Integrative and Comparative Biology, volume 51, number 1, pp. 151–157
doi:10.1093/icb/icr038

SYMPOSIUM

Identification and Evaluation of the Atlantic Razor Clam (*Ensis directus*) for Biologically Inspired Subsea Burrowing Systems

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From the symposium ‘‘Bioinspiration: Applying Mechanical Design to Experimental Biology’’ presented at the annual meeting of the Society for Integrative and Comparative Biology, January 3–7, 2011, at Salt Lake City, Utah.

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Synopsis In this article, we identify and analyze a subsea organism to serve as a model for biologically inspired burrowing technology to be used in applications such as anchoring, installation of cables, and recovery of oil. After inspecting myriad forms of life that live on or within ocean substrates, the Atlantic razor clam, *Ensis directis*, stood out as an attractive basis for new burrowing technology because of its low-energy requirements associated with digging (0.21 J/cm), its speed and depth of burrrowing (~1 cm/s and 70 cm, respectively), and its size and simplicity relative to man-made machines. As anchoring is a prime application for the technology resulting from this work, the performance of an *Ensis directus*–based anchoring system was compared to existing technologies. In anchoring force per embedment energy, the *E. directus*–based anchor beats existing technology by at least an order of magnitude. In anchoring force per weight of device, the biologically inspired system weighs less than half that of current anchors. The article concludes with a review of *E. directus*'s digging strategy, which involves motions of its valves to locally fluidize the substrate to reduce burrowing drag and energy, and the successful adaptation of *E. directus*'s burrowing mechanisms into an engineering system: the RoboClam burrowing robot, which, like the animal, uses localized fluidization to achieve digging energy that scales linearly with depth, rather than depth squared, for moving through static soil.

Introduction

The aim of the research presented in this article is to generate compact, lightweight, low energy, reversible, and dynamic burrowing systems for use in subsea applications. As many organisms have evolved mechanisms that allow them to embed themselves in undersea substrates, unsurprisingly, nature has provided a viable basis for a novel, efficient burrowing technology. This article focuses on investigating the performance of subsea burrowing organisms in engineering terms, identifying *Ensis directus*, the Atlantic razor clam, as a prime candidate for biomimicry, and demonstrating that an *E. directus*–based system would provide advantages over man-made technologies.

Industrial applications that could benefit from biologically inspired burrowing technology include anchoring, recovery of oil, installation of underwater cables, neutralization of mines, and placement of sensors. For example, autonomous underwater vehicles (AUVs)—robots that navigate without human control—are sometimes required to remain stationary relative to the floor of the ocean. Rather than expend the finite supply of energy in the AUV's batteries fighting currents or risk losing the vehicle altogether by landing it on the ocean's floor, a biologically inspired anchor that can self-burrow into the substrate, reposition if necessary, and retract when the AUV needs to relocate is desirable.

The idea of small, self-inserting, and retracting anchors also has significant value in the offshore and oil industries. Any existing anchor must be set, or at least retrieved, with human intervention, either directly or with a remotely operated vehicle (ROV) underwater robot. This can be difficult in applications such as ultra-deepwater oil drilling, where depths of the water as great as 4000 m (Chevron 2010) complicate the installation of moorings and

Advanced Access publication June 8, 2011

oil-recovery equipment. A system that enables this equipment to be lowered and then autonomously affixed to the bottom, as well as autonomously released for retrieval, would be valuable.

Identifying *E. directus* for bioinspiration

There are many examples of animals that live in particulate substrates and have adapted unique modes of locomotion. The sandfish lizard (*Scincus scincus*) wiggles its body from side to side and effectively "swims" through sand (Maladen et al. 2009). Smaller organisms, such as nematodes (*Caenorhabditis elegans*), have been observed to move quite efficiently via an undulatory motion in saturated granular media (Wallace 1968; Jung 2010). Sandworms (*Nereis virens*) are able to propagate and move through a crack in gelatin, a material with properties similar to cohesive soils, by using their body as a wedge (Dorgan et al. 2005).

