Soft Wearable Robots for Injury Prevention and Performance Augmentation

Israel Dominguez[1], Shuangyue Yu[1], Sainan Zhang[1], Junxi Zhu[1], and Hao Su[1]

[1]Biomechatronics Lab of Biomechatronics and Intelligent Robotics, Department of Mechanical and Aerospace Engineering, North Carolina State University and Joint NCSU/UNC Department of Biomedical Engineering, North Carolina State University, Raleigh, NC, 27695; University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA.

*Corresponding author. Email: hsu4@ncsu.edu

NC STATE UNIVERSITY

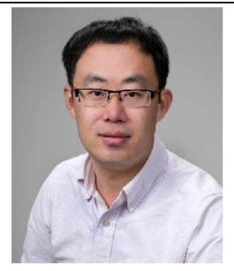
Joint Department of BIOMEDICAL ENGINEERING

UNC CHAPEL HILL · NC STATE UNIVERSITY

NSF

NIH National Institutes of Health

This work is in part supported by NIH under Grant R01EB029765, in part under National Science Foundation Future of Work under Grant 2026622



Hao Su (PI)

Israel Dominguez · Shuangyue Yu · Sainan Zhang · Junxi Zhu

BIRO — Biomechatronics and Intelligent Robotics

Website: http://haosu-robotics.github.io

Email: hsu4@ncsu.edu

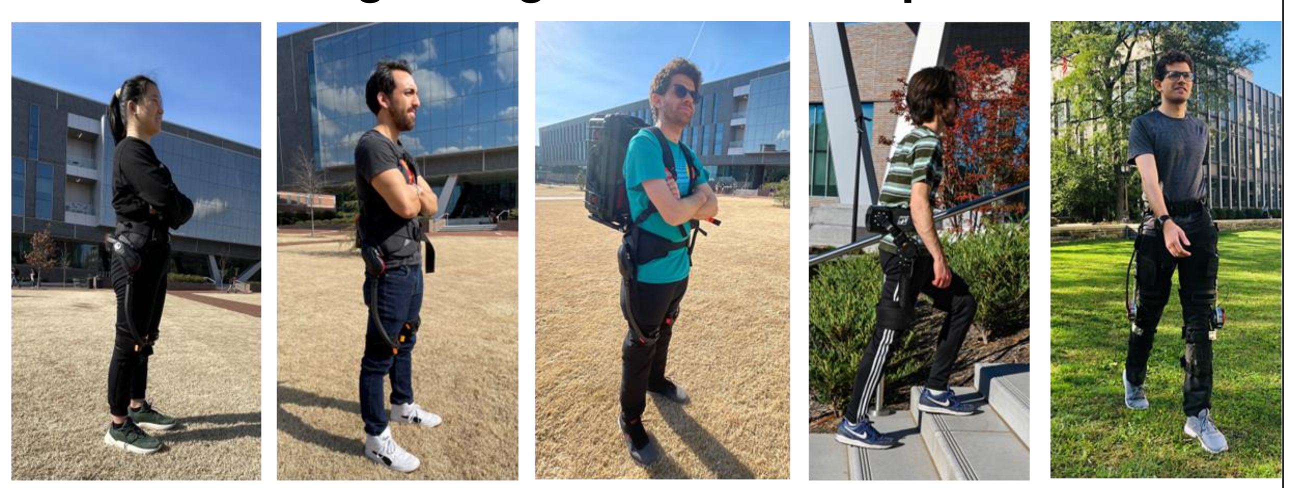
Objectives and Challenges

- More than $15 billion are paid yearly due to physical overexertion of workers
- Exoskeletons have the potential to mitigate injury incidence and augment human capabilities
- They are of high interest to occupational safety and health agencies and compensation insurers
- Current devices suffer from drawbacks: bulkiness, discomfort, and inadaptability to different users

Exoskeleton Systems

- We design exoskeleton systems using the Quasi-Direct Drive actuation paradigm.
- QDD employs a high torque-density motor and a low-gear ratio transmission to provide energy to the joint.
- Enabling high torque density and high bandwidth with low friction and low backlash in a lightweight option.

