Electrostatic attraction caused by triboelectrification in climbing geckos

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Abstract: Adhesion achieved through feet setae is fundamental for gecko agilely maneuvering. Although diverse hypotheses have been proposed, none of them thoroughly explains the setae function, implying a kind of hybrid-mechanism-based adhesion in geckos. In addition to van der Waals interactions and capillary force, the electrostatic attraction that emerges from triboelectrification was suggested as a component of setae adhesion. Nevertheless, the contribution by electrostatic attraction to the total setae attachment is still controversial. In this study, we analyzed the occurrence of electrostatic attraction at gecko setae through experiments and model analyses. By touching the substrates with only $\sim 1/70^{\text{th}}$ of the foot area, freely wall-climbing geckos developed tribocharge at their feet setae with a density of ~ 277 pC/mm², generating electrostatic attractions with a strength of ~ 4.4 mN/mm². From this perspective, the adhesion driven by triboelectrification could account for about 1% of total adhesion. Model analyses at spatula level indicated a similar result showing that the electrostatic force might account for $\sim 3\%$ of the adhesion that facilitates wall-climbing in geckos. The low contribution of the electrostatic force partly explains why geckos always face difficulty in maneuvering onto those substrates (e.g., teflon) where they could easily develop tribocharge but difficultly generate van der Waals force. However, long-range electrostatic forces may play other roles in a distance range where the van der Waals interaction cannot function. These findings not only add to our understanding of the mechanism of gecko adhesion, but also will help us advance gecko-inspired fibular adhesives.

Keywords: biotribocharge; electrostatic force; geckos; adhesion

1 Introduction

Geckos are recognized as one of the most excellent climbers that can maneuver on various terrains in all orientations [1–5]. Their stride frequencies can be as large as a dozen Hertz, and their speeds could be as fast as ~ 1 m/s. Previous studies have attributed the versatility of geckos in locomotion to their abilities to alter body dynamics and rapidly obtain proper adhesion through their compliant, hierarchical, and hairy footpads [6–8]. Therefore, understanding the physics of geckos' feet and the mechanism of

adhesion generation is of great significance to understand the biological attachment mechanism and inspire artificial adhesives.

Attempts aiming at determining the adhesion mechanisms of geckos can be traced back to the 1800s. In the last two centuries, many hypotheses, including adhesive secretion, suction, friction, and micro-interlocking, have been proposed to explain the adhesion mechanism of geckos [9–12], but were not supported by experimental observations [13–16]. In 1900, Haase [17] proposed that geckos probably adhere through intermolecular forces. Hiller [18] further

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found that the setae can stick to hydrophilic surfaces with high surface energies but cannot adhere to hydrophobic surfaces with low surface energies, confirming that the gecko adhesion involves intermolecular interactions which are related to the surface energies [19]. After separately considering the effects of the polarizability and hydrophobicity of substrate on setae adhesion, Autumn et al. [16, 20] rejected other proposals but supported that the van der Waals force is the primary source of setae adhesion, allowing a single seta of a gecko to generate shear and normal forces for 200 and 40 μN , respectively [20]. However, Huber et al. [21] found that the adhesive force of the spatulae increases with the humidity and declared that the capillary force (or capillary-related force) must also contribute to gecko adhesion, although Refs. [22–24] support that the high humidity softens the setae rather than inducing capillary force. Because a seta can only generate adhesion if it is pushed toward a substrate then slid for a short distance [20], and its main component (β -keratin [25]) is easily positively charged while touching other materials [26, 27], the electrostatic force that emerges from the tribocharge was also reasonably considered as a potential source of setae adhesion [10]. According to the findings in triboelectrification [28–31], the strength of electrostatic adhesion is determined by the properties of setae and substrate but urgently requires accurate quantifying in geckos.

