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Adhesive Contact in Animal: Morphology, Mechanism and Bio-Inspired Application

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Abstract

Many animals possess adhesive pads on their feet, which are able to attach to various substrates while controlling adhesive forces during locomotion. This review article studies the morphology of adhesive devices in animals, and the physical mechanisms of wet adhesion and dry adhesion. The adhesive pads are either 'smooth' or densely covered with special adhesive setae. Smooth pads adhere by wet adhesion, which is facilitated by fluid secreted from the pads, whereas hairy pads can adhere by dry adhesion or wet adhesion. Contact area, distance between pad and substrate, viscosity and surface tension of the liquid filling the gap between pad and substrate are the most important factors which determine the wet adhesion. Dry adhesion was found only in hairy pads, which occurs in geckos and spiders. It was demonstrated that van der Waals interaction is the dominant adhesive force in geckos' adhesion. The bio-inspired applications derived from adhesive pads are also reviewed.

Keywords: biomimetics, adhesion, animal, morphology, mechanism

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1 Introduction

Locomotion is a fundamental property of animals, which enables them to escape from predators, search for food, and to find mates. In order to move, animal has to overcome gravity and inertia of the body, and other external forces acting on the body[1]. The direction of the gravity is from the body to the centre of the earth, and the inertia force is always in the opposite direction of acceleration of the body.

When animals move through water or air (*i.e.* by swimming or flying), the interactions derived from hydro- or aerodynamic forces between the animals' body and the surrounding medium will not be discussed here. When animals move on land, particularly on substrates with an incline equal to or greater than 90˚ to the horizontal (*i.e.* a vertical substrate like a tree trunk or a wall of a building, and an inverted substrate like the underside of a leaf or a ceiling of a room), they have to find way to generate attraction force between their pads and the substrate in order to overcome the gravity. This attraction force is termed the adhesion, and is defined as the physical attraction or joining of two substances, especially the macroscopically observable attraction of dissimilar substances, or as the force that holds together the molecules of unlike substances whose surfaces are in contact.

During the course of evolution, animals have optimized several ways to climb various substrates, by developing claws and specialized adhesive pads[2]. The interaction of claws with substrates is determined by the roughness of the substrate, the friction coefficient and the relative dimension between claws and substrates. The stability of the interaction depends on the mechanism of mechanical interlocking[3].

However, on many smooth substrates, claws fail to interlock, and then the adhesive pads (smooth pads and hairy pads) are necessary to enable the animals to climb such substrates. Both smooth and hairy pads can generate adhesive forces, but their underlying mechanisms are different. The adhesion of hairy pads is thought to be due to dry adhesion, which is generated by van der Waals force. The adhesion of smooth pads is considered to be due to wet adhesion, originating from capillary force. As

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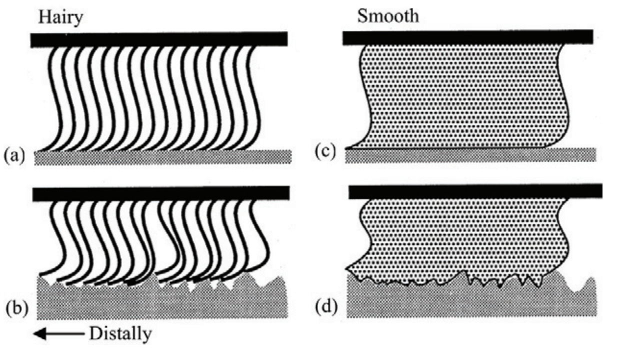


Fig. 1 Illustration on the adhesion of hairy (a, b) and smooth (c, d) pads on smooth (a, c) and rough (b, d) substrate. Both structures are able to adapt the substrate profile to maximum the real contact area[4].

shown in Fig. 1, both structures of pads are optimized to maximize contact area with the substrate, regardless of the microstructure[4].

Although the microstructure of the pads can be the same, the location of the pads along the legs can vary between different animals, as will be pointed out in Section **2**. The mechanisms of wet and dry adhesion will be discussed in Sections **3** and **4**, respectively, and the bionic studies and the possible applications will be introduced in Section **5**.

2 Adhesive devices in animals

Adhesive pads are adapted for holding onto smooth substrates (such as plant surface) where claws fail to get a grip[5]. Beutel and Gorb[4] published a review on the diversity of insect attachment pads. They found that the attachment devices of most hexapods are located on or near different parts of the legs, including claws, derivatives of the pretarsus, tarsal apex, tarsomeres, or tibia (Fig. 2). The reason why the variation in geometric scale was discussed is probably due to the differences in lifestyles (*e.g.* ground dwelling insects are more than arboreal insects) and/or differences in body weight. The structure of the attachment pads will now be discussed using a few examples.

The structure of the pad and hairs of flies are presented in Fig. 3. Flies *Brachycera* have adhesive pads called pulvilli at the terminal tarsomere. The pulvilli are covered with terminal setae, sometimes termed terminal hairs, which serve to increase the contact area. Proximal and distal terminal setae have different ultrastructures. The design of distal adhesive setae is adapted for the release of adhesive substances close to the area of contact[6]. No remarkable differences were observed in micro-topography of the adhesive device between male and female flies. This device would, therefore, perform similar functions and roles in both sexes[7].

