Biological Adhesion for Locomotion on Rough Surfaces: Basic Principles and A Theorist's View

B.N.J. Persson

Abstract

Surface roughness is the main reason why macroscopic solids usually do not adhere to each other with any measurable strength, and a root-mean-square roughness amplitude of only 1 μm is enough to completely remove the adhesion between normal rubber (with an elastic modulus $E \approx 1$ MPa) and a hard, nominally flat substrate. Biological adhesion systems used by insects and geckos for locomotion are built from a relatively stiff material (keratin or chitin–protein composite with $E \approx 1$ GPa). Nevertheless, strong adhesion is possible even to very rough substrate surfaces by using noncompact solid structures consisting of fibers (setae) and plates (spatulae). Biological systems use a hierarchical building principle, where the thickness of the fibers or plates decreases as one approaches the outer surface of the attachment pad, to optimize the binding to rough surfaces while simultaneously avoiding elastic instabilities, for example, lateral bundling of fibers.

Origins of Strong Adhesion

All natural surfaces and almost all surfaces of engineering interest have roughness on many different length scales.[1] Surface roughness has a tremendous influence on the adhesive interaction between solids and is the main reason why macroscopic solids usually do not adhere to each other with any measurable strength.[2–6] The interaction between neutral solids is very short-ranged, becoming negligibly small at separations of the order of a few atomic distances. Thus, strong interaction is only possible if at least one of the solids is elastically very soft so that the surface can bend and make close contact at the interface. In this case, there will be a large area of real contact, A, between the solids, and a small elastic energy, U_{el}, will be stored at the interface. During pulloff, this stored elastic energy is (partly) given back and may help to break the interfacial bonds. However, if the binding energy, $\Delta\gamma A$, where $\Delta\gamma$ is the change in the interfacial free energy per unit surface area as two flat surfaces of the two solids are brought together, is much larger than U_{el}, the stored elastic energy can be neglected. Thus, the first criterion for strong adhesion is that at least one of the solids must be elastically soft, so that the area of real contact is large and the stored elastic energy is small.

The second criterion for strong adhesion is that the interaction between the solids should involve long dissipative bonds. That is, during pulloff, the effective adhesive bonds should elongate a considerable distance and the elastic energy stored in the bonds at the point where they break should be dissipated in the solids rather than used to break the other interfacial adhesive bonds.

Synthetic adhesives often satisfy both of these criteria. Thus, for example, typical pressure-sensitive adhesives consist of thin, elastically soft polymer films that form thin filaments (effective bonds) during pulloff. These filaments can be extended a large distance—sometimes up to several millimeters—before they break, and the energy stored in the filament is mainly dissipated in the polymer rather than used to break other polymer filaments.[7] In addition, the effective elastic modulus of pressure-sensitive adhesives is very low (often in the kPa range), so the relative contact area, A/A_0, where A_0 is the nominal or apparent contact area, can be very large even for very rough substrates, and the stored elastic energy, U_{el}, may be relatively small.[8]

Biological adhesive systems used for locomotion cannot be built on the same principles as pressure-sensitive adhesives. First, pressure-sensitive adhesives are relatively weak materials (almost liquid-like) and would wear rapidly. More importantly, during repeated use on real contaminated surfaces, pressure-sensitive adhesives become rapidly covered by small particles (dust, pollen, etc.), and, because the particles cannot be easily removed, the adhesive fails after just a few contact cycles. In addition, much of the adhesive strength of pressure-sensitive adhesives comes from the formation of long polymer filaments. For biological systems (at least for insects), such long effective bonds would lead to disaster: an insect would need to lift its legs several millimeters to break the bond, which is impossible for small insects whose legs may be shorter than a millimeter. Thus, for biological locomotion, the effective adhesive bonds should be long (on an atomic scale) but not *too* long.

Biological adhesive systems used for locomotion are made from a keratin or chitin–protein composite that is elastically relatively stiff, with an elastic modulus in the GPa range, that is, 10^3 times stiffer than normal (cross-linked) rubber and perhaps 10^6 times stiffer than pressure-sensitive adhesives. Thus, the fundamental question is how this material is implemented by biological systems to design an adhesive that satisfies the two primary adhesion criteria.

