Reinforcement Learning through Physics-based and Data-driven Approaches for Exoskeleton Control in the Real World

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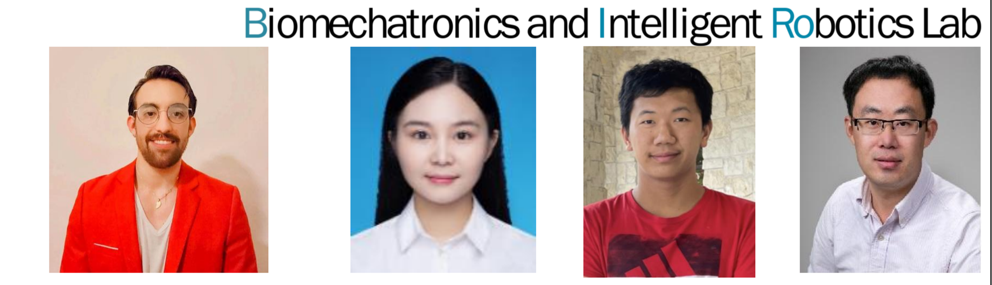
Biomechatronics and Intelligent Robotics Lab



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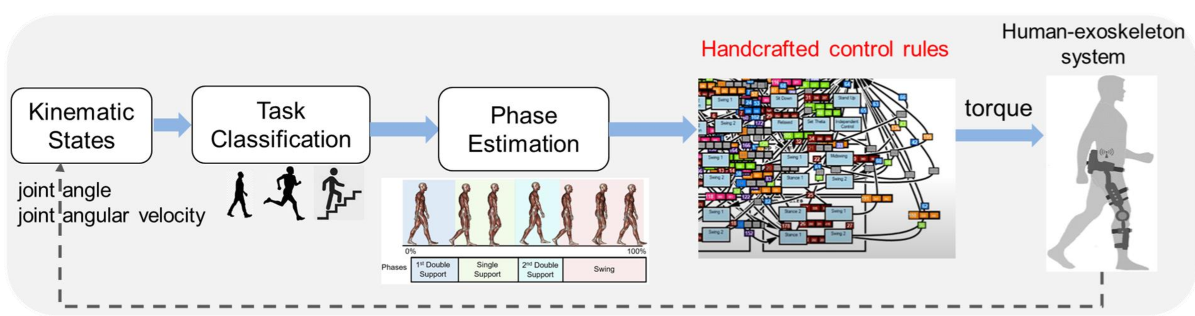
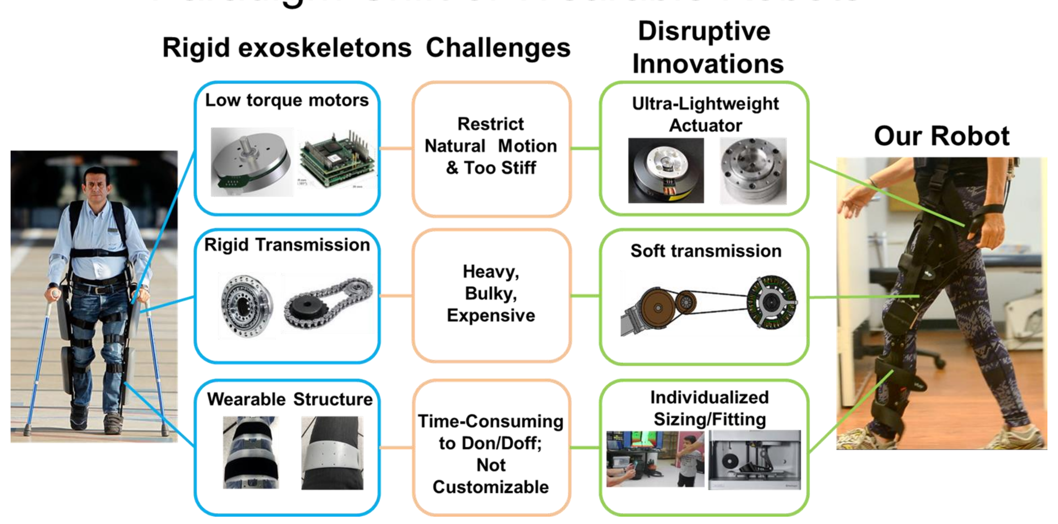
Objectives and Challenges

