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Micronanostructures of the scales on a mosquito's legs and their role in weight support

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We show here that the mosquito cannot only give rise to a higher water-supporting force than the water strider if the ratio of the water-supporting force to the body weight of the insect itself is compared, but also can safely take off or land on the water surface, and also can attach on any solid surface like the fly. We found that the mosquito's legs are covered by numerous scales consisting of the uniform microscale longitudinal ridges (nanoscale thickness and microscale spacing between) and nanoscale cross ribs (nanoscale thickness and spacing between). Such special delicate microstructure and/or nanostructure on the leg surface give a water contact angle of ~153° and give a surprising high water-supporting ability. It was found that the water-supporting force of a single leg of the mosquito is about 23 times the body weight of the mosquito, compared with a water strider's leg giving a water-supporting force of about 15 times the body weight of the insect.

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There are two biological movement phenomena that have attracted us for a long time: (a) why some small insects (usually with body mass less than 1 g), such as the water strider can float and glide effortlessly on the water surface [1–4], and (b) why some small animals and/or insects, such as the gecko [5–8], fly [9–13], etc., can run on a vertical wall or a smooth glass surface, and even on ceilings against its body weight. Studies [1–4] reveal that water striders have long hierarchically hairy legs that enable them to have the remarkable hydrophobic ability. These unique hierarchical hairy structures are responsible for the insect leg's superhydrophobicity and the strong water afloat ability, and make it so easy for the insect to stay, walk, run, and play just on the water surface. There are two means of walking on water according to the relative magnitudes of the body weight and the maximum curvature force associated with the surface tension [3]. If the ratio of the body weight to the curvature force is greater than 1, such water walkers as the basilisk lizard rely on the force generated by their feet slapping the water surface and propelling water download [14]. However, such insects with the ratio less than 1 as the water strider may reside at rest on the water surface, and are supported mainly by the curvature force generated by the distortion of the free surface. Bush and Hu [15] have recently given a very good review for the hydrodynamics of walking on water. The strong adhesion ability of the gecko is due to the van der Waals interaction between a contacting surface and hundreds of thousands of keratinous hairs or setae (nanoscale in diameter) on the gecko's foot pads [5–8]. Several adhesion skills are coupled together to give rise to the strong adhesion ability of the fly [9–13]. The skill of being able to reside and run on the water surface or to attach on any solid surface as mentioned above is very important for each of them to feed or to escape from an attack. Mosquito is a small insect that can not only reside effortlessly on the water surface partially like the water strider, but also can lay eggs, safely take off or land on the water surface, and can also attach on any solid surface like the fly. However most of the previous studies on mosquitoes were focused on the harmful sides that they bring to human beings [16,17]. Among the special skills of the mosquito, the water afloat ability may be the most surprising.

The average body weight of the studied mosquitoes captured in Dalian area of China is about 26 μN. The typical length of the adult mosquitoes is about 5–6 mm, which is almost the same as that of the *aëdes aerypti* with a characteristic length ~5–7 mm [16]. The mosquitoes have six long and scaly legs of characteristic length 7–10 mm, with a diameter ranging from 80 μm (foreleg) to 210 μm (hind leg). Each leg has seven sections fully covered by a large number of the oriented micrometer scales excluding the foot's pads. Scanning electron microscope (SEM) observation revealed that the scales on the leg surface have patterned microstructure and/or nanostructure (see Fig. 1). In the longitudinal direction of the scales (along the leg) there are about one-half to one dozen of the straight ridges. The spacing between the longitudinal ridges on a single scale is often quite uniform, ranging from 1.5 μm to 2 μm depending on species and scale type. The longitudinal ridges have a thickness of about 200–250 nm. In between the longitudinal ridges are numerous fine transverse ribs or cross ribs with the spacing between ranging from a few hundred nanometers to about 1 micrometer. The cross ribs have a thickness of about 100 nm. The longitudinal ridges are connected at intervals by a series of the cross nanoribs. Besides the mosquito's legs, the insect's body, wings, and the proboscis' labium are also partially covered by the similar scales. The scales on a mosquito's legs are quite similar to those on a butterfly wing [18,19]. However, for some butterflies the regions between the ridges and cross ribs of the scales are hollow. The main function of the butterfly's scales is to change its color and to adjust the body temperature [18,19]. Such microstructures and/or nanostructures as found on a mosquito's legs are believed to be at least responsible for its high water-supporting ability. The air trapped in the spaces between longitudinal ridges and cross ribs may form nanocushions at the leg-water interface that presents the legs from being wetted, as a result

