Sticky Feet: From Animals to Materials

Costantino Creton and Stanislav Gorb,
Guest Editors

Abstract

Many insects and some larger animals, such as geckos, skinks, and tree frogs, can easily climb vertical walls and even walk on the ceiling. These abilities require a method to attach the feet strongly but reversibly to a variety of surfaces—smooth or rough, hydrophilic or hydrophobic, clean or containing contaminants. This issue of *MRS Bulletin* examines how fibrils, absorbed water layers, geometry, and other factors make reversible adhesion possible, and how this understanding might be applied to robots and other artificially created structures that can climb walls, walk on ceilings, and get to other hard-to-reach places.

Overview: Reversible Adhesion in Locomotion

During the last decade, a diverse community of biologists, physicists, solid mechanics specialists, and, at the end of the chain, engineers designing robots have been busy studying the complex features of reversible adhesion in biological systems[1–7] and investigating which concepts could act as inspiration for the development of artificial reversible adhesive systems.[8–10] We felt that the field, although relatively new, was mature enough to be presented to a materials science audience for its creative concepts, some of which can be readily extrapolated to the field of materials adhesion.

The key concept behind this work is the understanding of locomotion in nature. Many insects[11,12] and some larger animals, including tree frogs and lizard species such as geckos and skinks, can easily climb vertical walls and even walk on the ceiling.[6,13–15] This ability requires a method for attaching the feet strongly but reversibly to a variety of surfaces—smooth or rough, hydrophilic or hydrophobic, clean or containing contaminants.

This feat is hardly possible with conventional adhesives. Pressure-sensitive adhesives (PSAs) can stick to most surfaces by simple contact and slight pressure,[16] but once they are detached, reattachment is usually difficult because of contamination issues. Furthermore, the detachment force cannot be tuned as a function of time. If the adhesive sticks, it will keep sticking: imagine yourself walking on the ceiling with double-sided tape on your feet. Force that you apply to the tape on one foot will generate substrate resistance, which will act with the same force on your other foot in contact and detach you from the ceiling. In other words, because of a global balance of forces, a compressive force on one foot generates tensile forces on the other foot or feet. For these reasons, pressure-sensitive adhesives are hardly applicable for wall- and ceiling-walking machines under ambient conditions.

Yet many animals, including flies, beetles, rather large spiders, and gekkonid lizards, have feet covered with tiny specialized hairs that allow them to run fast on the ceiling and support a force many times their weight. The foot of a chrysomelid beetle is shown as an example in Figure 1. Tree frogs, bees, and grasshoppers can do it without hairs by using the highly specialized material structure of their adhesive feet, which enables them to match perfectly the surface profile of the substrate.[17–21] The question is: Can we learn from these animals how to develop new materials able to reversibly stick to a variety of surfaces?

"Sticky Feet": Morphology and Mechanisms

Morphological research on the gecko has shown that adhesion is based on a hierarchical structure of fibrils that become smaller toward the contact regions with the surface.[1,6,22,23] The surface is contacted by thousands of 200-nm-long and 15-nm-thick stiff keratin structures called spatulae—thin fibers tipped with tapered plates—which form individual attachment points. Such a structure may rely solely on van der Waals forces to stick to the surface because of the multiple attachment points and extreme thinness of the contacting elements. An adsorbed water layer present on the majority of real surfaces under ambient conditions may enhance adhesion in this system by capillarity.[24]

Similar geometrical effects are known from numerous species of insects; however, because of the larger size of their spatulae, insects additionally use fluid

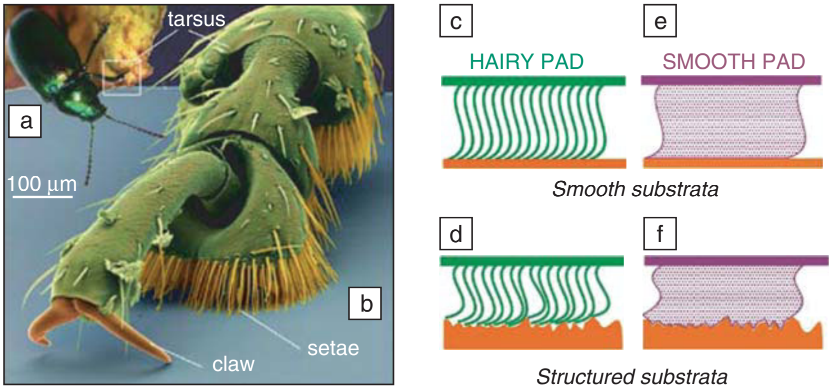

Figure 1. Biological systems with reversible adhesion. (a) Chrysomelid beetle *Gastrophysa viridula*. (b) Foot (tarsus) of the beetle attached to a smooth surface (from Reference 43). Diagram of the action of (c), (d) hairy and (e), (f) smooth pad attachment systems on smooth and structured substrata (from Reference 44). Both hairy and smooth systems are able to adapt to the smooth and rough surface profiles.