Portable and Lightweight Knee and Hip Exoskeletons



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)

Tethered High-torque Knee and Hip Exoskeletons

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

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

Published Journals

[1] Yang, Huang, Hu, Yu, Zhang, Carriero, Yue, Su. Spine-Inspired Continuum Soft Exoskeleton for Stoop Lifting Assistance. IEEE Robotics and Automation Letters, 2019

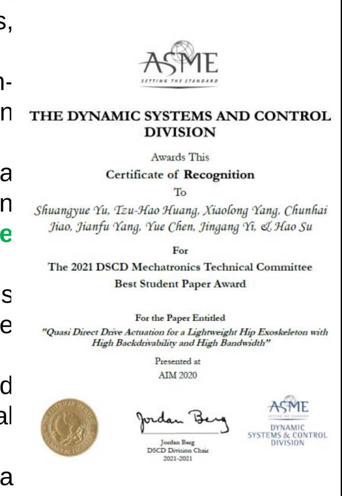
[2] Yu, Huang, Lynn, Sayd, Silivanov, Park, Tian, Su. Design and Control of a High-Torque and Highly-Backdrivable Hybrid Soft Exoskeleton for Knee Injury Prevention during Squatting . IEEE Robotics and Automation Letters (RA-L), 2019

[3] Yu, Huang, Yang, Jiao, Yang, Chen, Yi, Su. Quasi-direct drive actuation for a lightweight hip exoskeleton with high backdrivability and high bandwidth. Trans. on Mechatronics (T-MECH), 2020. **(Best Student Paper in Mechatronics by the ASME Mechatronics TC)**

[4] Huang, Zhang, Yu, MacLean, Di Lallo, Bulea, Su, Modeling and Continuous Stiffness Torque Control of Quasi-Direct-Drive Knee Exoskeletons for Versatile Walking Assistance, Trans. on Robotics (T-RO), 2022 (conditionally accepted)

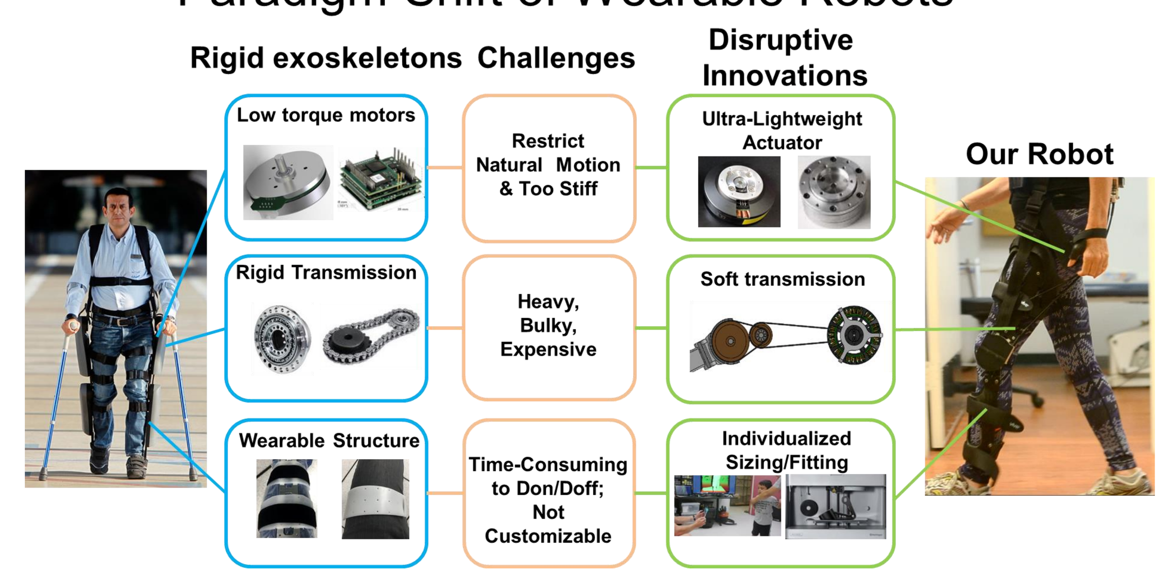
[5] Yu, Huang, and Su. Artificial Neural Network-Based Activities Classification and Gait Phase Prediction: Application for Exoskeleton Control, Annals of Biomedical Engineering (ABME), 2022. (in review)

