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INSIDE JEB

New theory sheds light on how soft bodies move

The tube feet on the bottom of a star fish's arm. Photo credit: Matt McHenry.

Creeping along slowly, star fish are propelled by hundreds of tube feet, but these are no ordinary limbs. The feet have more in common with your tongue or an elephant's trunk. Without bones for support, these so-called hydrostatic structures depend on internal fluid pressure to deform and move, 'like pressing on a water balloon', says Matt McHenry from University of California (UC), Irvine, USA, explaining that by squeezing a hydrostatic structure with muscles, it can expand in other directions, like sticking out your tongue. However, as McHenry and his colleagues Olaf Ellers and Amy Johnson (Bowdoin College, USA) looked closer into how star fish tube feet work, they began to realise that no one really understood how these fleshy structures exert forces. McHenry recalls, 'Amy and Olaf were supposed to be in my lab on sabbatical', but COVID19 put paid to that, so the team got their heads together over Zoom instead to create a theory for how hydrostatic skeletons exert forces and how those forces change as hydrostatic limbs extend.

Drafting in Johnson and Ellers' physics graduate student son, Kai-Isaak Ellers (UC Berkeley, USA) to help with the maths, the team started by building a series of equations for their theory, which predict the forces generated by a simple rigid-sided hydrostatic system of pistons, the hydraulic press, to figure out how it transmits force from a large to a small piston. Next, they turned to an artificial star fish foot, known as a McKibben actuator – an inflatable tube encircled with helical fibres – which lengthens when inflated. Refining the equations in the theory to more closely represent a flexible tube, the team then calculated how far the artificial tube foot can extend and the force it generates. They discovered that the structure transmits the most force during the initial stages of inflation, but as it extends farther, the artificial tube foot generates less force. In short, the force generated by the artificial star fish foot changes as the structure alters shape. But how much force do real hydrostatic skeletons generate and how does that force change as these structures extend?

The team adapted their theory to model real collagen fibre-wrapped star fish feet, which are lined with a single layer of muscle that behaves like an internal spring, storing energy to resist the foot's extension as fluid is pumped into it. This time, the theory predicted that the spring effectively smooths out the foot's extension, so it extends uniformly across the full range. And the researchers suspect that star fish feet are fine-tuned to exert the maximum force at an intermediate extension length, allowing the animals effectively to bounce as they crawl along, in addition to controlling how they place their feet more precisely.

Finally, the team turned their attention to burrowing earthworms and squid tentacles, to find out how well the theory would predict the forces exerted by these animals as they move. This time the equations predicted that as the angle of the helical collagen fibres wrapped around an earthworm's body alters, as the animal burrows forward like a piston, the outward force they exert on the surrounding soil increases when the body shortens and bulges, forcing soil out. And as squid propel their tentacles to ensnare a victim, the theory suggests that, initially, the short tentacle generates high forces to fling the limb forward, but as the tentacle extends further, the force declines and the tentacle – which has crosswise collagen fibres – is projected three times faster than if the fibres were wound around the tentacle cylindrically.

This new theory predicts how the forces generated by a soft body change as the structure extends and contracts and how these forces can be fine-tuned by springy collagen fibres that coil around the body. 'This theory is very much just a first step for gaining insight into how these systems operate', says McHenry, who is keen for researchers to test these new ideas to learn more about the movement of soft-bodied creatures.

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