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ORIGINAL PAPER

Ultrahydrophobicity indicates a non-adhesive default state in gecko setae

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Abstract Geckos may represent the world's most demanding adhesives application. The adhesive setae on the toes of climbing geckos must adhere strongly yet avoid fouling or attachment at inappropriate times. We tested the hypothesis that gecko setae are non-adhesive in their unloaded default state by comparing the water droplet contact angle (θ) of isolated setal arrays to the smooth surface of eye spectacle scales of tokay geckos (*Gekko gecko*). At equilibrium, θ was 98.3 ± 3.4° in spectacle scales of live geckos and 93.3 ± 3.5° in isolated spectacles. Isolated setal arrays were ultrahydrophobic, with θ of 160.6 ± 1.3° (means ± SD). The difference in θ of setal arrays and smooth spectacles indicates a very low contact fraction. Using Cassie's law of surface wettability, we infer that less than 6.6% of the surface of unloaded setae is solid and at least 93.4% is air space. We calculated that the contact fraction must increase from 6.6% in the unloaded state to 46% in the loaded state to account for previously measured values of adhesion. Thus gecko setae may be non-sticky by default because only a very small contact fraction is possible without mechanically deforming the setal array.

Keywords Adhesion · Contact mechanics · Locomotion · Reptilia · Nanotechnology

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Abbreviations

E	Young's modulus
E_{eff}	Effective modulus
f_{solid}	Fraction of surface area occupied by solid; contact fraction
f_{air}	Fraction of surface area occupied by air
γ	Surface energy
PSA	Pressure sensitive adhesive
PTFE	Polytetrafluoroethylene
θ	Water droplet contact angle
θ_{eq}	Equilibrium water droplet contact angle
θ_{ad}	Advancing water droplet contact angle
θ_{rec}	Receding water droplet contact angle
W	Adhesion energy

Introduction

Conventional pressure sensitive adhesives (PSAs) such as those used in adhesive tapes are fabricated from materials that are sufficiently soft and sticky to be considered tacky (Dahlquist 1969). When PSAs are applied gently to a substrate, adhesion forces cause the PSA to flow and make intimate and continuous surface contact. Tack is the ability of adhesive forces to self-deform a material to increase contact area with a substrate. Because they are tacky, PSAs also tend to foul, self-adhere, and attach accidentally to inappropriate surfaces.

The toes of arboreal pad-bearing geckos (Russell 1975) are perhaps the world's most demanding adhesives application. Geckos are capable of attaching and detaching their adhesive toes in milliseconds (Autumn et al. 2006) while running with seemingly reckless abandon on vertical and inverted surfaces. The adhesive structure on gecko toes differs dramatically from that of conventional adhesives. In most species, the toe pads consist of a series of scansors covered with uniform arrays of hair-like bristles formed from β-keratin (Wainwright et al. 1982; Russell 1986). A single seta of the tokay gecko is approximately 110 μm in length and 5 μm in diameter (Ruibal and Ernst 1965; Russell 1975; Williams and Peterson 1982) (Fig. 1). Setae are similarly oriented and uniformly distributed on the scansors. Setae branch at the tips into 100–1,000 more structures known as spatulae. A single spatula consists of a stalk with a thin, roughly triangular end, where the apex of the triangle connects the spatula to its stalk. Spatulae are approximately 0.2 μm in length and also in width at the tip (Ruibal and Ernst 1965; Williams and Peterson 1982).

Avoiding inappropriate attachment forces during climbing (Autumn et al. 2005) is perhaps as important as attachment itself. A small amount of most common household PSAs is more than sufficient to hold the mass of a large gecko (50 g). However, conventional PSAs are designed to bond spontaneously on contact, and it is amusing to consider the difficulties a gecko would have in climbing through a forest canopy with duct tape on its toes.

Prevention of inappropriate attachment is not due to weakness of the adhesive. All 6.5 million (Schleich and Kästle 1986; Irschick et al. 1996) setae of a 50-g tokay gecko attached maximally could theoretically generate 1,300 N of shear force—enough to support 133 kg, about the mass of two humans. This suggests that a gecko need only attach 3% of its setae to generate the greatest forces measured in the whole animal [20 N for two feet; (Irschick et al. 1996)]. Only less than 0.04% of a gecko's setae attached maximally are needed to support its mass of 50 g on a wall. Indeed the adhesive toes of *Phelsuma* are sufficiently tenacious that dead individuals remained adhered to the leaves of trees following a hurricane (Vinson and Vinson 1969). The

