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Of snakes and robots

John J. Socha

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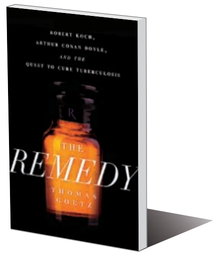

Survival skill. Sidewinder rattlesnakes are one of a few snake species that can move sideways up sandy slopes, helping them to survive in deserts.

APPLIED PHYSICS

Of snakes and robots

How can snakes and robots move up sandy slopes?

By **John J. Socha**

As anyone who has run up a sand dune can attest from burning calves, climbing a sandy slope is demanding. The root of the struggle—in animal and vehicle alike—comes from the behavior of the sand, a granular medium that can slip, slide, and flow like a fluid. Yet, desert-dwelling snakes can ascend sandy slopes with grace and energetic ease (*1*) through a process called sidewinding. Having no limbs to push off should make the matter worse, yet the snakes make it look simple. How do they do it? On page 224 of this issue, Marvi *et al.* (*2*) explore the physics of sidewinding in animal and robot, revealing how limbless locomotors can move up sandy slopes.

Among animals, only snakes sidewind, a behavior found mostly in vipers and a few other snake species that live in desert or muddy environments (*3*). Sidewinding gets its name from the orientation of the snake while slithering, appearing to move to the side rather than toward the head (see the figure) (*4*). As with most other forms of serpentine movement, the snake produces force by curving its body, but in sidewinding the body does not slide. Instead, it rolls and peels like a wheel (*4*, *5*), maintaining static rolling contact along a few points while the rest of the body is lifted in the air (*6*). Marvi *et al.* show that this contact and lifting are key to successful sand slope climbing in the sidewinder rattlesnake *Crotalus cerastes* (see the first photo) and in a snakelike robot composed of 17 modular segments (see the second photo).

Studying the snake and robot together was a reciprocally illuminating process: The robot was used as a model to probe the snake, and the snake was used to understand and improve the robot. Part of the motivation for working with this particular robot (dubbed "Elizabeth") arose from a real-world experience. On an archaeological mission in Egypt, Elizabeth was tasked to explore a sandy room with a slope, but failed miserably in its attempt to move forward, slipping and pitching over. Coauthor Choset had developed a long line of snakelike robots over the course of two decades, achieving various locomotor styles including sidewinding (*7*) and pole climbing (*8*), but sand climbing had remained elusive.

To determine patterns of movement in a controlled environment, the team investigated the robot and snakes on a custom-made, tiltable bed of sand. Built in the Zoo Atlanta for easy access to a broad range of

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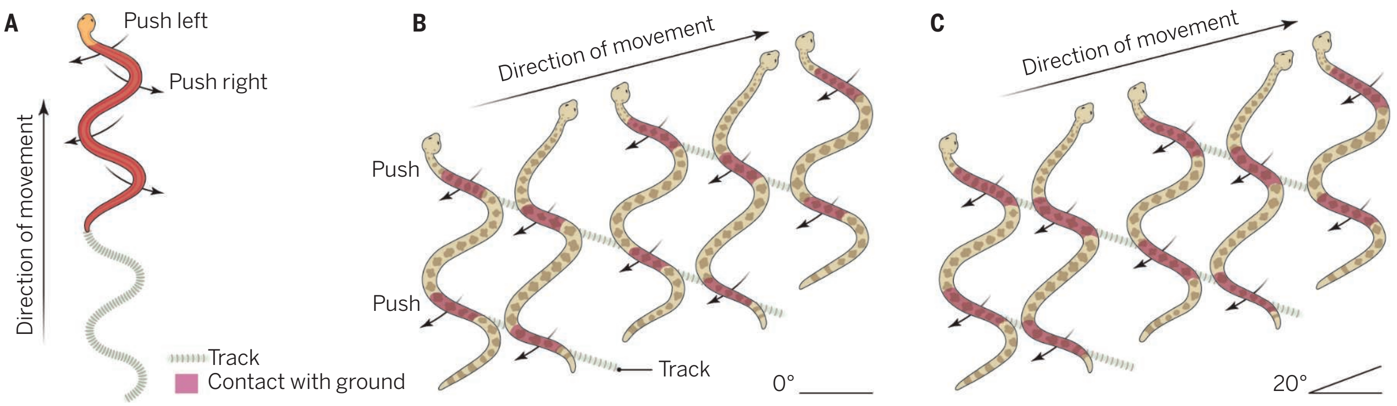

