Evidence for self-cleaning in gecko setae

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A tokay gecko can cling to virtually any surface and support its body mass with a single toe by using the millions of keratinous setae on its toe pads. Each seta branches into hundreds of 200-nm spatulae that make intimate contact with a variety of surface profiles. We showed previously that the combined surface area of billions of spatulae maximizes van der Waals interactions to generate large adhesive and shear forces. Geckos are not known to groom their feet yet retain their stickiness for months between molts. How geckos manage to keep their feet clean while walking about with sticky toes has remained a puzzle until now. Although self-cleaning by water droplets occurs in plant and animal surfaces, no adhesive has been shown to self-clean. In the present study, we demonstrate that gecko setae are a self-cleaning adhesive. Geckos with dirty feet recovered their ability to cling to vertical surfaces after only a few steps. Self-cleaning occurred in arrays of setae isolated from the gecko. Contact mechanical models suggest that self-cleaning occurs by an energetic disequilibrium between the adhesive forces attracting a dirt particle to the substrate and those attracting the same particle to one or more spatulae. We propose that the property of self-cleaning is intrinsic to the setal nanostructure and therefore should be replicable in synthetic adhesive materials in the future.

A single seta can resist 200 μN of force (1). Geckos use this adhesive to rapidly and repeatedly navigate a wide variety of surfaces (2, 3); they can even climb vertically on smooth surfaces at a speed >1 m/s (4). Locomotion with such a robust adhesive raises the following question: how do their feet stay clean (3)? Geckos neither groom their footpads, as do some beetles (5), nor secrete fluids that diffuse layer of particles. For direct comparison of isolated array and live digit measurements, we define the recovery index, \( R(n) = (F_a - F_{\text{dirty}})/(F_{\text{clean}} - F_{\text{dirty}}) \), representing the fraction of the initial loss in force that is recovered by step \( n \).

Materials and Methods

Isolated Setal Array Force Measurements. Tokays regrow the setal layer approximately every 2 months. Intact setal arrays can be isolated without harm to the animal. We isolated setal arrays from five live, restrained, nonmolting tokay geckos and bonded them within 2 min to acetate strips (0.25 × 0.1524-cm glass slide for the force plate. The setal array was mounted in a rigid holder at a slight angle to the glass plate and preloaded into the surface with a set force of 24.5 mN, flexing the acetate and aligning the array parallel to the glass. Shear forces were measured by pulling the array downward. We programmed closed-loop dc servo motors (Newport, Irvine, CA) attached to a micromanipulator to automatically preload and pull each array at 3 mm/s. We compared force after dirtying with force before dirtying for the same array. For each array, 10 pulls were completed to characterize the clean force, \( F_c \), and then we applied the microspheres and completed 5 additional pulls, each performed on a clean section of the force plate to avoid microsphere detritus. Size constraints of the force sensor prevented additional pulls on clean glass. Trials during which arrays broke or detached from the acetate were discarded. Real-time data accurate to 5 mN were collected and analyzed by using IGOR PRO 4.0 (WaveMetrics, Lake Oswego, OR) and STATVIEW 5.6.1 (SAS Institute, Cary, NC) software.

Live Digit Force Measurements. Measuring whole-digit forces requires a larger surface than measuring array forces, so we constructed a single-axis force plate by attaching a 5 × 5 × 0.1524-cm slide of optically clear glass (VWR Scientific) to a vertically mounted single-axis force sensor (Kistler 9207, Kistler Instrument, Winterthur, Switzerland) with a 2.5 × 2.5-cm glass slide for the force plate. The setal array was mounted in a rigid holder at a slight angle to the glass plate and preloaded into the surface with a set force of 24.5 mN, flexing the acetate and aligning the array parallel to the glass. Shear forces were measured by pulling the array downward. We programmed closed-loop dc servo motors (Newport, Irvine, CA) attached to a micromanipulator to automatically preload and pull each array at 3 mm/s. We compared force after dirtying with force before dirtying for the same array. For each array, 10 pulls were completed to characterize the clean force, \( F_c \), and then we applied the microspheres and completed 5 additional pulls, each performed on a clean section of the force plate to avoid microsphere detritus. Size constraints of the force sensor prevented additional pulls on clean glass. Trials during which arrays broke or detached from the acetate were discarded. Real-time data accurate to 5 mN were collected and analyzed by using IGOR PRO 4.0 (WaveMetrics, Lake Oswego, OR) and STATVIEW 5.6.1 (SAS Institute, Cary, NC) software.