Geckos, some insects, and frogs developed adhesive pads in the course of biological evolution. (For more detail, see the articles by Autumn and by Barnes in this issue of *MRS Bulletin*.) These adhesive pads consist of noncompact material in the form of either foam-like or fiber-like structures;[9] the effective elastic stiffness of these materials is much smaller than that of the compact material, and the first criterion above can be satisfied, particularly if the material exhibits a hierarchical (fractal-like) construction with thinner fibers or walls close to the outer attachment surface. However, the fibers and walls cannot be made arbitrarily thin, as this would result in a weak material and strong wear or collapse of the material as a result of the attraction between the internal surfaces of the solid. If by genetic mutation an animal would appear where the attachment system would fail because of this effect, the animal would be quickly eliminated by natural selection: thus, one may expect biological adhesive systems to be highly optimized and close to the limit of what is possible in terms of strength and stability.

The effective long dissipative bonds, which are required for strong adhesives, arise in different ways for hairy and smooth adhesion pads. For hairy systems, long, thin, flexible fibers adhere to the (rough) substrate. During pulloff, the fibers straighten out before the bond between the fiber and the substrate breaks. At the point of "snap-off," the elastic energy stored in the straightened fiber is lost. This results in effective bonds that are long, compared to the atomic dimension, and dissipative (the stored elastic energy is mainly dissipated in the solids rather than used to break other fiber adhesive bonds).[10] For smooth adhesive pads, the insect or frog injects a wetting liquid in the contact region between the pad and the substrate. During pulloff from a rough substrate, small liquid capillary bridges form at many toe pad–asperity contact regions, and the bridges elongate a long distance on the atomic scale before they break, because of capillary instabilities. The surface energy stored in the stretched capillary bridges is dissipated in the fluid because of the fluid viscosity, so again, we have effective long dissipative bonds acting between the surfaces.

Adhesion Using Noncompact Solids

Adhesive pads in biological systems are elastically soft on all relevant length scales, and are built from noncompact solids according to two different design strategies: fiber array structures (Figure 1) or foam-like structures.[11] These noncompact solids can be easily deformed to make contact with a substrate with roughness on length scales λ much longer than the thickness of the fibers and walls, respectively.[10,12–14] However, real surfaces have roughness on many different length scales, usually down to the atomic length scale. Because the fibers and walls are made from an elastically stiff material, the adhesional interaction is not able to deform the solids to make contact with the substrate at length scales shorter than the thickness of the fibers or walls. For this reason, biological adhesion pads are built in a hierarchical way: for fiber arrays, the thick fibers branch out into many thinner fibers that end in thin, plate-like structures (see Figure 1 and the article by Autumn in this issue); for foam-like structures, the wall thickness becomes smaller closer to the (outer) surface of the pad (see the article by Barnes in this issue).[10]

The toe pad separates from the surface during pulloff via interfacial crack propagation. If the fibers are curved or bent, then during pulloff, the fibers straighten out before the fiber–substrate bond is broken. This leads to a large energy per unit area, γ_{eff}, to propagate the interfacial crack. Because the pulloff force is (roughly) proportional to γ_{eff}, a strong increase in the pulloff force from the "long" fiber-mediated bonds between the solids is expected.