- Wearable robots like lower-limb exoskeletons have great potential for mobility restoration and human augmentation
- Challenge 1: Intensive human testing
- Challenge 2: Handcrafted control laws

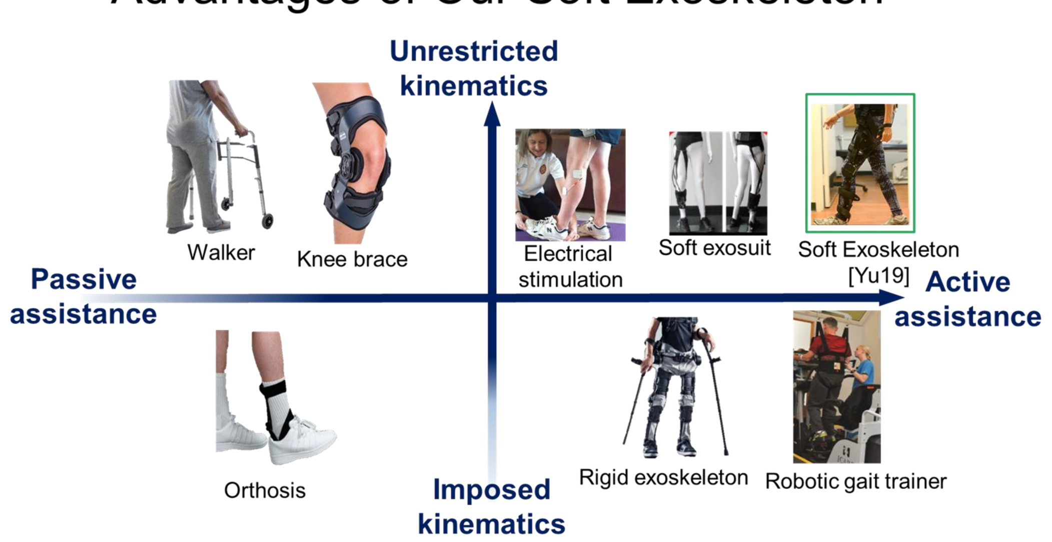


Our Lightweight and High Torque Soft Exoskeleton

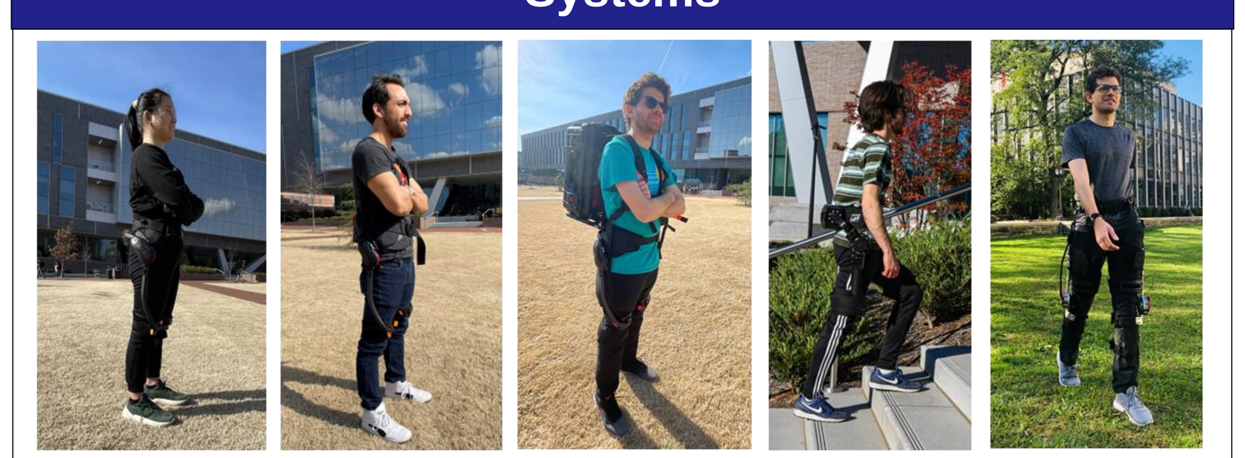
Paradigm Shift of Wearable Robots



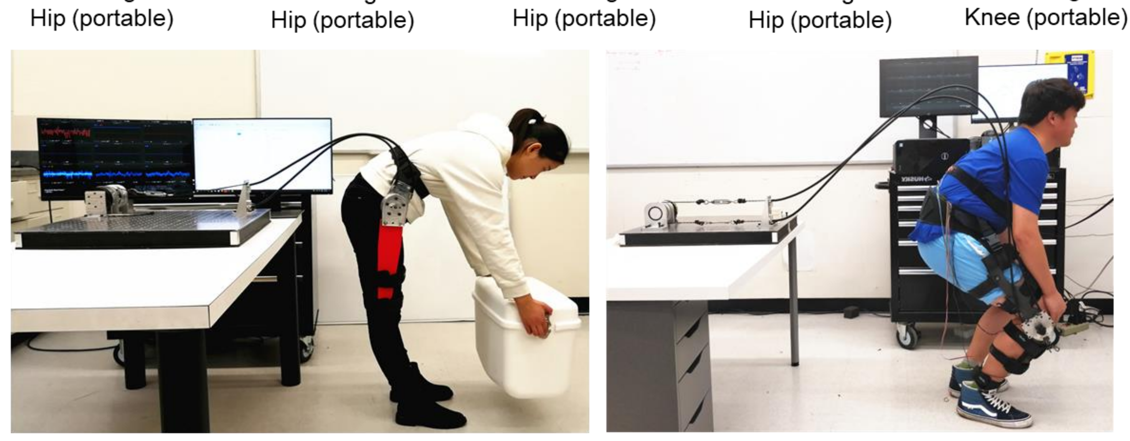
Advantages of Our Soft Exoskeleton