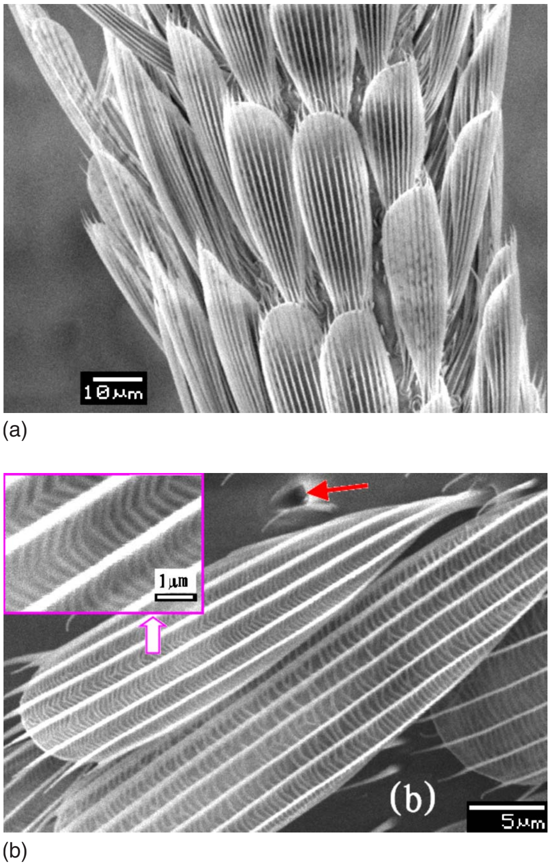


FIG. 1. (Color online) The hierarchical microstructures and nanostructures of the scales on a mosquito's leg (the fifth section of the hind leg). (a) The numerous scales on the leg surface oriented along the leg; (b) the elaborate arrangement of the longitudinal ridges and the cross ribs. Note the scale's theca as the (red) arrow points.

a mosquito can stay on the water surface quietly as long as it wants. The microroughened and/or nanoroughened scales of the mosquito leg gives a similar water-repellent effect as the lotus [20].

The contact angle of water on the mosquito's leg surface is found to be ∼153°, measured using Dataphysics ocah 200. Cassie's law for the wettability of a rough surface shows that the apparent contact angle of water θ is described by $\cos\theta = (1-f)\cos\alpha - f$, where α is the contact angle of water on the same smooth material surface as the mosquito leg, f is the air fraction between the leg and the water surface. A similar analysis using the Cassie's law as Gao and Jiang [4] shows that $f = 85.3\%$ if we take $\alpha = 105^\circ$ as what Holdgate [21] gave for the water strider cuticle.

We measured the water-supporting force of a single hind leg of the mosquito using the test system as shown in Fig. 2(a). The hind leg was adjusted to have an angle of about 30° with respect to the water surface. This angle is what a mosquito usually likes to use to land on a water surface. The measured maximum water-supporting force ranges from 540 μN to 735 μN, giving the average value of 600 μN which is about 23 times as large as the body weight of a single mosquito, compared with a water strider's leg [4] giving a water-supporting force of about 15 times the body weight of the water strider. A typical curve of the water-supporting force versus the moving displacement of the test machine is given in Fig. 2(b). When the long tiny hair on the mosquito's foot back started to touch the water surface, the water-supporting force increases slowly with the displacement. Also the leg started to have a small deflection. However, after the scaly leg touches the water surface, the water-supporting force increases roughly proportionally with the

