New method found for moving tiny artificial swimmers

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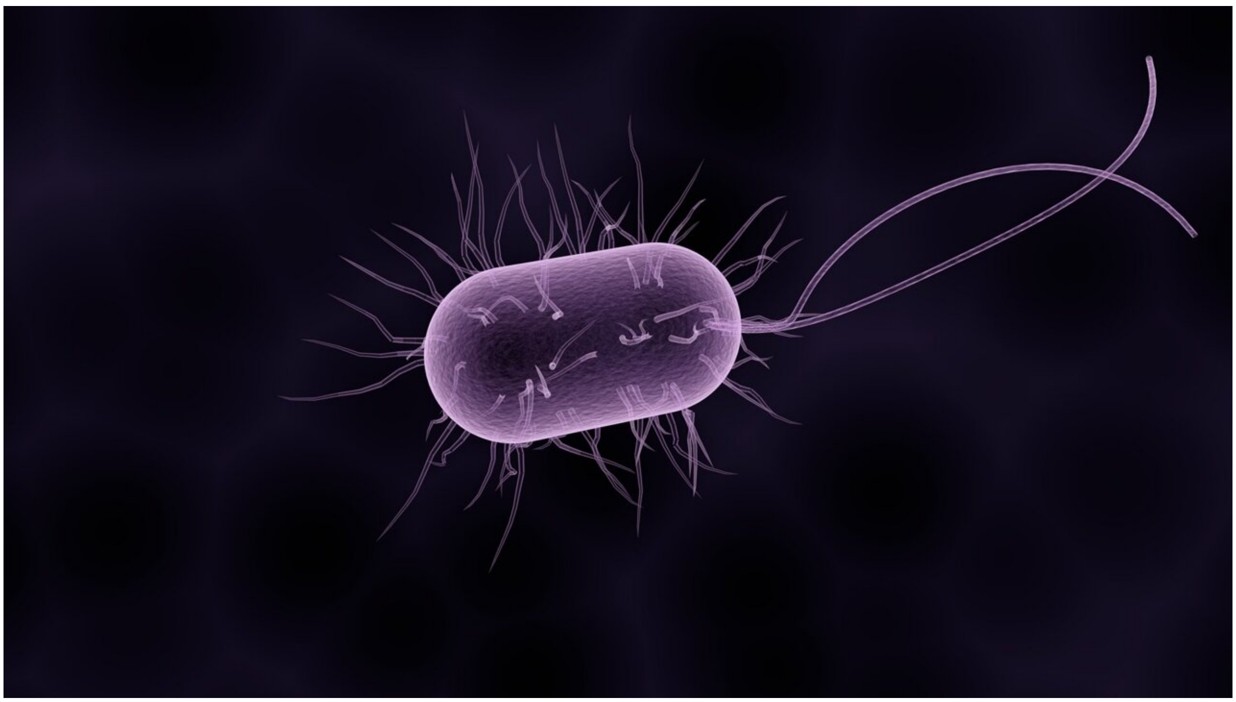

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Princeton researchers have debuted a novel way of generating and potentially controlling locomotion in tiny objects called artificial swimmers. These swimmers have sparked considerable interest for their potential applications in medicine, industry and other sectors.

Spherical in shape and sporting two tails, the Princeton swimmers—like many other artificial microswimmers—take a cue from bacteria, which rely on whip-like appendages called flagella and cilia to drive themselves through fluids. To date, scientists have tried out all sorts of impetuses for inducing tailed swimmer movement, including sound, light and magnetic fields. The Princeton swimmers, however, innovatively get their go from exposure to an electric field, leveraging a means of creating motion—known as Quincke rotation—never demonstrated before in the artificial swimming realm.

"We found something that's new in physics for locomotion generation in artificial swimmer systems," said Endao Han, a fellow in the Center for the Physics of Biological Function at Princeton University and lead author of a study describing the findings published online in the July 20 issue of the *Proceedings of the National Academy of Sciences*.

"What Endao and our colleagues have demonstrated in this study is beautiful physics that combines insights from a lot of different fields," said study senior author Howard Stone, the Donald R. Dixon '69 and Elizabeth W. Dixon Professor of Mechanical and Aerospace Engineering at Princeton University.