Prevenslik [32] theoretically analyzed the possibility of electrostatic adhesion in geckos but failed to provide experimental evidence. Izadi et al. [33] studied the adhesion of a kind of gecko-inspired adhesive made with teflon amorphous fluoropolymer (teflon AF) and confirmed the electrostatic adhesion in fibrous adhesives. They also studied the triboelectrification on gecko feet by sliding a gecko foot on a teflon AF film, obtaining a considerable amount of tribocharge, which was capable of generating an attraction twice the shear force they measured [34]. Therefore, they drew a well-reasoned conclusion claiming that the attraction driven by electrostatic interactions instead of the van der Waals force is the major source of gecko adhesion. However, as they mentioned, the hairs and teflon are almost the easiest to be tribocharged according to the tribocharge series [26, 27],

but nearly the most difficult to generate van der Waals adhesion [35]. Thus, the tribocharge measured by sliding geckos feet on teflon seemed to be overlarge whereas the force seemed to be insufficient, compared with running geckos on other materials. In our previous work [36], we measured the tribocharge at the geckos' feet when they were freely ascending an acrylic oligomer film and found a much lower charge [37], but failed to estimate the exact contribution of the tribocharge because of the unknown actual contact charge density. To accurately determine the charge density, and thereby electrostatic force, synchronous measurements of the tribocharge and contact area are required but currently almost impossible.

In this study, we took a step forward by comprehensively considering the contact, triboelectrification, and adhesion. Through experiments and experiment-based model analyses, we estimated the contribution of electrostatic force originating from triboelectrification to setae adhesion in freely climbing geckos. This study will not only provide an insight into the setae adhesion in geckos, but also help us advance the gecko-inspired fibrous adhesives.

2 Materials and methods

2.1 Animals

Five geckos (*Gekko gekko*) with masses of 78.3 ± 14.4 g were used in the experiments. They were purchased from Guangxi, China, raised in a temperature range of 26–28 °C and humidity of 55%–65%. The room was illuminated for 12 h (7 am–7 pm) every day. The geckos were provided crickets every two days and water daily.

The experiment was approved by the Jiangsu Association for Laboratory Animal Science and performed following the Guide of Laboratory Animal Management Ordinance of China. No animals were hurt during the experiments.

2.2 Experimental setup

As mentioned earlier, precisely estimating the electrostatic adhesion that emerges from triboelectrification requires an accurate and synchronous measurement

of the tribocharge, contact area, and reaction forces at the feet of geckos, which is almost impossible by using current techniques. Therefore, in this study, we used data obtained from two separate experiments, as described in Sections 2.2.1 and 2.2.2.

2.2.1 Synchronous measurement of tribocharge and reaction force

Zou et al. [26] established a standard for the measurement of contact charges. By using a similar principle to measure the tribocharge and measuring contact force via force sensors, we obtained the synchronous tribocharge and contact force at the feet of geckos when they climbed a substrate covered with acrylic oligomer film [36]. In this study, we used the charge data adopted from our previous work (Ref. [36]).

2.2.2 Synchronous measurement of contact area and reaction force

As shown in Fig. 1, an aisle was constructed using three-dimensional (3D) force sensors and clear acrylic sheets (160 mm × 60 mm × 3 mm). The contact angle of the acrylic sheet (68.1°) is similar to that of the substrate (64.8°) used in measuring the tribocharge so that the chemistries of the substrates do not significantly change the adhesion performance according to Hiller's findings [18]. Light strips were appended to the acrylic sheet to form frustrated total internal reflection (FTIR [37]) that can highlight the contact regions once the geckos touched the acrylic. Two baffles were used to constrain the geckos, a dust removal film was placed at the start of the aisle to clean the feet of geckos, and a darkened box was placed at the end of the aisle to induce the geckos to run. While the geckos climbed upward, we collected the force signals using a data acquisition (DAQ) module (National Instrument Inc., Texas, USA) at 1,000 Hz and monitored their climb from the back using a highspeed camera (500 fps, Ispeed-3, Olympus, Japan).