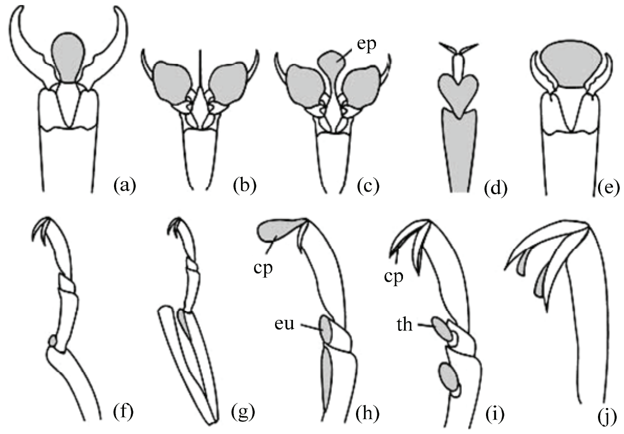


Fig. 2 Diversity of the leg attachment devices (gray areas) in insects. (a) Smooth arolium; (b) smooth or hairy pulvilli; (c) hairy empodial pulvilli (ep); (d) hairy adhesive soles of tarsomeres; (e) smooth eversible pretarsal bladder; (f) smooth eversible structure between tibia and tarsus; (g) hairy fossula spongiosa; (h) smooth euplantulae (eu) and claw pad (cp); (i) smooth tarsal thoms transformed into adhesive structures (th) and cp; (j) adhesive claw pad[4].

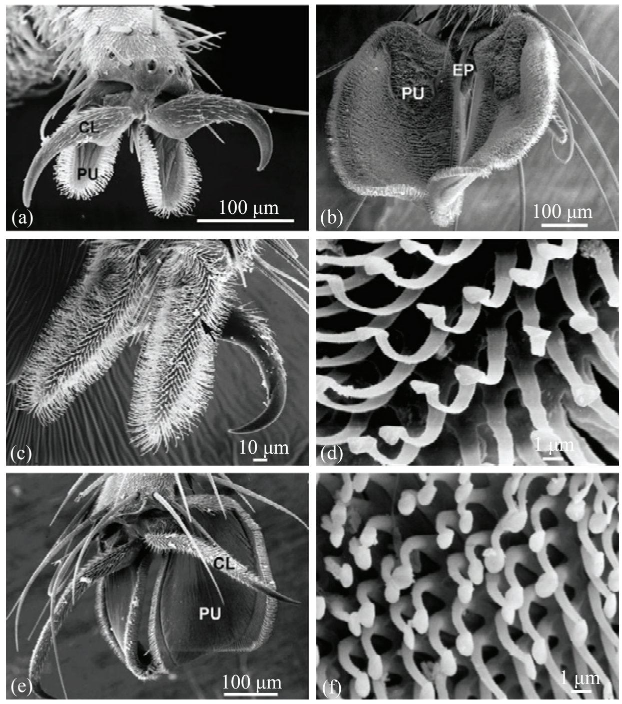


Fig. 3 The structure of hairy pads and the micro-structures of the hairs of flies. (a) Tarsomere of the blowfly, *C. chani*; (b) tarsomere of fresh fly *B. peregrina*; (c) tarsomere of the housefly *M. domestica*; (d) spatula-like tip of the tenent setae of *C. chani*; (e) tarsomere of the fresh fly *B. peregrina*; (f) spatula-like tip of the tenent setae of *C. pinguis*[7].

The bird spider *Aphonopelma seemanni* and the hunting spider *Cupiennius salei* are able to climb steep smooth glass surfaces. The hairs on their adhesive pads are composed of setae bent distally at their tips. The concave part of the bent seta is covered with fine cuticular outgrowths called setulae or microtrichia. The seta resembles a broom or a toothbrush. Because of its hierarchical structure, the entire seta with its microtrichia is able to adapt to a wide variety of surface roughnesses. The hairy attachment system of spiders requires a small proximal pull to establish an intimate contact between the flat spatula-shaped tips and the substrate, similar to what was found for the adhesive pads of geckos[8].

Geckos, as quadruped animals, possess an excellent ability to move on various substrates. The structure of the gecko's foot, the lamellae or seta arrays and the micro-structure of the setae have been extensively studied[9–11]. The key parameter for the hairy adhesion is the distance between the terminal part of the hair and substrate, which is in the range of a few nanometers in order to generate van der Waals forces. With an increase in body weight, the diameter of the seta would decrease to generate enough adhesion to balance the gravity of the animal[12] (Fig. 4).

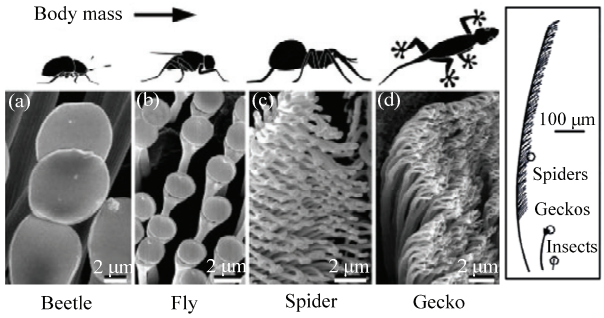


Fig. 4 Diameter of seta decreases with the increase in body weight[12].

