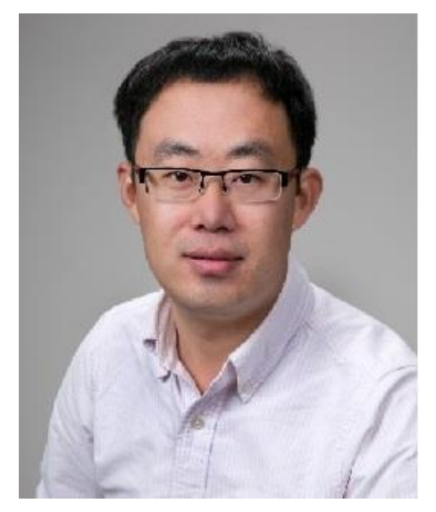

Hao Su
(PI)

Deep-Neural Network Reinforcement Learning-based Robust Control of Lightweight and Compliant Lower-Limb Exoskeletons for Versatile Walking

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BIOMECHATRONICS AND INTELLIGENT ROBOTICS

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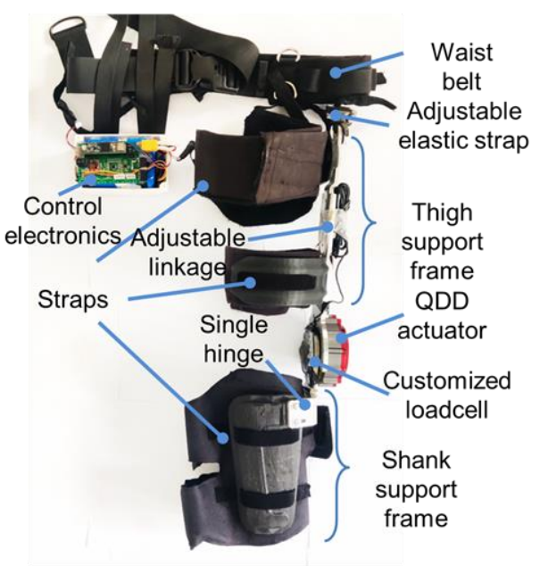
Objectives and Challenges

- Increasing number of people are suffering from neurological disorders, such as stroke, central nervous system disorder, and spinal cord injury (SCI) that affect the patient's mobility
- Wearable robots like lower-limb exoskeletons have great potential for mobility restoration and human augmentation
- Current devices suffer from drawbacks: bulkiness, discomfort
- Their controllers lack robustness to human exoskeleton interaction forces and their control laws vary based on patient-specific conditions.
- Furthermore, majority of the proposed controllers require rigorous heuristic handcrafting of control parameters.

Portable and Tethered Soft Exoskeleton Systems

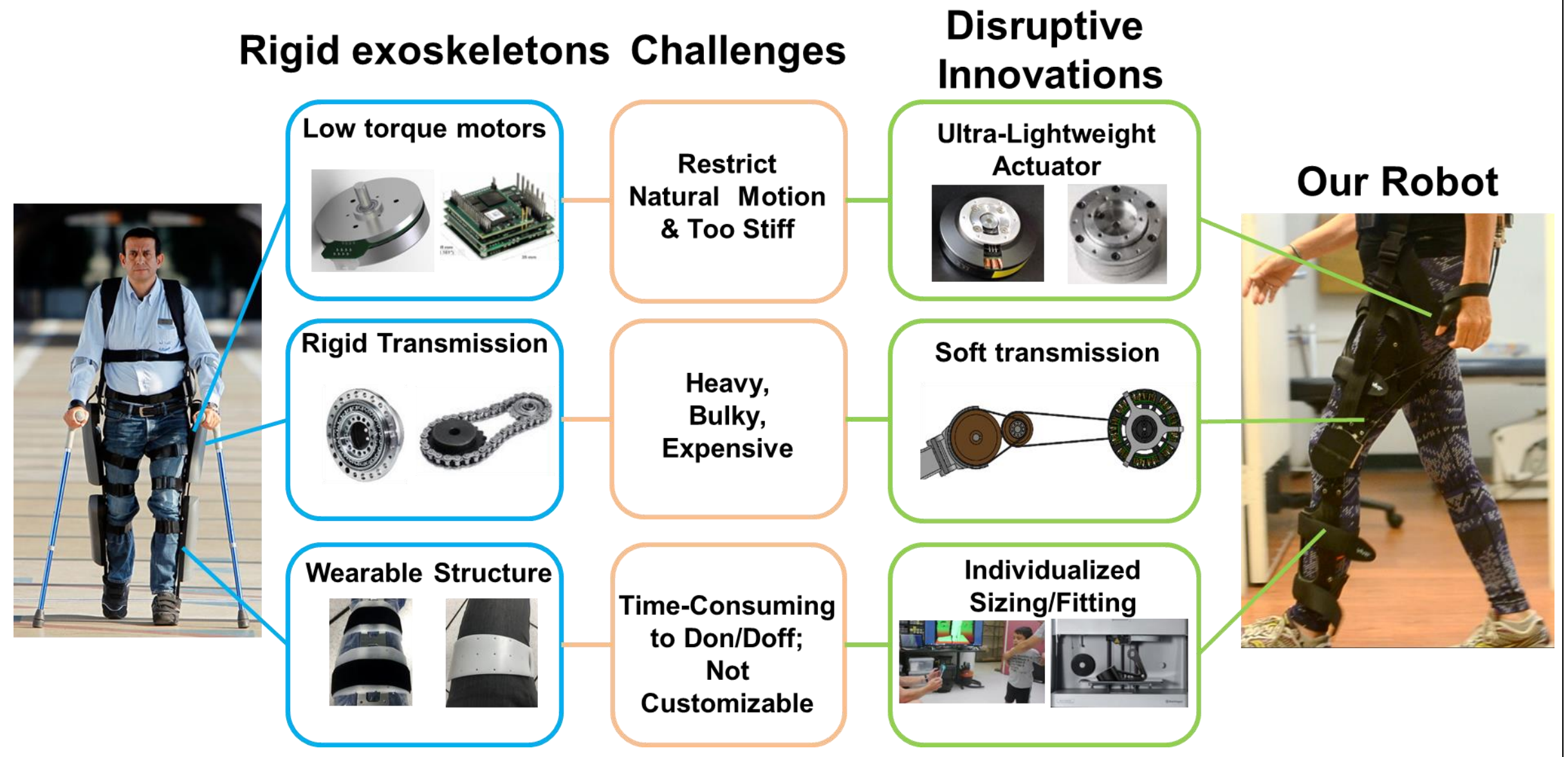
Portable System: high performance, versatile assistance in the field

