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Walking of spider on water surface studied from its leg shadows*

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Different from sculling forward of water striders with their hairy water-repellent legs, water spiders walked very quickly on water surfaces. By using a shadow method, the walking of water spiders had been studied. The three-dimensional trajectories and the supporting forces of water spider legs during walking forward were achieved. Results showed that the leg movement could be divided into three phases: slap, stroke, and retrieve. Employing an effective strategy to improving walking efficiency, the sculling legs supported most of its body weight while other legs were lifted to reduce the lateral water resistance, which was similar to the strategy of water striders. These findings could help guiding the design of water walking robots with high efficiency.

Keywords: water spider legs, shadow, walking forward, archimedes' principle

PACS: 47.55.df, 47.55.D–, 68.03.–g **DOI:** 10.1088/1674-1056/27/8/084702

1. Introduction

The water walking arthropod, such as water spiders, could walk on water surface freely with their hairy water-repellent legs[1] as shown in Figs. 1(a) and 1(b). This exceptional capability had inspired many researches on water walking robots.[2–7] For instance, Robostrider mimic the motion of a water strider.[2–4] Je-Sung Koh *et al.* proposed a jumping robot on water surface.[5] Metin Sitti *et al.* established a programmable and controllable micro-robot working above water surface.[6,7] Many researchers also focused on the mechanism of walking on water.[8–17] Such as, the leg movement of water strider during jumping upward had been studied by Song *et al.*[5] They found that to maximize momentum transferred to the water surface, water strider rotates its middle and hind legs rather than merely pushing them downward during jumping upward. Bush and Hu disclosed the mechanism of momentum transferring between the strider and the water.[2]

To design a water walking robot with actions of high similarity to those of natural water walking arthropods, the dynamics forces or trajectories of their legs during motions should be fully disclosed. The force acts on the legs and three-dimensional trajectory is the foundation to disclose locomotion mechanism of water spider and to design biomimetic water-walking robots with a higher efficiency. However, few former researches provided time-averaged force, three-dimensional trajectory of a leg during walking forward.

In a former study, we reported a shadow method that can be used to measure the floating forces of individual water strider legs at a static state.[18,19] In this study, this shadow method is adopted to observe the leg movement of water spider during walking forward, and to quantitatively analyze the forces acted on the propulsive legs during its locomotion on the water surface. These results are helpful to understanding the locomotion principles of water spider during walking forward and guiding the design of water walking robots with more appropriate control of motion parameters.[20–23]

2. Results

2.1. *In vivo* leg shadow capturing

Illuminated by a point light, lemon or ellipse shape shadows of water spider legs can be observed as shown in Fig. 1(a) with an apparatus as sketch in Fig. 1(c). The shadow mainly comes from the light refraction of the distorted surface pressed by the hydrophobic legs of water spider. The leg shadows are axisymmetric at a static state as shown in Fig. 1(a), showing the curvatures of surfaces are also axisymmetric.

To generate propulsive forces during walking forward, the legs of water spider pressed down impulsively. And then the water was pushed backward by the hydrophobic leg. The shadow of a propulsive leg is non-axisymmetric as shown in the inset of Fig. 1(d). According to former researches, the profile of the walking distorted dimple depth, h, is governed by the following equation[11]

$$h \sim C_0 x^{-7/2} \sin\left(-\frac{4x^3}{27} + \frac{\pi}{4}\right), \tag{1}$$

where C_0 is a constant, calculated by the width of shadow (on the left of y axis), x is horizontal coordinate, as indicated in the inset of Fig. 1(d).