[6] Yu, Huang, Zhang, Di Lallo, Fu, Su. Bio-Inspired Design and Torque Control of a Cable-Driven Knee Exoskeleton with High-Torque Actuators, Bioinspiration & Biomimetics. (in review)



Soft Exoskeleton Innovations

Paradigm Shift of Wearable Robots



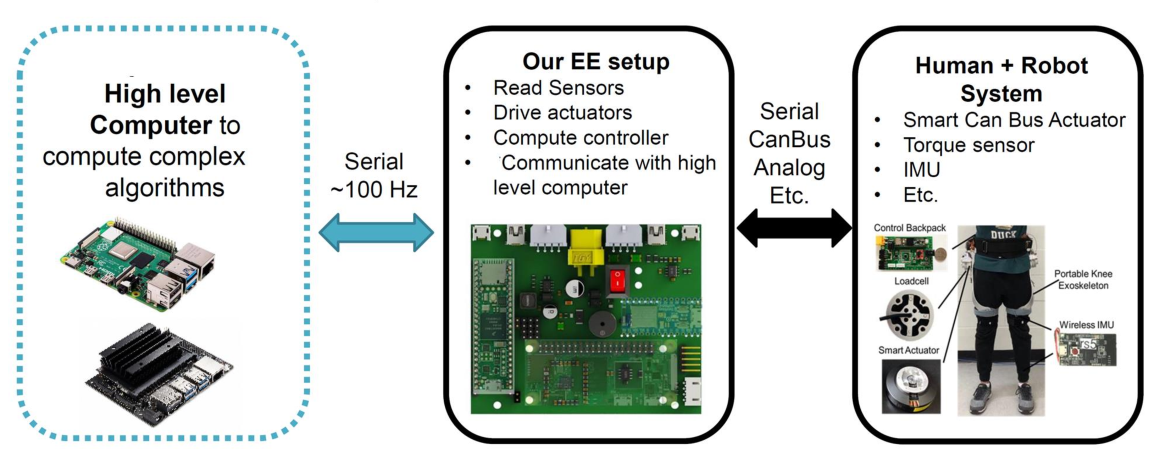
New Actuation Paradigm for Co-Robots

	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

Portable and Expandable Electronics Architecture

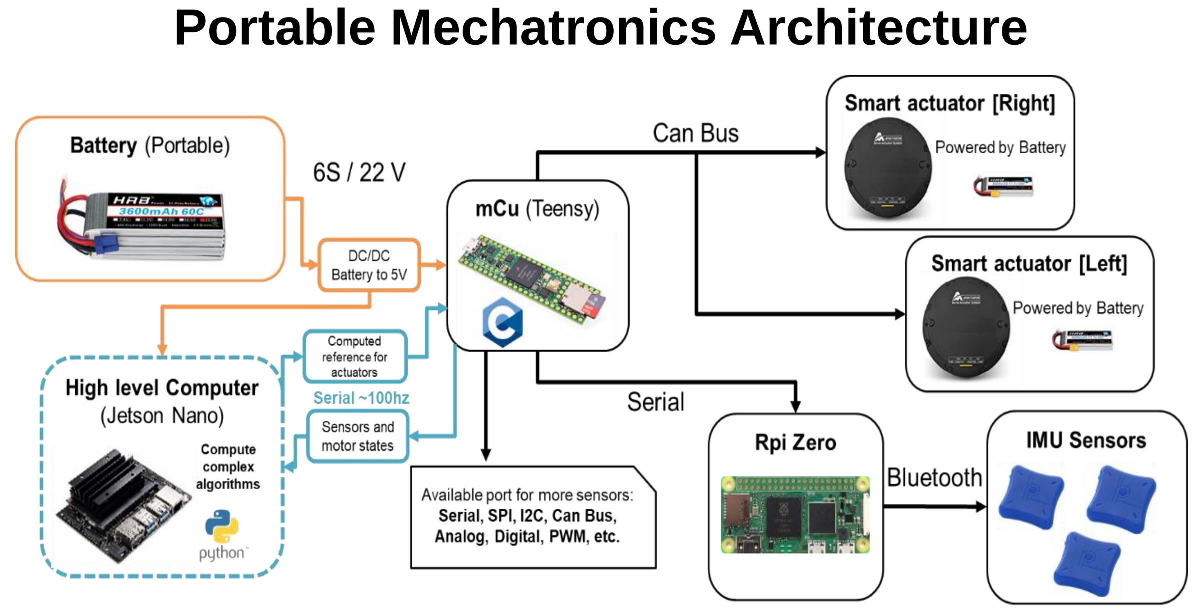
- We proposed a powerful electronics architecture using a hierarchical structure with a high-level computer and a low-level microcontroller.