Specification	
Motor Torque	2.2 Nm
Motor Speed	1500 RPM
Output Torque:	40 Nm
Output Speed:	16.2 rad/s
Range of Motion:	130 degree
Gear Ratio	6:1
Total Weight:	2.4 kg

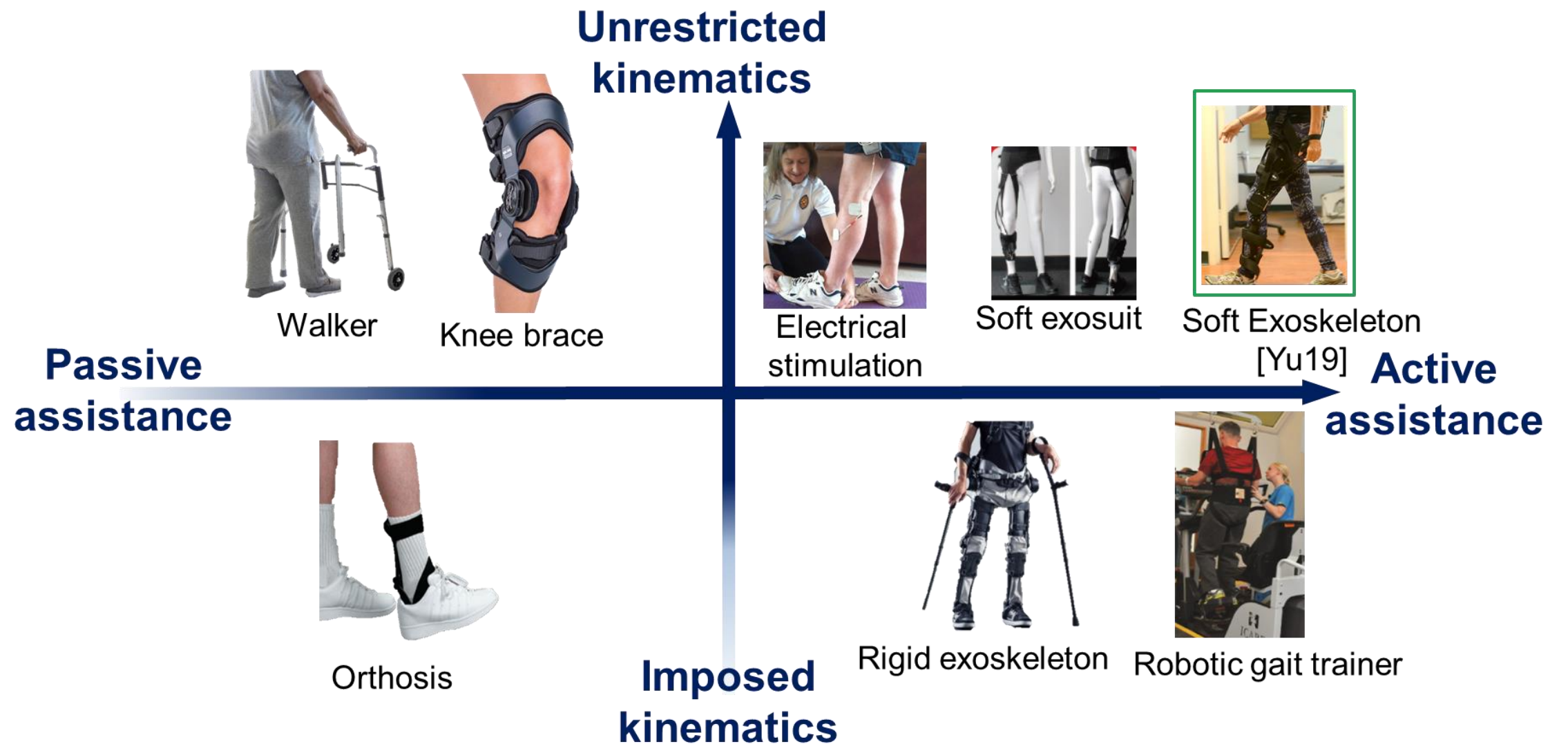


Soft Exoskeleton Innovations

Paradigm Shift of Wearable Robots



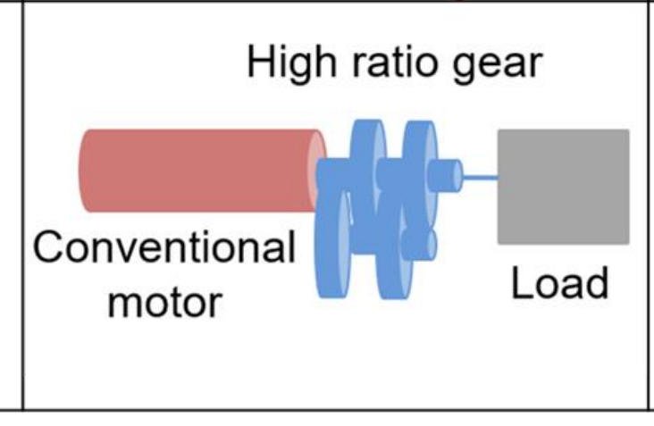
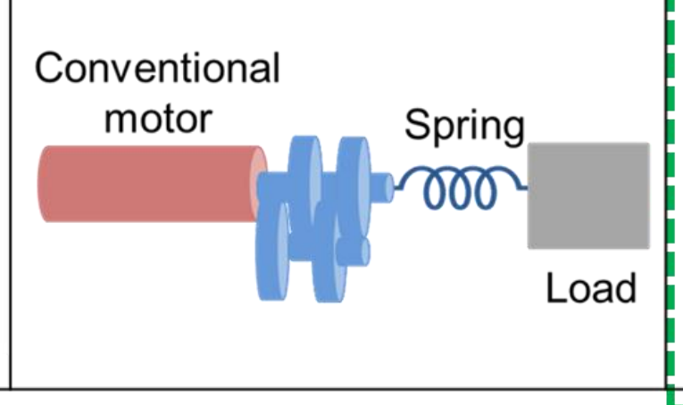
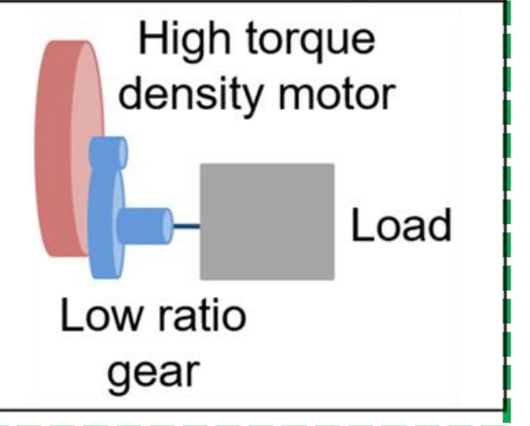
Advantages of Our Soft Exoskeleton



