ENGINEERING

Directional liquid dynamics of interfaces with superwettability

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Natural creatures use their surface structures to control directional liquid dynamics for survival. Learning from nature, artificial superwetting materials have triggered technological revolutions in many disciplines. To improve controllability, researchers have attempted to use external fields, such as thermal, light, magnetic, and electric fields, to assist or achieve controllable liquid dynamics. Emerging directional liquid transport applications have prosperously advanced in recent years but still present some challenges. This review discusses and summarizes the field of directional liquid dynamics on natural creatures and artificial surfaces with superwettabilities and ventures to propose several potential strategies to construct directional liquid transport systems for fog collection, 3D printing, energy devices, separation, soft machine, and sensor devices, which are useful for driving liquid transport or motility.

INTRODUCTION

Liquids tend to exhibit many unique and interesting dynamic behaviors at superwetting interfaces (*1*, *2*), including asymmetrical spreading, steady rolling, full bounce, and directional transport (*1*–*5*). These fantastic dynamic behaviors (*1*, *3*) belong to one of the important categories of bionics, which have facilitated a series of innovations and revolutions in several application areas ranging from agricultural irrigation, lubrication, fog collection, to microfluidic operation (*4*–*8*). With nature as the source of wisdom, the directional liquid dynamics of typical living organism interfaces open the gate for new inspirations. For example, the hydrophilic "wet-rebuilt" periodic spindle knots of spider silk (*9*) and the cone structure cactus spines (*10*) display the directional collection ability of tiny fog droplets from the air. The overlapping structured peristome of pitcher plants (*11*) shows super-slippery and microdrop directional spreading properties. These breakthrough findings have also led to disruptive changes in human research (*12*–*15*).

With this background, research on the directional liquid dynamics of interfaces with superwettability has experienced explosive growth during the past decade and is expected to continue (*12*–*17*). At the present time, it is most important to determine the relationship between fundamental research and practical applications (*1*, *2*). It is imperative for researchers to reveal the answers to three key questions: (i) How can we explore and explain the physical and chemical essence behind natural phenomena? This is the theoretical basis of the study of the directional liquid dynamics of superwetting interfaces and a guideline for the design of artificial materials (*2*–*5*). Only on a correct and stable theoretical basis is it possible to build a magnificent mansion of applications. (ii) How to endow artificial materials with great properties that approach or even exceed those of natural organisms? At present, it is a common method to enhance the directional dynamics of a liquid on a superwetting surface by an external field stimulation (*18*–*21*). Different external fields have their own (dis)advantages and applicable environments (*13*–*21*). Developing new responsive materials or optimizing the structure/composition of the existing materials is the way forward. (iii) How can the application be expanded on the basis of the directional liquid dynamics of superwetting interfaces? The ultimate goal of basic research is to solve the practical problems encountered in human production and life (*2*, *5*, *6*). Using the special dynamic behaviors of superwetting interfaces as a tool to solve challenges in other research areas may have unexpected effects. In general, in this critical period, it is necessary to summarize and sort out past research regarding the directional liquid dynamics of superwetting interfaces, which will effectively guide and inspire more breakthrough results in the future.

In this review, we first introduce some discovered representative directional liquid dynamic behaviors of typical living organisms' interfaces (Fig. 1). The mechanism behind this phenomenon is the focus of our attention. On the basis of this understanding, in the following sections, the directional liquid dynamic behaviors of bionic artificial interfaces under different external field stimulations are summarized (Figs. 2 and 3). As a major part, the response mechanism, real effect, and selection criteria are compared and analyzed. Last, we discuss recent progress in emerging applications in this field (Table 1). We briefly present our personal view of the open questions and remaining challenges that will inspire the next generation of bionic artificial materials with superwettability.

DIRECTIONAL LIQUID DYNAMICS

Directional liquid dynamics on natural creature surfaces

Studying nature to reveal the directional liquid dynamics on the surfaces of biological organisms is the most effective way to design and fabricate artificial materials (*22*–*27*). Selected examples of biological surfaces with directional liquid transport behaviors are shown in Fig. 1. To survive in harsh conditions, organisms living in arid areas have always evolved surfaces with special wettability and topography to collect fog or water vapor from the air (*9*–*11*). For example, desert beetles have patterns of hydrophobic troughs and hydrophilic bumps on their backs (*22*). On surfaces with periodic

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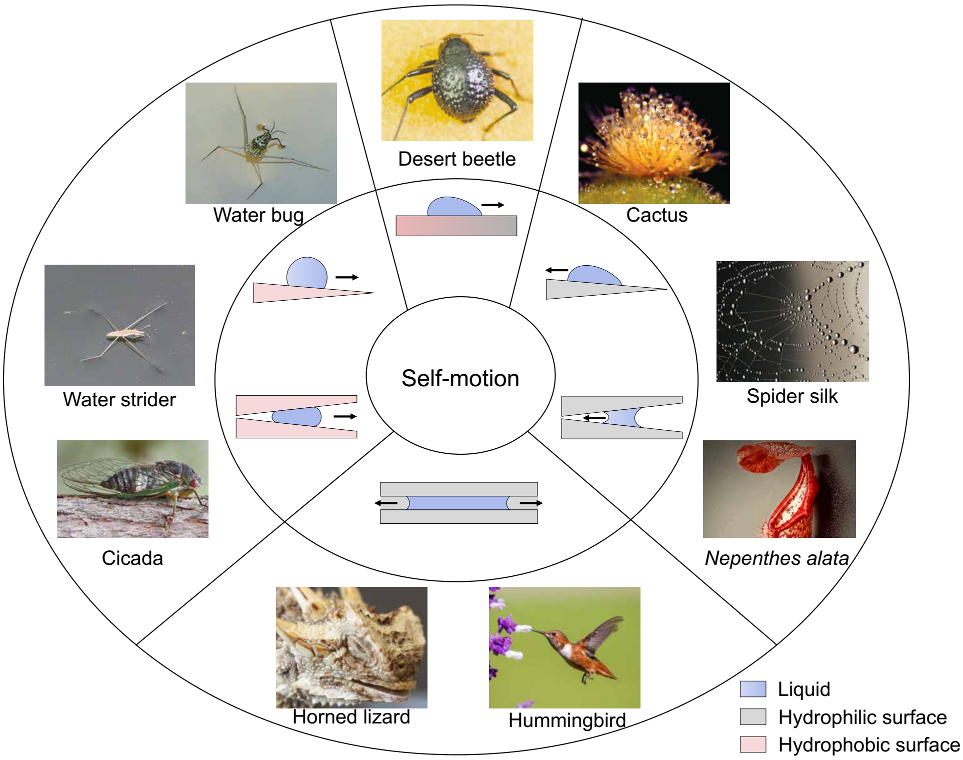

