BIOMIMETICS

Is intermittent swimming lazy or clever?

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The motor efficiency of a zebrafish-like robot helps to explain the advantages of burst-and-coast swimming.

Fish-inspired robots typically flap tail fins to generate thrust, often with a continuous oscillation pattern, like a sine wave. Real fish are more complicated: They often alternate between bouts of oscillation and gliding. This so-called "burst-and-coast," "bout-and-glide," or "intermittent" swimming style is not a niche strategy; it appears over a wide range of animal sizes and speeds—from zebrafish larvae to humpback whales (*1*).

It is generally accepted that burst-and-coast swimming can offer energetic benefits; the open questions are when and how those benefits occur. Writing in *Science Robotics*, Liu *et al.* (*2*) uncover a key piece of this puzzle. With their zebrafish-inspired robot, ZBot, they show that the advantages of burst-and-coast swimming can be explained using motor efficiency, offering a robotic explanation for what has historically been viewed as a hydrodynamic phenomenon. To better understand this discovery, we should first quantify "energetic benefit."

A popular energetic metric is the swimming economy: average swimming speed divided by average input power. This metric measures how far an animal travels per unit of energy, akin to the gas mileage of a car. Now consider two swimmers, one continuous and one burst-and-coast, but with the same average speed (Fig. 1A). Because they share an average speed, whichever swimmer requires less average input power has a higher swimming economy. But for average speed to be constant, all input power must be, on average, lost to the environment—otherwise, a robot would accumulate a surplus/deficit of kinetic energy. Therefore, whichever swimmer loses less average power to the environment has a higher swimming economy (Fig. 1B).

Prior studies have leveraged this focus on lost power to untangle the sources of burst-and-coast benefits. For example, base metabolic loss (minimum power needed to run even in an inactive state) cannot play a role, because it subtracts equally from continuous and burst-and-coast swimming economy. Drag loss (power lost because of towing resistance), once thought to be the primary differentiator between continuous and burst-and-coast swimming (*3*), is now thought to play a modest role in explaining the benefits of one versus the other (*4*). Metabolic and drag losses are the only sources of power loss in a coast phase. In a burst phase and in continuous swimming, drag and metabolic losses are mixed with other losses, but they still occur; they represent the power that would theoretically be required to tow an inactive robot at the same speed (*5*).

Additional power losses come in two forms: power lost to lateral momentum in the surrounding fluid (vortex losses) and power lost to friction in the actuator (actuator losses). In the past, discussions of these additional power losses have centered on vortex losses. For example, suppose the tail fin is more hydrodynamically efficient at a high reduced frequency k (frequency times body length divided by swimming speed). Burst-and-coast swimming offers, via short bouts of high-frequency motion, a way to access these more-efficient reduced frequencies while maintaining a constant average speed (Fig. 1C) (*6*).

What ZBot offers is a parallel explanation based on actuator losses. Suppose the robot's servomotor is more efficient at a high torque τ. Burst-and-coast swimming offers, via short bouts of high-torque motion, a way to access these more efficient actuator torques while maintaining a constant average speed (Fig. 1D). Liu and colleagues support this "actuator efficiency" hypothesis with a direct comparison between electrical power consumption and the payload-efficiency relationship of ZBot's servomotor.

One advantage of the actuator efficiency hypothesis is that it is easily generalized to real fish. Like electric motors, real muscles can be more efficient under certain loadings (*7*). ZBot highlights this biological relevance by using a bioinspired controller: It simulates the neural mechanisms known to produce burst-and-coast in zebrafish—namely, that central pattern generators (CPGs) produce tail oscillations, whereas higher-level gating mechanisms turn CPGs on and off (*8*). ZBot offers proof that a neuron-inspired circuit can coordinate burst-and-coast advantages enabled by a muscle-inspired efficiency mechanism.

Another advantage of the actuator efficiency hypothesis is that it does not depend on flow properties. Take the Reynolds number, a ratio of inertial to viscous forces known to explain many hydrodynamic differences between swimmers. Small larval swimmers may operate at Reynolds numbers of 100; large migrating fish may be at 1,000,000. The effects of reduced frequency tend to be Reynolds number dependent in a way that actuator efficiency cannot be. Liu and colleagues demonstrated this by salting their test pool to increase viscosity and thereby reduce the Reynolds number. Over Reynolds numbers ranging from about 1 to 10,000, ZBot maintained an advantage when using burst-and-coast swimming.