Publications

[1] 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. Published 2021 Jul 19.
[2] Yang, Huang, Hu, Yu, Zhang, Carriero, Yue, Su. Spine-Inspired Continuum Soft Exoskeleton for Stoop Lifting Assistance. *IEEE Robotics and Automation Letters*, 2019
[3] 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
[4] 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)**
[5] 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
[6] J. Zhu, C. Jiao, I. Dominguez, S. Yu, H. Su, "Design and Backdrivability Modeling of a Portable High Torque Robotic Knee Prosthesis With Intrinsic Compliance For Agile Activities", *IEEE/ASME Transactions on Mechatronics*, 2022

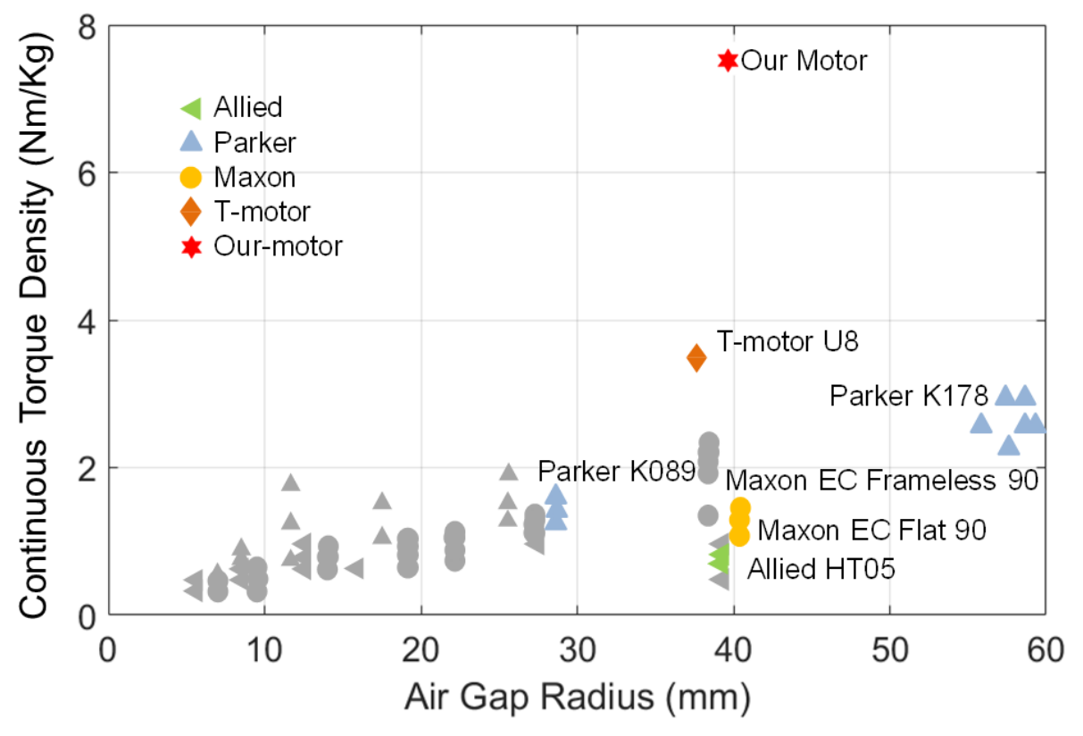
New Actuation Paradigm for Co-Robots

	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 Load Low ratio gear

Motor Torque Density Comparison

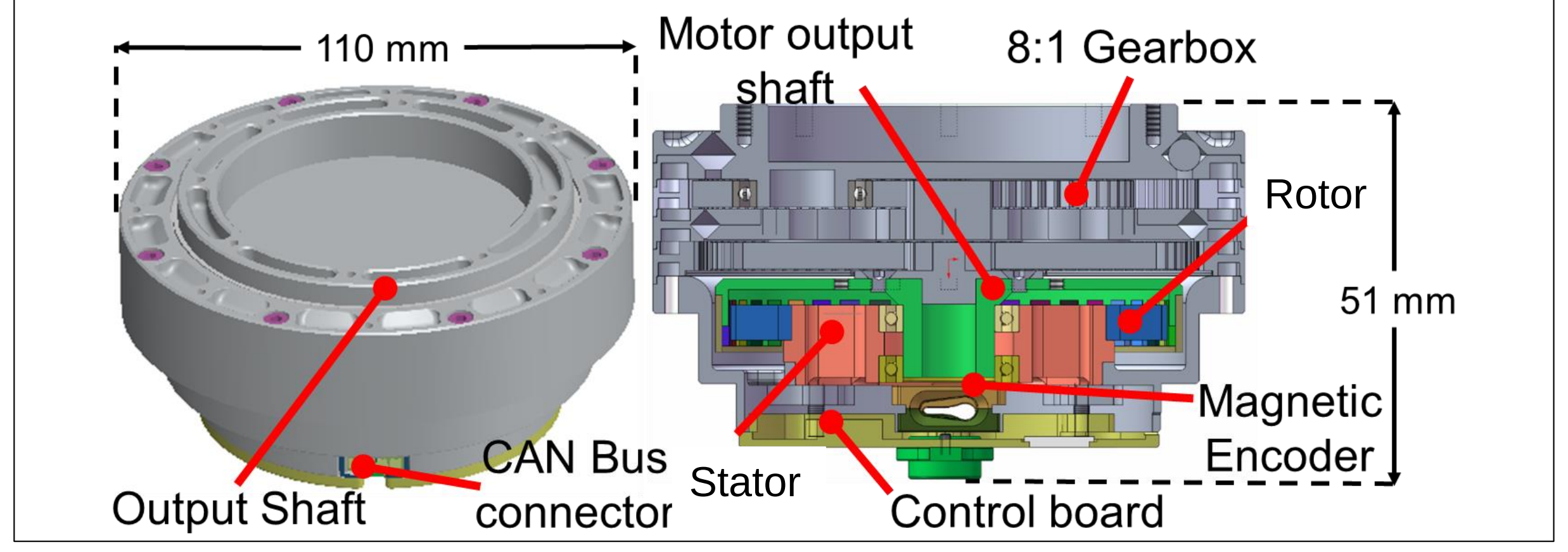
- Our custom-designed motor has the **highest torque density**