Fig. 1. Overview of spontaneous liquid dynamics on biological surfaces. Desert beetles condense water on hydrophobic-hydrophilic patterns on their backs. Photo was reproduced with permission from Parker and Lawrence (*22*). Spider silks and cactus spines use spindle knots and conical spines to directionally collect water from fog and mist. Photos were reproduced with permission from Ju *et al.* (*4*). The peristome of the pitcher plant self-constructs a water layer on the overlapping microcavity patterned surface. Photo credit: Zhichao Dong, Technical Institute of Physics and Chemistry. Texas horned lizards and hummingbirds acquire liquid by capillary rise behavior. Figure was reproduced with permission from Comanns *et al.* (*33*). Water strider legs, water bug legs, and cicada wings repel water to keep their surfaces dry. Figure was reproduced with permission from Wisdom *et al.* (*39*).

chemical wetting gradients, the liquid tends to move to the area with a higher surface energy. In this process, small fog droplets first nucleate on the non-waxy hydrophilic regions and then form fast-growing droplets and slide down the wax-coated hydrophobic slopes. The driving force, F_C, caused by the chemical wetting gradient can be inferred as $F_C \sim W\gamma(\cos\theta_r - \cos\theta_a)$, where W is the drop width and θ_a and θ_r are the advancing and receding contact angles of the microdroplet on the gradient surface, respectively.

Compared with surface chemical composition gradients, the driving force caused by the structure gradients is more notable. For example, as shown in Fig. 1, spider silks can collect and transport fog from hydrophilic wet-rebuilt periodic spindle knots to joints (*9*). Cacti use the conical spine of the stem to move condensate drops to collect water for survival (*10*). In both species, the Laplace pressure difference, $\Delta P = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$, induced by the cone structure is the main driving force for directional liquid transport (*23*–*25*), where γ is the surface tension of the liquid and R_1 and R_2 are the orthogonal radii of curvature. The transport velocity is tens of micrometers per second (Fig. 3A and table S1). To achieve fast liquid transport, in addition to the driving force, the resistance force (F_R) should be reduced. *Sarracenia* trichomes use a unique hierarchical microchannel structure to achieve ultrafast water transport (*26*). The water transport velocity is three orders of magnitude faster than that on the cactus spine (Fig. 3A). This difference is because around the trichome cone, a rapid thin film of water is formed inside the multiple channels, notably decreasing the moving resistance of the transporting water. In the same way, we can often observe on rainy days; a water strip typically slides along the previous water strip on the windshield (*27*). Compared with a dry surface, water tends to slide along the wet surface at a much faster speed.

In rainy tropical regions, plants also need to use surface structures to direct water directional transport for survival. Pitcher plants rely on prey-trapping pitcher organs for nourishment (*28*). The overlapping anisotropic V-shaped microcavities on the peristome can transport the secreted lubricant from the inner side to the outside at a speed of several millimeters per second (*13*). The self-constructed lubricating water layer on the peristome surface can slip insects into the bag when the insect walks on the peristome (*29*). A smaller condensate drop size means a small driving force for directional liquid dynamics. These measures may be effective for tiny insects and plants but are not suitable for animal drinking requirements (*30*–*32*). Shorebirds use the repeated opening and closing of their V-shaped beak for directional drinking and capturing (*30*). Briefly, by the repeated tweezer-like motion, birds move water from the tip of their beaks to their mouths in a stepwise ratcheting fashion. The droplet in the hydrophilic beak will form two concave liquid levels (Fig. 1). During this process, assisted by the Laplace pressure difference, contact angle hysteresis drives the drop motion directionally.

