Learning from bacteria

Good science anticipates the shortcomings of human intuition; it expects that the concepts so useful for interpreting the world around us, at the familiar human scale, may well prove unsuitable elsewhere. This is obvious enough in areas such as geophysics or quantum physics, in cosmology or astrophysics, which deal with physics on extremely large or small scales of space, time or energy. Yet it's equally true, though less obvious, in other circumstances that seem more ordinary.

A simple microscope suffices to reveal the chaotic yet effective techniques of transportation of single-celled organisms such as bacteria. These and other microbes propel themselves purposefully through fluids by a variety of mechanisms, many of which involve the flailing of flexible rod-like flagella, either singly, or in pairs or bundles depending on circumstances. Their performance is certainly impressive in numerical terms. A typical bacterium, with size of the order of one micrometre, can swim roughly 100 of its body lengths per second — far faster in relative measure than any macroscopic creature, including the fastest mammals. It's a speed comparable even to that of birds such as the peregrine falcon, which can slice through thin air at up to 150 km h^{-1}.

But how such propulsion actually works is less clear. What we do know is that the relevant fluid dynamics have little to do with those involved in the swimming of people or fish, or the aerodynamics of flight, and depend on a curiously efficient interaction of thin flexible filaments with the fluid medium.

The fluid flows created as a bacterium swims tend to have Reynold's number of order 10^{-6}, which implies that inertial forces take little part in comparison with viscosity. Unlike a swimming fish or human (Reynold's number roughly 100), a bacterium doesn't coast or glide on stopping its effort, but stops dead in its tracks, immediately. Bacteria labour through an environment similar to what we'd encounter if trying to swim through very thick oil, or as Thomas Powers of Brown University puts it, the movement of a swimming bacterium is analogous to "the motion of a screw through wood".

Indeed, many bacteria create a swimming thrust by rotating their flagella, using biomechanical motors embedded in the cell membrane. Biologists know that these flagella are naturally warped into a helical shape, coiled around the axis about which they rotate. But why? Although there is as yet no definitive answer, recent computer simulations and experiments suggest that this distortion is probably an adaptation, tuned delicately to fluid principles on this scale, which results in increased thrust.

As a scale model of a rotating flagellum, imagine an elastic rod fixed at one end and forced to rotate about an axis, so that its length traces out the surface of a cone. Several years ago, Manoel Manghi and colleagues explored the physics of this simple model with computer simulations, and found an intriguing result. Their simulations predicted that with increasing speed of rotation, an undistorted elastic rod would, at a critical value of the applied torque, undergo a spontaneous deformation into a helical shape. Moreover, their results suggested that the rod's motion would produce little thrust before this deformation, and a great deal afterwards.

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Strong evidence confirming this effect now comes from a delightfully simple experiment carried out by mechanical engineer Bian Qian, working with Thomas and others at Brown. In the experiments, they immersed an elastic rod — a steel spring wrapped in Teflon tape to provide extra stiffness — in silicone oil, and used a motor to make it rotate about one end at speeds of several rotations per minute, giving Reynold's numbers of about 10^{-2} — small, though not quite as small as those relevant for bacteria. At slow speeds, they found, the rod remained rigid, tracing out the surface of a cone. The experiments showed that this simple motion provides no net force, only a thrust that changes direction and cancels out over each cycle.

At higher speeds, however, more interesting things happen. Naturally, the flexible rod first begins to bend a little, backwards, because of friction caused by its movement through the liquid. This creates a very small net force. But then, at a certain critical speed, the friction force becomes large enough to deform the rod, abruptly, into a helix, much as in the computer simulations of Manghi *et al.* At this point the thrust becomes much larger. Although this experiment couldn't measure the propulsion force directly, Qian and colleagues estimate that it increased by roughly an order of magnitude by virtue of the helical bending transformation.

These results certainly suggest that the deformation of a rotating appendage may be crucial to its producing significant thrust. Which probably explains why bacteria have the flagella they do, already coiled into a helical shape. Very possibly, evolution learned this trick of fluid dynamics, and designed flagella to exploit it, increasing the thrust, even for slow rotation speeds. It's peculiar, of course, that the natural bending deformation of a rod should act to increase the thrust, but this happy coincidence may be something that engineers can use in creating microscopic mechanical swimmers that could deliver drugs in the body or position single cells precisely for delicate experiments.

Of course, this is all relatively tame compared with more 'extreme' physics exploited by other biological wonders. Shrimp, for example, by snapping their jaws, can create watery explosions so violent as to stun prey, and may even produce short bursts of light in a phenomenon linked to sonoluminescence. Some videos of these creatures show the jets producing cavitation bubbles that focus energy into tiny regions when they collapse. Yet both phenomena illustrate the sheer brilliance of evolution as a mechanism for discovering incredible solutions to difficult problems, even in regimes where we ourselves still lack understanding. For all our knowledge, we still have much to learn — even about physics — from the 'primitive' organisms around us.

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