Materials science

Light moves artificial cilia to a complex beat

Dhanya Babu & Nathalie Katsonis

The beating of hair-like structures that enable microorganisms to swim has been replicated in a polymer material that bends and twists with the help of light-sensitive molecular machines. **See p.76**

Cilia are microscopic hairs that grow on the outer surfaces of unicellular organisms, propelling the organisms through liquids by rhythmically beating in a specific pattern. This beating motion follows complex trajectories to achieve forward propulsion[1], a feature known as non-reciprocal movement that it shares with human swimming techniques. But although this motion might be familiar, it is difficult to replicate using synthetic materials, because the beating is driven by the synchronized operation of many nanoscale molecular machines. On page 76, Li *et al.*[2] reveal that light-sensitive artificial molecular machines can be used to drive similarly complex motion in polymer cilia constructed from a single material.

Non-reciprocal motion is essential to movement in organisms that are micrometre-sized. A counterexample is the scallop, which is typically 10–20 centimetres long, and can swim forwards or backwards simply by opening and closing the two halves of its shell. This motion is reciprocal, because the opening and closing follow the same trajectories. By contrast, micrometre-sized unicellular organisms experience water as a viscous fluid, like a human swimming through honey, and so they cannot rely on inertia to push them forwards[3]. Therefore, to swim in water, such organisms have developed strategies involving complex non-reciprocal movement patterns. Some grow a long flagellum that rotates in a corkscrew-like way; others grow cilia; and still others have bodies that can take on spiral shapes[4].

In artificial materials, cilium-like behaviour can be realized by inducing non-reciprocal shape transformations. Li and colleagues achieved this by using a molecular machine that flips back and forth in response to light[5].

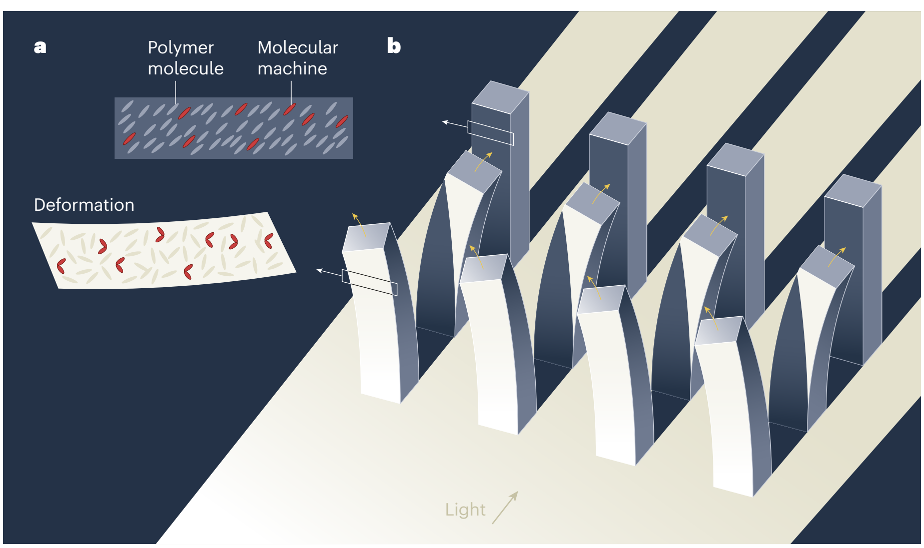

Figure 1 | Artificial hair-like structures (cilia) produce complex, collective beating patterns. a, Li *et al.*[2] have designed cilia that exhibit beating dynamics, by incorporating light-sensitive molecular machines into a liquid-crystalline polymer material. When light shines through the material, it activates the molecular machines, which change shape and thereby deform the illuminated area, leaving the rest of the material unperturbed. **b**, The authors demonstrate that arrays of these cilia display collective motion through a shadowing effect: one cilium blocks the light aimed at its neighbour, but as soon as it starts beating, light shines on the neighbouring cilium, which, in turn, starts moving. This creates a domino effect through the array.

