ACTIVE MATTER

Have tail, will travel

The flagella of microorganisms have provided inspiration for many synthetic devices, but they're typically not easy to produce. A new class of swimmer makes it look simple by spontaneously growing a tail that it can whip to self-propel.

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The ability to navigate in fluids is essential to the survival of microorganisms, enabling them to search for food and reproduce. And they do it so well that scientists have long tried to replicate their techniques — building synthetic microswimmers that are custom designed for everything from in vivo transport to drug delivery. One popular locomotion strategy imitates the whipping motion of the hair-like flagella found on many organisms[1], but this requires intricate actuation machinery, and thin elastic filaments that are difficult to manufacture. For this reason, many artificial microswimmers have instead made use of chemical power, thermal effects or external magnetic forces. But now, writing in *Nature Physics*[2], Diana Cholakova and colleagues have turned back to biology for inspiration, and come up with a swimmer that grows its own elastic tail to propel it forward.

The recipe for this swimmer is at once simple and elegant. The sole component is an alkane droplet, suspended in an aqueous surfactant solution. Upon cooling, a liquid-to-plastic phase transition triggers the spontaneous formation of a tail (Fig. 1). More specifically, a plastic phase forms at the surface, which is continuously fuelled by the liquid interior of the drop. This ever-expanding phase distorts the droplet into a spiked shape and is eventually ejected as a thin elastic filament. The extruded tail encounters viscous resistance, which in turn pushes the drop forward, enabling the droplet to swim. Upon heating, the swimmer 'recharges', meaning that the filament retracts, returning the droplet to its initial spherical shape.

How much the drop backtracks during its recharging phase is a legitimate concern. Small-scale swimmers operate in a low-Reynolds-number world, where viscous damping dominates over inertia. This imposes stringent constraints on their swimming strategies: any reciprocal motion — like waving a rigid arm back and forth — simply brings you back to your starting point[3]. To break time-reversal symmetry, many microorganisms resort to flexible flagella that produce asymmetric strokes.

The droplet reported by Cholakova et al. works on a similar principle, relying on the inherent elasticity of its tail not to backtrack all the way. In the propulsive phase, the extruded fibre buckles — as would a column suddenly bowing under compression — and then coils. The recharging phase does not feature this instability, which is specific to compression, and so the filament retracts along a different route. As a result, the swimmer achieves net motion over a temperature cycle.

Cholakova et al. characterized their new class of swimmer, measuring and analysing its propulsive performance. They determined that it achieves a forward and backward swimming speed of around 0.1–0.7 μm s^{-1}. The knobs to control velocity within that range are the cooling and heating rates, the type of oil used and the droplet size. These parameters set the number of tails formed, their extrusion and retraction speeds, and their diameter, which in turn determines the bending stiffness.

To better understand how these parameters factor into the swimmer's propulsive mechanism, the authors developed an elasto-hydrodynamic model, which balances the hydrodynamic Stokes drag on the extruded filament with the counteracting drag on the mother droplet. In other words, the net motion depends on who drags the most. The model suggests that although the filament experiences increased friction as it extends, the resulting propulsive force does not increase indefinitely. It is capped due to the tail's repeated buckling. On the basis of these intricate fluid–elastic couplings, Cholakova et al. derived a scaling relation for the swimming speed, and then validated it experimentally. The predictive ability of the model was further tested by showing that it quantitatively captures the wobbling motion of two-tailed swimmers.

This new system involves non-toxic components and mild temperature variations that are compatible with biological conditions. This offers it a distinct operational advantage over other synthetic swimmers that consume toxic chemical fuel to self-propel. As such, it joins the small family of existing biocompatible swimmers that have already demonstrated potential for biomedical applications such as targeted drug delivery, cargo transport, assisted fertilization or biofilm removal[4,5]. It also bridges active-matter studies on biological and synthetic swimmers, by potentially allowing the two to interact in a compatible environment.

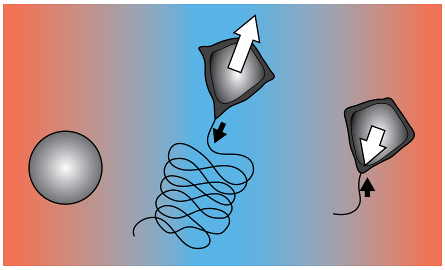

Fig. 1 | Flagellated swimmer. Upon cooling (red to blue gradient), the oil droplet grows an elastic tail through a liquid-to-plastic phase transition, and this tail propels it forward. The tail retracts on heating, effectively recharging the system. Figure adapted with permission from ref. [2], Springer Nature Ltd.

Beyond practical applications, these droplets can also serve as a tool to better understand the biological organisms from which they draw inspiration. For example, the mechanism behind the synchronized beating of the flagella of algae *Chlamydomonas reinhardtii* remains elusive. Two-tailed swimmers might shed light on the matter, because they bear resemblance to these algae, but are devoid of any biological machinery. Cholakova et al. report no sign of synchronization in their system and argue that this supports the idea that internal coupling has a central role for these algae, rather than hydrodynamics. But as the droplet's size and configuration are different from its biological counterpart, it is difficult to draw such clear conclusions.

This new swimmer is thus off to a promising start, despite some remaining limitations. It moves fairly slowly: about one thirtieth of its size per second, whereas other swimmers can cover ten times their size in the same time span. This is partly due to the low cooling rates required, which limits the tail extrusion speed. The motion is also partially irreversible so far, as the droplet significantly pulls back upon retraction of its filaments. Further fine tuning should nevertheless help to maximize the net motion over a temperature cycle. Finally, the growing filaments accumulate in the wake of the swimmers, which might cause steric hindrance in dense swarms and restrict applications in the study of emergent group behaviour.

Nonetheless, it is no small feat to create filaments so thin that they can bend at the micrometre scale, and devise actuation modes for locomotion. By way of comparison, previous implementations of artificial flagella involved advanced manufacturing. Some examples are chains of magnetic particles linked by DNA and actuated externally[6], or biohybrid polymeric filaments grafted with heart muscle cells that contract periodically[7]. Other low-Reynolds-number swimmers have circumvented the problem with centimetre-size systems that move in viscous liquid[8].

The beauty of the new swimmer comes from the fact that the propulsive machinery spontaneously self-assembles from simple components. It forms a minimal model swimmer comprising only a body and tails, and thus offers a powerful platform for physicists, who are adept at understanding complex phenomena by reducing systems to their simplest form. ❐

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References

1. Elgeti, J., Winkler, R. G. & Gompper, G. *Rep. Prog. Phys.* **78**, 056601 (2015).
2. Cholakova, D. et al. *Nat. Phys.* https://doi.org/10.1038/s41567-021-01291-3 (2021).
3. Lauga, E. & Powers, T. R. *Rep. Prog. Phys.* **72**, 096601 (2009).
4. Lee, S. et al. *Adv. Healthc. Mater.* **7**, 1700985 (2018).
5. Nelson, B. J., Kaliakatsos, I. K. & Abbott, J. J. *Annu. Rev. Biomed. Eng.* **12**, 55–85 (2010).
6. Dreyfus, R. et al. *Nature* **437**, 862–865 (2005).
7. Williams, B. J., Anand, S. V., Rajagopalan, J. & Saif, M. T. A. *Nat. Commun.* **5**, 3081 (2014).
8. Yu, T. S., Lauga, E. & Hosoi, A. E. *Phys. Fluids* **18**, 091701 (2006).

Competing interests

The author declares no competing interests.