To find an organism that could provide the inspiration for efficient, compact burrowing technology, we surveyed a myriad of undersea animals that stick to, cling to, or dig into the ocean's bottom. A plot of these animals, the substrates in which they live, and their burrowing/anchoring mechanisms are shown in Fig. 1. Burrowing bivalves stand out, not only because they live in nearly every type of particulate substrate, but also because they employ burrowing mechanisms that reduce the expenditure of energy required for embedment. For example, nearly all bivalves have an elastic ligament that acts as a torsional spring (Trueman 1975) that stores energy during contraction of the valves. This energy can be used later for re-expansion.

Out of all bivalves represented in Fig. 1, *E. directus* is distinct for its burrowing performance. It is composed of a long, slender set of two valves that rotate relative to each other on an axis oriented longitudinally to the animal. A foot, which is a dexterous, soft organ, resides at the bottom of the valves. *Ensis directus* burrows by using a series of valve-and-foot motions to draw itself into the substrate, as shown in Fig. 2.

The upper bound of expended mechanical energy per unit depth for *E. directus* to advance its valves into soil was estimated by adapting the measures of maximum pedal strength, valve displacement, hinge stiffness, and mantel cavity pressure made by Trueman (Trueman 1967). For linear motions, energy expended was calculated as $E = F\delta$, where F is force acting between the valves and foot and δ is valve displacement. Energy expended during rotational actuation of the valves was estimated as $E = \int T d\theta$, where T is torque developed about the valve hinge from stiffness of the hinge ligament and pressure in the mantel cavity acting on the valves, and θ is angular deflection. The resulting expended mechanical energy and attained displacements for each burrowing motion are: uplift (0.05 J, 0.5 cm), contraction (0.07 J, 20°), and penetration (0.20 J, 2.0 cm) of the valves, which combine for a total of 0.21 J/cm. Re-expansion of the valves is accomplished through elastic rebound of the hinge ligament and thus requires no additional energy input by the animal.

The low-energy requirement associated with burrowing by *E. directus* is attractive for engineering applications. To put 0.21 J/cm into perspective, *E. directus*, which is a relatively large animal at ~18-cm long and ~3-cm wide, can travel over half a kilometer on the energy in a AA battery (Energizer 2009). In summary, *E. directus* was chosen as the basis for a potential new biologically inspired burrowing technology because it has the following engineering merits:

- EFFICIENT: uses ~0.21 J/cm to advance its valves downwards.
- FAST: burrows at ~1 cm/s (Trueman 1967).
- LARGE: is about the the size of a real engineering device.
- SIMPLE: body is composed of two rigid valves with a single degree-of-freedom hinge, requiring simple control algorithms.
- DIGS DEEP: burrows to 70 cm, upwards of seven body lengths for juvenile clams (Holland and Dean 1977). (Holland and Dean 1977 relates to the stout razor clam, *T. plebeius*; burrowing depths on this order have also been observed by the author while collecting Ensis in Gloucester, MA.)

Biology versus technology

Nature may not always find the best solution to engineering problems; there are numerous examples of man-made technologies that, either for practicality or efficiency, outperform their biological counterparts. For instance, people decided long ago to smooth the land into roads in order to travel on wheeled vehicles, which are much simpler to engineer than legged systems. Similarly, decoupling propulsion and lift, rather than using a flapping wing system, has worked well for airplanes. The Boeing 747 is just as efficient as any bird when comparing wing loading to weight or weight to cruising speed (Tennekes and Tennekes 1996). Anchoring—one of the principal applications of our research—was chosen as the