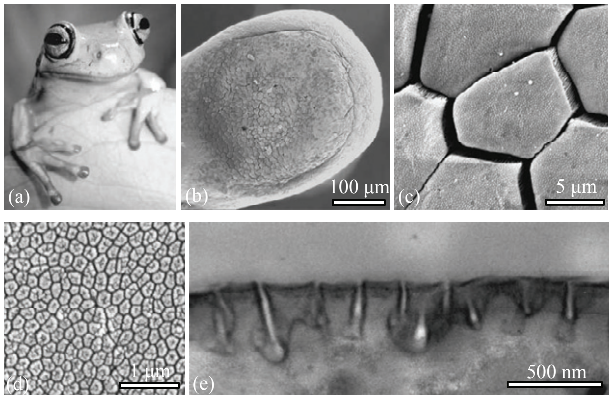


Fig. 5 Morphology of tree frog toe pads. (a) White's tree frog *Litoria caerulea*; (b) the toe pad, (c) the epidermis with hexagonal epithelial cells; (d) the high power view of the surface of a single hexagonal cell showing peg-like projections; and (e) TEM image of cross-section through cell surface[14].

Smooth and deformable cuticle pads are not only found in many insects[4,13] but also on the toe pads of tree frogs. They are characterized by hexagonal cells separated by deep channels into which mucus glands open (Fig. 5). The pads are wetted with mucus, which suggests that the adhesion is mainly due to capillary and viscous forces generated by the fluid-filled joints between the pad and substrate. The study by Federle and Barnes[14] showed that tree frog adhesive forces are also significantly enhanced by close contact and boundary friction between the pad epidermis and the substrate, facilitated by the highly regular pad microstructure. Tree frogs have less compliant pad surface layers, and so the adhesion to rough surfaces is only possible because the animals inject a wetting liquid into the pad–substrate contact area, which generates a relatively long-range attractive interaction due to the formation of capillary bridges[15].

The adhesive properties are significantly affected by the density of fibres, the thickness of superficial layer, and the compliance of pad. At a first glance, grasshoppers and locusts seem to have a similar pad structure, but their microstructures, effective elastic moduli, and adhesive properties of their smooth adhesive pads are different. It has been found that a locust pad has a thicker sub-superficial layer and a higher density of rods. Furthermore, indentation experiments showed a higher effective elastic modulus and a lower work of adhesion for locust pads[16]. During adhesion, the contact is mediated by a liquid[17]. This liquid appears to be secreted onto the surface of the pads through pore canals[6] or channels[13], but the exact pathway still needs to be explored. The experiments in Ref. [17] showed that the adhesive force generated by soft pads alone is not enough to counteract the body weight of the animal.

3 Wet adhesion mechanism

Flexible smooth pads occur in many insects (*e.g.* grasshoppers, locusts, ants, and cockroaches) and other animals like tree frogs. Strong adhesion between pad and rough substrate is only possible if at least one of the surfaces is elastically soft and the microstructure of the pad enables it to adapt and replicate the profile of substrate. The pad surface is covered with an adhesive secretion, which is essential for the attachment.

3.1 Physical mechanism

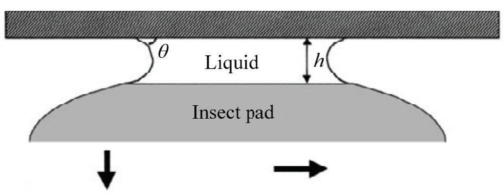
Wet adhesion is the mechanism employed by most smooth pads[4] and some hairy pads[18], where a liquid film between the pad and substrate gives rise to adhesive forces due to surface tension and viscosity (Fig. 6). In the direction perpendicular to the surface, static forces are created mainly by surface tension, but the dynamic forces are generated by the surface tension and viscosity of the liquid in relative motion. Friction forces parallel to the surface can be negligible for static adhesion, but they are quite big when relative motion happens due to a very small distance between the surfaces (boundary conditions). Several predictions for insect attachment forces follow from these considerations (Fig. 6)[19]:

(1) Static friction should be small because the liquid film between two solid surfaces generally acts as a lubricant, and the friction force depends on the relative speed. However, dynamic friction should be much larger for smaller distances, h, when pads attach to substrates. This may explain why frictional forces are much larger than adhesive forces.

(2) Friction should depend on velocity and the viscosity of the liquid. Due to shearing of the liquid film, the friction force should be stronger at higher sliding velocities.

(3) Because of the temperature-dependency of liquid viscosity and surface tension (though viscosity decreases much more strongly with decreasing temperature than surface tension), sliding friction should become smaller at higher temperatures, but static forces should be almost temperature-independent.

Therefore, contact area, distance between pad and substrate, and viscosity and surface tension of the liquid filling the gap between pad and substrate are the most important factors which determine the adhesion and friction of soft smooth pads (Fig. 6). The contact area depends on the force acting on the pad and the stiffness of the pad because the substrate, in most cases, is very hard compared to the pad. During attachment, the preload force which acts on the pad, to obtain enough contact area, has to be balanced by the adhesion acting on other pads, so animals tend to minimize the whole-body preload force. With decreasing stiffness of the pads, less preload is necessary in order to form a close contact with the substrate. However, softer pads are more prone to wear and abrasion. Another way to overcome this problem is to split the contact into smaller individual contacts, ending in the design structure of a hairy pad. The other factor is the performance of liquid secreted by animals. The viscosity of the liquid in the film, the wettability of the liquid on the substrate and the surface tension will determine the adhesion in the normal direction and the friction parallel to the contact surface.



	Vertical force (adhesion)	Parallel force (friction)	
Static	$F = 3\pi R\gamma_L \cos\theta$ (Fogden & White 1990)	Lubrication: Low friction expected	θ: contact angle h: liquid film height γ_L: surface tension η: viscosity v: velocity R: pad radius of curvature A: pad area
Dynamic	Additional viscosity contribution	$F = \frac{A}{h} \cdot v \cdot \eta$	

Fig. 6 Illustration of the wet adhesive contact and prediction from the wet adhesive mechanism. Static force was predicted on the hypothesis of soft sphere, and the dynamic force was predicted on the parallel plate with Newtonian liquid[19].