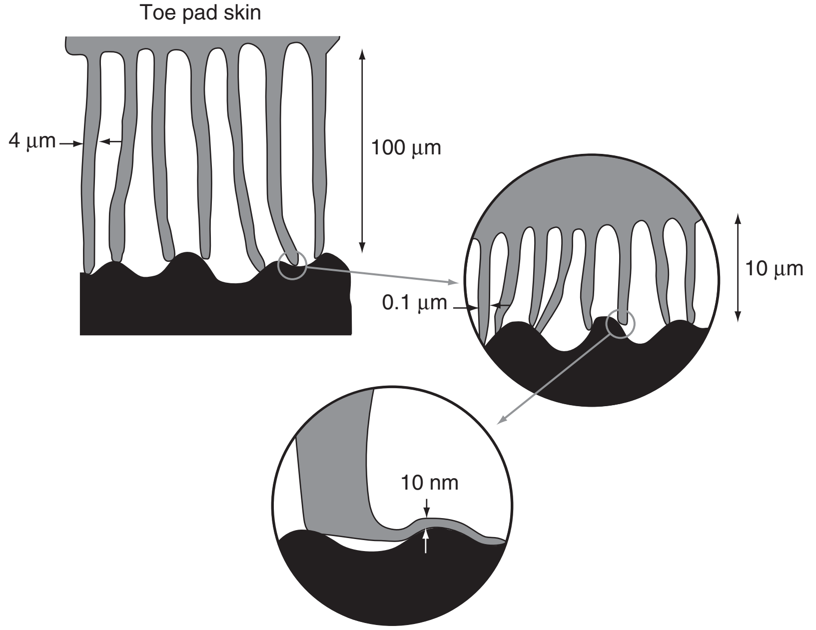

Figure 1. The toe pads of the gecko are covered by a dense layer of thin fibers or hairs. Each of these fibers branches out into several hundred thinner and shorter fibers. Each of these fibers ends with a leaf-like plate. The hierarchical nature of the gecko adhesive system is compliant on all relevant length scales and deforms elastically to optimize contact area and binding to a rough substrate.

Fiber Condensation and Plate Self-Binding

One may ask: why not make the fibers or walls very thin at the first stage in the hierarchical structure, in which case the solid would be elastically soft on all relevant length scales? The reason why this is impossible relates to strength and stability. Consider, for example, the fiber array system. In order to deform or bend to make contact with a rough substrate (see Figure 1), the fibers must be much longer than the amplitude of the substrate surface roughness on the length scale of the pad size (or rather, on a length scale where the toe pad skin can be considered as flat and rigid[10]). However, the thickness of the fiber may need to be just a few nanometers to make contact at the shortest length scale. Such a system of long thin fibers is unstable (see Figure 2) and would collapse into a dense mat of closely bound fibers (fiber condensation or bundling).[10,15] Also, the tensile strength of the fiber system would be very weak, and strong wear would occur. If the terminal plates are too thin or too long, they may self-bind, as shown in Figure 2, or bind to each other. Self-binding and plate–plate binding are reduced if the plates are slightly corrugated. This may be the reason why the terminal plates in most cases are slightly curved (cup-like). In addition, fiber bundling is reduced if the fibers have protrusions on them.[16,17] Figure 3 shows a beetle terminal plate adhering to a relatively smooth substrate. Note the sharp structures on the upper side of the plate that inhibit plate–plate binding.

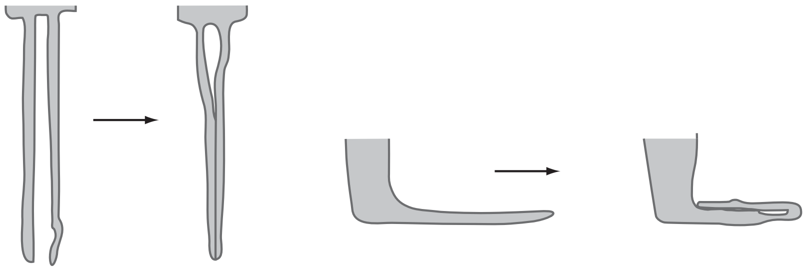

Figure 2. If the fibers of an adhesive structure are too thin or long, bundling may occur (left). Similarly, if the plates are too thin or long, self-binding may occur (right).

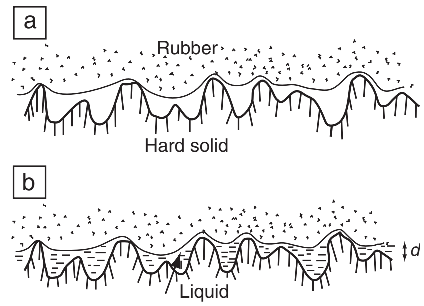

Figure 4. (a) For very rough surfaces, the area of real contact is very small and the adhesion is negligible. (b) In this case, a thin fluid film of a wetting liquid may enhance the effective adhesion by bridging the gap between the surfaces. A wetting liquid film with thickness d gives rise to a negative pressure $p \approx -2\gamma/d$ in the region between the two solids.

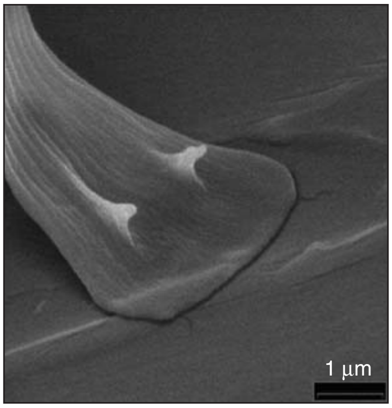

Figure 3. Beetle terminal plate adhering to a smooth substrate with a scratch on it. Note the sharp structures on the upper side of the plate, which inhibit plates binding to each other. (From Reference 12.)

