

Capillary slinky: Equilibrium and dynamics of a droplet in a soft springBidisha Bhatt¹ and Andreas Carlson^{1,2,*}¹*Mechanics Division, Department of Mathematics, [University of Oslo](#), Oslo, Norway*²*Department of Medical Biochemistry and Biophysics, [Umeå University](#), Umeå, Sweden*

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Springs can be found in many applications and biological systems, and when these are soft, they easily deform. At small scales, capillarity can induce a force leading to spring deformations when the elastocapillary number is small. We demonstrate through experiments the nontrivial equilibrium-shape liquid droplets adopt in these soft springs, which form an annulus, eruciform, and spherical shapes. When these droplets are set in motion, they display different flow regimes with significant dissipation generated by the internal rotational flow. The static and dynamics of droplets in such a capillary slinky are also used to demonstrate how surface tension can actuate springs by stretching/compression, while providing a way for active flow control in soft springs.

DOI: [10.1103/p9j4-hp5h](https://doi.org/10.1103/p9j4-hp5h)**I. INTRODUCTION**

Helical-shaped fibers are found across a wide range of engineering applications, such as in textile designs [1–3], humidity and flow sensors [4,5], fog harvesting [6,7], packaging [8], water purification/emulsification [9], and proposed as active materials, to name but a few examples. One such soft realization is a slinky, a classic toy made for kids to play with on stairs, which illustrates how these structures easily stretch, bend, and twist. Helical slender structures are also found across a wide range of biological systems [10] illustrated by the DNA [11], plant tendrils [5], bacterial flagella [12,13], plant vascular [14–16], and bird feathers [17]. The Namaqua sandgrouse (*Pterocles namaqua*) lives in desert areas, where the male uses its helical-shaped belly feathers to collect and transport water nearly 20 km with a speed of up to 60 km/h [17]. Fibers with helical/spiral shapes have also been shown to effectively collect moisture from the atmosphere, where Vogel and Müller-Doblies [18] found parts of the flora in the semidesert of Namaqualand in South Africa have evolved into a circinate, helical, tortuous, or serpentine shape to increase their water-harvesting potential. Despite the broad relevance of liquid transport in soft springlike systems, these flows have received little attention. Below, we show what happens when the spring is very soft and affected by capillarity, i.e., a relatively small elastocapillary number, which leads to complex static and dynamic interface configurations as well as a range of flow regimes.

A droplet deposited on a single fiber can adopt both a barrel and a clamshell shape [19,20]. If a droplet instead is deposited on multiple connected fibers that are parallel [21,22] or with a helical twist [23–25], the energy landscape becomes more complex with bistable regions. Bostwick and Steen [26] described the stability of the liquid bridge between the coils of a helical spring with

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an accompanying diagram corresponding to the pressure and volume of the liquid bridge. Two equilibrium shapes of a droplet were found in a nondeformable spring, where the stability limit between the two states was shown experimentally and analytically by Lowry and Thiessen [27,28]. The liquid-air interface in the helical spring is named a helicodynamical interface if it is symmetric about the axis. This stability limit suggests that the pitch-to-spring radius ratio should be $< \pi/\sqrt{3}$, to sustain the helicodynamical shape inside the helical geometry. However, these equilibrium configurations and stability criteria are only explored when the helical spring does not deform.

Helical spirals made by stimuli-responsive materials, e.g., nylon [29–31], silk [32,33], siloxanes [3,34], hydrogels [35,36], metal-polymer composite [4], and liquid crystals [7,37] have been used to mimic muscle fibers, sensor applications, and for adaptive or responsive systems. Artificial muscles made up of thermoresponsive nylon fiber can produce, impressively, 64 times the specific work of a mammalian skeletal muscle and lift more than one hundred times the weight of a natural soleus muscle with the same length and mass [29]. Similarly, helical springs made of a soft material, such as polydimethylsiloxane, embedded with magnetic particles have been proposed for strain sensing and are also used as flexible optical fibers for biomedical applications [3]. Several studies have demonstrated that external stimuli can contract or expand helical spirals, only possible with surface or bulk modification, as mentioned above.

The capillary interaction between two coils of a helical spring is similar to two straight fibers [38–42] where the liquid meniscus between the fibers pulls them together. Capillary contraction is also created by the spooling of a soft fiber around the droplets [43,44]. Ecribellate orb web has a silk fiber when wet, a fiber coil, and a buckle inside the droplet as the capillary force becomes larger than the Euler buckling load [43]. The interplay of the elastic buckling and the capillary forces is also observed in soft helical coils (made of vinyl polysiloxane) inspired by spider webs, which have shown an elastocapillary instability when pulled out of a silicone oil bath for a small elastocapillary number [40,43]. Transport of droplets along fibers is relevant for a broad range of applications, which has inspired studies of effects from fiber geometry [7,18,24,45–48], wind [49,50], coarsening [51,52], gravity [27,28], single and multiple connected fibers [23,27,28,42,53–55], soft fibers [56], non-newtonian fluids [57], and so forth. Our study complements existing literature and points to a new route for potential flow control and capillary actuations, as we demonstrate below for the static and dynamic properties of droplets in soft springs.

