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Integrated Control of Biological and Mechanical Power for Standing Balance and Gait Stability after Paralysis

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Objective and Motivation

Objective: Develop cyber-physical walking system (CPWS) that integrates:

(1) person with spinal cord injury (SCI)

(2) exoskeleton with DC motors for need-dependent joint power assistance;

(3) computational algorithms that continuously and automatically learn to improve standing and walking stability.

CPWS will enable users to achieve walking speeds (≈1.0 m/s) and distances (>500m) suitable for ambulation in the community far exceeding those reported for powered robotic exoskeletons or electrical stimulation alone.

Previous Work: Proved combination of muscular contractions caused by electrical stimulation and unpowered exoskeleton with gait dependent joint locking can enable individuals with SCI to walk in and out of the laboratory [1,2, 3].

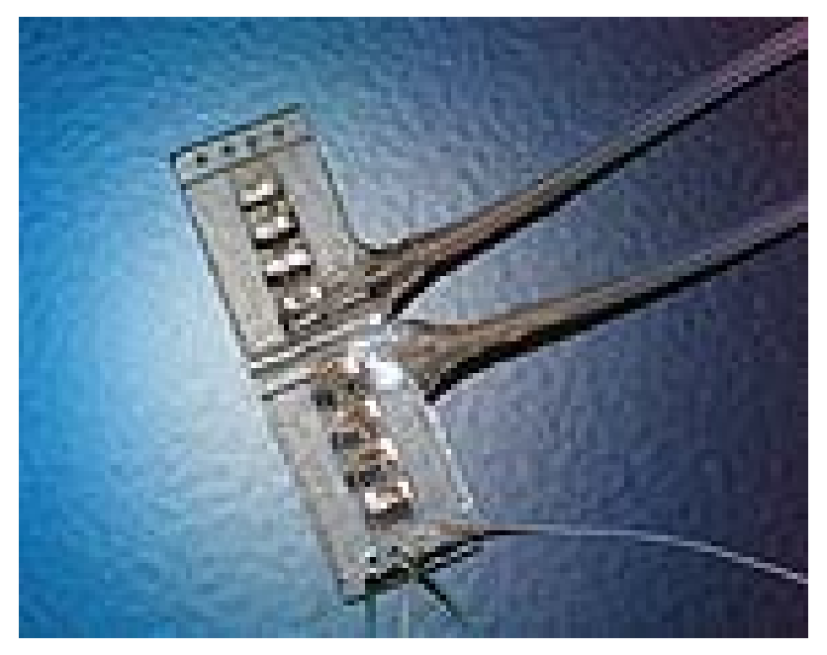
In our new "muscles first" approach, assistive motors are used as little as possible.

Advantages:

❑ provides maximum health benefits - due to exercise

❑ motors may be small and lightweight

LEFT: Individual with thoracic level SCI with implanted stimulating electrodes stands and walks while wearing a passive hydraulic exoskeleton. Context-dependent hip and knee mechanisms allow the joints to move during dynamic movements driven by neural stimulation and lock during standing so muscles can be deactivated and rest - decreasing muscle fatigue and prolonging standing times and walking distances.



RIGHT: Example of a Composite Flat Nerve Interface Electrode (C-FINE), one of several different implantable electrodes developed at Case Western Reserve University and the Louis Stokes Cleveland VA Medical Center.

Specific Aims

Aim 1: **Enhance standing stability** of SCI users with a CPWS while minimizing upper extremity effort through sensor-driven feedback control of the system state.

Aim 2: **Enhance dynamic stability of walking** with a CPWS while minimizing upper extremity effort through sensor-driven feedback control of the system state.

Aim 3: **Assess upper extremity reduction and balance** control in individuals with SCI using a CPWS for standing and ambulation.

