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Swimming in a granular frictional fluid[1]

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X-ray imaging reveals that the sandfish lizard swims within granular media (sand) using axial body undulations to propel itself without the use of limbs. To model the locomotion of the sandfish, we previously developed an empirical resistive force theory (RFT), a numerical sandfish model coupled to an experimentally validated Discrete Element Method (DEM) model of the granular medium, and a physical robot model. The models reveal that only grains close to the swimmer are fluidized, and that the thrust and drag forces are dominated by frictional interactions among grains and the intruder. In this talk I will use these models to discuss principles of swimming within these granular "frictional fluids". The empirical drag force laws are measured as the steady-state forces on a small cylinder oriented at different angles relative to the displacement direction. Unlike in Newtonian fluids, resistive forces are independent of speed. Drag forces resemble those in viscous fluids while the ratio of thrust to drag forces is always larger in the granular media than in viscous fluids. Using the force laws as inputs, the RFT overestimates swimming speed by approximately 20%. The simulation reveals that this is related to the non-instantaneous increase in force during reversals of body segments. Despite the inaccuracy of the steady-state assumption, we use the force laws and a recently developed geometric mechanics theory to predict optimal gaits for a model system that has been well-studied in Newtonian fluids, the three-link swimmer. The combination of the geometric theory and the force laws allows us to generate a kinematic relationship between the swimmer's shape and position velocities and to construct connection vector field and constraint curvature function visualizations of the system dynamics. From these we predict optimal gaits for forward, lateral and rotational motion. Experiment and simulation are in accord with the theoretical prediction, and demonstrate that swimming in sand can be viewed as movement in a localized frictional fluid.

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