27 Gecko Feet: Natural Attachment Systems for Smart Adhesion—Mechanism, Modeling, and Development of Bio-Inspired Materials

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Abstract. Several creatures, including insects, spiders, and lizards, have developed a unique clinging ability that utilizes dry adhesion. Geckos, in particular, have developed the most complex adhesive structures capable of smart adhesion—the ability to cling to different smooth and rough surfaces and detach at will. These animals make use of about three million microscale hairs (setae) (about 14000/mm^2) that branch off into hundreds of nanoscale spatulae (about a billion spatulae). This hierarchical surface construction gives the gecko the adaptability to create a large real area of contact with surfaces. Modeling of the gecko attachment system as a hierarchical spring model has provided insight into adhesion enhancement generated by this system. van der Waals forces are the primary mechanism utilized to adhere to surfaces, and capillary forces are a secondary effect that can further increase adhesion force. Preload applied to the setae increases adhesion force. Although a gecko is capable of producing on the order of 20 N of adhesion force, it retains the ability to remove its feet from an attachment surface at will. The adhesion strength of gecko setae is dependent on the orientation; maximum adhesion occurs at 30°. During walking a gecko is able to peel its foot from surfaces by changing the angle at which its setae contact a surface. A man-made fibrillar structure capable of replicating gecko adhesion has the potential for use in dry, superadhesive tapes that would be of use in a wide range of applications. These adhesives could be created using microfabrication/nanofabrication techniques or self-assembly.

Key words: Gecko feet, Adhesion, Surface energy, Nanostructures, Robots

27.1 Introduction

Almost 2500 years ago, the ability of the gecko to "run up and down a tree in any way, even with the head downwards" was observed by Aristotle (1918). This phenomenon is not limited to geckos, but occurs in several animals and insects as well. This dynamic attachment ability will be referred to as reversible adhesion or smart adhesion (Bhushan et al. 2006). Many insects (e. g., flies and beetles) and spiders have been the subject of investigation. However, the attachment pads of geckos have been the most widely studied owing to the fact that they exhibit the most versatile and effective adhesive known in nature. As a result, the vast majority of this chapter will be concerned with gecko feet.

Although there are over 1000 species of geckos (Kluge 2001; Han et al. 2004) that have attachment pads of varying morphology (Ruibal and Ernst 1965), the Tokay gecko (*Gekko gecko*) has been the main focus of scientific research (Hiller 1968; Irschick et al. 1996; Autumn 2006). The Tokay gecko is the second-largest gecko species, attaining respective lengths of approximately 0.3–0.4 and 0.2–0.3 m for males and females. They have a distinctive blue or gray body with orange or red spots and can weigh up to 300 g (Tinkle 1992). These geckos have been the most widely investigated species of gecko owing to the availability and size of these creatures.

Even though the adhesive ability of geckos has been known since the time of Aristotle, little was understood about this phenomenon until the late nineteenth century when microscopic hairs covering the toes of the gecko were first noted. The development of electron microscopy in the 1950s enabled scientists to view a complex hierarchical morphology that covers the skin on the gecko's toes. Over the past century and a half, scientific studies have been conducted to determine the factors that allow the gecko to adhere to and detach from surfaces at will, including surface structure (Ruibal and Ernst 1965; Russell 1975, 1986; Williams and Peterson 1982; Schleich and Kästle 1986; Irschick et al. 1996; Autumn and Peattie 2002; Arzt et al. 2003), the mechanisms of adhesion (Wagler 1830; Simmermacher 1884; Schmidt 1904; Hora 1923; Dellit 1934; Ruibal and Ernst 1965; Hiller 1968; Gennaro 1969; Stork 1980; Autumn et al. 2000, 2002; Bergmann and Irschick 2005; Huber et al. 2005b), and adhesion strength (Hiller 1968; Irschick et al. 1996; Autumn et al. 2000; Arzt et al. 2003; Huber et al. 2005a,b). Recent work in modeling the gecko attachment system as a system of springs (Bhushan et al. 2006; Kim and Bhushan 2007a–d) has provided valuable insight into adhesion enhancement. van der Waals forces are widely accepted in the literature as the dominant adhesive mechanism utilized by hierarchical attachment systems. Capillary forces created by humidity naturally present in the air can further increase the adhesive force generated by the spatulae. Both experimental and theoretical work support these adhesive mechanisms.