It seems then that the benefits of burst-and-coast are likely caused by a condition-dependent mix of hydrodynamic and robotic factors. With a physics-based framework now in place, future robots could optimize their burst-and-coast duty cycle by combining preestablished scaling laws with real-time tweaks. Real fish may even do this type of optimization themselves (*9*).

The idea that burst-and-coast swimming leverages both fluid physics and actuator physics helps to explain its prevalence across vastly

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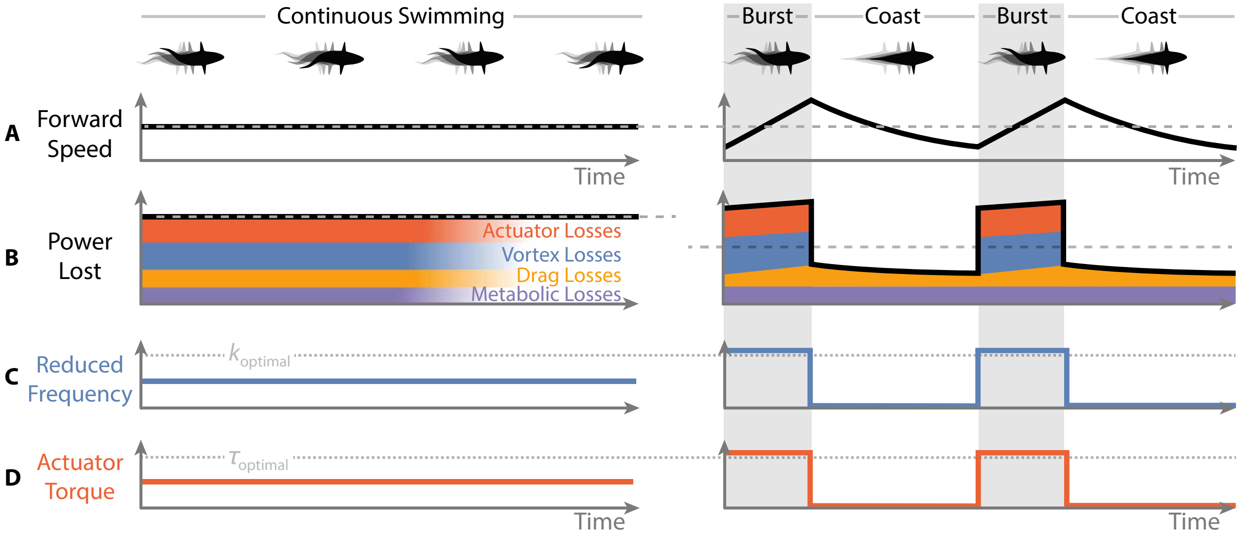

Fig. 1. Untangling the energy savings of burst-and-coast swimming. (**A**) Swimming speed is constant in continuous swimming and variable in burst-and-coast swimming yet can have the same average value (dashed line). (**B**) Power lost to the environment is the sum of four types of losses. Burst-and-coast can reduce average power loss (dashed lines). (**C** and **D**) Burst-and-coast offers a way to increase k or τ to optimal values (dotted lines) during bursts without changing the average swimming speed.

different locomotion types. For example, alternating between active and inactive states is also a popular concept in bird and bird-inspired robotics literature, where it is called "flap-bounding flight" (*10*). One could even imagine a wide range of engineered and biological systems falling on a spectrum ranging from launched projectiles (the ultimate burst-and-coast, that is, all thrust provided once at the beginning) to rotating propellers (the anti–burst-and-coast, that is, fully constant thrust).

How to stitch together this spectrum with a unifying framework remains for future work, but for now, burst-and-coast is a promising strategy at least for bioinspired underwater robots. Just this year, a koi-inspired robot also demonstrated savings from burst-and-coast swimming (*11*), and there will likely be more to come. Most importantly, the mechanisms responsible for these savings are more generalizable than previously thought, unlocking new ways that they could be leveraged.

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