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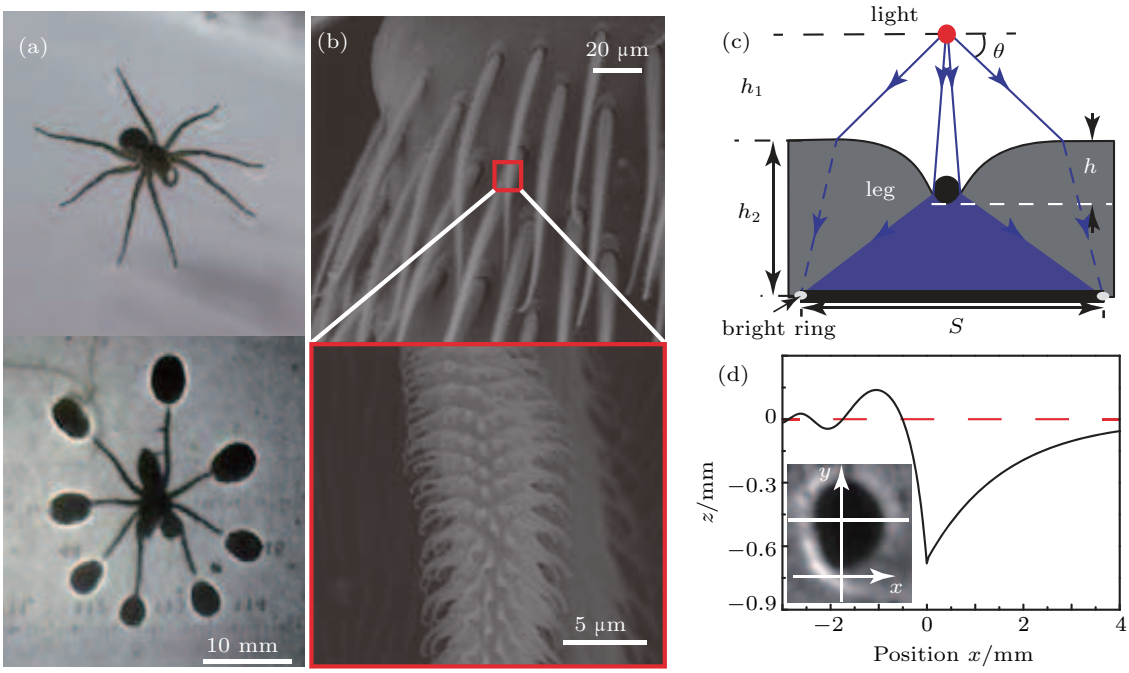


Fig. 1. (color online) Shadows of superhydrophobic legs of water spider under point light illumination. (a) A water spider standing on water surface and a typical water spider shadow on the bottom surface of vessel. (b) Micro-morphology of a water spider leg with nanometer saw teeth on each hair. (c) Sketch of the shadow taken method in laboratory. (d) A typical water spider leg shadow and the distorted water surface profile section.

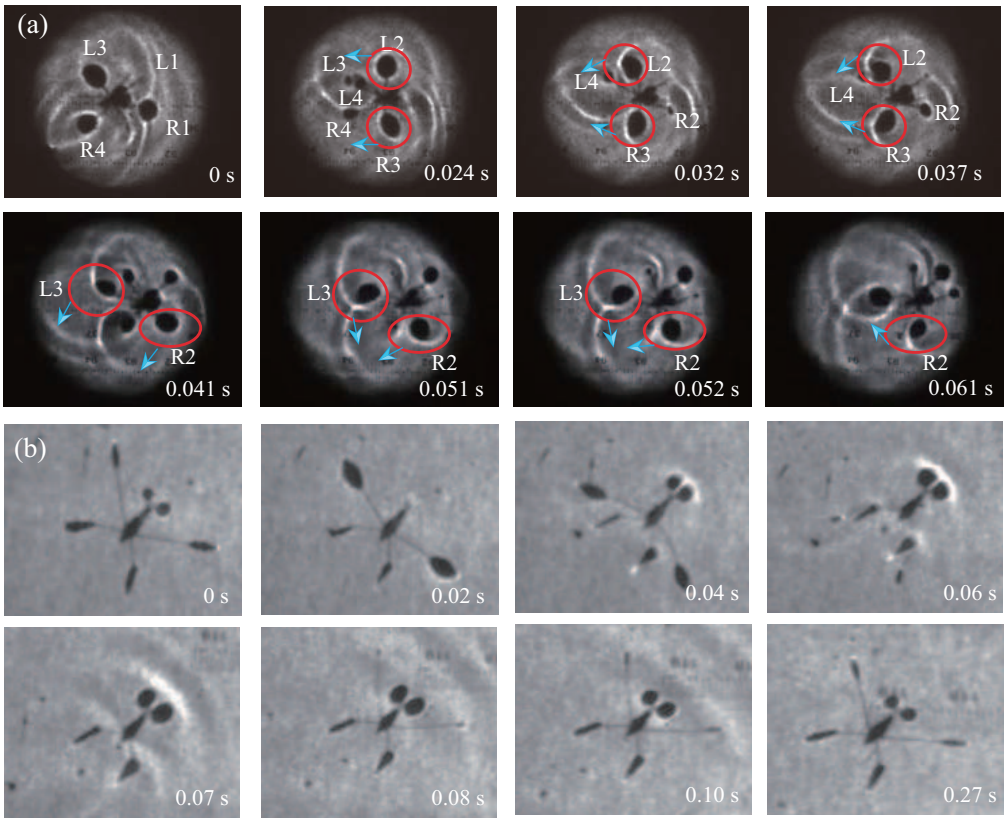


Fig. 2. Leg shadows of water spider (a) and water strider (b) in walking forward. Scale bar-rulers were on the background of the images.

