How insects evolved to ultrafast flight

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Moth and bee flight comparisons. Credit: Georgia Tech/Rob Felt

Mosquitoes are some of the fastest-flying insects. Flapping their wings more than 800 times a second, they achieve their speed because the muscles in their wings can flap faster than their nervous system can tell them to beat.

This asynchronous beating comes from how the flight muscles interact with the physics of the insect's springy exoskeleton. This decoupling of neural commands and muscle contractions is common in only four distinct insect groups.

For years, scientists assumed these four groups evolved these ultrafast wingbeats separately, but research from the Georgia Institute of Technology and the University of California, San Diego (UC San Diego) shows that they evolved from a single common ancestor. This discovery demonstrates evolution has repeatedly turned on and off this particular mode of flight. The researchers developed physics models and robotics to test how these transitions could occur.

The moth became the key species to unlock this evolution of flight. Unlike mosquitos, moths fly by pacing their flight muscles with every wing stroke with synchronous activation from their nervous system. Along with three other flying insects, the ancestors of moths evolved to have asynchronous flight but later lost it. Yet, even millions of years later, moths still retain the ability to perform asynchronous muscle contractions.

Despite showing the evolutionary pattern, the researchers still needed to explain how insects could transition back and forth between these two flight modes. To do so, they mapped the flight strategies onto the two fundamental ways that physicists think of oscillations. Using biophysical models and robotic platforms, they showed these two strategies are two sides of a single unified model. If evolution tweaked a few parameters, the insect could suddenly shift from synchronous flight to asynchronous flight and vice versa.

"Our findings are pretty robust to all different experimental conditions," said Jeff Gau, a Ph.D. graduate from Georgia Tech and one of the lead authors on the paper. "We're looking back 400 million years into how ancient insect muscles must have behaved from an evolutionary standpoint."

This work was inherently interdisciplinary, combining researchers in physics, evolutionary biology, and robotics. The results were published in *Nature* in the paper, "Bridging two insect flight modes in evolution, physiology, and robophysics," in October.

In sync

Many insects fly synchronously, matching the nervous system pulses to wing movement. But smaller insects don't have the mechanics for this and must flap their wings harder, which works only up to a certain point. That's where asynchronous flight comes in.

"As insects became smaller, their wingbeats increased to 100 times per second, and when you start getting up to that speed, there's sort of an inherent speed limit where the muscle can't contract and relax fast enough," said Simon Sponberg, Dunn Family Early Career Associate Professor of Physics and Biological Sciences at Georgia Tech. "If they tried to contract and relax the wings, they'd start overlapping and then eventually lock up."

Instead, smaller insects have evolved to use the nervous system to send a pulse of activity to the muscles, which are then primed to contract whether or not the wing needs to flap. With just a tiny stretch, the muscles activate and automatically generate the wingbeats. Asynchronous flight enables the wings to flap significantly faster than if the nervous system had to activate and relax the muscles each time.

Unlocking evolution

While this asynchrony has been known since the 1950s, scientists originally posited that insects happened to evolve this trait separately. However, new phylogenies, or family trees, of how different species evolved from each other came out recently. Using these phylogenies, the researchers developed models to determine how asynchronous flight evolved.

What they discovered was very surprising. Asynchrony didn't evolve separately four times but only evolved once for all flying insects. Some insect groups naturally lost that ability over time and switched to synchronous flight, while others kept it.

"One of the biggest evolutionary findings here is that these transitions are occurring in both directions and that instead of using multiple independent origins of asynchronous muscle, there's actually only one," said Brett Aiello, an assistant professor of biology at Seton Hill University and former postdoctoral researcher in Sponberg's lab who helped lead the study. "From that one independent origin, multiple revisions back to synchrony have occurred."

Modeling evolution of flight

Sponberg compares flight to the physics concept of oscillations, which can arise in one of two ways: regularly pushing the system, like a spring or pendulum; versus self-excitement, or when something in the system's mechanics automatically starts pushing back when pulled.

"If you've ever watched one of those dancing balloon guys at a car dealership, it goes up and collapses repeatedly," Sponberg said. "What's happening there is it's oscillating, not because you're poking it regularly, but you're actually providing a continuous air jet in the bottom, which is a trade-off with the force of gravity."

In effect, asynchronous flight is comparable to the balloon because the already-primed muscles act as a type of self-excitement. To study how this applied to insects, the researchers focused on moths, which use synchronous flight but still have the mechanisms to fly asynchronously.

Modeling moths

Making mathematical models and robotics systems of the moth demonstrated what caused the moth to switch between the two ways of flying and gave a more complete picture of why this shift happened. Gau developed mathematical models of how the muscle became primed for flight or stretch. Once the model existed, the robotics team at UC San Diego implanted it in robophysical models.

"You don't need robotics to learn something about biology," said Nick Gravish, an associate professor at UC San Diego. "But there's something about building a bio-inspired robot that forces you to put yourself in the animal's shoes."

The team made two robots. One, a large flapper robot modeled after a moth to better understand how the wings worked, was deployed in water, which has a viscosity similar to how a tiny insect moves through the air.

"The physics of this much larger robot moving much more slowly are similar to those of an insect that's a lot smaller and moving a lot faster," said James Lynch, a Ph.D. graduate from UC San Diego and co-lead on the paper.

They also built a much smaller flapper robot that operated in air to replicate the size of an actual moth and modeled after Harvard's Robobee. The robots demonstrated if the two models the researchers developed to explain these two types of flight and their transitions worked in real-world conditions. Effectively, they built the first robot capable of asynchronous flapping and showed that a single robot could recreate the transitions from evolution.

Making discoveries in evolution, physics, and robotics was only possible with such a wide breadth of expertise and knowledge among the researchers.

"It's that type of interdisciplinary research that is super important for finding these deep, robust understandings of the natural processes that govern animal movement," said Aiello, "and how we can implement that into a robotic system."

More information: Simon Sponberg, Bridging two insect flight modes in evolution, physiology and robophysics, *Nature* (2023). DOI: 10.1038/s41586-023-06606-3.
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