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



$$\text{Specific continuous torque}=\frac{\text{Coninuous torque}}{\text{Mass}}$$

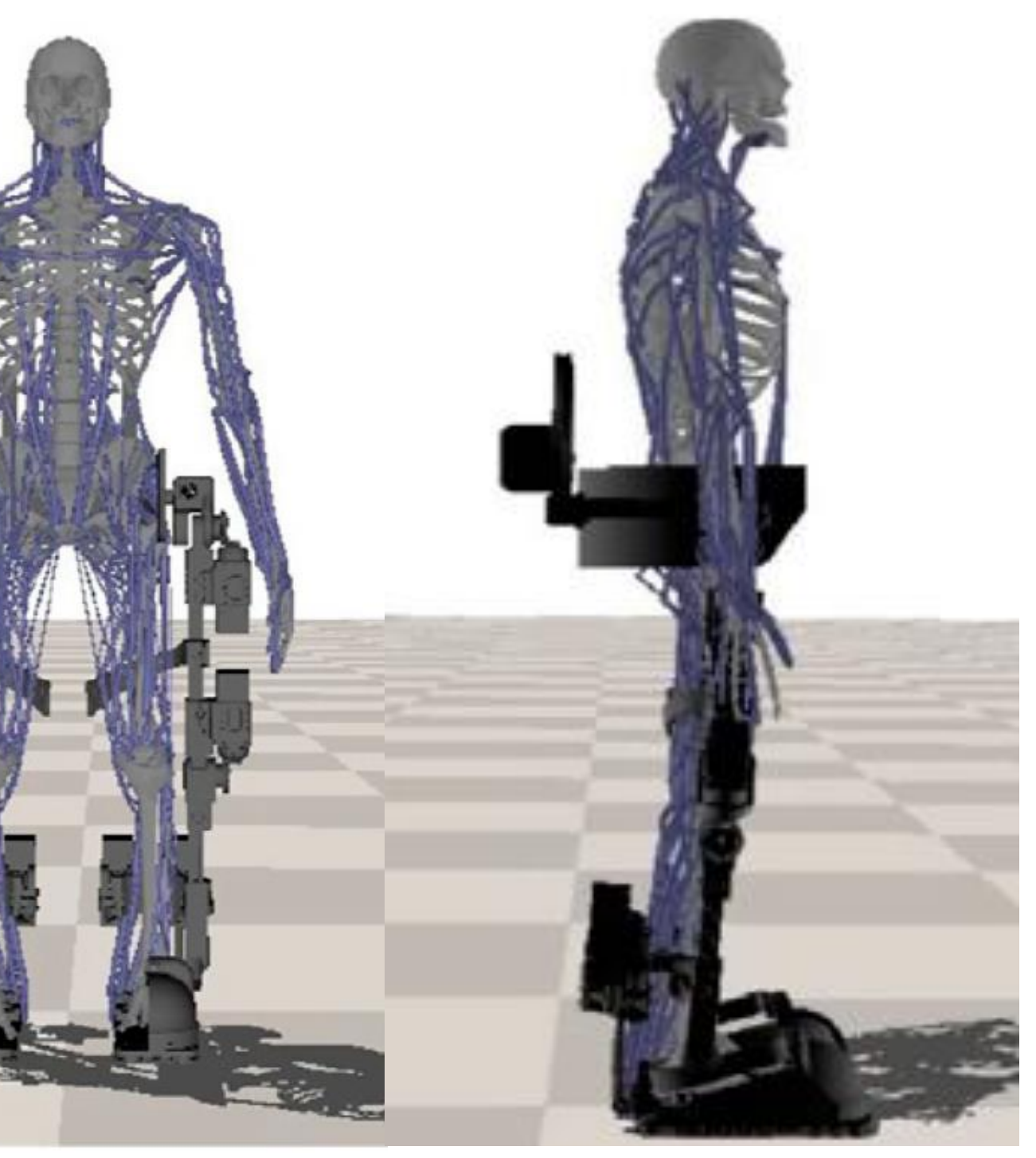
Customized High Torque Density Actuator

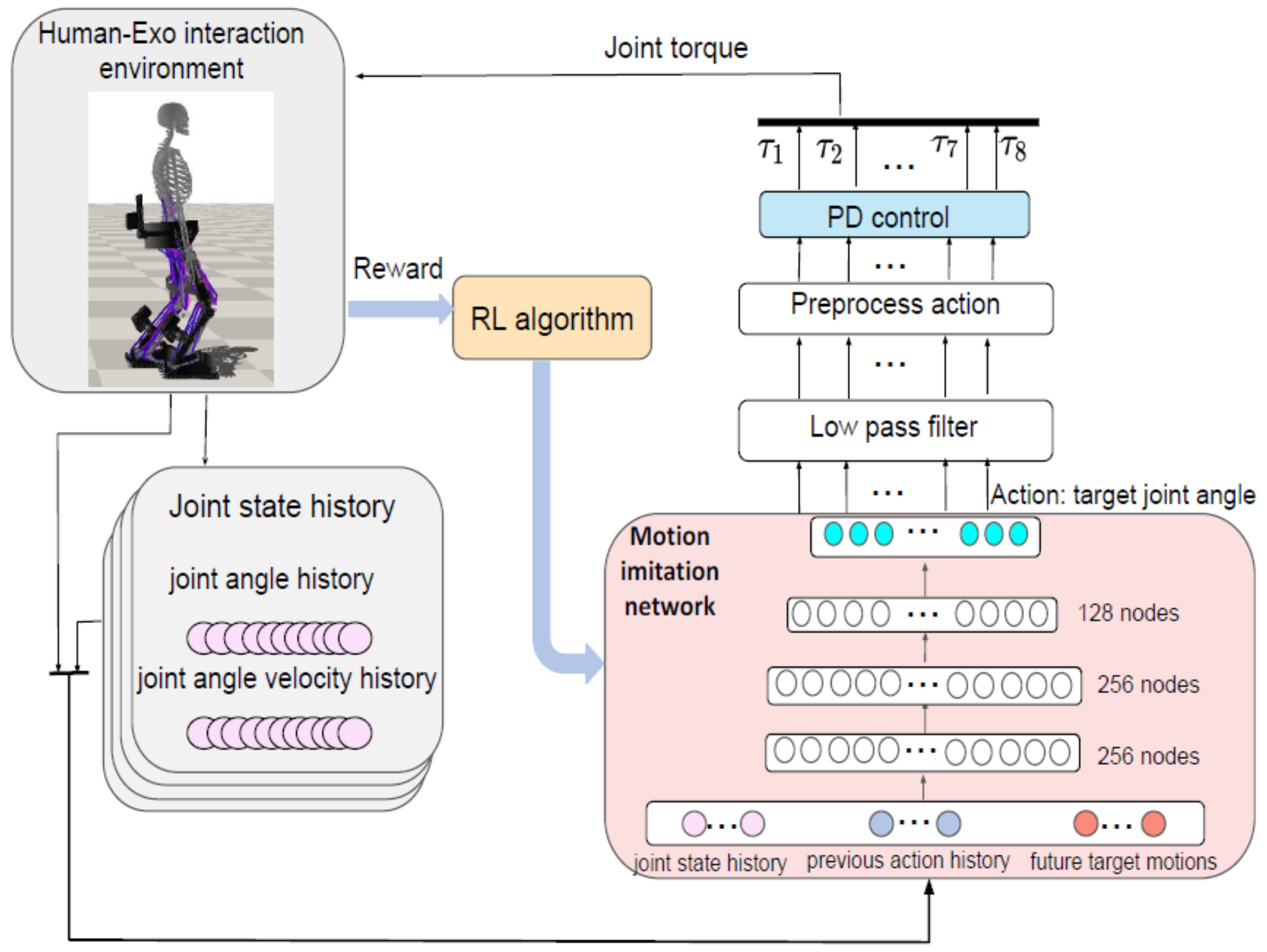


RL Based Robust Controller

- In this work, we propose a new deep neural network, reinforcement learning-based robust control strategy for providing gait assistance through lower limb rehabilitation exoskeletons that is:
  1. Robust to human-exoskeleton interaction forces.
  2. Independent of patient-specific characteristics.
  3. Not subject to myriad control parameter tuning
  4. Dynamics Model-free control
- Control policy is trained in simulation environment with rich high dimensional data and is transferred on to the exoskeleton controller for Realtime use.

Simulation Environment





- 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.

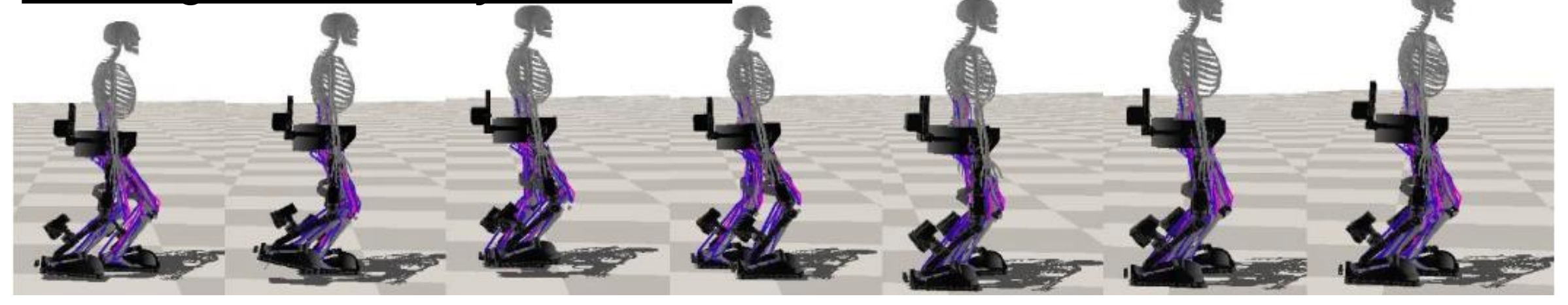
Dynamic Parameters	Training Range	Testing Range
Friction coefficient	[0.9,1.6]*default value	[0.7,2.0]*default value
Mass	[0.8,1.2]*default value	[0.7,1.5]*default value
Motor strength	[0.8,1.2]*default value	[0.7,1.3]*default value
Observation latency	[0,0.04]s	[0,0.06]s
Inertial	[0.5,1.5]*default value	[0.4,1.6]*default value
Center of Mass	[0.9,1.2]*default value	[0.8,1.3]*default value

- Open-source library DART was used to simulate the exoskeleton and Musculoskeletal model

