Wet adhesion and rubber friction in adhesive pads of insects

Walter Federle
Dept. of Zoology II,
Walter Federle
Dept. of Zoology II, University of Wuerzburg
Biozentrum, Am Hubland, 97074 Wuzburg, Germany
http://zoo2.biozentrum.uni-wuerzburg.de/biomechanics/
Tel. +49-931-8884321
Fax. +49-931-8884309

Abstract

Many animals possess on their legs adhesive pads, which have undergone evolutionary optimization to be able to attach to variable substrates and to control adhesive forces during locomotion. Insect adhesive pads are either relatively smooth or densely covered with specialized adhesive hairs. Theoretical models predict that adhesion can be increased by splitting the contact zone into many microscopic, elastic subunits, which provides a functional explanation for the widespread 'hairy' design.

In many hairy and all smooth attachment systems, the adhesive contact is mediated by a thin film of liquid secretion between the cuticle and the substrate. By using interference reflection microscopy (IRM), the thickness and viscosity of the secretion film was estimated in Weaver ants (*Oecophylla smaragdina*). 'Footprint' droplets deposited on glass are hydrophobic and form low contact angles. IRM of insect pads in contact showed that the adhesive liquid is an emulsion consisting of hydrophilic, volatile droplets dispersed in a persistent, hydrophobic phase. I tested predictions derived from film thickness and viscosity by measuring friction forces of Weaver ants on a smooth substrate. The measured friction forces were much greater than expected assuming a homogenous film between the pad and the surface. The findings indicate that the rubbery pad cuticle directly interacts with the substrate. To achieve intimate contact between the cuticle and the surface, secretion must drain away, which may be facilitated by microfolds on the surface of smooth insect pads. I propose a combined wet adhesion / rubber friction model of insect surface attachment that explains both the presence of a significant static friction component and the velocity-dependence of sliding friction.

Design of biological attachment systems - models for 'biomimetic' adhesives

As far back as in the 17th century, the pioneers of light microscopy were fascinated by the structure and function of insect adhesive pads (Hooke, 1665; Leeuwenhoek, 1690). From the following centuries to this day, numerous studies have been published on the adhesive pad morphology of a variety of animals such as insects, mites, spiders, bats, frogs and lizards (review in Scherge and Gorb, 2001). Despite the wide diversity of animals using adhesion and the variety of structures employed as adhesive organs, attachment pads on the legs of animals come in only two basic designs: 1) pads with a relatively smooth surface profile and 2) pads densely covered with specialized, microscopic setae. Smooth and hairy pads have evolved convergently in many different animal taxa, which suggests that both designs represent optimized solutions for possibly different aspects of surface attachment.

What are the advantages of both designs? Adhesive pads of animals must satisfy several performance requirements: The organs have to generate sufficient (1) adhesion and (2) friction forces to counteract gravity in climbing animals; (3) they must be flexible to adapt to surfaces of varying roughness; (4) the contact must be highly dynamic for rapid attachment and detachment during locomotion.

In this paper, I will first review information about the design and function of adhesive pads in insects. In the second part, I will present a study on the performance of a 'smooth pad' system, which includes an evaluation of the physical properties of the adhesive pad secretion and the test of a simple 'wet adhesion' model.

