IOP Publishing Bioinspiration & Biomimetics

Bioinsp. Biomim. **2** (2007) S117–S125 doi:10.1088/1748-3182/2/4/S01

Insects did it first: a micropatterned adhesive tape for robotic applications

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Received 20 August 2007
Accepted for publication 23 August 2007
Published 16 October 2007
Online at stacks.iop.org/BB/2/S117

Abstract
Based on the structural and experimental studies of more than 300 insect species from different lineages, we have developed and characterized a bioinspired polymer material with the ability of multiple glue-free bonding and debonding. The material surface is covered with a pattern of microstructures, which resembles the geometry of tenent hairs previously described from the feet of flies, beetles, earwigs and other insects. The tape with such a microstructure pattern demonstrates at least two times higher pull-off force per unit apparent contact area compared to the flat polymer. Additionally, the tape is less sensitive to contamination by dust particles than a commercially available pressure-sensitive adhesive tape. Even if the 'insect tape' is contaminated, it can be washed with a soap solution in water, in order to completely recover its adhesive properties. We have successfully applied the tape to the 120 g wall-climbing robot Mini-Whegs™. Furthermore, the tape can be used for multiple adhering of objects to glass surfaces or as a protective tape for sensitive glass surfaces of optical quality. Another area of potential applications is gripping and manipulation of objects with smooth surfaces.

(Some figures in this article are in colour only in the electronic version)

Walking on the ceiling

Among few other animal groups, insects possess a fascinating ability to walk on smooth vertical surfaces and even on ceilings. Such an ability is robust, fault tolerant and resistant to contamination. Insects can stick well to both hydrophobic and hydrophilic surfaces and detach in a very fast manner. In addition, there is a huge diversity of insect species specialized to particular species of plants. These observations suggest that attachment devices of insects can serve as a model for the development of artificial adhesive systems with similar functional properties.

The very first reports, which described structures responsible for the adherence and provided ideas about possible mechanisms of attachment, are known from the nineteenth century. Different hypotheses, ranging from microsuckers to the action of electrostatic forces, have been proposed. Tuffen West in 1862 mentioned that *the structure and action of the fly's foot have been so frequently treated of, and are so generally considered to be fully understood, that it may appear, at the first glance, as if nothing further could be done with so hackneyed a subject* (West 1862). This statement was of course rather premature, because the use of electron microscopy, micro- and nano-Newton range sensitive force transducers, recent developments in the adhesion theory all have contributed immensely to our understanding of insect adhesive mechanisms. Also, comparative accounts on hexapod attachment structures and a subsequent terminology (De Meijere 1901, Holway 1935, Dashman 1953) were important sources of comparative information for guiding further experiments on functional properties. From the biomimetics' point of view, the comparative approach in studies of biological adhesion also helped to extract information on essential features of biological

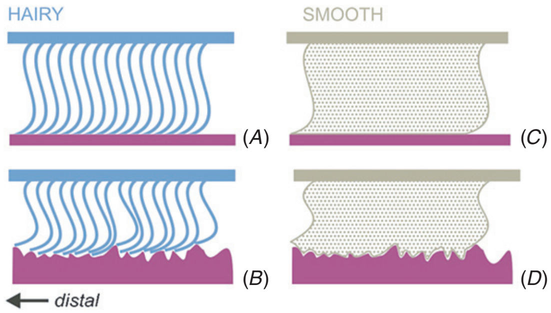

Figure 1. Diagram of the action of hairy (A, B) and smooth (C, D) pad attachment systems on smooth (A, C) and structured (B, D) substrata (Gorb 2001). Both systems are able to adapt to the surface profile.

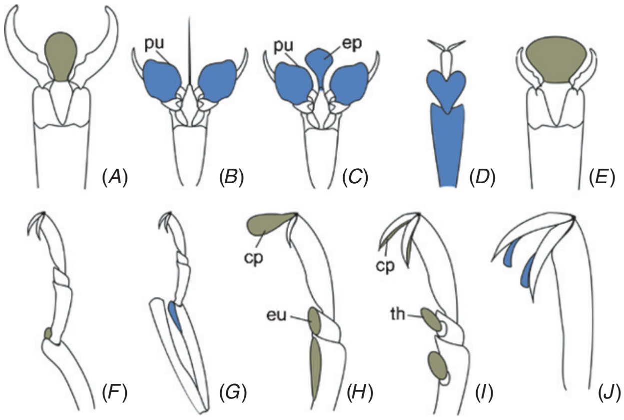

Figure 2. Diversity of the leg attachment devices (colored areas) in hexapods (Gorb and Beutel 2001). The blue color indicates hairy systems and the olive color indicates smooth systems. A: arolium, B: pulvilli, C: empodial pulvillus (ep), D: hairy adhesive soles of tarsomeres, E: eversible pretarsal bladder, F: eversible structure between the tibia and tarsus, G: fossula spongiosa, H: euplantulae (eu) and claw pad (cp), I: tarsal thorns transformed into adhesive structures (th), claw pad (cp) (both smooth) and J: adhesive claw setae.

systems that can be transferred into artificial systems. Of course, from one million of insect species recently known to science, only a few adhesive systems were carefully studied microscopically and only few selected model species have been examined experimentally.