Estimating Center of Mass Kinematics using Inertial Measurement Units

Able-Bodied Standing Experimental Setup:

❑ We estimated whole-body Center of Mass (CoM) kinematics from the motion of 44 reflective markers through a 16-camera motion capture system and anthropometric measurements of the subjects' limbs

❑ 5 subjects participated in the experiments

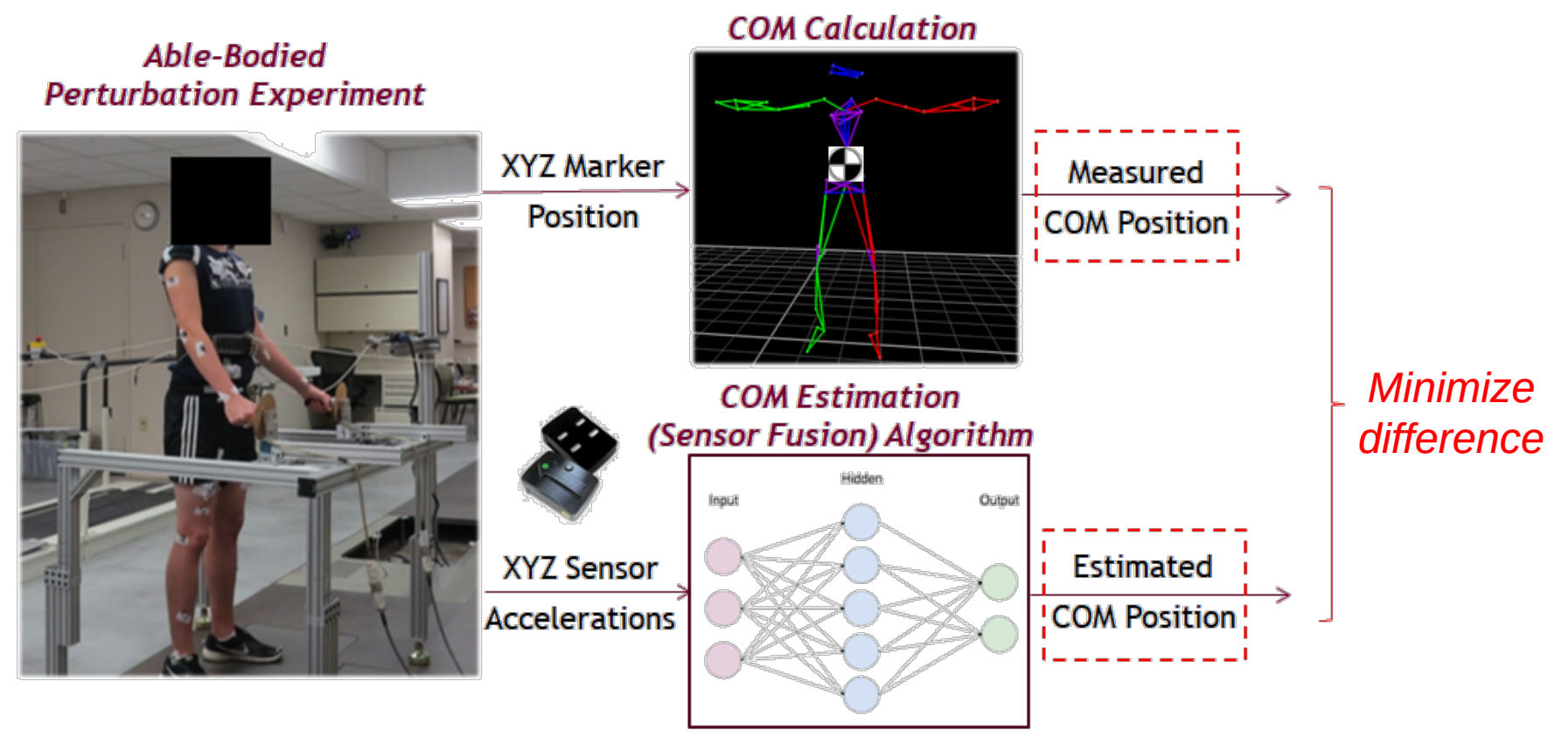
❑ We placed 10 Inertial Measurement Units (IMUs) on each subject (6 torso, 2 thigh, 2 shank) to measure reactive changes in acceleration caused by postural perturbations

❑ We applied perturbations to the test subjects to destabilize them and cause changes in their CoM position

ABOVE:

❑ External perturbations (left): 4 linear actuators randomly pull the test subject in the anteroposterior and mediolateral directions. Actuators are indicated by orange circles.