Our Portable and Tethered Soft Exoskeleton Systems



Omni-Hip12, 12 Nm peak torque, 2.3 Kg, Hip (portable)
Omni-Hip18, 18 Nm peak torque, 3.0 Kg, Hip (portable)
Omni-Hip28, 28 Nm peak torque, 3.6 Kg, Hip (portable)
Omni-Hip40, 40 Nm peak torque, 3.8 Kg, Hip (portable)
Omni-Knee18, 18 Nm peak torque, 3.0 Kg, Knee (portable)

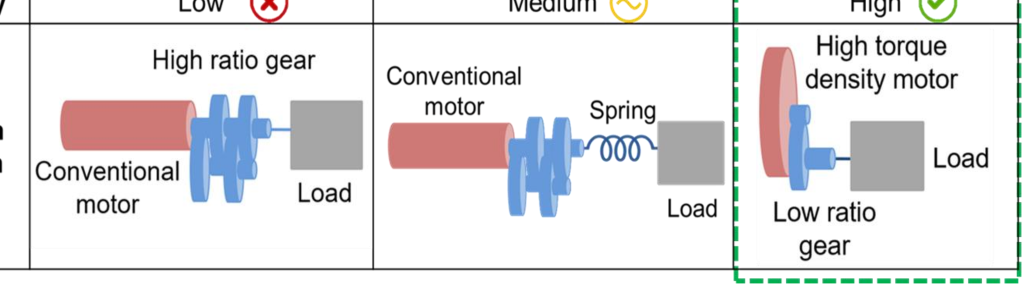


Omni-Hip72, 72 Nm peak torque, Hip (tethered)
Omni-Knee72, 72 Nm peak torque, Knee (tethered)