To date, both the morphological and ultrastructural bases of the insect's ability to walk on vertical surfaces have been studied in detail only in representatives of selected taxa, including Orthoptera, Thysanoptera, Heteroptera, Auchenorrhyncha, Dermaptera, Strepsiptera, Hymenoptera, Diptera and Coleoptera (see Gorb (2001) for a review). The comparative data show that the evolution of attachment mechanisms in insects has developed along two distinctly different mechanisms: smooth pads and hairy (setose, fibrillar) surfaces (Beutel and Gorb 2001, 2006).

Two solutions: smooth and hairy pads

Due to the flexibility of the material of the attachment pads or fine surface structures, both mechanisms can maximize the possible contact area with the wide range of substrate profiles (figure 1). These highly specialized structures are not restricted to one particular area of the leg. They may be located on different parts, such as claws, derivatives of the pretarsus, tarsal apex, tarsomeres or tibia (figure 2). A recent phylogenetic analysis has shown that both types of attachment structures have evolved several times independently in the evolutionary history of insects (Beutel and Gorb 2001, 2006).

Smooth pads consist of a fibrous material with a specific inner structure. For example, in some orthopterans, tiny filaments are located just under the epicuticle of euplantulae. In grasshoppers *Tettigonia viridissima*, the exocuticle is 45–50 μm thick and consists of the primary filaments (Kendall 1970, Henning 1974), oriented at some angle to the surface (Gorb *et al* 2000). Such a material structure contributes to very specific material properties (soft in compression and strong in tension), which are responsible for the ability of the material to replicate a surface profile. Some functional principles of smooth pads (adaptability, viscoelasticity, pressure sensitivity) are similar to those known from industrial pressure sensitive adhesion. Hairy attachment pads employed few other features, such as flaw tolerance, lower sensitivity to contamination and

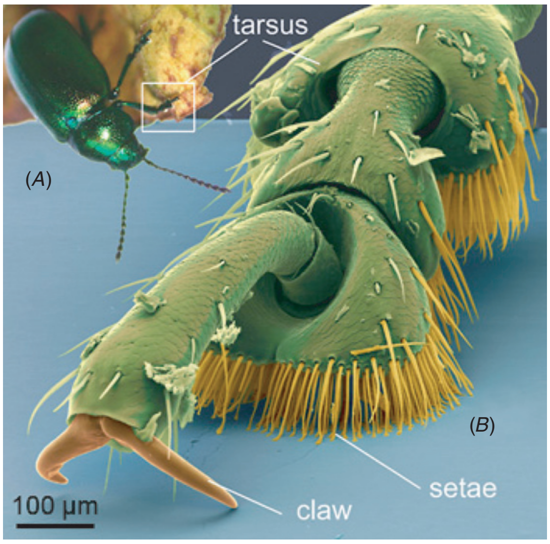

Figure 3. An example of the hairy attachment system. Tarsus (B) of the chrysomelid beetle *Gastrophysa viridula* (A) attached to the smooth surface (Gorb 2005) (colored scanning electron microscopy picture is the courtesy of Juergen Berger, MPI for Developmental Biology, Tuebingen, Germany).

roughness, which make them especially interesting from the biomimetic point of view.

Hairy attachment systems are typical for evolutionary younger and successful insect groups, such as Coleoptera (figure 3) and Diptera, and have a huge diversity of forms and ecological niches. This fact may indicate that such a design of adhesive surfaces must have an advantage for adhesion enhancement not only in biological systems, but also in artificial surfaces with similar geometry. There are several geometrical effects, such as multiple contact formation, high