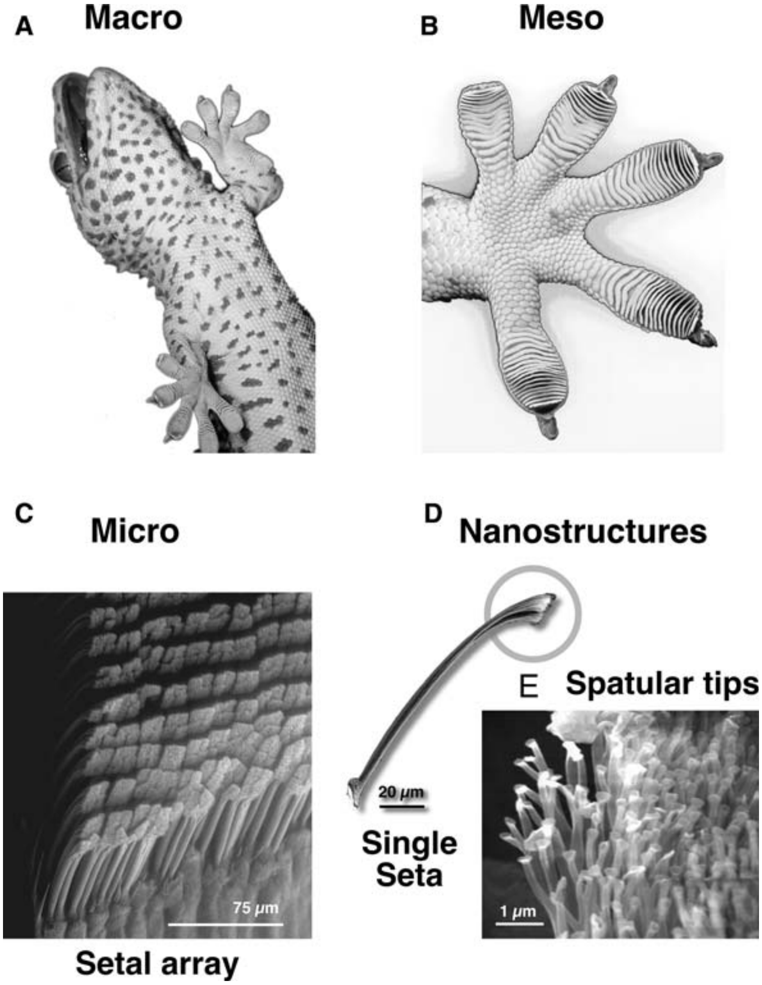

Fig. 1 Gecko adhesive structures. **a** Ventral view of a tokay gecko (*Gekko gecko*) climbing a vertical glass surface. **b** Ventral view of the foot of a tokay gecko, showing seta-bearing scansors. **c** Setae are arranged in a nearly grid-like array on the ventral surface of each scansor. **d** Single isolated gecko seta. *Circle* shows spatulae enlarged in (**e**). **e** Spatular tips of a single gecko seta

surprisingly large forces generated by gecko setae underscore the question of how geckos manage to avoid inappropriate attachment of their adhesive toes.

Do gecko setae minimize contact in their default state?

Isolated gecko setae have not been observed to adhere spontaneously to surfaces. ‘‘Preloading’’, a small push perpendicular to the surface, followed by a micrometer scale parallel drag, may be necessary to switch setae from an unloaded default state to an adhered state. Previously we showed that proper orientation, preload, and drag of single isolated setae increases attachment forces by 10–20-fold (Autumn et al. 2000). This discovery explains the load dependence and directionality observed at the whole animal scale by Dellit (1934), and is consistent with the structure of individual setae and spatulae (Ruibal and Ernst 1965; Hiller 1968). It also suggests a hypothesis addressed by this study: we hypothesize that gecko setal arrays are non-sticky in their default state. We hypothesize further that the non-sticky default state is due primarily to structure—setae do not adhere spontaneously to surfaces because their surface topology while unloaded may prevent contact by a large fraction of the setal area.

Estimating contact fraction using Cassie’s law of surface wettability

Water droplet contact angle (θ) methods provide a measure of surface energy (γ) available for adhesive bonding at a surface. Water droplet contact angle can be used as an index of hydrophobicity, with more hydrophobic surfaces having greater values of θ. Cos(θ) represents the interaction energy between water and the substrate, relative to the self-energy of water. For example, polytetrafluoroethylene (PTFE) has a large value of θ=104–111°, indicating that it is hydrophobic, and suggesting that PTFE possesses a low γ.