By considering each surface profile corresponding to a shadow width distorted, the water surface profile can be achieved from the shadow width of leg.[18] The gravity of expelled water volume of profile is equal to the floating force acted on leg according to Archimedes' principle.[12,13] The floating force acted on the leg, F_{n}, could be obtained by integrating all of the force strength.

The lateral force, F_{t}, is calculated according to former researches as

$$F_{\mathrm{t}} = F_{\mathrm{L}} + F_{\mathrm{d}}, \tag{2}$$

where F_d is the drag resistive caused by the fluid viscosity, F_L is the resultant of forces caused by the momentum conservation. F_L can be expressed as

$$F_L = \rho A U \Delta U, \tag{3}$$

where ΔU is the acceleration of velocity U, ρ is the fluid density, A is the area of the water surface profile.

F_d can be expressed as

$$F_d = 0.25\rho S_f U^2(1 + 10Re^{-2/3}), \tag{4}$$

where $Re = UL/\nu$ is the Reynolds number. $S_f = \pi hL/2$, L is the length of the walking leg's tarsal segment. For fresh water, ν is the kinematic viscosity of water at 20 °C (1.01×10^{-6} m^2·s^{-1}).

2.2. Actions of slap and stroke

A large size water spider (such as the weight above 35 mg) usually produces fuzzy leg shadows in walking due to its leg penetration into water surface. So a smaller water spider (10 mg) is used in the study. The shadow of a water spider walking forward is shown in Fig. 2(a) and Movie1 (Multimedia view). R1 stood for the first right leg, R4 stood for the fourth right leg. L1 stood for the first left leg and L4 stood for the fourth left leg. The status of leg motion, such as walking backward, contacts with water surface and dragged by body or apart with water surface, can be observed with its shadow. As shown in Fig. 2(a), at 0 s, three legs contacted with water: R1, R4, and L3, while others lift up without contacting with water surface. R4, is dragged by its body, losing energy at this leg. L3, whose shadow is non-axisymmetric shadow, scull backward to propel the body.

As shown in Fig. 2(b) and Movie2 (Multimedia view), all the eight legs of a water spider are utilized as propulsive legs or supporting legs during walking forward, which are much different to water strider. Only middle legs of water strider paddle water surface to provide propulsive force to body.[5] The back legs of water strider are used as supporting leg, which contact water during walking process, the front legs would contact water surface ahead of the propulsive legs to land the body as a cushion.

2.3. Force on the leg of water spider walking forward

The vertical supporting forces F_n and the lateral propulsive force F_t are measured based on leg shadows according to Archimedes' principle and dynamic analysis. Figures 3(a), 3(b), and 3(c) showed the floating forces of legs of a water spider in walking forward. Figure 3(d) shows the lateral forces of propulsive leg L2 and R3 of water spider in walking forward. During the whole walking cycle, the sum of supporting forces acts on the water spider legs fluctuated slightly between 100 μN to 120 μN. The maximum floating force of a single leg is about 45 μN (about 45% of body weight). The maximum force strength is 56 mN/m and less than the critical strength, $2\sigma = 144$ mN/m, at which the leg will penetrate the free water surface. The force of water spider during walking is less than water strider jumping upward.[5]