There is great interest among the scientific community to further study the characteristics of gecko feet in the hope that this information could be applied to the production of microsurfaces/nanosurfaces capable of recreating the adhesion forces generated by these lizards (Bhushan, 2007b). Common man-made adhesives such as tape or glue involve the use of wet adhesives that permanently attach two surfaces. However, replication of the characteristics of gecko feet would enable the development of a superadhesive polymer tape capable of clean, dry adhesion (Geim et al. 2003; Sitti 2003; Sitti and Fearing 2003a; Northen and Turner 2005, 2006; Yurdumakan et al. 2005; Zhao et al. 2006; Bhushan 2007a, Bhushan and Sayer 2007; Gorb et al. 2007). These reusable adhesives have potential for use in everyday objects such as tapes, fasteners, and toys and in high technology such as microelectric and space applications. Replication of the dynamic climbing and peeling ability of geckos could find use in the treads of wall-climbing robots (Sitti and Fearing 2003b; Menon et al. 2004; Autumn et al. 2005).

27.2 Tokay Gecko

27.2.1 Construction of Tokay Gecko

The explanation for the adhesive properties of gecko feet can be found in the surface morphology of the skin on the toes of the gecko. The skin is composed of a complex hierarchical structure of lamellae, setae, branches, and spatulae (Ruibal and Ernst