❑ Internal perturbations (right): subjects move 3 weighted jars to 4 different positions on a shelf

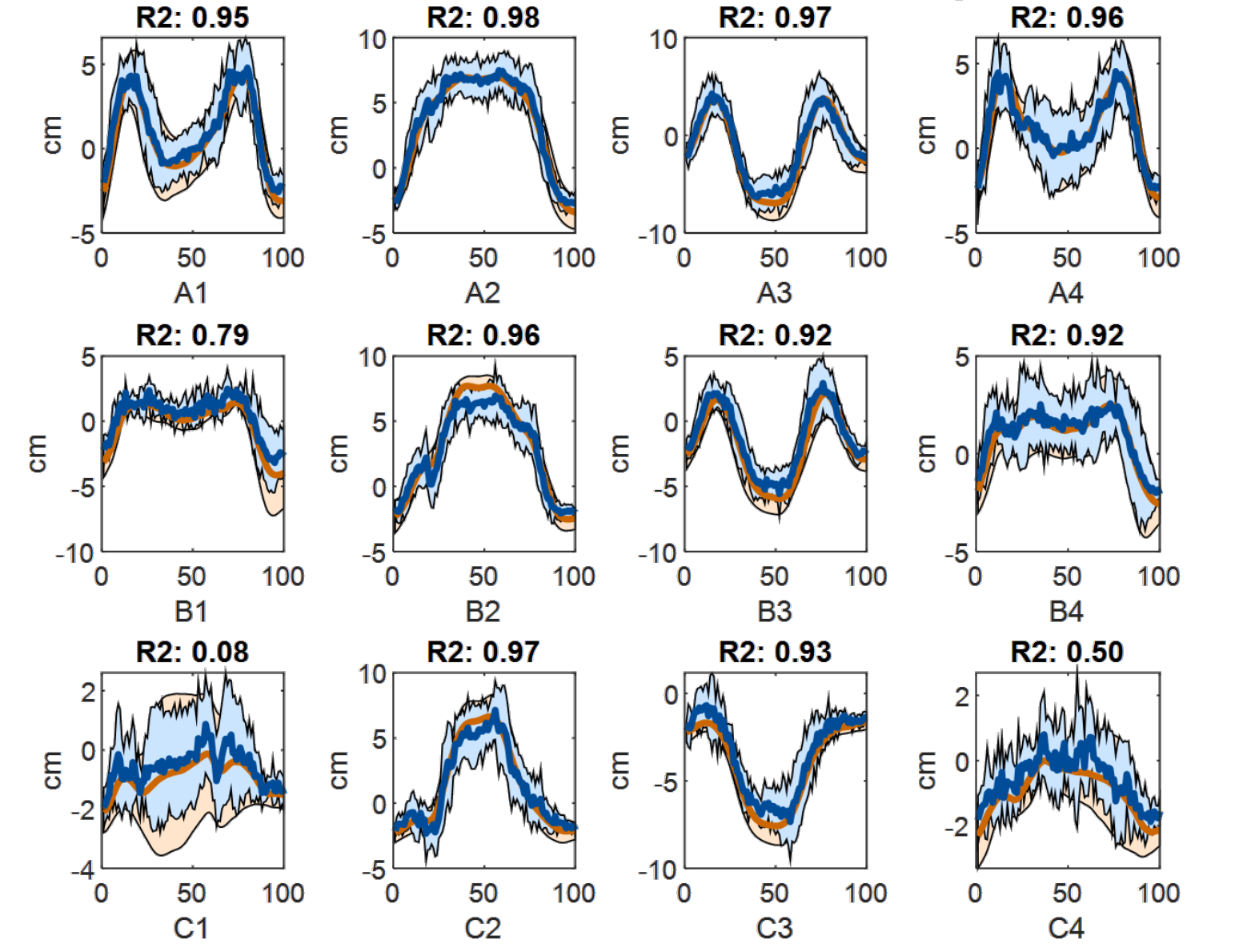


We used a CoM Estimation (Sensor Fusion) Algorithm to predict the CoM position by using the IMUs' acceleration signals as input.

BELOW:

Data from one representative subject (male, age 26, height = 1.7m, weight = 66kg), during the internal perturbation experiment, is shown below. Perturbations are separated and averaged by type (i.e. move Jar A to position 1). We then calculated the R^2 for each movement type.

Mediolateral Center of Mass Position per Movement



In this example, our algorithm is able to estimate CoM position with R^2> 0.90 for 80% of the movements. Poorer fit may be caused by less movement during the given task.