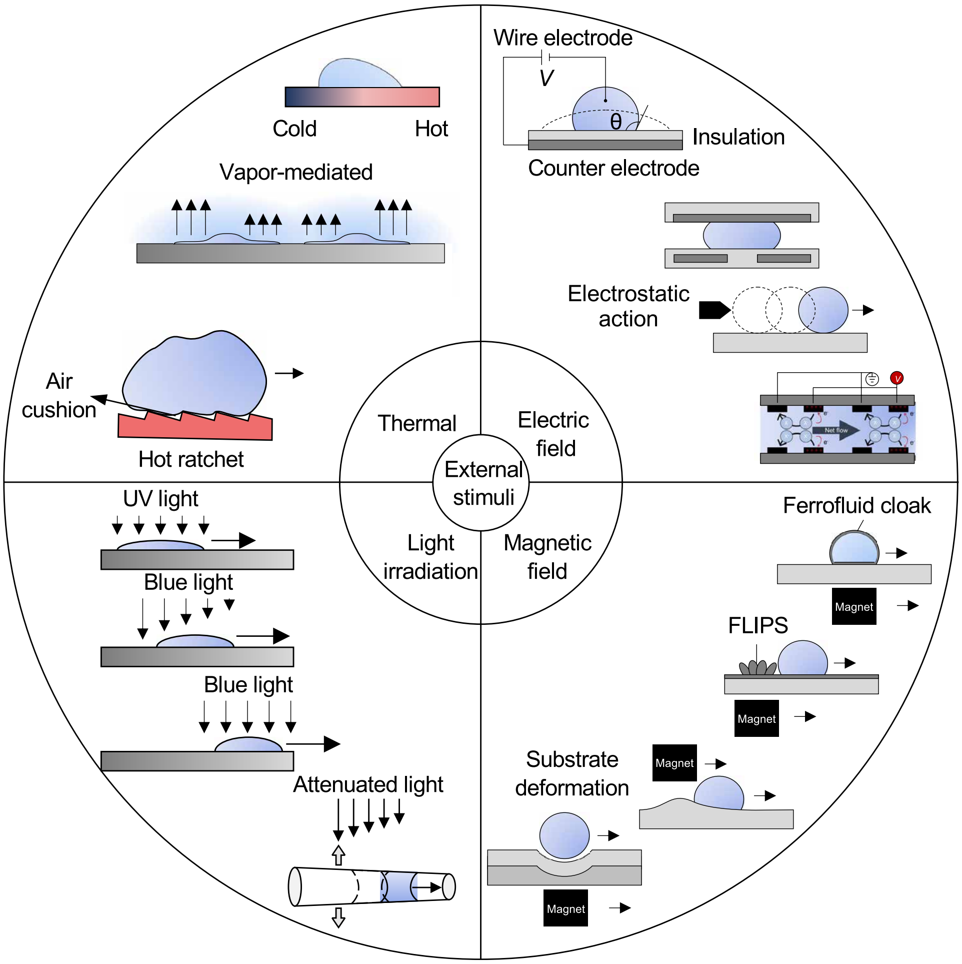

Fig. 2. Manipulated liquid dynamics by external stimuli. Examples of external field actuated drop motion: thermal, electric field, light irradiation, and magnetic field. Generally, the controlling directional movements are caused by surface modification, adding additives into liquid, and surface deformation.

In addition to dropwise motion, continuous water directional motion can be triggered by capillary rise behavior (Fig. 1). Plants use their vessel system to transport and uplift water from the soil to leaves (*31*). Many animals use their mouthparts, proboscises, or tongues for drinking and ingesting enough energy (*32*). For example, Texas horned lizards use their skin texture with half tubes to transport water from the ground to their mouths at a speed of several millimeters per second (*33*). Then, by means of capillary rise, water droplets are imported into their mouths (*34*). In addition, numerous and complicated branching networks of tubes in the lung airway of humans and animals are of vital importance for the blood recycling and gas exchange process to promote a smooth respiratory system (*8*, *35*). The study of the capillary rise phenomenon can be traced back to the Renaissance period. Leonardo da Vinci first recorded the capillary rise phenomena. In the following centuries, researchers have gradually concluded the detailed physical mechanism underlying the capillary rise process, summarized as the "Lucas-Washburn equation," combining the interactions of the surface tension force, viscous drag force, inertial force, and gravity (*36*). The equation can be written as the following formula $\rho\,[h\ddot{h} + (\dot{h})^2] = \frac{2}{r}\gamma\cos\theta - \frac{8}{r^2}\eta h\dot{h} - \rho g h$, where ρ is the liquid density, η is the liquid viscosity, γ is the liquid surface tension, *r* is the capillary radius, *g* is the gravity acceleration, *h* is the capillary rise height, $\dot{h}$ is the one-order derivative of height *h*, and $\ddot{h}$ is the second-order derivative of height *h*.

Besides water collection for survival, there are also many creatures using their unique structures to expel water directionally for preventing pollution, keeping dry, and walking quickly (*7*–*12*, *37*–*39*). For example, a butterfly wing obliquely inserted with periodic anisotropic nanotips can orientally expel raindrops to prevent wetting (*37*). In detail, the direction-dependent arrangement of wings with flexible overlapping microscales with nanotips causes an anisotropic adhesive force; this force acts on the droplets, causing them to easily roll along the radial outward direction but tightly pinning them in the opposite direction. Water striders can walk rapidly on a water surface because of the special hierarchical structure on their legs, which are covered by large numbers of oriented tiny microsetae with fine nanogrooves (*38*). In addition, the condensed microdroplets could spontaneously bounce off the two V-shaped superhydrophobic microsetae structures directionally. This is the result of a combination of two factors: the self-penetration effect and the sweeping effect along individual cones caused by the stiffness gradient (*39*).