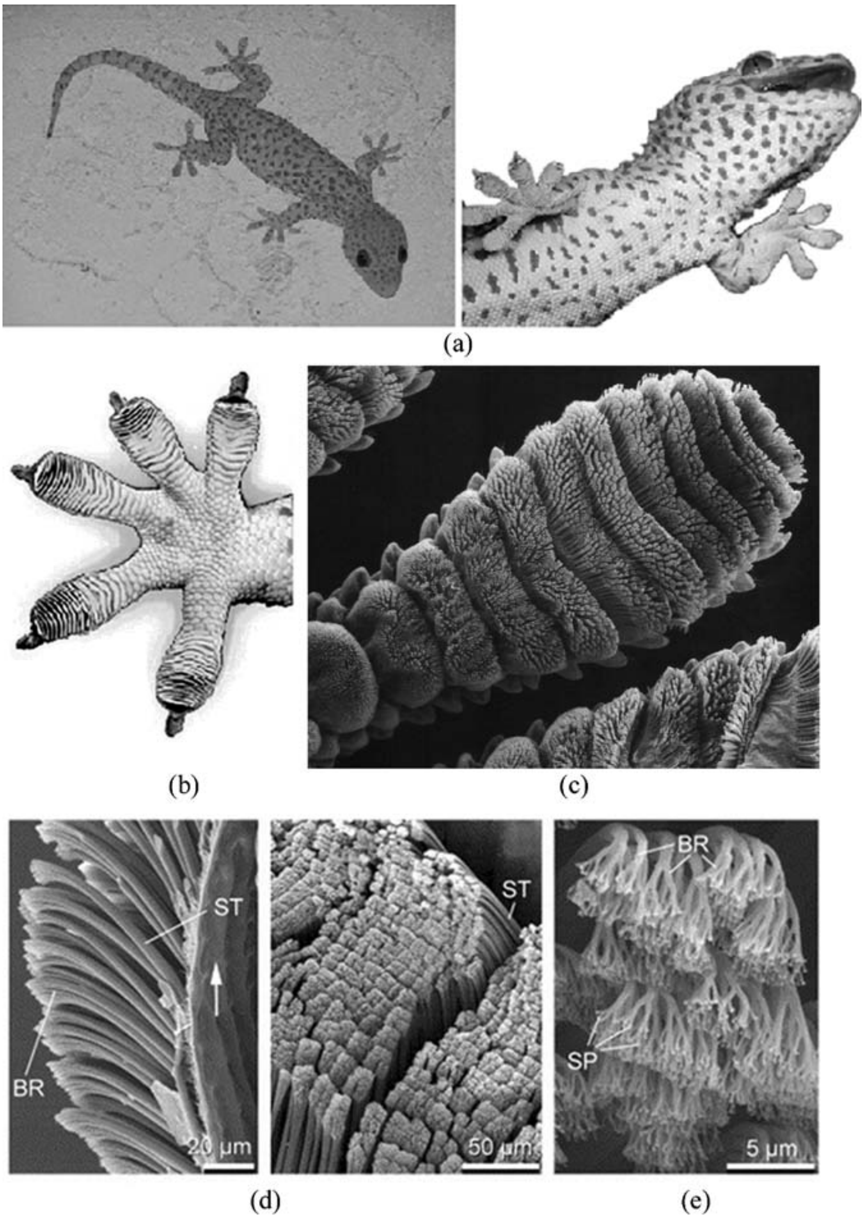

Fig. 27.1. **a** Tokay gecko (Autumn et al. 2000) The hierarchical structures of a gecko foot; **b** a gecko foot (Autumn et al. 2000) and **c** a gecko toe (Autumn 2006). Each toe contains hundreds of thousands of setae and each seta contains hundreds of spatulae. Scanning electron microscope (SEM) micrographs of **d** the setae (Gao et al. 2005) and **e** the spatulae (Gao et al. 2005). *ST* seta, *SP* spatula, *BR* branch

1965). As shown in Figs. 27.1 and 27.2 and summarized in Table 27.1, the gecko attachment system consists of an intricate hierarchy of structures beginning with lamellae, soft ridges that are 1–2 mm in length (Ruibal and Ernst 1965) that are located on the attachment pads (toes) that compress easily so that contact can be made with rough, bumpy surfaces. Tiny curved hairs known as setae extend from the lamellae with a density of approximately 14,000/mm^2 (Schleich and Kästle 1986). These setae are typically 30–130 μm in length and 5–10 μm in diameter (Ruibal and Ernst 1965; Hiller 1968; Russell 1975; Williams and Peterson 1982) and are composed primarily of β-keratin (Maderson 1964; Russell 1986) with some α-keratin components (Rizzo et al. 2006). At the end of each seta, 100–1000 spatulae (Ruibal and Ernst 1965; Hiller 1968) with a diameter of 0.1–0.2 μm (Ruibal and Ernst 1965) branch out and form the points of contact with the surface. The tips of the spatulae are approximately 0.2–0.3 μm in width (Ruibal and Ernst 1965), 0.5 μm in length, and 0.01 μm in thickness (Persson and Gorb 2003) and garner their name from their resemblance to a spatula.