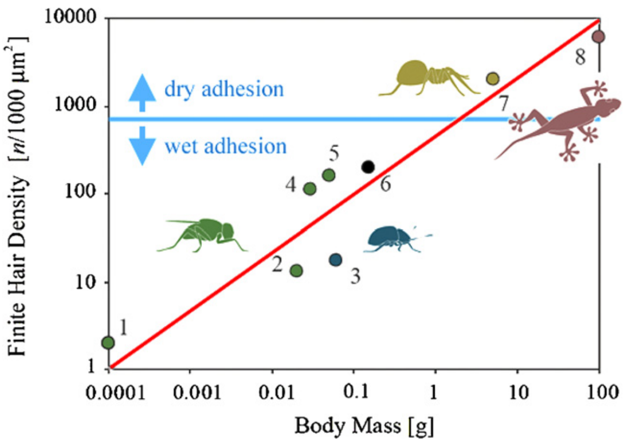

Figure 4. Dependence of the finite hair density of the attachment pads on the body mass in hairy pad systems of representatives from diverse animal groups. 1, 2, 4, 5: flies; 3: beetle; 6: bug; 7: spider; 8: gekkonid lizards. Adapted from Scherge and Gorb (2001). The systems located above the blue line rely on van der Waals forces (dry adhesion), whereas the systems below the line rely mostly on capillary and viscous forces (wet adhesion).

aspect ratio of single contact structures, peeling prevention using spatula-like tips of single contact elements that are responsible for the generation of a strong pull-off force in such attachment devices. These effects found in attachment devices of insects are an important source of information for further development of biomimetic patterned adhesives. The theoretical background pertaining to these physical effects has been intensively theoretically discussed in several recent publications (Arzt *et al* 2003, Persson 2003, Persson and Gorb 2003, Chung and Chaudhury 2005, Gao *et al* 2005).

We have previously shown that the density of hairs strongly increases with increasing body weight (Scherge and Gorb 2001) (figure 4). This relationship holds because animals cannot increase the area of the attachment devices proportional to the body weight due to the different scaling rules for mass and surface area (Gorb and Gorb 2004). Therefore, the increase of the attachment strength in hairy systems is realized by increasing the number of single contact points, i.e. by increasing the hair density. We have explained this general trend by applying the Johnson–Kendall–Roberts (JKR) contact theory (Johnson *et al* 1971), according to which splitting up the contact into finer sub-contacts should be the mechanism increasing adhesion (Arzt *et al* 2003). However, this trend is presumably different within each single lineage of organisms (Gorb *et al* 2001). The fundamental importance of contact splitting for adhesion on smooth and rough substrata has been explained by a very small effective elastic modulus of the array of hairs (Persson 2003). From the scaling analysis, we may suggest that animal lineages relying on the dry adhesion (lizards, spiders) possess much higher density of terminal contact elements compared to systems using the wet adhesive mechanism (insects). Since these effects are based on fundamental physical principles and mostly related to the geometry of the structure, they must also hold for artificial surfaces with similar geometry.

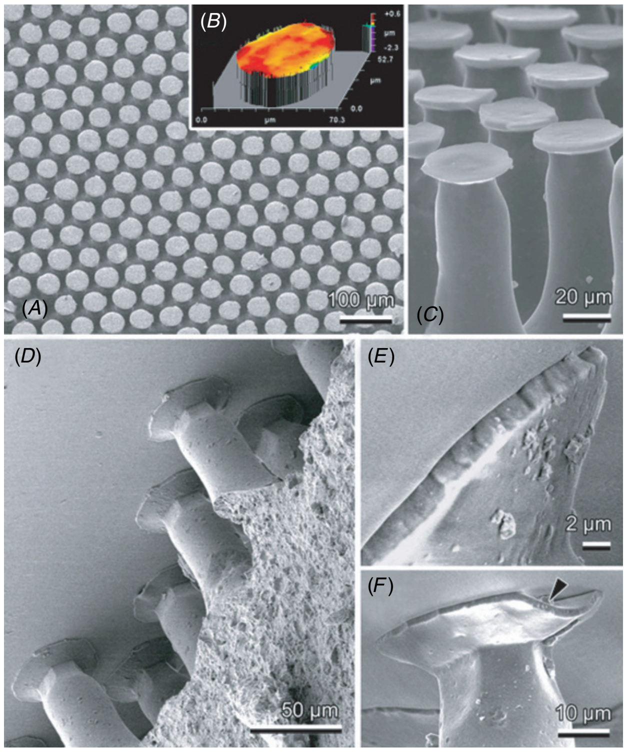

Figure 5. Patterned insect inspired polyvinylsiloxane surface. A: single structures are distributed on the surface according to the hexagonal pattern, in order to reach the highest packaging degree of single pillars (above aspect, SEM image). B: white-light interferometer image of single pillar head demonstrates an almost flat shape of the contacting surface. C: side aspect of the pillar array. D–F: behavior of structured PVS surfaces in contact with the glass surface (SEM images). The black arrowhead shows a dust particle in contact. Adapted from Gorb *et al* (2007).