The experiments were conducted at the temperature of ~25 °C and the humidity of ~55%. The animals ran at most three times every two days. They were allowed to rest for at least 1 h before running. The trials in which the animals suddenly stopped, speeded up, turned back, or touched the baffles

Fig. 1 Approach to synchronously measure the contact area and reaction force at the feet of climbing geckos. The coordinate system at the top-left indicates the positive directions for measured force. In particular, the lateral force (i.e., the force in x -direction) was set to be positive when it pointed to the outward as shown by the top-right inset, and the toes at the left feet were counted anticlockwise while those at the right feet were counted clockwise.

were discarded. Finally, we obtained seven trials from each gecko.

2.3 Data processing

The highspeed videos were processed using MATLAB 2018 (MathWorks Inc., Massachusetts, USA). Through image processing [37], the exact contact area (A_i) and orientation (ϕ_i) of gecko toes were calculated. In particular, by considering the bilateral symmetries of their limbs and the reaction force, the outward lateral force was set as positive (as shown by the coordinate system in Fig. 1), and the toe orientation calculated relative to the upward direction was counted anticlockwise and clockwise for the left and right feet, respectively.

Two methods were applied to calculate the adhesive strength of the feet of the geckos. First, the overall contact area was used, as in our previous work [36]. Second, the resultant contact area, which was calculated by regarding the direction of toes as vectors, was applied. To compute the resultant contact area, we used

$$\begin{aligned}
 A_x &= \sum_{i=1}^5 A_i \sin \varphi_i \\
 A_y &= \sum_{i=1}^5 A_i \cos \varphi_i \\
 A_s &= \sqrt{A_x^2 + A_y^2}
 \end{aligned} \quad (1)$$

where A_x and A_y are the resultant contact areas in x - and y -directions, respectively; and A_s is the resultant contact area concerning the shear force.

SPSS 19.0 (IBM, NY, USA) was used to perform the statistical analysis (general linear regression analysis and ANOVA) with a significance level of 0.05 used throughout the analysis.

3 Results

3.1 Nominal tribocharge density

As shown in Fig. 2(a), when geckos ascended the vertical wall and treaded on the acrylic oligomer film, we obtained the tribocharge and reaction force at their feet [36]. The result indicated that the tribocharge was proportional to the frictional adhesion, as both increased with the nominal contact area (Fig. 2(b)). Consequently, we found a nominal shear strength of ~ 1.9 mN/mm² and a nominal charge density of ~ 4.05 pC/mm² by dividing the measured force and charge with the nominal contact area. However, we failed to obtain the exact contact area for accurately estimating the exact contribution of the tribocharge, and could therefore determine a very tiny amount of electrostatic force by using the model shown in Fig. 2(c).

3.2 Real contact area and reaction force

As shown in Fig. 3(a), we measured the real contact area at the feet of the geckos through FTIR when they vertically climbed on the acrylic aisle. While contacting the substrate, the geckos did not concentrate adhesion to a specific toe but distributed it to multiple toes differing in orientations (Figs. 3(a) and 3(b)). The maximum overall actual contact area was about 4–6 mm² at a whole foot, much smaller than the nominal area of a gecko foot (Fig. 3(b)). Assuming that the toes function as vectors (Fig. 3(b)), we obtained the resultant contact area

Fig. 2 Tribocharge and adhesion in climbing geckos. The data was adopted from our previous work [36]. (a) The interaction between a gecko foot and an acrylic oligomer film; (b) the tribocharge and adhesion are related to the nominal contact area; and (c) a model that describes the electrostatic force between a gecko foot and the substrate. A , contact area; $\sigma(-)$, charge density; D , distance between foot and substrate; and ϵ , electric inductivity.

