# Learning in Simulation for Exoskeleton-Assisted Versatile Walking in Community Settings

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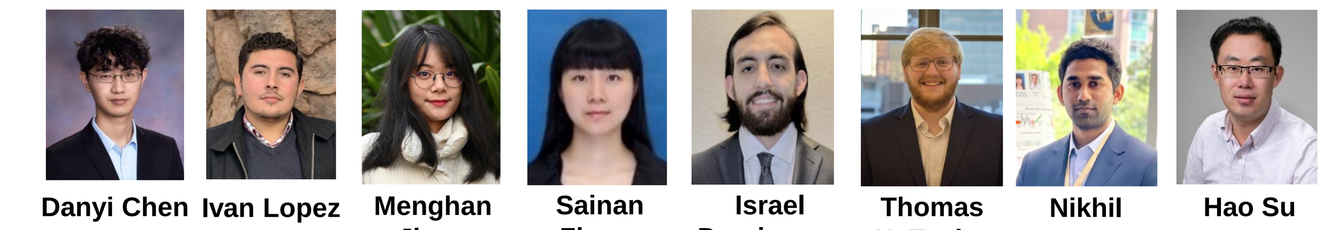
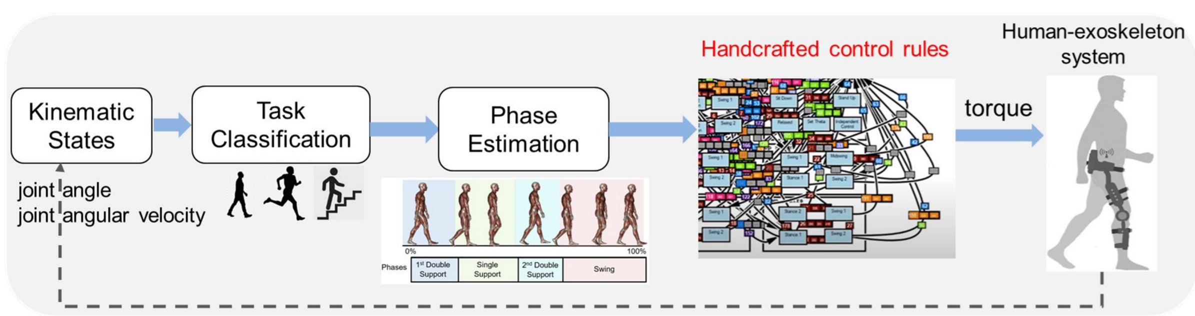


