Unified physics theory explains animals' running, flying and swimming

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A single unifying physics theory can essentially describe how animals of every ilk, from flying insects to fish, get around, researchers at Duke University's Pratt School of Engineering and Pennsylvania State University have found. The team reports that all animals bear the same stamp of physics in their design.

The researchers show that so-called "constructal theory" can explain basic characteristics of locomotion for every creature -- how fast they get from one place to another and how rapidly and forcefully they step, flap or paddle in relation to their mass. Constructal theory is a powerful analytical approach to describing movement, or flows, in nature.

They said their findings have important implications for understanding factors that guide evolution by suggesting that many important functional characteristics of animal shape and locomotion are predictable from physics.

The findings, published in the January 2006 issue of "The Journal of Experimental Biology," challenge the notion that fundamental differences between apparently unrelated forms of locomotion exist. The findings also offer an explanation for remarkable universal similarities in animal design that had long puzzled scientists, the researchers said.

"The similarities among animals that are on the surface very different are no coincidence," said Adrian Bejan, J. A. Jones Professor of Mechanical Engineering at Duke's Pratt School. "In fact, animal locomotion is no different than other flows, animate and inanimate: they all develop in space and in time such that they optimize the flow of material." In the case of animal locomotion, this means that animals move such that they travel the greatest distance while expending the least amount of energy, he said.

"From simple physics, based only on gravity, density and mass, you can explain within an order of magnitude many features of flying, swimming and running," added James Marden, professor of biology at Penn State. "It doesn't matter whether the animal has eight legs, four legs, two, even if it swims with no legs."

First conceived by Bejan and published in 1996, the constructal law arises from the basic principle that flow systems evolve so as to minimize imperfections -- energy wasted to friction or other forms of resistance -- such that the least amount of useful energy is lost.

The theory applies to virtually everything that moves, Bejan said. For example, his earlier work has examined how the law explains traffic flows, the cooling of small-scale electronics and river currents.

The researchers, funded by the National Science Foundation, report that the constructal law predicts universal relationships between animals' body mass and speed, as well as the frequency and force of the strides, beats or undulations that propel their bodies forward.

"Running, swimming and flying occur in vastly different physical environments and, likewise, involve quite different body mechanics," Bejan said of the new application of constructal law. "Nonetheless, there are strong convergences in certain functional characteristics of runners, swimmers and fliers."

For example, the stride frequency of running vertebrates bears the same relationship to the animals' mass as does the rate at which fish swim. Similarly, the velocity of runners conforms to the same principles as the speed of birds in flight.

The force generated by the muscular "motors" of runners, swimmers and fliers also conforms with surprisingly little variation to a universal value dependent only on muscle mass, Marden said. Why this relationship should be so had remained mysterious, he said.

In the absence of a unifying theory for such design features, biologists had looked to mechanical constraints for an answer, the researchers said. Many authors have suggested that effects of scale in locomotion stem from biomechanical safety factors: the need to avoid premature failure, for instance.

Marden said he first stumbled across the problem in the 1980s when studying the variability in flight performance of insects and other flying animals. He attached weights to them and got a "strange universal result." All the organisms he tested -- birds, bats, insects -- could all lift approximately the same amount of weight in relation to the size of their flight muscles regardless of their many other biological differences.

"The size of the wings didn't matter; nothing else seemed to matter." Marden said. "It was fascinating, but there was no explanation for this commonality when so much about the animals seemed to be different."

Years later, a student of Marden's suggested they analyze the function of jet engines, to determine whether they, too, followed the same principle. Although Marden said he at first dismissed the idea as ridiculous, a 2002 report by the two in "Proceedings of the National Academy of Sciences" showed that flying insects, birds and bats, running and swimming animals, piston engines, electric motors and jets all showed the very same pattern.

"We found that all of the motors used by humans and animals for transportation have a common upper limit of mass-specific net force output that is independent of materials and mechanisms," Marden said.

Unbeknownst to Marden, Bejan had already applied his constructal theory to a similar flight principle, the relationship of mass to flight speed in insects, birds and airplanes, ranging from the extremes of a house fly to a Boeing 747. The result was first published in Bejan's book "Shape and Structure, From Engineering to Nature" in 2000 by Cambridge University Press.

A fortuitous meeting of Bejan and Marden at a conference in 2004 led them to extend Bejan's constructal theory from flying to running. The theory shows that, to maintain a constant speed, runners and fliers alike must expend energy to account for two mechanisms of work destruction -- that which is destroyed at each jump and landing, or with each rise and fall in the air; and that lost to friction against the ground or air.

"To run or fly at optimal speed is to strike a balance between the vertical and horizontal loss of energy," Bejan said. Simple equations based on this idea closely predicted the actual velocities of animals running over a variety of terrains and the observed wingbeat frequencies of flying birds, bats and insects, the current study reveals.

"It was swimming that stumped us," Bejan said. "Everyone knows that, in water, fish are weightless."

In other words, they explained, fish are neutrally buoyant, or nearly so, meaning that their tendency to float counteracts the force of gravity and they do not sink or rise. In essence, then, scientists have considered fish to move as though unaffected by gravity.

Based on the data, swimmers exhibit the same body-mass scaling as runners and fliers. "The question was: How could a theory including gravity apply to swimming fish?" Marden said.

Bejan finally realized the answer. Although fish are neutrally buoyant, they still have to push water out of the way to move forward, he said. That water raises the surface √ a phenomenon that is often imperceptible as it may be spread across an entire lake, stream or ocean.

"The water can only go up because the bottom and sides of the channel are rigid," Bejan said. "That bulge, however undetectable, is the fish's footprint."

Fish must, therefore, work against gravity to lift an amount of water equal to their own mass for each body length they move forward.

"It puts fish in the same physical realm as runners and fliers," Marden said.

"The fact that the same proportionalities rule optimal running, flying and swimming is not a coincidence; rather it is an illustration of the fact that a universal principle is involved," Bejan said. "Running requires the least food when during each cycle a certain amount of work is destroyed by vertical impact and a certain amount to horizontal friction. The same balancing act is responsible for optimal flight and swimming.

"All animals, regardless of their habitat, mix air and water much more efficiently than they would in the absence of flow structure," he added.

The findings may have implications for understanding animal evolution, Marden said. One view of evolution holds that it is not a purely deterministic process; that history is full of chance and historical contingency. It is the idea purported by Steven Jay Gould and others that if you were to "rewind the tape" and run it again, evolution would proceed down a different path, Marden said.

"Our finding that animal locomotion adheres to constructal theory tells us that -- even though you couldn't predict exactly what animals would look like if you started evolution over on earth, or it happened on another planet -- with a given gravity and density of their tissues, the same basic patterns of their design would evolve again," Marden said.

Source: Duke University

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