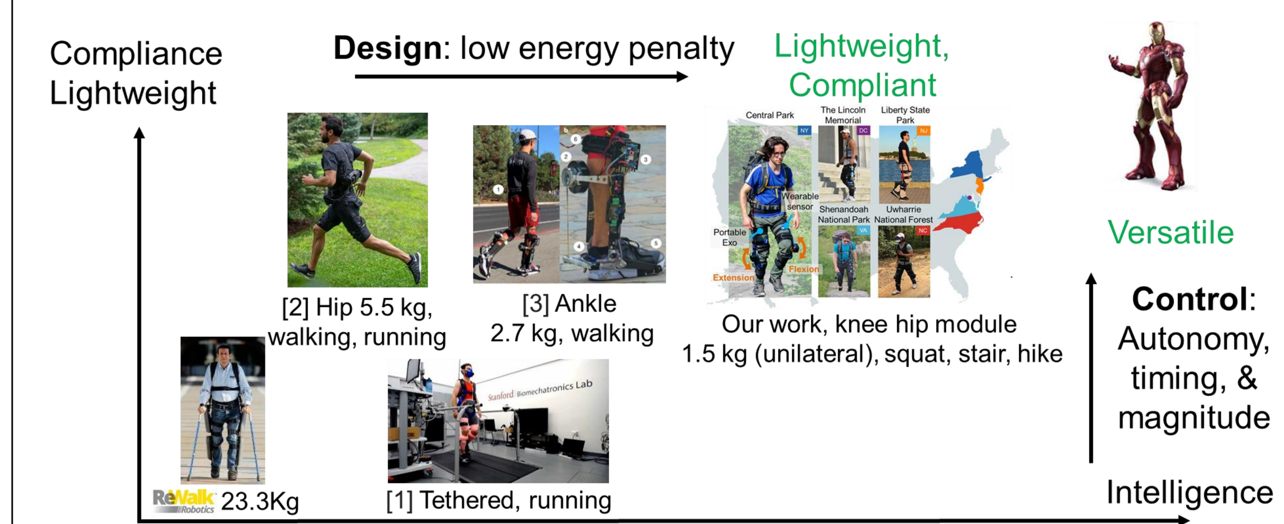
System Control Architecture



- 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.

