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Dynamics of digging in wet soil

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ABSTRACT

Numerous animals live in, and locomote through, subsea soils. To move in a medium dominated by frictional interactions, many of these animals have adopted unique burrowing strategies. This paper presents a burrowing model inspired by the Atlantic razor clam (*Ensis directus*), which uses deformations of its body to cyclically loosen and re-pack the surrounding soil in order to locally manipulate burrowing drag. The model reveals how an anisotropic body – composed of a cylinder and sphere varying sinusoidally in size and relative displacement – achieves unidirectional motion through a medium with variable frictional properties. This net displacement is attained even though the body kinematics are reciprocal and inertia of both the model organism and the surrounding medium are negligible. Our results indicate that body aspect ratio has a strong effect on burrowing velocity and efficiency, with a well-defined maximum for given kinematics and soil material properties.

1. Introduction

There are many examples of animals that live in particulate substrates which have evolved unique locomotion schemes [1]. Two common strategies observed in biological systems are an undulatory, snake-like motion [2–4,6] and a "two-anchor" system [5,7–12]. An example of the former is the sandfish lizard which wiggles its body from side to side in order to effectively swim through sand [2]. Similarly, smaller organisms like *C. elegans* have been observed to move quite efficiently via an undulatory motion through granular media [3,4]. In contrast, soft-bodied organisms that live in particulate substrates saturated with a pore liquid generally use a two-anchor system to burrow. In this strategy, one section of the animal expands to form a terminal anchor, while another section of the animal contracts to reduce drag. Once the contracted section is conveyed forward in the burrow, it is expanded to form the next terminal anchor and the previous terminal anchor is contracted and shifted forward.

The burrowing model presented in this paper is inspired by the two-anchor locomotion scheme and body geometry of the Atlantic razor clam (*Ensis directus*). *Ensis* is comprised of a long, slender set of valves (i.e. the two halves of the shell) which are hinged on an axis oriented longitudinally to the animal, and a dexterous soft foot which resides at the base of the valves. The burrowing cycle of *Ensis* is depicted in Fig. 1(a). The animal starts with its foot fully extended below the valves (A). Next, it uses a series of four shell motions to make downward progress: (B) the foot extends to uplift the valves while the valve halves contract to force blood into the foot, inflating it to serve as a terminal anchor; (C) the foot muscles contract to pull the valves downwards; and (D) the valves expand in order to form a terminal anchor and begin the cycle again.

The uplift and contraction motion of the valves draw water towards the animal's body, unpacking and locally fluidizing the surrounding substrate [13]. The initiation of valve contraction causes local soil failure around the animal and the uplift velocity is on the order of the pore fluid velocity required to induce a fluidized bed below the animal.[1] Although the animal is too weak to pull its shell through static soil (which exerts a resistance that linearly increases with depth [15]) to typical burrow depths, fluidization dramatically reduces drag, resulting in resistance forces that are depth independent [13]. The aim of this paper is to analyze the kinematic motion of the shell and demonstrate that reciprocal body deformations can produce unidirectional motion in a substrate of varying frictional properties.

2. Model

Fig. 1(b) shows the geometry of the simplified model organism and the dynamics inspired by *Ensis*. The body consists of two components: a long cylinder of length L and radius $r(t)$, which approximates the valves, and a sphere of radius $R(t)$ attached to the cylinder, acting as the foot. The radius of the cylinder, the radius of the sphere and the distance between the two are known functions of time dictated by the organism. The length of the shell, L, is considered constant.

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[1] A full description of *Ensis* burrowing mechanics is beyond the scope of this paper, but can be found in [13].

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