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Citation: Chin. Phys. B, 2020, 29 (**12**): 124703. DOI: 10.1088/1674-1056/abb7ff
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Revealing stepping forces in sub-mg tiny insect walking*

Yelong Zheng(郑叶龙)[1], Wei Yin(尹维)[2], Hongyu Lu(鲁鸿宇)[2], and Yu Tian(田煜)[2,†]

[1] *State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin* 300072, *China*
[2] *State Key Laboratory of Tribology, Tsinghua University, Beijing* 100084, *China*

(Received 5 August 2020; revised manuscript received 8 September 2020; accepted manuscript online 14 September 2020)

Measuring walking forces of small or tiny insects can help the comprehension of their locomotion principles. However, as their size and force are generally too small, walking forces of small insects in sub-mg mass have never been actually measured. In this work, a convenient multi-lens and jelly surface based shadow method was developed for simultaneous multiple walking forces measuring, ranged from nN to mN with a sensitivity of sub-nN/pixel under ambient conditions. Walking force of six legs of a 0.3 mg water treader was demonstrated. The obtained results disclosed a rapid and extending middle leg strategy of water treader in walking forward above a jelly surface. This method is cost-effective and high-resolution, which could be easily used in measuring other tiny forces.

Keywords: tiny force, shadow, walking forward, bean jelly

PACS: 47.55.df, 47.55.D−, 68.03.−g **DOI:** 10.1088/1674-1056/abb7ff

1. Introduction

Small-size robots inspired by insects can be used in many conditions. However, a small-size bionic robot is hard to run fast, which is limited by the small structures and actuators, although small-size creatures usually can run rapidly. There is still a big gap between the bionic robots and the imitated creatures. One of the reasons is that their locomotion mechanism has not been clearly revealed, which limits the design of bionic robot. Therefore, it is interesting and important to understand the locomotion mechanisms of insects to guide for the design of advanced bionic robots.

Recently, several methods have been developed to measure forces of animal legs by using commercial force platforms.[1,2] The forces acted on legs of geckos,[3] cockroach,[4,5] ant,[6,7] and guinea fowl[8] have been tested to uncover their locomotion mechanism. Dai *et al.* designed a force-measuring array which consisted of 16 separate 3D force sensors.[3] They measured the reaction forces acting on each individual foot of moving geckos on inverted, vertical, and horizontal substrates by this setup. To uncover the mechanism of insects running on elastic surfaces, Full measured the animal's center of mass dynamics using a novel accelerometer backpack.[4] Gorb measured the adhesion force on the attachment pads of insects.[5] Federle revealed the function of shear forces during locomotion for insects combining measurements of both pad area and whole-body adhesion force.[6] Goldman measured the single leg–wall reaction forces and mass center dynamics in death-head cockroaches by a three-axis force plate.[7] Daley measured the ground reaction forces acted on the leg of legged terrestrial animals by a force plate to study dynamic stability over rough terrain.[8]

However, the commercial force platforms cannot measure the force of tiny insects. Several nanomaterials have been developed to improve sensitivity to measure forces acted on legs of insects in a natural state.[9–11] A nanocomposite of silver nanowire network and polydimethylsiloxane (PDMS) elastomer was also used to design a strain sensor for the motion detection of fingers with a resolution of 2.9 μN, which is too large to measure forces acted on the legs of small insects.[10] Jiang proposed improved piezoelectric sensing nanofibers using nanoparticles to measure the movement of a walking ant, with a mass of 1 mg, lifting three legs simultaneously.[12] The impact force acted on the three legs of the ant would produce charge output, which is about 3.8 μN. The noise of the sensor without any load is about 0.4 μN. This method could not measure the force acted on a single leg. What is more, the low signal-to-noise ratio hindered the accurate force measurement. Researchers have done a lot of work to increase the gauge factor of the force sensors to improve the sensitivity. The maximum gauge factor in the former researches is about 50, which cannot accurately measure such small force.[9] In the existing method, the impact force associated with the footsteps of a small spider with a maximum resolution of 0.62 μN can be obtained.[9]