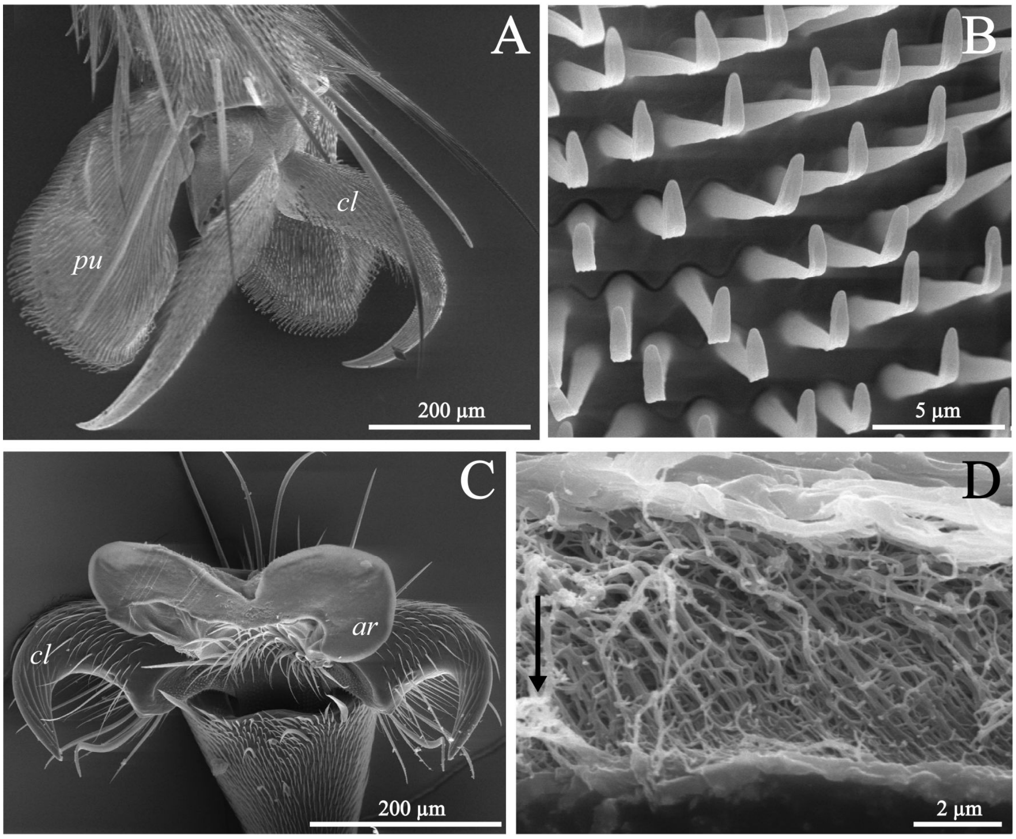

Fig.1. A-B. Hairy adhesive pad of a blowfly (*Calliphora vicina*) A. Pretarsus with claws (*cl*) and hairy pulvilli (*pu*). B. Adhesive setae on the pulvillus. C-D. Smooth adhesive pad of the ant *Oecophylla smaragdina.* C. Pretarsus with claws (*cl*) and smooth arolium (*ar*, shockfrozen prepation of foot in surface contact). D. lateral view of fibrous pad cuticle (freeze fracture, arrow points outward).

Hairy pad design

Adhesive pads of spiders, lizards and several insect orders (e.g. flies and beetles) feature a a highly regular, dense cover of micron-sized setae (Fig.1A,B). Individual setae of spiders and geckos can branch out into hundreds of minute setulae (spatulae), which make contact with the surface (Autumn et al., 2000; Scherge and Gorb, 2001; Gorb, 2001). A fibrillar adhesive system may not only help to achieve intimate contact to rough substrates, but it may also represent a design optimized for superior adhesion. It may seem counterintuitive that splitting the adhesive contact zone into many subcontacts can increase adhesion, since a hairy pad has a reduced total contact area. However, theoretical arguments indicate that a hairy design may in fact maximize adhesion:

1. Setal adhesion has been modelled using the Johnson-Kendall-Roberts theory ('JKR', Johnson et al., 1971), which predicts adhesive force to depend not on the contact area but on the radius of curvature of the adherend. A greater number of (smaller) setae per pad area should thus increase overall adhesion (Autumn et al., 2002). This argument has been used to explain the significant correlation of setal density with body size, because larger animals with relatively less surface area (such as geckos) need to have a more effective adhesive system per unit attachment area than smaller animals such as insects (Arzt et al., 2003). Setal density is limited by the sticking of setae to each other (Sitti and Fearing, 2003), which results in a loss of adhesive strength.
2. The setal geometry itself may enhance adhesion. Due to the elongation of the fibrils during detachment, the displacement necessary to break the contacts increases and thus the work of fracture (Jagota and Bennison, 2002; Persson, 2003). The energy stored in the fibrils is probably lost upon detachment (Jagota and Bennison, 2002).

