Deep Reinforcement Learning-Based Predictive Neuromechanical Simulation for Wearable Robots to Reduce Muscle Effort

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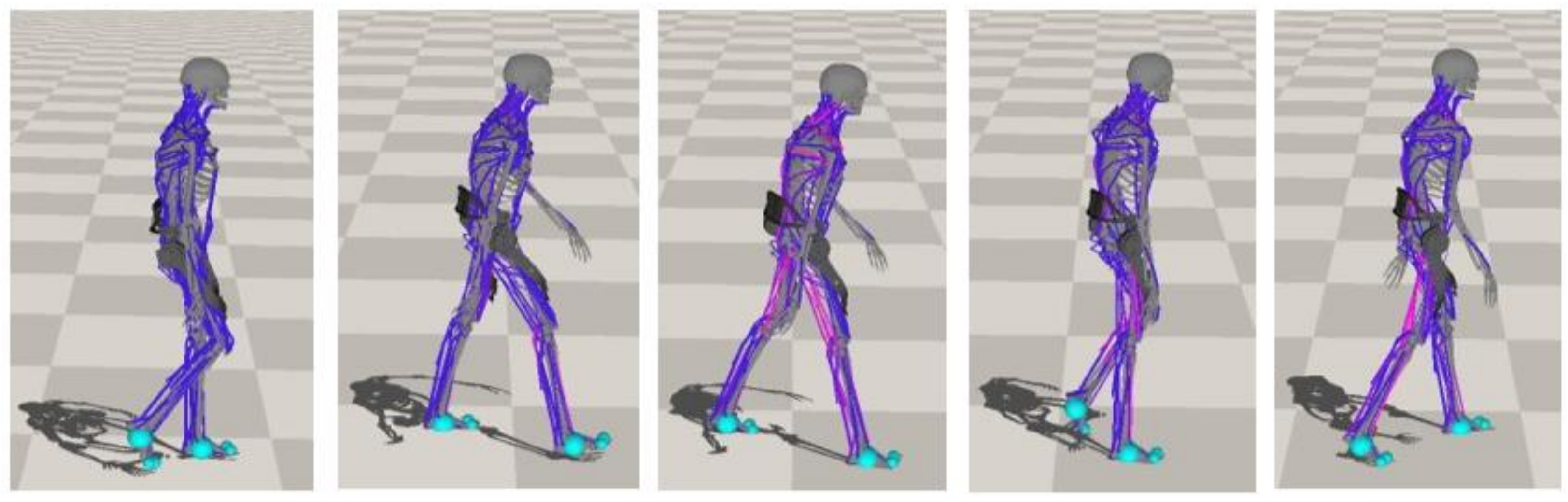
Robotics and Intelligent Learning Lab

