Hairy spiders crawling up walls: Prof. Dr. Stanislav Gorb of the University of Kiel and members of his team at the Max Planck Institute for Metals Research in Stuttgart, Germany, are fascinated by something that would send a shiver down the spine of most people. After long years of research on the adhesion mechanisms in different animals, they have compiled a kind of catalog of geometrical principles that are responsible for especially good adhesion on various substrates. These principles serve as a roadmap for the development of novel adhesive foils and other surfaces with special adhesion and friction properties.

→ **JB**

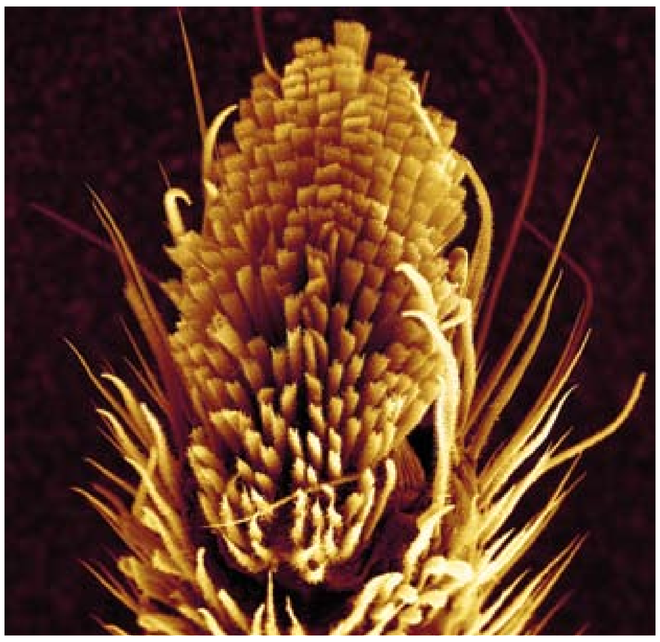
Hairs with Universal Adhesion

Prof. Dr. Stanislav Gorb
Zoological Institute of the University of Kiel, Germany

We are always impressed by the extraordinary locomotor abilities of living creatures, especially if a similar way of locomotion cannot be performed by humans. One example is walking on walls and the ceiling. Spiders seem to climb sleek, perpendicular walls without effort and even perform their walk on the ceiling. Like insects and geckos, they owe this extraordinary ability to extremely thin hairs. In addition, the feet of spiders and insects have fine hook-shaped claws that interlock with coarse surfaces.

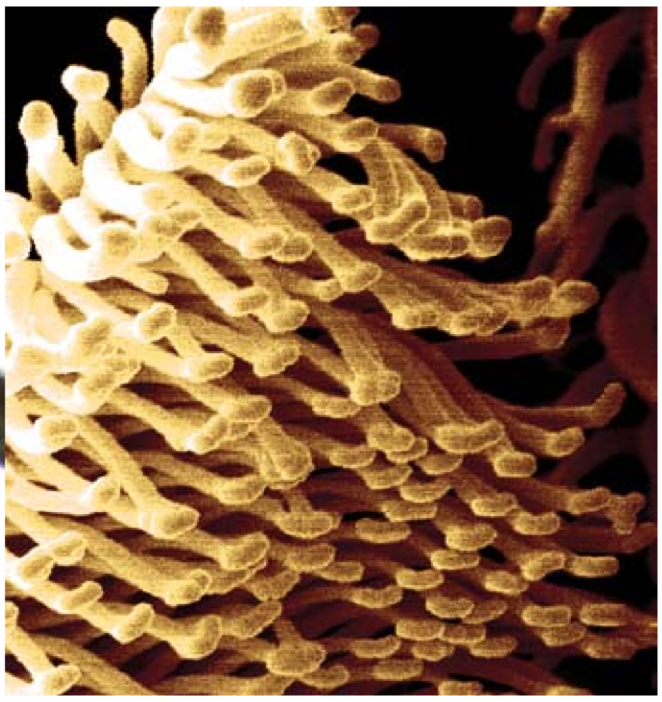
From what we know today, insects rely solely on their microhairs and have optimized the shape of these hairs for different substrates. Hairs that widen at their tips in the form of a spatula or a mushroom are especially clingy. But while the adhesive and the hook-and-pile principle have long been technically implemented in adhesive tape and Velcro fastener, respectively, foils coated with microhairs have yet to become a part of everyday life.

