Robotic Study on the Control and Power Consumption of Bout and Glide Swimming

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Background

Bio-inspired robots are valuable tools for studying adaptive behaviors, including locomotion and sensory processing[1]. By incorporating neural mechanisms, researchers can systematically investigate their effects under controlled conditions. Among the lab-animals, zebrafish larvae have emerged as an excellent system for studying locomotion and sensory processing due to their experimental advantages, such as transparency, small brain size, and ease of behavioral measurement[2][3]. Neural activity mapping in zebrafish larvae has revealed detailed insights into locomotion-related circuits. However, existing zebrafish-inspired robots lack integrated sensory feedback and neural mechanisms, limiting their ability to systematically study the role of these components in adaptive behavior[4] [5]. To address this gap, we developed ZBot, a zebrafish-inspired robotic platform designed to integrate sensors and test hypothesized neural mechanisms underlying swimming behavior.

Bout and glide swimming, also known as burst and coast swimming, is an intermittent swimming mode observed in zebrafish and various fish species, including tuna [6], koi carp[7], red-nose tetra fish[7] [8], and whales[9]. It consists of alternating active undulations and passive gliding phases. This strategy is thought to contribute to energy-efficient swimming[10], but the precise neural and biomechanical mechanisms remain poorly understood. While biological studies suggest that central pattern generators in the spinal cord and a supraspinal gating center control bout initiation and termination[2][11], few computational models have attempted to integrate and replicate these processes. Moreover, no robotic implementation with neural control has successfully reproduced bout and glide swimming. By analyzing kinematic recordings of zebrafish larvae[12], we propose a neural model of bout and glide swimming. The embodiment of the proposed neural model on the developed ZBot is capable of generating diverse bout and glide gaits that closely resemble those observed in real zebrafish swimming.

Understanding bout and glide swimming requires establishing relationships between key parameters such as tail-beating frequency, amplitude, bout duration, and their effects on swimming velocity and turning angle [13]. Unlike continuous swimming, where steady-state dynamics simplify analysis, intermittent swimming presents challenges due to the variability in swimming patterns, such as the brust velocity during the bout phase [12]. While prior studies have established relationships between swimming parameters and velocity for continuous swimming [13][14], limited data exist for modeling bout and glide swimming due to the difficulty of inducing animals to exhibit controlled behaviors.

The potential energetic benefits of intermittent swimming remain debated. Some studies suggest that bout and glide swimming reduces energy dissipation by minimizing drag during the gliding phase, leading to higher efficiency than continuous tail-beating swimming [7][10]. However, other studies argue that the energetic advantage is insignificant [8]. The energy efficiency in swimming depends on multiple factors, including neural control, actuation efficiency, body structure, and hydrodynamics. The studies have only considered part of the aspects, making it difficult to draw definitive conclusions. While animal experiments can help address these questions, they are inherently limited by the difficulty of controlling and measuring specific parameters.

Results

To overcome these challenges, we developed Zbot (Figure 1 (B) and (C)), a robotic platform designed to systematically investigate the relationships between swimming parameters and performance. Our results demonstrate that ZBot successfully reproduces zebrafish-like kinematics(Figure 1 (E) to (H)). Beyond the qualitative reproduction, by manipulating the parameters in the proposed neural model, it can generate diverse kinematic outputs that similar to the identified kinematics of the gaits of zebrafish larvae. By recording the swimming velocity and energy consumption, we show that intermittent swimming leads to a lower cost of transport than continuous swimming at low velocities, providing insights into the biomechanical and energetic principles underlying bout and glide swimming.

