have a smaller friction coefficient than NPB balls, despite rubbing with mud.

The present study has several limitations. First, the fingertip was in contact with the flat leather sheet of the baseball rather than the curved surface. Because of this, the result may not precisely reflect the same friction coefficient that would occur during an actual pitch. The contact between a finger and the curved ball (with and without seam) should theoretically increase the contact pressure, and therefore our values are likely conservative measures of friction. Because the normal force between fingertip and ball ranges from 0–80 N during the ball release[3], our results (<60 N) may correspond most closely to the fingertip–ball contact at the time near release. Secondly, typically baseball pitches primarily involve using two fingers, the index and middle finger, to grip a baseball. However, in the current study, only the index finger was tested. Third, our results were not obtained through an actual pitching trial where the dynamics of the ball in relation to finger position and motion differ from the current setting. Fourth, the sliding direction of the finger was only parallel to the length direction of the finger. Sliding normally to this direction is also common in actual pitching, and the effect of the sliding direction of the finger on the friction coefficient should be investigated in the future. Further research is needed in the actual pitching setting.

Another limitation of this study is the condition of the skin. No participants in this study had calluses, which may limit our results in terms of skin conditions that are different from baseball pitchers. The method of mudding and sanding used in our study may not be exactly the same as the one used in games, thereby being a limitation of our study. The tanning process and chemicals used for MLB and NPB balls could affect the difference in friction coefficients. In future, the effect of the tanning process and chemicals used for each ball on the friction coefficient between the finger and baseball should be investigated.

Conclusions

To the best of our knowledge, this is the first study to investigate the effect of a grip-enhancing agent on the sliding friction between a finger and an MLB ball. With MLB balls, we found that the application of rosin powder increased the friction coefficient between a finger and baseball (27.0% with seam and 23.9% without seam), and a sticky substance further increased the friction coefficient (54.9% with seam and 61.0% without seam). The rosin application drastically reduced the between and within-participant variation of friction, while the sticky substance slightly reduced the between-participant variation and increased the within-participant variation. Our results also demonstrated that the friction coefficient of the MLB balls is lower than that of NPB balls (16.6% with seam and 23.1% without seam). MLB balls tended to have a lower friction coefficient than NPB balls (13.9% with seam and 22.0% without seam) even after rubbing with mud or sand. Our findings indicate that there is room for modifying friction in MLB balls. Overall, we found that while sticky substances can increase the friction that can positively affect pitching performance, such as the ball spin rate, the nonlinear relation between normal force and friction force may be an unstable factor for the accuracy of ball control. However, the rosin application can help maintain constant friction during pitching (with respect to normal force) and across pitchers, which could contribute to the fair playing field in baseball pitching in terms of a finger–ball friction.

Methods

Participants. Nine healthy adult males (21–44 years., mean age: 25.1 ± 7.1 years) participated in the sliding friction test. All of these nine participants were right-handed, and two of the nine participants played baseball. The participants were informed of the study protocol, and informed consent was obtained from each participant prior to the experiment. All methods/experiments were conducted in accordance with relevant guidelines and regulations. The study protocol was approved by the Institutional Review Board of Tohoku University.

Experimental procedure. The sliding friction test between an index finger and a baseball leather sheet was performed using a capacitive six-axis force sensor (Dyn Pick WEF-6A200-4-RCD-B; WACOH-TECH Inc., Japan) under conditions with (Fig. 1a) and without seam (Fig. 1b). A ball consists of two pieces of leather sheet and seams connecting the leather sheet pieces. Most of the surface area is covered by the leather sheet, while the pitcher grips a ball with his/her fingertips on the seam. As the dynamics of interaction between fingertip-hand and ball are not fully revealed, we decided to measure the friction between a fingertip and a ball in these two conditions. The rated capacity of the force sensor in the *x*, *y*, and *z* directions was ± 200 N. Two types of balls were used, i.e., the official balls used in MLB (Solid Baseball MLB Official Match Ball, Rawlings, St. Louis, USA) and NPB baseball (1BJBH55000; MIZUNO Corporation, Tokyo, Japan). The leather sheet with or without seam was extracted from the ball. It adhered to the force sensor with adhesive tape (Fig. 1a, b). In this way, the friction coefficient between the fingertip and a flat leather sheet was measured. The leather material is specified in the official baseball rules 2019 edition of MLB[19] as white horsehide or cowhide; however, a cowhide ball is used in MLB. The official baseball rules of the NPB[20] specified cowhide as the leather material. The thickness of the leather sheet sample was measured using a vernier caliper at five points in three balls of MLB and NPB each (15 points in total for each type of ball). The MLB leather sheet (1.24 ± 0.08 mm) was significantly thinner than the NPB leather sheet (1.39 ± 0.08 mm) (student *t*-test, $p < 0.001$).

The protocol for the sliding friction tests has been described in a previous study[4]. For the leather sheet with seam, the participant was instructed to place their index fingertip on the seam as shown in Fig. 1a, and then to slide their finger in the proximal direction (the minus *y*-direction in Fig. 1) five times, with an increasing level of vertical force at each time, i.e., resulting in five different levels of normal force once per level of force. The normal force between a fingertip and a ball varies widely during the ball-releasing process in pitching[3,21]. Thus, we measured the friction coefficient under several normal force conditions[4]. The participants were asked to slide their fingers over ~40 mm within periods of ~0.4 s, resulting in a mean sliding velocity of ~100 mm s^{-1}. The participants were given a practice period to become accustomed to the demands of the experiment by sliding their index fingers under different levels of normal force on the leather sheet under no application conditions at the instructed sliding speed.