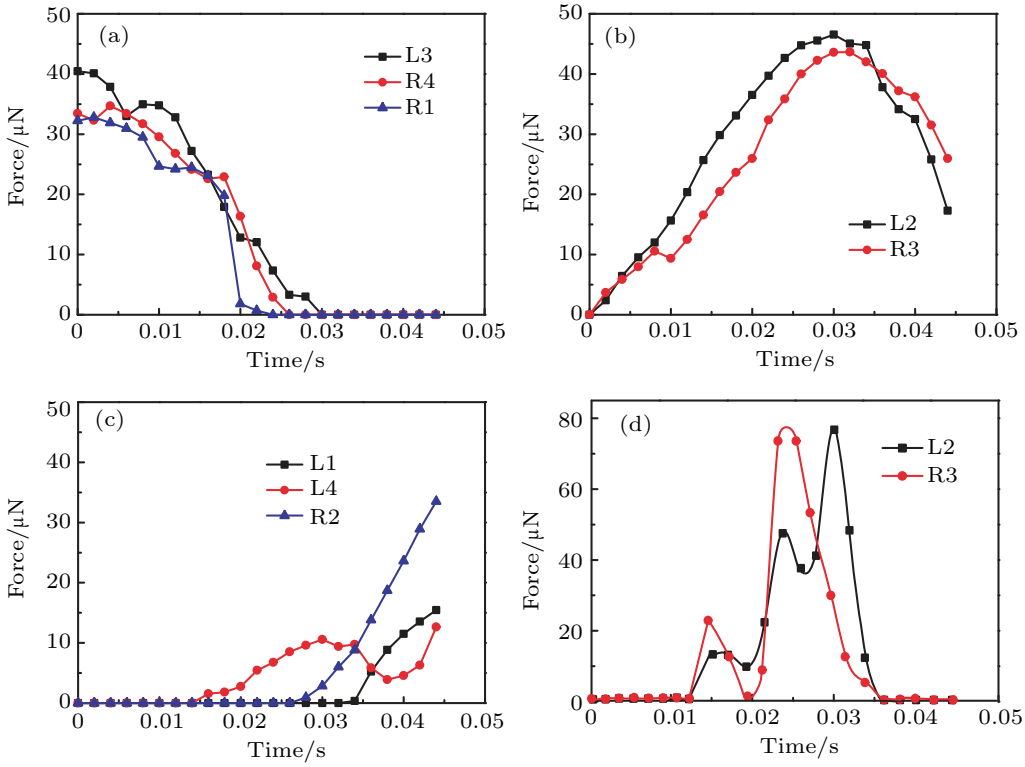


Fig. 3. (color online) The forces of water spider legs in walking forward. (a) The floating forces of legs L3, R4, and R1. (b) The floating forces of legs L2 and R3. (c) The floating forces of legs L1, L4, and R2. (d) The lateral forces acted on legs L2 and R3.

During 0.015 s ∼ 0.037 s, the maximum U is 0.2014 m/s. The maximum Re is 997, which is similar to the Reynolds number of the water strider during walking forward of about 1000.[2] The average values of the propulsive force of legs L2 and R3 at a stroke state are about 26.8 μN and 23.7 μN (about 24% and 21% of body weight). The maximum sum of the two propulsive forces is about 121 μN (about 120% of body weight). The maximum propulsive force of single leg is 74 μN, the maximum force strength is 92.5 mN/m.

3. Discussion

The three-dimensional trajectory of a water spider leg is very difficult to be achieved by traditional method. Gao *et al.* had simulated the propulsion of the water walker by using numerical method and an idealized leg trajectory.[15] A real trajectory of the stroke is unavailable at that time, which should be very useful for disclosing the principle of the locomotion. The shadow method can accomplish the task by measuring the plane coordinates and the maximum pressed depth of legs simultaneously. The three-dimensional trajectory of propulsive leg can be obtained when contacts with water surface, however if the leg departs from water surface, the trajectory cannot be measured. The trajectory of leg L2 of water spider in walking forward is shown in the Figs. 4(a), 4(b), and 4(c). The sketch of leg movement of water spider is shown in Fig. 4(d).