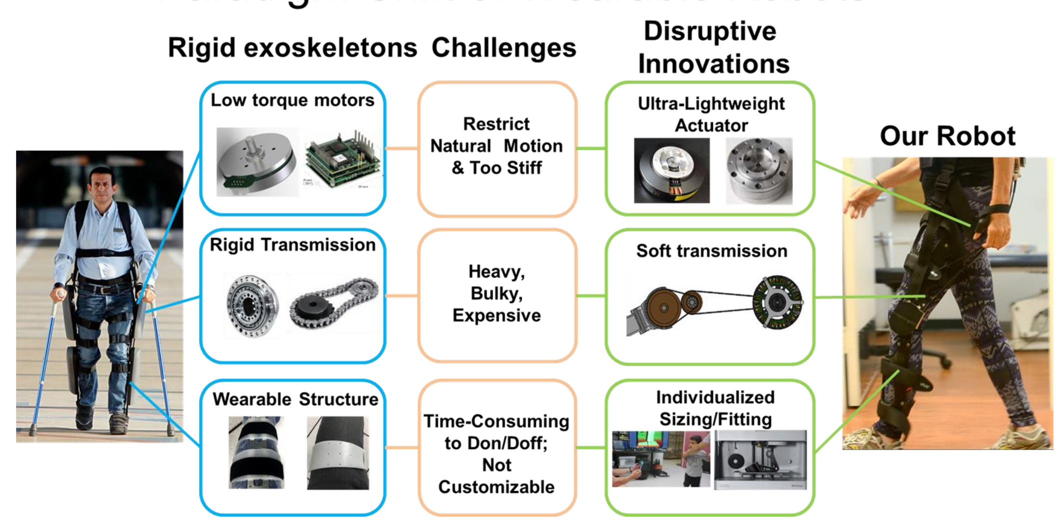

## Objectives and Challenges

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

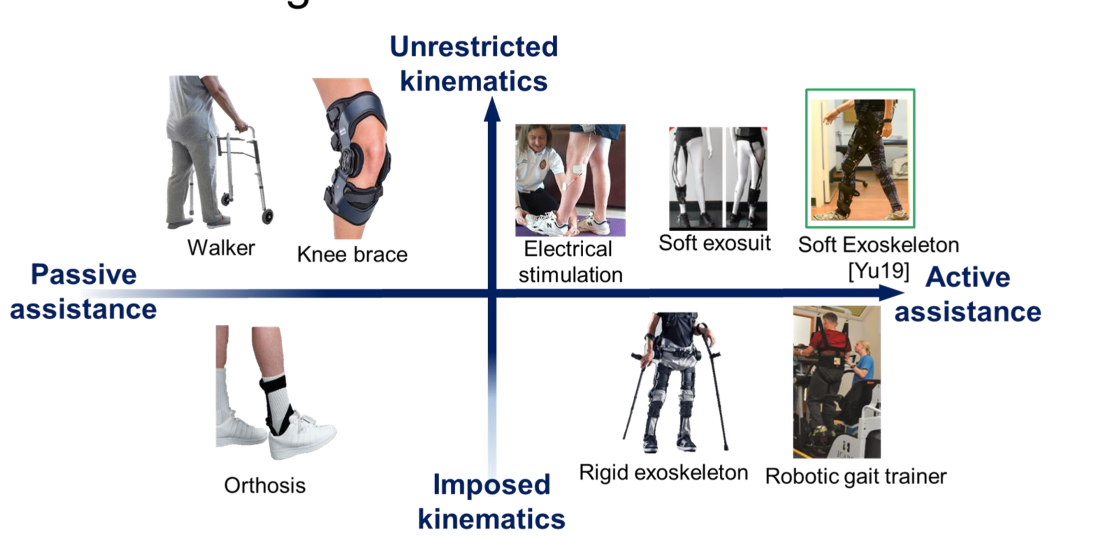



## Our Lightweight and High Torque Soft Exoskeleton

### Paradigm Shift of Wearable Robots




### Advantages of Our Soft Exoskeleton




## Our Portable and Tethered Soft Exoskeleton Systems

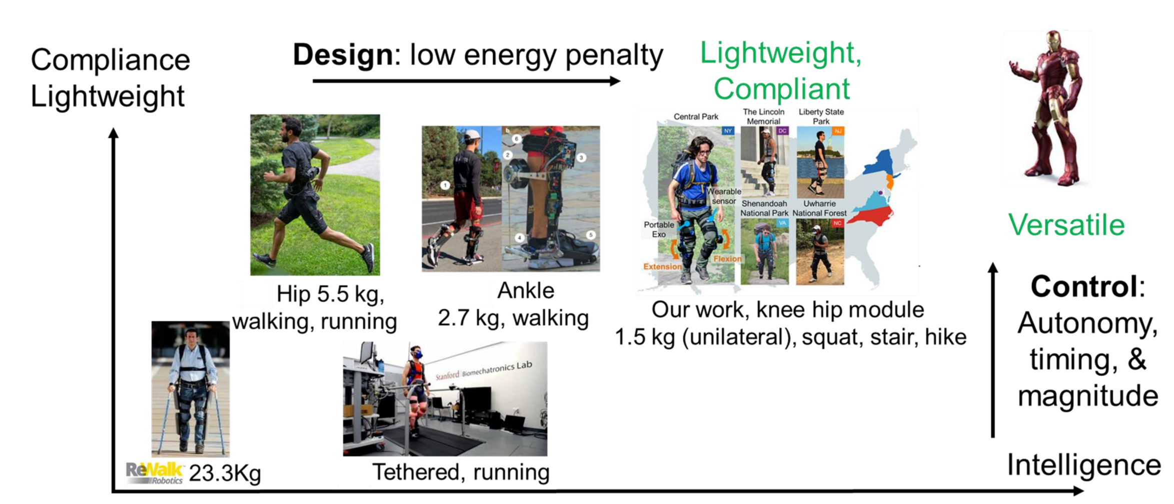
Omni-Hip12: 12 Nm peak torque, 2.3 Kg, Hip (portable)
Omni-Hip18: 18 Nm peak torque, 3.0 Kg, Hip (portable)
Omni-Hip28: 28 Nm peak torque, 3.6 Kg, Hip (portable)