II. RESULTS AND DISCUSSION

A. Experimental system

We develop an experimental system consisting of a soft helical spring of length L (initial length 10 cm, variable with the pitch of the helical spring due to stretching) and radius $R = 0.77 (\pm 0.1)$ mm as shown in Fig. 1(a). The spring is custom made from polyester with a Young’s modulus (E) of 2.5 GPa and a fiber radius of $r = 0.05$ mm, where data for different radii are shown in the Supplemental Material (SI5) [58]. The method for preparing the helical spring is described in SI1 (Materials and methods, which includes Ref. [29]) [58]. The initial pitch λ , before any deformation, is defined as the length between two coils and is varied by stretching the spring so that it also leads to changes in the spring coefficient (measured independently). The spring is attached to a solid base at both ends to help minimize radial deflections during the droplet-sliding experiments. The spring constant k is measured by adding a small weight to its end, which is found to follow Hooke’s law, see SI2 for details [58], where the elastic modulus E , the fiber radius r , spring pitch λ , and spring radius R can all be used to alter k . The ratio between the spring constant k and the surface-tension coefficient γ helps define an elastocapillary number $N_{EC} = k/\gamma$ [40], where $N_{EC} < 1$ surface tension is expected to deform the spring (as shown below). The springs are surface treated so that they are nearly perfectly wetted by droplets of water or a water-glycerol mixture, i.e., equilibrium contact angle ≈ 0 . These droplets have a volume $V \in [2–10]$ μl . Liquid is continuously dispensed between the coils of the spring and does not initially form a spherical droplet shape.

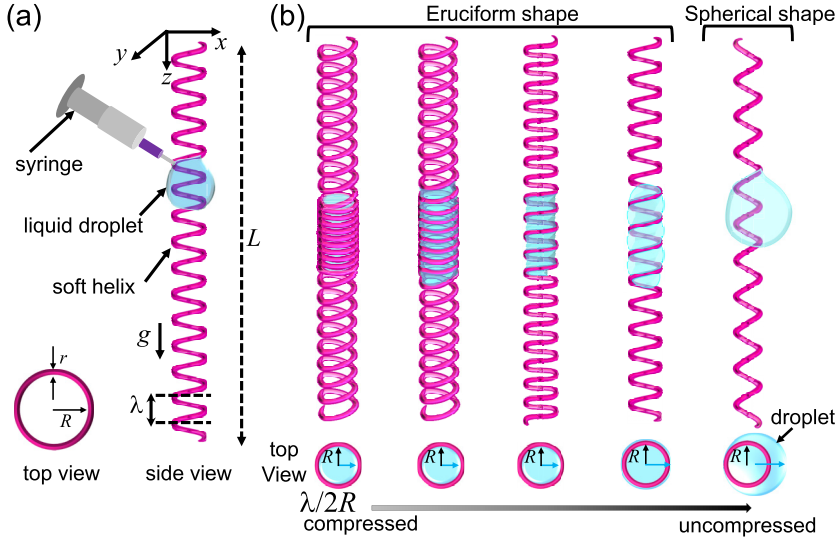


FIG. 1. Soft helical spring: (a) Schematic of the experimental system (top and side view), with a droplet of volume V and soft helical spring of pitch λ and radius R , and axis of the helical spring is aligned in z direction with g gravity and r the fiber radius; (b) From left to right represents the static configurations; Eruciform (helicosymmetric) to spherical droplet in the helical spring as increase with $\lambda/2R$. The bottom row shows the top view of the corresponding side view, showing the droplet and spring dimensions. Blue arrow is the droplet radius, and black arrow is the spring radius.

B. Static droplet-spring configurations

We start by systematically examining how the ratio of $\lambda/2R$ versus the droplet volume V affects the resulting interface shape, when the Bond number $Bo = \Delta\rho g R^2 / \gamma$, where $\Delta\rho$, g are density difference between droplet and air and acceleration due to gravity, respectively, (ratio between gravity and capillary forces) is still below a critical value, and droplets find a static configuration in the soft spring. R is fixed in our experiments, which means we are altering V for a range of $\lambda/2R$ by slowly injecting liquid between the helical coils. The spring material is nearly perfectly wetting, so the liquid subsequently starts to wet the helical structure. Several different equilibrium-interface shapes are observed experimentally, as illustrated in the schematic in Fig. 1(b) (side and top view), with different degrees of spring compression.

We start with a small $\lambda/2R \leq 0.1$, which we define as regime I. As water meets the spring, a capillary bridge forms between the two coils that spreads across in a radial direction. It forms an “annulus” with a liquid film filling the gap between the wetted coils, and the spring is still “hollow” inside, filled with air. A consequence of the liquid meniscus is the generation of a large surface-tension force that is sufficiently strong to contract the elastic spring. For small injected volumes ($t \leq 0.06$ s), the wetted region forms a capillary bridge extending across multiple coils, where capillarity has contracted the spring so much that the coils nearly touch [Fig. 2(a)]. By further increasing V , the spreading in z direction halts, likely a consequence of the clamped conditions at spring edges as the dry areas of the spring are stretched, which needs to be compensated by a larger capillary force. Instead, the liquid starts bulging inwards, occupying the air-filled core of the spring while connected to a capillary bridge above and below. The convex curvature inside the fiber continues to grow with V , first near the needle tip before being distributed along the radial direction, where the bulge finally seals at the center of the spring, and the middle part of the wetted spring has a liquid-filled core, see Fig. 2(a) (see Supplemental Material, movie SM1 [58]). The interfacial configuration in the spring consists of a combination of filled and hollow regions with a liquid

