The Muscular Machinery of Tentacles, Trunks and Tongues

Scientists discover a new way for muscles to work

By STEFI WEISBURD

An arm without bones could not bend. A person who tried to bend such an arm would instead end up with a short, fat bulge of biceps. This might score big points at a Mr. Universe contest, but would be fairly useless otherwise. In order to move effectively, muscles – which shorten but cannot lengthen on their own accord – need bones to work against.

Not all animals have bones, however. In insects and other arthropods, for example, muscles instead pull against an external skeleton. And in other invertebrates, including many worm-like animals and polyps such as the sea anemone, muscles work against cavities filled with incompressible fluids.

But what of squids, octopi, chambered nautiluses and other cephalopods, which have neither hardened skeletons nor hydrostatic cavities? "According to everything we're taught, these animals shouldn't be able to function," says biologist William M. Kier at the University of North Carolina in Chapel Hill.

Kier and Kathleen K. Smith, an anatomist at Duke University in Durham, N.C., have solved this muscular mystery by working out the biomechanical principle behind cephalopod movement. Moreover, they've found that the same biomechanics can explain how elephant trunks and human and lizard tongues – none of which possess skeletons or hydrostatic cavities – are able to move so deftly. According to Kier, scientists had remarked on the similarities between the musculature of elephant trunks, tongues and cephalopods in the last century. But until now, no one had attempted to explain how all these muscles work, he says. "It was just waiting for us."

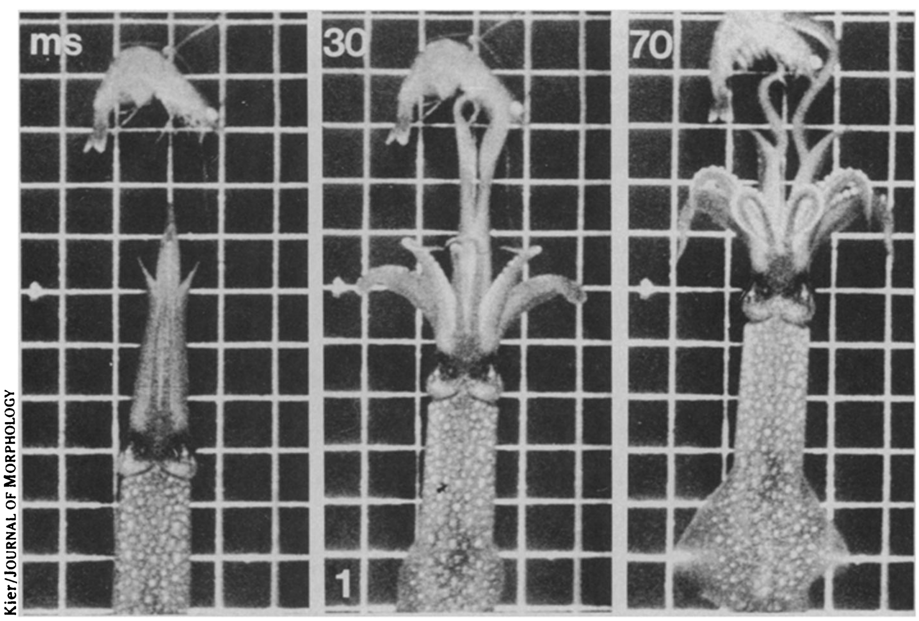
Kier and Smith's discovery of this important but previously unrecognized kind of muscular action is adding a new dimension to the well-studied field of muscles. It is prompting biologists to hunt for other animals possessing cephalopod-like muscular arrangements, which may have been overlooked in the past, and it has already changed how physiologists view the beating of the human heart.

And the explanation turned out to be surprisingly simple, Kier notes. Muscles are made up primarily of water, an incompressible fluid. This means that regardless of the motion, a muscle's volume remains constant: A muscle that contracts in length gets fatter in width. When a squid shoots out its tentacles to ensnare prey, for example, the muscles that are aligned at right angles to each tentacle's long axis contract and the resultant fattened parts push against one another to extend the tentacle along its length.

Thus, the squid's muscles not only power motion but also serve as the skeletal support, says Kier, and their particular arrangement enables the animal to lengthen, shorten, bend and twist its appendages with ease. In a paper recently submitted to the JOURNAL OF ZOOLOGY, he extends his previous studies of these muscle structures, which he calls "muscular hydrostats," to the fins of cuttlefish and squid.