Protuberances on the hairy pads of Coleoptera, Dermaptera and Diptera belong to different types. Representatives of the first two lineages have socketed setae on their pads. Setae range in length from a few micrometers to several millimeters. Dipteran outgrowths are acanthae: single sclerotized protuberances originating from a single cell (Richards and Richards 1979). Ultrastructural features of adhesive hairs have been previously reported for flies (Bauchhenss 1979, Gorb 1998): the acanthae are hollow inside, and some of them contain pores under the terminal plate. Such pores, presumably, deliver an adhesive secretion directly in the contact area. Pore canals at the base of the shaft may additionally transport secretions to the surface. The membranous cuticle of hairy pads is a fibrous composite material with loosely distributed fibers. In coleopterans, the hair bases are embedded in this material, which provides flexibility to the supporting material and helps the pad to adapt to a variety of surface profiles (Gorb 2001).

'Dry' versus 'wet' adhesion

Hairy attachment pads of reduviid bugs (Edwards and Tarkanian 1970), flies (Bauchhenss 1979, Walker *et al* 1985) and beetles (Ishii 1987, Kosaki and Yamaoka 1996, Eisner and Aneshansley 2000) secrete fluid into the contact area. Such a secretion contains non-volatile, lipid-like substances, but in some species it is two-phasic emulsion presumably containing water-soluble and lipid-soluble fractions (Gorb 2001). Hairy attachment systems of the gekkonid lizards and spiders do not produce fluids. In these animals, van der Waals interactions are mainly responsible for the generation of strong attractive forces (Autumn *et al* 2000); however, an adsorbed water layer on the surface of solids under ambient conditions can additionally contribute to adhesion in such a 'dry' adhesive system (Homann 1957, Huber *et al* 2005).

In the case of insects, different basic physical forces contribute to the overall adhesion. Attachment was impaired when hairy pads of the bug *Rhodnius prolixus* were treated with organic solvents (Edwards and Tarkanian 1970). Experiments with beetles have strongly suggested that cohesive forces, surface tension and molecular adhesion, mediated by pad secretion, may be involved in the mechanism of attachment (Stork 1980a). Recently, multiple local force–volume measurements were carried out on individual terminal plates of the setae of the fly *Calliphora vicina* by application of atomic force microscopy (Langer *et al* 2004). Local adhesion is about two times stronger in the center of the terminal plate than on its border. Adhesion strongly decreases as the volume of the secretion decreases, indicating that a layer of pad secretion, covering the terminal plates, is crucial for generation of the strong attractive force. These data provide the direct evidence that, beside van der Waals and Coulomb forces, attractive capillary forces mediated by the pad secretion are a critical factor in the fly's attachment mechanism. One may speculate that the combination of different physical mechanisms is important to generate sufficient adhesion despite variation in the physico-chemical properties of the surface (hydrophobic, hydrophilic), surface profile (rough, smooth) and environmental condition (dry, wet). However, we lack experimental data showing which specific conditions require certain adhesion mechanisms.

Biomimetic applications

There are few artificial surfaces previously described in the literature that were claimed to improve pull-off forces in contact with the flat surface. These materials have been produced using different micro- and nanofabrication methods ranging from laser technology, carbon nanotube packaging to various lithography techniques (Geim *et al* 2003, Peressadko and Gorb 2004a, Northen and Turner 2005, Yurdumakan *et al* 2005, Majidi *et al* 2005). Some of these materials do not demonstrate an improvement of adhesion measured in a flat-on-flat scheme. These materials were strongly limited in the patterned area or/and in the number of adhesion cycles, despite increases in the pull-off forces achieved by the surface patterning. The overall patterned area is usually restricted to few square centimeters, and the increased adhesion occurs only for a few cycles. Recently, we reported on the large-scale bioinspired silicone surface with the overall area in the range of 500 cm^2. The microstructures were inspired by those found in male beetles from the Chrysomelidae family (Stork 1980b, Pelletier and Smilowitz 1987, Gorb 2001). The pad surface, responsible for this effect, consists of a pattern of hairs (fibers, pillars) with broad flattened tips and a narrowed flexible region just below the flattened tip. These features, as well as a hexagonal distribution pattern of pillars, responsible for the high packing density (Ball 2001) were implemented in the design of the patterned polymer tape (Gorb *et al* 2007) (figure 5).

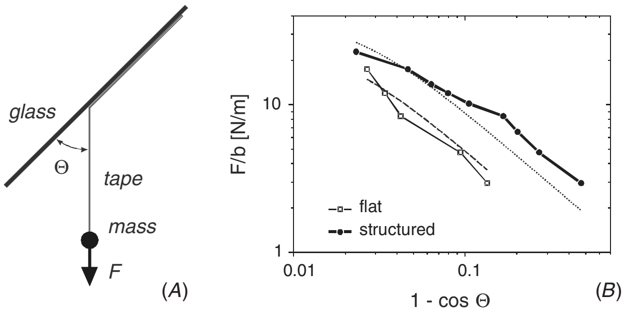

Figure 6. Results of the peeling test. A: diagram of the peeling experiment, B: normalized equilibrium force F/b versus peeling angle Θ obtained for the flat and structured surfaces. The dashed lines indicate fit corresponding to Kendall's model of peeling (Kendall 1975). From Daltorio *et al* (2005b).