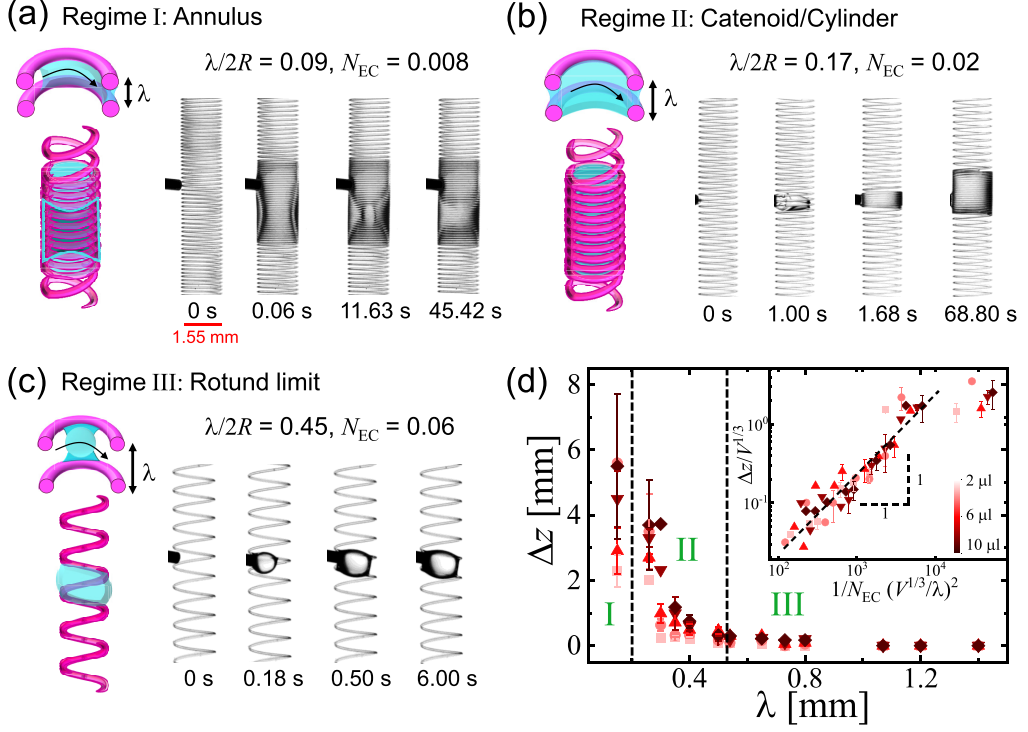


FIG. 2. Equilibrium shapes: (a)–(c) optical images at different times from regime I ($N_{EC} = 0.008$) to regime III ($N_{EC} = 0.06$); labeled as annulus, catenoid/cylinder, and rotund, based on their curvature in lateral direction; (d) total compression of the spring in the z direction (Δz) with the λ , scaled plot of the compression shows dependency on the λ , V , k , γ (inset) using Eq. (1). The scale bar is the same for all the optical images.

film connecting the coils. Additional experiments have been performed to ensure that the snapshots illustrated in Fig. 2 are indeed equilibrated shapes, limited by the time scale for the evaporation of the liquid, see SI3 and SI4 [58]. The needle has not been removed from the spring after droplet deposition, because of the strong interaction between water-needle and water-spring, it needs a strong force to remove it, and the equilibrium shape can be disturbed.

If increasing the pitch λ , i.e., increasing the spacing between coils, leads only to a slightly larger elastocapillary number N_{EC} , the capillary interface takes a very different shape as compared to regime I. In regime II ($0.1 < \lambda/2R < 0.32$), the liquid immediately fills the interior of the spring, and water bulges from the inside of the helical spring between the two coils and forms a semicircular shape between the two fibers [Fig. 2(b) schematic] (see Supplemental Material, movies SM2, SM3 [58]). The droplet-shaped capillary bridge starts spreading between coils with the increase in volume, compressing the spring. For the largest $\lambda/2R$ in regime II, we also notice that the liquid adopts finally as a cylinder-shape fully compressed spring with catenoid or cylinder curvature in the lateral direction. Note that, by increasing $\lambda/2R$, the compression of the spring decreases and the spring constant of the helical spring increases, as shown in the SI2 [58] with a slightly larger elastocapillary number, although $N_{EC} \ll 1$.

If we continue to increase $\lambda/2R > 0.32$, which we label as regime III, a spherical droplet shape forms between the spring coils where the interface bulges outwards (see Supplemental Material, movie S4 [58]). Here, there is nearly no compression of the spring, and the droplet interface is wrapped by the spring.

To establish the effect of wettability on compression of the spring, a hydrophobic spring was also prepared; optical images are shown in SI5 [58]. It is clear that wettability plays a major role

in spring compression, as no compression is observed in a spring made of a hydrophobic fiber. Similarly, to check the effect of the elastic modulus of the material, a copper fiber (completely wettable by water $\sim 0^\circ$ contact angle, similar to soft springs made up of polyester) is used to prepare a solid helical spring (SI6 [58]). Since the elastic modulus of copper is ~ 80 GPa, which is 40 times higher compared to the polyester/nylon fiber, it shows no compression even for a value of 0.09 of $\lambda/2R$, while the flow regimes are still preserved but different values of $\lambda/2R$. In all cases, the length of the helix is sufficiently large compared to the deformation of the helix to avoid the error in compression dynamics. Additional experiments have also been conducted with a helical spring composed of 0.2-mm fiber diameter, having an average spring constant of 0.06 Nm^{-1} , which exhibits very small capillary-induced deformations (see SI7 [58]). So, the compression of the spring depends on the balance between the capillary and elastic forces between the coils.