In our former research, a shadow method was used to achieve a sensitive force measurement of sculling legs of water strider.[13] The force acted on multiple legs of insects in locomotion was measured simultaneously at nN level with the shadow method.[13] In this study, the shadow method was extended from the liquid surface to solid elastomer materials, such as transparent colloids. The improved system could be used to measure the forces acted on the legs of water tread-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 51323006 and 51425502).
†Corresponding author. E-mail: tianyu@tsinghua.edu.cn
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ers and other tiny insects, who could run rapidly on soft surface[14] as shown in Fig. 1(a).

2. Results

Water treaders (with a weight of 0.3 mg) usually leave clear rounded inner dark shallows with bright rings outside on the CCD under paraxial light illumination, as shown in Fig. 1(b), with a multi-lens system as shown in Fig. 1(c). In this apparatus, a white light source, which was placed 1000 mm right above the solid elastomer, irradiated on the insect walking on the elastomer to form shadows on the bottom screen of the vessel.

In experiments, as the transparent substrate was distorted by the legs, leading to a meniscus. The leg shadows with bright edges were caused by the light refraction of the meniscus. The depth of the meniscus can be calculated as[15]

$$h(x,R,P) = \frac{(1-\nu^2)P}{\pi E}\left\{(x+R)\ln\left(\frac{x+R}{R}\right)^2 - (x-R)\ln\left(\frac{x-R}{R}\right)^2\right\}, \quad (1)$$

where ν is the Poisson's ratio, E is the Young's modulus, R is the radius of a leg, x is the position on x-axis, and P is the pressure.

To improve the sensitivity of force measuring, two methods were taken: (1) Bean jelly embedded with nanofibers lignin was used as a novel force substrate material. (2) A multi-lens system was designed to amplify the shadows.