Omni-Hip40: 40 Nm peak torque, 3.8 Kg, Hip (portable)
Omni-Knee18: 18 Nm peak torque, 3.0 Kg, Knee (portable)
Omni-Hip72: 72 Nm peak torque, Hip (tethered)
Omni-Knee72: 72 Nm peak torque, Knee (tethered)

## QDD Actuation Paradigm for Exoskeleton

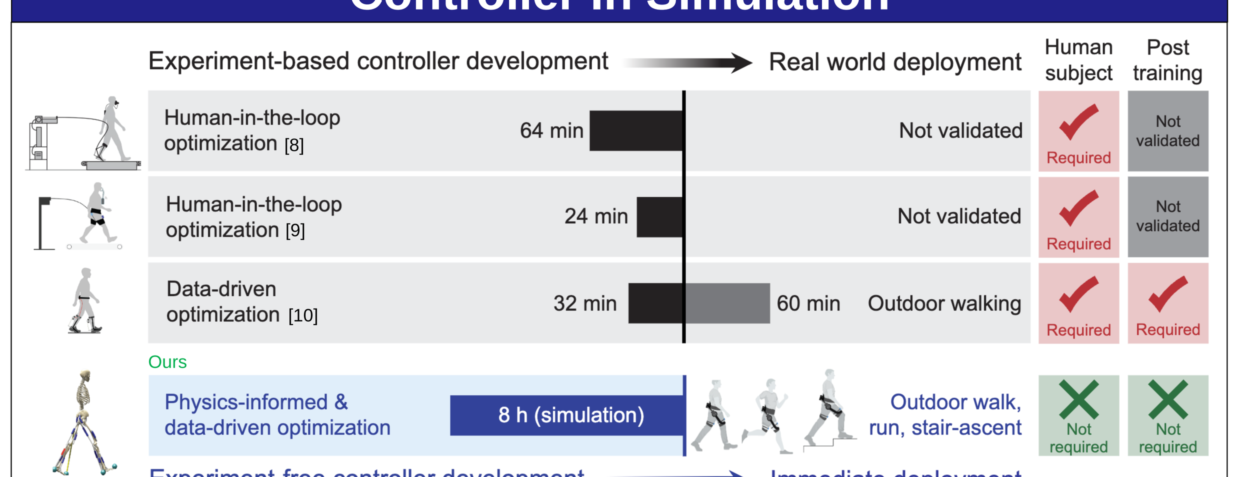
### New Actuation Paradigm for Co-Robots

| | Geared Motor with Force/Torque Sensor | Series Elastic Actuator | Quasi Direct Drive Actuator [Ours][7] |
|---|---|---|---|
| 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 |