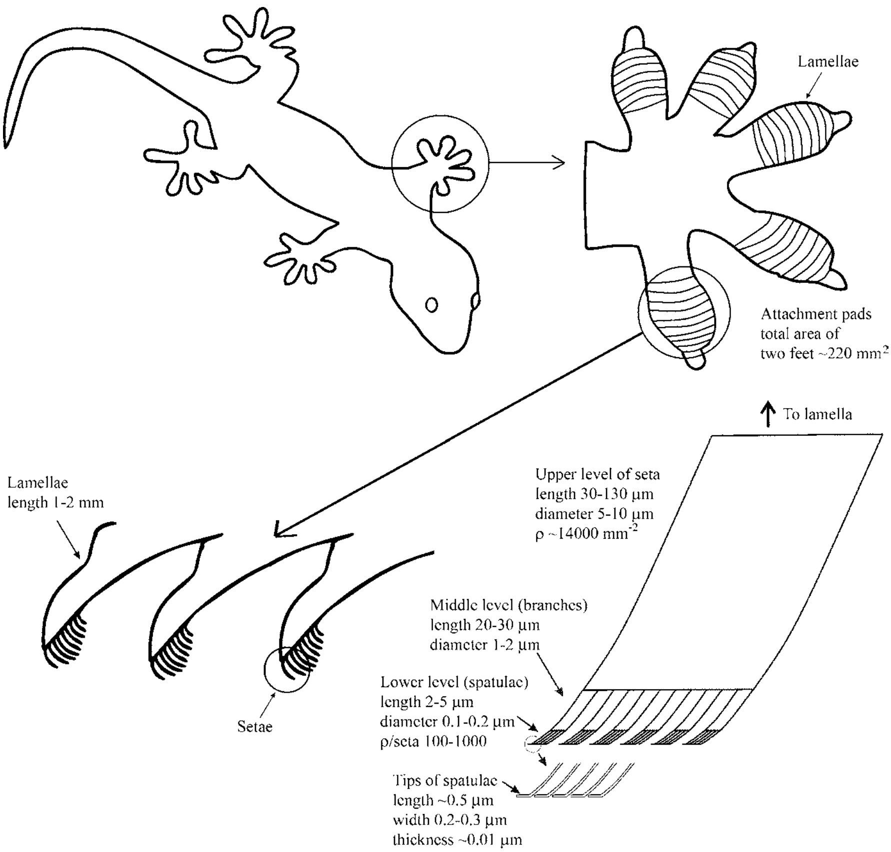

Fig. 27.2. A Tokay gecko including the overall body, one foot, a cross-sectional view of the lamellae, and an individual seta. ρ represents number of spatulae

Table 27.1. Surface characteristics of Tokay gecko feet

Component	Size	Density	Adhesive force
Seta	30–130[a–d]/5–10[a–d] length/diameter (μm)	$\sim$ 14000[f,g] setae/mm^2	194 μN[h] (in shear) $\sim$ 20 μN[h] (normal)
Branch	20–30[a]/1–2[a] length/diameter (μm)	–	–
Spatula	2–5[a]/0.1–0.2[a,e] length/diameter (μm)	100–1000[c,d] spatulae per seta	–
Tip of spatula	$\sim$ 0.5[a,e]/0.2–0.3[a,d]/ $\sim$ 0.01[e] length/width/thickness (μm)	– –	11 nN[i] (normal)

Young's modulus of surface material, keratin 1–20 GPa (Russell 1986; Bertram and Gosline 1987)
[a]Ruibal and Ernst (1965)
[b]Hiller (1968)
[c]Russell (1975)
[d]Williams and Peterson (1982)
[e]Persson and Gorb (2003)
[f]Schleich and Kästle (1986)
[g]Autumn and Peattie (2002)
[h]Autumn et al. (2000)
[i]Huber et al. (2005a)

The attachment pads on two feet of the Tokay gecko have an area of about 220 mm^2. About three million setae on their toes can produce a clinging ability of about 20 N [vertical force required to pull a lizard down a nearly vertical (85°) surface] (Irschick et al. 1996) and allow them to climb vertical surfaces at speeds over 1 m/s with capability to attach and detach their toes in milliseconds. In isolated setae, a 2.5-μN preload yielded adhesion of 20–40 μN and thus the adhesion coefficient, which represents the strength of adhesion as a function of preload, ranges from 8 to 16 (Autumn et al. 2002).

