# Swimming algae offer insights into living fluid dynamics

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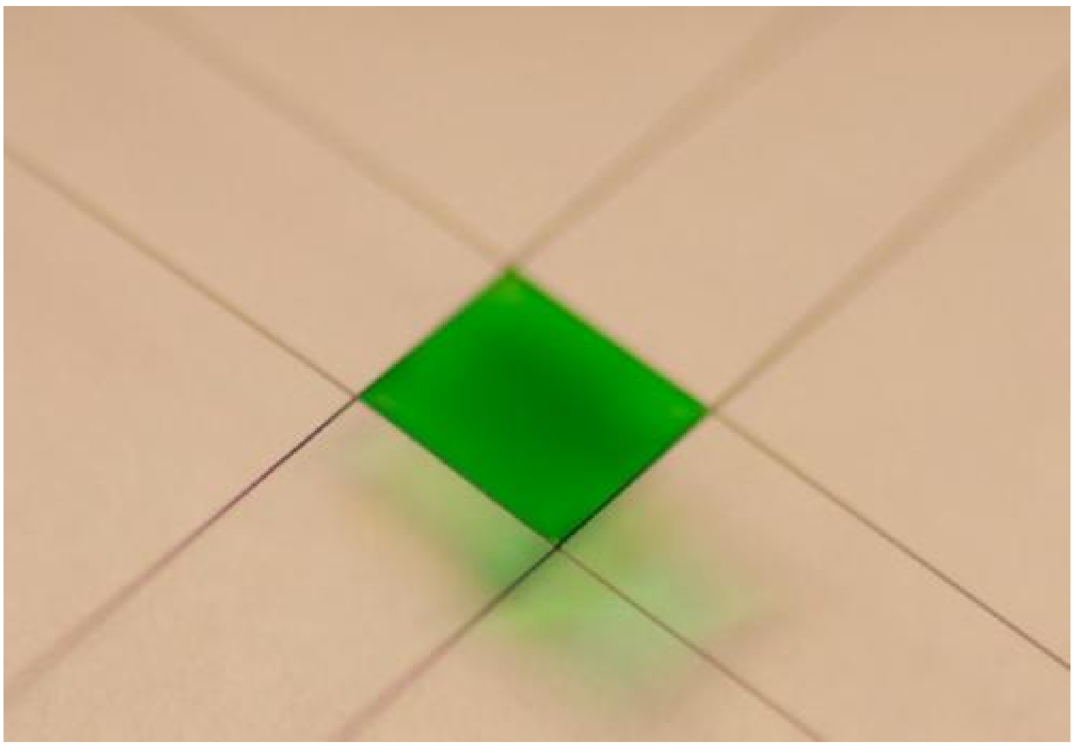

Algae swimming on a 30 micron thin liquid film that rests in the middle of a wire frame scaffold.

None of us would be alive if sperm cells didn't know how to swim, or if the cilia in our lungs couldn't prevent fluid buildup. But we know very little about the dynamics of so-called "living fluids," those containing cells, microorganisms or other biological structures.

"Living fluids are found everywhere, from vaccines to yogurt to biofuels," said Paulo Arratia, an associate professor in the Department of Mechanical Engineering and Applied Mechanics in the University of Pennsylvania School of Engineering and Applied Science. "We just don't usually think about them in that sense. We'd like to develop knowledge about how they flow and behave, the same way we've developed it for nonliving fluids."

Understanding the behavior of living fluids starts with understanding the swimmers themselves. With that goal in mind, Arratia's lab group conducted a study examining the swimming dynamics of *Chlamydomonas reinhardtii*, a unicellular green alga that propels itself with two whip-like flagella, in fluids exhibiting a range of properties.

The researchers discovered that *C. reinhardtii* changes its swim stroke dramatically in elastic fluids, those with both liquid and solid-like properties, compared with non-elastic, or Newtonian, fluids.

"This algae's flagellum has the same biological structure as the cilia in our lungs," Arratia said. "We hope this can become a model for how the lungs move mucus, a fluid which possesses elasticity."

Such a model may help researchers to understand and treat lung diseases that involve excessive fluid buildup, including cystic fibrosis.

Graduate student Boyang Qin was lead author on the study, published in *Nature*'s *Scientific Reports*, which also included contributions from current and former mechanical engineering postdoctoral researchers Arvind Gopinath and Jin Yang, as well as Jerry Gollub, a professor of physics at Haverford University.

Most of our understanding of microbial swimming patterns comes from studies conducted in water. Yet many of the fluids we encounter in our everyday lives are much more viscous than water. Viscous fluids that contain chain-like molecules known as polymers are also elastic, meaning they possess both liquid and solid-like behavior. These so-called "viscoelastic fluids" include familiar household items such as yogurt, toothpaste and lotion. Despite the ubiquity of complex fluids, the consequences of viscosity and elasticity for the physics of swimming are not well understood.

"Many environments that microbes swim in, such as soil, mucus and tissue, are not just plain water but contain particles and polymers," Arratia said. "We're interested in learning how organisms behave in these more complex and realistic environments."

