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Swimming and running through sand: resistive force theory in granular media[1]

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Resistive force theory (RFT) is often used to analyze the movement of microscopic organisms swimming in fluids. In RFT, a body is partitioned into infinitesimal segments, each of which generates thrust and experiences drag. Linear superposition of forces from elements over the body allows prediction of swimming kinematics and kinetics. While RFT does not always show quantitative agreement with experimental measurements in fluids [e.g. Rodenborn et al, PNAS, 2013], we show that it quantitatively models the locomotion of animals and robots that move on and within dry granular media. RFT shows excellent agreement when the medium is slightly polydisperse, in the regime where frictional forces dominate material inertial forces, and when locomotion can be approximated as confined to a plane. Within a given plane (horizontal or vertical) relationships that govern the force versus orientation of an elemental intruder are functionally independent of the granular medium. We use RFT to explain features of locomotion–these include muscle activation patterns during sand-swimming by the sandfish lizard and optimum limb shape for legged robot walking.

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