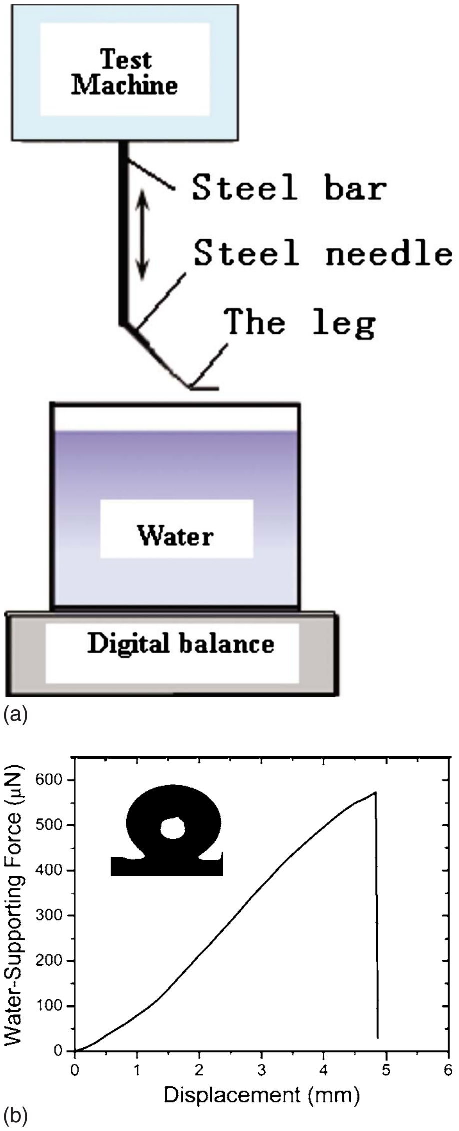


FIG. 2. (Color online) (a) The test system used to measure the water-supporting force of a single leg of the mosquito. The test machine together with the steel bar and the needle can move vertically with a controlled speed of 1 mm/min. The first section of the mosquito leg was glued to the tip of the needle. The initial angle of the leg with the water surface can be adjusted by changing the angle of the needle with the bar. The digital balance has a high precision of 0.1 μN. (b) A typical curve measured for the water-supporting force versus the moving displacement of the machine after the leg just touches the water surface. The contact angle of a water drop on the surface of the mosquito leg is ∼153° (see the inset). The temperature in the laboratory is 20 °C and the relative humidity is about 50%.

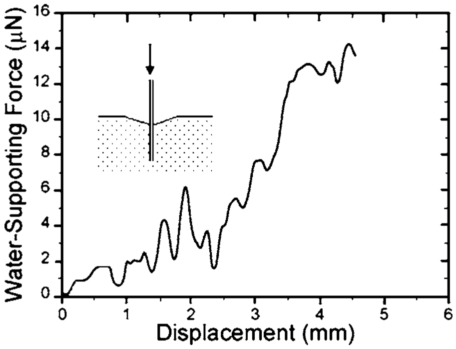


FIG. 3. The measured water-supporting force versus the moving displacement when the leg was vertically penetrating the water surface.

displacement as shown in Fig. 2(b), forming a dimple on the water surface. Finally, the supporting force reaches the maximum followed by a sudden disappearance of the dimple, i.e., the leg penetrates the water surface. After the leg was taken out from the water and then the same test was repeated again, a very good repeatability for the water-supporting force curve was obtained.

Generally speaking, the water-supporting force consists of two components: buoyant force and curvature force associated with the surface tension, generated by the dislocation of the free surface [3]. In order to check the buoyant force of the leg, we adjusted the leg as straight as possible and then moved it vertically into the water. In this case the leg can easily penetrate the water surface. Compared with the water-supporting force as indicated in Fig. 2(b), the water-supporting force measured this way is too small (~14 μN) to be considered (see Fig. 3). This indicates that the mosquito's foot's pads (detailed structure will be shown as below) do not play an important role in the water afloat ability. In such a case, the air can hardly be trapped in the spaces between longitudinal microridges and cross nanoribs on the leg's scales because air can easily escape from the space between the longitudinal ridges (see Fig. 1), indicating that the surface curvature force dominates the water afloat force of the mosquito's leg.