We used a two-component dental wax (polyvinyl-siloxane—PVS, President light body, Coltene, Switzerland) to obtain negative casts from the template surface at room temperature (Gorb *et al* 2007). The fluid PVS was spread over the template surface located on the stiff polished surface (glass, metal, polymer) and covered with the flat stiff material. After 10 min of polymerization, the casts were removed from the template surface. Young's modulus of the polymerized material ranges from 2.5 to 3.0 MPa (Peressadko and Gorb 2004a).

The adhesive properties of the newly developed micropatterned tape were characterized using a variety of measurement techniques and compared with those of the flat tape made of the same polymer. Compared to a flat PVS tape, the microstructure patterned tape demonstrated considerably higher adhesion in a peeling test (Daltorio *et al* 2005b) (figure 6) and higher pull-off force per unit apparent contact area in measurements according to the flat-to-flat scheme (Varenberg *et al* 2006) (figure 7). An excellent performance of the patterned polymer tape with a similar pillar shape has also been demonstrated elsewhere (Kim and Sitti 2006). The structured tape is less sensitive to contamination by dust particles than the flat tape or a regular scotch tape (figure 8). After being contaminated, the structured tape can recover its initial adhesive properties completely when washed with an aqueous soap solution.

Why does surface patterning influences adhesion?

Multiple mechanisms are responsible for adhesion enhancement in surfaces patterned in a specific (bioinspired) way. The most fundamental explanation is that

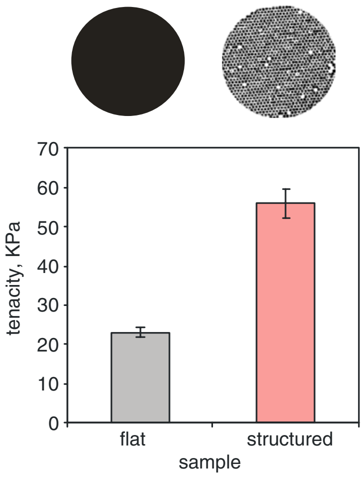

Figure 7. Results of the adhesion test of two different PVS samples according to the flat-on-flat scheme. Tenacity represents adhesion normalized to the real contact areas between the polymer sample and glass. The insets demonstrate an optical image of the real contact area of polymer samples tested. Based on data from Gorb *et al* (2007).

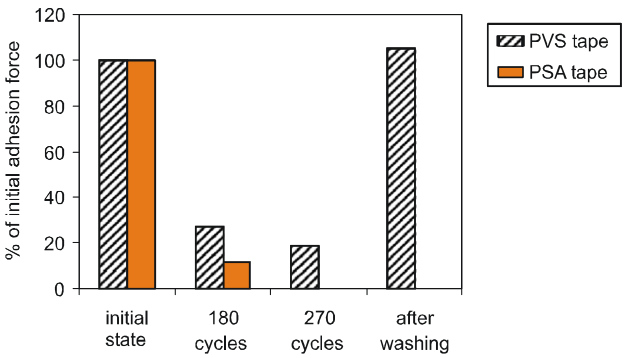

Figure 8. Change of the tape performance depending on the degree of contamination (five tapes of each type were tested). *PVS tape*, biologically inspired microstructured PVS tape. *PSA tape*, tape coated with pressure-sensitive adhesive (Scotch^{TM} tape). *Initial state* indicates the performance of fresh clean tape on the clean glass surface. *180 cycles* and *270 cycles* show tape performance after 180 and 270 adhesive cycles on an unclean glass window, respectively. *After washing* shows forces measured on both tapes after washing in a light soap solution of deionized water.

the pull-off force is proportional to the contact perimeter between two bodies (Varenberg *et al* 2006). Thus, an increase of density of terminal contact elements in biological systems, discussed above, increases adhesion. In fact, patterns of smaller structures with higher density produce a larger contact perimeter at the same, or even smaller, contact area compared to larger structures, and therefore adhere better (compare data on two patterns made of the same material (Peressadko and Gorb 2004a, Varenberg *et al* 2006, Gorb *et al* 2007). Interestingly, this effect holds for patterns with pillars, as well as for patterns with dimples (Varenberg *et al* 2006). Increased adhesion takes place only if the amount of elastic energy stored during contact formation is minimized. Higher loads are required to bring elements into contact with a surface, if the surface structures vary in height, and some of this energy will be elastically stored in the deformed structures. This energy will work against adhesion in contact, explaining why only patterned surfaces composed of structures of equal heights can build contact with minimal elastic energy stored and maximum adhesion force. The same principle explains why patterns with a stochastic distribution of contact element heights usually reduce adhesion (Peressadko and Gorb 2004b), as in the case of plant surfaces covered by crystalline waxes (Gorb and Gorb 2002, 2006).