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uncurling and to mimic the preload procedure necessary for setal attachment (1). Then, we pulled the foot downward until the toe detached from the glass. Digits adhered so strongly that clean measurements often involved peeling of the superficial layer of skin of the lamellae, so we used contralateral digits for clean and dirty measurements. It should be noted that clean foot force measurements quantify the maximum force that the outer layer of integument can withstand, not the maximum force of attachment by the setae. Shear force is strongly correlated with pad area (12), which differs among digits, so we standardized digit measurements by pad area. Force of attachment of clean toes on glass was measured for every digit on the left side of each animal. To clog the toe pads, we applied 0.20 g of silica-alumina ceramic microspheres dispersed on glass (G-200 Zeeospheres; 2.5-μm mean radius) to each digit, resulting in saturation of the adhesive areas. Measurements then were taken for the two right feet, allowing a number of steps ranging from 0 until the point at which shear force was substantially restored and increases in force between successive trials were small (up to 18 steps). Full strides were not used, because inducing the gecko to take a specified number of steps without otherwise disturbing its feet was not feasible. Digital hyperextension did not occur. Because the measurement itself was much like a step, we gently cleaned the soiled foot with compressed air and deionized water to dislodge and flush away clogging microspheres. We reclogged the same foot between successive trials instead of counting the measurement as a step itself. After each day of experiments, the gecko’s feet were fully rehydrated and allowed to recover for 24 h. Real-time data accurate to 6 mN were collected in MAACL/CHART V.3.6.5 (A. D. Instruments, Milford, MA) at 40 Hz. Data were analyzed with commercial software (STATVIEW V5.6.1, SAS Instruments, and SUPERANOVA, Abacus Concepts, Berkeley, CA). To obtain the toe pad areas, we scanned each gecko’s foot on a flatbed scanner (Agfa Snapscan) and measured areas with commercial software (CANVAS 8, ACD Systems, Saanichton, BC, Canada).

Results and Discussion

Experimental Support for the Self-Cleaning Hypothesis. After application of microspheres, arrays lost 59.95% (SD = 17.45%; n = 5 arrays; 30 measurements) of shear force. Four simulated steps on clean glass restored 51.00% (SD = 23.64%) of this functional loss (Fig. 2B). All arrays exhibited increasing force with increasing number of pulls after contact with microspheres, independent of force magnitude. For digits, force measured immediately after application of microspheres was below the sensitivity of the force sensor (F0 < 6 mN); at two steps the loss of force was still 92.99% (SD = 3.40%; n = 3 geckos; 133 measurements), the value we used to represent the force of a dirty toe. After eight simulated steps, 35.65% (SD = 34.09%; n = 3 geckos; 133 measurements) of this loss was recovered, although each gecko recovered shear capacity at a different rate as indicated by the large SD (Fig. 2B). Average recovered digit force after eight steps was well over the force required for an animal to support
its body mass (43 g) by a single digit (Fig. 3). Additionally, we visually examined dirty arrays by scanning electron microscopy and compared them with clean arrays to confirm self-cleaning (Fig. 4).