Fig. 3 Estimation of real contact area and reaction force at the feet of climbing geckos. (a) The measurement of contact area at the feet of a gecko when climbing an acrylic board; (b) distributed toes functioning as vectors; and (c) the frictional adhesion strength calculated using resultant contact area (F_{SR}) and overall contact area (F_{SS}). (a,b) The white parts show the contact regions. The scale bars are 20 mm, and the resultant contact area was calculated by regarding toe contacts as vectors with angles of φ_i and values of A_i , as shown in (b). Significance level: ★ $P \geq 0.05$; ★★ $P \geq 0.01$; ★★★ $P < 0.01$.

at the feet by Eq. (1). The general linear regression analysis of the contact area and adhesion at midstance indicated that the adhesion (F) was proportional to A_s by $F = 164.1A_s$ ($r^2 = 0.71$, linear regression, $P < 0.01$). We calculated a shear strength (F_{SR}) of 172.6 ± 36.3 mN/mm², a result agreeing with another test [5], by dividing the force with the resultant contact area, as shown in Fig. 3(c). However, the result (F_{SS}) reduces to 130.3 ± 32.3 mN/mm², when using the overall contact area (ΣA_i) instead (Fig. 3(c); ANOVA, $P < 0.01$).

4 Discussion

4.1 Exact tribocharge density

Hiller [18] determined that the gecko adhesion is highly dependent on the surface energies of the substrates. As the acrylic board in our experiment #2 possesses a similar contact angle (surface energy) with the acrylic oligomer film in our experiment #1, we assumed that the chemistry of the substrates would not significantly affect the adhesion. Furthermore, according to Huber et al. [38], the surface irregularity of the acrylic oligomer film (~500 nm) does not significantly weaken the setae adhesion either. The temperatures and humidity in both experiments were similar. Therefore, we believed that the geckos possess similar characteristics in frictional adhesion and triboelectrification on both substrates.

By comparing the nominal (1.9 mN/mm²) and the exact (130.3 mN/mm²) adhesion strengths, we found that the real adhesion strength is ~69 times that of the nominal one, indicating that the real contact area at a foot is about 1/69th of its whole area (~250 mm² in our experiments). This result is coincident with our measurements. As we observed a positive charge at the footpads of the geckos but a negative charge with a net nominal density of ~4.04 pC/mm² on the acrylic materials (Fig. 2), the actual tribocharge density could be further estimated as ~277.7 pC/mm². Considering that the setae density at the foot of a gecko is about 14,400 mm⁻² [39], a 19.3 fC tribocharge may be expected from a single seta.

4.2 Electrostatic attraction at gecko feet

First, we considered the electrostatic force caused

by tribocharge at the foot level, similar to that in Ref. [34]. As shown in Fig. 2(c), the footpad and substrate can be simplified as two parallel flat surfaces after the edge effect and tribocharge nonuniformity are neglected [40]. Thus, we can calculate the strength of attraction (F_e) caused by the tribocharge as follows [40]:

$$F_e = -\frac{\sigma^2}{2\epsilon} \quad (2)$$

where $\sigma = 277.7$ pC/mm². Air was considered as the medium with relative electric inductivity of 1.

By taking $8.854187817 \times 10^{-12}$ F/m as the ϵ in a vacuum, we finally obtained the strength of the electrostatic force as $F_e = 4.4$ mN/mm². Unsurprisingly, this result is smaller than that (47 mN/mm²) reported by Izadi et al. [34] by one order of magnitude. Izadi et al. [34] obtained a shear strength of 2.3 N/cm² (i.e., 23 mN/mm²) when they slid a gecko foot on a teflon AF film. As we suspected, this value is merely 1/6th of that we obtained in freely running geckos. The electrostatic force they estimated was nearly twice the shear force that they measured. Thus, they concluded that the electrostatic force originating from the tribocharge, rather than other force or interactions, is the dominant source of gecko adhesion.

Presumably, a substantial coefficient of friction (CoF) is required to convert the normal electrostatic attraction here into shear force if there are no other interactions at the setae-substrate interface [41]. In particular, the CoF of the teflon film should be about 0.5 if the measured shear force was caused by the electrostatic attraction. However, it is generally less than 0.1, sometimes even less than 0.05 [42]. Such a conflict partly explains why geckos always fail to maneuver on surfaces made with teflon. Thus, when geckos freely climb a wall, we are prone to support that the gecko adhesion is unlikely to be completely driven by electrostatic interactions. In comparison, the CoF of the acrylic in our experiments was about 0.2. Therefore, the strength of the shear force caused by the electrostatic attraction in our experiment was 0.89 mN/mm², a value about 1/5th of that Izadi et al. [34] determined by sliding gecko feet, and accounting for merely 0.7% of the total shear force that we measured.