Apart from superior adhesion, fibrillar adhesive systems may bring various other unique benefits, including self-cleaning ability, direction-dependent adhesion and controllable release mechanisms (Autumn et al., 2002; Arzt et al., 2003). All these properties would also be highly desirable in technical adhesives and consequently, the biomimetic fabrication of fibrillar adhesives has recently excited considerable interest (Geim et al., 2003; Sitti and Fearing, 2003).

Smooth pad design

Adhesive organs of many insect orders (e.g. ants, cockroaches, lice, stick insects), and adhesive toe pads of frogs and salamanders are not hairy, but relatively smooth (Fig.1C). The surface profile of these pads is usually not perfectly flat, but features regular microfolds. In some insects (bushcrickets, Beutel and Gorb, 2001) and in toe pads of tree frogs (Green, 1981), the contact zone is divided into regular, hexagonal subcontacts. The material of smooth pads has to be particularly soft in order to make sufficient contact to a rough substrate. For example, the elastic modulus of the smooth adhesive euplantulae in bushcrickets was measured to be 27 kPa (Gorb et al., 2000), whereas gecko seta keratin is several orders of magnitude stiffer (ca. 1-15 GPa, Sitti and Fearing, 2003). The smooth pad cuticle of insects has a characteristic inner structure of fine fibers projecting at an oblique angle toward the surface (Gorb et al., 2000; Fig.1D).

Function of insect adhesive secretion

In both the 'smooth' and the 'hairy' insect adhesive pads, the surface contact is mediated by a thin film of liquid secretion between the pad and the surface (e.g. Walker et al., 1985; Lees and Hardie, 1988; Jiao et al., 2000; Gorb, 2001; Vötsch et al., 2002). Experimental attempts to remove this fluid using solvent or silica gel treatment suggested that the pad secretion is essential for adhesion (Edwards and Tarkanian, 1970; Dixon et al., 1990), but the observed effects are hard to separate from reduced adhesion due to pad desiccation (Jiao et al., 2000). The presence of a liquid secretion has given rise to the hypothesis that properties of the liquid alone (i.e., surface tension and viscosity) account for the observed adhesive forces (e.g., Stork, 1980; Walker et al., 1985; Lees and Hardie, 1988). We tested this 'wet adhesion' hypothesis by comparing predictions derived from a simple 'wet adhesion' model (Fig.2A), with frictional and adhesive forces generated by Asian Weaver ants (Federle et al., 2002, 2004).

Wet adhesion model. A wetting liquid film sandwiched between two solids generates perpendicular, attractive forces due to surface tension and viscosity. However, a continuous liquid film between the pad cuticle and the surface (as assumed by the 'wet adhesion' hypothesis, Fig.2A), will lubricate the contact and lead to reduced friction. The contribution of surface tension to frictional forces is negligible (Federle et al., 2004). As a consequence, it is expected that static friction is small and that pads readily start sliding. When sliding occurs, it will shear the liquid film. The resulting friction force (assuming a simple parallel plate model with a Newtonian liquid) should increase with sliding velocity and viscosity, but should decrease with the fluid film's thickness.

Direct pad-substrate interaction. As an alternative to the wet adhesion model, the pad cuticle could also interact directly with the substrate (Fig.2B). Direct interaction may have various physical causes. It can be related to the direct contact of the highest surface asperities with the cuticle across the adhesive liquid film (Roberts, 1971) or to the formation of dry contacts by dewetting of a metastable, 'triboactive' liquid film (Martin et al., 2002). Even if no dry contacts are formed, the adhesive secretion could behave like a solid due to non-Newtonian fluid properties (if the liquid has a finite yield stress) or due to molecular ordering of the liquid at zones where the film becomes thinner than a few molecular layers (e.g. Granick, 1991). Both dry contacts and solid-like behavior would generate static friction forces larger than zero.