In static spring configurations, we measure directly the contractility Δz (see SI8 [58]) of the spring by comparing the undeformed spring with the final placements of the wetted coils. The capillary force can be estimated based on the n number of wetted coils, where the capillary pressure $\sim \gamma/\lambda$ gives a scaling relation for the net force induced by capillarity to be $F_{\text{cap}} \sim nR^2\gamma/\lambda$, where $n = (V/\pi\lambda R^2)$ is related to the injected volume V and the spring radius R . The capillary force is balanced by the elastic force exerted by the spring, which we assume follows Hooke's law $F_E = k\Delta z$, with Δz the compression of the spring in the z direction. By balancing these two forces, we get

$$\frac{\Delta z}{V^{1/3}} \sim \frac{\gamma V^{2/3}}{k\lambda^2} \sim \frac{1}{N_{\text{EC}}} \left(\frac{V^{1/3}}{\lambda} \right)^2. \quad (1)$$

The scaling relation gives a prediction for the potential capillary contractility of the spring as a function of the pitch λ , droplet volume V , and the effective Spring coefficient k that is linked to the material choice and spring geometry. To test the scaling prediction, we extract Δz from the static experiments, as shown in Fig. 2(d), where we have also indicated the approximate transition regions between the different regimes described above. In these experiments, λ , k , and V are varied, where we notice a dramatic effect in terms of the induced compression with the decrease in λ . The dimensional data in Fig. 2(d), see also the inset, is recast into a dimensionless form based on Eq. (1), which we see follows the predictions well, given that both hollow (liquid bridge between coils) and filled states can be found for the smallest realization of $\lambda/2R$. The magnitude of the spring compression is overestimated in Eq. (1), as the curvature of the meniscus is significantly less than $1/\lambda$ in the experiments, as seen in Fig. 2.

C. Capillary flow in a soft spring

When the injected volume V exceeds a critical value, the droplet transitions from a static shape in the springs to a state where it is flowing downwards. It is gravity g that is the driving force for the droplet motion, with interfacial dynamics as a complex interplay of viscous and inertial effects in combination with capillarity, and a dynamic wetting (contact line) process. In Fig. 3(a) we show a snapshot of flowing droplets when Reynolds number Re , the ratio of inertia and viscous forces, is $Re \sim \rho v_z R / \mu \in [1-40]$ for $\lambda/2R \in [0-0.9]$, where ρ , v_z , μ are the density, downward velocity, and viscosity of the droplet, respectively. For the snapshot shown in Fig. 3(a), the Capillary number, which is the ratio of viscous force and capillary force, is $Ca \sim \mu v_z / \gamma \in [2 \times 10^{-5} - 3 \times 10^{-4}]$, as we change $\lambda/2R \in [0-0.9]$. The droplet flows in a soft spring is contrasted with the flow of a droplet in a perfectly wetting capillary tube, i.e., similar to $\lambda/2R = 0$. Figure 3(a) clearly illustrates that the soft spring has a highly nontrivial effect on flow compared to the capillary tube. For a perfectly wetting capillary tube, we observed the characteristic concave shape of the interface with a wettinglike front ahead of the droplet as it moves downward along the z direction. Even with a fairly small $\lambda/2R = 0.16$, the concave shape has disappeared, and the interface at the front and back is nearly flat (see the Supplemental Material, movie SM5 [58]). As we further increase the pitch $\lambda/2R \approx [0.3-0.8]$,

