

ABSTRACT

The scientists of today think deeply instead of clearly. One must be sane to think clearly, but one can think deeply and be quite insane.

Nikola Tesla (1856 – 1943).

Studying animal locomotion provides key insights for designing energy-efficient and adaptive robots. Although many organisms navigate air, land, and water with remarkable agility, robots still struggle to reproduce comparable maneuverability in dynamic environments. Among aquatic species, Antarctic krill serves as the model organism of this study and exemplifies a highly efficient metachronal swimming gait characterized by posterior-to-anterior limb sequencing that minimizes drag and enhances thrust, allowing precise maneuverability across both horizontal and vertical planes. Despite this remarkable efficiency, the underlying mechanisms that enable this biomechanical strategy remain insufficiently explored. To address this gap, this study seeks to elucidate its principles through a robotic platform, providing insights that we believe will pave the way for future improvements in robotic propulsion and energy efficiency.

Conventional robotic systems have typically replicated such coordination using multiple actuators, each mimicking the action of an individual muscle. In contrast, this work introduces a bio-inspired, mechanically intelligent design in which a single motor drives a closed-loop metachronal mechanism to coordinate multiple pleopod-like limbs through intrinsic kinematic constraints. A generalized degree-of-freedom formulation and new kinematic equations capture limb synchronization, phase lag, and stroke asymmetry, forming a unified framework for metachronal motion and real-time thrust estimation. Experimental validation confirmed that metachronal coordination enhances thrust while reducing energetic cost, and higher actuation rates promote a hydrodynamic transition from viscous to inertial flow, improving propulsive efficiency. These results establish the first mechanically intelligent krill robot that unifies structural synthesis, kinematic and dynamic modeling, numerical simulation, and experimental validation. Collectively, these findings demonstrate that embedding coordination within morphology simplifies control while maintaining high performance, providing a foundation for next-generation underwater robots that combine efficiency and maneuverability.