To investigate the mechanism of insect attachment, it is necessary to compare predictions derived from physical models with the actual performance of adhesive pads. However, such a comparison requires several parameters of the adhesive contact to be known (i.e., the thickness of the fluid film between pad and surface; the contact angle, surface tension and viscosity of the adhesive secretion). I used interference reflection microscopy (IRM) to obtain quantitative estimates of these parameters (Federle et al., 2002) in an insect with 'smooth' adhesive pads, the Asian Weaver ant (*Oecophylla smaragdina*). The predictions derived from these estimates were compared with frictional forces of insect pads (Federle et al., 2004).

Properties of insect adhesive secretion

Interference reflection microscopy (IRM) is a quantitative optical method, which has been applied by cell biologists to study cell-substrate contact (e.g. Curtis, 1964; Gingell and Todd, 1979). Through the analysis of interference images, the vertical distance between the adjacent, reflecting interfaces can be determined with nanometer resolution so that a 3D reconstruction of the surface microtopography becomes possible. IRM represents a powerful technique to investigate the adhesive contact of insects, because it yields quantitative information about 1) 'footprint' droplets and 2) *in vivo* properties of the adhesive pad surface contact (Fig.3A).

Contact angle and hydrophobicity of footprint droplets. IRM of footprint droplets showed that footprint droplets on glass were generally flat with contact angles ranging from 5° to 25° (Fig.3C). Contact angles were even lower on hydrophobic substrates (Federle et al., 2002). The hydrophobic nature of the droplets was also demonstrated by their insolubility in water. Footprint droplets were extremely persistent and showed virtually no volume loss over several hours at room temperature.

Two-phase adhesive secretion. By performing *in vivo* IRM of pads in surface contact, we found that the adhesive secretion is an emulsion consisting of two liquid phases ('Liquid A' and 'Liquid B', Federle et al., 2002). Liquid A occurs in droplets between the pad and the surface, surrounded by liquid B (Fig.3B). As liquid A droplets are highly volatile, the remaining hydrophobic footprint material almost exclusively consists of liquid B, which is highly persistent. Because of its insolubility in liquid B, liquid A is hydrophilic.