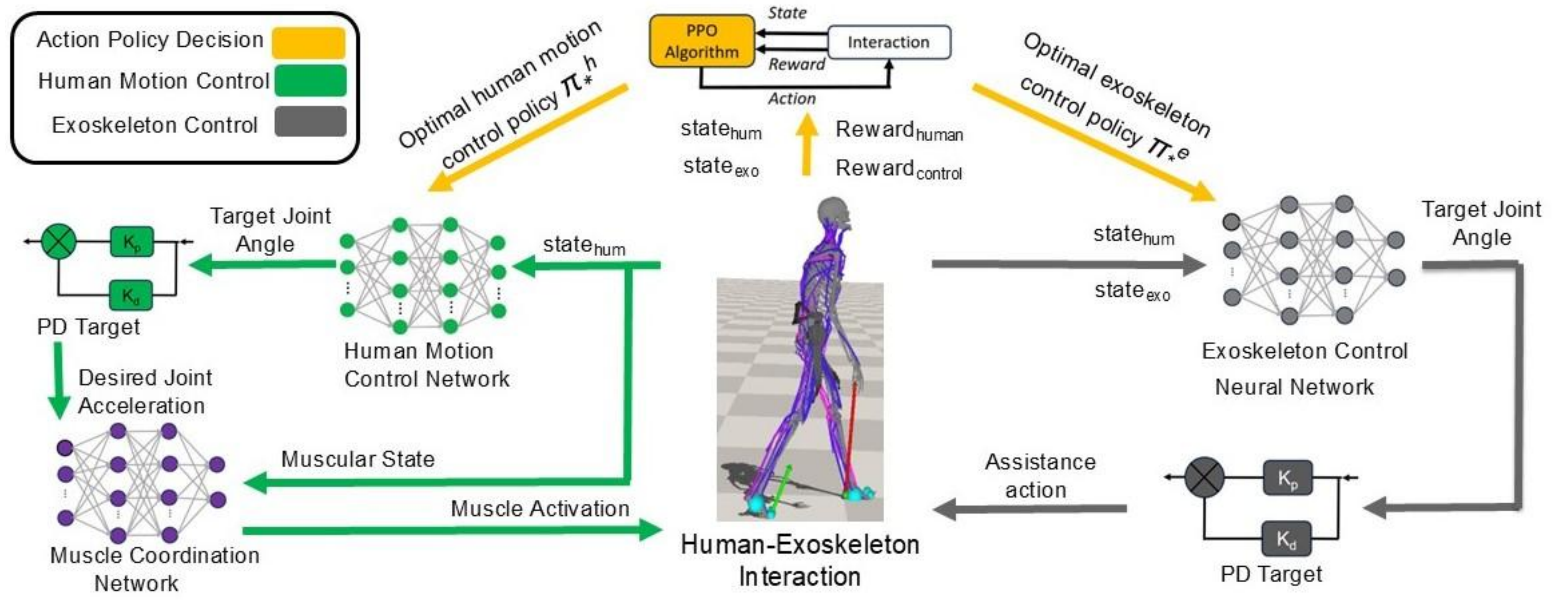
Mingyi Wang, Shuzhen Luo, Mechanical Engineering Department, Embry-Riddle Aeronautical University, Daytona Beach, Florida, USA

Overview

Exoskeletons have been shown to reduce muscle effort and joint stress, highlighting their potential for injury prevention in occupational settings. This research presents a deep reinforcement learning-based, closed-loop human-robot interaction framework that predicts biomechanical responses and optimizes torque assistance to reduce muscle effort. The learned control policy directly maps human kinematics to optimal torque assistance. Experimental results demonstrate a 13.04% reduction in hip joint torque, a 7.31% reduction in rectus femoris activation, and a 12.21% reduction in biceps femoris activation. Real-world implementation of the learned control policy on the exoskeleton confirmed its effectiveness in reducing lower-limb muscle activation.



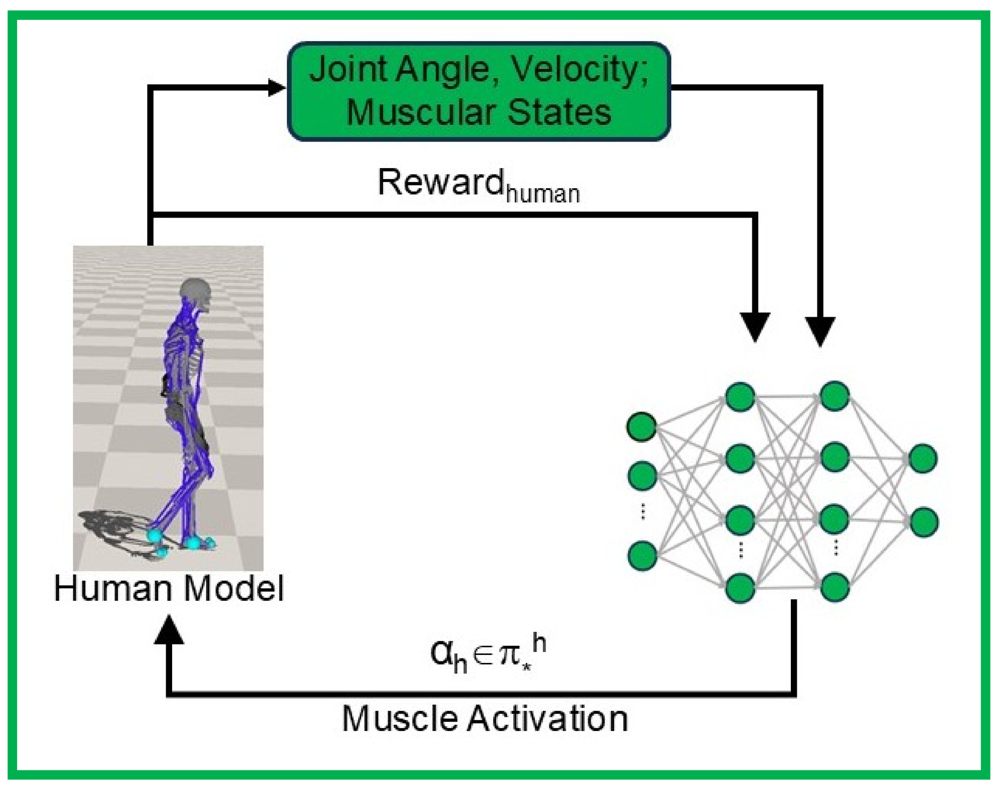
Deep Reinforcement Learning-Based Closed-Loop Human-Robot Interaction