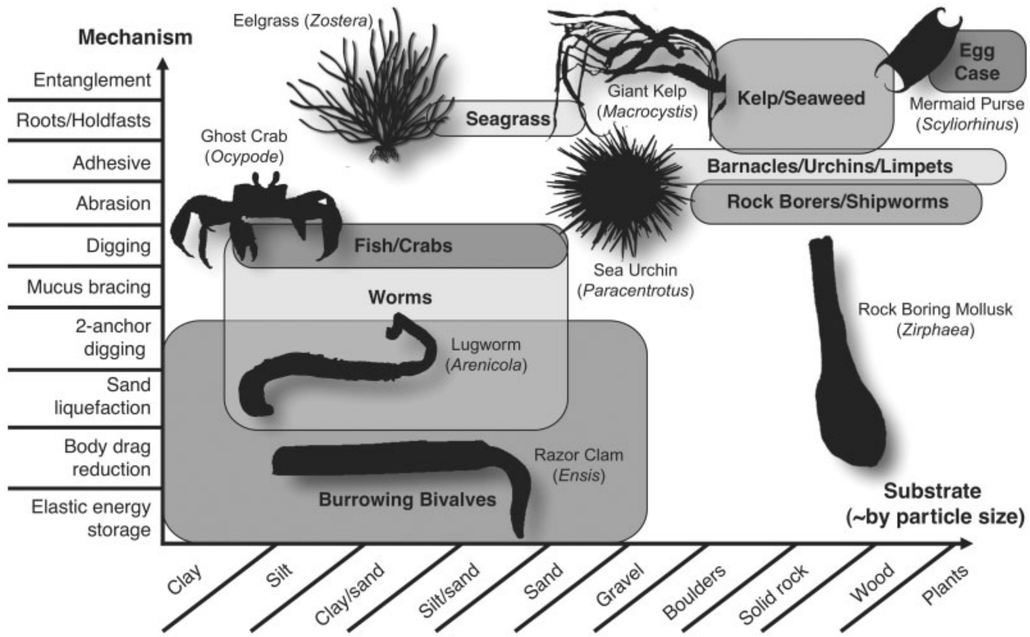

Fig. 1 Burrowing/anchoring mechanisms of undersea animals. Each group of animals is categorized by its burrowing or anchoring mechanisms (vertical axis) and habitat substrates (horizontal axis). Representative animals from each group are also shown in silhouette. Data for this figure were collected from different sources (Lloyd 1896; Drew 1900; Parker 1916a, 1916b; Coker 1922; Miller 1924; Miller and Boynton 1926; Lane 1955; Macnae and Kalk 1962; Fager 1964; Carroll 1965; Trueman 1966a; Trueman 1966b, 1968b, 1968a, 1970; Trueman et al. 1966; Evans 1968; Nair and Ansell 1968; Nott and Foster 1969; Stanley 1969, 1972, 1975; Jones and Trueman 1970; Hurley 1973; Mann 1973; Holland and Dean 1977; Sebens 1983; Williams 1990, 1995; Olesen and Sand-Jensen 1994; Coyne et al. 1997; Dormon et al. 1997; Ellis and Shackley 1997; Kamermans et al. 1999; Denny and Blanchette 2000; Shin et al. 2002; Green 2004; Koehl and Hadfield 2004; Peck et al. 2004; Aoyama et al. 2005; Dorgan et al. 2005; Gaisner 2005; Pinn et al. 2005; Riisgård and Larsen 2005; Rosenberg and Ringdahl 2005; Santos et al. 2005; Chan et al. 2006; Ruocco et al. 2006; Zeil and Hemmi 2006).

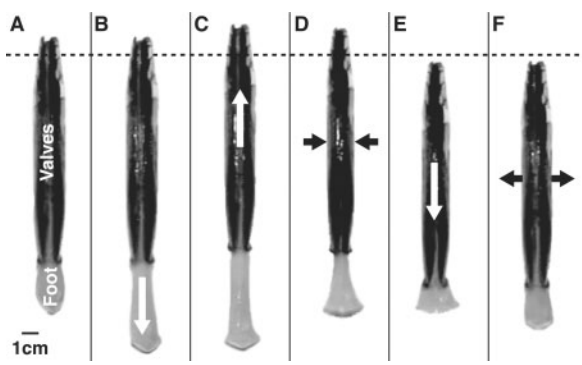

Fig. 2 *Ensis directus* kinematics during a burrowing cycle. Dotted line denotes a depth datum. Arrows indicate movements of the valves and foot. (**A**) *Ensis directus* at initiation of a digging cycle. (**B**) Extension of foot. (**C**) Valve uplift. (**D**) Valve contraction, which pushes blood into the foot, expanding it to serve as a terminal anchor. (**E**) Retraction of foot and downwards pull on the valves. (**F**) Valve expansion, reset for next digging cycle.

benchmark of comparison to evaluate whether *E. directus*–based burrowing systems could provide an advantage over currently available technologies.