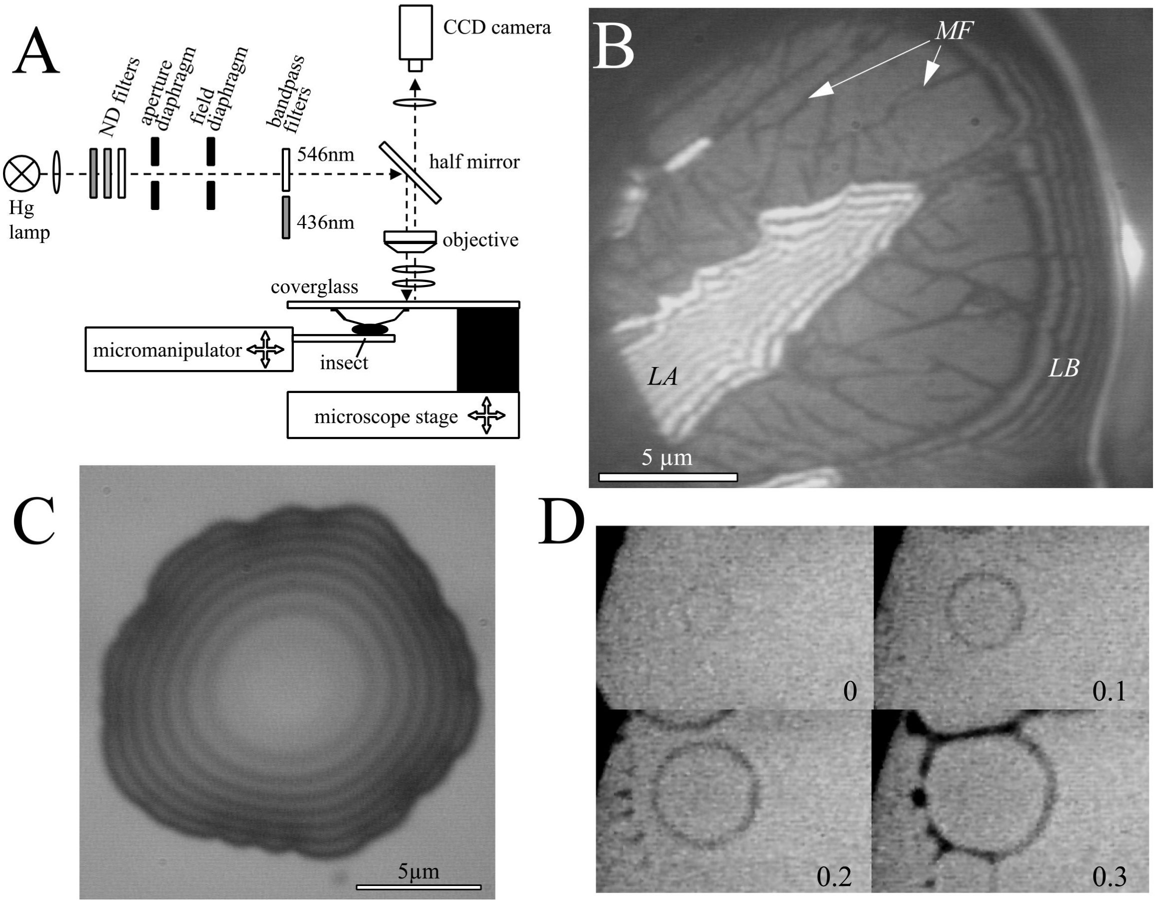

Fig.3. Interference reflection microscopy (λ = 546 nm) of ant adhesive pads. A: microscope setup C: footprint droplet B. Two-phase adhesive secretion (*LA, LB*: Liquids A and B) in the pad contact zone of an *O. smaragdina* ant in contact with glass (*MF*: microfolds). D: Dewetting of a thin film of adhesive secretion on glass. Numbers denote time in seconds.

Viscosity of the secretion. By observing the dynamic behavior of the adhesive secretion using IRM, an estimation of the fluid's viscosity can be obtained (Federle et al., 2002). When an adhesive pad slides across a glass surface, a homogenous film of secretion is deposited at the trailing edge of the pad. These films are unstable and disintegrate into small droplets. This 'dewetting' process starts with the formation of round dry patches that grow at a constant radial velocity (Fig.3D). Dewetting velocity has been shown to depend on the surface tension and viscosity of the fluid as well as on its contact angle with the surface (Redon et al., 1991). In *O. smaragdina*, we measured a mean dewetting velocity of 60 µm/s. Assuming a surface tension of 30 mN/m, a viscosity estimate of 40 to 150 mPas is obtained (Federle et al., 2002).

Thickness of adhesive liquid film. The thickness of the adhesive liquid film represents a critical parameter of the adhesive contact. Even though it may have a weaker effect on adhesion than hitherto supposed, it nevertheless strongly determines frictional forces. IRM makes it possible to directly quantify the liquid film thickness *in vivo* (Federle et al., 2002). As in the analysis of droplet images, the interference patterns visible at the edges of the pad contact zone was converted into height information. Due to the ambiguity of the interference fringe order, however, we imaged the pad contact zone at different wavelengths (436 and 546 nm) as well as varying numerical aperture and compared the interference pattern with theoretical predictions (Federle et al., 2002). Using this method, the thickness of the adhesive liquid film was estimated in ants (*O. smaragdina*) and stick insects (*Carausius morosus*) to range between 90 and 160 nanometers near the edge of the contact zone.