secretion to enhance capillary adhesion between their spatulae and the substrate.[25,26]

The details of the mechanisms for attachment and detachment of animal feet remain complex and difficult to reproduce artificially. However, several laboratories have designed biologically inspired artificial surfaces (Figure 2) to investigate the more tractable problems[8,27–32] of the effect on macroscopic adhesive forces and energies of replacing a single large contact with many more much-smaller contacts.

In This Issue

In this issue of *MRS Bulletin*, we first present the biological point of view through the work of two specialists in the area of reversible biological adhesion, Kellar Autumn and Jon Barnes. They present tutorials on the current understanding of the main mechanisms by which these attachment pads work in nature.

These two articles are followed by a more theoretical article from Bo Persson, who is a world specialist on friction and adhesion phenomena of rough surfaces. He contributes his view on the fundamental physical principles of locomotion based on contact adhesion. This overview provides a transition from the study of biological systems to the design of bio-inspired but necessarily simpler artificially patterned adhesive surfaces.

The next two articles, by Jagota et al. and Chan et al., discuss in more detail the mechanics of fibrillar adhesion. In particular, these authors outline how to optimize the ratio of diameter to length of the fibrils in relation to the modulus, and discuss in detail the difference in crack propagation and crack initiation between different surface patterns. A properly designed fibrillar interface will fail by multiple crack initiation rather than by the propagation of a single crack. This important point is at the heart of the design of bio-inspired fibrillar structures.

The article by Anand Jagota, Nicolas Glassmaker, Tian Tang, and Herbert Hui first addresses the question of why simple fibrillar interfaces can be of interest in making adhesive surfaces. The authors then present some of the challenges facing materials scientists in designing functional fibrillar interfaces and the specific solid-mechanics problems that need to be overcome to proceed from the general concept to a practically useful material.

Some of the questions posed in the Jagota article are addressed in the next article contributed by Edwin P. Chan, Alfred J. Crosby, Christian Greiner, and Eduard Arzt, who present the state of the art in the emerging field of optimization of fabricated fibrillar structures for reversible adhesion, both from the theoretical and experimental points of view.

For materials scientists, these studies emphasize the necessity to couple the inherent material properties of the adhering material with the geometry of the contact.[33–37] The efficiency of natural systems cannot of course be copied directly, but some of the concepts can be translated to the materials world to design surfaces with optimized micro- and nanostructures in terms of wavelength, depth, and stiffness. Some of these functional principles are shown in Figure 3.

Finally, this issue would not be complete without an article emphasizing applications of the biomimetic strategies. The most promising area for these applications is that of robotics, where the design of intelligent robots requires an efficient and reliable locomotion system, possibly inspired by nature. Insects—in particular, cockroaches, beetles, and flies—provide excellent models in terms of locomotion in rough and adverse terrain. Several solutions implemented by insects[38–41] can be adapted to artificial motion systems. Some examples are discussed in the final article, by Kathryn Daltorio, Andrew Horchler, Terence Wei, Roy Ritzmann, Roger Quinn, Stanislav Gorb, and Andrei Peressadko.

In conclusion, the take-away message for the materials specialist is that there is a close link between mechanics, chemistry, and physics when it comes to adhesion. Nature provides a rich source of solutions for many surface-related problems in materials science (for a review, see Reference 42), but mimicking them is only possible after attaining a detailed understanding of functional principles. The examples from biology emphasize the importance of mechanics, but the artificial solutions are not achievable without a combination of clever mechanical design and well-adapted materials solutions.

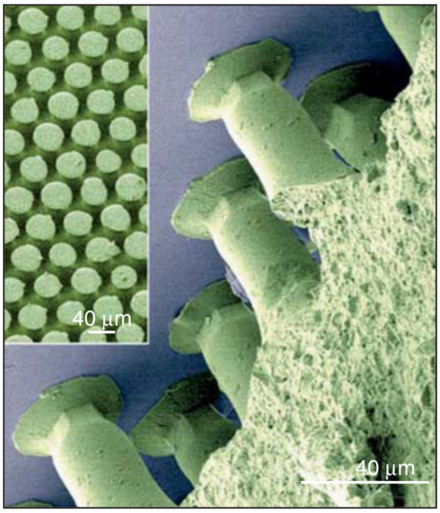

Figure 2. Patterned polymer surface with adhesive strength more than six times greater than flat specimens made of the same polymer (from Reference 33).