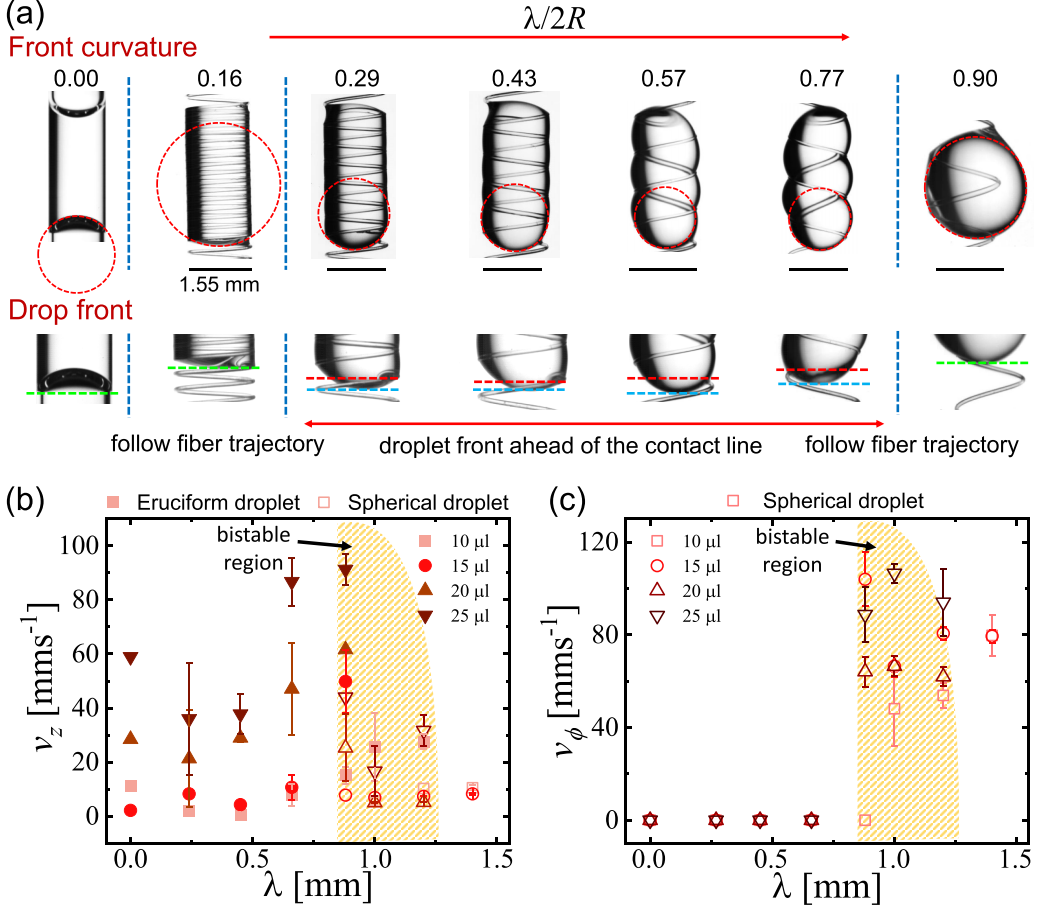


FIG. 3. Droplet on a fiber; (a) Eruciform-to-spherical droplet transition with $\lambda/2R$ for $V = 10 \mu\text{l}$, where $\lambda/2R = 0$ is for capillary tube. The first row corresponds to the droplet equilibrium shapes on different $\lambda/2R$ and curvature (red circle) of the droplet front while moving downward, and the second row shows the droplet front ahead of the contact line with $\lambda/2R$. The green dashed line indicates that the droplet front and contact-line positions are the same, while the blue dashed line represents the droplet front and the red dashed line represents the contact-line position, if they are different. The scale bar is the same for all the optical images. (b) Downward velocity v_z for an eruciform and spherical droplet with λ , (c) azimuthal velocity v_ϕ for an eruciform and spherical-shape droplet. The yellow shaded region is the bistable region.

the front and back of the droplet form instead a convex shape where it looks as if it is more and more “squeezed” in the spring as the pitch increases (see Supplemental Material, movie SM6 [58]). Here, the droplet adopts an eruciform shape much similar to a caterpillar, and counterintuitive as one might have anticipated such a shape for a hydrophobic material, in contrast to the nearly perfectly wetting springs in Fig. 3(a).

As $\lambda/2R \geq 0.8$, a nearly spherical droplet is formed in the spring (see Supplemental Material, movie SM7 [58]). These different shapes provide a clue that there are also very different flows within these droplets. In particular, we notice that for small $\lambda/2R \approx 0.16$ the apparent contact line is the same as the advancing front of the droplet that advances as it wets the spring, consequently compressing the spring at the leading edge of the droplet while spring coils relax as they “leave” the droplet’s trailing edge [Fig. 3(a)]. While for the eruciform droplet interface, $\lambda/2R > 0.2$ appears to move ahead of the apparent wetting contact line. For a spherical droplet, its leading edge appears

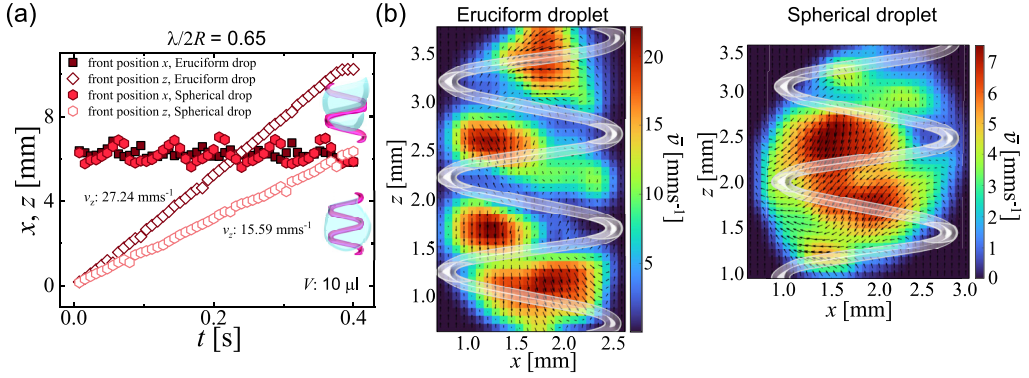


FIG. 4. Flow inside helical spring. (a) x, z position of the advancing front of an eruciform and spherical droplet for $\lambda/2R = 0.65$ and $V = 10 \mu\text{l}$, (b) PIV images for internal velocity $\bar{v} = (v_z^2 + v_x^2)^{1/2}$ for an eruciform- and spherical-shape droplets for $V = 10 \mu\text{l}$, and $\lambda/2R = 0.65$. A helical-spring schematic is added over the PIV images to guide the droplet shape.

to follow the evident spreading front. The dashed lines in Fig. 3(a), second row, show the droplet front/single-advancing front, while the blue and red dashed line shows the difference in advancing front and contact line.

To quantify in more detail the differences between these flows, we extract from the experiments the mean velocity in z direction v_z and the azimuthal velocity $v_\phi = s\omega$, with s the radial distance from center of helical spring axis and ω the angular velocity based on the droplet's center of mass (see SI9 [58]). By extracting these velocities, we show that there is a nonmonotonic relationship between v_z and λ . The nonmonotonic behavior of v_z is somewhat counterintuitive, as the spring's wetted area is larger when the droplet is in eruciform versus a spherical shape. Moreover, there appears to be a range of λ over which the droplet may adopt both an eruciform and a spherical shape, a bistable region illustrated by the shaded areas in Fig. 3(b). By comparing data from these two regimes/droplet shapes, it is clear that the droplet with an eruciform shape moves downward much faster compared to the corresponding spherical shape, as shown in Fig. 4, as also seen within the bistable regime [Fig. 3(b)]. It is only the spherical-shaped droplets that have a $v_\phi \neq 0$, as the eruciform-shaped droplet has a center of mass lying on the axis of the spring, i.e., $v_\phi = 0$. The rotation velocity v_ϕ of the spherical droplets around the helix is plotted in Fig. 3(c). The higher the pitch and the larger the liquid volume, the greater the rotational velocity of the droplet. For a larger pitch $\lambda/2R > 0.65$, and for larger liquid volume, the spherical-shape water droplet starts to follow the fiber geometry, and due to that, it gives oscillations in the spring's radial direction. Although the eruciform-shaped droplets have $v_\phi = 0$, it is clear that they have an azimuthal velocity within the fluid, as the videos clearly illustrate how the interface appears to be “arching” through the spring.