27.2.2 Other Attachment Systems

Attachment systems in other creatures such as insects and spiders have similar structures to that of gecko skin. The microstructures utilized by beetles, flies, spiders, and geckos can be seen in Fig. 27.3a. As the size (mass) of the creature increases, the radius of the terminal attachment elements decreases. This allows a greater number of setae to be packed into an area, hence increasing the linear dimension of contact and the adhesion strength. Arzt et al. (2003) determined that the density of the terminal attachment elements ρ_A per square meter strongly increases with increasing body mass m in kilograms. In fact, a master curve can be fit for all the different species (Fig. 27.3b):

$$\log \rho_A = 13.8 + 0.669 \log m \, . \qquad (27.1)$$

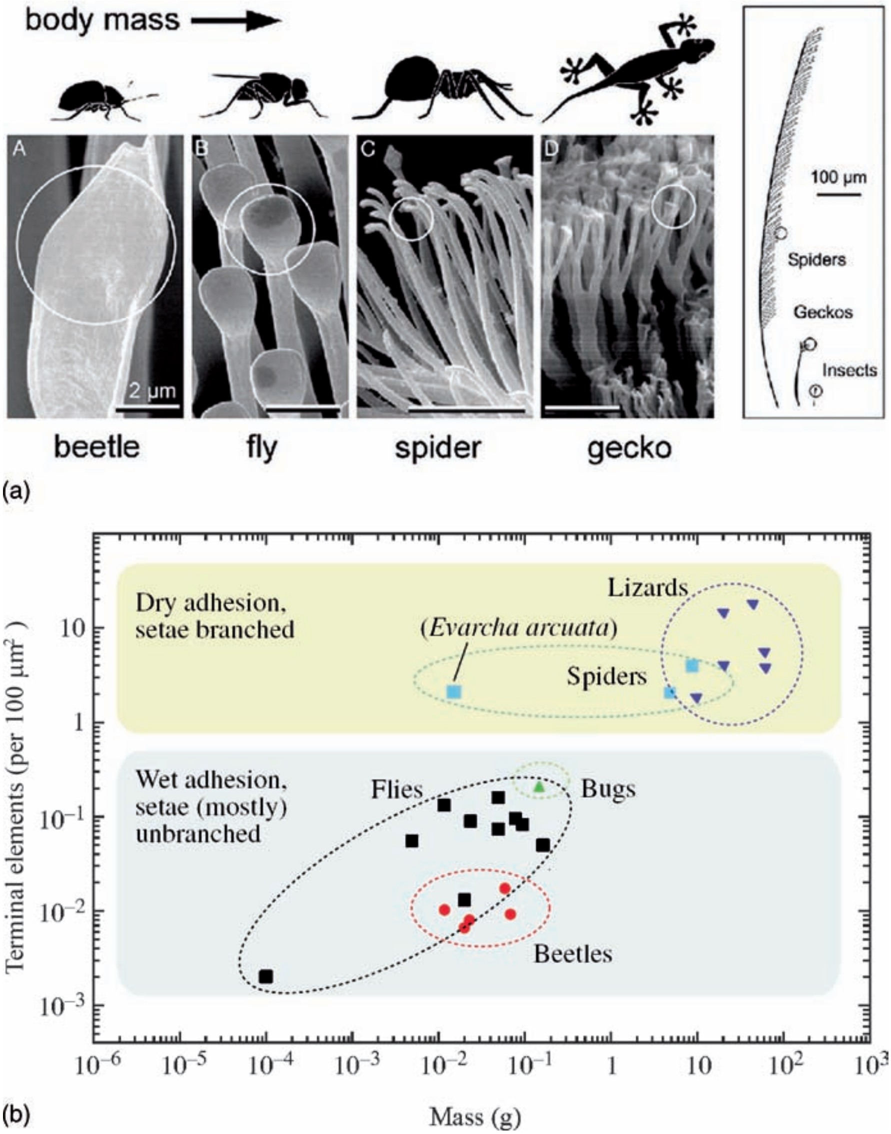

Fig. 27.3. a Terminal elements of the hairy attachment pads of a beetle, fly, spider, and gecko shown at two different scales (Arzt et al. 2003) and **b** the dependence of terminal element density on body mass (Federle 2006). (The data are from Artz et al. 2003 and Kesel et al. 2003)

The correlation coefficient of the master curve is equal to 0.919. Flies and beetles have the largest attachment pads and the lowest density of terminal attachment elements. Spiders have highly refined attachment elements that cover the leg. Geckos have both the highest body mass and the greatest density of terminal elements (spatulae).