Enhancement of contact formation and contact tolerance

The majority of other effects responsible for stronger adhesion of patterned surfaces are related to the enhancement of the contact formation. Lower surface rigidity of structured samples provides a higher adaptability to the substrate profile. The presence of several hierarchical levels of structures in biological systems may presumably increase this effect, especially on natural surfaces with fractal profiles, where different roughness wavelengths are superimposed. The adaptability of the fibrillar surface can be increased by making single fibers taller, thinner and softer, but all these three approaches lead to fiber condensation (lateral collaps, conglutination), which results in adhesion decrease (Jagota and Bennison 2002, Spolenak *et al* 2005b). Hierarchical design is the solution that optimizes contact formation with the minimal degree of fiber condensation. Whereas in insects there is only one hierarchical level of outgrowths on the attachment organ, a second level of outgrowths is present in spiders (Gorb 2001). Even more levels have been reported for geckos (Hiller 1968, Autumn *et al* 2000, Huber *et al* 2005a, 2005b, Rizzo *et al* 2006). A flat sample is able to build real contact only at the tips of substrate irregularities and, therefore, generates only rather low total contact area.

A very small effective elastic modulus of the fiber array is of fundamental importance for adhesion on smooth and rough substrates. During pull-off, the fibers may elongate many micrometers before the force in the fiber is high enough to break the bond to the substrate. Since the spring constant, associated with a long (curved) fiber, is very small, the displacement may be very large leading to a very large effective surface energy. Therefore, it was previously suggested that strong adhesion may result from 'long bonds' rather than from 'strong bonds' (Persson 2003).

Effects of crack propagation prevention

Another functional advantage of patterned adhesion systems is the prevention of crack propagation. In a multicontact system, the crack will be stopped at the level of a single contact element, and the new crack has to be formed at each subcontact during detachment. Formation of new cracks requires a higher amount of energy than during crack propagation in flat-to-flat contact. Therefore, contact breakage of a patterned tape affects higher energy dissipation (Kendall 2001). This behavior is analogous to the fracture mechanics of solids: cracks propagate easier in a uniform material compared with the composites

(Gao *et al* 2003). Crack propagation behavior on the patterned adhesive films leads to a significant enhancement of fracture energy (Chung and Chaudhury 2005). In addition to this effect, a crack can be stopped at the level of each single outgrowth in the material we described above, because of the lip-like rim at the tip of each pillar (Gorb *et al* 2007).

Role of mushroom-like tips and narrowing below the terminal plate

An additional functional principle is related to the spatula- or mushroom-shaped tips of the setae, which are responsible for the proper contact formation with the substrate due to the low bending stiffness of the plates without or with a minimum of a normal load (Persson and Gorb 2003). While sliding over the surface, thin plate-like spatulae of insects, spiders or geckoes may easily make contact with the surface by adapting to the surface profile and replicating surface irregularities of a certain length scale. Additionally, such thin plate-like structures provide higher adaptability to an uneven surface profile. In the biomimetic material described here, the thin lip-like rim of the pillar tip is able to replicate surface irregularities of a certain length scale and, in combination with a narrowed flexible area below the tip, may adapt to the local slope of the substrate (Peressadko and Gorb 2004b). Also, the combination of the rim and narrowing below the rim increases contact tolerance against external disturbances. This material demonstrates not only an excellent adhesion in the flat-to-flat adhesion test, but also rather high tolerance against crack propagation in the peeling test.

Functional hierarchy of the structured sample

As we have described, the patterned material presented here has several structural and functional hierarchical levels that together account for its adhesive properties. The first level is the thin backing responsible for tape adaptability to the surface unevenness. The thickness, and therefore bending stiffness, of the backing has to be set to the lowest possible degree (Geim *et al* 2003). The second level is represented by pillars, which provide adaptability to surface features at the level of dozens of micrometers. The third level is the flexible narrowing aiding in adjustment of the terminal plate to the local substrate slope. Finally, the thin rim or lip is capable of replication of roughness and dust particles at the level of single micrometers. A certain degree of redundancy of a number of hierarchical levels makes the tape more robust on the non-ideal profile of the real surface.