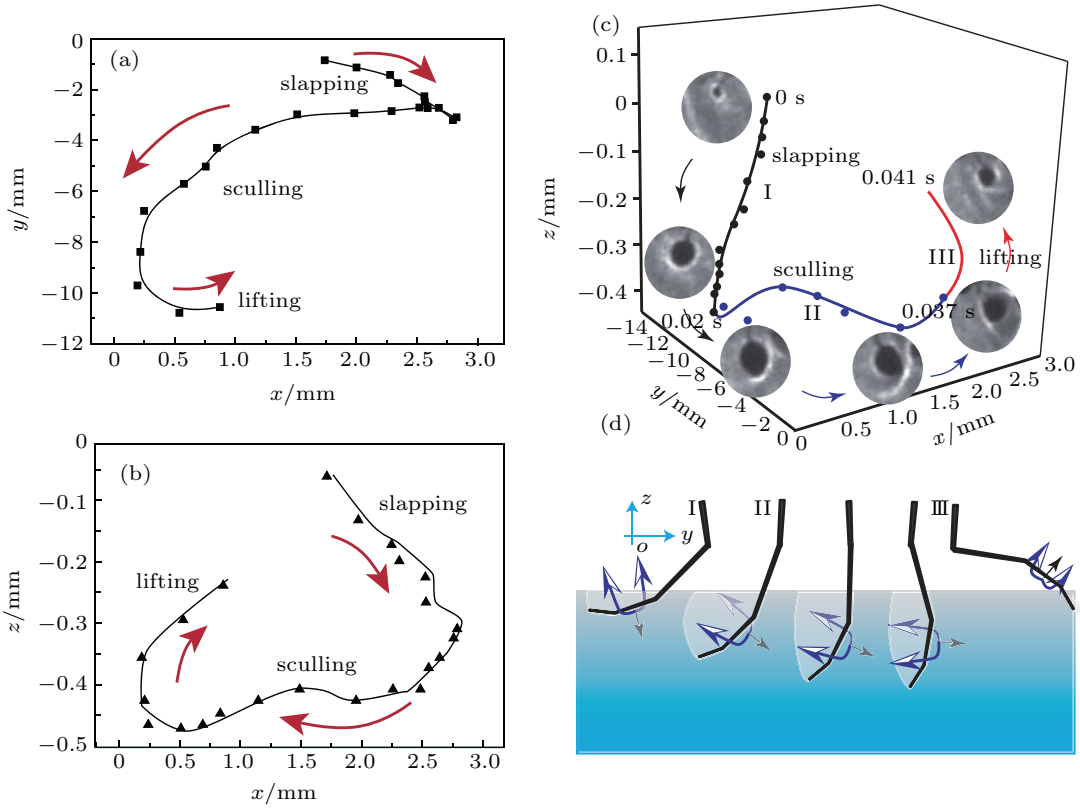


Fig. 4. (color online) Three dimensional trajectory of leg L2 of water spider in walking forward relative to its own body. (a) The trajectory in x–y plane. (b) The trajectory in x–z plane. (c) The three-dimensional trajectory. (d) The schematic plot of the leg movement of water spider.

The leg movement of a water spider leg during walking can be divided into three phases: the slap, stroke, and retrieving. A complete cycle of L2 (left 2) is shown in Fig. 2. In slap state the leg is pressed down to the water surface. From 0 s∼ 0.02 s, the legs L2 pressed down (slap) to support its body. The leg shadows are axisymmetric, indicating the profiles of water surfaces are axisymmetric. The stroke in the walking process is used to generate propulsive force. From 0.02 s, the leg L2 starts to propel the body by pushing backward. The leg shadows are non-axisymmetric because of the distorted profile of water surface under lateral hydrodynamic pressure of water. From 0.037 s, the legs L2 starts to lift up (retrieve) to reduce the water resistance. The leg shadows at this state are axisymmetric.

In this study the water spider can move 0.1 m in one second, 10 times of its body length, 10 mm, during walking forward. As shown in the force acted on legs of water spider and its trajectory, a strategy of water spider is used to scull forward rapidly and efficiently. The propulsive legs generate a large vertical force to support its weight of body (the depth of propulsive leg is about 0.45 mm) and simultaneously increases the propulsive force. In this way, a water spider can experience much less water drag resistance from other legs. If non-propulsive legs are used to support body, these legs will contact with water, cause some drag resistances and reduce the energy efficiency. As recently reported, the efficiency of a wa-

ter strider robot designed by Metin Sitti is about 6% with a maximum speed of about 0.03 m/s.[7] Most of the weight of water walking robot are supported by the non-propulsive legs contacted with water throughout the walking process.

4. Methods

A water spider is put into an acrylic (PMMA: polymerthylmethacrylate) vessel (10 cm×15 cm×20 cm, with a wall thickness of 5 mm), filling with a deionized water with a depth of 50 mm. A 3-W white point light source (ZHPL-0803, Beijing Hezhong HangXun Sci. Tech. Corp. China) is placed 1000 mm right above the vessel to irradiate the water spider residing above water surface to generate shadows of the legs on the white paper attached to the bottom of the vessel outside. The shadow images are captured by a camera (MQQ13 MGON, 1000 Hz, 1024 × 512, Beijing Hezhong HangXun Sci. Tech. Corp. China), whose size of pixel is 5.3 μm. An object lens of HX8X-T65D with a magnification of 0.1.

5. Conclusion and perspectives

In summary, the time-averaged force, three-dimensional trajectory of water spider legs in walking forward, and their subtle behaviors, such as lifting legs at the end of a walking stroke had been disclosed and quantitatively analyzed by a shadow method. These results can be used to guide the design and control of sculling motion of biomimetic water-walking robots with a higher efficiency. This method can also be easily extended to the analysis of other water walking arthropods locomotion of jumping and turning.

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