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Bioinspired Dry Adhesive Materials and Their Application in Robotics: A Review

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Abstract

Dry adhesives inspired from climbing animals, such as geckos and spiders, rely on van der Waals forces to attach to the opposing surface. Biological fibrillar dry adhesives have a hierarchical structure closely resembling a tree: the surface of the skin on the animal's feet is covered in arrays of slender micro-fibrils, each of which supports arrays of fibrils in submicron dimensions. These nano-meter size fibrils can conform closely to the opposing surfaces to induce van der Waals interaction. Bioinspired dry adhesives have been developed in research laboratories for more than a decade. To mimic the biological fibrillar adhesives, fibrillar structures have been prepared using a variety of materials and geometrical arrangements. In this review article, the mechanism and selected fabrication methods of fibrillar adhesives are summarized for future reference in adhesive development. Robotic applications of these bioinspired adhesives are also introduced in this article. Various successful applications of bioinspired fibrillar adhesives can shed light on developing smart adhesives for use in automation.

Keywords: bioinspired gecko adhesive, van der Waals forces, biomimetic, climbing robot, bioinspired tape

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1 Introduction

Geckos, a type of creatures that can climb rapidly everywhere, have been amazing humans for centuries[1]. The secret of their extraordinary climbing ability, however, was revealed just a decade ago[2–4], thanks to continuously improving electron microscopy techniques and micro-fabricated sensors. What appeared to be soft and smooth skin on the gecko's climbing feet has been shown to be hierarchical fibrillar structures that provide compliancy with the climbing surface[5–7]. The hierarchical fibrillar structures on climbing animals possess fibrils in different length scales, which are arranged in a pattern closely resembling a tree[8]. The open ends of these tree-like structures consist of nano-meter size arrays of fibrils, which can conform to both smooth and rough surfaces with the help of the hierarchical structures. Millions of nano-fibrils, in close proximity to the contacting surface, each induces van der Waals force and collectively provide enough attraction forces to support the weight of the climbing animal[2,3]. The discovery of hierarchical fibrillar structures on the feet of animals has inspired not only the adhesives mimicking the mechanism of fibril-surface interactions, but also robotic applications using these fibrillar adhesives.

In this article, the development and applications of bioinspired fibrillar adhesives are reviewed in the following sections: The mechanism of biological and artificial fibrillar adhesives is introduced in section **2**; fabrication of bioinspired fibrillar adhesives using different materials and methods is introduced in section **3**; recent advances in functionalized dry adhesion as a new research direction are introduced in section **4**; robotic applications making use of the bioinspired fibrillar adhesives are introduced in section **5**; and finally conclusions of this review study are drawn in section **6**.

2 Mechanism of the bioinspired fibrillar adhesive

Geckos[2,4] and spiders[9–12] are two of the animals that have been found to have nano-scale fibrillar adhesives on their climbing feet. These fibrillar adhesives are different from the structures that are found on beetles[13,14], which rely on chemical secretion to create "wet

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contact” with the climbing surfaces. Therefore the fibrillar adhesives are referred to as “dry adhesives”[4] because they don’t rely on wet contact. There are seven properties that summarize the gecko’s dry adhesive[15,16]: 1) anisotropic attachment (adhesion is different when the adhesive is pulled from different directions); 2) high pull-off to preload ratio (high pull-off adhesion measured with low compression preload at interfaces engagement); 3) low detachment peeling force (easily being removed by peeling rather than pull-off); 4) material independence (the adhesive is able to provide similar adhesion to surfaces with different materials); 5) self-cleaning (adhesive is reusable with no need to be cleaned); 6) anti-self matting (the fibrillar adhesive will not degrade due to possible fibril collapsing); and 7) non-sticky default state (the adhesive is not activated when no load is applied on it). These seven properties can be summarized into three key aspects to investigate gecko adhesives: geometry, material and climbing gait; these aspects are reviewed in this section.

