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Anacondas get vertical on the ground

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Snake locomotion comes in many shapes. A mathematical model explains the non-planar S-start, where parts of the snake's body lift off the ground.

Speed is not what comes to mind when you think of an anaconda. One of the longest and heaviest snakes on Earth, these beasts lurk in the swamps of the Amazon rainforest and slowly patrol the water's edge in search of prey[1]. Swift, impulsive movements on land seem out of place. Now writing in *Nature Physics*, Nicholas Charles and colleagues study a zippy form of locomotion in anacondas, dubbed the S-start[2]. With their mathematical model, the team showed that the S-start depends on twisting and lifting parts of the body in the right sequence, and that body size might limit the behaviour to smaller snakes.

The S-start is one form of locomotion among many used by the more than 3,500 species of snakes. Within their tubular body is a series of hundreds of repeated muscle and bone elements, a design that provides a large number of degrees of freedom for a wide range of modes of locomotion[3]. Beyond slithering on the ground, snakes can fold like an accordion to inch through a channel[4], stiffen to cantilever across a gap[5], or wrap like a lasso to shimmy up a tree[6]. They can even leave terra firma and swim across a river or glide through the air[7].

But the vast majority of snake locomotion occurs on the ground. Slithering is most recognizable, but perhaps just as perplexing as other forms of motion. As the snake activates waves of muscles to promote sideways bending, the snake's body follows its own line forward, fooling the eye into thinking the mid-body is not moving. Maintaining contact with the ground throughout, the body is mostly planar. This locomotion depends on three factors: frictional anisotropy between the snake's body scales and the ground, active weight distribution along the body, and the pattern of movement of the body. But in environments where friction anisotropy is low or almost non-existent, such as on a sandy beach, some snakes can tweak the template, employing non-planar motions to actively regulate the forces between their body and the ground.

Sidewinding is one such motion, a form of movement where the snake's body is lifted off the ground in a series of waves, with only a few strips of contact between the snake and the ground (Fig. 1a). These contact areas are shifted along the body as the snake moves, generating thrust while minimizing slippage. To do so, a sidewinder forms vertical waves that move laterally and forward[8], allowing the snake to traverse highly yielding substrates, such as sand, with high efficiency.

Similar to sidewinding, the S-start includes a vertical wave that travels from the head to the tail, and at any given time, part of the body remains on the ground with almost no velocity (Fig. 1b). However, in the S-start, there is typically only one primary contact area with the ground that experiences minimal slippage. This single contact area does not ensure stability, and often two additional regions, closer to the head and tail, slide on the ground. By contrast, sidewinding involves almost no sliding regions, as the body's contact points shift with little slippage.

a Sidewinding **b** S-start
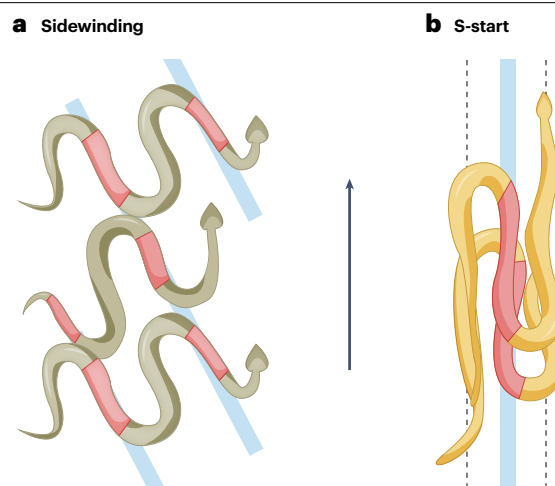
Fig. 1 | Sidewinding and S-start may be two sides of a similar coin. a,b, Both locomotor behaviours, sidewinding (**a**) and S-start (**b**), are only found in snakes and both involve parts of the body that are lifted in the air while other parts roll statically on the ground (red shaded areas). However, in an S-start (**b**) two parts of the body slide on the ground (dotted lines), and the body is oriented at a less angled posture relative to the direction of net forward motion (black arrow). The black arrow also indicates the direction of net forward motion for the sidewinder.

Charles and colleagues' mathematical model helps explain the S-start, combining internal actuation with material properties to generate an array of potential motions. The snake body is modelled as an active Cosserat rod – a slender one-dimensional filament capable of elastic stretching, bending, and twisting – whose shape changes are driven by internal forces (muscular torques). The model connects internal shape changes to body displacements through an anisotropic environmental friction force. Sweeping across parameters, the model predicts whole-body twisting and moving that spans from feasible to unrealistic, providing potential insight into biomechanical limitations of the S-start behaviour. As such, their model finds a sweet spot of body weight and muscle forces that results in 'proper' S-start locomotion. In theory, the S-start does not work with very small snakes, which are too strong and flail about, or large snakes, which are too weak and do not move forward. The model is mostly congruent with their actual live-animal observations, with the most effective S-starts observed in juveniles of intermediate body size (134–165 cm in length), less effective in smaller newborn specimens (44–60 cm), and not observed at all in two larger adults (264 and 297 cm).

However, a previous anecdotal report of a snake from the Peruvian Amazon rainforest[9] suggests that larger anacondas can also employ the S-start. Described as sidewinding, video of the reported event shows a large anaconda (275 cm) moving through an asymmetrical 'S', with a static central body, loops of the body lifted off the ground, and two adjacent body segments sliding on the grassy ground. The head and forebody appear to move more straight forward, less angled than

a sidewinder. Overall, this snake's movements are highly reminiscent of the S-start reported by Charles and colleagues, suggesting targets of improvement in future iterations of the model.

The authors also suggest that the S-start may represent an evolutionary building block for sidewinding locomotion. But anacondas are a specialized group of snakes, not closely related to the sophisticated sidewinders[10], and may have evolved the S-start independently. The static section and lifted sections of body that give the behaviour its resemblance to sidewinding may simply reflect evolutionary convergence, enabled by the flexibility of the snake body template. Comprehensive analyses of kinematics, muscle motor patterns and morphology — across a broad range of species, couched in a phylogenetic context — are needed to address this question.

The results by Charles and colleagues are intriguing — the team attributes the observed movements to a topological quantity propagated in localized pulses down the body. However, more work is needed to fully understand the consequences and implications, from both mathematical and biological perspectives. More generally, the approach by Charles and colleagues highlights a gap between the beautiful and complex behaviours observed in biology, and the underlying theoretical and mathematical descriptions that can provide deeper insights into them. With the advances in the quality of experimental data, we are well-poised to embrace and expand connections between fields to address this gap.

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