Fiber Size and the Role of Capillary Bridges

Geckos are the heaviest living objects able to adhere to a smooth vertical surface without artificial aids. Because the surface area of a body increases more slowly than the volume (or mass) with an increase in the linear size of the body, the adhesive system in large living bodies such as geckos must be more effective (per unit attachment area) than in smaller living objects such as flies or beetles. This implies that geckos have the most effective adhesive system in biological evolution for the purpose of locomotion. This is supported by electron microscopy studies that show the fibers and plates are much thinner in geckos than in flies and bugs.[9,12,18] This results in a more compliant surface layer, a larger (relative) area of real contact, and less stored elastic energy per unit area for geckos as compared with insects. In addition, whereas the fibers in insects are mostly unbranched, in geckos they are always branched. Thus, the fibers in insects are so thick that no or negligible fiber bundling occurs, whereas for geckos, the terminal fibers are so thin that bundling would occur if the fibers were unbranched.

Geckos use dry adhesion; no liquid is injected in the contact area between the thin plates (which are just a few nanometers thick at the thinnest place[12]) and the rough substrate.[18] Flies and beetles, on the other hand, have terminal plates so large and thick that under dry conditions negligible adhesion probably would occur to rough substrates. For this reason, they inject a (wetting) liquid in the contact region between the plates and the substrate. A wetting liquid is able to fill out the space between the plates and the substrate and form capillary bridges. If d is the thickness of a capillary bridge, a negative pressure of the order of $-2\gamma/d$ (where γ is the liquid surface tension) will prevail in the liquid bridge, and for micrometer-thick (or less) liquid films, this pressure is typically around –1 MPa or more and will give rise to strong adhesion, even if the area of real contact between the solid plates and the substrate is very small, as depicted in Figure 4 for the case of adhesion of rubber to a solid.

We mentioned earlier that the terminal plates are curved, and that the physical origin of this may be to avoid self-binding. Another reason may be that for rough surfaces, and for wet conditions, a much stronger capillary bridge can form if the terminal plate is curved downward toward the substrate at its edges. In this case, the thickness d of the liquid film at the boundary of the contact region may be much smaller than for a flat plate or a plate with opposite curvature (see Figure 5). Because the negative pressure in the liquid capillary bridge is proportional to $\sim 1/d$, this gives rise to a much larger adhesion than for a flat plate or a plate with opposite curvature. Visual inspection of electron micrographs reveals that the terminal plates are curved in such a way as to maximize the strength of capillary bridges.[19] It seems clear that the shape of the terminal plates is naturally optimized to maximize adhesion[20] while simultaneously providing fast contact breakage.

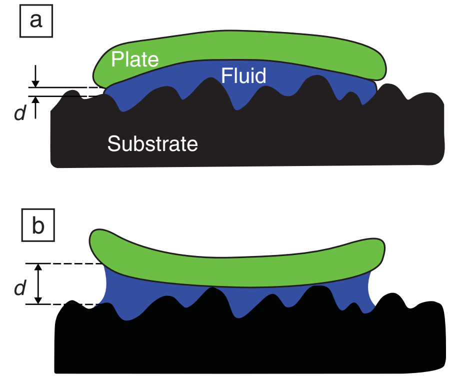

Figure 5. If the terminal plate is curved toward the substrate at its periphery, as in (a), a much stronger capillary bridge can be formed as compared to a plate that is flat or bent upward (b). The distance between the plate and the substrate is given by d.

Adhesion on Humid and Wet Surfaces

How is it possible for geckos to move on a vertical stone wall during a heavy rain? The van der Waals interaction between two surfaces is effectively very short-ranged and is already negligibly small at a separation of a few nanometers. Thus, the first step in building up adhesive contact is to squeeze out most of the water between the gecko's toe pad and the stone wall. This is a very complex problem in elastohydrodynamics,[21] but it is clear that the open structure of the toe-pad fiber array system will facilitate this by enabling water to flow laterally in the space between the fibers. This flow channel becomes very important for very thin water films, because for flat surfaces the time t it takes to squeeze the liquid film down to the thickness d diverges as $t \sim d^{-2}$. Complete squeeze-out of the liquid between the thin plates and the solid wall is unlikely to occur, as most stone walls consist of polar oxides that are hydrophilic, making a dewetting transition unlikely to occur.[22–24] However, if the liquid layer thickness is ~1 nm or less, and if the van der Waals interaction between the solid walls is attractive[25] (which is likely to be the case for a fiber array system involving a keratin–water–stone interface), then the interaction may be strong enough to enable the gecko to move on a stone wall under very wet conditions.

