Experiment-Free Reinforcement Learning for an Unobtrusive and Compact Hip Exoskeleton with High-Torque-Density Actuators

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ABSTRACT

Exoskeletons have enormous potential to enhance human locomotion performance in daily life. However, widespread adoption remains hindered by two core challenges. First, current control strategies in software often demand hours of subject-specific experiments, limiting seamless transfer to different locomotion activities. Second, bulky and heavy hardware designs compromise comfort and practicality in real-world usage. In this work, we introduce an experiment-free learning-in-simulation (LIS) framework for assistive robotics and validate it on real-world exoskeleton hardware to seamlessly bridge the sim-to-real gap without human-in-the-loop experiments. We then develop a foldable, compact hip exoskeleton equipped with a newly custom high-torque-density actuator, further improving comfort and performance for multi-gait assistance. This integrated software–hardware approach demonstrates how fundamental innovations can collectively overcome key challenges in the widespread adoption of assistive robotics.

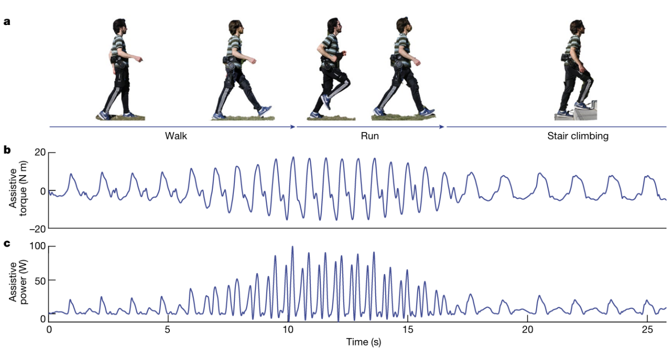

Fig. 1: Representative Assistive Torque During Various Activities and Locomotion Transitions

On the software side, the LIS framework uses a data-driven, dynamics-aware reinforcement learning pipeline to couple a 50-degree-of-freedom (208-muscle) human musculoskeletal model with a physically accurate hip exoskeleton model. Three interconnected neural networks—motion imitation, muscle coordination, and exoskeleton control—are jointly trained over roughly 3,500 iterations (under 8 hours total) on an NVIDIA RTX 3090 GPU only, producing an end-to-end controller that directly maps wearable sensor inputs to continuous assistive torque without human-in-the-loop tuning. Deployed on our custom hip exoskeleton, this controller provides automatic assistance across walking, running, and stair climbing in real-world tests, reducing metabolic costs by 24.3%, 13.1%, and 15.4%, respectively.

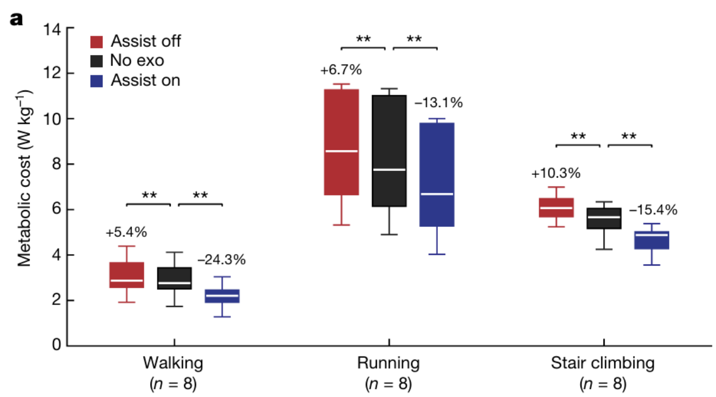

Fig. 2: Metabolic Rate Reduction for Different Locomotion

On the hardware side, we developed an electromagnetic model to guide the design of a high-torque-density, quasi-direct-drive motor.