The exploration of these natural phenomena is important for developing artificial materials with similar properties to meet the

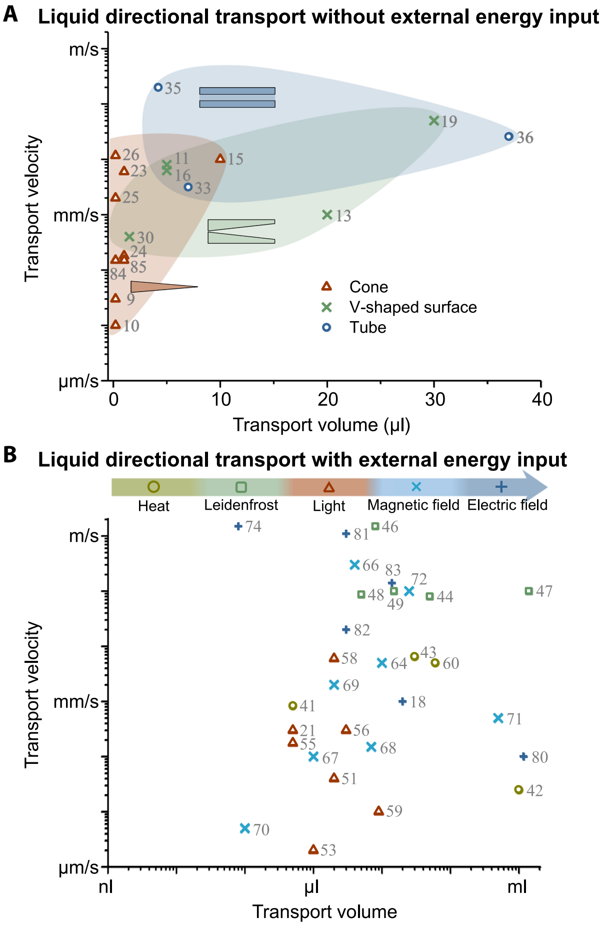

Fig. 3. Transport velocity of liquid on the solid surface. (**A**) Self-motion velocities and volumes of liquid drops on biological surfaces without external energy input. Cone, V-shaped surface, and tube introduce imbalanced forces to drive the liquid's motion. (**B**) Transport velocities and volumes of liquid drops under the external field. Light irradiation, thermal, electric field, and magnetic field drive the drop motion. The detailed parameters are listed in tables S1 and S2.

different needs of our daily life and industry (*12*–*17*, *25*–*27*). For example, researchers have constructed the bump or cone-shaped structures mentioned above by simple chemical etching or masking methods with similar or better liquid directionally manipulation ability than the surface of natural organisms (*12*–*15*, *29*, *30*). In recent years, researchers have successfully produced biomimetic surfaces via three-dimensional (3D) printing technology, which has excellent directional liquid transport capability (*3*–*5*, *7*, *13*–*17*). These works not only realized the unification of the structure and function of biomimetic materials but also developed some new functions beyond nature, such as the separation of oil and water microdroplets (*3*, *6*, *25*, *40*).

External field–induced gradient for directional liquid dynamics

To achieve controlled and fast liquid directional transport for applications in relevant fields, an external stimulation, such as heat, light, magnetic, and electric, is performed to trigger drop motion (Fig. 2).

Thomas Young proposed the cohesion of fluids in 1805, where the existence of forces is equivalent to the tension of the surface of a liquid that is uniform in all directions (*41*–*43*). In practice, the tensile force is not the same if the drop contains different liquids, such as the "tears of wine" phenomenon, or the drop deposits on thermal gradient surfaces. Today, this phenomenon is called the Marangoni effect or the Gibbs-Marangoni effect (*42*, *43*). A liquid with a surface tension field flows along its gradient, which can be built by thermal interaction directly or indirectly. The vapor emitted by neighboring two-component droplets of miscible liquids constructs a "long-range attraction" and "short-range chasing" style. In response to the evaporation-induced surface tension gradients, neighboring droplets move autonomously and directionally (*41*). Cooperating with surface modifications, thermocapillary convection can perform more efficiently. Induced by the thermal interaction, the property and morphology of surfaces can be changed (*42*, *43*). Adaptive super-amphiphilic organohydrogels with a reconfigurable surface topography was developed and showed a self-healing capacity for programmable liquid transport (*14*).

The levitation of drops away from the surface is an effective way to reduce friction (Fig. 2). A volatile drop can levitate above its own vapor on a solid with a much higher temperature than the boiling point of the drop, which is commonly referred to as the Leidenfrost effect (*44*). Because the vapor vitally influences the behavior of the Leidenfrost drop (*45*, *46*), the ratchet is a typically used asymmetric structure to investigate and manipulate the rapid motion and directional transport of the Leidenfrost drop by its close influence on vapor (*47*). The transport speed of a droplet is typically tens or hundreds millimeters per second (Fig. 3B and table S2). In the absence of external asymmetry, a millimeter-size Leidenfrost droplet was observed to rotate in a manner similar to wheels and then spontaneously propel in the wheel direction after detachment because of a ratchet-like mechanism caused by its imbalanced rapid internal flow (*48*). In addition, topographically patterned surfaces were fabricated to create two concurrent thermal states, the Leidenfrost region and contact-boiling region, to achieve the directional transport of high-temperature Janus droplets (*49*).

Unlike the energy sources from heating or evaporation, the energy originating from photoirradiation can be absorbed and converted to thermocapillary, chemical compositional, or photo-electrowetting gradients (Fig. 2). There are two typical compounds that are responsive to light (*50*–*54*). TiO_2 under ultraviolet (UV) light can change the surface wettability from hydrophobic to amphiphilic, as reported by Wang *et al.* (*50*), and azobenzene dyes can change between cis- and trans-configurations under the radiation of different wavelengths, leading to surface wettability changes (*51*). Compared with other methods, as shown in Fig. 3B, the motivation time is quite long and typically takes over 30 min of irradiation by UV light (*52*). Since then, much effort has been devoted to investigating and improving the photo-induced directional motion of objects at interfaces (*53*). The combination of microfluids and photocontrol has generated a new field of research interest, called optofluidics, and has wide applications in labs-on-chips, microreactors, and actuators (*54*). To date, there are generally three ways to control directional movements caused by light: (i) surface modifications, such as azobenzene compounds and rotaxane decoration; (ii) introducing additives into liquids to change the stimuli-responsive properties; and (iii) deformable polymers that can bend under light irradiation.