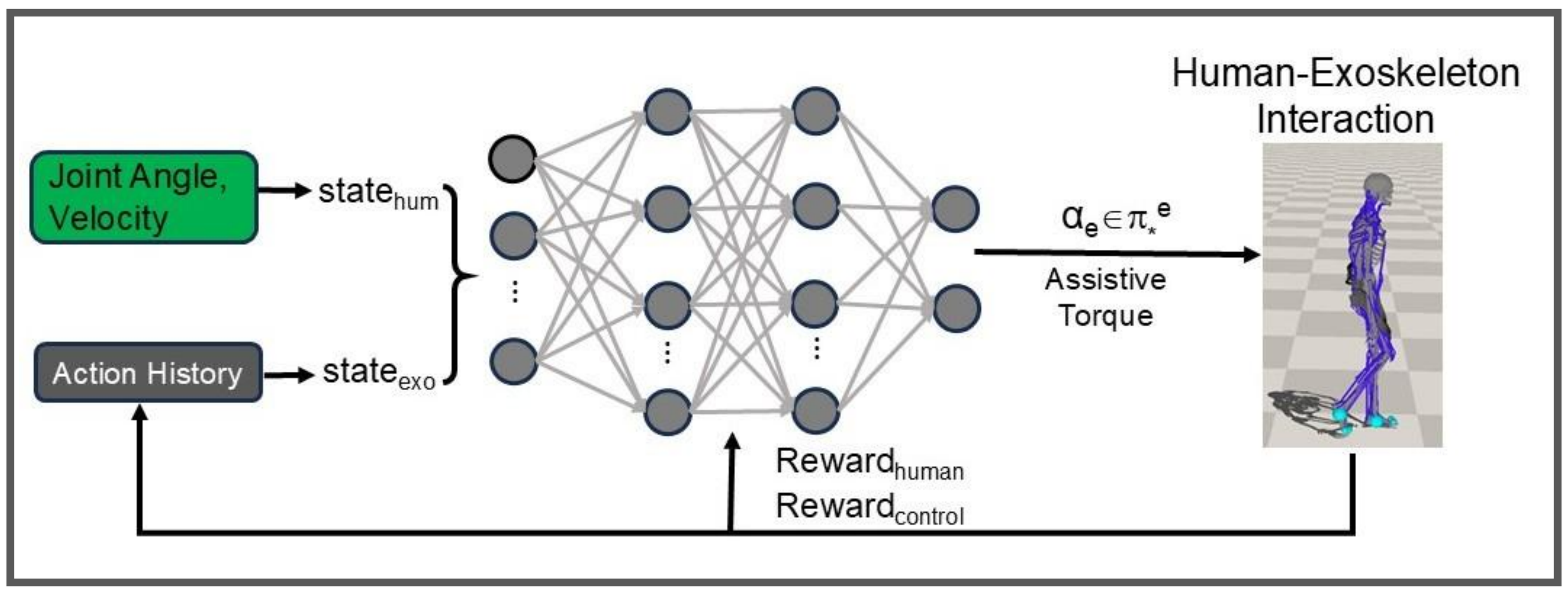
- Two deep reinforcement learning loops (PPO algorithm) optimize action control policies: human motion control and exoskeleton control. The human model's joint angles and velocities are human state ($state_{hum}$) and exoskeleton history actions are ($state_{exo}$).