## Lightweight, Compliant, and Smart Exoskeletons

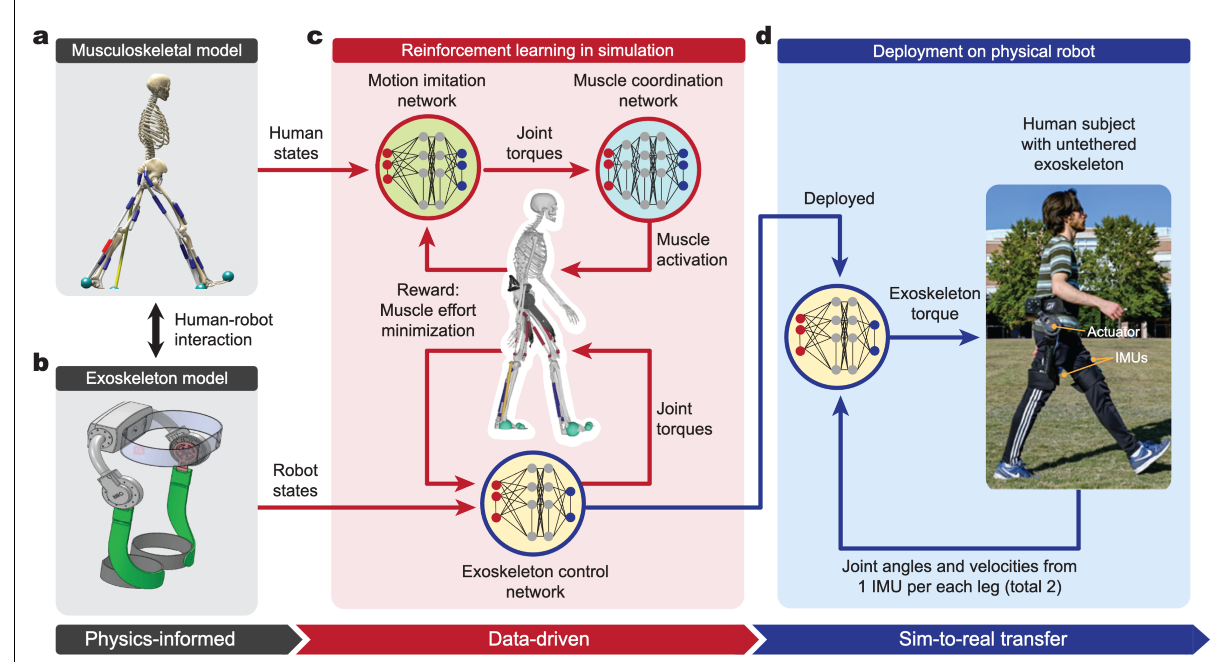



## Experiment-free Learning of Exoskeleton Controller In Simulation




- Drawbacks of state-of-the-art methods to get exoskeleton controllers:
  - Requires intensive human experiments for training → This adds formidable cost when applied to another activity or participant
  - Typically for a single activity with steady-state motion → It cannot handle versatile activities or transitions between different activities
- Learning controllers entirely in simulation eliminates the need for human experiments. However, it is still unavailable for wearable robotics community. Key challenges are:
  - Incorporating controller design in the simulation
  - Incorporating human-robot interaction in the simulation
- Our Solution:
  - Eliminates the need for human experiments, learns the exoskeleton controller purely from simulation, and provides immediate energetic benefit to humans
  - Provides synergistic assistance to different subjects for walking, running and stair-climbing