In this study, we compared θ in tokay gecko setal arrays to θ of the smooth surface of the spectacle, which is an optically clear β-keratin scale covering the eye. Assuming that the β-keratin surfaces (Maderson 1964; Stewart and Daniel 1972; Bereiter-Hahn et al. 1984; Fraser and Parry 1996; Alibardi 2003) of setae and spectacle are hydrophobic ($\theta > 60°$) and similar in γ, we can apply Cassie’s law of surface wettability (Cassie and Baxter 1944; Chen et al. 1999; Patankar 2003, 2004; Gao and Jiang 2004) to determine the area fraction composed of solid and air at the seta–water interface:

$$\cos(\theta_{\mathrm{seta}}) = f_{\mathrm{solid}} \cos(\theta_{\mathrm{spec}}) - f_{\mathrm{air}} \tag{1}$$

It follows that since $f_{\mathrm{solid}} + f_{\mathrm{air}} = 1$,

$$f_{\mathrm{solid}} = \frac{1 + \cos(\theta_{\mathrm{seta}})}{1 + \cos(\theta_{\mathrm{spec}})}, \tag{2}$$

where f_{solid} and f_{air} are the fractions of surface area occupied by setae and air, respectively. θ_{seta} and θ_{spec} are the water droplet contact angles on setal array and smooth spectacle.

A high value of θ_{seta} would support the hypothesis that the gecko setae have low surface energy in an unloaded state. $\theta_{\mathrm{seta}} >> \theta_{\mathrm{spec}}$ would yield a small contact fraction, f_{solid}, supporting the hypothesis that a low surface energy in an unloaded state is due primarily to structure.

Methods

Water droplet contact angle measurement on gecko setal arrays and spectacles

Contact angles on isolated setal arrays

We carefully peeled single setal arrays from five restrained, non-molting tokay geckos (*Gekko gecko*) using the methods of Hansen and Autumn (2005). Using cyanoacrylate gel glue, these setal arrays were affixed, setal side up (Fig. 2), to glass slides that had been previously cleaned with acetone and ethanol. The fixed setal arrays were oriented such that the setae formed a flat surface on which contact angles could be measured.

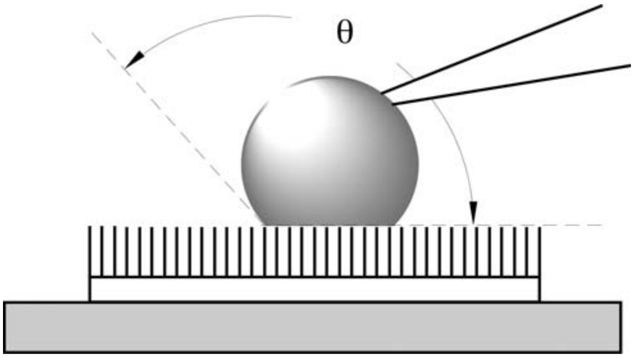

Fig. 2 Schematic of experimental procedure. We used a wax-tipped pipette to apply small deionized water droplets to the surface of isolated tokay gecko setal arrays fixed to a glass substrate. The water droplet contact angle (θ) is the angle between the substrate plane and a tangent to the droplet at the point of contact

To measure water droplet contact angle, we placed a right-angle prism (Newport Corporation, Irvine, CA, USA) under a microscope (Nikon SMZ1500) and positioned the glass slide with the fixed setal array in front of the prism so that both top view and the reflected side view were visible. This dual-view setup allowed us to measure the droplet contact angle from the side while correctly positioning the droplet within the field of view of the microscope. We placed deionized water droplets of variable size (approximately 0.5–2 mm diameter) onto the setal array using a fine wax-tipped capillary tube. Images (2,048×1,536 pixels) of each droplet at 72× magnification were captured on a digital camera (Nikon Coolpix 995; Fig. 3). Images were taken during three droplet stages: increasing volume, constant volume, and decreasing volume. These stages yielded advancing, equilibrium, and receding droplet contact angles (Chen et al. 1999). Angles were measured in Canvas 8 (Deneba, ACD, Saanichton, British Columbia, Canada). All measurements were completed within 24 h of isolating the setal array.

