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Direction-dependent adhesion of water strider's legs for water-walking

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ABSTRACT

We report the direction-dependent adhesion of water strider's legs for fleetly walking on water surface. The flexibly oriented setae of legs involving the hierarchical micro/nanostructure tune effectively the solid–liquid–air three phase interfaces in two opposite directions: the direction along the setae and opposite the setae, generating different adhesion dependent on the direction. A model is proposed to elucidate the underlying mechanism of water-walking based on direction-dependent adhesion induced by the orientation of the aligned setae. This finding will improve our understandings of the interaction between the oriented structured surface and water surface, and is significant to boost biomimetic structured surface that can be applied into microfluidics and aquatic microdevices.

1. Introduction

Water striders are well-known water-walking insects for their remarkable abilities to freely stand and fleetly walk on water surface, which attracted great attention in foundational and biomimetic researches [1–13]. Recently, Bush et al. gave a reasonable explanation on hydrodynamics of water striders in water surface propulsion and climbing menisci [4–7]. Our previous work proposed that the unique micro/nano-hierarchical structures of the aligned setae with nanoscale grooves on water strider's leg endow it with superior water repellency [8,9]. However, an aspect related to the effect of setae orientation of water strider's leg on the water-walking is still not clear so far. It has been known that the asymmetric patterned structure can induce anisotropic interfacial properties of bio-surfaces responsible for special functions [14–18]. For instance, rice leaf enables droplet roll off along parallel to the direction of leaf edge due to the papillae aligned parallel to the direction of leaf edge [14], and butterfly wing forms directional adhesion to water droplet by means of the oriented arrangement of the stepwise stacked scales on the wing [15]. Inspired by nature, these direction-dependent properties were excellent exhibited on artificial micro-patterned surface consisted of oriented grooves and asymmetric sawteeth rough surface. They could be applied in microfluidic devices, evaporation-induced pattern formation, and easy-cleaning coatings [19–24].

In this work, we reveal that the orientally aligned setae on the water strider's legs induce direction-dependent adhesion to water at one-dimensional level in two opposite directions: i.e., the directions along the setae (defined as AS direction) and opposite the setae (defined as OS direction). Water droplets roll along leg more easily in AS direction than in OS direction, more obvious adhesion is observed when water droplet slides along the leg in OS direction, as well as larger resistance exists when the leg is immersed in water in OS direction. A model is proposed to explain the underlying mechanism of direction-dependent adhesion induced by the orientation of the aligned setae. According to the experimental results, a reasonable elucidation on the assistant role of oriented-structure-induced adhesion in water strider's effortless surface standing and moving is provided. The investigation will offer an insight into the propulsion of water-walking via the superhydrophobic oriented structured surface, and is significant to boost the novel biomimetic structured surface design that can be applied into microfluidics and aquatic microdevices [21,23,25].

2. Experimental

2.1. Preparation of sample

The water striders specimens' weight is about 10 mg and the middle/hind legs of which were about 20 mm long. To study the

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structured morphology and wetting properties, water strider's legs were carefully selected and cleaned through blowing with nitrogen gas. All the samples were taken from living water strider just before the experiments in order to keep the freshness and real performance.

2.2. Characterization of microstructure

The structured morphology of water strider's leg was observed under a field-emission scanning electron microscope (FE-SEM, JSM-6700F, Japan) and an environmental scanning electron microscope (ESEM, Hitachi S-3000N, Japan).

2.3. Measurement of the directional rolling angle

The wetting properties of water strider's leg were measured using a contact angle meter system (OCA20, Dataphysics, Germany). In order to test the directional water repellency of the legs, eight well-chosen legs with diameters of about 220 μm were close packed and fixed on a glass slide to form a plane surface, with the setae of which inclining to the same orientation. Subsequently, the sample of the as-prepared close-packed-leg surface was placed on the tilting board, so distinct rolling angles of water droplet (3 μL) on the sample in the AS or OS direction could be observed. Meanwhile, a high speed CCD camera was used to monitor rolling behaviors of the water droplet during the measurements.

2.4. Adhesive behaviors of a droplet sliding along leg

A 5 μL water droplet was hung on a syringe needle, and then it was controlled to slide along a single water strider's leg back and forth. Adhesive behaviors between water droplet and leg in different sliding directions were observed and recorded by a CCD camera.

2.5. Immersion experiments

To explore the interactions between water and water strider's leg with different setae orientation, an immersion experiment was designed using a high-sensitivity microelectronic balance system (DCAT 20, Dataphysics, Germany). At first, a well-chosen straight part of water strider's leg was vertically suspended on the sample holder of the balance, and the force of the balance was initialized to zero. Then, a water vessel placed below the sample was lifted upwards to the leg at a constant speed of 0.1 mm/s, so the leg was gradually immersed in water up to a given depth of 5 mm. During the immersion process, the force–depth curves were automatically recorded by the microelectronic balance system. Deionized water was used in all the tests, which were carried out at the ambient temperature of 20 °C.