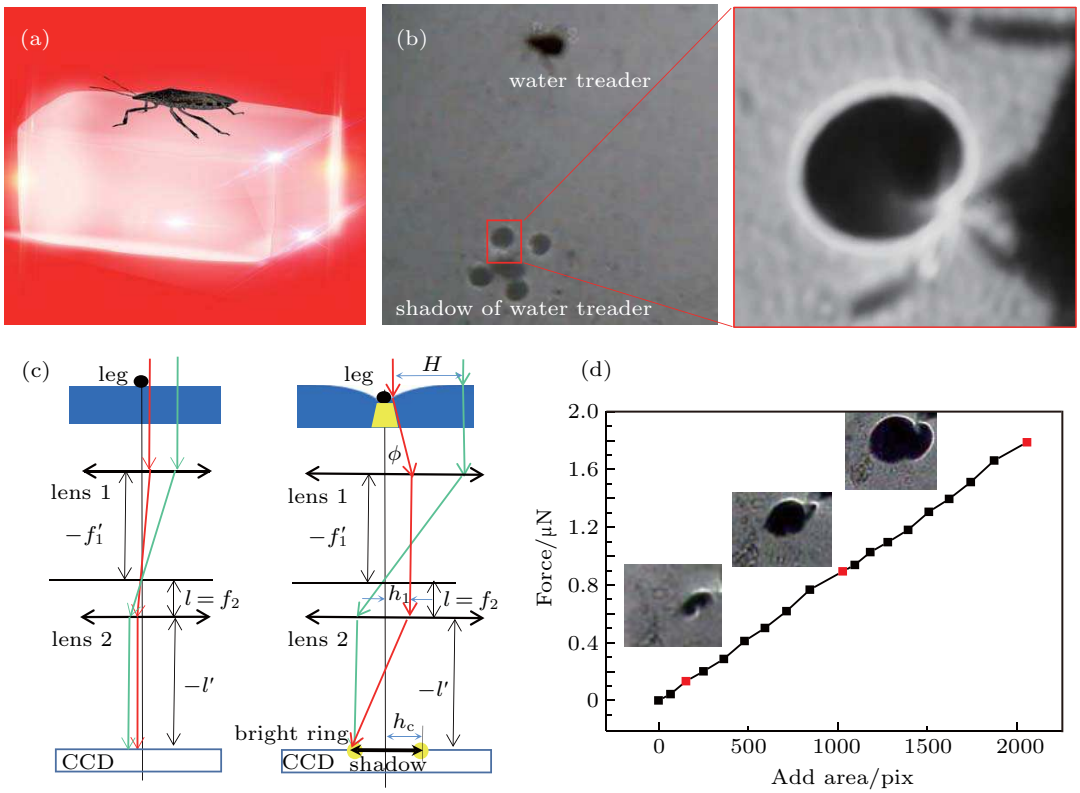


Fig. 1. Shadows of hydrophobic slim poles on transparent elastomer under point light illumination. (a) A water treader on BJNF surface. (b) A shadow of water treader. (c) Light path diagram of the force measurement system. (d) Calibration result of force and shadow area.

2.1. Force measurement using bean jelly–nanofiber

A Chinese food bean jelly was used as a novel force substrate material that is highly sensitivity to forces acting on the legs of animals and insects in their natural state. To increase the hardness of the jelly, nanofiber (lignin powder) was added to the bean jelly. Young's modulus of bean jelly was 0.0078 MPa, which was measured by a self-made force measurement setup. One leg shadow corresponds to a force of 0.5 μN. One leg shadow occupies about one-hundredth of the whole image of a typical camera of approximately 30 million pixels (such as Nikon D 810). Hence, the force measurement sensitivity could reach about 0.2 nN/pixel level.

As a kind of environmental friendly functional material, the bean jelly has the features such as easy-biodegradation and innocuity. The method of fabricating bean jelly–nanofiber (BJNF) is as follow:

Step 1. Mix 10 g starch, 10 g cold water, and 10 g nanofiber.

Step 2. Heat 90 g water to 100 ℃.

Step 3. Mix the mushy cold jelly into the boiled water.

Step 4. Heat the mixture and mix it for approximately 5 min.

Step 5. Put the mix into a transparent box at 20 ℃ for approximately 30 min.

2.2. Multi-lens system

When legs of water treader were pressed on BJNF, a meniscus would occur on the surface of BJNF. When the lights passed through BJNF, refraction would occur. As the pressing depth of leg increased, the refraction angle would increase, as shown in Fig. 1(c). The maximum refraction angle was very small due to the tiny force. The shadow without any optical system would be very vague.

A multi-lens system was designed to focus these lights in which f_1 and f_2 are focus lengths of these two lenses. The bottom of the vessel was placed above lens 1. The size of bright ring, h_1, can be calculated by

$$h_1 = f_1 \tan(\phi). \tag{2}$$

For $\phi = 1^\circ$, $f_1 = 10$ mm, h_1 can be calculated as 0.17 mm. However, the shadow size is too small to character the forces. Accordingly, another lens was used to amplify the shadow. The size of shadow, h_c, can be calculated by

$$\frac{h_c}{h_1} = \frac{l'}{l}, \tag{3}$$

where l is the distance of lens 2 from the focal plane of lens 1, and l' is the distance between lens 2 and CCD. In this way, a clear shadow with bright ring could be formed on the CCD.

To calibrate force measurement based on the shadow, an electronic balance (ME235S, Sartorius Corp., resolution 0.01 mg) was used to measure the vertical force acting on a treader leg. The isolated leg was pressed on the surface of the BJNF by a precision stage (with 1 nm resolution). The leg shadow and the force were simultaneously captured by a camera and the electronic balance.[16–19] The relationship between the area of leg shadows and the force is shown in Fig. 1(d). The results showed that the force approximately increases linearly with the increase of press depth.

3. Discussion

The proposed method can measure the vertical force acting on legs of insects during walking forward, which could be used for biomechanics and biomimetic design of various robots.[20] As an example, a small water treader (0.3 mg) was used in the present study. To obtain the whole period of walking forward, a large field view lens was used, whose magnification was 1. The typical shadows of the water treader in walking are shown in Fig. 2(a) and Movie 1 (multimedia view).

