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Walking on water

John W. M. Bush and David L. Hu

The ingenious methods employed by insects and spiders to move across a water surface rely on microphysics that is of little use to larger water walkers but of considerable interest to the microfluidics community.

John W. M. Bush is a professor of applied mathematics at the Massachusetts Institute of Technology in Cambridge. **David L. Hu** is an assistant professor of mechanical engineering and biology at the Georgia Institute of Technology in Atlanta.

Humans have long sought to walk on water—a feat associated with the divine, a metaphor for conquering one’s fears. Our attempts to do so have relied on portable flotation devices, but other animals, large and small, have evolved a natural ability to walk on water. For large creatures, the feat requires considerable power and skill, substantially more than we humans can muster. For small creatures, the topic of this Quick Study, it is a subtle art that relies on multiscale processes ranging from the creature-scale motion of the driving leg to the submicron-scale dynamics of the leg’s interaction with the water surface. As such, it is a rich interdisciplinary subject that engages biologists, fluid mechanics, and materials scientists.

Animals move by applying a force to their environment; the equal and opposite reaction force propels them forward. Terrestrial creatures apply forces to solid ground, generating a propulsive reaction force known as traction. Fish move their bodies so as to generate hydrodynamic forces that propel them forward; in so doing, they sweep fluid backward. Similarly, a bird hovers by sweeping air downward, and the resulting propulsive force balances its weight. Likewise, many water-walking creatures generate propulsive forces by transferring momentum to the underlying fluid; they must do so, however, across the air–water interface.

The world of water-walking insects and spiders is dom-

inated by surface tension, the property of an air–water interface that makes it behave like a trampoline. Surface tension is a tensile force per unit length that acts tangentially to the surface. It enables the surface to support small objects denser than water, such as a paper clip, a water-walking spider (figure 1a), or an insect (figure 2a). Variations in surface tension, which may result from gradients in surface chemistry, drive flow. As an emergency escape mechanism, certain insects release a chemical behind them that reduces the surface tension; the resulting force propels the insect forward (figure 1b).

The surface tension σ at an air–water interface is approximately 70 dynes/cm. Given that a dyne is the weight of a mosquito, surface tension generates puny forces on the human scale. Nevertheless, it dominates gravity at scales smaller than the capillary length $\ell_c = \sqrt{\sigma/\rho g} \approx 2.6$ mm, where ρ is the density of water and g the gravitational acceleration. Consequently, surface tension has an enormous impact on some of the world’s smallest denizens, particularly residents of the water surface. Insects and spiders have developed myriad ways of coping with and exploiting surface tension. For example, they have evolved water-repellent coats that prevent their sinking through the surface; moreover, many have adaptations enabling them to propel themselves along, clasp, or cross a water surface.

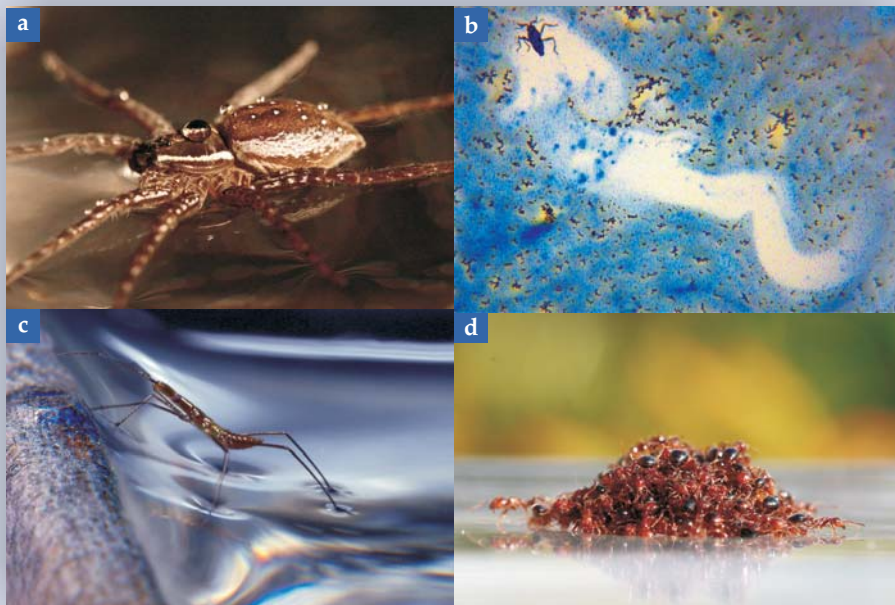


Figure 1. Microphysics enables water walking. **(a)** Surface tension serves as a trampoline that supports the weight of small water walkers, such as this fisher spider. Note the beaded drops on the spider’s water-repellent coat. **(b)** By releasing a lipid, this *Microvelia* generates a surface-tension difference that propels it forward. **(c)** Some insects, like this *Hydrometra*, can climb a meniscus by clamping it with the hydrophilic claws on its front and hind legs. **(d)** During times of flood, fire ants assemble into a floating, water-repellent raft.

Roughing it

Insects are among the most numerous and diverse creatures on Earth. Entomologists have cataloged more than a million insect species, of which roughly 90% can fly and 3% can swim. Only 1200 species, about 0.1%, have evolved the ability to walk on water—a remarkable fact given that water covers 70% of the planet. Ants and most other terrestrial insects move with great difficulty on the water surface: Lacking water-repellent coats, they typically adhere to the fluid surface, where they become ensnared. Provided they have water-repellent coats, some of the smallest insects can walk on water as if it were land; they generate traction through the microscale interactions between their coats and the surface. The most efficient water walkers have adapted to life at the air–water interface, with both their gaits and surface structures being highly specialized.