Table 1. Disciplinary applications involving liquid dynamics.

Applications	Manipulation mode	Liquids	Challenges	References
Fog collection	Chemical gradient Structure gradient Electric field	Fog Mist	Durability Large-scale fabrication High flux and efficiency	*1–5*, *9*, *10*, *22*, *26*, *27*, *84–86*
3D printing	Fused deposition modeling Electro-pump Stereolithography apparatus or digital light processing	Ink Resin	Printing speed Printing resolution Fatigue resistance	*13*, *14*, *36*, *40*, *87–93*
Liquid-liquid separation	Wettability contrast Magnetic field	Wastewater Oily water	Multiphase separation Miscible liquid Salt separation from liquid	*1–3*, *15*, *25*, *40*, *94*
Soft machine	Electric field Microfluidic	FC 40	Biocompatibility Durability Flexibility Stretchability	*29*, *61–63*, *65*, *67*, *69–72*, *95–97*
Sensor	Wettability gradient	Sweat	Multifunctional properties Easy processing methods	*36*, *41*, *54*, *60*, *61*
Energy device	Electric field Irradiation	Water	Mechanical durability Easy processing method Self-healable capacity	*1*, *2*, *4*, *5*, *24*, *27*, *47–49*, *74*, *78*, *81*, *98–102*

In the case of additives, photothermal effects are used for changing liquid properties, which can achieve direct optical-to-hydrodynamic energy conversion (*55–61*). Photothermal nanoparticles dispersed in liquids can generate heat when focused illumination is at the liquid/air interface, which turns a liquid into vapor and thus accelerates the directional liquid motion (*55*). The surface tension gradient caused by the photothermal effect also works via propulsion and drives oil motion at the liquid-liquid interface (known as the chromocapillary effect); even the deformation of polydimethylsiloxane membranes can facilitate directional liquid transport (*56*). A stronger photothermal effect results in plasmonic heating–induced vapor flow; for example, this approach was applied to fabricate a motor by coating a piece of floating paper with a gold nanoparticle film. This new propulsion can directionally drive and control object motion on a liquid under light irradiation. The other way to achieve directional liquid transport is by introducing additives, such as liquid marbles, which was proposed by Aussillous and Quéré (*57*). Coated with hydrophobic particles, a droplet cannot be wetted by a liquid or a solid. Light-induced Marangoni flow can drive the liquid marble to move with and against it (*58*), the speed of which is several millimeter per second (Fig. 3B and table S2). In addition to directional liquid transport, materials contained in the liquid marble can also be precisely released at the target.

Recent research carried out by Kwon *et al.* (*59*) has overcome the shortcoming that UV light is necessary for a wettability change, where a dye-sensitized TiO_2 surface is fabricated and can be engineered to have its wettability state optically modulated upon illumination by visible light owing to the electrical potential difference established between the surface and the liquid upon incident illumination. Except for traditional materials, a light controllable paraffin-infused porous graphene film was reported in 2018 by Wang *et al.* (*60*), which provides programmable wettability pathways to guide liquids directionally. In 2018, multiresponsive surfactants based on functionalized nanoparticle dimers were synthesized, which integrated all responsive properties into one system (*61*).

Photomechanical polymers, usually prepared by a single film of a liquid crystal network containing azobenzene, can bend directly under light (*27*, *62*). In 2016, this photodeformable material was used as a tubular microactuator, which can change asymmetrically via light irradiation, and liquid slugs inside the deformed conical tube can transport spontaneously. By incorporating azobenzene derivatives with fast cis-trans thermal relaxation, this photoactive liquid crystal network–formed polymer can exhibit continuous, directional, macroscopic mechanical waves under light illumination (*27*, *63*).

Among all the drop motion driving strategies, magnetic actuation has unique merits, including noncontact, real-time control, fast response, free of specific environmental requirements, and excellent compatibility with current biomedical technologies (Fig. 2). The design principles of the magnetoactuation of liquid droplets can be extended to two different categories: adding magnetic particles into droplets and surface deformations by the magnetic field (*64–70*). Commonly, a superparamagnetic liquid droplet, which can be magnetic in itself or embedded with magnetic particles, can move in response to an external magnetic field. Deformable magnetoresponsive surfaces can manipulate droplet motion directionally (*64*). Under a gradient magnetic field, superparamagnetic liquid droplets are attracted to the high–magnetic field region (*64–66*). Magnet-actuated droplet manipulation methods, such as droplet movement, coalescence, and splitting on the hydrophobic surface, provide a general means for manipulating and monitoring small volumes of liquids without the use of pumps, valves, or a microfluidic container (*65–67*). Compared with hydrophobic surfaces, superhydrophobic surfaces can reduce friction (Fig. 3B). For example, superparamagnetic microdroplets and ferrofluid droplets can generate controlled motion behavior on superhydrophobic ratchets and surfaces at a high motion speed (*65*). At the same time, the manipulation of paramagnetic liquid oxygen and ferrofluid under an external magnetic field has also been reported (*67*).

Magnetoresponsive surfaces are an emerging magnet actuation technique that does not necessarily incorporate magnetic particles into the liquids. Magnetoresponsive surfaces provide a flexible and controllable fluidic control platform and may greatly expand the application fields of magnetoresponsive microfluidics (*68*–*72*). To obtain magnetic responsive surfaces, researchers embedded magnetic particles into a soft matrix. For example, Zhu *et al.* (*68*) reported the real-time manipulation of the spreading directionality, fluid drag, and optical transmittance of a liquid through magnetically tunable micropillar arrays with uniform, continuous, and extreme tilt angles. In addition, Lei *et al.* (*72*) manipulated liquid droplets in a magnetic tubular microactuator by an adjustable capillary force generated by magnetism-induced asymmetric deformation. This work achieved a speed of 10 cm/s, representing the highest speed of liquid motion driven by an external stimulus–induced capillary force in a closed tube found to date (Fig. 3B and table S2). Magnetic liquids are also used to fabricate magnetically responsive surfaces (*72*). Wang *et al.* (*70*) developed ferrofluid-impregnated surfaces and realized topographical reconfiguration with spatial and temporal dynamics and numerous functions.