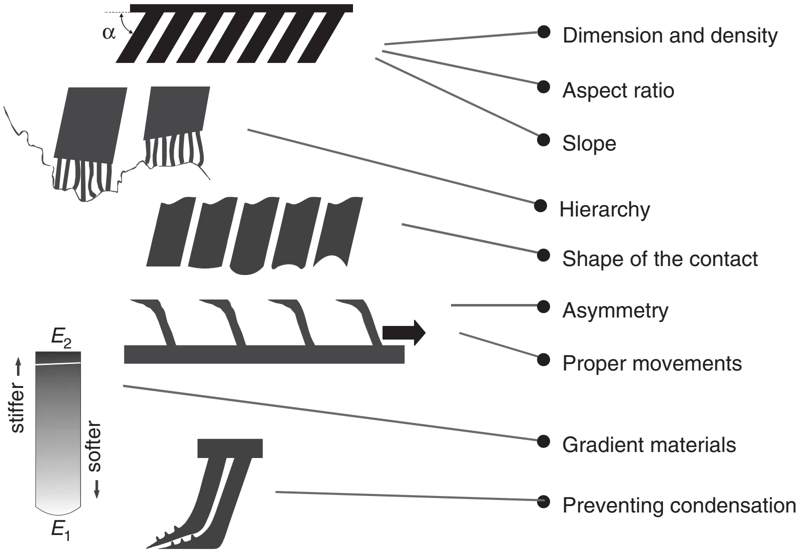

Figure 3. Some functional principles involved in reversible biological adhesive systems. Their simultaneous implementation in one artificial system is hardly possible. However, depending on the requirement for a particular material or system, one principle or a combination of a few of them can be implemented. E_1 and E_2 are Young's moduli, and α is a slope angle of fibrils.

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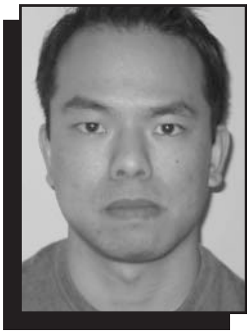

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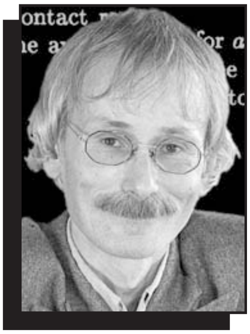

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In recent years, the Ritzmann laboratory has exploited parallel analysis strategies in examining how insects deal with barriers to forward locomotion. Beyond the basic neurobiological principles of movement that this work has revealed, the understanding gained is being used by collaborator Roger D. Quinn in the design and implementation of legged robots. In return, many of the robots designed by Quinn's Biorobotics Laboratory provide hardware models in which biological hypotheses can be tested and refined.

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Tian Tang is an assistant professor in the Mechanical Engineering Department at the University of Alberta, Canada. She received her BS degree in engineering mechanics from Tsinghua University, Beijing, in 2001, and her PhD degree in theoretical and applied mechanics from Cornell University in 2005. At Cornell, Tang studied mechanics of adhesion in micro- to nano-sized systems under the supervision of Chung-Yuen Hui. Afterward, Tang worked with professor Anand Jagota in the Chemical Engineering Department

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Her general research interests are at the interface of applied mechanics and materials science. Tang's recent studies include multiscale modeling and simulation of nanobiomolecular hybrid materials, adhesion in biological and biomimetic systems, and statistical theory of failure mechanisms in compliant solids.

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Terence E. Wei received his PhD degree in mechanical engineering in 2005 from Case Western Reserve University in Cleveland, Ohio. While performing research at Case's Biologically Inspired Robotics Laboratory, he developed many types of vehicles, including single-legged hopping robots and six-legged walking robots. He has designed dynamic simulations for the purposes of optimizing robotic design and robot–ground interaction. Wei also created several specialized apparatus for the purposes of obtaining insect locomotion and climbing behavior data, as well as novel feeding mechanisms for robotic manufacturing work cells.

After finishing his PhD degree, Wei received an Intelligence Community postdoctoral fellowship. As a postdoctoral fellow, he worked on the design and integration of insect-inspired attachment mechanisms for climbing robots. His other interests include mechanism design and vehicle dynamics.

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