It was demonstrated recently that the pulloff force for a single fiber plate from a flat glass surface submerged in water is about six times smaller than under dry conditions.[26] That is, the high permittivity of water reduces the van der Waals interaction between the solids,[25] and furthermore, a few monolayers of water may separate the solids in the contact region, giving rise to the small observed adhesive interaction. It is clear that the adhesion force of a whole gecko foot is reduced substantially, and this seems to be in agreement with observations of geckos when running on wet surfaces.

Typical pressure-sensitive adhesives will not adhere on wet substrates. Because the surface of an adhesive tape is compact and locally flat, it will take a very long time to reduce the water film thickness to the nanometer range where the van der Waals interaction *may* give rise to binding between the walls.

Self-Cleaning Biological Adhesive Systems

Geckos can move on contaminated surfaces, for example, a dirty vertical stone wall. Because the gecko toe pad is able to bind strongly to solid surfaces, one would expect that small solid particles—stone fragments, dust, pollen—would bind to the pad surface and quickly "passivate" it. However, this does not seem to occur, and the geckos never clean their toe pads by grooming, in contrast to flies, beetles, and other insects. In fact, a gecko's toe pad retains its stickiness for up to six months[27] (the time period between molts) seemingly without being actively cleaned. It was recently suggested[28] that small solid particles may bind more strongly to the substrate surface (e.g., a stone wall) than to the toe pad so that after pressing a contaminated toe pad against a clean surface, the particles are removed from the toe pad. This does not seem a plausible explanation, because a similar argument would lead to the conclusion that adhesive tape contaminated by similar particles should bind strongly to solid surfaces via the particles, which is not the case. In fact, if Scotch® tape is pressed just a couple of times against a dirty surface, it will permanently lose its adhesive properties. Thus, one may ask how a gecko is able to keep its toe pads clean enough to be able to move on dirty solid walls.

I believe that the remarkable self-cleaning properties of gecko adhesive pads are explained by minute lateral movements of the toe pads relative to the substrate that scratch away the particles. To bind strongly to a substrate, the gecko must shear the toe pad in a special direction to line up (or bend) the binding plates into a position that gives strong bonding to the substrate. I suggest that motion in the opposite direction, while the toe pad is squeezed against the (rough) substrate, will scratch away solid particles trapped on the toe pad surface (see Figure 6).

Deterioration of Adhesive System and Fiber Wear

Geckos have a highly optimized adhesive system for locomotion. Because adhesion tends to increase when the fibers and plates are thinner, it is likely that the thickness of gecko fibers and plates are close to the limit of what is mechanically possible in terms of stability and strength,[29] which is consistent with experimental observations. Thus, broken fibers adhering to glass have been observed after shearing the toe pad along the surface.[30] Because the gecko usually does not need to adhere to very smooth surfaces, such as a glass surface, the plate–substrate binding will in most cases be much weaker than for the glass surface, and the toe pad wear (per unit distance moved) correspondingly much smaller. Nevertheless, in geckos in their natural environment, the toe–pad substrate adhesion is at a maximum after molt and rapidly decreases thereafter;[27,30] and this is most likely because of fiber wear.

Attachment and Detachment

Experiments have shown that a 25 g gecko may bind so strongly to a flat substrate that a force of the order of 10 N or more may be necessary to detach the gecko from the substrate. The binding to rough substrates may be much weaker but still strong enough for the gecko to move rapidly on the surface without falling. This brings up two questions: Why does the gecko keep its legs and arms pointing away from its body with small angle θ to the substrate? How is it possible for the gecko to rapidly break the toe–pad substrate bond during rapid motion on the substrate? Both problems are related to interfacial crack propagation (or peeling), and can be understood by a simple analogy with peeling adhesive tape.

