

Biological and artificial attachment devices: Lessons for materials scientists from flies and geckos

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Abstract

In insects, spiders, and geckos, adhesion to surfaces is mediated by finely structured contact elements. We have studied the structure and function of these elements on the micro and nano level by microscopical and nanomechanical techniques. Local mechanical properties and adhesion forces are measured by novel test methods and compared with predictions based on theoretical contact mechanics. Structure, size and shape of the contact elements are found to play important roles; in particular the principle of “contact splitting” has been identified: finer contact elements (down to sub-micron level) produce larger contact forces in heavier animals. The insight gained in studying biological systems can be transferred to the development of optimized artificial attachment devices. From our findings, the desired mechanical parameters of attachment structures can conveniently be delineated in newly developed adhesion design maps. Based on these investigations, a clearer strategy for producing optimum bio-inspired attachment structures is beginning to emerge. This paper gives an overview of our recent work in theory and experimental measurement of such adhesion phenomena.

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1. Introduction

Mechanics rules biology: living systems rely for their survival, to a large extent, on mechanical functions. This is true at the level of the cells, which adhere to substrates in controlled and dynamic ways and are known to communicate by mechanical means. It also applies, on the molecular level, to folding and unfolding processes, which may be viewed and studied as mechanical events. Another important case is the adhesion of various animals, e.g. beetles, flies, spiders, and geckos, to surfaces during locomotion, e.g. Refs. [1–5]. These animals exhibit fibrous attachment organs which are finely structured down to micron and sub-micron dimensions. The micromechanisms of adhesion in these animals are still under debate. Whereas spiders and geckos are believed to rely entirely on van der Waals forces between the feet and a substratum [6–8], it has long been known that adhesion is enhanced by capillary forces in animals producing secretions (flies and beetles) [9–11].

Controlled adhesion is also important in everyday life and in technological applications, e.g. in sticky tapes, car tires, wafer bonding or micro-objects in the packaging industry. “Intelligent” adhesion, which is reversible and does not lead to alterations of the surfaces involved as in conventional adhesives, is potentially of great practical interest. Largely through “bio-inspiration” and trial and error, first prototypes of such artificial contact systems have recently been designed in the laboratory [12–14]. In developing such devices, it is helpful to study the physical mechanisms found in biological systems and to derive important principles from them. This research direction has, under the name of “biomimetics” or “bionics”, gained much momentum and popularity in recent years.

The present paper describes and summarizes our recent investigations into the micromechanics of biological attachment devices. First, we render the relevant concepts of contact theory, especially concerning the size and shape dependence of van der Waals contact forces (Section 2). Recent micromechanical measurements of adhesion forces for single gecko spatulae are described in Section 3. The disciplines involved

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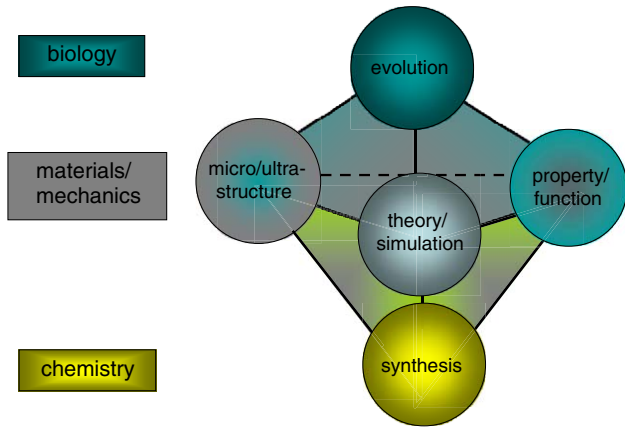


Fig. 1. The interplay between different disciplines in the investigation of attachment systems. A thorough understanding of evolutionary principles and of the functional properties in biological systems, coupled with detailed micro/ultrastructural studies and theoretical calculations, creates the knowledge base for synthesizing optimum artificial structures.

in this comprehensive study are depicted in Fig. 1: obviously, an interdisciplinary approach is indispensable for uncovering and understanding the lessons offered by nature.