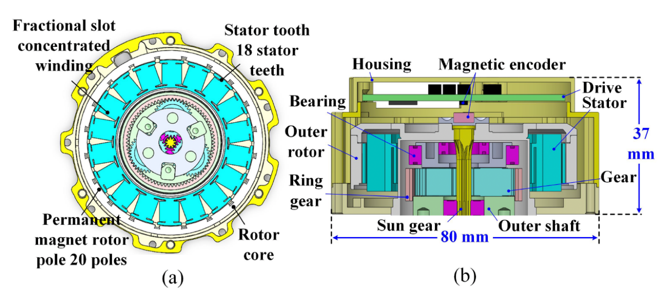

Fig. 3: Our Highly Integrated Actuator and its Mechatronic Design

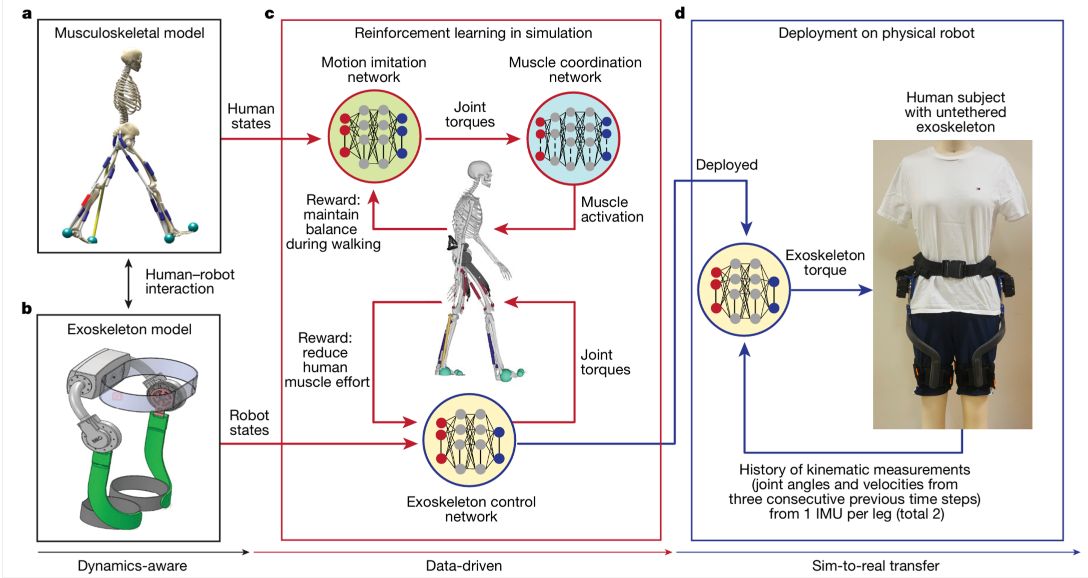

Fig. 4: Learning-in-Simulation Framework and Our Physical Hip Exoskeleton (2.7 Kg, 18 Nm Peak Torque)

Specifically, by optimizing three key parameters—stator end winding length, stator pole pairs, and rotor pole pairs—our custom actuator comes with a 9.67:1 gear ratio planetary reducer, achieving a peak torque of 18 Nm within limited volume. Additionally, we introduced two foldable mechanisms to enhance wearer comfort and adaptability: (1) a foldable waist belt with self-alignment that improves portability and fit, and (2) a foldable thigh brace with a linear slider that accommodates different body shapes and mitigates alignment errors between the actuator and the hip joint. Compared to our previous exoskeleton (which only had software updates), this new system improved the package factor by 27%, reduced overall volume by 55%, and lowered total weight by 29%. It further decreased the average metabolic cost for stair climbing to 20.64%, a 34% improvement over the prior (software-updated) hardware design, constituting more than a 100% total performance gain over the earlier state-of-the-art hip exoskeleton solution.

Fig. 5: No Hinderance and Full mMobility

In summary, our work bridges the sim-to-real gap in assistive robotics via a reinforcement learning framework that requires no human experiments on the software side, and achieves a compact, lightweight, and unobtrusive hardware design featuring a high-torque-density motor and foldable mechanisms on the hardware side. This fully integrated approach establishes a benchmark for end-to-end exoskeleton development and holds promise for broader applications in assistive robotics, benefiting both able-bodied individuals and those with mobility impairments who need multi-activity assistance.

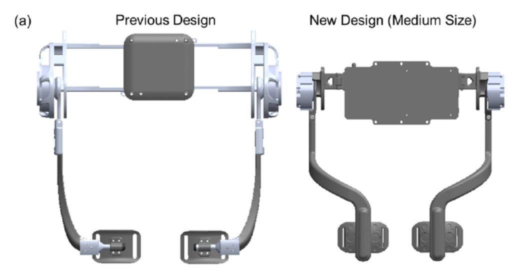

Fig. 6: Previous Design Vs Current Design

Keywords: Exoskeleton, Learning in Simulation, Reinforcement Learning, High Torque Density, Foldable Mechanism, Sim-to-Real.

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