Consider a thin elastic film bonded to a flat substrate, as indicated in Figures 7a and 7b. If we can neglect the elastic energy stored in the film, the normal component of the pulloff force is given by[2,12]

$$F_{\perp} = F\sin\theta = \Delta\gamma B\sin\theta/(1 - \cos\theta), \qquad (1)$$

where θ is the peel angle and B the width of the film. For a small peel angle, this gives

$$F_{\perp} \approx 2\Delta\gamma B/\theta, \qquad (2)$$

so that the perpendicular pull-off force $F_{\perp}$ diverges as the peel angle θ approaches 0.

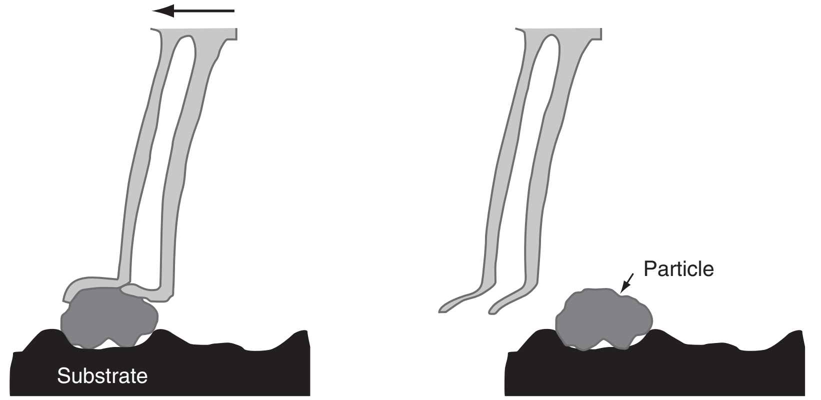

Figure 6. Removal of a dirt particle from foot fibers via lateral shear (scratch motion).

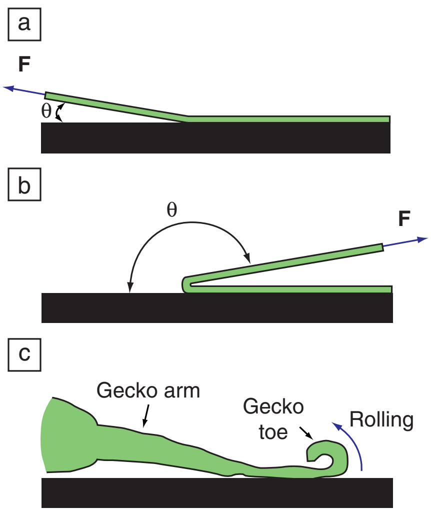

Figure 7. Peeling adhesive tape from a flat substrate. (a) If the peel angle θ is small, the pulloff force is very large, while the opposite is true when the peel angle is large (b). (c) The gecko removes the contact to the substrate by rolling its toes upward from the substrate.[31]

This is why a very large pulloff force is necessary to remove a rigid block taped to a flat substrate; this case corresponds to $\theta = 0$. The gecko adheres by applying muscle force that keeps the angle θ between its legs and the substrate very small. This will maximize the pulloff force, which may be important on very rough and contaminated surfaces.

The peeling angle θ should be large to quickly break the toe pad–substrate bond during fast motion on the substrate. In particular, note that $F_{\perp} \to 0$ as $\theta \to \pi$. Although this limiting case cannot be realized by the gecko, a large peel angle results from the novel way in which the gecko breaks the toe pad–substrate contact by rolling or peeling the toe, from the tip,[31] off the substrate (see Figure 7c). It is also possible that at any given time, the gecko only attaches the fraction of toe pad fibers necessary to obtain sufficient adhesion to the substrate.

Summary and Conclusion

All natural surfaces have roughness on many different length scales. Natural selection has optimized the adhesive pads of many animals for attachment and detachment to natural surfaces. The construction of these adhesive pads is mainly the result of two principles:

1. Maximum adhesion requires using noncompact solids built from thin fibers and plates (or walls).
2. The fibers and plates (or walls) cannot be too thin, as this would result in collapse or bundling of the structures.

It is clear that a detailed description of the function of biological adhesive systems used for locomotion needs to include not only the finer points of the mechanics of contact (attachment and detachment) on smooth and rough surfaces, but also interfacial interactions and the active biological functions performed by the animal. Although very complex and irreproducible synthetically, such an integrated system may inspire new ideas leading to improved reversible synthetic adhesive systems based on similar principles. Such systems will have great advantages over adhesives used today, and may make possible new applications; for an example, see the article by Daltorio et al. in this issue that discusses wall-climbing robots.