QDD Actuation Paradigm for Exoskeleton

New Actuation Paradigm for Co-Robots

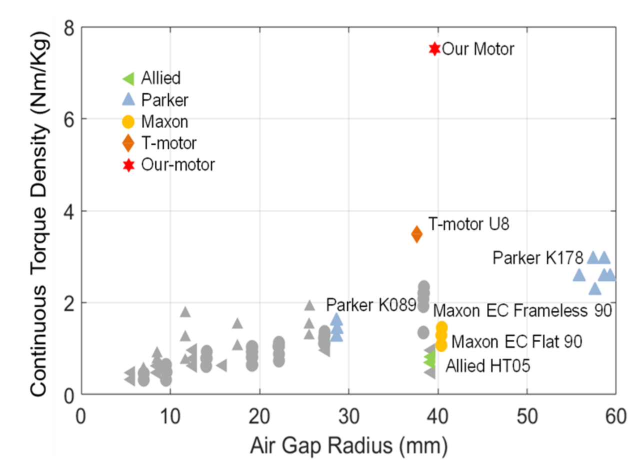
	Geared Motor with Force/Torque Sensor	Series Elastic Actuator	Quasi Direct Drive Actuator [Ours]
Compliance	Low ✗	Medium ~	High ✓
Bandwidth	High ✓	Low ✗	High ✓
Efficiency	Low ✗	Medium ~	High ✓
Actuation Paradigm	High ratio gear; Conventional motor; Load	Conventional motor; Spring; Load	High torque density motor; Low ratio gear; Load



Motor Torque Density Comparison

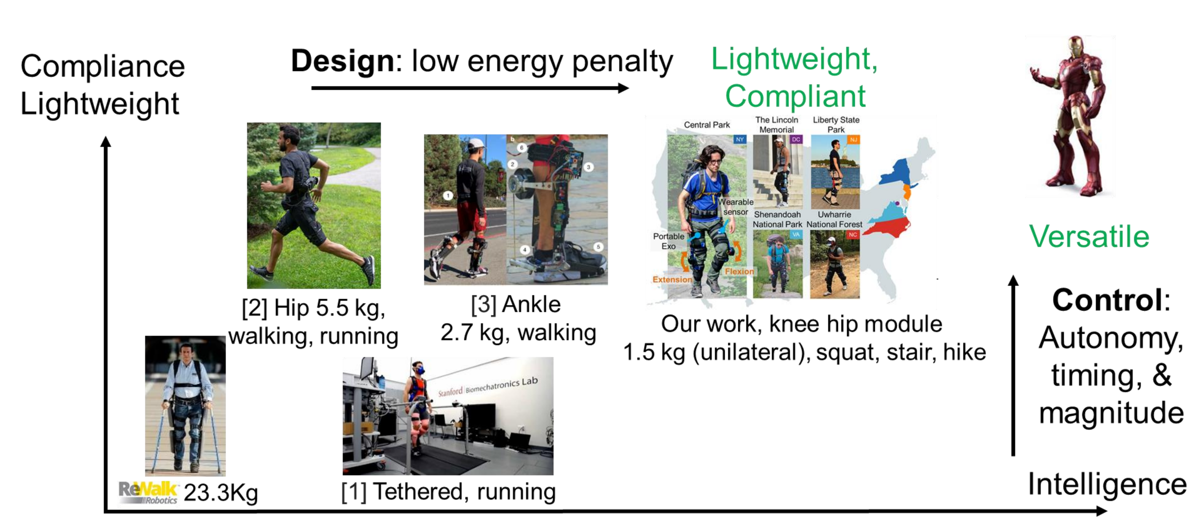
Our custom-designed motors have **high torque density**

Property	Our motor	EC-90 Flat
Motors:		
Mass(g):	244	648
Nominal Power(W):	314	107
Nominal Voltage(V):	42	48
Nominal Current(A):	7.47	2.12
Nominal Torque(Nm):	2	0.5
Nominal Speed(RPM):	1500	2080
Nominal Speed(rad/s):	157	217
Power Density(W/Kg):	1145	165
Torque Density (Nm/Kg):	7.29	0.76



