**Biomimetic Bidirectional Switchable Adhesive Inspired by the Gecko**

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**ABSTRACT**
See Attached

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ABSTRACT
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1. Introduction

The complex anisotropic and hierarchical structure of the gecko provides a compliant surface with an effective modulus of \( \sim 100 \text{ KPa} \) \(^1\) although the setal structures are composed of relatively hard \( \beta \)-keratin \((-1-2 \text{ GPa})\). The resulting compliance allows for the thin terminal structures of the setae and spatula pads to come into intimate contact with opposing surfaces, which maximizes the attractive weak, short-ranged van der Waals interactions\(^2\) required for high adhesion \((-1 \text{ N/cm}^2)\) and friction \((-10 \text{ N/cm}^2)\) forces. The anisotropic adhesion\(^3\) of gecko pads originates from the fact that the setae are tilted at an angle of \(-45^\circ\).\(^4\) Several types of gecko-like adhesive materials have been developed over the last decade\(^5-12\) yet a true mimic still remains elusive because of limitations in current surface nanofabrication techniques as well as limitations involved in incorporating gecko-like adhesives into devices that offer proper articulation. In 2003, Geim et al.\(^5\) were the first to microfabricate a gecko-like material out of a soft polymer, although the latter did not possess anisotropic adhesive properties and required relatively large preloads \(\text{(i.e., the force applied after contact)}\) to activate the adhesion. New developments in the fabrication of gecko-like adhesives included the addition of tilt to the structures,\(^11-13\) using carbon nanotubes,\(^16,17\) introducing angled mushroom tips,\(^18\) functionalizing the gecko-like surface with mussel adhesive proteins,\(^19\) using surface strains\(^20\) or shear\(^21\) to tune adhesion. Other polymer-based structures have been developed\(^22\) although they lack the property of shear-induced adhesion \(\text{(i.e., the maximum adhesion and friction forces are only attained upon shearing the surface whereas without shear, the adhesive shows minimal adhesion forces)}\) or required relatively large normal pressures to activate the release mechanism.\(^23\) Recently, our group developed a general approach to easily incorporate a desired tilt angle into gecko-like fibrillar structures\(^24\) and the resulting gecko-like surface was reminiscent of the tribological properties of gecko pads. With our current design, the structures show anisotropic adhesion and friction properties even in the absence of tilt in the structures although adding tilt to the structures does increase the magnitude of both friction and adhesion for gripping.

Here, we introduce a new generation of polyurethane-based gecko-like structures (hereafter referred to as “prismatic” pillars), consisting of 2 levels of hierarchy (Figure 1): a triangular prism base \((30 \mu m \times 25 \mu m \times 25 \mu m, \text{and} 80 \mu m \text{ high})\) terminated...
demonstrate the anisotropic effects of the judicious prismatic pillar design. In the gripping direction, a large contact area is formed between the adhesive pads and the opposing surface (larger circle in Figure 2A). In addition, the apex of the triangular prism only allows for a point contact between neighboring pillars (smaller circle in Figure 2A) thus minimizing nearest neighbor adhesion. The latter is essential to allow the pillars to elastically regain their original configuration when they are unloaded. If the adhesive interactions between neighboring pillars cannot be overcome by the stored elastic energy (within the pillars), self-matting or clumping occurs \[25\] (i.e., the pillars remain stuck to each other), which is undesirable. In the releasing direction, the apex of each triangular prism (smaller circle in Figure 2C) now serves to prevent the adhesive pads from forming good contact with the opposing surface (larger circle in Figure 2C). Corresponding top-view optical microscope images of the prismatic pillars under shear against a transparent microscope glass slide in the gripping and the releasing directions (Figure 2B, D) also confirm the anisotropic contact mechanics of our structures. The large contact area between the adhesive pads and the glass surface generated in the gripping direction (Figure 2B) allows for both high friction and adhesion forces. The latter pin the adhesive pads to the opposing surface and upon further shearing leads to small peeling angles in the bifurcation region between the adhesive pads and the opposing surface, which enhances the adhesion forces.\[26,27\] By contrast, in the releasing direction (Figure 2D), a relatively small contact area is formed between the adhesive pads and the glass surface thus reducing both the friction and adhesion forces. Upon further shearing, the small friction forces are not sufficient to pin the adhesive pads, and sliding or detachment occurs. Figure 3 shows the tribological properties of a tilted prismatic surface (tilt angle $\theta = 63^\circ$ in the unloaded