## Physics-informed And Data-driven Reinforcement Learning

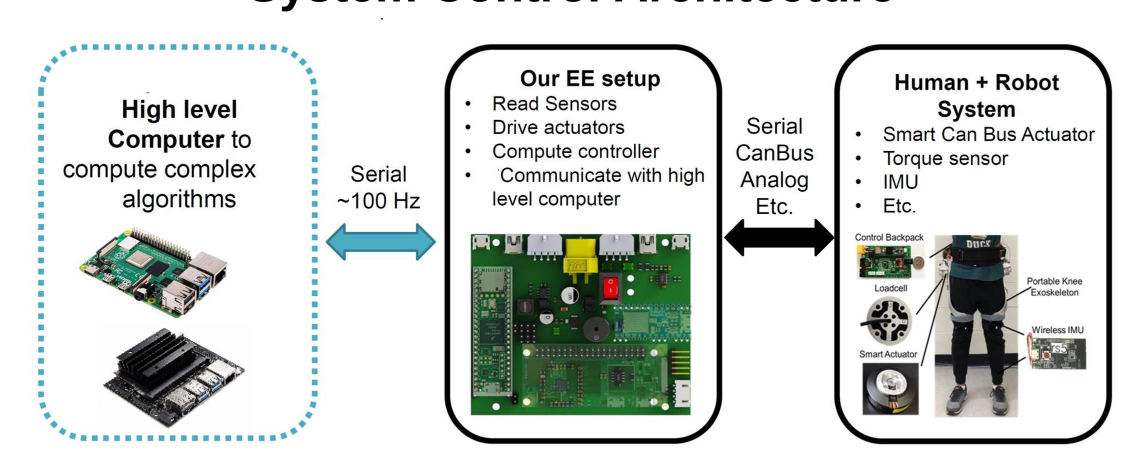



- Our learning method incorporates both physics-informed modeling and data-driven learning:
  - Physics-informed modeling of human musculoskeletal dynamics, exoskeleton, and human-robot interaction
  - Data-driven learning through publicly available human kinematic motion capture dataset
- Our learning method consists of three neural networks that are trained simultaneously for co-evolution:
  - Motion imitation network
  - Muscle coordination network
  - Exoskeleton control network
- Dynamics randomization was used to facilitate Sim-to-real transfer of the trained control policy

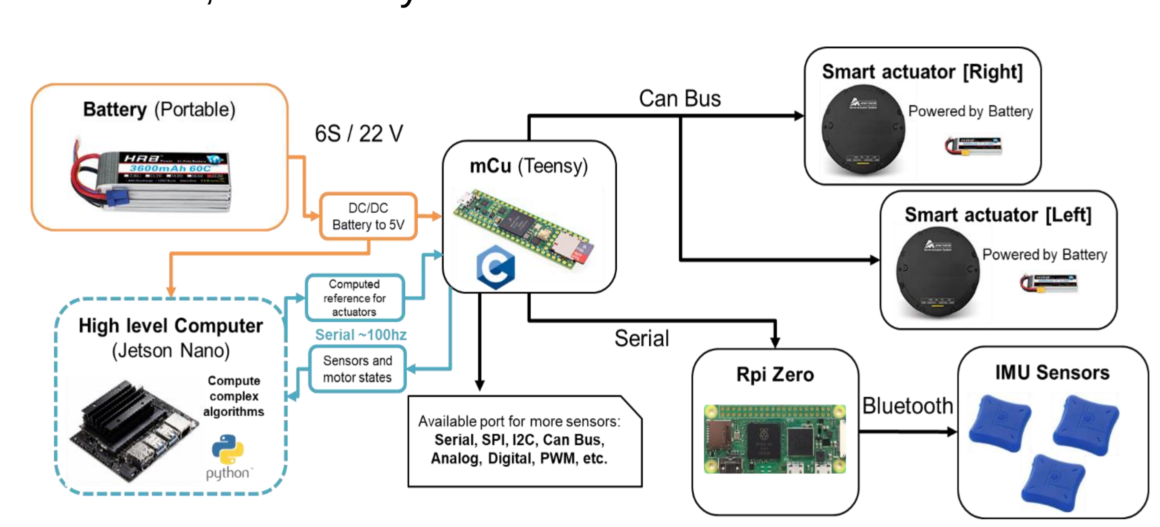
## Portable Mechatronics Architecture

- Powerful electronics architecture using a hierarchical structure with a high-level computer and a low-level microcontroller