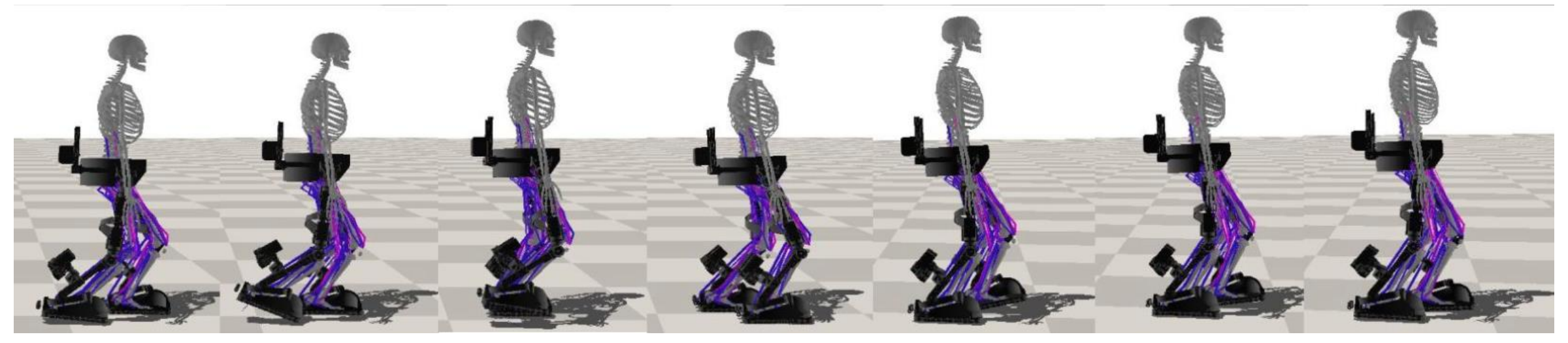
Controller Testing Results

- Rigorous numerical experiments were conducted using the simulated environment to assess the efficacy of the trained controller for robust walking.
- Following figures show snapshots of simulation during walking with various conditions.

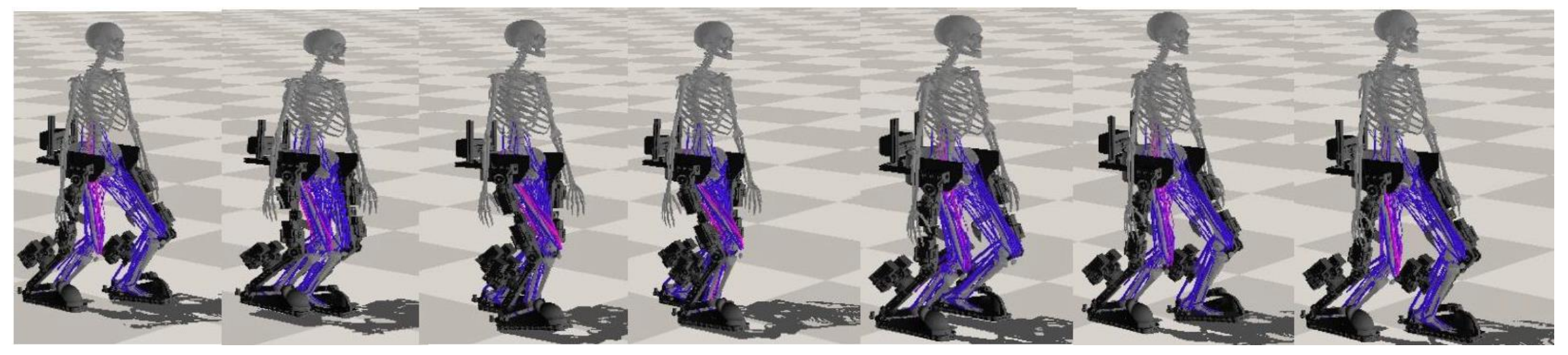
Walking with Healthy Individual



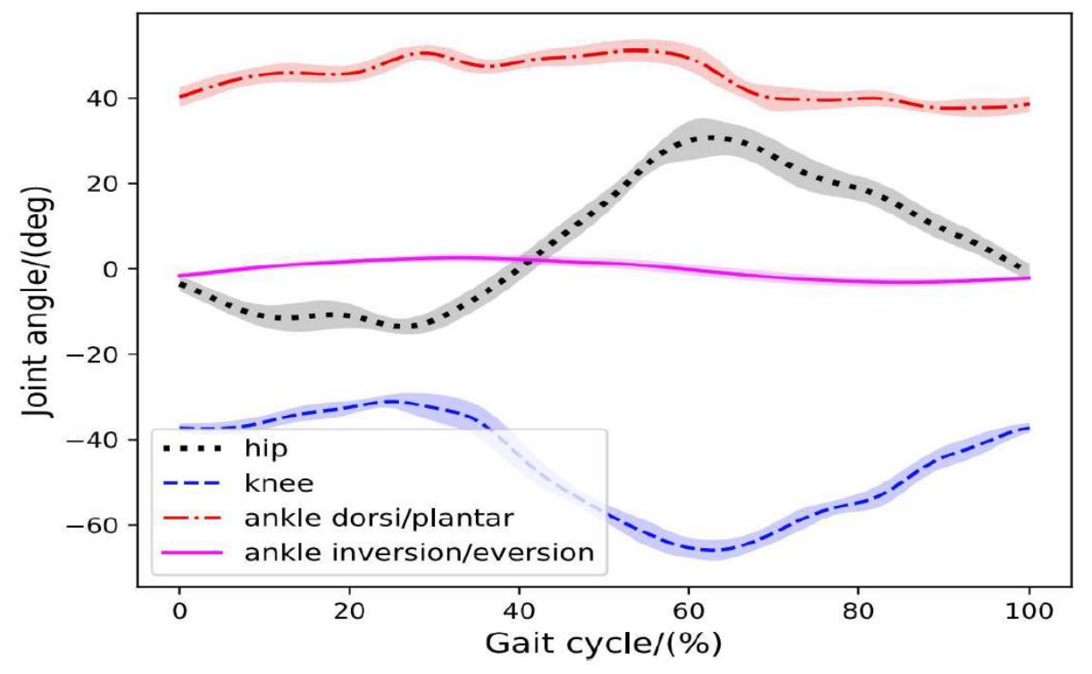
Walking with Individual Experiencing Muscle Weakness