Resistance to contamination

The first experimental evidence on contamination reduction in biological hairy adhesive systems recently has been done for the gecko system (Hansen and Autumn 2005). This effect was explained by better adhesion of contaminating particles to the substrate than to gecko setae, because of a larger contact between the particle and substrate than between the particle and gecko spatulae. Similar effects are probably applicable to the patterned polymer surface studied here. Another effect reducing the contamination of an adhesive patterned surface is sinking dust particles into the gaps between pillars (Gorb *et al* 2007). However, another important property of the patterned tape is a stronger adhesion even at a relatively strong degree of contamination. This effect relies on a higher adaptability of a flexible rim of each pillar, even if the contact formation of single pillars is hampered due to little dust particles. Adaptability of lip-like margins of terminal elements provides an additional tolerance to contamination by small dust particles. Pressure-sensitive adhesives fail much faster after a number of adhesive cycles, if compared to the patterned PVS tape (figure 8). Pressure-sensitive adhesives fail completely after washing, whereas the PVS tape recovers completely.

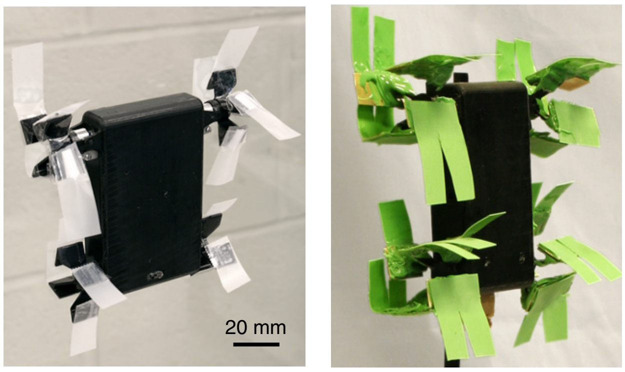

Figure 9. Mini-Whegs™ 7 on vertical glass with office tape feet (left) and with microstructured polymer feet and 25 cm long tail (tail not shown) (right). From Daltorio *et al* (2005b).

Robotic applications

Robots that could climb smooth and complex inclined terrains like insects and lizards would have many applications such as exploration, inspection or cleaning (Menon *et al* 2004, Sangbae *et al* 2005). The problems of fault tolerance, robust adhesion to different surfaces, resistance to contamination are all design constraints that similarly affect biological and engineered systems. Wall-walking robots are being developed using new adhesives inspired by insect attachment mechanisms mentioned above (Daltorio *et al* 2005a, 2005b) (figure 9).

Observations of insects have inspired the kinematics of the legs in the glass-wall-climbing robot. Flies make initial contact with the entire broad, flexible attachment organ (pulvillus) (Niederegger and Gorb 2003). A slight shear component is present in the movement, which provides a preload to the surface of the attachment device. Similar shearing motion has been previously described as a part of the attachment mechanism of a single gecko seta (Autumn *et al* 2000). Minimal force expenditure during detachment is also important. Disconnecting the entire attachment organ at once requires overcoming a strong adhesive force, which is energetically disadvantageous. This principle of contact formation with the entire pad surface and peeling-like detachment has been applied here to the design of a robot with climbing ability (figure 9(left)).

Mini-Whegs™ are a series of small robots that use a single motor to drive their multi-spoke wheel-leg appendages for locomotion (Morrey *et al* 2003). The spokes allow Mini-Whegs™ to climb over larger obstacles than a vehicle with

