Simulated 'Frankenfish brain-swaps' reveal senses control body movement

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In a new study featured in the journal eLife, researchers have computationally modeled the various brains and bodies of a species of weakly electric fish, the glass knifefish (Eigenmannia virescens), to successfully simulate "fish brain transplants" and investigate. Credit: NJIT

Plenty of fictional works like Mary Shelly's Frankenstein have explored the idea of swapping out a brain from one individual and transferring it into a completely different body. However, a team of biologists and engineers has now used a variation of the sci-fi concept, via computer simulation, to explore a core brain-body question.

How can two people with vastly different-sized limbs and muscles perform identical fine-motor tasks equally well, such as hitting a baseball or sending a text? Is it a unique tuning between our brain and nervous system with the rest of our body that controls these complex motions, or is feedback from our senses taking charge?

In a new study featured in the journal *eLife*, researchers have computationally modeled the various brains and bodies of a species of weakly electric fish, the glass knifefish (Eigenmannia virescens), to successfully simulate "fish brain transplants" and investigate.

The team's simulations, which involved swapping models of the fishes' information processing and motor systems, revealed that after undergoing a sudden jump into the different body of their tank-mate, the "Frankenfish" quickly compensated for the brain-body mismatch by heavily relying on sensory feedback to resume control of fine-motor movements required for swimming performance.

Researchers say the findings provide new evidence that animals can lean on feedback from the senses to aid the interplay of the brain, body and stimulus from their external environment in guiding locomotor movement, rather than depending on precise tuning of brain circuits to the mechanics of the body's muscles and skeleton. The team also says the findings reinforce the case for the future design of advanced robotics that employ robust sensory feedback control systems; such systems may better adapt to unexpected events in their environment.

"What this study shows is the deep role of sensory feedback in everything we do," said Eric Fortune, professor at NJIT's Department of Biological Sciences and author of the study, funded by the National Science Foundation. "People have been trying to figure out how the animal movement works forever. It turns out that swapping brains of these fishes is a great way to address this fundamental question and gain a better understanding for how we might control our bodies."

"The Frankenfish experiment demonstrates a common idea in control theory, which is that many of the details of how sensation is converted to action in a closed feedback loop don't matter," said Noah Cowan, professor at John's Hopkins University's (JHU) Department of Mechanical Engineering, co-author and longtime collaborator of Fortune. "While not any random brain would work, the brain has a lot of freedom in its control of the body."

In the study, the team set out to specifically explore how behavioral performance of the fish might change if they experimentally altered the fishes' connection between controller, or the sensory systems and neural circuits used to process information to generate motor commands, and plant, the musculoskeletal components that interact with the environment to generate movement.

Using experimental tanks outfitted with high-res cameras in the lab, the researchers tracked the subtle movements of three glass knifefish of different shapes and sizes as they as shuttled back and forth within their tunnel-like refuges—a common behavior among electric fish that includes rapid and nuanced adjustments to produce sensory information that the fish need for keeping a fixed position within the safety of their hidden habitats, also known as station-keeping.

The team collected various sensory and kinematic measurements linked to the exercise—most notably, the micromovements of the fishes' ribbon-like fins that are critical to locomotor function during shuttling activity—and applied the data to create computer models of the brain and body of each fish.

"We took advantage of the animal's natural station-keeping behavior using a novel virtual reality setup, where we can control the movements of the refuge and record the movements of the fish in real time," explained Ismail Uyanik, assistant professor of engineering at Hacettepe University, Turkey, and former postdoctoral researcher involved in the study at NJIT. "We showed that movements of the ribbon fin could be used as a proxy of the neural controller applied by the central nervous system. The data allowed us to estimate the locomotor dynamics and to calculate the controllers that the central nervous system applies during the control of this behavior."

"The ribbon fin was the key to our success in modeling the motor system, which others have been trying to do using other sophisticated techniques for decades," said Fortune. "We were able to track this virtually invisible fin and the counter-propagating waves it creates in slow motion using our cameras and machine-learning algorithms. ... Without those technologies it wouldn't have been possible.

"We logged nearly 40,000 ribbon-fin movements per fish during their shuttling to get the data we ended up using to help build models of each fish's locomotor plant and controller."

With their models, the team began computationally swapping controllers and plants between the fish, observing that the brain swaps had virtually no effect on the models' simulated swimming behaviors when they included sensory feedback data. However, without the sensory feedback data included in the models, the fishes' swimming performance dropped off completely.

"We found that these fish perform badly... They just can't adjust to having the wrong brain in the wrong body. But once you add feedback to the models to close the loop, suddenly they continue their swimming movements as if nothing happened. Essentially, sensory feedback rescues them," explained Fortune.

The team says the findings could help inform engineers in the design of future robotics and sensor technology, and similar further studies of the electric fish's ribbon fin may improve our understanding of muscle physiology and complex statistical relations between muscle activations that allow humans to outperform robots when it comes to controlling body movement.

"Robots are a lot better than humans at generating specific velocities and forces that are far more precise than a human, but would you rather shake hands with a human or robot? Which is safer?" said Fortune. "The problem is of control. We want to be able to make robots that perform as well as humans, but we need better control algorithms, and that's what we are getting at in these studies."

More information: Ismail Uyanik et al, Variability in locomotor dynamics reveals the critical role of feedback in task control, *eLife* (2020). DOI: 10.7554/eLife.51219

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