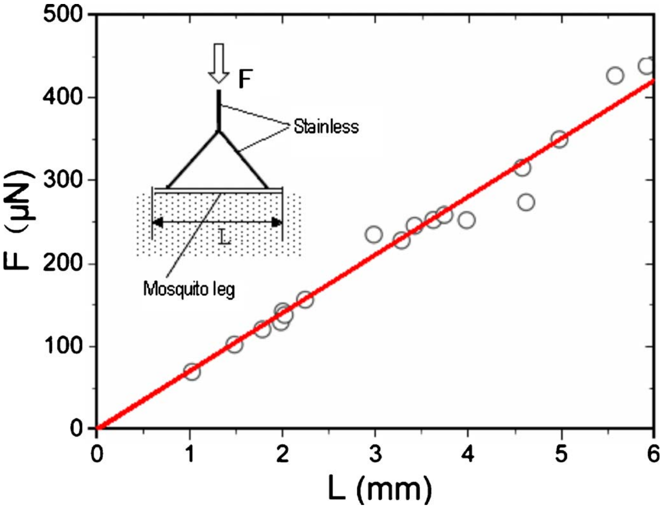
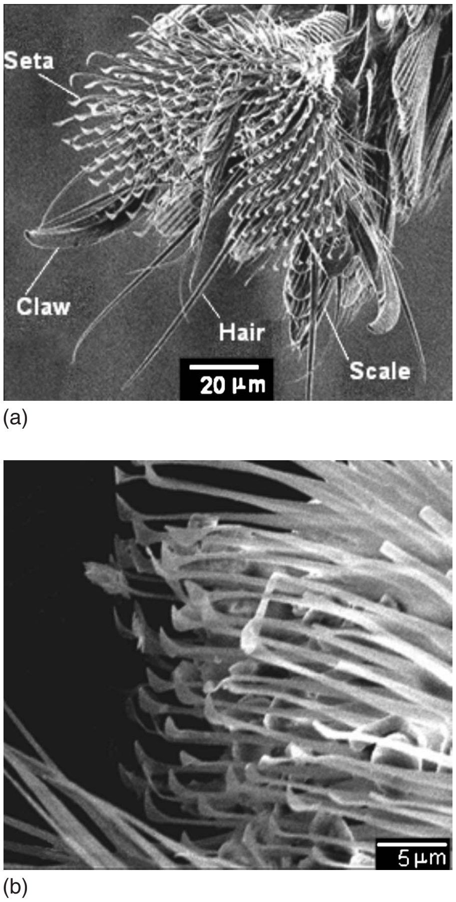


FIG. 4. (Color online) The measured water-supporting force versus the moving displacement (dimple depth) when the cut leg was parallelly pushed down the water surface.



(a)

(b)

FIG. 5. The micostructures and nanostructures of a mosquito's foot: (a) the foot consists of two claws and two first level composite pads formed by hundreds of setae, together with some long tiny hair and scales covering the foot back; (b) the sideview of the setae. On the tip of the seta there is the second level of a tiny pad, the shape of which looks like a microman's foot with length about 2–3 μm, width about 1 μm, and thickness varying from ~200 nm to ~500 nm. The diameter of the seta ranges from 200 nm to 250 nm.

We have also measured the water-supporting force of the cut mosquito's leg parallel with the water surface as shown in the inset of Fig. 4. The cut section of the leg was glued on the stainless steel tripod tips (diameter 100 μm) using cyanoacrylate instantaneous adhesive. It is found that the water-supporting force is proportional to the length of the cut leg. However, because the two ends of the cut section cannot deflect like the mosquito leg arranged as a cantilever as shown in Fig. 2(a), they can easily penetrate the water surface. The maximum depth of the dimple formed here ranges from about 1.2 mm to 2.6 mm. The shorter the cut leg, the smaller the dimple depth.