Contact angles on intact spectacle scales

We affixed the spectacle scale from the shed skin of two healthy tokay geckos to glass slides in the same manner as for setal array. Spectacles were dissected into smaller pieces before gluing to allow them to flatten. Advancing, equilibrium, and receding contact angles were measured and analyzed as for the setal array. All measurements were completed within 24 h of shedding.

Using a custom-made mount, we rotated the microscope in the experimental setup by 90° in order to measure water droplet contact angles on the large spectacle scales of five live, restrained, horizontally resting tokay geckos. The horizontal orientation of the microscope resulted in a side view of the droplet on the spectacle similar to that from the right-angle prism mentioned previously. We positioned the pipette tip just above the spectacle and allowed small droplets to fall onto the surface and captured images of constant-volume droplets. From these we measured equilibrium contact angles using the analysis methods described above. We did not measure dynamic angles in order to avoid possible injury to the animals' eyes from the pipette tip.

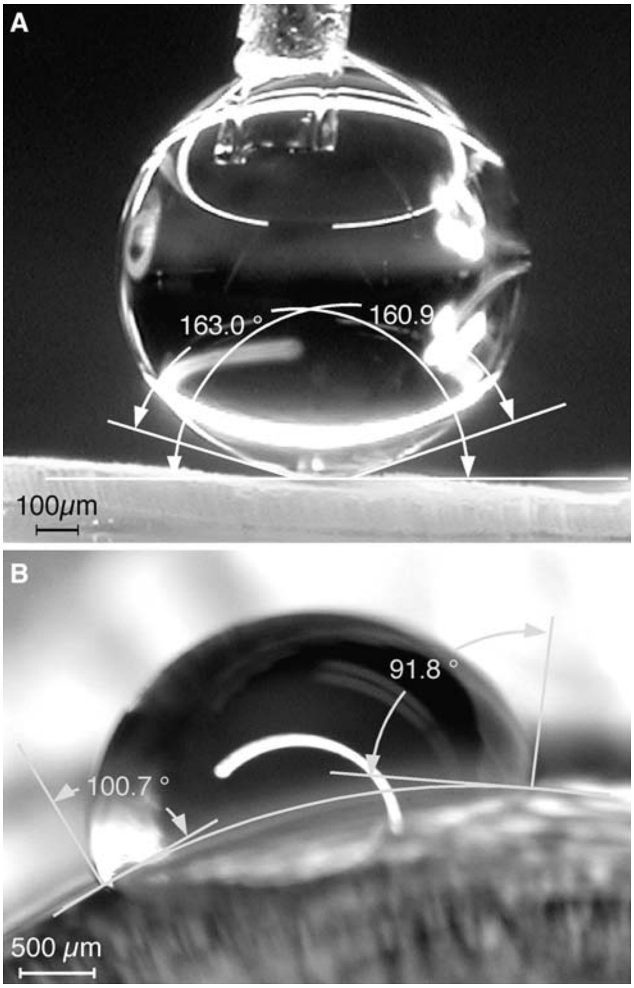

Fig. 3 Representative images of deionized water droplets (0.5–2 mm diameter) on isolated tokay gecko setal array (**a**) and eye spectacle scale (**b**). Note that the *bright arcs* on the water droplets are reflections of the microscope illuminator. Mean θ on isolated setal arrays was 160.6 ± 1.30° (SD). In contrast, θ on smooth spectacle scales was 93.3 ± 3.51° (SD). The large difference in θ between setal arrays and smooth spectacles suggests that the ultrahydrophobic nature of setal arrays is due to the highly rough surface topology that permits only a small (~6%) contact fraction with the water droplets

Results

Equilibrium water contact angle (θ) of isolated gecko spectacles was 93.3 ± 3.51° (*n*=6; mean ± SD). Receding values of θ were significantly smaller than advancing and equilibrium values (ANOVA, *F*=15.7; *df*=2, 9; *P*=0.001). θ of live gecko spectacles was 5% greater than in isolated samples (Table 1). Equilibrium water contact angle (θ) of gecko setal arrays was 160.6 ± 1.30° (*n*=10; mean ± SD), 72% greater than for isolated spectacles, and 63% greater than on the spectacles of live geckos (Fig. 3). Equilibrium, advancing, and receding values of θ of setal arrays did not differ significantly (ANOVA, *F*=1.02; *df*=2, 27; *P*=0.37).

Contact angle hysteresis, the difference between advancing and receding contact angles, was 1.4° for setal arrays and 18.6° for isolated spectacles.