Why the eruciform-shaped droplets have a higher velocity as compared to a spherical-shaped droplet can be explained by their internal flow fields as they traverse the helical spring. These flows are illustrated by seeding the liquid with 0.2% of $10 \mu\text{m}$ silver-coated hollow glass spheres. The analysis of the downward flow is done by using the particle image velocimetry (PIVlab) tool in MATLAB [59] and averaged over multiple time sequences, as shown in Fig. 4(b) for an eruciform and a spherical droplet. The advancing and receding fronts do not have sufficient contrast between particles and background; due to this, the mean internal velocity is not quantitatively measurable at these locations. The mean internal velocity in Cartesian coordinates, $\bar{v} = (v_z^2 + v_x^2)^{1/2}$, where v_x is the velocity in the x direction, is shown for an eruciform and spherical droplet shapes in Fig. 4(b) for $\lambda/2R = 0.65$ and $V = 10 \mu\text{l}$. The heat map shows that, for an eruciform droplet, the internal flow is not only downward but also rotational as it moves downward. The high internal velocity [red color in Fig. 4(b)] appears when the droplet follows the fiber curvature and takes turns to move downward. While for a spherical droplet, the internal flow is also rotational, but the angle

of this rotational flow with gravity is low compared to an eruciform droplet. In the images, the fiber also influences the analysis of internal flow, and therefore, the total internal velocity cannot be quantitatively predicted at those locations using the PIV analysis. This internal rotational flow appears with the increase in the pitch; we have observed no internal flow at a small pitch. With the $\lambda/2R > 0.43$, the droplet interface in the lateral direction becomes convex and with a more complex internal flow having $Re > 1$ (see SI10 [58]). While an eruciform droplet is moving downward, it experiences spiral curvature; due to this, the droplet has different flow orientations at the advancing and receding ends. The flow of the liquid has an angle with respect to the direction of gravity, so the advancing front increases the outward flow, which in turn enhances the overall downward flow. We have considered that the center of the mass of the droplet is aligned with the axis of the helical spring, resulting in zero azimuthal velocity around the spring. For $\lambda/2R > 0.43$, when the droplet is spherical, internal flow as well as the droplet rotates around the axis of the helical spring with a small angle with the gravity compared to an eruciform droplet, resulting in an increase in azimuthal velocity and reducing v_z as shown in Fig. 3.

The larger the value of $\lambda/2R$, the less the eruciform droplet is influenced by the presence of the fiber geometry, while the spherical droplet starts to experience wall adhesion (droplet is pinned between the coils while moving downward) and behaves as a drop behaves in Wenzel state (see SI11 [58]). Since the droplet moves within the helical spring and follows its geometry, for $\lambda/2R > 0.9$ and volume $> 20 \mu\text{l}$, due to centrifugal force, the droplets start detaching from the helical spring. Also, we observed that for $V > 30 \mu\text{l}$, small liquid droplets began to eject from the receding part of the eruciform droplet (see SI12 [58]).

D. Influence of viscosity

We also show the effects of the viscosity μ , which is varied by altering the fraction between water and glycerol, with $\mu \in [0.001\text{--}1.4] \text{ Pa s}$ (SI13 [58], which includes Ref. [60]). Viscosity can alter flow dynamics, but it also affects the eruciform-to-spherical shape transition, likely through changes in the capillary number. For water and water-glycerol solutions of μ up to 0.006 Pa s , the transition is observed around $\lambda/2R = 0.43$, but the transition is observed at $\lambda/2R = 0.29$ for larger μ . This shape transition involves the time scale associated with the dispensing rate to flow within the helical spring. For large μ , the liquid adopts a spherical shape first and then starts flowing along a helical fiber. Similarly, if enough time is not provided to spread the liquid between the coils, it always forms a spherical droplet in the spring. So, the boundary between different regimes depends on λ and the dispensing rate of the liquid when the viscosity is high. v_z of the droplets in an eruciform droplet and a spherical droplet is shown in Fig. 5(a). Intuitively, the increase in viscosity decreases v_z .