To understand the mechanism of wet adhesion, a model was proposed to explain the force between pad and surface (Fig. 6), where the contact area will shrink or extend when an insect pad is pulled off or pressed. In this model, the adhesion force is presented as[19]

$$F = 3\pi R\gamma_L \cos\theta. \quad (1)$$

3.2 Contact mechanics of soft smooth pads

The effect of macrostructure and the topology of material distribution on wet adhesive pads was studied by using a Finite Element Modelling (FEM) method[13]. The contact mechanics, stiffness, friction force generated at the contact area, and the restrained forces on the pad were obtained (Figs. 7 and 8)[2,16].

Figs. 7a and 7b show the deformation vectors of a grasshopper's adhesive pad, and Figs. 7c and 7d are detailed images of the contact zone (marked by rectangles in Figs. 7a and 7b) for the Soft-Solid (SS) model and Fluid Contained (FC) model, respectively. It was believed that both the geometric structure and the material topology make the displacement vector fields so different. The geometric design made it possible for the pads to move outwards, but this tendency was more strongly restrained by the SS structure than that of FC structures. As a fluid, hemolymph can bear only compressive stress, not shear stress or tensile stress. The

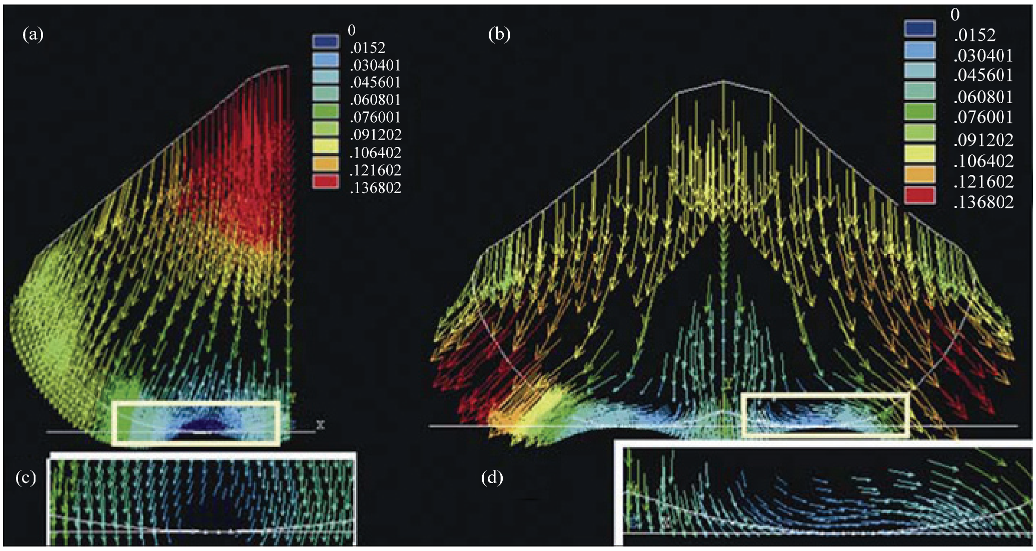


Fig. 7 Vector field of displacements. (a) SS model and (c) detail of contact zone. The vectors in contact zone are perpendicular to the target surface, there is no relative movement between pad and target surface, so no friction force is generated during contact. (b) FC model and (d) detail of contact zone. The vectors in the contact zone are parallel to the target surface, a relative movement at reversed directions between pad and target surface is observed and thus reversed friction force will be generated during contact. The displacement vectors near contact zone in FC model ((b) and (d)) are much larger than those in SS model ((a) and (c)), suggesting that the increase rate of contact area in FC model is larger than in SS model[13].

compressive stress generated by the Ground Reaction Force (GRF) on the contact area and hard cuticle boundary was transmitted by hemolymph to the outside of container-like structure, leading to the displacement of node point in the FC model in reversed directions (towards the outside). On the contrary, the soft material can bear shear, tensile and compressive stresses, which restrains the motion of node point in the SS model from moving outside.

Knowledge of the function of GRFs on an animal's locomotion is fundamental to understanding its evolutionary development. Dickinson[1] examined the effects of GRF on the locomotion of animals, and pointed out that GRF on each adhesive pad is toward the centre of the body. It has been demonstrated in gecko that the setae only generate significant forces when the setae are subjected to a small pull on the surface[20]. Several three-dimensional sensors were developed to measure the GRF of gecko *Gecko gecko*, stinkbug *Erthesina fullo* and lantern-fly *Lycorma delicatula* on floor, wall and ceiling substrates[5]. All the data suggest that lateral forces are always larger than the normal forces when animals run on walls or ceilings[10], and are in the same order of magnitude when they run on the floor. The tangential force, resultant force of lateral force and for-aft force, generated between the attached pad and the substrate, is redundant to enhancing the adhesion reliability and stability.

Fig. 8a shows the relationship between displacement and load. Lower stiffness is useful for reducing impact force during landing and preventing other parts of leg from being over-loaded, which may result in the failure in transmission gears in legged robots. This suggests that the geometric design of the grasshopper foot may be applicable to the design of legged robots as it may reduce impact forces.