4.3 Contribution of tribocharge to spatulae adhesion

Gecko seta is typically hierarchical and branch into 100–1,000 nano spatulae (~200 nm in size) at the ends [39]. To further determine the contribution of the electrostatic force that emerges from the tribocharge to setae adhesion, we attempted to estimate the adhesive force of a single spatula. Assuming the densities of the setae and spatula are ρ_h (14,400 /mm² here) and ρ_s (500 per seta here), respectively, the charge at a single spatula was obtained as $c = \sigma / (\rho_h \rho_s) = 3.85 \times 10^{-17}$ C. Then, two models were applied to estimate the adhesion that occurs at a spatula.

1) Sphere–flat model

In this model, the spatulas were treated as particles with a diameter (d) of 200 nm, and the substrate was considered as a flat surface, which is large enough than a single spatula.

According to the Gauss theorem [40], the field strength (E) of the flat substrate possessing a charge density of σ can be written as

$$E = -\frac{\sigma}{2\epsilon} \quad (3)$$

when the charge of a single spatula c approaching to the flat, the electrostatic adhesive force is $F_c = -(\sigma c) / 2\epsilon$.

Compared with the electrostatic force, the van der Waals force naturally occurs between two surfaces in contact [19]. In this model, the van der Waals force (F_v) between a spatula with diameter d and a flat substrate can be estimated as follows [19], when the effects of tribocharge are overlooked:

$$F_v = -\frac{H}{6D^2} \frac{d}{2} \quad (4)$$

where H is the material-dependent Hamaker constant, and D is the distance between the spatula and substrate.

Notably, Eq. (4) holds if $d \gg D$. As some parameters that may weaken the force are neglected, this model presents the upper limit of the electrostatic and van der Waals force.

2) Sphere–sphere model

In this model, the spatulae were also regarded as spheres, whereas the substrate was viewed as a flat surface comprising great quantities of virtual

particles of the same size (d) and the same amount of charge (c). Assuming (1) each spatula interacts with a virtual particle, and (2) there is no coupling, the adhesion of the tribocharge is obtained as [40]

$$F_c = -K \frac{c^2}{(d+D)^2} \quad (5)$$

where K is the Coulomb constant that equals 8.98755179×10^9 Nm²/C².

In this model, the van der Waals attractive force is [19]

$$F_v = -\frac{H}{6D^2} \frac{d}{2} \quad (6)$$

Compared with the previous spherical–flat model, the coupling among virtual particles that may enhance the force was not considered. Consequently, this sphere–sphere model achieves a lower boundary of the electrostatic and van der Waals force.

Following Autumn et al. [20], the typical Hamaker constant in the current study was taken as 10^{-19} J. By computing the above-mentioned data, we obtained the electrostatic and van der Waals force for a single spatula, as shown in Fig. 4.

The red area in Fig. 4 shows the range of F_v . When the distance between the substrate and a spatula is 0.3 nm [16], the van der Waals force between them ranges from 9.3 to 18.5 nN. Nevertheless, the van der Waals force decreases rapidly when the distance increases to 1 nm. If the distance is more than 2 nm, the van der Waals force is almost zero. In comparison, the force originating from the tribocharge remains virtually unchanged when the distance increases from 0.3 to 5 nm. The upper boundary value remains 0.6 nN, while the lower boundary value decreases from 0.33 to 0.3 nN in the calculated distance range (the blue region in Fig. 4). As a result, the total force that includes both varies between 9.6 and 19.1 nN when the distance between the substrate and spatula is 0.3 nm (Fig. 4, green area). The final force also reduces rapidly with an increase in the gap. Interestingly, the force of a spatula (~10 nN) determined by Huber et al. [43] falls into the range we found here, indicating that our model is reasonable. Moreover, based on the force estimated from a spatula, we found that the adhesion strength could be 69.1–137.7 mN/mm², a