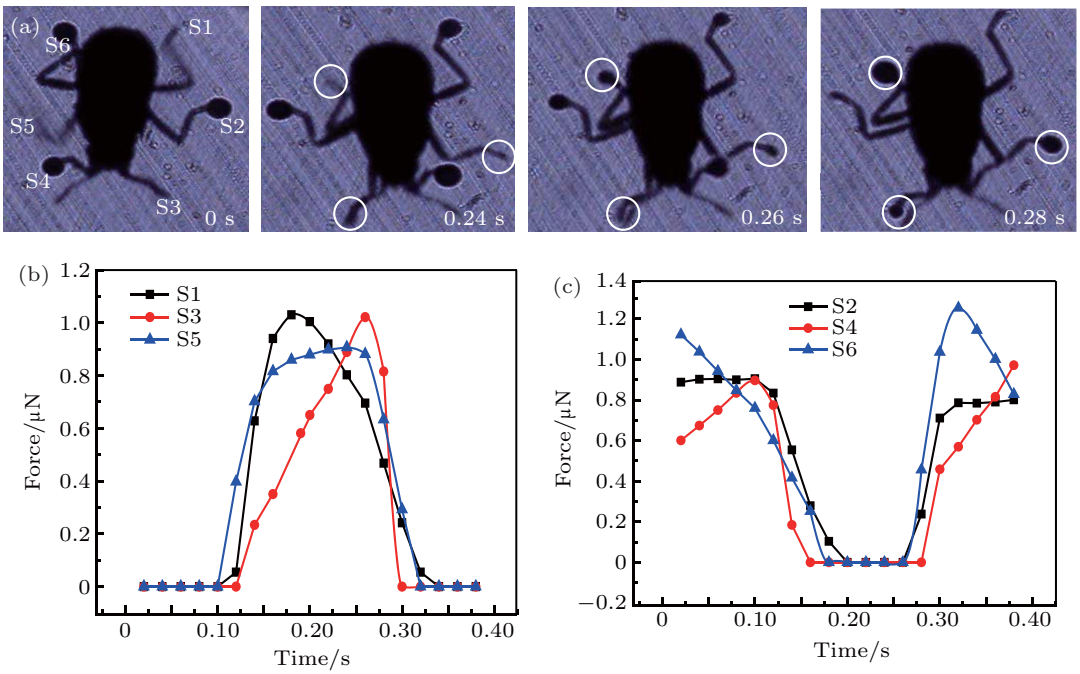


Fig. 2. Shadows of water treader legs in walking forward and the vertical forces acted on the legs. (a) The shadow of water treader in walking forward. (b) and (c) The vertical forces on the legs of water treader.

In the walking acceleration phase, the driving forces were generated by the backward swing of the middle leg with the help of the middle and front legs on the other side. At 0 s, the middle leg (S2) swung forward. At the same time, the back and front legs on the other side also swung forward. The swing motion of these three legs lasted approximately 0.25 s. At about 0.1 s, the swing legs alternated to legs S1, S3, and S5. The alternation lasted about 0.05 s, during which all six legs contacted the substrate. The middle right-side leg of water treader (S2) and the back left-side leg (S6) synchronously swung forward.

The vertical supporting forces F_n were measured based on leg shadow. Figures 3(b) and 3(c) show the supporting forces of the legs of a water treader in walking forward. During the

whole walking cycle, the maximum vertical force acted on a single leg was approximately 1.2 μN (∼ 40% of body weight).

The velocity of a water treader (with body length ∼ 1 mm) can reach approximately 3 mm/s, about 3 times the length of its body per second. As shown by the forces acting on the legs of the water treader and the trajectory of the legs, the strategies of the water treader were to swing legs forward as far as possible and control the contact time with the substrate (see Fig. 3). To enlarge the amplitude of the swing, the front and back legs were kept close to its body. To balance the moment of the whole-body during walking, the water treader tuned this distance (see Fig. 3).