Lower stiffness also means that the pad is more flexible, and larger contact area can be obtained during adhesion. Fig. 8b shows the contact area for both the SS and FC models, where the lengths of contacted lines were obtained by checking the reaction forces on the nodes of the contact elements. The results suggest that by mimicking the geometric structure of the grasshopper's pad, multiple targets, namely decreasing the landing impact force, increasing the contact area and enhancing the adhesion, can be reached at the same time. These characteristics are required in developing three-dimensional obstacle-free robots.

It is suggested that the grasshopper could adjust the internal pressure of its adhesive pad, very much like inflating and deflating a balloon or an airbag, by pumping haemolymph into or out of the pad in order to decrease the impact force during landing or increasing the pressure to minimize adhesion before jumping.

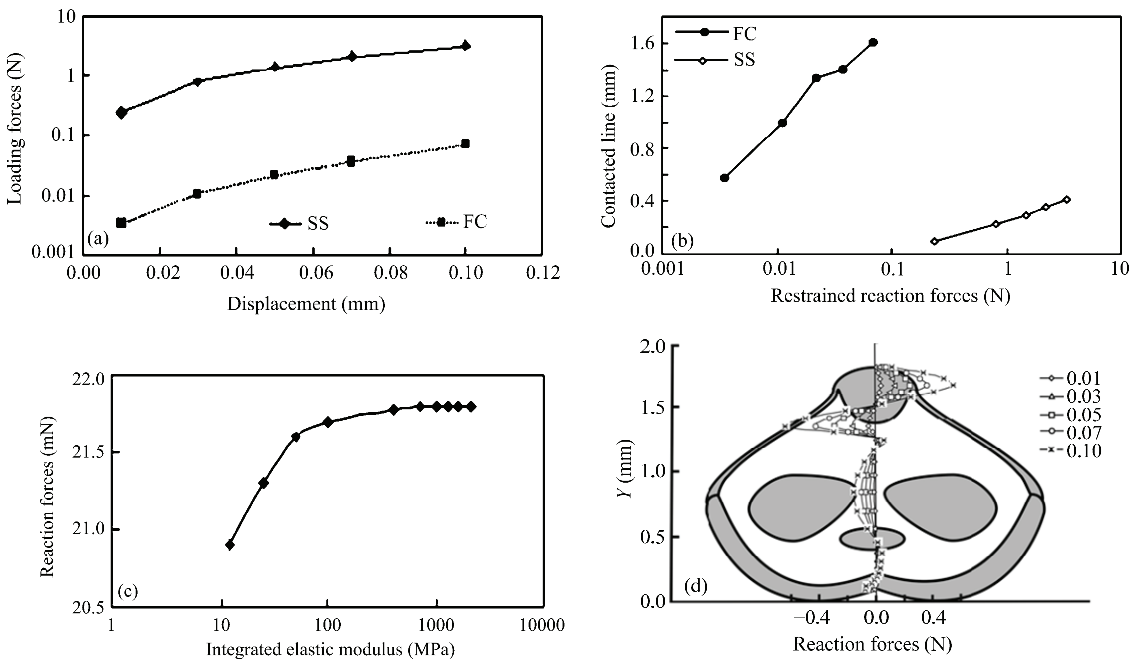


Fig. 8 (a) Reaction forces F_R for various pre-restrained displacement D_R; (b) relationship of contacted area with pre-restrained distance and restrained reaction forces. The results mean that with the same restrained displacement, reaction forces of FC model are much lower than that of SS model, but the contact line are much higher than in SS model; (c) reduction of integrated elastic modulus reduces the reaction forces for a given restrained displacement; (d) reaction forces at restrained points for different preloads. With increasing loads, the restrained reaction forces are also increased. But the forces are always zero at the place where the flexor tendon is located[13].

When the pressure modulation of the airbag is low, the integrated elastic modulus is also low (Fig. 8c). The results show that when the integrated modulus is lowered enough (lower than 60 MPa), the stiffness is heavily decreased. This suggests the possibility that the grasshopper can control the contact status by modulating the pressure in its pad.

Fig. 8d shows the reaction forces at restrained points in Y direction. The results show that, with an increase in load, the reaction force also increases. The biggest reaction force is located in the hard cuticle zone and nearby, but in reverse direction, in the rod based exocuticle that supports the superficial layer. The reaction force in the hemolymph zone is lower than in the neighbouring exocuticle. Interestingly, the restrained force in the tendon area is zero. This result could explain why the tendon can keep its position in the hemolymph.

Geometric evolution of grasshopper pads has been optimized to increase contact area, reduce landing impact forces, and to increase contact stability by generating reversed tangential force during contact formation. The effects of elastic modulus on the contact parameters suggest that the grasshopper may have the ability to modulate contact status by controlling the pressure within its pads.

4 Dry adhesion mechanism

Dry adhesion is found only in hairy pads, which occurs in geckos and spiders[21]. It was demonstrated that van der Waals interaction is the dominant adhesive force in geckos' adhesion[9]. Research has showed that the distance between the terminal ending of the hairs on the pads and substrate is much smaller than that between soft smooth pads and substrates[2].

Studies on the locomotor abilities of geckos can be traced back to two thousand years ago, and scientific researches on their adhesive capabilities have been carried out for decades[22]. The adhesive mechanism of van der Waals force was not discovered until 2000. Furthermore recent studies found that the geckos' setal arrays show self-cleaning abilities and an almost constant detachment angle of around 30° between setae and substrate. Some studies assumed that capillary force may also contribute to the adhesive force. Recently, the biochemical structure of the gecko seta was also revealed[23], helping to mimic the setae for artificial pads. Our work showed that most animals had more than one tool to make it hold on substrate stably[2].