These molecular machines can be bound covalently into a polymer made from a liquid-crystalline compound[6]. The approach is not entirely new; it has been used to mimic some of the complex movements found in the plant kingdom[7] – from the winding of cucumber tendrils[8] to the bursting of seedpods[9], the snapping of flytraps[10] and the light tracking of sunflowers[11]. But the authors have paired this technique with microfabrication, and with a model that predicts the motion of a cilium as a function of molecular misalignment with respect to its main axis, and the direction of illumination. The model can be used to guide the design of functional cilia.

Here, light plays a crucial part. When the polymer material absorbs light, a gradient of illumination intensity is established over the width of each cilium. As the light passes through the material, it activates the molecular machines, causing them to bend. This disrupts the liquid-crystalline order of the polymer and creates a gradient in molecular disorder[12] (Fig. 1a). As a result, the homogeneous material is converted into two layers with different shape-shifting properties. The illuminated areas shrink preferentially along the orientation of the liquid-crystal molecules, which is also that of the molecular machines, whereas the 'dark' areas of the cilium remain unperturbed. This forces the cilium as a whole to both bend and twist.

The authors found that they could establish feedback loops in this system. As the cilia twist, they expose different faces to the light, leading to changes in the travelling front of the light as it moves through each cilium. This change, in turn, affects the distribution between ordered and disordered areas over time, resulting in complex movements that Li *et al.* were able to manipulate by varying the intensity and direction of the illumination. And, once the light was switched off, the material relaxed by performing a movement that was different from the forward, light-induced movement. Li and co-workers concluded, therefore, that a on–off light cycle could induce a cilium beat that constitutes a non-reciprocal motion.

The authors then demonstrated that arrays of their beating cilia could exhibit collective motion by 'communicating' with each other through shadowing effects: when illumination induces one cilium to bend, it blocks the light aimed at its neighbour, and so on (Fig. 1b). This domino effect leads to the appearance of propagating waves, indicating that the movement of light-driven molecular machines can be transduced into collective movement. In this system, collective movement is induced by light, and could not be achieved by heat or chemical reactions.

The next frontier in this research could be to prepare the artificial cilia by going beyond microfabrication techniques and instead inducing the cilia to grow

From the archive

Making the connection between mosquitoes and disease, and reports of volcanic activity at Mount Vesuvius.

100 years ago

The death of Sir Patrick Manson ... has taken from the medical profession one of its most distinguished leaders ... [I]t was not until 1874 ... that he learned fully of Lewis's discovery of a microscopic filaria ... in the blood ... [H]e saw that the series of events by which the microfilariae living in the blood of one man became the adult filariae living in ... other men ... might possibly be initiated by ... a mosquito ... He ... demonstrated the essential realities of a great original conception ... that a common bloodsucking insect is *the essential factor* in the maintenance and dissemination of a ... parasitic disease. In 1894 ... Manson found his opportunity of applying this great principle to the problem of malarial infection ... Manson's mosquito-malaria theory ... inspired and guided Ross in his wonderful discovery of the sexual cycle of the malaria parasite.

From *Nature* 6 May 1922

150 years ago

The great eruption of Mount Vesuvius, with the telegraphic accounts of which the readers of the daily papers have been familiar for the past week, is undoubtedly one of the most considerable of modern times. Whether the worst is yet over seems still uncertain while we are writing; but even if this be the case, the mass of molten lava ejected, and the amount of damage done, will appear to bear comparison with those of almost any recent eruption. One account speaks of it as the grandest eruption since 1631 ... The fall of cinders, even at Naples, is spoken of as so heavy that the sky seemed hidden by them, and they fell everywhere like rain ... [P]eople were walking with umbrellas to protect themselves from the downpour ... Great credit is due to Prof. Palmieri, who has remained at his post at the Observatory to watch the eruption, and from whose observations a great advance of science may be anticipated.

From *Nature* 2 May 1872

spontaneously through interactions between the constituent molecules[13]. Another challenge would be to engineer a way of avoiding the need for bespoke illumination conditions that involve continuously switching the light on and off[14].