Specific continuous torque $= \frac{Continuous\ torque}{Mass}$

Lightweight, Compliant, and Smart Exoskeletons

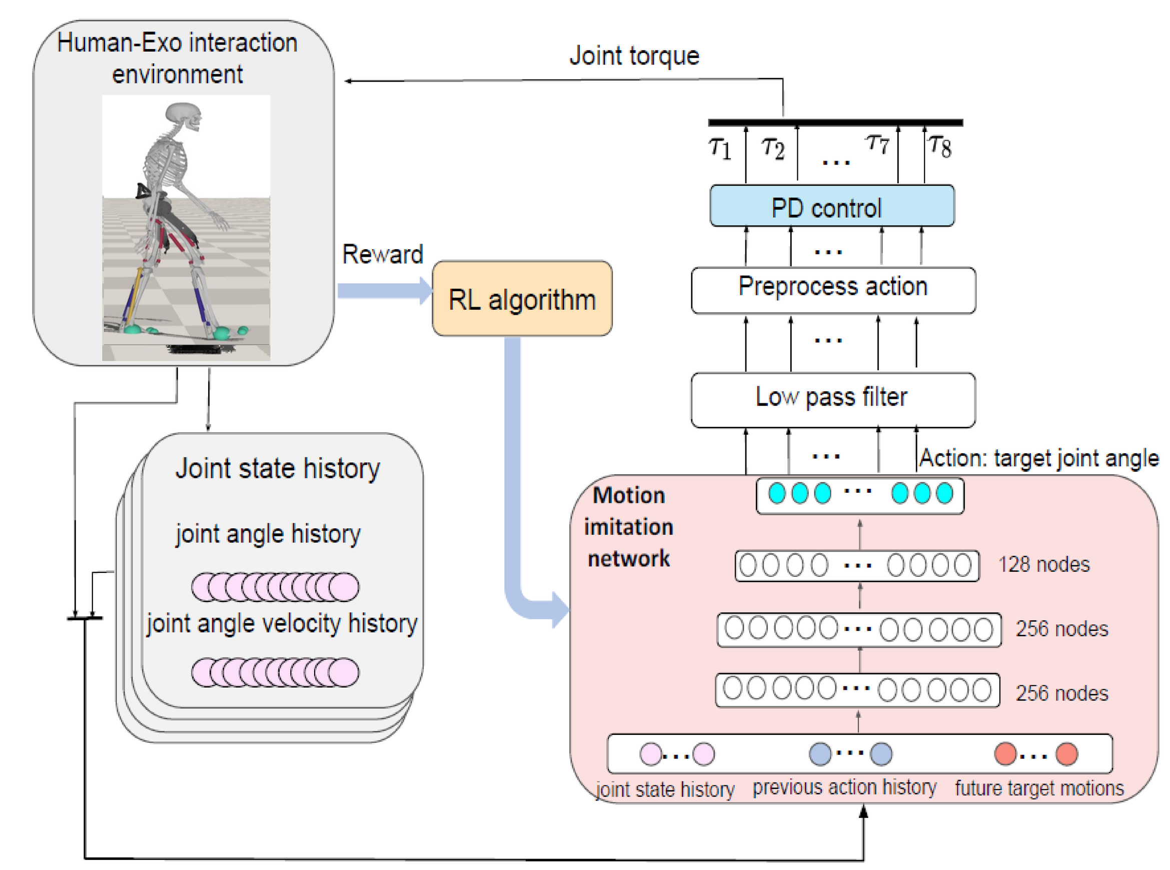


Physics-informed and data-driven Musculoskeletal Modeling

- Learning controllers entirely in simulation is still unavailable for researchers working in wearable robotics.
- The key challenges include the difficulty in accurate modeling of human musculoskeletal system and the inextricable coupling between the human and robots
- Our Solution: We modeled musculoskeletal movements and human-robot interaction, while imitating versatile activities via motion imitation network to simulate human response to an exoskeleton during these activities.
- 2 Neural Networks are trained using reinforcement learning paradigm.
  - Motion Imitation Network
  - Muscle Co-ordination Network

Exoskeleton Controller

- Solution 1: Physics-informed and data-driven reinforcement learning
- Solution 2: Simultaneous training of multiple neural networks via closed-loop control