Acknowledgments

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References

1. B.N.J. Persson et al., *J. Phys.: Condens. Matter* **17**, R1 (2005).
2. K. Kendall, *Molecular Adhesion and Its Applications* (Kluwer, New York, 2001).
3. K.N.G. Fuller, D. Tabor, *Proc. R. Soc. London, Ser. A* **345**, 327 (1975).
4. B.N.J. Persson, *Eur. Phys. J.* **E8**, 385 (2002).
5. B.N.J. Persson, *Surf. Sci. Rep.* **61**, 201 (2006).
6. V.N. Samoilov, I.M. Sivebaek, B.N.J. Persson, *J. Chem. Phys.* **121**, 9639 (2004).
7. K.R. Shull, C. Creton, *J. Polym. Sci.* **B42**, 4023 (2004).
8. B.N.J. Persson, O. Albohr, C. Creton, V. Peveri, *J. Chem. Phys.* **120**, 8779 (2004).
9. S. Gorb, *Attachment Devices of Insect Cuticle* (Kluwer, Dordrecht, 2001); M. Scherge, S. Gorb, *Biological Micro- and Nanotribology: Nature's Solutions* (Springer, Berlin, 2001).
10. B.N.J. Persson, *J. Chem. Phys.* **118**, 7614 (2003).
11. Y. Jiao, S.N. Gorb, M. Scherge, *J. Exp. Biol.* **203**, 1887 (2000).
12. B.N.J. Persson, S. Gorb, *J. Chem. Phys.* **119**, 11437 (2004).
13. C. Carbone, B.N.J. Persson, *Phys. Rev. B* **70**, 125407 (2004).
14. N.J. Glassmaker, A. Jagota, C.-Y. Hui, J. Kim, *J. R. Soc. Interface* **1**, 23 (2004).
15. A. Jagota, S.J. Bennison, *Integr. Comp. Biol.*, **42**, 1140 (2002)
16. F. Haas, S. Gorb, *Arthropod Struct. Dev.* **33**, 45 (2004).
17. W. Federle, *J. Exp. Biol.* **209**, 2611 (2006).
18. K. Autumn et al., *Proc. Natl. Acad. Sci. USA* **99**, 12252 (2002).
19. E. Arzt, S. Gorb, R. Spolenak, *Proc. Natl. Acad. Sci. USA* **100**, 10603 (2003).
20. H. Gao, *Mech. Mater.* **37**, 275 (2005). In this reference, the optimal shape of an elastic solid for maximal pulloff force from a perfectly smooth substrate is discussed. However, geckos need to adhere to randomly rough surfaces and in this case there exists no unique optimal shape.
21. B.N.J. Persson, *Sliding Friction: Physical Principles and Applications* (Springer, Heidelberg, 2nd ed., 2000).
22. B.N.J. Persson, F. Mugele, *J. Phys.: Condens. Matter* **16**, R295 (2004).
23. F. Brochard-Wyart, P.G. de Gennes, *J. Phys.: Condens. Matter* **6**, A9 (1994); P. Martin, F. Brochard-Wyart, *Phys. Rev. Lett.* **80**, 3296 (1998); P. Martin, A. Buguin, F. Brochard-Wyart, *Langmuir* **17**, 6553 (2001).
24. B.N.J. Persson, A. Volokitin, E. Tosatti, *Eur. Phys. J.* **E11**, 409 (2003); C. Carbone, B.N.J. Persson, *J. Chem. Phys.* **121**, 2246 (2004).
25. J. Israelachvili, *Intermolecular and Surface Forces* (Academic Press, London, 1992).
26. G. Huber et al., *Proc. Natl. Acad. Sci. USA* **102**, 16293 (2005).
27. U. Hiller, R. Blaschke, *Naturwissenschaften* **54**, 344 (1997).
28. W.R. Hansen, K. Autumn, *Proc. Natl. Acad. Sci. USA* **102**, 385 (2005). The argument presented in this reference for self-cleaning may work for perfectly smooth substrates and particles, but real surfaces have roughness on many different length scales, and in this case the binding of a hard particle to a hard substrate will be negligible.
29. R. Spolenak, S. Gorb, E. Arzt, *Acta Biomater.* **1**, 5 (2005).
30. S. Gorb, private communication.
31. Y. Tian et al., *Proc. Natl. Acad. Sci.* USA **103**, 19320 (2006).