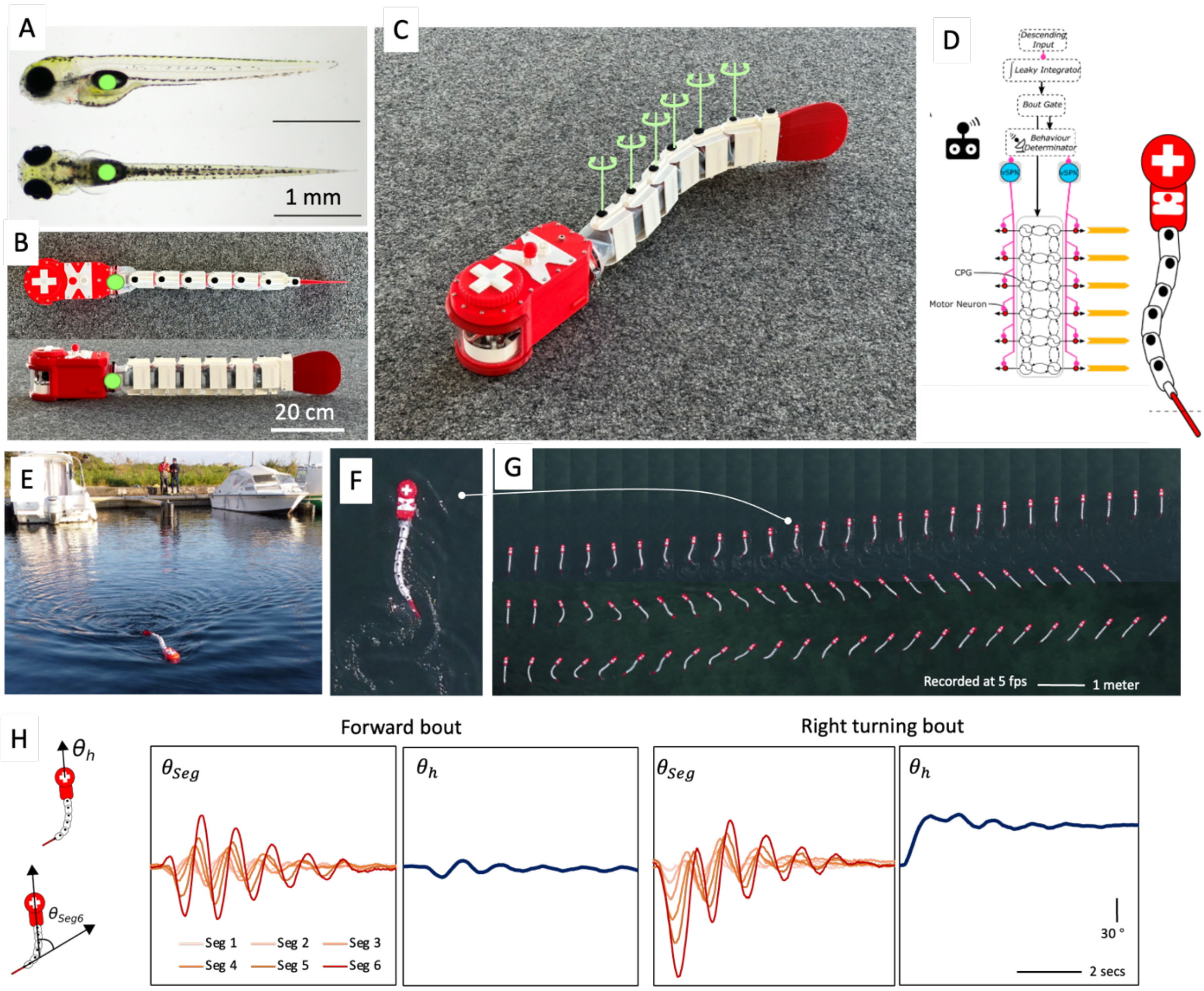

Figure 1 presents an overview of the zebrafish-inspired robotic system and its experimental setup. (A) shows photos of a zebrafish larva, captured by Guillaume Valentin at the Center of PhenoGenomics, EPFL fish facility. (B) and (C) display the developed ZBot, featuring six hinge joints on its tail actuated by servomotors. (D) illustrates the neural model driving bout-and-glide swimming. (E) depicts the experimental setup in stationary water at a harbor on Lake Geneva (Lac Léman). (F) and (G) provide frames of forward, leftward turning, and rightward turning bouts, including a zoomed-in drone view of a forward bout. (H) visualizes the head direction and accumulated segmental angles during a forward bout and a turning bout, highlighting the robot's kinematic behavior.

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