Anchoring technologies considered in this analysis include umbrella piles, which are pounded into soil; propellant anchors, which are shot into soil like a bullet; vibratory anchors, which have a vibrating mass that breaks force chains (Cates et al. 1998) in the soil, allowing the anchor to be inserted with lower force than that required to penetrate static soil; helical anchors, which screw into soil; and drag anchors, which have a special geometry that forces the anchor to dig into the substrate as it is dragged along the ocean's floor. All of these devices achieve holding force by transferring loads to the soil through flukes that extend from the body of the anchor and increase the area of the anchor acting on the soil. The vertical pulling force an anchor can withstand can be calculated using

$$F = A\left(c\bar{N}_c + \Delta\rho g D\bar{N}_q\right)\left(0.84 + 0.16\frac{B}{L}\right), \qquad (1)$$

which was empirically derived (McCormick 1979). In Equation (1), F is anchoring force, c is the cohesive strength of the soil, $\bar{N}_c$ is a cohesive fitting factor, $\Delta\rho$ is the difference in density between the water and soil, g is the gravitational constant, D is the anchor's depth in the soil, $\bar{N}_q$ is a buoyancy fitting factor, and B/L is the fluke's aspect ratio. For scaling purposes, if

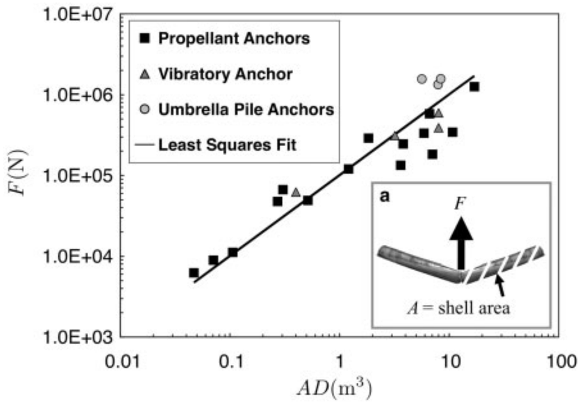

Fig. 3 Performance of existing anchoring technology. Plot shows historical data for various types of anchors (McCormick 1979) and their performance in regards to anchoring force *F* versus fluke area *A* and submerged depth in soil *D*. Inset a depicts the effective fluke area and embedded orientation of an *E. directus*–inspired anchor.

only granular (noncohesive) soils are considered, and $(0.84 + 0.16B/L) \approx 1$ for most flukes, Equation (1) simplifies to

$$F \approx \bar{N}_q \Delta \rho g A D \quad (2)$$

Figure 3 shows historical data of the maximum pulling force in sand for anchors of varying size and embedment depth (McCormick 1979). Using the simplified expression for anchoring force in Equation (2), a least-squares fit of these data yields a buoyancy fitting factor of $\bar{N}_q = 6.2$. With this result, the anchoring force of an *E. directus*–based system can be predicted from the depth of the animal's burrow and the area of its valves, approximated as fluke area, in the orientation shown in inset a of Fig. 3.

Two metrics were chosen to compare the performance of an *E. directus*–based anchor with current technology. The first is anchoring force developed per unit of insertion energy. This metric is of particular importance when choosing an anchor for an AUV, for which energy is at a premium. Figure 4A shows that an *E. directus*–based anchor out-performs other technologies by at least an order of magnitude.

The second metric for comparison is anchoring force per unit device weight. Fig. 4B shows that an *E. directus*–based anchoring system achieves the same anchoring force for half or less the weight of other devices. It should be noted that, in reality, many of the existing anchors have a much greater effective weight than that represented in Fig. 4B because of the equipment required for installation. For example, umbrella piles are hammered into soil with a pile driver, and drag anchors require the pulling force from a boat to be embedded.