These results show that microspheres interfere with attachment of gecko toes and in isolated arrays. Reproducing the seta–substrate interactions of a step significantly restored capacity to resist shear in both cases. Self-cleaning occurred in the toes of live geckos and did not require strides or extra toe movement to remove rapidly even copious amounts of microspheres. We conclude from the digit experiment that self-cleaning is a function of contact with a substrate and not simply a consequence of foot motion. Likewise, cleaning occurred in setal arrays apart from the gecko. We further conclude that self-cleaning is an inherent property of the setae; the “self” refers to the adhesive, not the animal.

The unique distally directed peeling motion of live gecko toes (digital hyperextension) during attachment and detachment (4) would seem to be a candidate for a cleaning mechanism. However, a rough calculation suggests that dynamics of the foot alone are not the primary mechanism of cleaning. With a step frequency of 30 Hz (4), assuming sinusoidal motion of a 1-cm digit, a 2.5-μm microsphere (mass = 1.6 × 10^{-11} kg) adhering to the spatulae of the distalmost lamella on the 1-cm digit is acted on by an inertial force, \( F_i = 5.8 \times 10^{-11} \text{ N} \), >2 orders of magnitude smaller than the force of a single spatula (10^{-8} N) (1, 13). While attached to N spatulae, the particle would experience an adhesive force of \( N \times 10^{-8} \text{ N} \). For the particle to be detached by inertia during foot placement, the acceleration required is at least \( a = N \times 6 \times 10^4 \text{ m/s}^2 \), or \( a = N \times 6,000 \times \text{ gravity} \), making detachment by macroscale foot movement unlikely. Stride elements such as digital hyperextension and lamellar positioning may aid the speed and effectiveness of the cleaning process, possibly by sliding or rolling particles and thereby easing detachment (14); however, we must consider substrate–particle interactions to explain the basic phenomenon.

**Fig. 2.** Recovery of force by self-cleaning, \( R(n) = (F_n - F_{\text{dirty}})/(F_{\text{clean}} - F_{\text{dirty}}) \). (A) \( R(n) \) for isolated gecko setal arrays on glass after \( n \) simulated steps. (B) \( R(n) \) for digits of live geckos, standardized by adhesive area.

**Fig. 3.** Mean shear stress in clean, dirty, and self-cleaned gecko digits. Dotted line indicates minimum shear stress required to support one gecko’s body weight (43 g) by a single toe (area = 0.19 cm²). After clogging with >2.5-μm-radius microspheres, four steps on clear glass restored setal force to a level sufficient to support the gecko by a single toe.

**Fig. 4.** Scanning electron micrographs of arrays. (A) Representative array after dirtying with microspheres. Arrow indicates a microsphere adhering to several spatulae. (B) Array from the same animal after five simulated steps. Microspheres are still present, but spatular surfaces are mostly clean. (Scale bars: 10 μm.)
In the case of $N$ spatulae attached to each particle, approximately half of the particles will remain attached to the wall, and self-cleaning will occur with each step, assuming a clean substrate is encountered. If less than $N$ spatulae are attached to each particle, self-cleaning will occur rapidly as a consequence of energetic disequilibrium; particles tend to remain attached to the wall rather than to the spatulae.

In our study, $R_p = 2.5 \mu m$ and $R_s = 0.1 \mu m$. Therefore, \[
N = \frac{26 A_{ps} D_{ps}}{A_{pw} D_{pw}}. \tag{4}
\]

This model suggests that $>26$ spatulae would need to be attached simultaneously to a single 2.5-$\mu m$-radius dirt particle in order for self-cleaning not to occur, assuming similar Hamaker constants and gap distances. Hamaker constants are unlikely to vary by more than a factor of 2 (16); if we take the worst case where $A_{ps} = 2A_{pw}$, energetic equivalence occurs with 13 spatulae attached. Gap distance remains an unknown parameter in the model. Until measurements are available, we will assume that $D_{ps}$ and $D_{pw}$ have similar probability distributions, and thus can be assumed to be approximately equal.