"We'd gotten complacent about our understanding of muscle," comments biologist Stephen Wainwright at Duke University. "Bill and Kathleen have shown . . . a totally new mechanism for the useful action of muscle. It means that all muscular systems should now be looked at again to see where we might have overlooked this mechanism before."

In particular, Wainwright and his students suspect that muscular hydrostats power sharks, eels and dolphins when they swim. And he notes that the muscular hydrostat idea has already reshaped physiologists' thinking about how the human heart expands after contraction. The traditional view, he says, has been that blood pressure in the veins re-inflates the heart, even though scores of physiology students know that when a dissected frog's heart is disconnected from its blood flow and is taken out of the

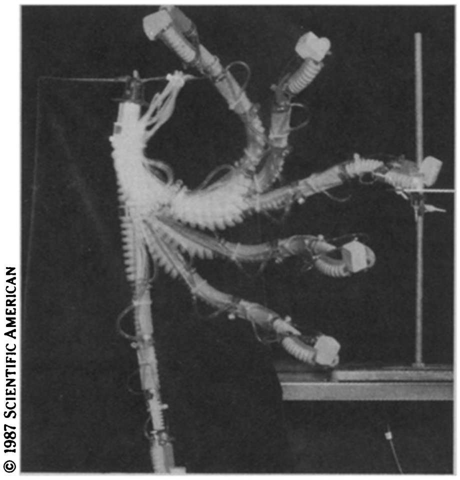


Kier/JOURNAL OF MORPHOLOGY

Even though the squid doesn't have bones or any other of the usual kinds of skeletal supports, it's no slouch. With its arrangement of muscles, the squid's tentacles can snap up a shrimp in 30 milliseconds, and its graceful arms can then maneuver its prey with great dexterity.

body, it keeps on beating. Now scientists have found that the fattening of some contracting heart muscles is responsible for the heart's re-expansion.

In recent work, Kier has also discovered that the muscle arrangement in squid tentacles, which can snatch prey in an impressive 30 milliseconds, is similar to that in the slower-moving squid arms, which bend to manipulate the food during eating. "This was a little surprising because they're doing such different things," he says. "In vertebrates, two muscle masses serving different functions are usually arranged differently." But using an electron microscope, Kier discovered that tentacle muscles instead contain especially fast-contracting muscle fibers never before seen in cephalopods. "Here, then, is a case in which the arrangement is the same but the muscle itself has evolved for a special function."



If elephants can do it, why not robots? This pneumatic arm is based on similar muscular principles. This photograph, taken with a strobe light, captures a sequence in which the arm grabs an object from the table and then puts it on the shelf above, all in less than five seconds.

As important as muscular hydrostats can be, they have their disadvantages. Squids, for example, are not as good burrowers as animals with cavities; nor would they be impressive runners or jumpers on land like skeleton-containing animals. They also require unusually complex nerve circuitry to control movement – for instance, there are three times as many neurons in the nerve chord of an octopus' arm as in its brain, according to Kier. This suggests that considerable peripheral nervous processing is going on in the arms.

Nonetheless, Kier notes that squids and related animals have many capabilities that are unavailable to animals with other types of muscle-skeleton systems. "In general, they're capable of much finer control, more precise bending and manipulative movements," he says. Without being constrained to bend only where there are joints, for example, an octopus is able to scratch its right "elbow" with its right "hand," says Wainwright.

This kind of flexibility has caught the eye of Duke University's James F. Wilson and his colleagues, who have recently built a pneumatically driven robot arm. The arm, reminiscent of an elephant's trunk, is made of partly corrugated polyurethane tubes that work as half-bellows, expanding and bending when air is pumped into them. Guided in part by nature's muscular hydrostat examples, Wilson expects that such compliant robot arms will be more robust and will be able to operate in tighter, more awkward work spaces than their conventional, rigid-limbed counterparts.

Kier believes that many more innovative designs and concepts would arise if biologists and engineers were less shy about muscling in on one another's traditional territories. "The wonderful thing we see as zoologists is the incredible diversity [of nature]. Many things have been tried and have been successful over the course of millions of years. Natural selection has a real power and creativity that could provide a lot of interesting ideas for engineering. That sort of interaction would be a really neat thing to foster." □