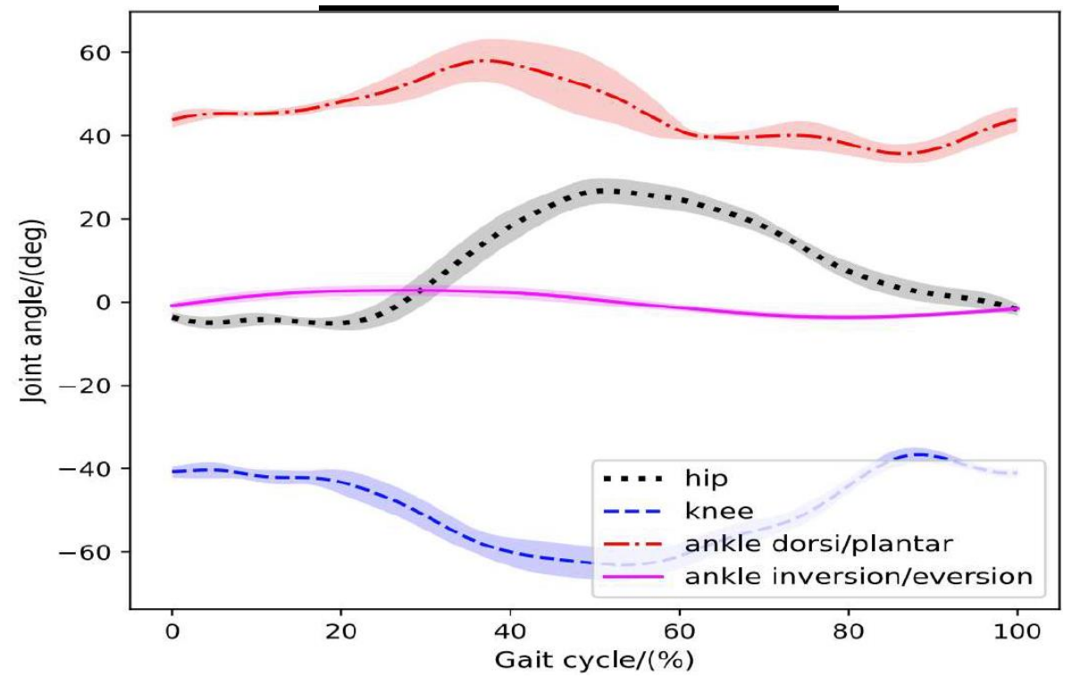
Walking with Individual with Left Hemiparesis