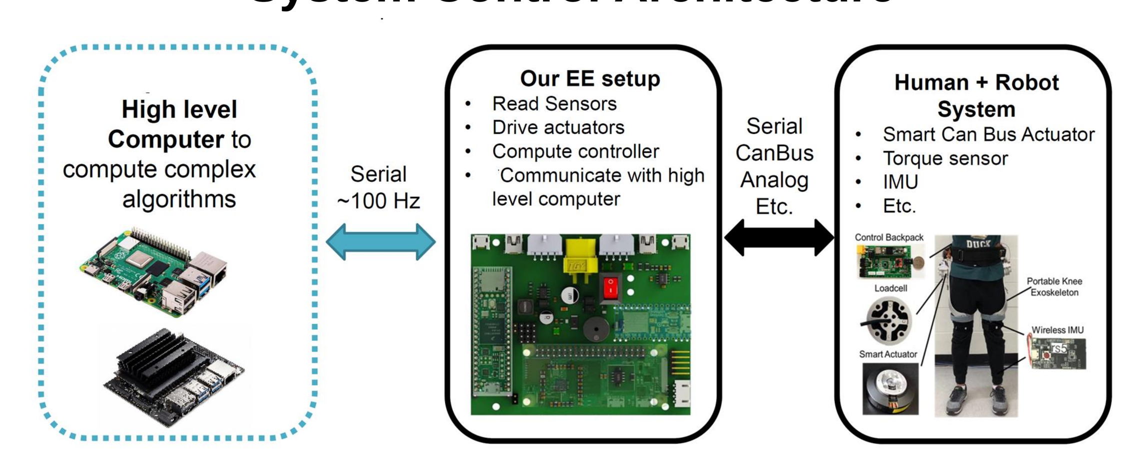


- Proximal Policy Optimization was used to optimize the control policy.
- Dynamics Randomization was used to facilitate Sim-to-Real transfer of the trained control policy.

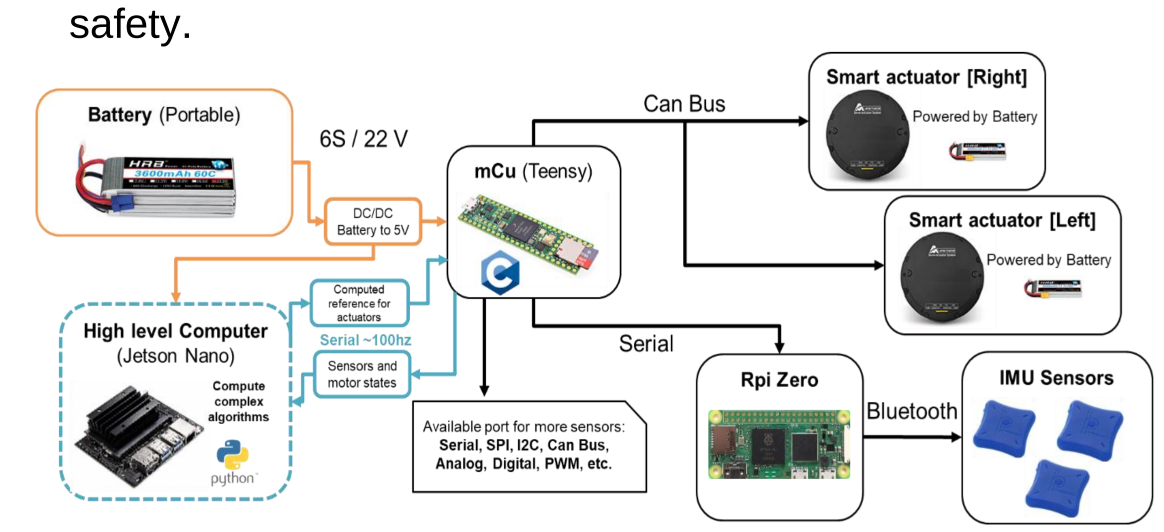
Portable Mechatronics Architecture

- We proposed a powerful electronics architecture using a hierarchical structure with a high-level computer and a low-level microcontroller.