Interestingly, with microhairs, there is no simple explanation for the mechanism. The secret rather lies in a combination of micro- and nanostructured surfaces, viscoelastic materials, biphasic fluids and their transporting systems, as well as the manner of movement itself. Some of these properties are trivial from the physical point of view; others are highly complex and need further experimental studies and theoretical considerations. In addition to locomotory attachment devices, there is an enormous diversity of attachment systems with non-locomotor function.



Ventral view of the adhesive pads (scopula) at the tip of a spider's leg *(Clubiona caerulescens)*.

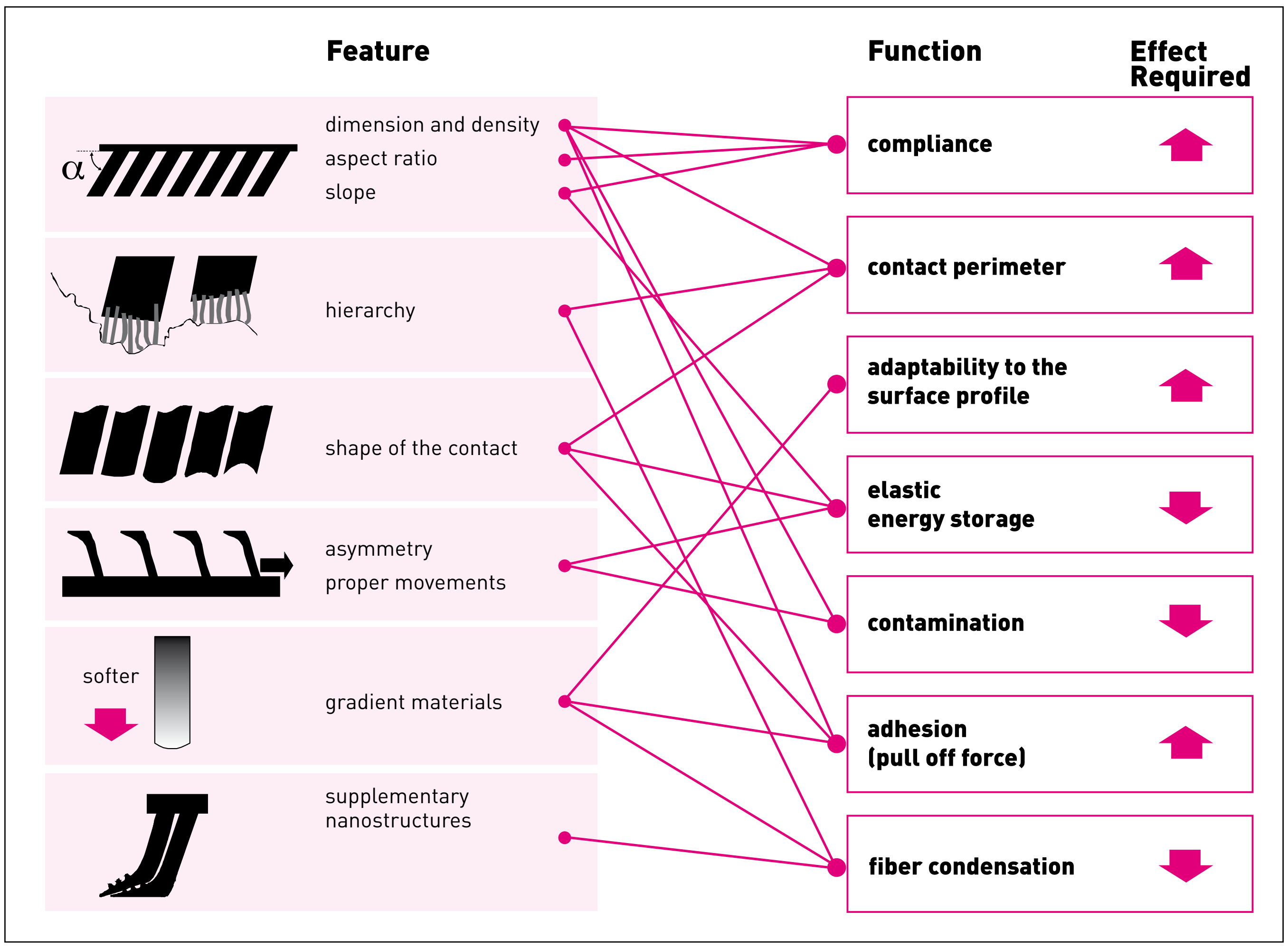
Costa Rican zebra tarantula *(Aphonopelma seemanni)*.
Image: Senta Niederegger