Sessile drops of water can change shape or "dance" on the dielectric surface in the presence of an alternating current electric field. Upon the application of 700-V, 50-Hz electric voltage on the solid, the water drop started to experience a wetting-dewetting state and was directionally transported at a speed of 0.15 mm/s (*73*). The electrowetting method to trigger liquid transport is typically relayed on patterning electrodes on the substrate (*74*–*76*). This wetting behavior is approximated by the well-known Young-Lippmann equation $\cos\theta_w = \cos\theta + \varepsilon_i\varepsilon_0 V^2/(2\gamma_{lv}t)$, where γ_{lv}, θ_w, and θ are the relatively large liquid-vapor surface tensions and the wetted and static contact angles, respectively; ε_i and ε_0 are the dielectric permittivities of the insulator and vacuum, respectively; V is the applied voltage; and t is the thickness of the insulator (*77*). The advantage of this method is that the direction and path of the droplet movement can be well controlled. Liquids are suitable for a wide range of applications without the need for additives to achieve directional liquid transport. The disadvantage is that electrowetting requires complex material processing and construction. In addition to the need to manufacture the electrodes, it is also necessary to build the circuit of the electrodes. To improve the accuracy, the number and accuracy of electrode patterns need to be improved, which increases the complexity of the overall operation (*78*–*82*).

A charged object can attract an uncharged object to move on the substrate surface. During this process, the traction of charged droplets is induced by the use of triboelectricity on the electrodes or by light (*18*). Printing surface charges to perform a pattern on the substrate can direct the movement of droplets on the substrate (*78*). The use of a nonuniform electric field distribution can suddenly direct the trajectory of droplet movement (*79*). Adding additives or injecting a charge into the liquid can reduce the complexity of manipulation, which can realize the attraction or repulsion of liquid droplets (*80*–*83*). A better understanding of the physics of droplet actuation is derived from electrodynamic analysis, which explains the phenomenon of electrical forces generated on the free charges in a droplet meniscus (in the case of conductive liquids) or on dipoles inside of the droplet (in the case of dielectric liquids). These forces can be calculated by integrating the Maxwell-Stress tensor, T_{ij}, $T_{ij} = \varepsilon\left(E_i E_j - \frac{1}{2}\delta_{ij}E^2\right)$, over any arbitrary surface surrounding the droplet, where i and j refer to pairs of x, y, and z axes, δ_{ij} is the Kronecker delta function, and E is the electric field surrounding the droplet. Unlike electrowetting, this formulation explains the motion of dielectric liquids and liquids that do not experience a change in the contact angle. This method not only can realize the sudden reversal of the direction of the droplet in the 2D plane (*82*) but also can realize the directional trajectory of the droplet in the 3D space (*81*).

There are currently several ways to implement droplet drives using electricity. The speed of the droplet's movement is subject to various restrictions. One restriction is a fast speed and a short moving distance. For example, traditional electric infiltration has a high instantaneous speed when electricity starts to trigger, but the duration is relatively short. One restriction is a slow speed, but the distance traveled is relatively long (*18*). Another restriction is a fast speed and a long moving distance. For example, in the work driven by the charge method (*81*) and the electric field (*82*), the electrostatic force that the charged droplet receives in the electric field is continuous.

EMERGING APPLICATIONS

Superwettability is now playing an increasingly important part in numerous applications. Especially, recent research has centered upon these materials' application in the field of fog collection, 3D printing, energy device, liquid-liquid separation, soft machine, sensor, etc.

Fog collection

Water provides indispensable nutrients to creatures. Fog collection as a sustainable solution is of great importance not only for the survival of humans in many water scarcity regions but also for many natural creatures to drink, move, and defend themselves (*1*–*5*). Over the past two decades, scientists have revealed the mechanisms of the fog harvesting behaviors of many creatures (*9*, *10*, *22*). For example, desert beetles have patterns of hydrophobic troughs and hydrophilic bumps on their backs (*22*), spider silks have intrinsic hydrophilic wet-rebuilt periodic spindle knots and joints (*9*), cactus stems have conical spines to transport water droplets consistently in a specific direction (*10*), and *Sarracenia* trichomes have a unique hierarchical microchannel organization (*26*). Learning from nature, a large number of bionic liquid transport and collection devices have been developed and fabricated (*27*, *84*–*86*). For example, Park *et al.* (*84*) proposed a combination of strategies that were learned from three distinct biological examples—Namib desert beetles, cacti, and *Nepenthes* pitcher plants—to integrate the growth and transport of water droplets. Inspired by the microstructures of Namib desert beetles and *Nepenthes* pitcher plants, as well as the pumping strategy of emergent aquatic plants, Zhang *et al.* (*85*) fabricated a multibioinspired slippery surface for efficient droplet manipulation by combining bottom-up colloidal self-assembly, top-down photolithography, and microstructured mold replication. Damak and Varanasi (*86*) achieved efficient fog collection by using an additional electric force to overcome the aerodynamic drag force and propel the fog droplets toward the collector. In a broad future prospect, if we can combine the additional stimulation while using the excellent structural model of natural creatures, the fog collection efficiency will be further improved.