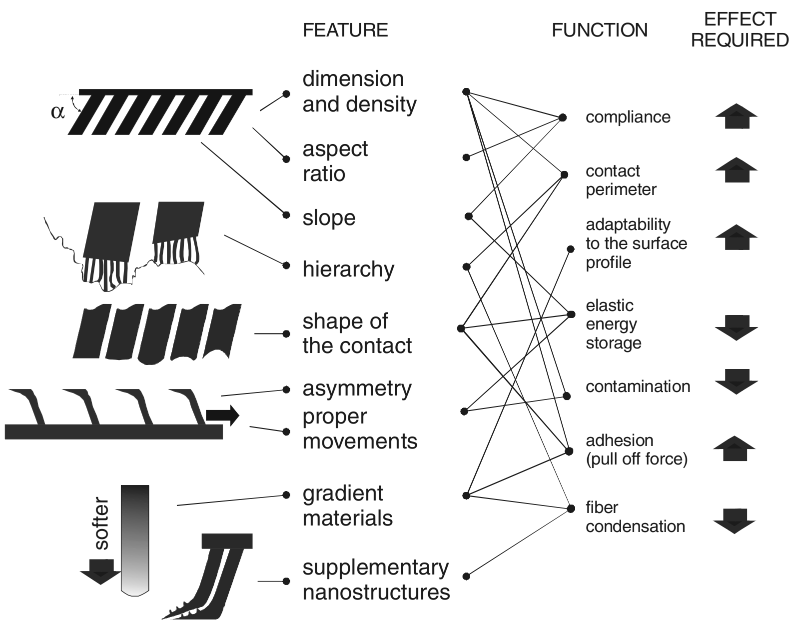

Figure 10. Some principles FEATURES, at which reversible biological adhesive systems operate, and their relationship to specific FUNCTIONS. The resulting effect required for producing strong adhesion is shown on the right-hand side (the up-arrow indicates an increase of the function by a specific design feature). A simultaneous implementation of all these features in one artificial system is desirable, but hardly possible. However, one principle or a combination of few of these biological insights can be implemented depending on the requirement for a particular biologically inspired material or system.

similarly sized wheels. We previously developed a Mini-Whegs™ that can be used to test new bio-inspired adhesive technologies for wall climbing (Daltorio *et al* 2005a). Mini-Whegs™ 7 (5.4 cm by 8.9 cm, 87 g) is power autonomous, radio controlled and has a total of four wheel legs, each with four spokes. The feet are bonded to contact areas on the ends of the spokes and the flexibility of the feet acts as a hinge between the feet and spokes. The feet contact the substrate, bend as the hub turns, peel off the substrate gradually and spring back to their initial position for the next contact. We previously reported that this robot can climb glass walls and ceilings using standard pressure-sensitive adhesives (Daltorio *et al* 2005a). Later, we demonstrated results for that robot walking on glass walls and ceilings using adhesive feet made from a biologically inspired material (Daltorio *et al* 2005b). The patterned surface was successfully applied to feet of the 120 g wall-climbing robot (figure 9). The ability to transition between orthogonal surfaces, steer and overcome small obstacles is feasible for a robot with such compliant adhesives.

Further robotic developments

A lighter robot would be more stable on the substrate, allowing more complex maneuvers. In addition, a lighter robot may not need a tail, which can get in the way of transitions. With a body flexion joint, the robot may even be able to make transitions around more difficult external angles (Ritzmann *et al* 2004). Mounting the axles farther away from the wall than the center of mass, would allow more space for longer spokes and feet without losing stability. The addition of an anisotropic frictional material on the tail of the robot, where the normal forces are compressive, may reduce the tendency to slip down the substrate. Whereas the current robot only walks on a clean smooth glass, a practical climbing robot would be able to traverse rougher and dirty surfaces as well. This will require the adhesives to be even more resistant to dust and oils. Additionally, alternative attachment mechanisms, such as insect-like claws or spines, could be added to take the advantage of surface roughness.

Other potential applications for a bioinspired tape

Additionally, a tape can be used for multiple adhering of objects to glass surfaces (novel fastening systems) or as a protective tape for sensitive glass surfaces of optical quality. Another area of potential application is the manipulation of materials with smooth surfaces such as lenses, CDs, DVDs. Thus, the tape represents a considerable step toward the development of industrial dry adhesives based on the combination of several principles inspired by biology.

Where to go?

For material scientists, results obtained on biological objects emphasize the necessity to couple the inherent material properties of the adhering material with the geometry of the contact (Spolenak *et al* 2005a, 2005b). The efficiency of the natural systems cannot, of course, be copied directly, but some of the concepts can be translated to the materials' world to design surfaces with particular properties and functions we observed in our long-term biological studies. Some functional principles, at which reversible biological adhesive systems operate, are given in figure 10. These principles relate to the dimension and density of surface structures, their aspect ratio and slope. The hierarchical design of surface features may enhance adaptability to real surfaces, which normally have fractal roughness. The shape of the contact may aid in tuning pull-off forces at the level of single contact elements. By changing the shape, one may adjust adhesive properties of the material to particular application. An asymmetrical shape of a single contact element in combination with the proper movements may provide the way to switchable adhesives. Additional structured coatings and the use of gradient materials together with a properly selected aspect ratio, density and elastic modulus may prevent the condensation of structures.

Acknowledgments

Travel grant by Georgia Institute of Technology (Atlanta, GA, USA) and personal efforts by Marc Weissburg in editing text, as well as comments of two anonymous reviewers, are greatly acknowledged. The project on the releasable bioinspired adhesives was initiated and supported by the Federal Ministry of Education, Science and Technology, Germany to SG (BMBF project BioFuture 0311851 'Design and biomechanics of biological frictional systems for biomimetics'). Recent studies on this topic are supported by the BMBF project InspiRat 01RI0633D. The work on the robotic applications was supported by NSF/IGERT grant DGE-9972747 and U.S. Air Force contract F08630-03-1-0003.

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