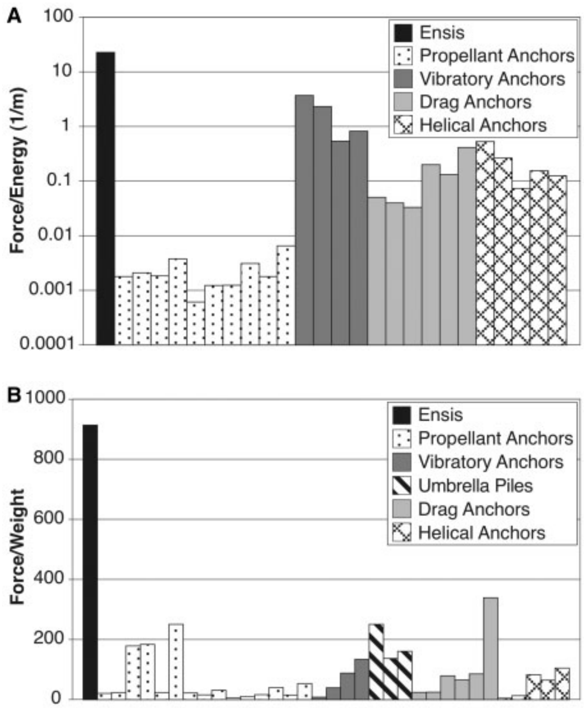

Fig. 4 *Ensis directus*–based anchor versus existing technologies. (**A**) Anchoring force developed per unit of insertion energy. Performance of the *E. directus*–based system was computed with an energetic expenditure of 0.21 J/cm, calculated from (Trueman 1967), and a maximum burrow depth for the animal of 70 cm (Holland and Dean 1977). The figure shows that an *E. directus*–based system is predicted to outperform every technology by at least an order of magnitude. (**B**) Anchoring force developed per unit weight of the device. Performance of the *E. directus*–based system was computed by assuming the device has the same density as water (similar to the animal). The figure shows that an *E. directus*–based system is predicted to weigh less than half as much, per unit anchoring force, as other technologies. In both (A) and (B), data for existing anchoring systems were adapted from Chance (2008), Hinz (2001), McCormick (1979) and Springer (2006), with each bar representing a historical test.

Conclusion

This article presents the method and analysis used to identify a suitable organism for bioinspired subsea-burrowing technology. The mechanisms used by numerous organisms for embedment and attachment were evaluated in engineering terms, yielding *E. directus* as a promising candidate for the basis of a new burrowing technology because of its efficiency, speed, size, digging depth, and simplicity. To ensure that an *E. directus*–based burrowing system could provide benefits over existing technology, the application of anchoring was chosen as a benchmark of comparison. The performance of an *E. directus*–based anchor, calculated from anchoring theory and historical data, was predicted to provide considerable savings of energy and weight over current systems.