The energetic cost of wetting a solid determines whether the solid is hydrophilic or hydrophobic. Roughening a surface increases its effective surface area and so amplifies its intrinsic wettability. The rough, waxy surface of the lotus leaf, for example, has inspired the development of water-repellent surfaces now commonly used for their corrosion-resistant, drag-resistant, and self-cleaning properties. The wax renders the leaves hydrophobic and the roughness renders them water-repellent: Impinging drops encounter negligible adhesive forces and readily roll off. Similarly, water-walking insects and spiders repel water by virtue of a dense mat of waxy hairs that allows them to survive momentary submersion or impacts with raindrops. The mat also prevents water from penetrating the portals through which they breathe. Thus some insects can breathe underwater for extended periods; others, indefinitely.

The water strider is one of the most common and highly adapted water-walking insects. To generate a propulsive force, it strikes the surface with its middle pair of legs in a sculling motion. Flexible grooved hairs on the driving legs point toward the leg tips (figure 2b); similar surface microstructure on butterfly wings ensures that raindrops roll only toward the wingtips. The strider's microstructure assists both propulsive force generation during the driving stroke and adhesive force reduction during the gliding phase. Water striders row using their legs as oars, with only the tips of the leg hairs penetrating the surface (figure 2c). To the naked eye, the only visible manifestation of the driving stroke is a field of rearward propagating ripples. However, flow visualization demonstrates that those waves are accompanied by pairs of vortices that transfer momentum backward (figure 2d). The strider is typical of small water-walking insects in that it relies on surface tension for weight support and subsurface momentum transfer for propulsion.

There are insects that can propel themselves along the water surface without moving a muscle. Although the surface of a stagnant pond is flat on human scales, those parts that adjoin land and emergent vegetation have topography consisting of smooth, curved menisci with a characteristic height given by the capillary length ℓ_c . A relatively large insect can reach or leap across a meniscus, but a smaller creature cannot and so must try to glide up it—an impossible task if the creature's peak speed is less than the critical value of $\sqrt{2g\ell_c}$, about 23 cm/s. Some species have thus developed an ingenious meniscus-climbing technique that exploits the lateral forces felt between small floating bodies: They use retractable hydrophilic claws to clasp the surface and pull it upward, thereby generating a lateral force that draws them up the meniscus (figure 1c).

Some creatures can successfully navigate the water sur-

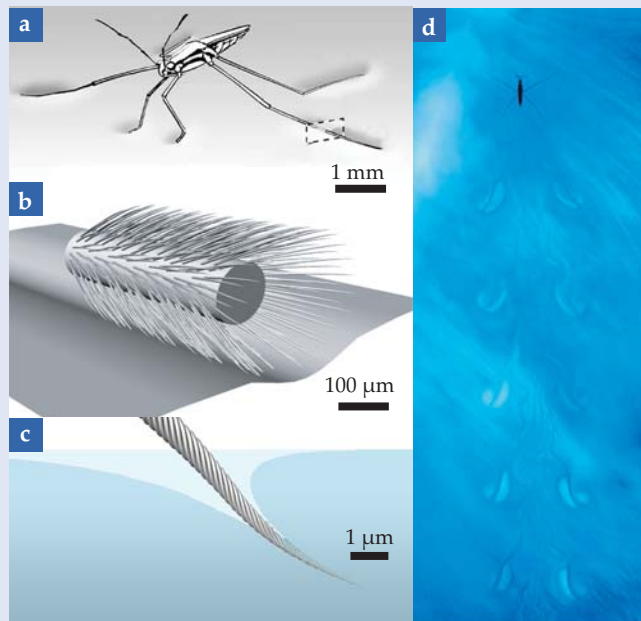


Figure 2. The sophisticated water strider. (a) The water strider has a waxy, hairy surface that renders it water-repellent and prevents it from sinking through the surface. Note the regions of interfacial curvature, or menisci, beneath each of its support legs. (b) The directionality of the strider's surface roughness contributes to its propulsive efficiency. This schematic of the strider's hairy leg is a magnification of the boxed area in panel a. (c) Visible here is an individual hair penetrating the planar water surface. When the hair is submerged, nanogrooves trap air so that the hair is not completely wetted. (d) Each of the strider's driving strokes generates a pair of vortices—one vortex for each leg.

face only as a collective. Fire ants have colonies that can number tens of thousands. Individual ants are poor water walkers, but the colony has a clever communal means of surviving floods. By linking their legs together, ants form a raft whose rough surface, corresponding to an entanglement of legs, renders it water-repellent (figure 1d). The ant raft, whose average density is 15% that of water, thus remains dry and will quickly surface if submerged. It is a natural example of a self-assembling, water-repellent body and can preserve the colony for months as the ants drift in search of a new home.

Within the past decade engineers have developed small water-walking robots with various degrees of sophistication. As is the case for other human-made water-walking contraptions, the devices generally lack the elegance and robustness of their natural counterparts, and their shortcomings highlight the importance of the anatomical subtleties of water-walking creatures. Such subtleties inform and inspire devices in microfluidics, the burgeoning field concerned with handling tiny fluid volumes and, in particular, lab-on-a-chip technologies. Many microfluidics problems present exciting new technological challenges that have long since been solved by nature.

Additional resources

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- ▶ D. L. Hu, J. W. M. Bush, "The Hydrodynamics of Water-Walking Arthropods," *J. Fluid Mech.* **644**, 5 (2010). ■