The new study builds on theoretical work led by coauthor Lailai Zhu, a former postdoc in Stone's lab at Princeton and now at the National University of Singapore. In studies published in 2019 and 2020, Zhu simulated in a computer program that spherical artificial swimmers with elastic tails should move through a medium, driven by Quincke rotation. This rotation can occur when insulating materials are submerged in a weakly conductive liquid and exposed to an electric field. The electric field, although itself steady and constant, nonetheless creates an instability that manifests as a twisting force, causing the material—usually shaped as a sphere—to rotate within the fluid. When a tail or tails are placed on the rotating sphere, the tails can bend into the helical shapes commonly relied on by bacteria to generate thrust.

This sort of motion, known as nonreciprocal motion, is necessary for microorganisms and other tiny things, natural or artificial, to travel through fluids. At human scales, basic reciprocal motion, "like the back-and-forth movement of a boat oar," said Stone, overcomes water's inertia and viscosity. Viscosity is measure of internal friction, akin to the "thickness" of a fluid. But at small scales, viscosity can prevent reciprocal motion from translating into forward motion. For microorganisms and artificial micro-swimmers, instead a corkscrew-like movement of non-reciprocal motion successfully pushes the fluid medium backwards, and thus simultaneously the swimmer forward.

For the artificial swimmer in their study, Han and colleagues went with something relatively large and thus easy to observe—namely, a plastic sphere about six millimeters across. The researchers then glued on nylon surgical sutures to serve as tail-like filaments. The fluid medium in the experiment also proved similarly low-tech. To see if the theorized Quincke rotation method would work in real life, the researchers had to identify an oil with the right electrical properties and matching the density of the swimmer. Meeting these criteria involved going through a period of trial and error with various store-bought cooking and other vegetable oils used in manufacturing. Ultimately, the researchers hit upon a mixture of half olive oil and half castor oil.

Within this medium, the experiments showed that a swimmer with two tails translated rotation into movement better than a single-tailed swimmer. By varying the electric field strength and the angle between the two tails, the researchers ultimately demonstrated three distinct kinds of motion. Two of the motions functioned similarly as the pitch and roll of airplane flying, with the former appearing as the tails stick out to either side of the rotating sphere, and the latter as the tails point behind the sphere as it spins. The third motion was self-oscillatory, meaning the sphere swiveled one way, then back the other way, and back again, repeatedly, even though the power source, the electric field, was constant and without any oscillation.

Overall, the multiple kinds of obtained motions surprised the researchers and hinted at the levels of dynamic control that could be achieved.

"As our experiment went on, we found even richer phenomena than we expected," said Han. "We found that this system might not only be a new way to make things move, but also that we might be able to effectively control the swimmer's motion, which makes it much more useful."

Eric Lauga, who was not involved in the research, commented on the progress the study represents for the field of artificial swimming. "It's a field driven by theory mostly, so it's always a big leap forward when artificial swimmers are realized in the lab," said Lauga, a professor of applied mathematics at the University of Cambridge. "There are only so many [swimmers] that have been fabricated and quantified in a way that is fully understood, so it's always exciting when that happens."

Han and Stone added that the simplicity of their artificial swimmer system means it can be readily scaled up or down. Scaling down to very small devices could potentially lead to industrial uses in oily media and environments, for instance. A nearer-term outlook for the research is to use the system for further exploring a novel means of generating motion. Researchers will therefore want to further study the physics of individual swimmers. Scaling up to groups of swimmers, meanwhile, could provide insights into how groups of bacteria locomote, as well as the swarming behaviors exhibited by bacteria or larger organisms.

"We're just starting to see what the possibilities are with this kind of artificial swimmer," said Han. "We look forward to gaining more insights and realizing its potential usefulness."

Joshua Shaevitz, a professor of physics and the Lewis-Sigler Institute for

Integrative Genomics at Princeton, is also a coauthor of the study.

More information: Endao Han et al, Low-Reynolds-number, biflagellated Quincke swimmers with multiple forms of motion, *Proceedings of the National Academy of Sciences* (2021). DOI: 10.1073/pnas.2022000118

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