2. Contact mechanics considerations: from contact splitting to adhesion design maps

Theoretically, van der Waals forces can produce contact stresses of astonishing magnitude. In the hypothetical case of ideal match between smooth surfaces, the theoretical contact strength can be estimated as

$$\sigma_{th} \approx \frac{\gamma}{b} \quad (1)$$

where $\gamma = \gamma_1 + \gamma_2 - \gamma_{12}$ is the work of adhesion with γ_1 and γ_2 as the specific surface energies of the two bodies in contact and γ_{12} is the specific energy of the interface formed between them; b is the characteristic length of surface interaction. By choosing typical values (e.g. $\gamma = 50 \text{ mJ/m}^2$ and $b = 2 \cdot 10^{-10} \text{ m}$), the theoretical adhesion stress is found to be of order 200 MPa.

Such high adhesion stresses are hardly ever encountered in real systems, mainly for two reasons: the contact between a body of finite dimensions and an infinite half-space sets up stress singularities at the edges which reduce the pull-off force [15] and the contacting surfaces never match perfectly, which lowers the area of true contact and requires accommodating elastic deformation of one or both solids [16,17]. The celebrated model for adhesion is the Johnson–Kendall–Roberts (JKR) theory [16], which balances the elastic distortion of the contact pair against the reduction in surface energy due to the formation of the adhesive contact. It predicts the force necessary for producing a contact area with radius a between two spherical solids of radius R as

$$F = \frac{4}{3} \frac{E^* a^3}{R} - \sqrt{4\pi E^* \gamma a^3} \quad (2)$$

Here E^* is the (reduced) Young's modulus of the contact pair. The first term in Eq. (2) corresponds to the Hertz solution

in the absence of attractive surface forces. The assumption of such forces leads to the prediction of a theoretical pull-off force between a sphere and a plane given by

$$F_c = \frac{3}{2} \pi R \gamma \quad (3)$$

Surprisingly, this result is independent of the elastic properties of the spheres. This is however due to assuming the special case of spherical surfaces; for other shapes such as flat punch or torus the independence of Young's modulus is lost [18].

Application of the JKR model to living systems has—despite the simplifying assumptions—been surprisingly successful: calculations give adhesion forces of similar magnitude as in the experiments [6,19]. As an important consequence of the model, the principle of “contact splitting” has been identified [20]: If one large contact is subdivided into n smaller contacts, with identical apparent contact area, the adhesion force rises by a factor $n^{1/2}$. Consider an adhesive structure consisting of parallel fibers with hemispherical tips (with radius R and area fraction f) adhering to an ideally flat substrate. Its apparent contact strength, defined as the adhesion force divided by the apparent contact area, is then [21]:

$$\sigma_{app} = \frac{3f\gamma}{2R} \quad (4)$$

In the course of evolution, nature has repeatedly developed such “hairy” attachment structures (Fig. 2). Their size reflects the principle of contact splitting as heavier animals from different lineages display progressively finer contact elements [20]: assuming that the adhesion force is proportional to body mass, a theoretical dependence of number of contacts versus animal mass was derived which is exactly observed by different lineages including flies, beetles, spiders and lizards.

The shape of the contact elements also influences contact strength [18]. Microscopic studies show that nature provides a variety of contact shapes, many of which differ substantially from spherical ones [1]: structures similar to flat punches are found in grasshoppers and echinoids, many animals have tape-like contact elements (spatulae) and the contact region of a fly

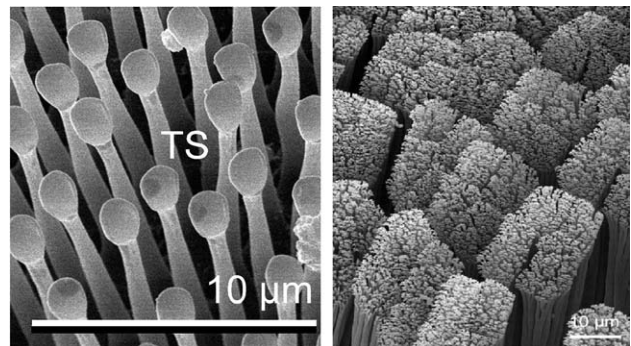


Fig. 2. Contact elements in flies (left) and geckos (right). The terminal setae (TS) of flies consist of insect cuticle, i.e. chitin-fiber reinforced protein, and have typical dimensions of $2 \mu\text{m}$. The terminal elements (“spatulae”) of the gecko are made of keratin and have typical dimensions of 200 nm (micrographs courtesy of S. Gorb, Max Planck Institute for Metals Research).

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