When walking forward, the distance from the tip of the middle leg to the center of the body, L_{M}, is much larger than that from the front and back legs to the center of the body, L_{F} and L_{B}. The force on the middle leg is approximately 0.9 μN, which is almost equivalent to the average of the forces acting on the front and back legs.

The BJNF is too soft to support an arthropod with large weight. For example, a crab would penetrate the surface.[21] The substrate should be altered to PDMS to support the weight of larger arthropods. Young's modulus of the PDMS was 3.18 MPa. As an example, the forces acting on the legs of an ant (with a weight 2 mg) and the legs of a crab (with a weight of 31.7 g) in walking could be quantified using the data of *ex vivo* calibrations (see Figs. 4(b) and 4(c)). By changing the substrate, the proposed method could measure the force from nN to N levels.

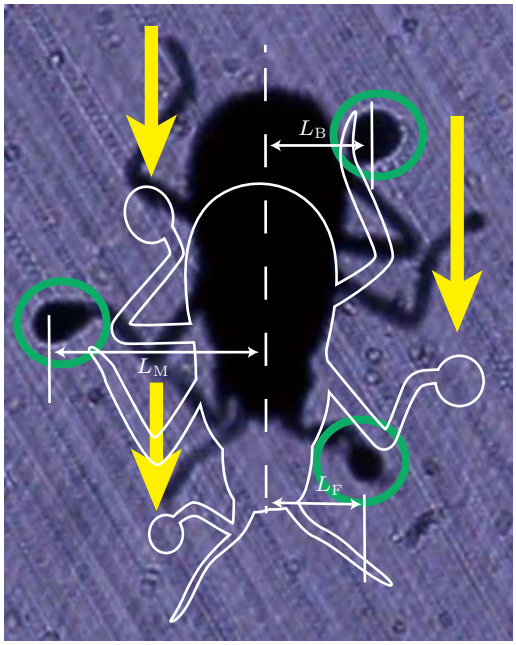


Fig. 3. Strategies for water treader walking rapidly.

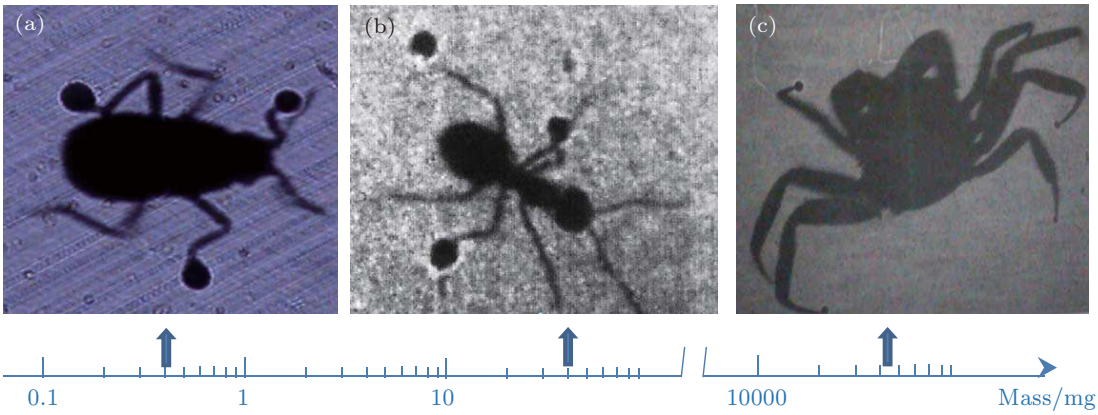


Fig. 4. Typical shadow of water treader (a), ant (b), and crab (c) obtained in the laboratory.

4. Conclusion and perspectives

A novel method is presented which is capable of high sensitivity measurement of the vertical force acting on the leg of an insect with weight from sub micro gram to several gram levels. Unfortunately, the lateral force acting on the leg could not be measured using the proposed method. Accordingly, future work will involve designing a new mechanism that is sensitive to the lateral force.

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