Portable Mechatronics Architecture

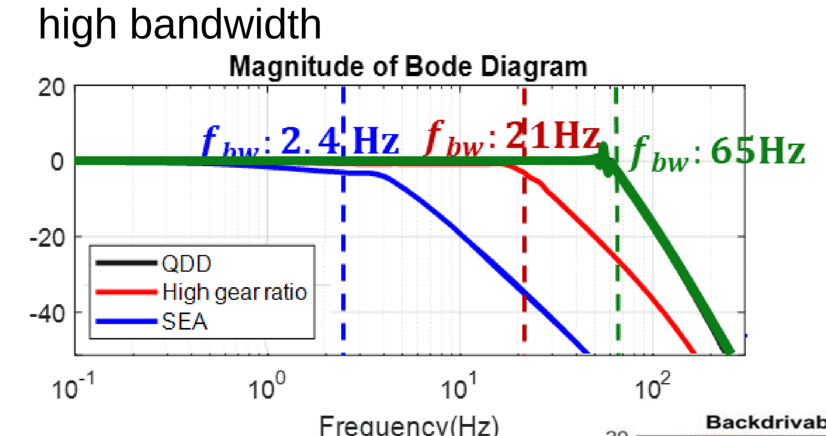




Quasi-Direct Drive for Exoskeletons

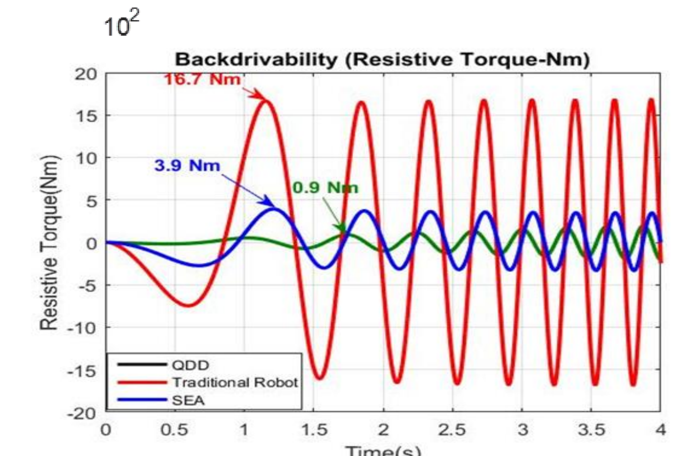
Quasi-Direct Drive Enables High Compliance/Bandwidth

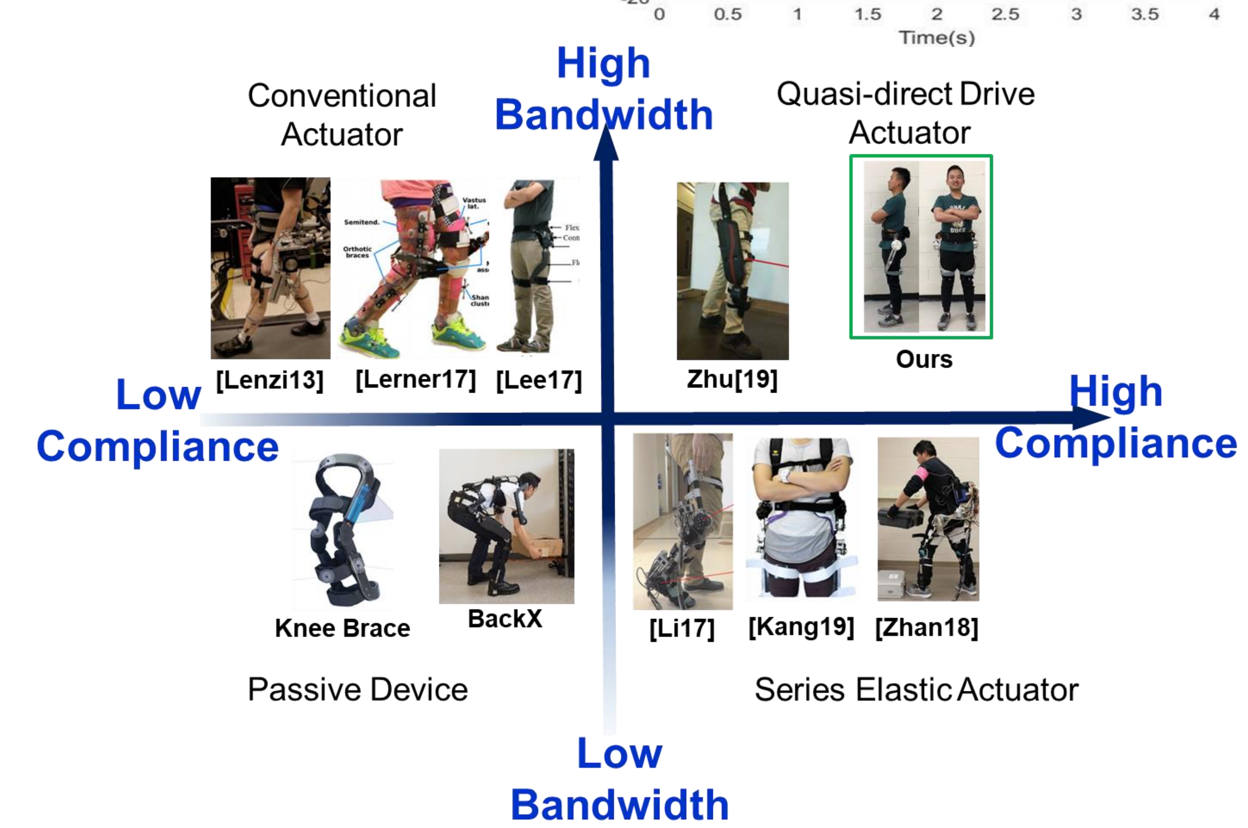
Our actuator has small resistive torque (high compliance) and high bandwidth