Table 1 Mean ± SD of equilibrium, advancing, and receding water droplet contact angles (θ)

	θ_{eq}	θ_{adv}	θ_{rec}
Setal array	160.6 ± 1.30 (10)	160.7 ± 3.65 (10)	159.3 ± 2.04 (10)
Spectacle, isolated	93.3 ± 3.51 (6)	96.0 ± 1.91 (3)	77.4 ± 7.68 (3)
Spectacle, live	98.3 ± 3.89 (5)	–	–

Number of samples is in parentheses

Using Eq. 2, and θ_{eq} of spectacles of live geckos, the estimated contact fraction (f_{solid}) of setal arrays is 0.066. Using θ_{eq} of isolated spectacles, the estimated contact fraction (f_{solid}) of setal arrays is 0.060.

Discussion

Ultrahydrophobicity

There are two principle measures of ultrahydrophobicity, high equilibrium water droplet contact angle (>150°) and low contact angle hysteresis [typically only a few degrees (Johnson and Dettre 1963; Chen et al. 1999)]. The latter is considered by some to be the definitive measure of hydrophobicity (Johnson and Dettre 1963; Wolfram and Faust 1978; Chen et al. 1999). Low contact angle hysteresis indicates that a water droplet is unlikely to become energetically pinned to the substrate; the droplet will readily roll off the surface at a small tilt angle. We found that gecko setae are ultrahydrophobic by both criteria (θ =160.6°, hysteresis=1.4°; Fig. 3a; Table 1), as predicted for β-keratin structures (Wainwright et al. 1982; Bereiter-Hahn et al. 1984; Russell 1986). In contrast, spectacle scales are not ultrahydrophobic (θ =93.3–98.3°, hysteresis=18.6°; Fig. 3b; Table 1). Considering that both surfaces are composed of β-keratin, we conclude that the ultrahydrophobicity of setal arrays is due to their microstructure.

Gecko setae: a smart adhesive that is non-sticky by default

Typically, adhesives are liquids that are chemically compatible with both surfaces and that have sufficiently low viscosity that wetting of the surfaces occurs either spontaneously or with a small amount of pressure (Kinloch 1987; Pocius 2002). Surface treatments are often needed to raise the interfacial energies between one or both surfaces and the adhesive. Conventional PSAs are fabricated from soft viscoelastic materials that satisfy Dahlquist's (Dahlquist 1969; Pocius 2002) criterion for tack, a Young's modulus, E, of 300 kPa or less. Tacky materials are those that exhibit spontaneous plastic and elastic deformation that increase true area of contact with the surface at the molecular scale. Additives known as tackifiers are commonly used to promote plastic deformation in PSAs during contact (Pocius 2002). In contrast, the adhesive on the toes of geckos is made of β-keratin, a stiff material with E four to five orders of magnitude greater than the upper limit of Dahlquist's criterion. Therefore, one would not expect a β-keratin structure to function as a PSA by readily deforming to make intimate molecular contact with a variety of surface profiles. However, since the gecko adhesive is a microstructure in the form of an array of millions of high aspect ratio shafts (setae) the effective elastic modulus, E_{eff} (Persson 2003; Sitti and Fearing 2003; Persson et al. 2005; Spolenak et al. 2005) is much lower than E of bulk β-keratin (Bonser and Purslow 1995; Bonser 2000). E_{eff} of gecko setal arrays is the subject of a separate study (Geisler et al. 2005).

Adhesion and friction between two molecularly smooth coplanar surfaces can be large (Baier et al. 1968; Johnson 1985) since all molecules of both surfaces can interact at the sub-nanometer scale. The area fraction of sub-nanometer interactions is reduced when one or both surfaces are rough. Thus, roughness greatly decreases adhesion between rigid bodies (Baier et al. 1968; Johnson 1985; Israelachvili 1992; Gay and Leibler 1999). However, given sufficient preload pressure, plastic and elastic deformation can create areas of contact between rough surfaces that approach or exceed that of smoother surfaces (Johnson 1985). The performance of gecko setal adhesives is due largely to the billions of spatulae (Fig. 1e) on compliant stalks that can conform to a substrate sufficiently well to approach the behavior of smooth surfaces in coplanar contact—even when the substrate is rough—without large preload pressure (Autumn et al. 2000, 2002; Autumn and Peattie 2002; Persson and Gorb 2003). The Johnson–Kendall–Roberts model (Johnson et al. 1973) suggests that smaller spatulae increase adhesion pressure, assuming dense packing on the surface (Arzt et al. 2002, 2003; Autumn and Peattie 2002; Autumn et al. 2002).