2. Results and Discussion

Scanning electron microscope (SEM) images of the prismatic surface sheared in the gripping and releasing directions by a rectangular tip (20 $\mu$m x 20 $\mu$m x 7 $\mu$m), arranged in a rectangular lattice (30 $\mu$m center-to-center in the tilt (x-axis) direction, and 37 $\mu$m center-to-center along the in-plane or y-axis). Through proper articulation (i.e., to activate either gripping or releasing) of the prismatic gecko-inspired adhesive, we obtain anisotropic frictional-adhesive properties, which allow for reversible attachment and detachment over multiple cycles.

![Figure 1. Gecko-inspired switchable adhesive. SEM image of a gecko-inspired adhesive consisting of tilted prismatic pillars with a first level of triangular prism structures and a second level of thinner rectangular adhesion pads biased towards one of the flat edges. The inset is a schematic illustration of the terminal end of a prismatic pillar.](image)

![Figure 2. Side-view SEM images of the prismatic gecko-inspired adhesive under shear. (A) In the gripping direction, a large contact area (larger circle) is formed between the adhesive pads and the opposing surface. The apexes of the triangular prisms (smaller circle) prevent large area contacts between neighboring pillars. (C) In the releasing direction, a smaller contact area is formed between the adhesive and the opposing surface (larger circle). The apexes of the triangular prisms (smaller circle) prevent large area contacts between the adhesive pads and opposing surface. (B,D) Optical microscope images of the gecko-inspired surfaces sheared against a transparent glass microscope slide in the gripping direction, and releasing direction, showing the very different anisotropic contact areas formed between the adhesive pads and the glass surface.](image)
and inverted horizontal surfaces. [28, 29] Data for the maximum preloads allow for robust and efficient locomotion on vertical surfaces. Low friction forces measured for over 4 weeks. A potential application for these switchable gecko-like adhesives involves moving delicate parts (e.g., electronic parts or computer chips) in assembly lines without using mechanical gripping or leaving a residue on the parts.

Similarly, the tribological properties of the prismatic surface were measured while shearing in the gripping direction, followed by shearing in the releasing direction, and finally pulling off to simulate the detachment process (Figure 4). The maximum adhesion force \( F_{\parallel} \) in the releasing direction was lower than in the gripping direction. The magnitude of the friction force \( F_{\parallel} \) in the releasing direction was also found to be considerably lower than in the gripping direction (cf. \( F_{\parallel} \sim 0.9 \) N in the gripping direction versus \( -0.13 \) N in the releasing direction). To demonstrate the practical applications of the prismatic surface, two configurations were tested to suspend weights on vertical and horizontal surfaces, thus simulating walls and ceilings.

In the horizontal configuration (Figure 5B), a sliding stage was fabricated to apply and maintain a lateral shear force on the prismatic surface in the gripping direction allowing for a large adhesion force to be generated in the vertical direction. Reversing the lateral shear force would cause detachment. To our knowledge, this is the first demonstration of using a gecko-like adhesive with shear-induced adhesion and friction properties to hold weights from inverted (ceiling-like) horizontal surfaces. In both cases, the weights have remained suspended for over 4 weeks. A potential application for these switchable gecko-like adhesives involves moving delicate parts (e.g., electronic parts or computer chips) in assembly lines without using mechanical gripping or leaving a residue on the parts. To demonstrate the proof of concept for such an application, we show (Supplementary video 1) how it is possible to exploit the friction forces to pick up, translate, and drop a 100 g weight repeatedly. In particular, we note the minimal preload required to activate the adhesion in the gripping direction, and instantaneous detachment of the weight once the shear force is released. The video also shows (Supplementary video 2) how it is possible to exploit the adhesion forces to pick up, translate, and drop a 50 g weight repeatedly. In this configuration, a lateral shear force in the gripping direction was required to activate the adhesion while a shear force in the opposite direction caused instantaneous detachment of the weight.
self-cleaning property, we are able to recover the initial high adhesion and friction by rinsing the prismatic surface with deionized water and allowing it to dry. Our new design of prismatic structures opens the way for new gecko-like adhesive surfaces that do not rely on intensive nanofabrication but rather on judicious engineering of surface microstructures and proper articulation of the surfaces.