Sidewinding explained. Rather than moving in the direction of the head as do other snakes (**A**), sidewinding snakes move sideways both on level ground (**B**) and up slopes (**C**). Marvi *et al*. show that when snakes sidewind up a slope, they increase the body length that is in contact with the ground, thereby reducing slip.

snake species for comparison, the bed was tilted from level to 20°, just below the critical incline where the sand will flow with any perturbation. The sand was air-fluidized, producing a repeatably uniform volume and flat surface before each trial and thus enabling precise measurement of intrusion depth, contact length, and body lifting by the sidewinding locomotors.

The properties of granular media vary with features like particle size and shape, friction, and compaction (*9*). Mindful of this depend ence, Marvi *et al.* went the extra mile to provide the snakes with a realistic substrate. In

Sidewinding robot. By studying snakes and robots, Marvi *et al*. were able to elucidate how snakes sidewind and to modify a robot so that it could also achieve this feat.

ILLUSTRATION: P. HUEY/*SCIENCE*; PHOTO: NICO ZEVALLOS

an unprecedented feat of experimental rigor and determination, they trucked hundreds of pounds of sand in from the Yuma Desert of Arizona to ensure that the experimental conditions matched those of the native environment of the sidewinder rattlesnake.

The authors discovered that the sidewinding snakes create two waves of bending, one horizontal and one vertical, which move simultaneously from head to tail with an offset of a quarter period. Elizabeth also used two orthogonal waves to sidewind on level ground (*7*), but could not sidewind up a slope. What was the missing ingredient?

Marvi *et al.* found that the snakes dealt with the challenge of increasing slope not by digging in deeper, but by increasing the length of body contact with the sand, correspondingly decreasing the amount of body lifted in the air (see the figure). Effectively, as the slope became steeper, the snake laid down more body, increasing its purchase on the sand until nearly half the body was in contact. By modifying the robot, the authors found a range of contact lengths that produced sidewinding up the slope, but as the slope became steeper, fewer options resulted in effective climbing. This suggests that the snakes are physically constrained to certain movement patterns to move up a slope.

Why do the snakes not dig in deeper? It is energetically costly to displace level sand (*10*), but the important question is how yield force changes with increasing slope. (Yield occurs when the deformed sand cannot return to its original state when the force is removed.) In follow-up experiments, the authors dragged a flat plate through sand and showed that yield occurred with smaller forces at greater inclines. This means that the maximum force that the snake can generate without slipping becomes smaller with greater slope. The snake has to do something to compensate, and what it does is increase its contact length. This led to a new model of sidewinding locomotion: the snake produces two offset waves of bending—a neuromechanical "template" (*11*)—and varies contact length to prevent slip.

The team also tested 13 other closely related species of pit vipers. Although only some specialized snake species excel at sidewinding, many others were thought able to adopt this mode given the right conditions (*3*, *6*, *12*, *13*). Yet, none of the other snake species switched to sidewinding when presented with the sandy substrate. Some could move forward haltingly using other means of locomotion, but when the bed was tilted at a small angle, all but one were stopped in their tracks, with some flailing helplessly. This suggests that the evolution of sidewinding may have required a change in neuromotor control (*14*), shifting the timing of muscle activation to match the required template for sidewinding.

The work of Marvi *et al.* demonstrates the strength of integrating biology, engineering, and physics, providing the finest example to date of the reciprocal use of animals and robots for mutual illumination. The drive to understand the mechanics of sidewinding has brought us one step closer to achieving lifelike locomotion in robots. The upshot seems to be that going up slippery slopes with no legs simply requires a double wave to target the right pattern of contact. ■

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