Although the authors showed that their artificial cilia could display complex movements reminiscent of cilia in living organisms, these structures are yet to rival their natural counterparts in terms of functionality. In biological systems, the beating of cilia is used to make a cell swim and to support the varied motile dynamics that enable the survival[15] and competitive behaviour of bacteria[16]. Moving from motion to motility requires materials to show even better performance than that reported by Li and colleagues, calling for smaller structures, faster movement and higher amplitudes of oscillation. However, the authors' work represents a crucial step towards functional artificial cilia. Along the way, it will doubtless inspire advances in microfluidics, and might even propel our understanding of cilia and cellular motility forward.

Dhanya Babu and **Nathalie Katsonis** are at the Stratingh Institute of Chemistry, University of Groningen, 9747 AG Groningen, the Netherlands.
e-mails: d.babu@rug.nl; n.h.katsonis@rug.nl

1. Geyer, V. F., Howard, J. & Sartori, P. *Nature Phys.* **18**, 332–337 (2022).
2. Li, S. *et al. Nature* **605**, 76–83 (2022).
3. Purcell, E. M. *Am. J. Phys.* **45**, 3–11 (1977).
4. Jarrell, K. F. & McBride, M. J. *Nature Rev. Microbiol.* **6**, 466–476 (2008).
5. Groppi, J., Baroncini, M., Venturi, M., Silvi, S. & Credi, A. *Chem. Commun.* **55**, 12595–12602 (2019).
6. Gelebart, A. H. *et al. Nature* **546**, 632–636 (2017).
7. Burgert, I. & Fratzl, P. *Phil. Trans. R. Soc. A* **367**, 1541–1557 (2009).
8. Iamsaard, A. *et al. Nature Chem.* **6**, 229–235 (2014).
9. Asshoff, S. J. *et al. Angew. Chem. Int. Edn* **56**, 3261–3265 (2017).
10. Wani, O. M., Zeng, H. & Priimagi, A. *Nature Commun.* **8**, 15546 (2017).
11. Liu, L. *et al. Adv. Opt. Mater.* **8**, 2000732 (2020).
12. Pilz da Cunha, M., Debije, M. G. & Schenning, A. P. H. J. *Chem. Soc. Rev.* **49**, 6568–6578 (2020).
13. Cholakova, D. *et al. Nature Phys.* **17**, 1050–1055 (2021).
14. Lancia, F., Ryabchun, A. & Katsonis, N. *Nature Rev. Chem.* **3**, 536–551 (2019).
15. Miyata, M. *et al. Genes Cells* **25**, 6–21 (2020).
16. Gude, S. *et al. Nature* **578**, 588–592 (2020).

The authors declare no competing interests.

Human behaviour

Virtual collaboration hinders idea generation

Emőke-Ágnes Horvát & Brian Uzzi

Experiments and fieldwork show that teams working together online produce fewer ideas than those collaborating in person — a first step towards answering the question of which modes of communication are generally best for creativity. **See p.108**

Despite some awkward fumbling with Zoom, many workers have adopted videoconferencing as the new normal for interacting with socially isolated colleagues during the COVID-19 pandemic, and are increasingly demanding to work from home permanently. The resulting shift from in-person teamwork to virtual collaborations has become a central concern for employers and educators. On page 108, Brucks and Levav[1] provide fresh insight into how the creativity of teams collaborating through videoconferencing stacks up against that of teams working together in person.

Conventional wisdom holds that innovation is driven by in-person interactions that bring diverse perspectives together through a fluid, back-and-forth dialogue rich in verbal information and body language (Fig. 1). Seminal research[2] has shown that many great innovations in mathematics, science and the arts from the likes of Charles Darwin, the Funk Brothers and Marie Curie came about because of in-person interactions in teams or networks — a trend that still holds in many modern fields of endeavour[3,4]. Indeed, the scarcity of in-person meetings during the COVID-19 pandemic has been blamed for permanently denting scientific innovation[5]. With so much at stake, it is crucial to understand how computer-mediated interactions change creative thinking.

Brucks and Levav compared how two measures of creativity — ideation performance and idea-selection quality — differ when teams interact virtually or in person. Ideation performance quantifies the number of ideas generated. This is a key metric, because the more ideas there are, the greater is the potential for finding good solutions to problems. As the two-time Nobel laureate Linus Pauling was fond of saying, "The best way to have a good idea is to have lots of ideas."

Idea-selection quality characterizes how