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Biological and robotic movement through granular media[1]

DANIEL GOLDMAN, Georgia Institute of Technology

We discuss laboratory experiments and numerical simulations of locomotion of biological organisms and robots on and within a granular medium. Terrestrial locomotion on granular media (like desert and beach sand) is unlike locomotion on rigid ground because during a step the material begins as a solid, becomes a fluid and then re-solidifies. Subsurface locomotion within granular media is unlike swimming in water for similar reasons. The fluidization and solidification depend on the packing properties of the material and can affect limb penetration depth and propulsive force. Unlike aerial and aquatic locomotion in which the Navier-Stokes equations can be used to model environment interaction, models for limb interaction with granular media do not yet exist. To study how the fluidizing properties affect speed in rapidly running and swimming lizards and crabs, we use a trackway composed of a fluidized bed of of 250 μm glass spheres. Pulses of air to the bed set the solid volume fraction $0.59 < \phi < 0.63$; a constant flow rate Q below the onset of fluidization (at $Q = Q_f$) linearly reduces the material strength (resistance force per depth) at fixed ϕ for increasing Q. Systematic studies of four species of lizard and a species of crab (masses $\approx$ 20 grams) reveal that as Q increases, the average running speed of an animal decreases proportionally to $\sqrt{M/A - const}(1 - Q/Q_f)$ where M is the mass of the animal and A is a characteristic foot area. While the crabs decrease speed by nearly 75% as the material weakens to a fluid, the zebra tailed lizard uses long toes and a plantigrade foot posture at foot impact to maintain high speed ($\approx$ 1.5 m/sec). We compare our biological results to systematic studies of a physical model of an organism, a 2 kg hexapedal robot SandBot. We find that the robot speed sensitively depends on ϕ and the details of the limb trajectory. We simulate the robot locomotion by computing ground reaction forces on a numerical model of the robot using a soft-sphere Molecular Dynamics code.

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