System Control Architecture

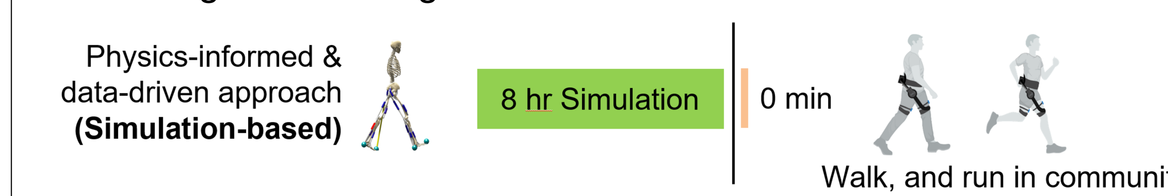


- It computes complex algorithms and improves the accuracy, speed, and efficiency of the exoskeleton's control system,
- leading to better performance, user experience, and safety.

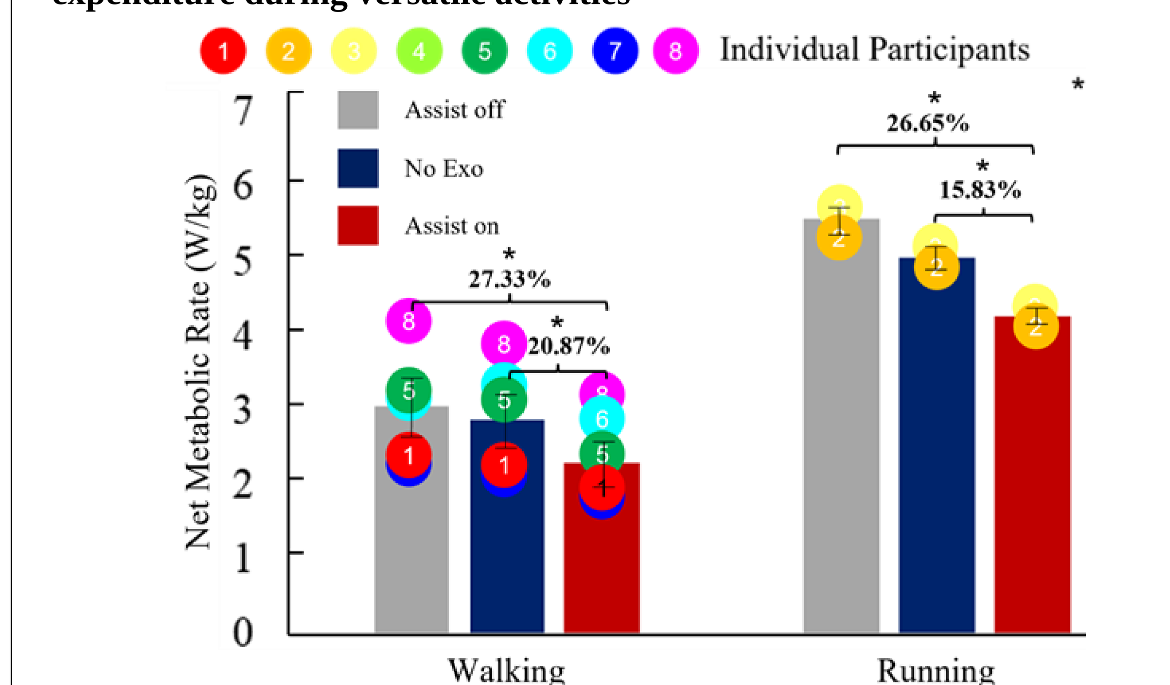


Successful Sim-2-Real Transfer

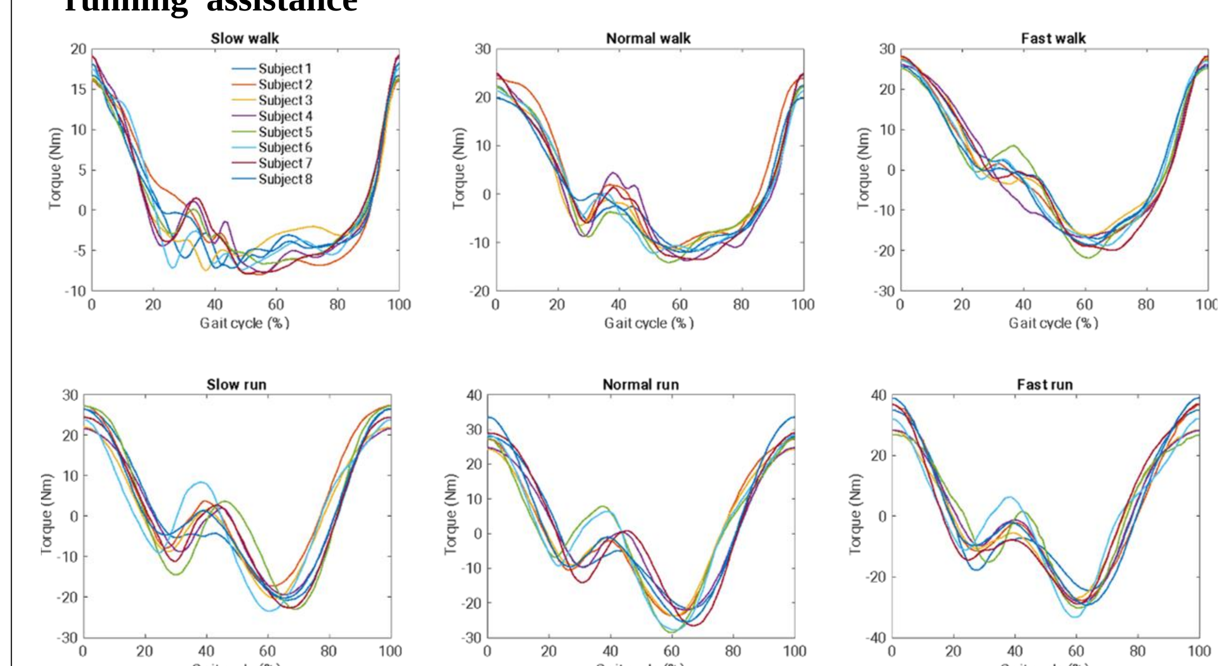
- 8 human subject (5 males, 3 females) experiments utilizing a lightweight, untethered and compliant hip exoskeleton.
- Following figures highlight successful sim-2-real transfer on physical hardware to assist during versatile activities such as walking and running.



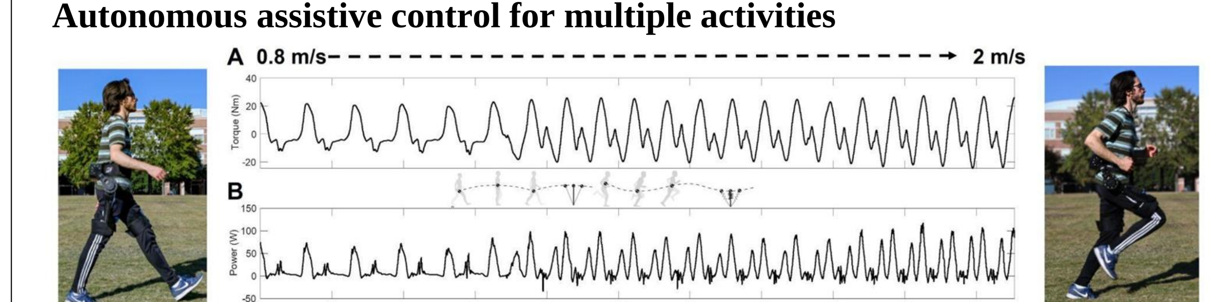
Effective real-time assistance via significant reduction in energy expenditure during versatile activities



Automatically learning effective torque profile for versatile walking and running assistance



Autonomous assistive control for multiple activities



Publications

[1] Luo, Shuzhen, et al. "Robust Walking Control of a Lower Limb Rehabilitation Exoskeleton Coupled with a Musculoskeletal Model via Deep Reinforcement Learning." *Journal of neuroengineering and rehabilitation* (2023).
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[6] Huang, Zhang, Yu, MacLean, Zhu, Di Lallo, Jiao, Bulea, Zheng, & Su, Modeling and Stiffness-based Continuous Torque Control of Lightweight Quasi-Direct-Drive Knee Exoskeletons for Versatile Walking Assistance, *IEEE Transactions on Robotics*, 2022