Fig. 4 Adhesion at a single spatula. The results are calculated from the models shown. The blue area shows F_e , the red area shows F_v , and the green area shows the total force. The contribution of electrostatic force is indicated by the yellow lines. The dashed lines indicate the lower boundaries, and the solid lines indicate the upper boundaries. The black circles illustrate the cross-points of the electrostatic and van der Waals forces. The insets show the models used for calculation. In the models, $d = 200$ nm, $c = 3.85 \times 10^{-17}$ C, $\sigma = 277.7$ pC/mm², $H = 10^{-19}$ J, $\epsilon = 1 \times \epsilon_0 = 8.854187817 \times 10^{-12}$ F/m, and $K = 8.98755179 \times 10^9$ N·m²/C².

range within which our measured result falls.

As indicated by the black circles in Fig. 4, despite the electrostatic adhesion being smaller than the van der Waals force when the distance is 0.3 nm, they are equal when the distance expands to about 1.6 nm (0.3 nN for the lower boundary at $D = 1.6$ nm and 0.6 nN for the upper limit at $D = 1.65$ nm). The similar values of D indicate that the estimations from the tow models are compatible.

After obtaining the electrostatic adhesion and van der Waals adhesion at a single spatula, we evaluated the contribution of electrostatic force by dividing it with the overall force (Fig. 4, yellow lines). No significant difference was observed between the results calculated from the upper and lower boundary models. If the distance is 0.3 nm, the contribution of the electrostatic force to the overall force is 3.3%, a value that is slightly larger than 0.7% obtained from the foot model. However, Wang and Wang [28] pointed out that the distance between two solids would be 0.2 nm after the occurrence of triboelectrification. At this distance, the van der Waals force will be more significant, whereas the electrostatic attraction remains almost unchanged. Therefore, the contribution of electrostatic attraction will be a bit smaller than 3.3%. According to Fig. 4, although the

contribution of electrostatic force may increase with the distance, the total force is rather small.

Although the value of the electrostatic force is much smaller than the maximum van der Waals attraction, the electrostatic force possesses a much longer range of function than that of the van der Waals force. Such a long action-range might be beneficial to other properties of geckos' feet, such as self-cleaning and anti-self-adhesion, encouraging us to carry out further experimental explorations on setae level or even spatulae level. Moreover, as the van der Waals force originates from polarized molecules and the electro field can affect the polarization [40], the tribocharge at geckos' feet may also contribute to adhesion through affecting the polarization, encouraging us to carry our future study from this angle.

5 Conclusions

In addition to the van der Waals interactions and capillary force, the electrostatic attraction was declared to be contributive to geckos adhesion, but has yet to be fully understood in running geckos. In this study, we determined that during an upward climb, the exact contact area of a gecko foot could be about 1/70th of the area of the whole foot. For the

first time, we quantitatively evaluated the contribution of electrostatic forces resulting from the tribocharge occurring during free climbing to the overall frictional adhesion. The estimation at foot level showed that the tribocharge could generate an attraction of ~ 4.4 mN/mm² at a foot, causing a shear strength which accounts for about 1% of the overall shear. The results from the model analyses at the spatula level were similar to that estimated from the foot level, showing that the electrostatic attraction might contribute about 3% to the overall adhesion when the distance between a spatula and the substrate is 0.3 nm. These findings partly explain why geckos always fail to maneuver on teflon surfaces even though they may obtain large tribocharge.

Limited by the testing techniques, we conducted analyses based on data collected from separate experiments. In the future, simultaneous measurements of the tribocharge, contact area, and reaction force may provide more accurate data. The findings also encourage us to perform experimental investigations at seta or even spatulae levels. Nevertheless, the results in this study significantly enhanced our understating of the hairy adhesion of geckos.

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