To rationalize the downward speed v_z of the droplets, we turn to a scaling prediction by balancing $F \times v_z \sim \phi_\mu$ where $F = \rho V g$ is the gravitational force and ϕ_μ is the viscous dissipation. Using the center of the spring as a point of reference and adopting a cylindrical polar-coordinate system (r^*, ϕ, z) we can estimate the viscous dissipation in the bulk of the droplet to be $\phi_\mu = \mu \int (\frac{\partial v_z}{\partial r^*})^2 dV + \mu \int (r^* \frac{\partial}{\partial r^*} (\frac{v_\phi}{r^*}))^2 dV$. The droplet has both vertical and rotational flows within it, where the latter is believed to dominate, given that parts of the droplet are exposed to air with free slip. Using this assumption, the main part of the dissipation would come from $\phi_\mu \sim \mu \int (r^* \frac{\partial}{\partial r^*} (\frac{v_\phi}{r^*}))^2 dV$, where $r^* \sim R$ (the radius of the spring). Inserting these scaling relations together with $v_\phi = 2\pi R v_z / \lambda$, connecting the droplet flow v_z and the spring geometry with v_ϕ , gives

$$v_z \sim \frac{\rho g \lambda^2}{4\pi^2 \mu} \quad (2)$$

the scaling prediction gives a link between the rotational flow within the droplet and the flow speed through the spring. We use Eq. (2) to rescale the velocity for a range of viscosities μ , volumes V , and pitch λ in Fig. 5(b). The scaling prediction is expected to hold for $Re < 1$, and, as expected, the data deviate from the scaling prediction for $Re > 1$ as shown in Fig. 5(b). When $Re > 1$, inertia starts to dominate the viscous effect in the flow. There are other factors also involved, such as enhanced

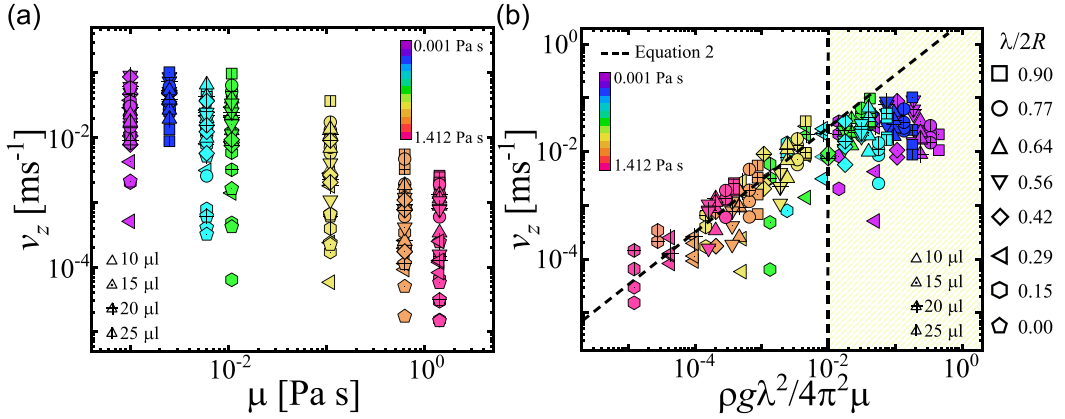


FIG. 5. Droplet flow dynamics. (a) v_z of the eruciform and spherical droplet for $\mu \in [0.001\text{--}1.412]$ Pa s, (b) scaled v_z of the eruciform- and spherical-shaped droplets with $\mu \in [0.001\text{--}1.412]$ Pa s, $\lambda/2R \in [0.15\text{--}0.9]$ and $V \in [10\text{--}25]$ μl . The black dashed line is the scaling prediction in Eq. (2) (slope 1), and the vertical black dashed line indicates the transition where $\text{Re}=1$, to the right of the line $\text{Re} > 1$.

internal rotational and secondary flow, spring oscillation, and a droplet is pinned between two spiral coils with similarities to a Wenzel state [61].

E. Lifting weights with droplets and actively tuning droplet flow

Now we turn to illustrate how these understandings of equilibrium and droplet dynamics can be used to demonstrate actuation and active flow control. We start by illustrating how actuation is achieved by converting capillary energy into spring energy. To demonstrate this, we attach a weight $m = [39, 49] \pm 1$ mg to the end of the soft spring as shown in Fig. 6(a). After the weight has been placed, the spring is allowed to relax before liquid is dispensed. For a $m = 39$ mg weight and $m = 49$ mg, the stretched spring has an $\lambda/2R = 0.12$ and 0.16 , respectively, and water from $2\text{--}20$ μl (weight $\approx 2\text{--}20$ mg) is dispensed on the spring. As water is dispensed, the spring contracts and, after equilibration, reaches a static shape. The total deformation of the helical spring for the two added weights is shown in Fig. 6(b). This total compression corresponds to the injected-liquid volume, which has its potential surface force. To estimate the potential work by tensile actuation to do work, generated by the surface forces, we extract $\Delta L/L \times 100$, with ΔL the spring deformation and L the spring length. We note that only a small fraction of the coils are wetted and as such are responsible for the compression. If additional coils have been wetted, one may expect that the total deformation could be much greater. As such, the specific work measured here corresponds only to the wetted area of the spring; optical images are shown in Fig. 6(a). The highest tensile actuation observed is 73% for a weight of $m = 0.049$ g, but if the total length of the spring is taken into account, it would reduce to 12%. The maximum specific work ($F_{\text{cap}} \Delta L/m$, where, m is the attached mass) done by the 20 μl droplet is 54 J/kg, which is higher than the specific work done by the mammalian skeletal muscle, 38.6 J/kg, but less than the hydrothermal-induced compression on coiled nylon, 2860 J/kg studied before [29], i.e., only 10% of the total length is wetted, and with a small volume. It should be noted that the system here is not optimized for the amount of wetted area of the spring. The specific work is calculated when only 10% (length of the droplet/total length of the spring) of the length of the spring is responsible for lifting the weight.

