Swimming mechanics of the gossamer worm revealed

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The gossamer worm (Tomopteris sp.) lives in the midwater—an open expanse of water far below the surface and far above the seafloor. It is always on the move, and MBARI researchers and their collaborators have revealed its unique swimming mechanics. Credit: MBARI

Many animals in the midwater—the vast expanse of water between the surface and the deep seafloor—are always on the move. Unlike its bottom-dwelling kin, the gossamer worm (Tomopteris sp.) lives in constant motion. This ethereal worm is a graceful swimmer that "dances" through the midwater with the rhythmic paddling of its swimming legs.

A new study published in *Integrative and Comparative Biology* this summer from MBARI researchers Joost Daniels and Kakani Katija, with collaborators Karen Osborn and her team at the Smithsonian National Museum of Natural History, has revealed the swimming behavior of gossamer worms in fine detail.

"When you come across Tomopteris worms in the midwater, what catches your eye is the way they move around," said Joost Daniels, a senior research engineering technician at MBARI and lead author on the study. "When you see them swimming around, it just looks like a little dance—they swim forwards, backwards, make these quick turns, and have all these little legs moving so rapidly."

The worm's flexible body plan allows it to combine two different modes of propulsion to achieve effective—and elegant—swimming. This makes the gossamer worm's anatomy and swimming mechanics interesting for engineers. In the future, this worm could inspire new designs for everything from underwater propulsion to medical technology.

The gossamer worm is a type of polychaete (pronounced "poly-keet") worm or segmented bristle worm. Most polychaetes are crawlers, burrowers, or have sedentary lives inside tubes. The gossamer worm is one of several unusual holopelagic species—it spends its whole life in open water without ever coming into contact with the seafloor.

"Gossamer worms are a beautiful example of animals specifically adapted to their unique environment," said Karen Osborn, research zoologist and curator of annelids and peracids at the Smithsonian National Museum of Natural History and a coauthor on the study. "They're so completely different from most marine worms, and studying these extreme examples of adaptation teaches us about the requirements for life in the deep, open ocean. It's also just fun to see how what is essentially an elaborate water balloon manages to outswim our rather expensive ROV."

Scientists have described about 60 species of gossamer worm. Most gossamer worms are transparent—an adaptation that allows them to hide in plain sight from both predators and prey. Most are only a few centimeters in length, but the largest are more than 60 centimeters (two feet) long, including their long extendable tails. Despite these dramatic differences in size, and thus how they experience the water they swim through, all gossamer worms are fast and effective swimmers.

"We see this wavy pattern in the body, the legs paddling, but what is really going on?" said Daniels.

The team recorded the animal's swimming behavior in the field using MBARI's remotely operated vehicles (ROVs). Those same robotic submersibles allowed researchers to collect specimens for study in the laboratory. The researchers were able to record the gossamer worm's rapid swimming behaviors using specialized photo tanks in the lab, high-speed cameras, and sophisticated illumination systems. Slowing the high-speed video down helped them see behaviors in more detail. By projecting a laser sheet on worms as they swam, researchers could also see how the water moved around the animal as it paddled along.

Over four years, eight Smithsonian National Museum of Natural History undergraduate interns marked and then tracked up to 52 points in each frame of the high-speed video, amassing a trove of data—more than a million individual data points. The laborious task of labeling landmarks on the worm's body allowed researchers to calculate swimming speed, body wave speed, the angular motion of swimming legs, and the thrust generated by swimming. That data allowed them to find the patterns in how a gossamer worm moves its legs and the rest of its body, and unlock the secrets to its superb swimming.

The research team focused on two components of the swimming motion of the gossamer worm—a body wave traveling forward towards the head and the movement of the swimming legs called parapodia.

Many marine animals swim by undulating their bodies, similar to snakes on land. Eels—like MBARI's mascot, the gulper eel (Saccopharynx lavenbergi)—move with a body wave that travels from the animal's head to its tail. This form of swimming works well in animals with smooth bodies. There is not too much drag on the posterior part of the animal as it swims.

A gossamer worm (Tomopteris sp.) undulates its body as it swims. However, unlike an eel, that body wave moves forward, not backward, to provide propulsion. Credit: MBARI/NOAA

Some swimming worms have a lot of appendages—their bodies are not smooth, but rough. The rough body means the body wave travels from back to front, the opposite of a snake or eel. This movement is similar to caterpillars on land.

However, the body wave does not provide much forward thrust. Instead, a series of swimming legs powers propulsion in gossamer worms.

Unlike other polychaete worms, the gossamer worm lacks the bristly, hair-like chaetae (pronounced "kee-tee") that define polychaetes, but also aid in movement. Instead of building leaky paddles out of fans of bristles like other swimming worms, gossamer worms have fleshy swimming legs that are separated into two flaps at the ends. It turns out that these appendages provide critical additional power for locomotion.

"With high-speed cameras, we can look at exactly how one swimming leg moves in relation to the one in front of it and the one behind it. We're looking at those differences at very short time intervals," explained Daniels.

Gossamer worms exhibit metachronal paddling—the sequential movement of multiple appendages. This type of propulsion is common in many ocean animals, like the mesmerizing rows of ciliary plates on comb jellies or the rhythmic kicking of swimming legs in crustaceans.

The high-speed video revealed another swimming strategy for the gossamer worm.

Paddling fleshy swimming legs called parapodia helps propel a gossamer worm (Tomopteris sp.). The legs move back and forth, and as they do, the divided ends slide back and forth across each other to make the paddle larger and smaller during power and recovery strokes. Credit: Rob Sherlock, MBARI

The gossamer worm can change the surface area of its paddles. By spreading and contracting the two fleshy ends (rami) of each parapodia, the worm creates differences in drag between power and recovery strokes. Daniels compared this to the stroke of (human) swimmers, "Tomopteris can spread those legs out much like a swimmer uses an open hand during the power portion of their stroke but then closes and angles their hand as they bring it back in front of them."

In addition, while the body wave does not provide much forward thrust, it does push the parapodia farther out. Extending the parapodia out into undisturbed water increases the space for the swimming legs to stroke and thus enhances thrust. The researchers are not aware of any other animal that uses such a unique combination of a body wave and paddling legs.

"These worms have all these little techniques that add up to more effective swimming. This is an animal that's really well developed for spending a lot of time swimming in the midwaters," said Daniels.

Daniels is part of MBARI's Bioinspiration Lab, which looks to nature for solutions to engineering challenges in the human world. Led by MBARI Principal Engineer Kakani Katija, the team has been studying gossamer worms for their extraordinary propulsion system.

"Through evolution, animals in the deep sea have developed so many different solutions to thrive in this environment. By studying these adaptations of marine life, like how gossamer worms swim, we may be able to one day unlock their keys to success and apply it to other engineering technologies to transform how we live."

Understanding the worm's swimming behavior may one day inspire new methods for propelling instruments and vehicles underwater. "We all think of propellers and jet propulsion underwater, but there is so much more that's out there," said Daniels. "This worm, in particular, is a curiosity that we'd love to explore further to see how we could apply this motion in robotics or vehicles."

More information: Joost Daniels et al, Metachronal Swimming with Flexible Legs: A Kinematics Analysis of the Midwater Polychaete Tomopteris, *Integrative and Comparative Biology* (2021). DOI: 10.1093/icb/icab059

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