Friction forces of insect pads

We measured friction forces of *O. smaragdina* ants using a simple centrifuge technique (Federle et al., 2004). Ants were placed onto smooth Plexiglass turntables. Using a strobe light synchronized to the revolutions of the centrifuge, a standing image of the insect on the rotating surface could be observed and videotaped. When strong shear forces were acting, the ants did not detach, but gradually slid outward, their adhesive pads being in continuous contact with the turntable. From the recorded radial 'slides', a relationship between force and sliding velocity was determined. Maximum adhesive contact area was quantified after the experiments to obtain shear stress (friction force per unit contact area). At 15°C, we found a relationship between shear stress and sliding velocity of $F/A = 81.4 + v \times 181.1$ (kPa, where v is velocity in mm/s). Only the dynamic but not the static part of frictional forces was found to be temperature-depedent (Federle et al., 2004).

The smooth sliding of the ants' pads, the linear relationship between friction and sliding velocity and the observed temperature dependence all seem to be consistent with the predictions from the wet adhesion model. However, the considerable static friction (corresponding to more than 100 times the ant's body weight) contradicts the proposed simple liquid film model. Moreover, the measured, velocity-specific increase of friction was much larger than the shear force expected due to the viscosity of the liquid film: Assuming a simple, parallel plate model, a liquid film (of viscosity η and thickness h) generates a velocity-specific shear stress of: $F/A = v\eta/h$. We calculated shear stress based on the fluid properties measured by IRM (see above). Even the most conservative estimate (using a viscosity of 150 mPas and a film thickness of 90nm) was clearly inconsistent with the shear stress observed in ants (Fig.4).

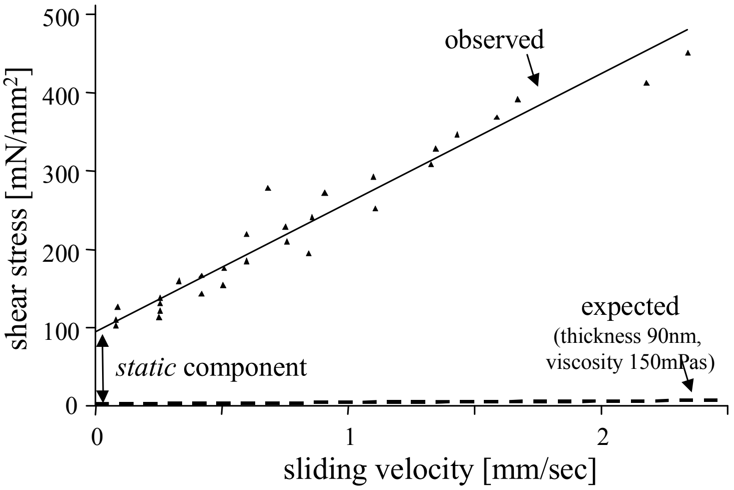

Fig.4. Comparison of the velocity-specific shear stress measured in *O. smaragdina* with predictions derived from estimates of the viscosity and thickness of the adhesive secretion.

Evidence for direct pad–surface interaction and rubber friction

Our fndings show that a simple wet adhesion model of a continous liquid film between the adhesive cuticle and the substrate is inconsistent with the performance of insect pads. Both the considerable static friction and the magnitude of the rate-specific increase of friction force indicate that the adhesive secretion alone cannot explain the large frictional forces observed (Federle et al., 2002, 2004). Thus, the large frictional forces and their static component can only be explained by a direct interaction of the soft arolium cuticle with the surface.

The finding that the direct pad-cuticle interaction is important for the generation of attachment forces does not imply that the adhesive secretion has no function. Due to the longer range of capillarity as opposed to 'dry' intermolecular forces, a liquid film on the pad surface will help to create and maximize the pad's contact area when the foot is put down, and particularly so on substrates that are not perfectly smooth as most surfaces found in nature.