Experimental observation [16] showed that only female mosquitoes bite human and animals with their special proboscis [22,23]. The mosquito's legs firmly attach to the skin of the victim when it is stinging the skin. After its stomach is full of blood the mosquito will find a wall, ceiling or any other solid surface to stay there, sometimes, for as long as a

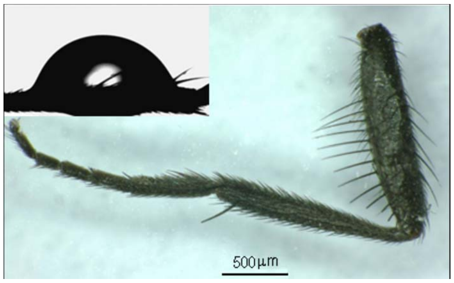


FIG. 6. (Color online) Microscope image of the hind leg of a fly. The setae on the fly leg surface are much larger than those on the mosquito's leg, giving a space between about 50–120 mm. The contact angle of a water drop on the fly leg surface ranges from ~45° to ~75°, giving a hydrophilic property.

couple of days. The adhesion function of the mosquito, contributed by its special foot pads, is similar to that of the fly [11]. Figure 5 shows the SEM image of a mosquito's foot. The foot consists of two claws, two pads (left and right) formed by hundreds of setae, and a few long tiny hairs on the foot back. The setae were arranged in uniform rows and columns. Spacing between rows (perpendicular to the claw) and columns (parallel with the claw) are ~ 5 μm and ~ 3 μm, respectively. On the tip of the seta there is a tiny pad (the second level pad) with a bottom surface area of about 2–3 square micrometers. If a man of 180 cm height having a foot length of 25 cm were reduced by 8×10^4 times, he would become a microman with a body height of 22.5 μm and a foot length of 3 μm. The shape of the tiny pad on the tip of the seta of the mosquito foot pad looks like such a microman's foot. This special design of the pads enables the mosquito to adhere to any solid surface. For hanging on to a rough surface it is believed that the two claws are used, but for a smooth surface only the setae are used (in a manner similar to a fly due to the combination action of van der Waals, Coulomb, and attractive capillary forces [13]). We found that the mosquito can attach upside down a glass surface with 1.5 nm of roughness (root of mean square), but it does not like to walk or run as the fly.

We have also measured the water-supporting force of a fly leg. It is only about 300 μN, i.e., about 3 times as large as the body weight of the fly. The contact angle of water on a fly leg surface usually ranges only from ~45° to ~75° (see Fig. 6), giving a hydrophilic property. The setae on the fly leg surface are much larger than those on the mosquito's leg, giving a space between about 50–120 μm. That may be why a fly cannot stand or run on water surface due to its hydrophilic legs. We forced an alive fly to drop on the water surface and found that it could hardly escape alive directly from the water surface. Only if it struggled and in case climbed to the bank it might escape. However, for a mosquito, it can take off from the water surface without any difficulty.

Water strider's leg surface (Gerris remigis) is covered by numerous oriented hierarchically hairy microstructures and/or nanostructures, which gives the maximal supporting force of a single leg of about 15 times the body weight of the insect [4]. However, here we found that the average water-supporting force that a single leg of the mosquito gives is about 23 times the mosquito body weight. The mosquito can safely take off or land on the water surface, and can also attach on any solid surface like the fly. We found here that the mosquito's legs are covered by numerous scales consisting of the uniform microscale longitudinal ridges (nanoscale thickness and microscale spacing between) and nanoscale cross ribs (nanoscale thickness and spacing between). Such special microstructures and/or nanostructures on the leg surface are believed to give the mosquito a surprising high water afloat ability. The mosquito can attach upside down on a nanosmooth glass surface due to its hierarchical foot pads like those of the fly.

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