High Bandwidth

High Compliance





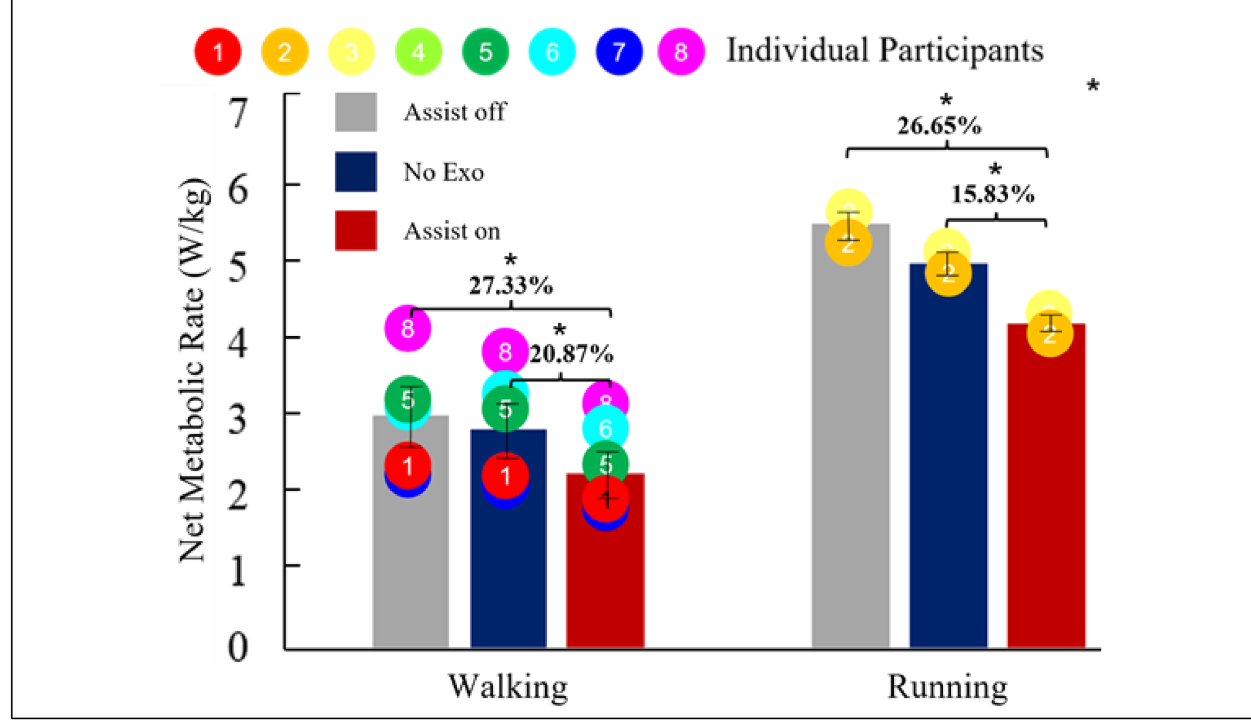
Acknowledgments

The authors would like to acknowledge the Biomechatronics and Intelligent Robotics Lab at NC State University for providing the equipment and resources to support this project. We would also like to acknowledge Dr. Hao Su for mentoring this project, as well as lab members Shuangyue Yu, Antonio Di Lallo, Saurav Kumar, Sunil Rajendran, Shuzhen Luo, Junxi Zhu, Menghan Jiang, Chinmay Swami, Nikhil Kantu, Jason Huang, and Alexis Ayala for their support and mentorship of the authors.