3D printing

3D printing technology as an additive manufacturing method has led to an innovation of traditional technology to achieve the rapid design and fabrication of materials without the need for expensive tooling, dies, or lithographic masks (*13*, *14*, *36*, *40*). Light-based 3D printing methods have the advantages of low energy consumption, low cost, high feature resolution, smooth surface, and good repeatability (*87*). However, the adhesion and resin refilling properties between the resin and curing interface can lead to printing failure and reduce the printing speed. Recently, inspired by the slippery behavior of the pitcher plant, researchers replaced the curing interface with a lubricant-infused membrane or only the lubricant (*88*, *89*). The uncured resin directional refills the curing interface to sustain the continuous 3D printing (*88*). In addition, the constructed curing interface can greatly reduce the adhesion and increase the resin refill velocity (*89*). In addition to light-based 3D printing, direct ink writing (DIW) is also redesigned. Skylar-Scott *et al.* (*90*) exploited a biomanufacturing method, that is, patterning a sacrificial ink inside the liquid matrix to create various hollow, complex biological organs. During DIW, viscoelastic inks are extruded out of a 3D printer's nozzle directionally as printed fibers, which are deposited into patterns when the nozzle moves. Scientists have made great efforts to take various measures to improve printing accuracy. By controlling the directional liquid dynamics, Yuk and Zhao (*91*) obtained ink fibers smaller than the inner diameter of the needle by simply stretching the extruded viscoelastic ink fibers. Harnessing the deformation, instability, and fracture of the viscoelastic ink can notably improve the printing accuracy. Inspired by the lotus leaf margin, Dong *et al.* (*92*) obtained smaller droplets by adjusting the nozzle surface wettability from hydrophilic to superhydrophobic. In the future, these methods are expected to be used in the field of printing to notably improve the printing accuracy. To enhance the resolution, we can use an external field, such as static electricity, to drill the liquid fiber directionally and reduce its diameter. In addition, we can directly write the stimulated responsive liquid inks, such as writing the liquid crystal material directly to print a soft robot (*93*). The shape of the liquid fibers can be adjusted through an external field. Without moving the needle circularly, one-step printing of more complex and variable structures can be achieved readily.

Liquid-liquid separation

Liquid-liquid separation is of great importance for industrial processes and daily life, such as the resolution of industrial water and oil spills, efficient separation of chemical reaction products, and sewage treatment in environmental protection (*15*, *25*, *40*). Among them, the oil-water separation process still faces the greatest challenge in liquid-liquid separation, as oil and water are both liquids. When oil and water are mixed, due to oxidation or the addition of surfactants, stable emulsions are formed (*15*). It is worth noting that the energy consumption for the separation of this mixture worldwide accounts for 10 to 15% of the world's total energy consumption (*40*). Developing a practical and energy-efficient method for separating emulsions, especially those with stable surfactants, is very important and challenging. Recently, interfacial materials with integrated superwettability (combining superhydrophobicity and superoleophilicity) have proven to be highly efficient for this purpose (*94*). Traditionally, membrane-based separation is based on acting as selective barriers to permit the transport of targeted chemical species. However, this method is only suitable for separating a small volume of the emulsion. For the separation of large-scale oil-water mixtures, porous sponge-based absorption materials are suitable (*1*–*3*). Metal/covalent-organic framework meshes, porous carbon materials, and fluorinated polymers can be made into oil-removing materials after surface modification and increasing their surface roughness. However, the transmembrane separation and sponge absorption method adopts the mode of "blocking one phase and circulating the other phase." These methods are vulnerable to oil pollution and thus cannot separate liquids multiple times and continuously. In addition, the liquid will consume energy during transmembrane separation. It is difficult to achieve the separation of several microliters of oil-water mixed microdroplets. To overcome the limitations of these separation methods, another type of separation is through the "go-in-opposite ways." Li *et al.* (*81*) designed a separation device using two surfaces with heterowettabilities on two curved substrates. These authors found that after oil-water microdroplets were continuously dripped between the two films, the water phase moves along the upper surface to one side, while the oil collects along the lower surface to the other. In this way, the tiny water-in-oil droplets can be separated into pure water and oil. This method can be used for the separation of oil-in-oil droplets with a surface energy difference as small as 14.7 mN/m between the oil phases and high-viscosity liquids with viscosities up to several hundred centipoises, which greatly broadens the micromix applications of droplet separation (*40*). In a broad sense, manipulating the liquid dynamics of interfaces with superwettability, special structures, and external stimuli can be used to achieve a more efficient and energy-saving liquid-liquid separation device. An all-in-one liquid-liquid separation device can be applied to multiple environments and multiple-scale mixed liquid systems with high flux and high selectivity.

Soft machine

Different from traditional hard machines, many insurmountable technical problems, such as the high inertia of a motor drive, heavy movement, and the hard control of the interaction between rigid and soft bodies, still exist (*29*, *61*–*63*). In recent years, with the rise of bionic technology and smart materials, machines made of soft materials have bridged life sciences and engineering (*65*, *67*, *69*, *70*, *72*). Scientists have developed soft machines using flexible smart materials with superwettability and functions, such as shape-memory alloys and polymers, to imitate biological structures and directional motion (*95*). Advances in soft materials have led to skin-like sensors and muscle-like actuators for soft robots and wearable devices. Because of their inherent flexible and stretchable properties, liquids are expected to be used in the preparation of soft machines (*69*–*72*, *96*). Recently, using a perfluorinated liquid as a dielectric fluid based on charge-injection electrohydrodynamics, Cacucciolo *et al.* fabricated a class of soft-matter bidirectional pumps. These solid-state pumps are flexible, stretchable, modular, scalable, quiet, and rapid. By directly manipulating the dielectric liquid, wearable intelligent temperature management, self-contained fluidic "muscle" can be achieved. Stretchable pumps have potential uses in wearable laboratory-on-a-chip and microfluidic sensors, thermally active clothing, and autonomous soft robots (*97*).

