Propulsion of microorganisms by a helical flagellum

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AUTHOR SUMMARY

The motion of bacteria and nanobots propelled by rotating helical flagella is often interpreted using resistive force theory (1, 2), which approximates the total force on a flagellum by summing the forces from each small segment, ignoring long-range fluid interactions. We test this theory in laboratory measurements on rotating helices and compare the measurements to predictions of resistive force theory and also to slender body and Stokeslet theories, which include long-range fluid interactions. The predictions from our numerical simulations of slender body and Stokeslet theories are found to agree well with our laboratory measurements, but the results of these simulations and experiments differ greatly from the predictions of resistive force theory.

The propulsion of a microorganism by a rigid rotating helix can be completely described by a symmetric $2 \times 2$ propulsive matrix that depends only on the helical geometry. We determine the four elements of the propulsive matrix in laboratory measurements of the thrust and torque on a rotating, nontranslating helix and the drag on a translating, nonrotating helix. Our model helical flagella, driven by a small electric motor, are macroscopic (radius $R = 6.5$ mm), but they swim in a highly viscous fluid.

Our measurements of the dependence of the force, torque, and drag on the length and wavelength of a helix differ both qualitatively and quantitatively from the predictions of resistive force theory but agree well with our numerical simulations of slender body (2, 3) and Stokeslet theories (4), as shown in Fig. P1. Further, our simulations of slender body and Stokeslet theories as a function of the thickness of a helical filament agree well in the biologically relevant regime (5), although the slender body theory diverges from Stokeslet theory for the thicker filaments used in some nanobots.

In conclusion, our experiments reveal that resistive force theory fails to provide an accurate description of microscopic swimmers driven by a rotating helical flagellum. Resistive force theory has been attractive for interpreting the behavior of bacteria because its predictions are given by simple explicit expressions, whereas the slender body and Stokeslet approaches require a numerical simulation for each flagellum geometry. However, the continued use of resistive force theory is unnecessary because our numerical simulation code presented in the Supporting Information provides a user-friendly method for accurately predicting propulsion by a rotating helix of any microorganism or nanobot.

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