Metabolic Reduction Results

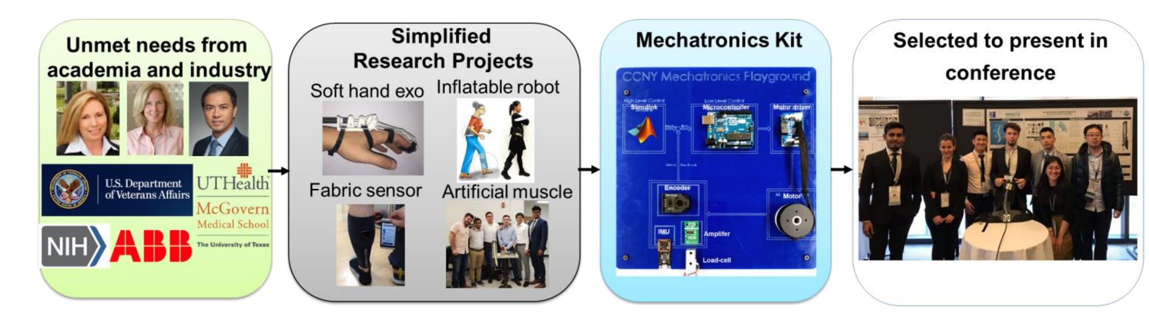
- The study involved 8 participants, comprising of five 5 and three 3, who used our lightweight, untethered, and compliant hip exoskeleton.
- The study aimed to demonstrate that our exoskeleton design is effective for metabolic reduction during walking and running.

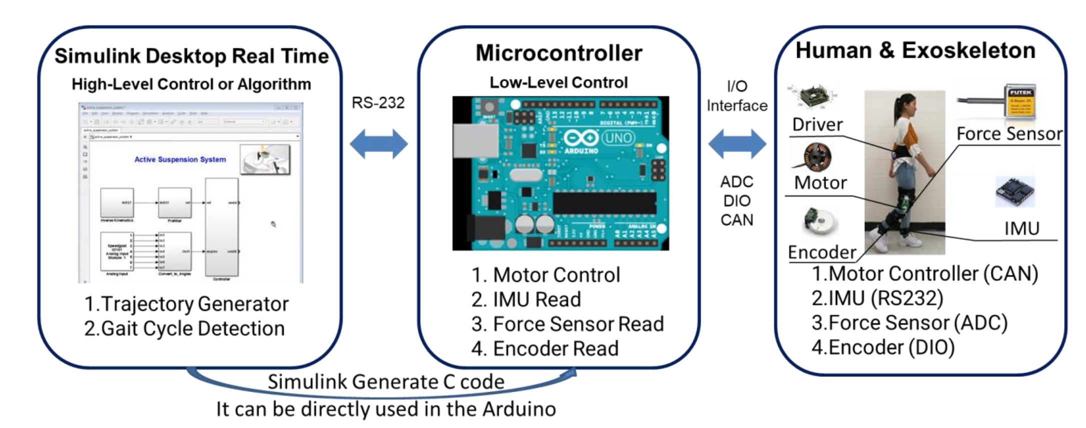
Providing efficient assistance in real-time while minimizing energy consumption across a variety of tasks.



Lowering Barriers To Learn Robotics

- Advanced Mechatronics Education





- International conferences (2 awards) + 18 undergrad student projects

1. Salmeron, Juca, Mahadeo, Yu, and **Su**, International Conference of Wearable Robotics Association (WearRAcon), 2020 (2nd prize, Innovation Challenge)
2. Salmeron, Juca, Ma, Yu, **Su**, "Untethered Electro-Pneumatic Exosuit for Gait Assistance of People with Foot Drop", Design of Medical Devices Conferences, 2020 (2nd prize, Three-in-Five Competition)
3. Yuen, Nogacz, Chi, Ferdousi, Yu, **Su**, "Oxeous Back-Support Exoskeleton: Soft, Active Suit to Reduce Spinal Loading", Design of Medical Devices Conferences, 2019.
4. Yu, Perez, Barkas, Mohamed, Eldaly, **Su**, "Soft High Force Hand Exoskeleton for Assistance of Stroke Individuals," Design of Medical Devices Conferences, 2019
5. Yang, Huang, Yu, Su, Spungen, Tsai, "Machine Learning Based Adaptive Gait Phase Estimation Using IMU Sensors," Design of Medical Devices Conferences, 2019

Cable Drive Exo-Glove · Jumping Robotic Leg · Soft Submersible Inspection Robot

Pneumatic Ankle Exoskeleton · High Force Hydraulic Artificial Muscle · Cooling Vest · Soft Human Intention Detection Sensor · Functional Electrical Stimulation Device