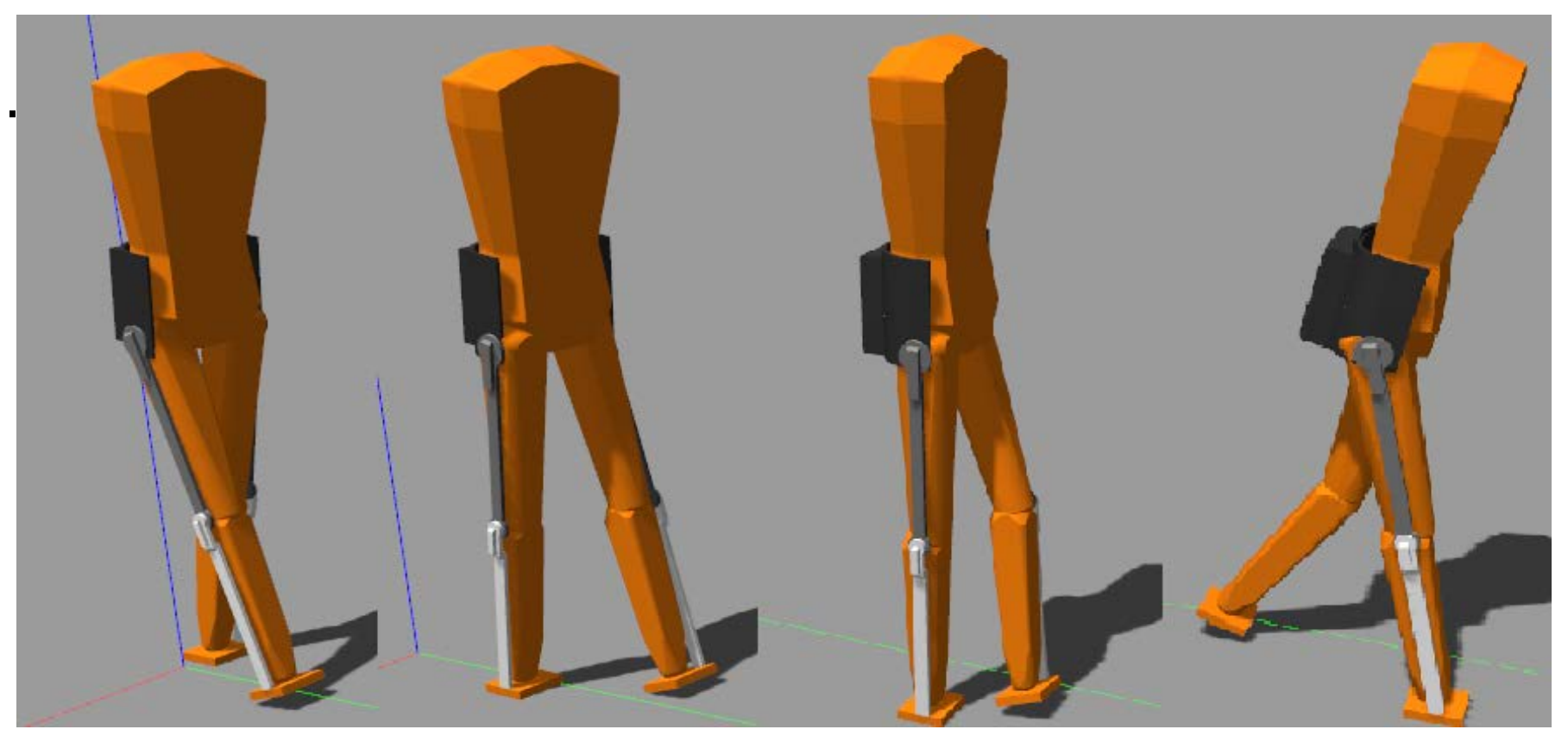
Future Work

❑ Estimate the CoM inferior-superior component by using a regression model and joint angles during squat activities

❑ Expand the algorithm to include able-bodied walking at three different speeds

Reinforcement Learning for Controlling Dynamic Walking

Our biped model was extended to include 3D motions.