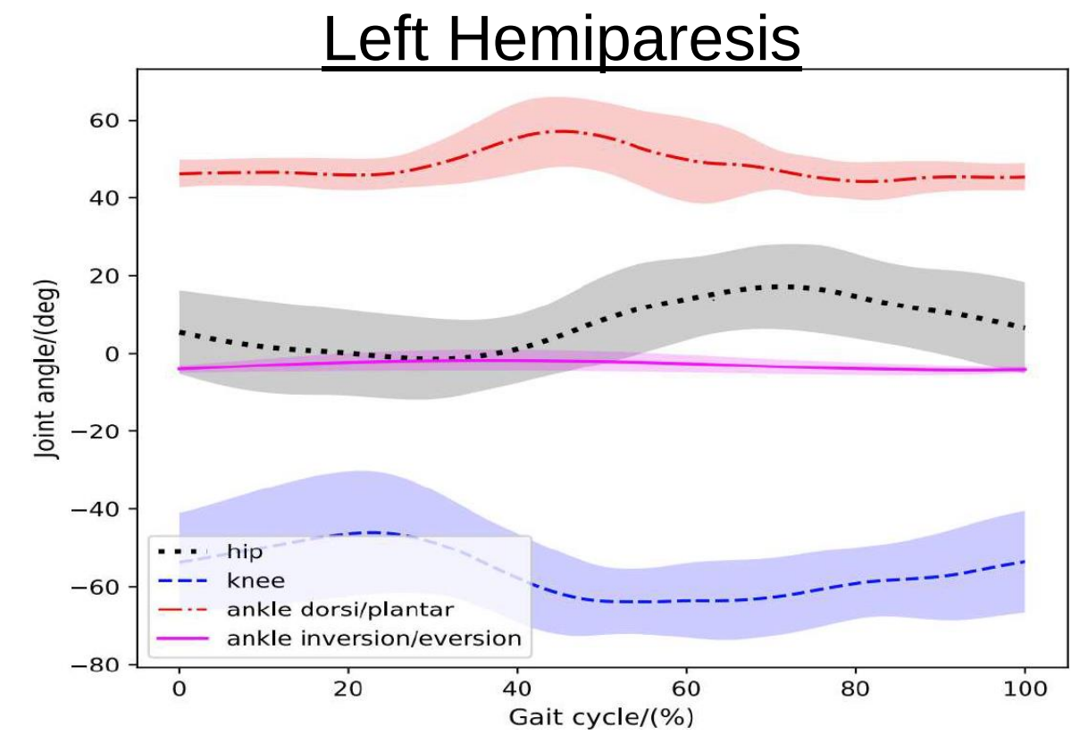
Healthy Individual



Muscle Weakness

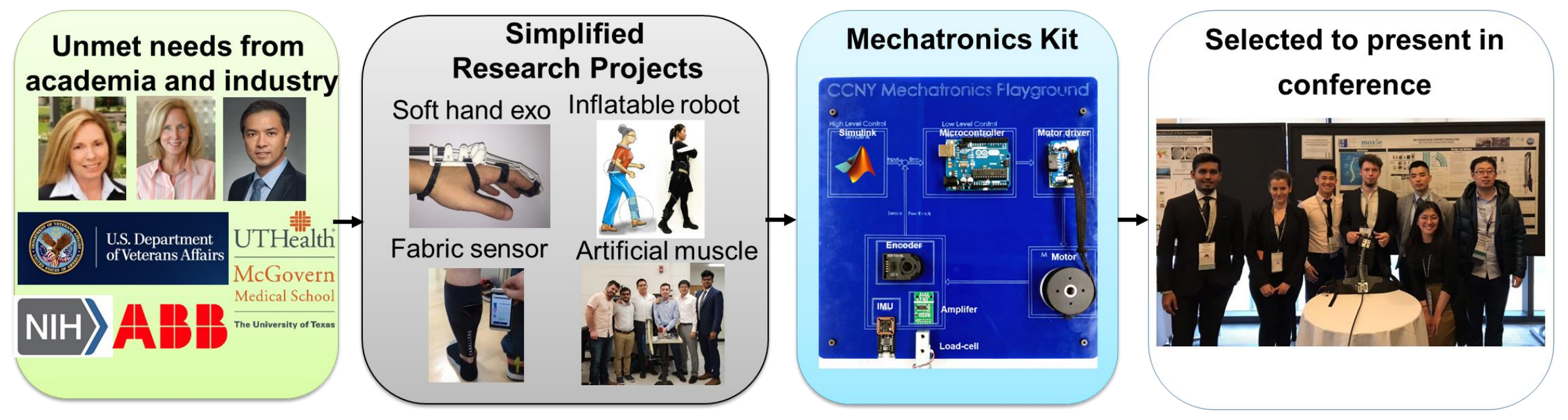


Left Hemiparesis

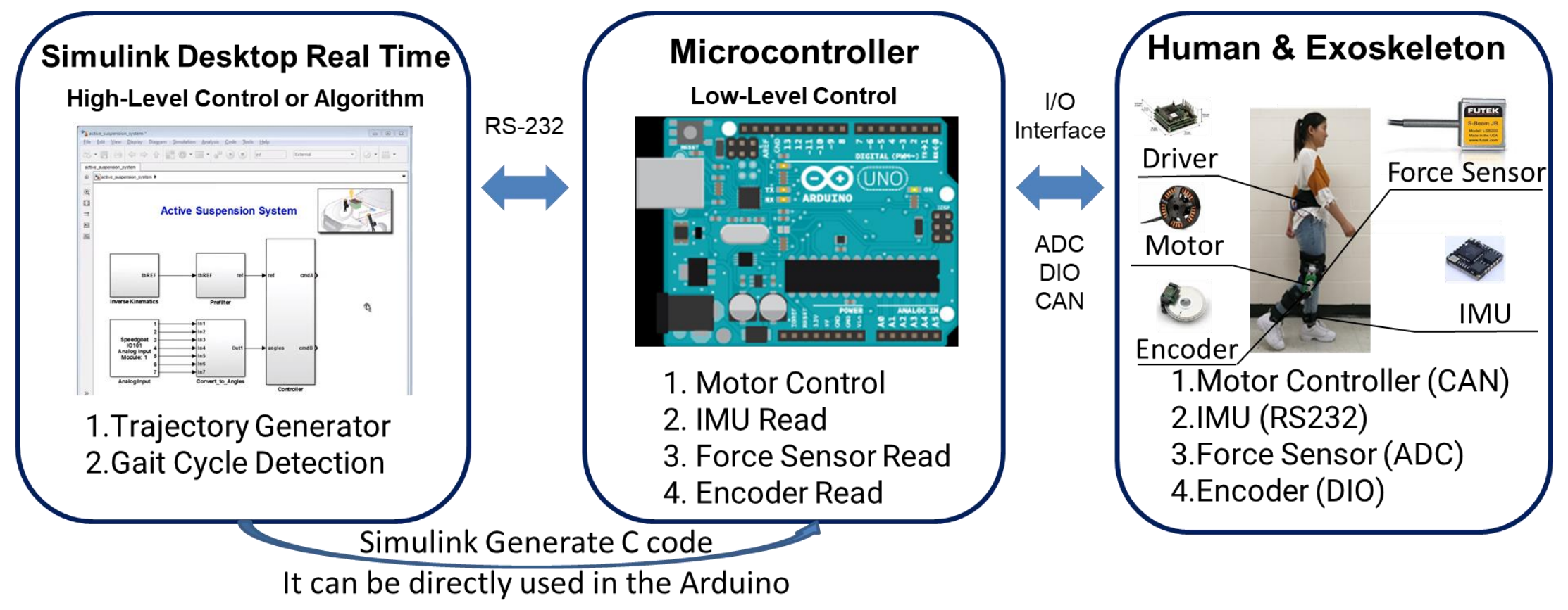


Lowering Barriers To Learn Robotics

- Advanced Mechatronics Education



- System Control Architecture

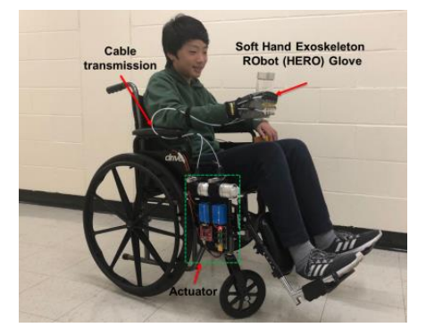


Simulink Desktop Real Time: 1.Trajectory Generator 2.Gait Cycle Detection
Microcontroller: 1. Motor Control 2. IMU Read 3. Force Sensor Read 4. Encoder Read
Human & Exoskeleton: 1.Motor Controller (CAN) 2.IMU (RS232) 3.Force Sensor (ADC) 4.Encoder (DIO)