4.1 Physical mechanism

The adhesive force of a single seta of gecko was measured[9], indicating that only van der Waals forces are acting in the dry, hairy system[24]. This attractive force exists in any polar or non-polar molecule and is caused by fluctuations in the instantaneous dipole moments of two atoms due to the uneven distribution of electrons in their electron clouds. Two adjacent particles tend to synchronize their dipole moment fluctuations to minimize the total potential energy; therefore van der Waals forces are usually attractive in nature. The van der Waals forces are the smallest among all intermolecular forces, but they become significant when a large number of particles are involved at a suitable (nano-scale) distance. The van der Waals attraction between two solids can be calculated by integrating the London dispersion energy over all particles in both volumes, and differentiating with respect to the separation distance between them[25].

From a microscopic point of view, the potential energy of an intermolecular pair is obtained by summing the attractive potential energy, E_A, and repulsive potential energy, E_R, resulting in the Lennard-Jones equation, where m and n is 12 and 6, respectively[25]:

$$\begin{aligned} E_{\mathrm{vdW}} &= -E_{\mathrm{A}}(r/r_0)^{-n} + E_{\mathrm{R}}(r/r_0)^{-m} \\ &= 4\varepsilon[(r_0/r)^{12} - (r_0/r)^6], \end{aligned} \tag{2}$$

where, ε is a constant of interaction potential, the subscript 'vdW' is abbreviation of van de Waals. The intermolecular potential and force are illustrated in Fig. 9.

The Fig. 9 shows the relationship of potential and force to the distance between two particles. When this distance $r = r_0$, the repulsive force equals to the attractive force, the potential of the system becomes a minimum; when two particles are pressed to $r < r_0$, the molecular interaction F_{vdW} is repulsive, which will dramatically increase with the decreasing distance r; when the distance between two particles falls into $r > r_0$, the interaction becomes attractive and increases with the increase of distance until $r_0 < r < r_0+\delta$; then, the attractive force decreases with the increasing distance, so the force reaches its maximum $F_{\mathrm{vdW}}^{\max}$ (the 'adhesion' force) at distance $r = r_0 + \delta$. When $r > r_0 + \delta$, the interaction is still attractive, but it decreases with the increasing distance, so the attractive link will soon be broken. The summed force of a setal array is an integration of repulsive forces and attractive forces of each hair on the array. To obtain bigger adhesive forces, animals have evolved techniques to reduce the repulsive force and increase the attractive force by inclining the seta to decrease the contact stiffness of the seta to the substrate.

Supposing the terminal part of the seta and the substrate are two parallel surfaces (Fig. 10), the adhesive force to a surface can be roughly modelled for the configuration per unit contact area as

$$F_{\mathrm{vdW}} = A/6\pi r_0^3, \tag{3}$$

where A is the Hamaker constant that depends on the materials of the two surfaces, the typical value is in the order of 10^{-19} J between two solids, and does not vary significantly for different materials. Note that there is a significant difference between real and apparent contact areas. Solid surfaces are rarely ideally planar; therefore, the real contact area is merely the total of the areas between the few opposing asperities actually in a position to touch each other[26,27].

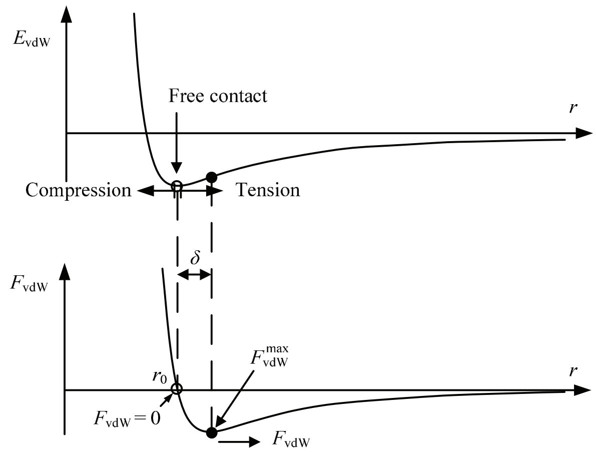


Fig. 9 The Lennard-Jones potential energy and force between two particles[25].

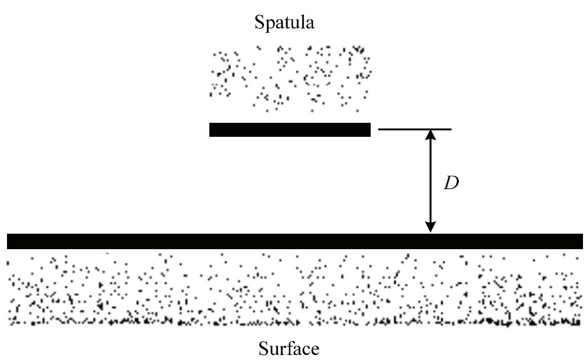


Fig. 10 Spatula and surface approximated as two parallel surfaces in contact[26].