Spiders and geckos can generate high dry adhesion, whereas beetles and flies increase adhesion by secreting liquid at the contacting surface.

27.2.3 Adaptation to Surface Roughness

Typical rough, rigid surfaces are only able to make intimate contact with a mating surface over a very small portion of the perceived apparent area of contact. In fact, the real area of contact is typically 2–6 orders of magnitude less than the apparent area of contact (Bhushan 2002, 2005). Autumn et al. (2002) proposed that divided contacts serve as a means for increasing adhesion. A surface energy approach can be used to calculate adhesion force in dry environments in order to calculate the effect of division of contacts. If the tip of a spatula is considered to be a hemisphere with radius R, the adhesion force of a single contact F_{ad} based on the Johnson–Kendall–Roberts (JKR) theory is given as (Johnson et al. 1971):

$$F_{ad} = \frac{3}{2}\pi W_{ad} R\,, \tag{27.2}$$

where W_{ad} is the work of adhesion (units of energy per unit area). Equation (27.2) shows that adhesion force of a single contact is proportional to a linear dimension of the contact. For a constant area divided into a large number of contacts or setae, n, the radius of a divided contact, R_1, is given by $R_1 = R/\sqrt{n}$ (self-similar scaling) (Arzt et al. 2003). Therefore, the adhesion force of (27.2) can be modified for multiple contacts such that

$$F'_{ad} = \frac{3}{2}\pi W_{ad}\left(\frac{R}{\sqrt{n}}\right) n = \sqrt{n}\,F_{ad}\,, \tag{27.3}$$

where F'_{ad} is the total adhesion force from the divided contacts. Thus, the total adhesion force is simply the adhesion force of a single contact multiplied by the square root of the number of contacts.

For a contact in the humid environment, the meniscus (or capillary) forces further increase the adhesion force (Bhushan 1999, 2002, 2005). The attractive meniscus force (F_m) consists of a contribution from both Laplace pressure and surface tension (Orr et al. 1975; Bhushan 2002). The contribution from Laplace pressure is directly proportional to the meniscus area. The other contribution is from the vertical component of surface tension around the circumference. This force is proportional to the circumference as is the case for the work of adhesion (Bhushan, 2002). Going through the analysis presented earlier, one can show that the contribution from the vertical component of surface tension increases as a surface is divided into a larger number of contacts. It increases linearly with the square root of the number of contacts n (self-similar scaling) (Bhushan 2007b; Kim and Bhushan 2007d):

$$\left(F'_m\right)_{\text{surface tension}} = \sqrt{n}\,(F_m)_{\text{surface tension}}\,, \tag{27.4}$$

where F'_m is the force from the divided contacts and F_m is the force of an undivided contact.

The models just presented only consider contact with a flat surface. On natural rough surfaces the compliance and adaptability of setae are the primary sources of high adhesion. Intuitively, the hierarchical structure of gecko setae allows for greater contact with a natural rough surface than a nonbranched attachment system. Modeling of the contact between gecko setae and rough surfaces is discussed in detail in Sect. 27.5.

Material properties also play an important role in adhesion. A soft material is able to achieve greater contact with a mating surface than a rigid material. Although, gecko skin is primarily comprised of β-keratin, a stiff material with a Young's modulus in the range of 1–20 GPa (Russell 1986; Bertman and Gosline 1987), the effective modulus of the setal arrays on gecko feet is about 100 kPa (Autumn et al. 2006), which is approximately 4 orders of magnitude lower than for the bulk material. Nature has selected a relatively stiff material to avoid clinging to adjacent setae. Division of contacts, as discussed earlier, provides high adhesion. By combining optimal surface structure and material properties, mother nature has created an evolutionary superadhesive.