Each participant performed the tasks in eight different conditions, i.e., MLB ball with and without seam under no application, rosin powder application, and sticky substance application (i.e., two ball conditions with three application conditions) as well as NPB ball with and without seam under no application (i.e., two ball conditions with one application condition). Note that MLB and NPB balls used for these trials were not rubbed with mud or sand. A block of trials was conducted for each condition. For the rosin powder application, the participant was asked to touch a rosin bag (2ZA-416; MIZUNO Corporation, Tokyo, Japan) five times to ensure that rosin powder covered the entire fingertip of the index finger (Fig. 1d). For sticky substance application, a wax-like sticky substance (iTac2 Pole Fitness Grip-Extra Strength, iTac2 Pty Ltd., Australia) was used as one of the sticky substances in sports. The ingredients of this sticky substance include plant-based ester, beeswax, and N/R isoparaffin. The participant was asked to rub the sticky substance with their index fingertip to ensure that the substance covered the entire fingertip, then wait for two minutes to dry it before the test.

We additionally performed sliding friction tests to investigate the effect of rubbing MLB and NPB balls with mud and sand, respectively, on their friction coefficients. Five out of nine participants participated in this test. The MLB and NPB balls were rubbed with mud (Baseball Rubbing Mud: Personal size, Lena Blackburne Baseball Rubbing Mud, New Jersey, USA) and sand (2ZA450; MIZUNO Corporation, Tokyo, Japan), respectively, approximately 2 h before the friction test. We added water to the mud for rubbing MLB balls. Then, the leather sheet with or without seam was extracted from the balls and adhered to the force sensor.

The moisture level of the fingertip (under no application condition) was measured using a skin sensor (Triplesense® MORITEX Corporation, San Jose, CA, USA)[4,22,23] before each block of trials to ensure that participants maintained a constant moisture level during the experiment. The device uses electrical capacitance to measure the moisture level of the skin. The leather sheet was replaced with a brand new one after every trial block. The order of each block of the trial was randomized. The tests were conducted in a room at 24.4 °C ± 0.6 °C and 38.9 ± 3.1% relative humidity.

Data analysis. The friction coefficient μ was calculated from normal (F_z) and horizontal (F_y) forces measured as follows:

$$\mu = \frac{F_y}{F_z} \tag{4}$$

The sampling frequency of the forces was 1000 Hz, and these were low pass–filtered with a cutoff frequency of 50 Hz. As shown in Fig. 1f, the maximum value of the friction coefficient μ_{max}, which is recognized as the static friction coefficient, in each of the five sliding trials and the horizontal force $F_{y\_\mu max}$ and normal force $F_{z\_\mu max}$ at the instant of each μ_{max} were used for subsequent analyses (Fig. 1f). The mean μ_{max} was calculated as the gradient of the least square linear regression line for the relation between $F_{y\_\mu max}$ and $F_{z\_\mu max}$ without constant (zero intercept) as shown in Fig. 1g. We confirmed that the coefficients of determination for the linear regression were greater than 0.8 for each application and seam condition.

The CV of μ_{max} within each participant (under different normal force conditions) was also calculated to compare the effect of normal force $F_{z\_\mu max}$ on the μ_{max} among conditions as shown in Fig. 1h. Normality of μ_{max} within participants for each condition was verified using the Shapiro–Wilk normality test.

We performed a two-way repeated measures ANOVA to investigate whether the group mean value of mean μ_{max} and the within-participant CV of μ_{max} for MLB ball were affected by seam and application of rosin and sticky substance. A post hoc paired *t*-test with Bonferroni correction was used to determine specific significant differences in the group mean value of mean μ_{max} and the within-participant CV of μ_{max} by seam and application conditions.

The CV of mean μ_{max} among participants was calculated for each application condition to investigate the effect of the application of rosin and sticky substance on the between-participant difference in mean μ_{max}. We also conducted the Pearson correlation test to investigate the correlation between the moisture level of the finger and the group mean value of mean μ_{max} at each application condition.

We also conducted a two-way repeated measures ANOVA to test whether the group mean value of mean μ_{max} and the within-participant CV of μ_{max} were affected by seam and types of the ball (MLB and NPB balls) for no application condition. A post hoc paired *t*-test with Bonferroni correction was used to determine specific differences in the group mean value of mean μ_{max} and the within-participant CV of μ_{max} by seam and type of ball.

Two-way repeated measures ANOVA was performed to investigate whether the group mean values of mean μ_{max} were affected by the type of ball (MLB vs. NPB) or by rubbing with mud/sand. Moreover, a post hoc paired *t*-test with Bonferroni correction was used to determine specific differences in the group mean value of mean μ_{max} according to the presence of rubbing and type of ball.

The effect size in terms of η_p^2 for ANOVAs and Cohen's *d* for post hoc *t*-tests were also reported. η_p^2 values of 0.25, 0.09, and 0.01 were considered as large, medium, and small effect sizes, respectively, while a Cohen's *d* of 0.2–0.4, 0.4–0.8, and >0.8 indicated small, moderate, and large effects, respectively[24].

All statistical analyses were performed using SPSS Statistics for Windows, Version 19.0 (IBM, Armonk, NY, USA). The significance level was set at $p = 0.05$.

Data availability

The data that support the graphs within this paper are available from the corresponding author upon reasonable request.

Received: 3 March 2022; Accepted: 8 November 2022;
Published online: 15 December 2022

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Author contributions

T.Y., D.N., and K.M. conceived the project and designed the study. T.Y. performed friction measurements and data analysis. T.Y., K.M., and D.N. performed the interpretation of data and wrote the manuscript. All authors contributed to revising the manuscript and have approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43246-022-00317-4.

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Peer review information *Communications Materials* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editor: Aldo Isidori. Peer reviewer reports are available.