4.2 Contact mechanism of the hairy system

The extraordinary climbing ability of geckos is considered a remarkable design of nature that results from the fine structure of its toes, which contain setal arrays consisting of hundreds of spatula on each seta. Although the micro-meter dimensions of the terminal elements of the setae are sufficient for flies and beetles, geckos require nano-meter devices to ensure sufficient adhesion[28]. Each toe of a Tokay gecko contains up to 20 rows of sticky lamellae, and each lamella contains many setal arrays consisting of thousands of setae, which amounts to 200,000 setae per toe, and each seta consists of hundreds of spatulae at its terminal. These fine structures allow for intimate contact between the spatulae and surface, and to obtain high adhesion and friction forces on various substrates[27]. Autumn[9] provided the first direct experimental evidence for the dry adhesion of gecko setae by van der Waals forces, and rejected the use of mechanisms relying on high surface polarity, including capillary adhesion. A van der Waals mechanism implies that the remarkable adhesive properties of gecko setae are merely a result of the size and shape of the tips, and are not strongly affected by surface chemistry[24].

To understand the animals' climbing skills, the contact stiffness of the hair was modelled using the factorial method. Fig. 11 shows a model to calculate the contact stiffness of a hair along and perpendicular to the seta when it is vertical (a) or with a slope angle α (b). The relationship of stiffness with slope angle is presented in Fig. 11c. The spring constant k_a along the cantilever beam (Fig. 11a) can be defined as

$$k_a = \frac{\pi}{4}\frac{Ed^2}{l}. \tag{4}$$

The spring constant k_p perpendicular to the cantilever beam (Fig. 11 a) can be defined as

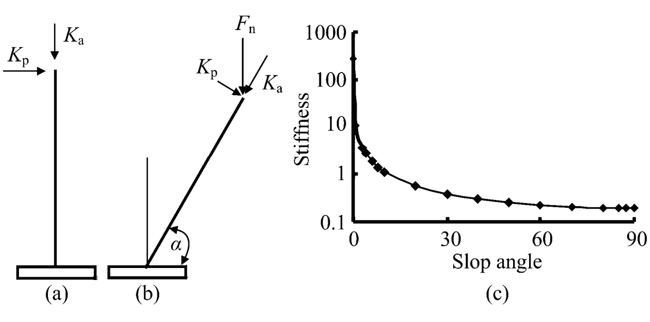


Fig. 11 Contact model and stiffness. (a) Mechanical model for a vertical cantilever; (b) mechanical model for a slop cantilever; and (c) contact stiffness *vs*. slop angle of cantilever.

$$k_p = \frac{3\pi Ed^4}{64 l^3} = \frac{3\pi}{64}\frac{Ed^2}{l}\left(\frac{d}{l}\right)^2. \tag{5}$$

When the typical elastic modulus and the geometry of gecko spatula and seta are introduced into the above equations, Table 1 can be obtained.

Table 1 The geometrical scales and the stiffness of gecko spatula and setae

	E (GPa)	d (μm)	l (μm)	K_a (N·m^{-1})	K_p (N·m^{-1})	K_a/K_p
Gecko setae	1	1	30	26.18	0.0054	4800
		5	130	151.04	0.0419	3605

The results suggest there is a great difference in the contact stiffness along (k_a) and perpendicular (k_p) to the gecko seta. The stiffness along the hair is up to ten thousand times the stiffness perpendicular to the hair, which means that when forces act in a direction perpendicular to the hair, the hair would be very soft and have more points coming into contact. The analysis results may explain why no animals' adhesive hair settles vertically.

When a hair is oblique to a flat surface at an angle α, we obtain the stiffness k along the direction of force

$$k = \frac{1}{\sqrt{\left(\frac{\sin\alpha}{k_a}\right)^2 + \left(\frac{\cos\alpha}{k_p}\right)^2} \cdot \cos(\alpha-\gamma)}. \tag{6}$$

The relationship is shown in Fig. 11c and suggests that when force acting in a direction shifts away from along the hair's very small angle, the stiffness will decrease dramatically. For example, shifting the angle 4˚ will decrease the stiffness to 1% along the hair. In nature, the gecko's setal arrays are sloped to the surface from 27˚ to 70˚[29], and during contact the toes slide on the target surface. This procedure further increases the angle of a gecko's hair and results in a decrease of contact stiffness.

Pesika[30] proposed a tape-peeling model based on the geometry of the spatula to predict the peeling behaviour of adhesive tapes at peel angles less than or equal to 90˚. This model has been applied to the gecko adhesive system, and predicts a spatula peel angle of 18.4˚ to achieve the adhesive force reported for a single seta. The model captures the fact that adhesive forces can be significantly enhanced by peeling at a specific angle, thereby exploiting high friction forces between the detaching material and the substrate.

We measured the three-dimensional reaction forces of a toe/foot of a freely moving gecko on floor, wall and ceiling[10] by using a newly developed force measuring array[20]. We found that the shear force generated during the adhesion of a toe on a substrate is always along the toe and points from the centre of the foot to the terminal of the toe (Fig. 12).

When geckos move on a ceiling or on a vertical wall, the positions of fore-feet and hind-feet are similar. However, the reaction forces of toes, angles between adjacent toes are different. When geckos move on ceilings and walls, they adjust the angles among their toes appropriately to change the directions of the reaction forces of their feet, so as to accomplish changes in force safely and efficiently to satisfy the locomotion requirement on the premise of safety. As shown in Fig. 13,

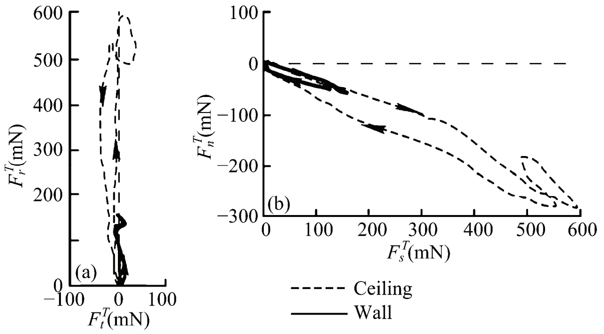


Fig. 12 The shear forces acting on toe when gecko freely moving on ceiling and wall. (a) Radial force vs tangential force; (b) normal adhesive force vs. shear force[10].

