ICCES, 2026, vol.36, no.1

Tech Science Press

DOI: 10.32604/icces.2026.013862

PROCEEDINGS

Mechanistic Study of Neural Signal Modulation and Propulsion Efficiency in High-Fidelity Digital Swimmers

Tao Li[1,2], Hao Ma[1,2], Ji Hou[1,2], and Chunze Zhang[1,2,*]

[1]The College of River and Ocean Engineering, Chongqing Jiaotong University, Chongqing, 400074, China

[2]National Inland Waterway Regulation Engineering Research Center, Chongqing, 400074, China

[*]Corresponding Author: Chunze Zhang. Email: zhangchunze@whu.edu.cn

ABSTRACT

Fish achieve highly energy-efficient propulsion in complex hydrodynamic environments through a multi-level, tightly coupled "neural–musculoskeletal–body–fluid" system. This integrated mechanism provides a compelling biological blueprint for biomimetic underwater robots intended for long-endurance missions. Replicating this advantage in engineered platforms, however, requires more than kinematic descriptions and curve fitting: kinematics alone has limited ability to illuminate the control principles underlying efficient swimming. More fundamentally, the key is to identify and model the neuromuscular control principles that drive efficient swimming and their coordinated coupling with fluid–structure interactions (FSI). Guided by this view, we developed a physics-constrained deep reinforcement learning (DRL) framework for neuromuscular control simulation. The framework coupled DRL with a FSI solver, a Hill-type muscle model, and multibody dynamics in a closed-loop simulation. This platform can directly quantify the swimmer's active and passive muscular work and characterize the entire dynamic chain of force transmission during swimming locomotion. Within this unified setting, a DRL agent learned end-to-end—without an explicitly prescribed control law—the spatiotemporal transformation from neural activation to muscle force generation to body deformation in a high-fidelity digital swimmer, while also capturing the resulting swimming speed and muscular work. After sufficient training, the agent found a clear, repeatable family of Pareto-optimal solutions and spontaneously discovers interpretable physical patterns consistent with prior experimental observations. These results demonstrate the value of DRL for exploration and optimization in high-dimensional, strongly coupled, effectively black-box physical systems, while also provide a testable quantitative framework for elucidating the neuromuscular control mechanisms underlying fish swimming, and offering valuable insights for actuator selection, structural design, and energy-management system design in biomimetic underwater robots.

KEYWORDS

Musculoskeletal model; fluid-structure interaction; swimming; deep reinforcement learning

Funding Statement: This study was jointly funded by the Chongqing Water Conservancy Science and Technology Project (Grant No. CQSLK-2024021 (Chunze Zhang), CQSLK-2025016 (Ji Hou)), Chongqing Deepflow Intelligent Computing Technology Co., Ltd. Innovation & Research Fund (Chunze Zhang).

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

Copyright © 2026 The Author(s). Published by Tech Science Press.
This work is licensed under a Creative Commons Attribution 4.0 International License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.