27.2.4 Peeling

Although geckos are capable of producing large adhesion forces, they retain the ability to remove their feet from an attachment surface at will by peeling action. The orientation of the spatulae facilitates peeling. Autumn et al. (2000) were the first to experimentally show that the adhesion force of gecko setae is dependent on the three-dimensional orientation as well as the preload applied during attachment (see Sect. 27.4.1.1). Owing to this fact, geckos have developed a complex foot motion during walking. First the toes are carefully uncurled during attachment. The maximum adhesion occurs at an attachment angle of 30°—the angle between a seta and the mating surface. The gecko is then able to peel its foot from surfaces one row of setae at a time by changing the angle at which its setae contact a surface. At an attachment angle greater than 30° the gecko will detach from the surface.

Shah and Sitti (2004) determined the theoretical preload required for adhesion as well as the adhesion force generated for setal orientations of 30°, 40°, 50°, and 60°. We consider a solid material (elastic modulus E, Poisson's ratio ν) in contact with the rough surface whose profile is given by

$$f(x) = H \sin^2\left(\frac{\pi x}{\chi}\right) , \tag{27.5}$$

where H is the amplitude and χ is the wavelength of the roughness profile. For a solid adhesive block to achieve intimate contact with the rough surface neglecting surface forces, it is necessary to apply a compressive stress, σ_c (Jagota and Bennison 2002):

$$\sigma_c = \frac{\pi E H}{2\chi\left(1-\nu^2\right)} . \tag{27.6}$$

Equation (27.6) can be modified to account for fibers oriented at an angle θ. The preload required for contact is summarized in Fig. 27.4a. As the orientation angle