Direct pad-surface interactions may not only influence the static but also the dynamic forces. When a rubbery, viscoelastic material slides on a rough surface, the substrate exerts oscillating forces on the rubber which lead to energy dissipation (internal friction) in the rubber (Persson, 1998). Rubber friction also depends on sliding velocity and temperature; it has a maximum at the velocity where the viscous losses in the rubber are maximal (Persson, 1998). Thus, all aspects of the ants' sliding behavior can be qualitatively explained by a rubber friction model.

'Drainage problem'. Independent of the detailed mechanism of pad–surface interaction, the liquid film has to be squeezed out locally to achieve very close contact between the cuticle and the substrate. The time needed to approach two parallel disks of radius R immersed in a liquid of viscosity η a given distance h_2-h_1 under a load F is predicted to be (Reynolds, 1886):

$$t_R = \frac{3\pi}{4} \cdot \frac{\eta R^4}{F_R} \cdot \left(\frac{1}{h_1^2} - \frac{1}{h_2^2} \right)$$

The approach time strongly increases with decreasing thickness of the fluid film. The 'drainage problem' will be facilitated if the pad surface is not perfectly flat, but contains channels in which the liquid can flow away (see Fig.3B). If these grooves divide a pad surface into n separate smaller contact zones (of radii $r < R/\sqrt{n}$), the drainage time will be n times smaller, because $F_r = F_R/n$ and $t_r \propto r^4/F_r \propto t_R/n$. Many 'smooth' insect adhesive pads feature conspicous patterns of microfolds (Beutel and Gorb, 2001). Moreover, a division of the contact zone into regular, hexagonal subcontacts has convergently evolved in insects (bushcrickets, Beutel and Gorb, 2001) and in toe pads of tree frogs (Green, 1981).

Analyzing the design features of animal adhesive organs is not only of biological relevance but may also provide valuable inspiration for future biomimetic adhesives and tribological applications. Due to the development of micro- and nanofabrication technology, it has now become possible to mimic natural microstructures that have proved useful during millions of years of evolution. This fascinating field of research will greatly benefit from a close collaboration between biologists and engineers.

Bibliography

Arzt, E., Gorb, S. and Spolenak, R., 2003. From micro to nano contacts in biological attachment devices. Proc. Nat. Acad. Sci. USA 100, 10603-10606.

Autumn, K., Liang, Y.A., Hsieh, S.T., Zesch, W., Chan, W.P., Kenny, T.W., Fearing, R. and Full, R.J., 2000. Adhesive force of a single gecko foot-hair. Nature 405, 681-685.

Autumn, K., Sitti, M., Liang, Y.A., Peattie, A.M., Hansen, W.R., Sponberg, S., Kenny, T.W., Fearing, R., Israelachvili, J.N. and Full, R.J., 2002. Evidence for van der Waals adhesion in gecko setae. Proc. Nat. Acad. Sci. USA 99, 12252–12256.

Beutel, R.G. and Gorb, S.N., 2001. Ultrastructure of attachment specializations of hexapods, (Arthropoda): evolutionary patterns inferred from a revised ordinal phylogeny. J. Zool. Syst. Evol. Res. 39, 177-207.

Curtis, A.S.G., 1964. The mechanism of adhesion of cells to glass. A study by interference reflection microscopy. J. Cell Biol. 20, 199-215.

Dixon, A.F.G., Croghan, P.C. and Gowing, R.P., 1990. The mechanism by which aphids adhere to smooth surfaces. J. Exp. Biol. 152, 243-253.

Edwards, J.S. and Tarkanian, M., 1970. The adhesive pads of Heteroptera: a re-examination. Proc. R. Ent. Soc. London (A) 45, 1-5.

Federle, W., Riehle, M., Curtis, A.S.G. and Full, R.J., 2002. An integrative study of insect adhesion: mechanics and wet adhesion of pretarsal pads in ants. Integ. and Comp. Biol. 42, 1100-1106.

Federle, W., Baumgartner, W. and Hölldobler, B., 2004. Biomechanics of ant adhesive pads: frictional forces are rate- and temperature-dependent. J. Exp. Biol. 207, 67-74.