4. Experimental Section

4.1. Fabrication of Patterned Silicon Mold

Silicon master wafers were fabricated using standard microfabrication techniques. Briefly, 4 in. silicon wafers (test grade, University Wafers) were cleaned in an oxygen plasma, after which a 600 nm oxide layer was grown using plasma-enhanced chemical vapor deposition. Next, positive photosresist (Shipley 1813, MicroChem Corp.) was spun onto the wafers, patterned with rectangular structures mimicking the gecko spatulae, and developed. The oxide layer was then etched by reactive ion etching with CF4. The patterned oxide layer formed the bottom of the two-layer etch mask. The remaining photosresist was stripped off, and a new layer of photosresist (Shipley 1818, MicroChem Corp.) was spun onto the wafers. This new layer was patterned with the triangular prismatic structures mimicking the gecko setae, and developed. The photosresist layer formed the top of the two-layer etch mask. Once the two-layer etch mask was in place, the hierarchial structure itself was formed using deep reactive ion etching. First, the wafer was etched to a depth of 80 μm. The photosresist was then stripped from the wafer, revealing the bottom layer (oxide) etch mask. The wafer was then etched an additional 20 μm to form the final rectangular pad structure.

4.2. Fabrication of Prismatic Dry Adhesive

Two-level hierarchical polyurethane (PU) based (ST-1060 BJB Enterprise, Inc., Tustin, CA) dry adhesives were fabricated in a multi-step process as previously described.[24] Briefly, in the first step, a silicon master wafer was used as a mold to create an inverse polydimethylsiloxane (PDMS) replica. To facilitate the peeling of the PDMS inverse mold from the silicon master, the latter was pretreated with a self-assembled monolayer of octadecyltrichlorosilane (OTS) coating. Sylgard 184 PDMS (Dow Corning, Midland, MI) was mixed in a 10:1 (pre-polymer/cross-linker) ratio. After removal of air bubbles formed during mixing, the viscous liquid was poured onto the silicon master and cross-linked at 75 °C for 40 min. The partially cured PDMS replica was then laterally sheared in a home-built shearing device by applying a predetermined shear distance to achieve the desired tilt angle (ranging from 60° to 90°). The PDMS replica was then fully cured in its sheared state at 75 °C for 24 h, resulting in the PDMS replica mold with tilted triangular holes and tips. PU was then poured onto the PDMS inverse mold from the silicon master, the latter was pretreated with a self-assembled monolayer of octadecyltrichlorosilane (OTS) coating. The PU-based dry adhesive was peeled off from the PDMS replica.
glass surface was brought into contact with the sample with a preload of 50 mN. The glass surface was dragged in the gripping direction at a velocity of 10 μm/s after which it was pulled off at 90° from the sample at the same speed. For the detachment experiments, after shearing in the gripping direction (to activate the adhesion), the glass surface was then dragged in the opposite (releasing) direction and pulled off at 90° from the sample. Samples with tilt angles θ of 90° (i.e., no tilt) and 63° were tested to study the influence of the tilt angle. Prior to each experiment, the glass surface was cleaned with ethanol while the samples were tested without pre-cleaning.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Figure 5. Supporting weights from both vertical and inverted horizontal surfaces, i.e., walls and ceilings. (A) Optical image of a 450 g weight supported from a vertical glass microscope slide using a prismatic surface of area ≈ 2 cm². Friction forces (F∥) are predominantly used in this configuration. An upward stroke of the prismatic surface would cause the weight to detach. (B) Optical image of a 50 g supported from a horizontal silicon wafer using a prismatic surface of area ≈ 1.6 cm². Corresponding schematic illustrations are shown below each image. In the horizontal gripping configuration, (B), the shear motion of the slider (red arrow) was used to generate the friction forces (F∥) that activated the adhesion forces (F⊥) to hold the weight. Reversing the shear direction would cause the weight to detach. The weights have been hanging for several weeks.