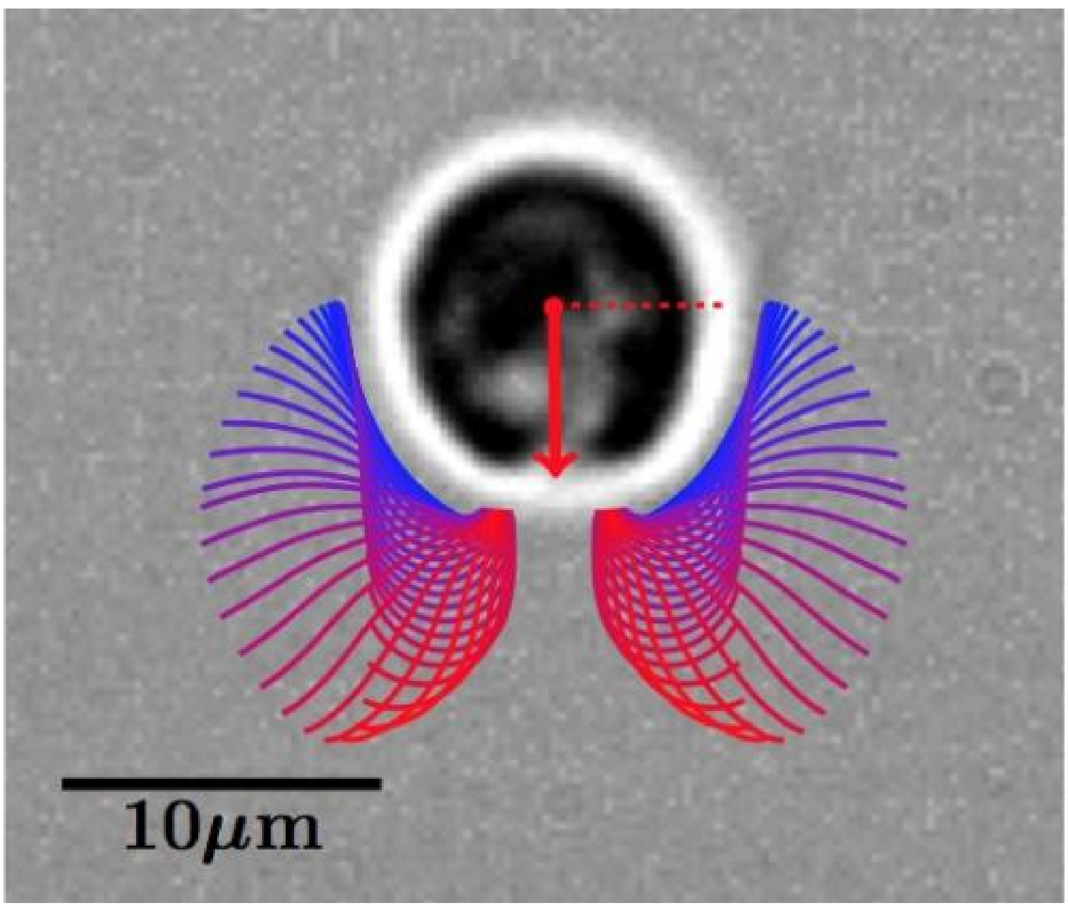


Image tracking of flagellar positions and the cell body of an alga.

To do so, the researchers set up experiments to examine the effects of viscosity and elasticity on the swimming behavior of *C. reinhardtii,* a common model organism. They prepared Newtonian solutions that spanned a 10-fold range of viscosities by dissolving a sugar-like compound in water. They also prepared viscoelastic solutions that spanned a 50-fold range in elasticity, by dissolving small amounts of a polymer in water. They then suspended samples of *C. reinhardtii* in each solution and captured the alga's swimming behavior using a microscope equipped with a high-speed camera. The images were then analyzed to assess how the fluid media influenced both the beating frequency of *C. reinhardtii's* flagella and the shape of its swim stroke.

As viscosity increased for Newtonian fluids, the researchers observed a decrease in beating frequency. This result was intuitive: a person, for instance, would swim more slowly in a pool of honey than in a pool of water.

While the alga's flagella beat faster when the viscosity of Newtonian solutions was increased, the overall shape of the swim stroke did not change. This, however, was in sharp contrast to what they observed in viscoelastic solutions.

"Once you add a little elasticity, the stroke shape becomes completely different," said Gopinath. "On top of that, we were surprised to find that, when we increased elasticity, the beating frequency became much higher."

The reason *C. reinhardtii* changes its swim pattern so dramatically in elastic fluids is not yet clear. One potential explanation is that the polymers present in elastic fluids are deforming the microbes, producing additional stress forces.

"Extra stresses imparted by the polymers can restrain the way you swim, changing the shape of your stroke," said Qin. "But the increase in beat frequency is still a bit of a mystery."

That mystery is an ongoing area of exploration. One future step for Arratia's research team will be to tease out whether the faster beating of flagella in elastic fluids is a passive response, or if the microbes are actively modifying their behavior to the environment.

"When you swim, you know if you're actively adapting to the fluid," Arratia said. "Likewise what we're seeing here could be an adaptive response, but it could also be that the flagella's motion is being actuated by the liquid."

Separating the two possibilities is important when considering artificial swimmers, such as micro-robots, which may in the future be deployed within the human body to deliver drugs or target disease. If researchers want to predict the patterns of an artificial swimmer based on a microbial model, knowing what aspects of microbial swimming are behaviorally controlled will be critical.

To that end, Arratia's group is developing two types of artificial cilia, a passive responder and an active responder, to determine whether these different modes of response affect swimming.

Another future step will be to understand whether the swim behavior of groups differs from that of individuals.

"For this study, we only looked at one alga swimming at a time," Arratia said. "We'd also like to know what would happen if you had a denser suspension of them, whether there would be collective swarming behavior, for instance."

Arratia, who has studied complex fluids for years, sees living fluids as an exciting new research direction.

"Anyone who has tried to get ketchup out of a bottle can appreciate how different complex fluids are from water," Arratia said. "These differences are caused by polymers and particles. Living fluids are also suspensions of particles in water, but now the particles are alive. That raises many interesting questions about even their most fundamental properties."

**More information:** "Flagellar Kinematics and Swimming of Algal Cells in Viscoelastic Fluids." *Scientific Reports* 5, Article number: 9190
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