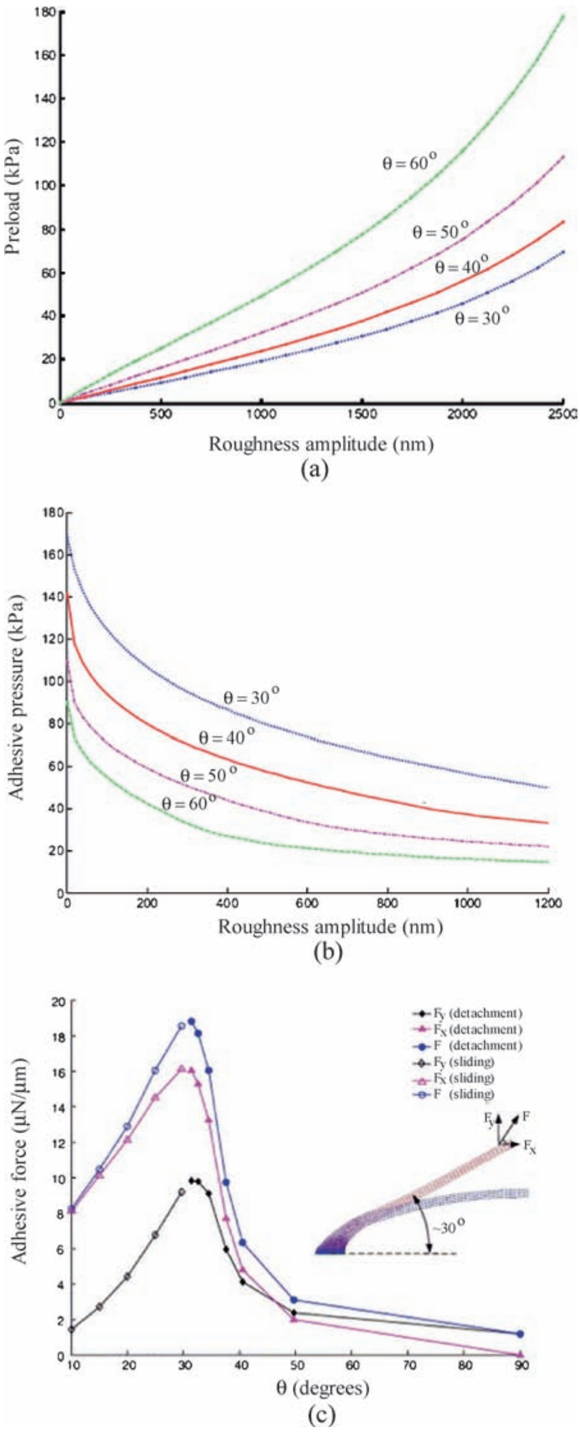

Fig. 27.4. Contact mechanics results for the affect of fiber orientation on **a** preload and **b** adhesive force for roughness amplitudes ranging from 0 to 2500 nm (Shah and Sitti 2004). **c** Finite-element analysis of the adhesive force of a single seta as a function of pull direction (Gao et al. 2005)

decreases, so does the required preload. Similarly, adhesion strength is influenced by fiber orientation. As seen in Fig. 27.4b, the greatest adhesion force occurs at $\theta = 30°$.

Gao et al. (2005) created a finite-element model of a single gecko seta in contact with a surface. A tensile force was applied to the seta at various angles, θ, as shown in Fig. 27.4c. For forces applied at an angle less than 30°, the dominant failure mode was sliding. In contrast, the dominant failure mode for forces applied at angles greater than 30° was detachment. This verifies the results of Autumn et al. (2000) that detachment occurs at attachment angles greater than 30°.

Tian et al. (2006) have suggested that during detachment, the angular dependence of adhesion and that of friction play a role. The pulling force of a spatula along its shaft with an angle between 0 and 90° to the substrate has a normal adhesive force produced at the spatula–substrate bifurcation zone, and a lateral friction force contribution from the part of the spatula still in contact with the substrate. High net friction and adhesion forces on the whole gecko are obtained by rolling down and gripping the toes inward to realize small pulling angles of the large number of spatulae in contact with the substrate. To detach, the high adhesion/friction is rapidly reduced to a very low value by rolling the toes upward and downward, which, mediated by the lever function of the setal shaft, peels the spatula off perpendicularly from the substrate.

27.2.5 Self-Cleaning

Natural contaminants (dirt and dust) as well as man-made pollutants are unavoidable and have the potential to interfere with the clinging ability of geckos. Particles found in the air consist of particulates that are typically less than 10 μm in diameter, while those found on the ground can often be larger (Hinds 1982; Jaenicke 1998). Intuitively, it seems that the great adhesion strength of gecko feet would cause dust and other particles to become trapped in the spatulae and that they would have no way of being removed without some sort of manual cleaning action on behalf of the gecko. However, geckos are not known to groom their feet like beetles (Stork 1983) nor do they secrete sticky fluids to remove adhering particles like ants (Federle et al. 2002) and tree frogs (Hanna and Barnes 1991), yet they retain adhesive properties. One potential source of cleaning is during the time when the lizards undergo molting, or the shedding of the superficial layer of epidermal cells. However, this process only occurs approximately once per month (Van der Kloot 1992). If molting were the sole source of cleaning, the gecko would rapidly lose its adhesive properties as it is exposed to contaminants in nature (Hansen and Autumn 2005).

Hansen and Autumn (2005) tested the hypothesis that gecko setae become cleaner with repeated use—a phenomenon known as self-cleaning. The cleaning ability of gecko feet was first tested experimentally by applying 2.5-μm-radius silica–alumina ceramic microspheres to clean setal arrays. It was found that a significant fraction of the particles was removed from the setal arrays with each step taken by the gecko.

In order to understand this cleaning process, substrate–particle interactions must be examined. The interaction energy between a dust particle and a wall and spatulae can be modeled as shown in Fig. 27.5. The interaction between a spherical dust

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Applied Scanning Probe Methods X
Biomimetics and Industrial Applications
Bhushan, B.; Fuchs, H.; Tomitori, M. (Eds.)
2008, LIX, 427 p., Hardcover
ISBN: 978-3-540-74084-1