Tip of an adhesive hair of the spider *Cupiennius salei*. The fine branches with the spatula-shaped tips are visible.

→ **Prof. Dr. Stanislav Gorb** was born in Alexeevka (Ukraine) in 1965. He studied biology in Kiev from 1982–89 and received his Ph.D. degree in zoology and entomology at the Schmalhausen Institute of Zoology of the Ukrainian Academy of Sciences in Kiev in 1991. In 2006, he obtained his postdoctoral lecturing qualification (Habilitation) in ecology at the Institute of Zoology at the University of Freiburg with a thesis on „Attachment devices in insects". Gorb was a postdoctoral researcher at the University of Vienna, a research assistant at the University of Jena, a group leader at the Max Planck Institute for Developmental Biology in Tuebingen, and a visiting professor at both the University of Washington and the Nanjing University of Astronautics and Aeronautics in China. Gorb's research focuses on morphology, structure, biomechanics, physiology, and evolution of surface-related functional systems in animals and plants, as well as the development of biologically inspired technological surfaces and systems. In 1995, he received the Schlossmann Award in Biology and Materials Science. He was the 1998 BioFuture Competition winner for his works on biological attachment devices as possible sources for biomimetics. Gorb has authored three books, including „Attachment Devices of Insect Cuticle" and „Biological Micro- and Nanotribology". He published more than 100 scientific papers in renowned peer-reviewed journals, and he is co-owner of three patents. → **JB**

Tokey Gecko at a glass wall
Geckos are able to cling to almost any surface, without any glue. How do they do this? The naked eye can make out only fluffy lamellae on their toes. Under the electron microscope, tiny spatula-like hair tips, only 200 nm in size, are visible.



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 at the right hand side (arrows indicate increase or decrease of the function by a specific design feature). Simultaneous implementation of all these features in one artificial system is desirable but hardly possible. However, one principle or a combination of a few of these biological insights can be implemented, depending on the requirement for a particular biologically inspired material or system.

During the last decade, the interest in biological attachment devices was renewed, because of the latest developments in experimental techniques enabling high-speed video recordings, force measurements and elaborate microscopy methods. Biological attachment structures turned out to possess characteristics important for evolutionary and ecological studies. Additionally, detailed information about attachment structures and mechanisms have a huge potential for biomimetic applications.

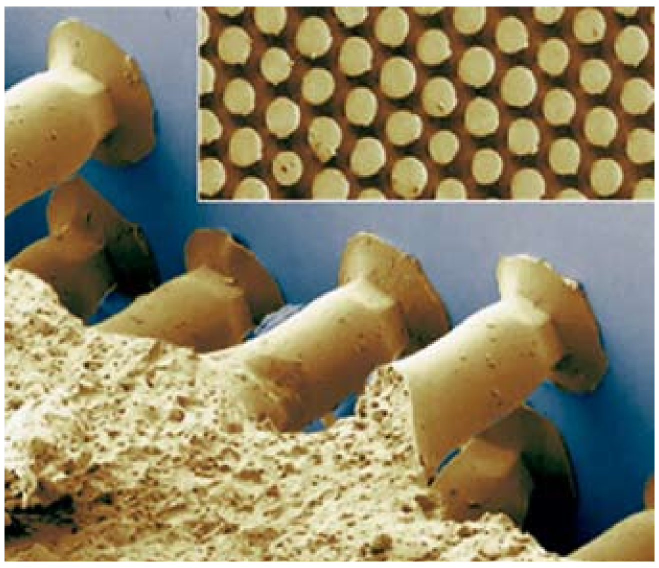
In cooperation with partners in the industry, scientists in our lab were able to, for the first time, successfully mimic several of the functional principles of microhairs in a synthetic adhesive. The adhesive force of this biomimetic structure relies on microstructures shaped like tiny mushrooms. After studying over 300 different adhesion systems (see figures) we decided to use the design of a microstructure that is common in the foot sole of males of different beetle species.