Simulink Generate C code
It can be directly used in the Arduino

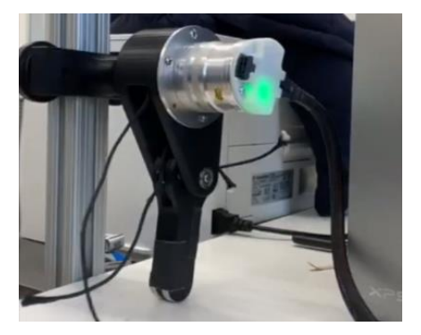
- International conferences (2 awards) + 18 undergrad student projects

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

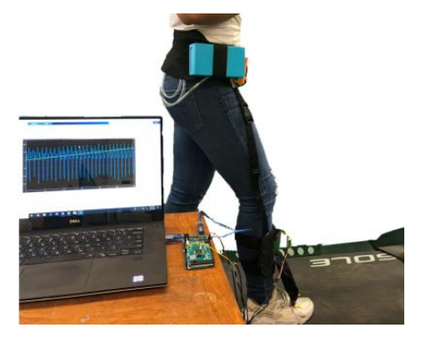


Jumping Robotic Leg

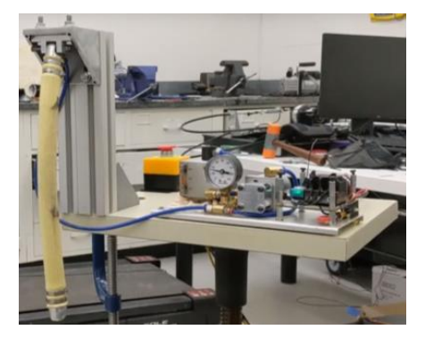


Soft Submersible Inspection Robot

Pneumatic Ankle Exoskeleton



High Force Hydraulic Artificial Muscle



Cooling Vest

Soft Human Intention Detection Sensor

Functional Electrical Stimulation Device