Biological dry adhesives contain fibrils in different length scales. For example, on a gecko’s dry adhesives, there are four length scales of structures which effect the level of adhesion[8]: the soft skin on the flexible skeleton of the geckos form the macro-scale of structure (see Fig. 1a); the millimetre-scale “lamellar” structures are arranged as thin blades (see Fig. 1b); on the surface of the ends of the lamellar structures, micrometre-scale of “setae” are arranged as arrays (see Fig. 1c); at the end of each seta (single form of setae), arrays of nanometre-scale “spatulae” are the “end-effectors” to create intimate contact with the climbing surfaces (see Fig. 1d). Millions of spatulae induce van der Waals forces with the contacting surfaces, collectively forming a firm grip to support the gecko’s own weight. The hierarchical fibrillar structures on geckos are proven to provide compliancy to conform to rough surfaces[5,17–19]. The material that makes up the skin on geckos is called “beta-keratin”, which has a Young’s modulus of ~1.4 GPa[20,21]. However, the effective elastic modulus of the dry adhesive structure, when taking the four layers making up the structures into consideration, is calculated to be ~100 kPa, which is between the definition of “tacky” and “non-tacky” according to the Dahlquist’s criterion[8,21–23]. The softness provided by the hierarchical structures helps the gecko feet to conform to the climbing surface. A model based on spider adhesives[24] is given in another work, which compares the adhesion performance of spiders and geckos. Adhesion in spiders is comparable in strength to the one in gecko. Claws assist the spider’s adhesive to climb on rougher surfaces.

The fibrils in the tree-like hierarchical structures are closely packed in order to create a large contact area. The slender and close-packed fibrils can collapse together if they are formed of hydrophilic materials. Due to the low surface energy of beta-keratin[20], the hierarchical fibrillar structures do not clump together and instead provide flexibility for each fibril to extend into contact with the contacting surface. In addition to the low surface energy property, the hierarchical structures are self-cleaning and reduce the adhesion of dust and contamination picked up from the climbing surfaces[25–27].

The gecko is an efficient climber with step intervals of ~ 15 milliseconds[15]. The gecko’s adhesives can hold approximately three orders of magnitude more than their own weight[3]. The gecko’s fibrillar adhesives are often referred to as “smart” adhesives[15] for their “programmable” activation and de-activation: the curvature of the fibrils allows the adhesives to engage climbing surfaces at an angle of ~ 30˚, and detach from the surfaces at an angle of slightly higher than 30˚[2]. The attaching and detaching angles affect the movements that geckos use to climb - they use a “Load-Drag-Pull” series of movement in order to interact with the climbing surfaces during each step[28–30]. During climbing, the gecko brings its foot into contact with the climbing surface and

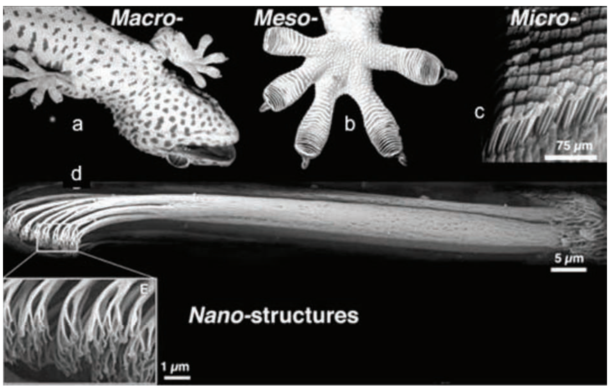

Fig. 1 Hierarchical surface structures forming the gecko’s dry adhesives. Images are adapted from Ref. [8]. a) Flexible body and skin of the gecko forms the marco-scale structures; b) lamellar structures on the toes form the meso-scale; c) arrays of setae form the micro-scale structures; d) magnified view of a single seta (~130 μm long); the inset provides a magnified view of the tip of a seta which is formed of arrays of nano-scale spatulae.