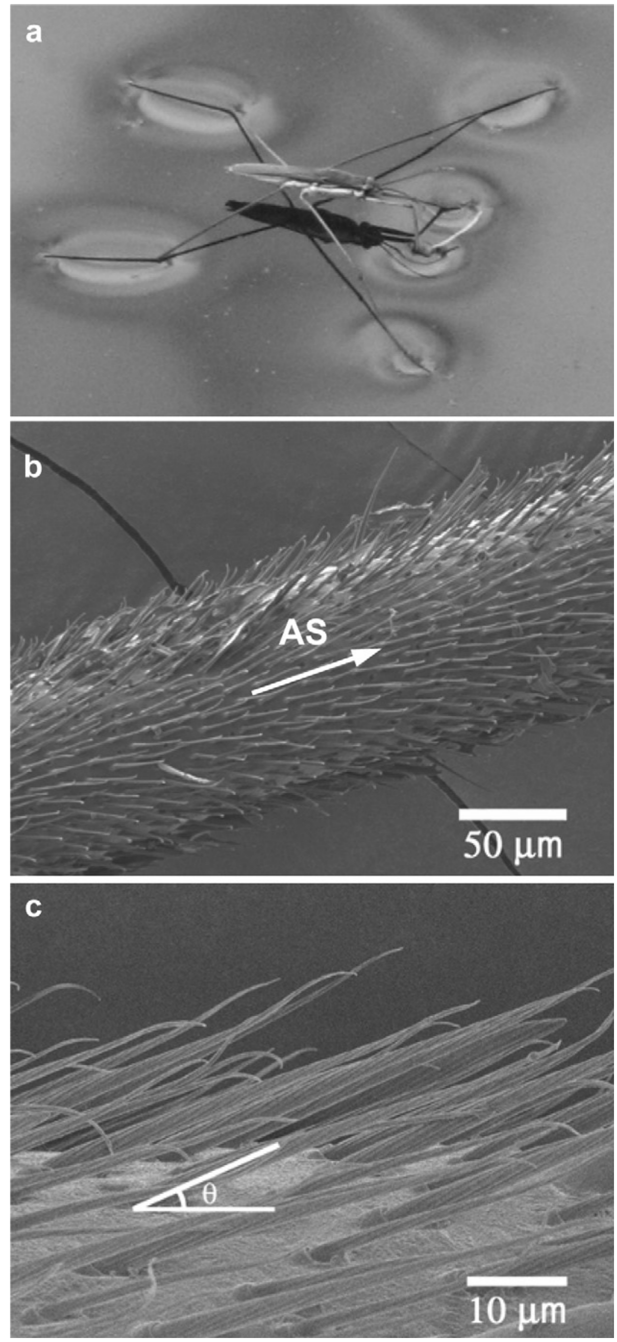

Fig. 1. SEM images, oriented morphology of water strider's leg. (a) A living water strider stands on water surface. (b) Aligned setae on a water strider's leg incline orientally, and the arrow denotes the orientation of the aligned setae (i.e., AS direction). (c) Aligned setae with an inclination angle of θ to leg surface.

3. Results and discussion

To reveal the direction-dependent properties, the details of microstructure of water strider's legs are firstly observed by SEM. As shown in Fig. 1, numerous aligned chitinous setae exist on the leg, with many regular elaborate nanoscale grooves. Most of tiny setae are ∼50 μm in length and ∼2 μm in diameter, with the distance of ∼10 μm between adjacent setae. All the aligned setae orientally incline to the direction of leg tip, with an inclination angle θ of about 25° to leg surface. The solid–liquid contact ways can modulate the contour, length, and continuity of the solid–air–liquid three-phase contact line (TCL), which could impact the contact angle hysteresis, rolling angle and surface adhesion [26,27]. For the aligned setae orientally inclined, similar to the stepwise stacked scales on butterfly wings, the solid–liquid contact ways could be tuned by the setae orientation, so water droplets on such an oriented structured surface may display directional adhesion at one-dimensional level. Conventionally, rolling behavior of a water droplet on surface reflects the surface adhesion with water, so a water droplet is used to act on the leg to measure the rolling angle. However, a water droplet could not stay on a single cylindric leg steadily and easily rolls off, due to the superhydrophobicity of the surface and less water contact area. The observed result shows that the rolling angles of water droplet vary little in the AS or OS direction, with a difference less than 1°, which demonstrates no distinctly different adhesion on water strider's leg