Sensor

Sensors have attracted recent attention for various applications, such as the detection of chemical compounds or biomolecules or metal ions in mixed solutions, blood typing, and various other biomedical applications (*36*, *41*, *54*, *60*). With the advent of the age of intelligence, a broad set of emerging sensing modalities and advanced materials/device designs in body-integrated flexible platforms capable of analyzing biofluids can be captured in a noninvasive or minimally invasive fashion (*54*, *60*). When we perform physical activities, are exposed to heat/humidity, or take warm showers, significant sweating is inevitable. The analysis of the sweat dynamics and chemical composition is a promising method for intelligent physiological testing (*61*). To achieve effective adhesion, the removal of surface sweat water is important. To achieve effect analysis, the directional transfer of sweat water to the analysis part is important. Challenges remain in terms of the stability, selectivity, sensitivity, and directional transport of the active components and in the mechanical properties of the overall platforms. Learning from natural creatures, we can design better devices to control the directional sweat dynamics effectively for better analysis.

Energy device

Currently, there is considerable interest in techniques that achieve efficient energy conversions by manipulating liquids, such as condensation heat transfer enhancement, liquid generators including liquid engines, hydrovoltaic technology, and triboelectric nanogenerators (*98*–*103*). In practical applications, such as in thermal management systems, vapor condensation is a ubiquitous and essential part (*103*). When water vapor condenses on surfaces with high surface energy, the condensate forms a liquid film (*4*, *5*). Instead, on surfaces with low surface energy, distinct droplets form. The latter, termed dropwise condensation, is desired because the condensate can be more easily removed from the surface directionally, which can notably increase heat and mass transfer (*27*). Research has focused on using superhydrophobic surfaces that combine roughness and chemical functionalization to create dropwise condensation, whereby droplets easily roll off the surface due to gravity (*1*, *2*). However, achieving the rapid removal of condensed droplets from flat superhydrophobic substrates directionally remains a challenge. Therefore, the role of the external stimuli needs to be introduced (*24*, *27*). In nature, there are numerous examples in which a similar property is exhibited, such as the sudden spore discharging behavior of ballistospore mushrooms. Inspired by natural design, Li *et al.* (*81*) achieved efficient drop detachment by ballistic jumping from a flat superhydrophobic surface via an electrostatic field, opening the possibility of rapid liquid expulsion for various applications, such as even anti-icing in external energy devices in some cold areas. In addition, Miljkovic *et al.* (*100*, *101*) used external electric fields to prevent jumping droplets from returning to the condensation surfaces and thus enhanced the heat transfer of condensation. Liquid manipulation can also be widely used in electric energy generators (*74*, *78*). Liquids such as water contain tremendous energy in a variety of forms, but very little of this energy has yet to be harnessed. With the rapid development of the preparation of various nanomaterials, Zhang *et al.* (*98*) found that water evaporation from the surface of a variety of nanostructured carbon materials can be used to generate electricity. In addition, Xu *et al.* (*102*) demonstrated a simple, low-cost, and effective approach for harvesting large-scale blue energy using the charging process in friction to convert mechanical energy into electric power, that is, the triboelectric nanogenerator. Ever since the steam engine in the 18th century to today's turbines, reducing frictional loss has been a pressing problem that scientists and engineers have been attempting to solve. Recently, researchers exploited the Leidenfrost levitation of a liquid to convert temperature differences into self-rotating motion (*47*–*49*). The frictional resistance in this heat engine is effectively reduced. In the future, combining bionics and using superhydrophobic surfaces or reducing pressure to reduce the Leidenfrost temperature will greatly facilitate the industrialization of this method and many other integrated application systems, such as microchip heat dissipation.

CONCLUSION AND OUTLOOK

Until recently, 200 years of wettability research did not show any logical connection between directional liquid dynamics and interfaces with superwettability. Since 2001, superwettability has been facilitated through recent advances in bioinspired research and micro- and nanotechnology. In addition, the recent renaissance in the field of the characterization of directional liquid dynamics at interfaces, especially the direct imaging of liquid dynamics on solid/liquid/vapor triphase interfaces at high speeds and resolutions, has facilitated the development of the relevant theories and the fabrication methods for the bioinspired superwetting materials. A variety of interfaces with superwettabilities have been interpreted and together combined to manipulate directional liquid dynamics. Progresses in dynamic wetting on natural and bioinspired artificial 1D fibers, 2D substrates, and 3D architectures show various liquid-manipulation capabilities. As we have highlighted in this review, the superwettability systems–controlled directional liquid dynamics are established on the basis of integrated innovations.

In a broad future prospect, if we can combine the additional stimulation while using the excellent structural model of natural creatures, the efficiency of directional liquid dynamics will be further improved. Combining the interface structure deformation and the external stimulation, the controlled and fast liquid directional transport can be achieved at the interfaces with superwettability in a facile way. In addition, the use of a superhydrophobic surface can reduce the frictional force between the droplet and the substrate, which increases the directional droplet motion speed. In the future, directional liquid dynamics of superwetting interfaces with unprecedented properties and functionalities would be generated and integrated into devices for emerging applications. Various disciplines, including chemistry, physics, engineering, and biology, are interplayed in the field of liquid dynamics and interfaces with superwettability. We hope that this review will inspire readers to discover more breakthroughs at interfacial science and stimulate further exciting ideas to introduce the system of superwettability-controlled directional liquid dynamics into their own researches.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/37/eabb5528/DC1

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