$$Reward_{interaction} = \underbrace{\omega_{ctr} r_{ctr}}_{Reward_{control}} + \underbrace{\omega_{ang} r_{ang} r_{ee}}_{Reward_{human}}$$

$$r_{ctr} = exp[-\sigma_{ctr} \sum \| \tau_i \|^2]$$
$$r_{ang} = exp[-\sigma_{ang} \sum \| p \|^2]$$
$$r_{ee} = exp[-\sigma_{ee} \sum \| x \|^2]$$



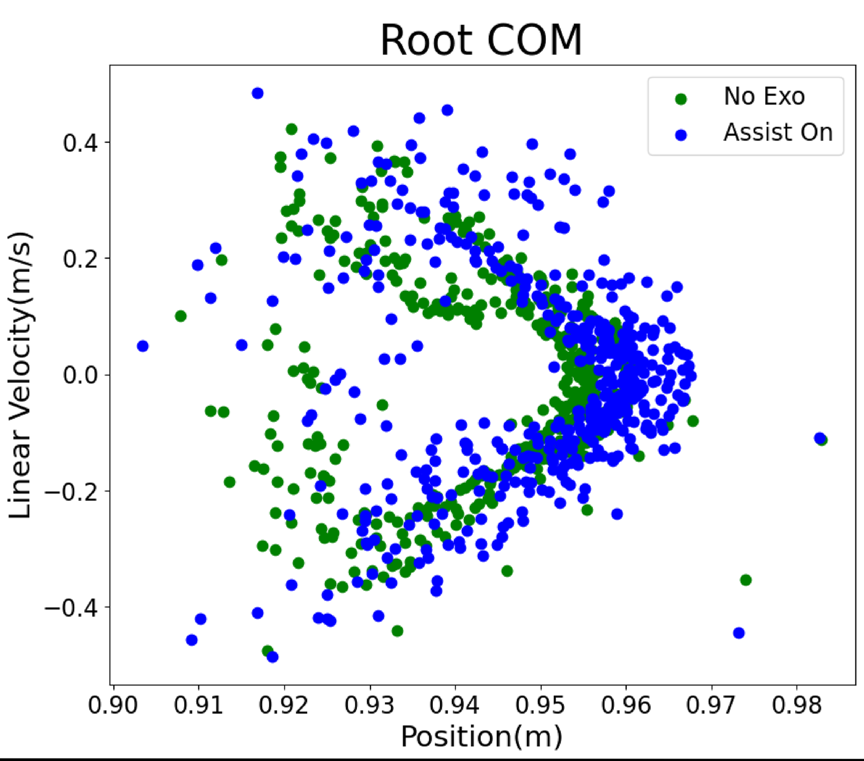
Human Motion Control Neural Network



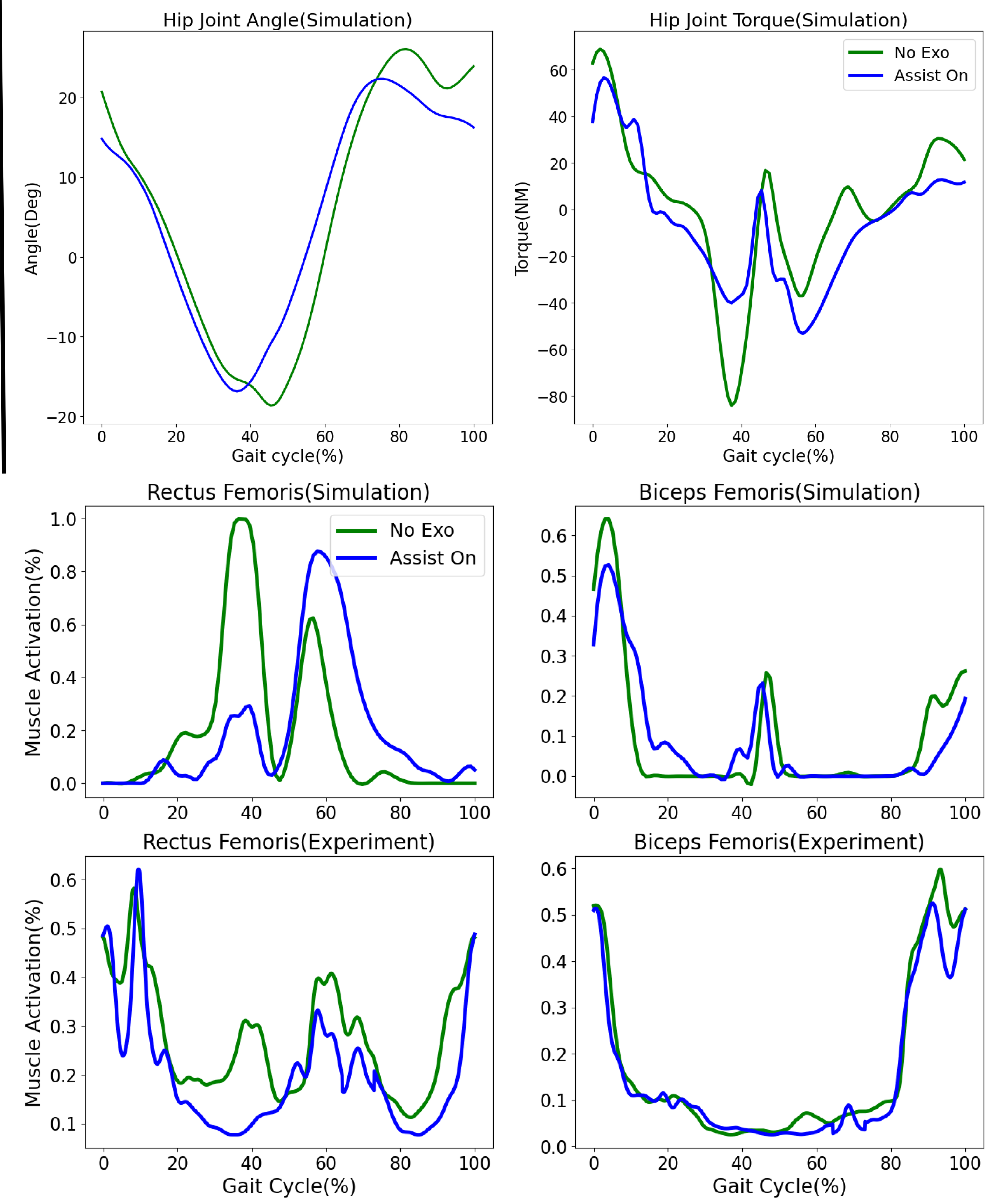
Exoskeleton Control Neural Network

- $Reward_{human}$ considers the human model's joint tracking error(σ_{ang}), as well as end-effector position tracking error (σ_{ee}).
- $Reward_{control}$ is designed for the exoskeleton control neural network to reduce muscle activation.

Results & Future Work



- We analyze the center of mass (CoM) position and vertical velocity to assess the stability of a deep neural network-based human walking/exoskeleton controller.
- The results show that the relationship between the CoM's linear velocity and position is well-clustered during the simulation, indicating stable control performance of the neural networks.



- Conducting experimental tests with three human subjects to validate simulated joint angles and muscle activations.
- The simulated joint angles and muscle activations closely match experimental data, with assist-on conditions showing RMS reductions of 22.12% for RF and 11.45% for BF, confirming the simulation's accuracy.
- Our framework offers a generalizable and scalable strategy for the rapid development and widespread adoption of exoskeletons for activities such as overhead work and lifting in construction. Future work will enhance human-robot interaction and support the development of more adaptive, personalized assistive technologies.

Joint/Activation (Simulation)	RMS (NoExo)	RMS (Assist On)	Reduction (%)
Hip Joint Torque	31.71	27.6	13.04
Rectus Femoris	0.35	0.32	7.31
Biceps Femoris	0.19	0.16	12.21

Reference: 1) Luo, Shuzhen, et al. "Experiment-free exoskeleton assistance via learning in simulation." *Nature* 630.8016 (2024): 353-359.
2) Wang, Mingyi, and Shuzhen Luo. "AI-computing, deep reinforcement learning-based predictive human-robot neuromechanical simulation for wearable robots." *Applied Intelligence* 55.6 (2025): 1-19.

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