Minimizing contact in the default state

Assuming that the β-keratin surfaces (Maderson 1964; Stewart and Daniel 1972; Bereiter-Hahn et al. 1984;

Fraser and Parry 1996; Alibardi 2003) of setae and spectacle are similar in surface energy (γ), our results suggest that the setal array is highly rough in its default state. Using Eq. 2, we calculate that less than 6.6% ±0.009 (SD) of setal area is available for initial contact with a smooth surface. This suggests that, initially, during a gecko's foot placement, the contact fraction of the distal region of the setal array must be very low. Yet the dynamics of the foot must be sufficient to increase the contact fraction substantially to achieve the extraordinary values of adhesion and friction that have been measured in whole animals (Irschick et al. 1996; Autumn et al. 2002; Hansen and Autumn 2005) and isolated setae (Autumn et al. 2000, 2002; Hansen and Autumn 2005).

Thus gecko setae may be non-sticky by default because only a very small contact fraction is possible without mechanically deforming the setal array. Prior observations (Autumn et al. 2000) suggested that attachment requires a ‘‘mechanical program’’ (preload and drag) to initiate adhesion and high friction. Indeed the strength of frictional interaction can be programmed by modulating the amount of preload and/or drag (Autumn et al. 2000), perhaps determining the number of spatulae brought into contact. Bending is a likely mode of deformation of setae (Persson 2003; Sitti and Fearing 2003; Spolenak et al. 2005). It is likely that bending of the setal shaft during preload and drag acts to promote spatular contact at the tip (Fig. 1d). The force associated with deformation of setal arrays is the subject of another study (Geisler et al. 2005).

Maximizing contact in the adhered state

Empirical and theoretical estimates of spatular adhesion (Autumn et al. 2000, 2002; Arzt et al. 2003; Spolenak et al. 2004; Hansen and Autumn 2005; Huber et al. 2005) suggest that each spatula generates approximately 10–40 nN with approximately 0.02 μm^2 area, or approximately 500–2,000 kPa. A single seta can generate 40 μN over approximately 43 μm^2 of area (unpublished data), or approximately 917 kPa of adhesive stress. Using the higher spatular force of 40 nN to provide a conservative estimate of setal contact area, we calculate 917/2,000 kPa=0.46 contact fraction. This suggests that unless the force of adhesion of a spatula has been greatly underestimated, the contact fraction must increase by approximately 7.5-fold following preload and drag in order to account for our prior measurements of 917 kPa of adhesive stress.

Implications for self-cleaning

Strongly adhesive materials are not unusual (see Pocius 2002 for review), nor are very weakly adhesive surfaces that are ultrahydrophobic (Barthlott and Neinhuis 1998). The gecko adhesive system is unique in that it combines strong adhesive capabilities and avoidance of inappropriate adhesion. The very low surface energy of unloaded gecko setae may aid in avoiding inappropriate adhesion not only to nearby surfaces, but to dirt particles as well. The results of this study suggest that like water droplets, dirt particles may not adhere strongly to the setal surface in the unloaded default state.

Highly hydrophobic rough surfaces can be washed clean by water droplets. This is known as the lotus effect (Barthlott and Neinhuis 1997, 1998; Neinhuis 1997) and is observed for plants with micro-rough epicuticular wax layers, for nano-rough pilot whale skin (*Globicephala melas*) (Baum et al. 2002), and possibly for the feet of non-adhesive gecko species (e.g., *Stenodactylus khobarensis*) (Russell 1979). This study showed that non-adhered setal surfaces are highly non-wettable. Thus non-adhering setae should exhibit the lotus-like wet self-cleaning characteristic of non-adhesive micro- or nano-rough surfaces. Particles contacting the unloaded surface should wash away easily in the presence of water. However it is not known if geckos' feet often become wet.

We have shown previously that gecko setae are capable of self-cleaning from dirt particles even when strongly adhered to numerous spatulae in the loaded state (Hansen and Autumn 2005). Self-cleaning may occur 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.

Thus, there are three related self-cleaning mechanisms that can be utilized by natural and engineered adhesive nano-structures: (1) setae can form an ultrahydrophobic surface that resists unwanted adhesion, (2) setae may become cleaner by the lotus effect if they encounter water, and (3) setae may self-clean during normal use (Hansen and Autumn 2005). All three mechanisms are due to a micro- and nano-rough topology that reduces adhesion with solid and liquid surfaces.

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