### System Control Architecture

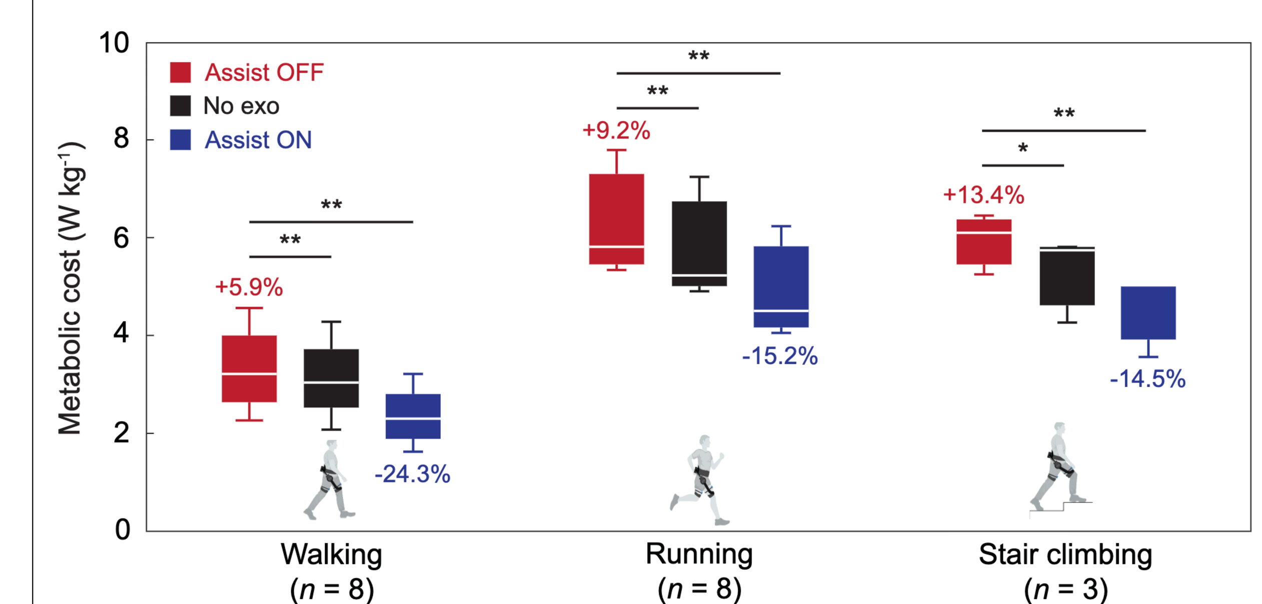



- Able to run complex control algorithms and improve the accuracy, speed, and efficiency of the exoskeleton's control system, leading to better performance, user comfort, and safety