A few square centimeters of the microstructured material are able to hold objects weighing several pounds to a smooth-surfaced glass wall; at the ceiling, however, they hold up to ten fold less weight. Smooth structures, like glass or polished wood, are well suited substrates for these adhesive strips, ingrain wallpaper however, is hardly practical. Insects have trouble walking on finely coarse surfaces as well, this is a fundamental problem associated with the mechanism of adhesion.

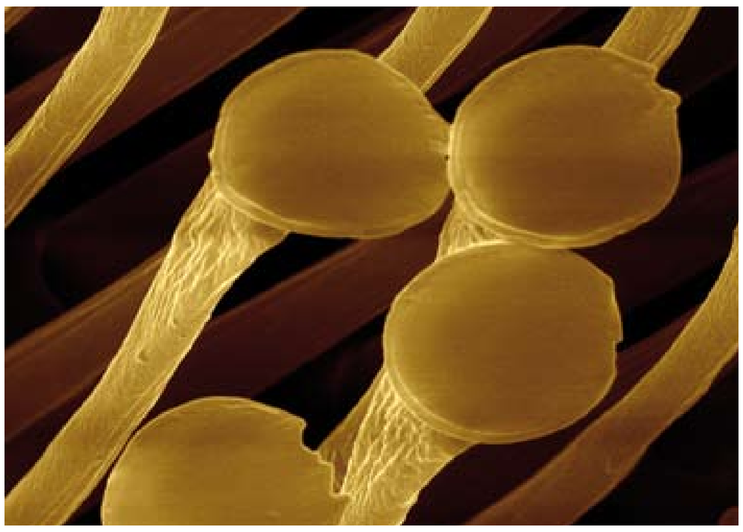
The material leaves no visible traces on the surface after detachment. It still sticks after it has been attached and pulled off again hundreds of times. In contrast to adhesive tape, it can be washed if dirty without loosing its adhesive capacity. The hairy adhesive material can be used, for example, as protective foil for delicate glass or simply as a reusable adhesive strip – say goodbye to refrigerator magnets, here come microhairs, which also stick to mirrors, wardrobes and window panes. The material has already proven its performance capacity in dynamic processes as well: a robot weighing about 4 ounces could climb a perpendicular glass wall with the synthetic adhesive fibers on the soles of his feet.

The manufacturing process uses a mould as a template – much like a baking pan – in which the desired substrate is poured creating a negative image of the pan. The mould is filled with a polymerizing mixture. After the curing, the plastic is separated from the template. The greatest challenge was the construction of the microstructure baking pan. Optimizing the polymer mixture took a lot of patience as well: if too liquid, it simply runs out of the form, if too viscous, it does not fill it out in the first place. Currently, extensive studies are conducted regarding the optimization of the polymer. The aim is to refine the structures, and to ensure, for example, that it also adheres under water, or is slidable in one direction. The team has still a lot of work to do until the foil is fully characterized in different conditions (e.g. with respect to humidity, coarseness of the substrate, dirty and smudgy surfaces, maximum number of adhesion cycles, etc.).