If $R_p < R_s$, it follows from Eq. 3 that a particle of radius of <50 nm would result in $W_{pw} < 1.5 W_{ps}$, yielding $N < 1.5$. However, because it is unlikely that more than one spatula could attach to a 50-nm particle, we suggest that self-cleaning should occur for spherical spatulae interacting with spherical particles of all sizes.

Spatulae as flexible strips. If we model spatulae as nanoscale strips of adhesive tape (13, 15, 17) that peel during detachment, the particle–spatula pulloff force is given by \[
F_{ps} = 2R_s W_{ps}, \tag{5}
\]

where $W_{ps}$ is the adhesion energy at the dirt particle–spatula interface, $2R_s$ is the width of the spatula (0.2 $\mu m$), and assuming negligible elastic energy storage (17). By using a value of $W_{ps}$ typical for van der Waals interactions, 50 mJ/m² (16), $F_{ps}$ is $\approx 10$ nN, as also shown empirically by Huber et al. (13) and consistent with measurements of single setae (1).

The pulloff force of the dirt particle from a planar wall, by using the Johnson–Kendall–Roberts model (18), is \[
F_{pw} = \frac{3}{2} \pi R_p W_{pw}. \tag{6}
\]

By using a value of $W_{pw} = W_{ps}$ of 50 mJ/m² (16), the pulloff force of a dirt particle with $R_p = 2.5 \mu m$ is $\approx 590$ nN. This result suggests that if spatulae act as flexible strips, >59 spatulae would need to be attached simultaneously to each 2.5-$\mu m$-radius particle to prevent self-cleaning. It follows from Eqs. 5 and 6 that as the diameter of the dirt particle approaches the width of the spatula, $N$ approaches $3\pi/4 \approx 2.4$, suggesting again that self-cleaning can occur for spherical particles of all sizes.

Few spatulae adhere to each particle. Spatular density at the tips of the tokay setae in our sample was 3.79 per $\mu m^2$ (39.3 $\mu m^2$ in surface area) is 149 spatulae, well above $N$ for spherical or strip models. In reality, many fewer spatulae seem to be attached to a single microsphere (Fig. 4). This outcome is due to most particles remaining superficial to the spatular branches. The curvature of the particles relative to the roughly planar field of spatulae at the setal tip likely limits the number of spatulae that adhere to a single particle. Particles that are strongly impacted by the setal surfaces could become reversibly attached to numerous spatulae. We observed some particles lodged between spatular branches and between setae (Fig. 4). The fate of particles
Self-Cleaning: Lotus Effect and Gecko Effect. Roughness can make surfaces highly hydrophobic (19–21) and results in surfaces that are self-cleaning in the presence of water droplets. This microstructure-based resistance to soiling and facile cleaning by water is known as the lotus effect (22–24) and is observed for plants with microrough epicuticular wax layers, for nano-rough pilot whale skin (Globicephala melas) (25), and possibly for the feet of nonadhesive gecko species (e.g., Stenodactylus khobarenensis) (26).

The phenomenon of self-cleaning in gecko setae is surprising because setae are adhesive and can self-clean when dry. Adhesion in gecko setae is a consequence of many divided contact points (spatulae) that deform to achieve intimate, high-density contact with the surface, whereas lotus-like surfaces remain slippery because their rough, and in some cases waxy, cuticle prevents intimate contact. Lotus-like surfaces require water as a cleaning agent (22–24), whereas self-cleaning in gecko setae may occur because it is energetically favorable for particles to be deposited on the surface rather than remain adhered to the spatulae.

Interestingly, one fundamental mechanism may underlie self-cleaning in gecko and lotus-like surfaces: Both gecko and lotus-like surfaces become cleaner after contamination for structural reasons; both possess a micro- or nano-rough topology that reduces adhesion with solid and liquid surfaces alike. Nonadhering setae should exhibit lotus-like wet self-cleaning characteristic of nonadhesive micro- or nano-rough surfaces. Nonadhering lamellar surfaces do appear to be highly nonwettable, with hered lamellar surfaces do appear to be highly nonwettable, with