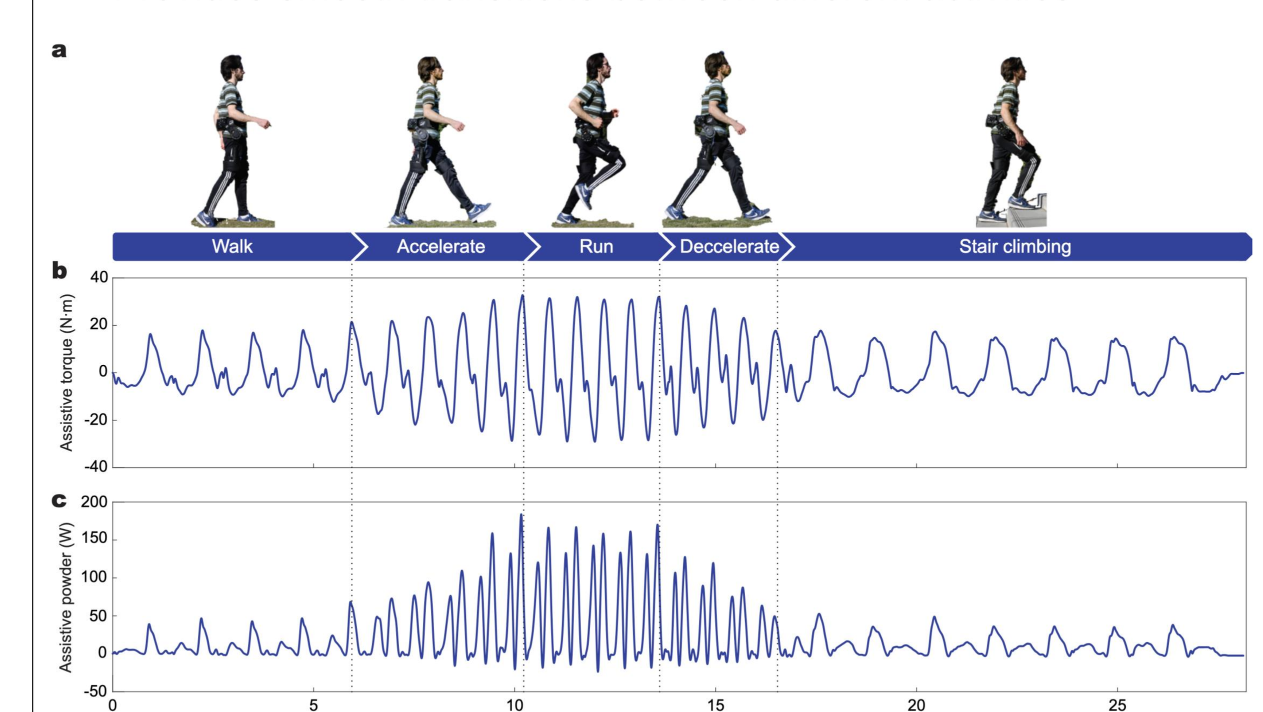

## Significant Energetic Cost Reductions on Versatile Activities

- 8 human subject (5 males, 3 females) experiments utilizing a lightweight, untethered and compliant hip exoskeleton
- Reduced significant metabolic cost by 24.3% for walking, 15.2% for running, and 14.5% for stair climbing




- More metabolic cost reduction than state-of-the-art robots


- Provides smooth transitions between different activities




## References

[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).
[2] Luo S, Androwis G, Adamovich S, Su H, Nunez E, Zhou X. Reinforcement Learning and Control of a Lower Extremity Exoskeleton for Squat Assistance. *Front Robot AI*. 2021;8:702845.
[3] Yang, Huang, Hu, Yu, Zhang, Carriero, Yue, Su. Spine-Inspired Continuum Soft Exoskeleton for Stoop Lifting Assistance. *IEEE Robotics and Automation Letters*, 2019
[4] Yu, Huang, Lynn, Sayd, Silivanov, Park, Tian, Su. Design and Control of a High-Torque and Highly-Backdrivable Hybrid Soft Exoskeleton for Knee Injury Prevention during Squatting. *IEEE Robotics and Automation Letters*, 2019
[5] Yu, Huang, Yang, Jiao, Yang, Chen, Yi, Su. Quasi-direct drive actuation for a lightweight hip exoskeleton with high backdrivability and high bandwidth. *IEEE Transactions on Mechatronics*, 2020. **(Best student paper award)**
[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
[7] Zhu, Jiao, Dominguez, Yu and Su, "Design and Backdrivability Modeling of a Portable High Torque Robotic Knee Prosthesis With Intrinsic Compliance for Agile Activities," in IEEE/ASME Transactions on Mechatronics, vol. 27, no. 4, pp. 1837-1845, Aug. 2022 **(2022 Best Paper in Mechatronics Award)**
[8] Awad, Bae, O'donnell, De Rossi, Hendron, Sloot, Kudzia, Allen, Holt, Ellis and Walsh. A soft robotic exosuit improves walking in patients after stroke. *Science Translational Medicine*, 9(400), p.eaai9084 (2017).
[9] Veneman et al. Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 15, 379-386 (2007).
[10] Slade, Kochenderfer, Delp and Collins. Personalizing exoskeleton assistance while walking in the real world. *Nature* 610, 277-282 (2022).