Geim, A.K., Dubonos, S.V., Grigorieva, I.V., Novoselov, K.S., Zhukov, A.A. and Shapoval, S.Y., 2003. Microfabricated adhesive mimicking gecko foot-hair. Nature Materials 2, 461-463.

Gingell, D. and Todd, I., 1979. Interference reflection microscopy: a quantitative theory for image interpretation and its application to cell-substratum separation measurement. Biophys. J. 26, 507-526.

Gorb, S., Jiao, Y. and Scherge, M., 2000. Ultrastructural architecture and mechanical properties of attachment pads in *Tettigonia viridissima* (Orthoptera Tettigoniidae). J. Comp. Physiol. A 186, 821-831.

Gorb, S., 2001. Attachment devices of insect cuticle. Kluwer Academic Publishers, Dordrecht, Boston.

Granick, S., 1991. Motions and relaxatons of confined liquids. Science 253, 1374-1379.

Green, D.M., 1981. Adhesion and the toe pads of otree frogs. Copeia 1981, 790-796.

Hooke, R., 1665. Micrographia, London.

Jagota, A. and Bennison, S.J., 2002. Mechanics of adhesion through a fibrillar microstructure. Integ. and Comp. Biol. 42, 1140-1145.

Jiao, Y., Gorb, S. and Scherge, M., 2000. Adhesion measured on the attachment pads of *Tettigonia viridissima* (Orthoptera, Insecta). J. Exp. Biol. 203, 1887-1895.

Johnson, K.L., Kendall, K. and Roberts, A.D., 1971. Surface energy and the contact of elastic solids. Proc. R. Soc. Lond. A 324, 301-313.

Lees, A.D. and Hardie, J., 1988. The organs of adhesion in the aphid *Megoura viciae*. J. Exp. Biol. 136, 209-228.

Leeuwenhoek, A., 1690. Collected works II (3).

Martin, A., Clain, J., Buguin, A. and Brochard-Wyart, F., 2002. Wetting transitions at soft, sliding interfaces. Phys. Rev. E 65, 031605.

Persson, B.N.J., 1998. On the theory of rubber friction. Surface Science 401, 445-454.

Persson, B.N.J., 2003. On the mechanism of adhesion in biological systems. J. Adhes. Sci. Technol. 118, 7614-7620.

Redon, C., Brochard-Wyart, F. and Rondelez, F., 1991. Dynamics of dewetting. Phys. Rev. Lett. 66, 715-718.

Reynolds, O., 1886. On the theory of lubrication and its application to Mr Beauchamp Tower's experiments, including an experimental determination of the viscosity of olive oil. Phil. Trans. R. Soc. Lond. 177, 157-234.

Roberts, A.D., 1971. The shear of thin liquid films. J. Phys. D Appl. Phys., 433-440.

Scherge, M. and Gorb, S.N., 2001. Biological micro- and nanotribology : nature's solutions. Springer, Berlin, New York.

Sitti, M. and Fearing, R.S., 2003. Synthetic gecko foot-hair micro/nano-structures as dry adhesives. J. Adhes. Sci. Technol. 17, 1055-1073.

Stork, N.E., 1980. Experimental analysis of adhesion of *Chrysopolina polita* (Chrysomelidae: Coleoptera) on a variety of surfaces. J. Exp. Biol. 88, 91-107.

Vötsch, W., Nicholson, G., Müller, R., Stierhof, Y.-D., Gorb, S. and Schwarz, U., 2002. Chemical composition of the attachment pad secretion of the locust *Locusta migratoria*. Insect Biochem. Mol. Biol. 32, 1605–1613.

Walker, G., Yule, A.B. and Ratcliffe, J., 1985. The adhesive organ of the blowfly, *Calliphora vomitoria*: a functional approach (Diptera: Calliphoridae). J. Zool. Lond. (A) 205, 297-307.