Using the fluid to guide microswimmers

Squirmers in nematic liquid crystals: Guiding microswimmers by an anisotropic medium

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Recommended with a Commentary by Thomas R. Powers, School of Engineering and Department of Physics, Brown University

One of the practical motivations for the study of active matter is to develop new materials with life-like functionality. For example, living cells are capable of spontaneous directed motion, which is critical for nutrient transport and wound repair. One of the barriers to creating artificial micron-scale autonomous self-propelled particles that act like cells is that the astounding miniaturization utilized by Nature is beyond the reach of current human technology. Therefore, much effort is currently focused on using external influences such as forces and flows to guide the direction of self-propelled particles. Recent experiments [1, 2, 3], as well as the recommended paper [4], have shown that the fluid itself can guide swimmers if the fluid is a nematic liquid crystal. For example, flagellated bacterial tend to swim along the direction of alignment in a nematic liquid crystal [1, 2], and the bacteria tend to collect in the cores of +1/2 topological defects but deplete from the cores of -1/2 topological defects [3].

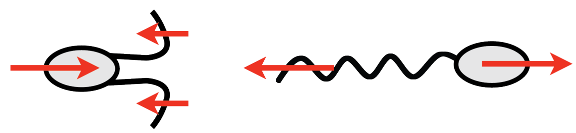

Figure 1: Sketch (not to scale) of *Chlamydomonas*, a puller (left), and *E. coli* (right), a pusher. Both are swimming to the right; the red arrows denote the direction of forces the cells' body parts exert on the fluid. Figure adapted from [6].

What is the mechanism that aligns the cells with the molecular order? In the experiments, both elastic and hydrodynamic forces are present, and it is difficult to disentangle them due to the complexity of the relation between stress and strain in a nematic liquid crystals. Lintuvuori, Würger, and Stratford [4] introduce a simplified model problem of a single swimmer to shed light on the torque that aligns a swimmer in a nematic liquid crystal. They consider an idealized model first studied by Lighthill and known as a 'squirmer' [5]. The squirmer was inspired by cells which are covered by cilia that beat in traveling wave patterns over the surface of the cell. The beating cilia are replaced by a prescribed tangential slip velocity u at the surface of the sphere,

$$u(\theta) = v_0 \sin\theta(1 + \beta\cos\theta), \tag{1}$$

where θ is the polar angle on the sphere, v_0 determines the scale of the slip velocity, and β is a parameter that determines whether the squirmer is a 'puller' ($\beta > 0$) or 'pusher' ($\beta < 0$). When $\beta > 0$, the largest values of the slip velocity occur in the front half of the squirmer ($0 < \theta < \pi/2$), and the swimmer is pulled through the fluid, analogous to the way *Chlamydomonas* algae pull themselves through water using flagella in the front of the cell (Fig. 1, left). Likewise, when $\beta < 0$, the largest values of the slip velocity occur in the back half of the squirmer, and the swimmer is pushed through the fluid, analogous to the way *Esherichia coli* cells push themselves through water by rotating flagella at the back of the swimming cells (Fig. 1, right). In this model, the propulsion mechanism picks out a direction but the shape of the swimmer is isotropic.

Lintuvuori *et al.* first consider the case of zero anchoring, in which the surface of the swimmer exerts no torque on the liquid crystal molecules adjacent to the swimmer. The nematic fluid thus exerts zero elastic torque on the swimmer, and any torque must arise from hydrodynamics. Using lattice Boltzmann calculations, they show that pushers align with the liquid crystal, but, strikingly, pullers align with their swimming direction perpendicular to the direction of molecular order.

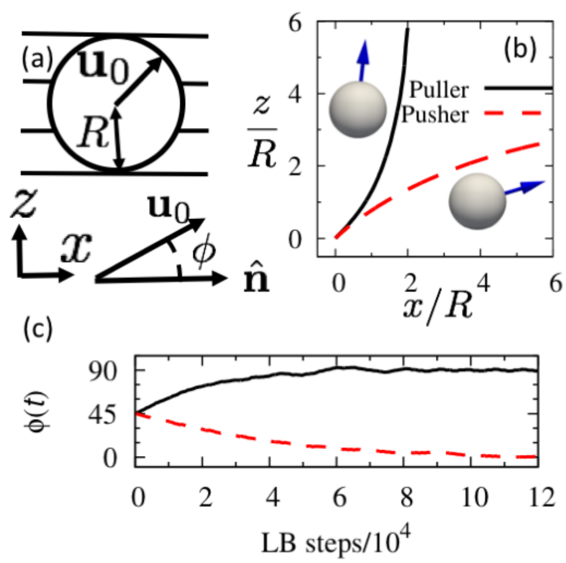

Figure 2: Figure from Lintuvuori *et al.* [4], courtesy of Lintuvuouri *et al.* (a) Spherical microswimmer in a nematic liquid crystal, with molecules aligned along the x direction. (b) Pushers tend to move along the direction of the molecules, and pullers move perpendicular to the direction of the molecules. (c) Evolution of the orientation of the swimmer as a function of time in units of lattice-Boltzmann steps, for pullers (black line) and pushers (red dashed line).

Since the elastic torque vanishes, the aligning torque must be hydrodynamic. Lintuvuori *et al.* present a simple theoretical calculation to give insight to their result. Although as mentioned the nematic stress is a complicated function of the strain rate and nematic configuration, it turns out that the hydrodynamic torque on the squirmer in a nematic liquid crystal is dominated by vorticity of velocity field. Evaluating this contribution to the torque using Lighthill's *isotropic* flow field and a constant director field leads to a simple formula for the torque which indeed predicts that pushers should swim along the nematic and pullers should swim perpendicular to it. This approximation has been used before in the study of the Brownian motion of a colloidal particle in a nematic fluid [7], where it was seen to give errors of about 10%. Further numerical calculations with strong anchoring show the conclusions about alignment continue to hold, suggesting they have some robustness against changes in the details of the swimmer. It will be very interesting to see if the simple and striking prediction of Lintuvuori *et al.* for the different behavior of pushers and pullers in a nematic crystal is born out by new experiments.

References

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