Next, we apply these concepts and knowledge to the control of droplet dynamics in a soft spring, demonstrating this as a proof of concept for flow control. The analysis of static shapes illustrates how droplets can “freeze” into different configurations, while the droplet-flow analysis indicates that the spring wavelength λ can control the droplet-flow regime. We utilize this method as an active means

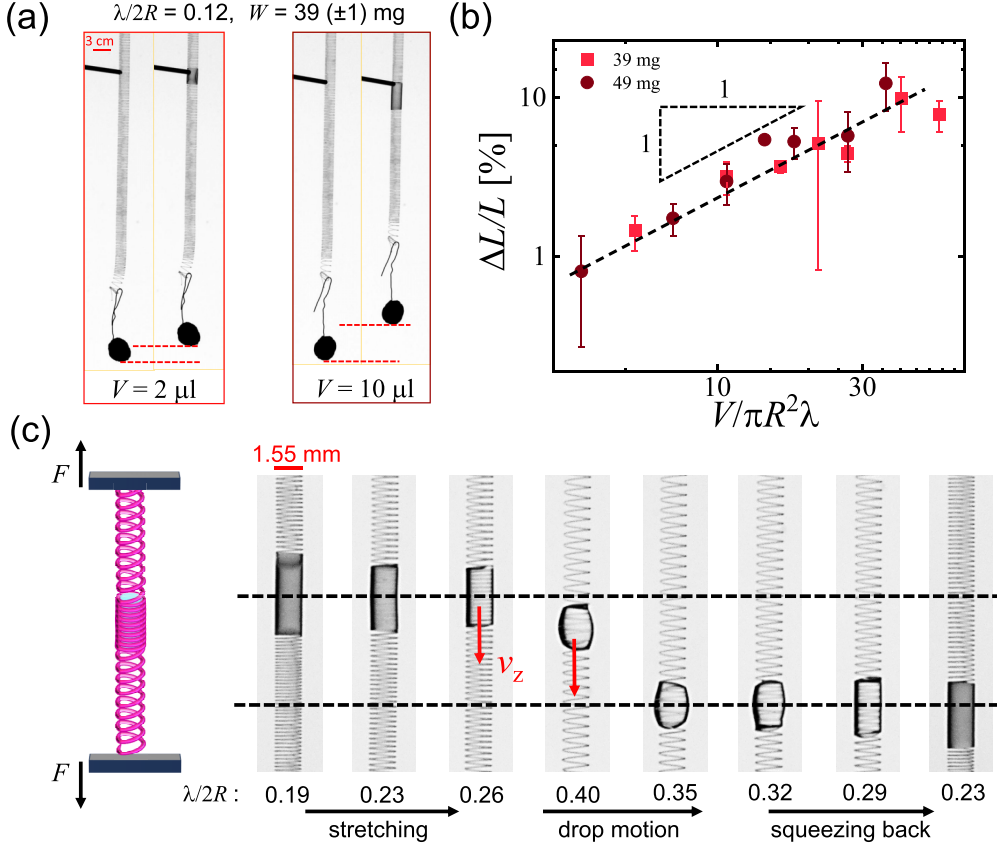


FIG. 6. Lifting weights with droplets. (a) Optical images of the spring-deformation weight due to capillary force. (b) Tensile actuation $\Delta L/L [\%]$ for different droplet volumes with the weights $m = 0.039 (\pm 0.01) \text{ g}$ and $m = 0.049 (\pm 0.01) \text{ g}$, (c) droplet flow control by active stretching and squeezing the spring while the spring is filled with $10 \mu\text{l}$ water.

to both stop and induce droplet flow in these springs, as illustrated in Fig. 6(c). Water is deposited in the spring with $\lambda/2R = 0.19$ and finds a static form in the spring (regime I). The wavelength is then changed by stretching the two ends, and since $\lambda/2R = 0.26$, we observe that the droplet flows with an eruciform shape in the spring. Imagine that we now also want to control the speed of the droplet, and we can use insights from the different flow regimes as a function of $\lambda/2R$. As the spring is further stretched, water transitions from the eruciform to a spherical droplet shape, significantly reducing the descent speed. Now, this dynamics is reversible (qualitatively), upon compressing the spring, the droplet speed increases, and it forms an eruciform shape before returning to its static, arrested shape, as seen in Fig. 6(c). Due to the compression and decompression, the system requires additional force for the transitions, introducing hysteresis in the tunable dynamics. This investigation of the hysteresis and potential use of the system is an interesting future avenue to be investigated.

III. CONCLUSION

We have shown how a soft spring system behaves when introduced to a liquid, demonstrating that capillarity can significantly compress the spring, i.e., for a small elastocapillary number. The spring geometry plays a crucial role in determining both the equilibrium shape and the dynamic

flow of droplets. A range of complex interface shapes is determined for the equilibrium shapes of the spring and droplets. Beyond a critical volume, these droplets start to flow, and λ is a key parameter to determine the flow regime. For small λ , droplets flow with a cylindrical shape and a velocity profile along the z direction of the spring. When $\lambda/2R > 0.3$, it takes the shape of a caterpillar, with an eruciform shape arching through the spring with an increased velocity and also a slight flow in the azimuthal direction, although its center of mass stays put at the center of the spring. When increasing further $\lambda/2R > 0.77$, the droplet adopts a spherical shape, significantly reducing the settling velocity and with a motion of its center of mass in the azimuthal direction.

Through an understanding of the equilibrium and dynamics of droplets in soft springs when the elastocapillary number is small, we showed how these effects can be adopted to induce actuation and flow control. There are many more interesting aspects of these capillary slinkies that warrant future studies, which this work can hopefully stimulate, including the decoupling of gravitational influences, liquid-film deposition, partial wetting, and computations of equilibrium shapes and droplet flow.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [62].

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