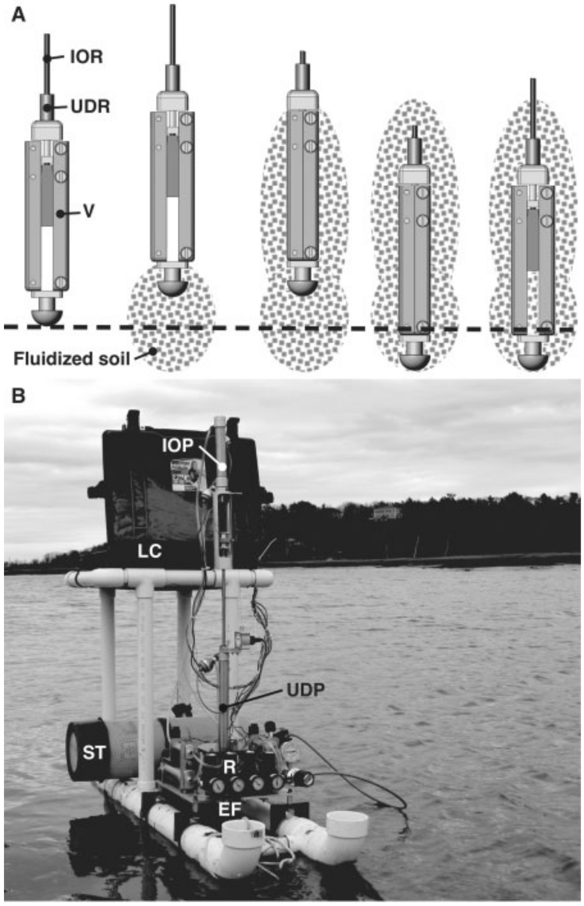

Fig. 5 RoboClam. (**A**) End effector kinematics that replicate razor clams' burrowing motions and the resulting locally fluidized soil regions. Dotted line denotes depth datum. The valves (V) are moved in and out via the in-out rod (IOR) and moved up and down via the up-down rod (UDR). When the end effector is in soil, it is covered by a neoprene boot to prevent particles from jamming the mechanism. (**B**) RoboClam burrowing in a mud flat off the coast of Gloucester, Massachusetts. Major functional components: in-out piston (IOP) that connects to the in-out rod; up-down piston (UDP) that connects to the up-down rod; end effector (EF) that attaches to the up-down rod under the robot; pneumatic pressure regulators (R); scuba tank (ST); and laptop case (LC), where the computer that controls the robot is stored.

Ensis directus's burrowing energetics indicate that the animal must manipulate the substrate to reduce drag. We discovered that *E. directus* uses the motions of its valves (Fig. 2) to locally fail and then fluidize substrate surrounding its body (A. G. Winter V and A. E. Hosoi, submitted for publication). Fluidized soil can be modeled as a Newtonian fluid (Eilers 1941; Ferrini et al. 1979), with density and viscosity that do not change with depth. As a result, *E. directus* experiences depth-independent drag on its body during burrowing, opposed to drag that linearly increases with depth in static soil (Robertson and Campanella 1983). This means that the energy for burrowing, calculated by $E = \int Fdz$, scales linearly with depth for *E. directus*, rather than with depth squared, even though some energy is required to locally fluidize the soil.

To verify that the process of reducing drag via localized fluidization can be transferred to engineering applications, we developed RoboClam, a robot that replicates *E. directus*'s digging kinematics. RoboClam was designed to yield insight into the relationships between environmental and engineering parameters, such as type of substrate, depth, size of device, burrowing velocity, and required power. Figure 5A shows the end effector of RoboClam—the mechanism on the robot that digs by mimicking the motion of *E. directus*'s valves to locally fluidize substrate—going through its burrowing cycle. In RoboClam, *E. directus*'s foot has been replaced by a pneumatic piston that pushes down on the end effector, as we found that only the valve's motions contribute to localized fluidization and that this configuration allows for the actuators and sensors to be located above the water.

In order to avoid wall effects caused by a container and to capture the peculiarities of real soil with heterogeneous composition and the presence of organic matter, RoboClam was designed to be tested in real marine substrates. The main power source is compressed air from a scuba tank for saltwater compatibility. Figure 5B shows the robot and its main functional components while burrowing in real *E. directus* habitat off Gloucester, Massachusetts. Using a genetic algorithm to optimize digging motions, RoboClam was able to burrow with an energy-depth power law relationship of $n = 1.13$, close to the linear relationship for *E. directus* (Winter et al. 2010a). In subsequent laboratory testing using a perfectly granular substrate composed of soda-lime glass beads 1 mm in diameter, RoboClam was able to achieve ideal localized fluidization burrowing, with an energy-depth power law relationship of $n = 1.00$ (A. G. Winter V et al., submitted for publication).

Acknowledgements

The authors would like to thank C. Becker, M. Bollini, R. Deits, D. Dorsch, K. Ray, D. Sargent, and A. Slocum for their experimental and analytical assistance. In addition, D. Flammang and M. Porter deserve thanks for organizing the symposium "Bioinspiration: Applying Mechanical Design to Experimental Biology" and for the invitation to participate.

Funding

Battelle Memorial Institute; Bluefin Robotics; Chevron Corporation.

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