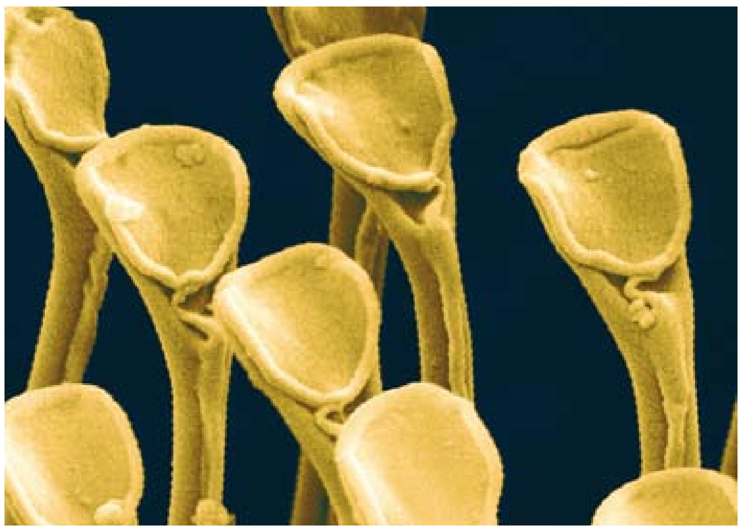
Rear view of the tip of a house fly's leg *(Musca domestica)*.
Lobe-like adhesive structures (pulvilli) and claws are visible.



Microscopic image of the biomimetic surface structure of a synthetic adhesive material. The material inspired by the soles of insects feet (in ocher) clings to glass (in blue).



Adhesive hairs of a male potato beetle *(Leptinotarsa decemlineata)*.



Adhesive hairs in the fly *Calliphora vicina*.

With the mushroom-shaped adhesive hairs, only one of the mechanisms insects use for adhesion is technically implemented. Clearly, the adhesive technique of insects is still superior to artificial systems: insects, spiders and geckos can switch between different adhesion and clinging mechanisms, depending on the type of substrate they are walking on. In a collaboration with the Robotics Group lead by Prof. Dr. Roger Quinn (Case Western Reserve University, Cleveland, OH, USA) and the company Tetra GmbH (Ilmenau) such principles are implemented in climbing robots. There's a lot left to do.

For materials 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 interface. 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 observed in biological systems. We believe that the huge diversity of biological attachment mechanisms will continuously inspire material scientists and engineers to develop new materials and systems. Therefore, more broad comparative functional studies on biological surfaces should be conducted in order to extract essential structural, chemical and mechanical principles behind their functions. Using living nature as an endless source of inspiration might be another reason for saving biological diversity.

This work, was supported from funds by the German Science Foundation DFG (contract No GO 995/4-1) as part of the European Science Foundation EUROCORES Program FANAS, the EC Sixth Framework Program (contract No ERAS-CT-2003-980409) and the Biona Project of the Federal Ministry of Education and Research (BMBF Biona 01 RB 0802A).

Further reading

Books

S.N. Gorb (2001) Attachment devices of insect cuticle. Dordrecht: Springer.
M. Scherge and S. N. Gorb (2001) Biological micro- and nanotribology. Berlin: Springer.
S.N. Gorb, editor (2009) Functional surfaces in biology. Dordrecht: Springer.

Original articles

S. N. Gorb (2006) Functional surfaces in biology: mechanisms and applications. In: Biomimetics Biologically Inspired Technologies, edited by Y. Bar-Cohen, Boca Raton: CRC Press, p. 381-397.
S.N. Gorb, M. Varenberg, A. Peressadko and J. Tuma (2007) Biomimetic mushroom-shaped fibrillar adhesive microstructure. J. R. Soc. Interface 4: 271-275.
S.N. Gorb, M. Sinha, A. Peressadko, K.A. Daltorio and R.D. Quinn (2007) Insects did it first: a micropatterned adhesive tape for robotic applications. Bioinspiration and Biomimetics 2: 117-125.
S.N. Gorb and M. Varenberg (2007) Mushroom-shaped geometry of contact elements in biological adhesive systems. J. Adhesion Sci. Technol. 21: 1175-1183.
M. Varenberg and S. Gorb (2008) Close-up of mushroom-shaped fibrillar adhesive microstructure: contact element behaviour. J. R. Soc. Interface 5: 785-789.

sgorb@zoologie.uni-kiel.de