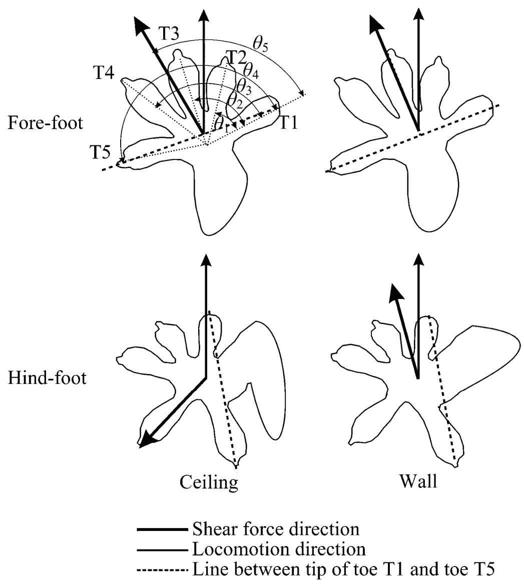


Fig. 13 The positions of fore- and hind-feet on ceiling and wall. The angles between the first toe T1 and other four toes (T2 through T5) are θ_1, θ_2, θ_3 and θ_4 (θ_5 is angle between the first toe and the direction of shear force)[10].

the function of toe T3 in moving is very important particularly for the fore-feet. The angle θ_4 between toes T1 and T5 of the fore-feet and hind-feet show distinctive differences when comparing climbing on a ceiling with climbing on a wall, but both are larger than 180°. The projections of the shear forces of toe T1 and T5 are co-linear but reversed, which forms a redundant binding force to increase reliability of adhesion in response to external shock. Animals can move freely in the whole space because of this redundant structure which enhances their safety and improves the flexibility of locomotion.

5 Bio-inspired applications

Learning from and mimicking nature enables us to come up with lots of useful inventions and techniques.

Sitti and Fearing[31] fabricated synthetic gecko foot-hairs as dry adhesives for wall-climbing robots. Preliminary micro/nano-hair prototypes showed adhesion close to the predicted values for natural specimens (around 100 nN for each hair). Menon and Sitti[32] proposed two climbing robots, each with a synthetic adhesive bearing a gecko-mimicking structure. The first was designed considering macro-scale operations on earth and in space, and the second was scaled down for micro-scale applications. Sameoto *et al.*[33] also presented an all polymer foot design for use with a hexapod climbing robot, and the fabrication method to improve reliability and yield. Daltoriol *et al.*[34] developed a vehicle to test bio-inspired adhesives for wall climbing. The modified Mini-Whegs^{TW} can walk on inclined, vertical surfaces and make transitions around concave corners using Scotch tape as the foot adhesive. It performs these tasks consistently until its feet are contaminated or damaged. It attaches and peels its feet from the surface in a similar way to wall-climbing animals. Daltorio *et al.*[35] also tested a new, reusable insect-inspired adhesive on the robot Mini-Whegs. The robot was capable of ascending vertical smooth glass surfaces using the structured polymer adhesive.

With the use of multi-tiered porous anodic alumina template and capillary force assisted nanoimprinting, Ho *et al.*[36] successfully fabricated a gecko-inspired hierarchical topography of branched nano-pillars on a stiff polymer. The hierarchical topography improved the shear adhesion force over topography of linear structures by 150%. The multiscale modelling proposed by Hu *et* *al*.[37] provided an approach to bridge the microlevel structures of the carbon nanotube array with its macrolevel adhesive behaviours. The predictions from this modelling gave an insight into the mechanisms of gecko-mimicking dry adhesives. Kim *et al*.[38] reported that hydrophilic polyurethane mushroom shaped microfiber arrays possess wet self-cleaning ability using the lotus effect as biologically inspired synthetic fibrillar adhesives. Murphy *et al*.[39] presented a novel technique for fabricating similar multilevel structures from polymer materials and demonstrated the fabrication of arrays of two- and three-level structures, wherein each level terminates in flat mushroom-type tips. These adhesion enhancements are the results of increased surface conformation as well as increased extension during detachment. Polymer microfiber arrays with mushroom-shaped tips are shown to adhere well to a soft, smooth substrate. The adhesion can be enhanced by increasing the compliance of the microfibers in addition to maximizing single-fiber adhesion. Lee *et al*.[40] reported the fabrication from a hard polymer of lamellar structures that act as base support planes for high-aspect ratio nanofiber arrays on lamellae, which can adhere to both planar and nonplanar surfaces.

Tree frogs secrete wetting liquid into the pad–substrate contact area, which generates a relative long-range attractive interaction due to the formation of capillary bridges. This system is relevant for some technological applications, for instance, tires for passenger cars have draining channels to speed up the removal of water from the tire–road footprint area under wet road conditions (Fig. 14). The word ‘draining’ is to move the water from one region in the footprint area to another region. If the water film thickness on the road surface is small enough, the water under the tread blocks can be transferred to the channels without completely filling them. Persson[15] noted that these cuts cannot absorb any large volume of displaced water, but may be very important to increase the tire–road grip on snow-covered road surfaces.

Fig. 14 Tire with a network of wide and narrow channels[15].

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