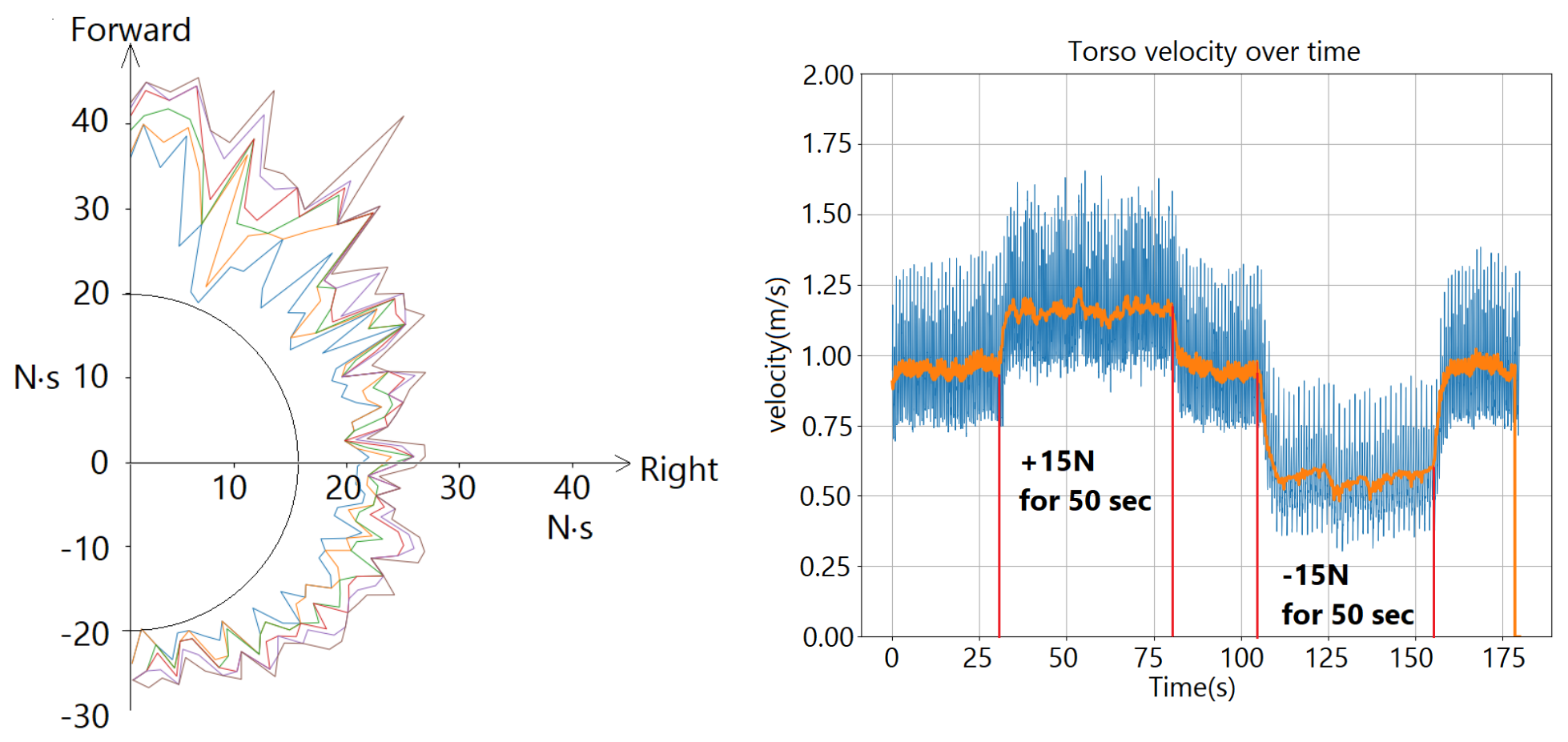
❑ **Two neural networks** were trained in the GAZEBO dynamic simulator using PPO-CMA and NEAT to predict ideal foot placement for the swing leg and to maintain stability with the stance leg during walking despite external disturbances [4].

One neural network was trained for the swing leg and another was trained for the stance leg to reduce complexity and dimensionality. The stance leg controller was tuned first to maintain torso stability. The swing leg controller was trained next to predict the best placement of the foot for stability at the next step. The two networks are alternately trained so that they can better incorporate the dynamics of each other.

❑ Additional PID controllers for pelvis joint movement during swing phase, and ankle joint torque during toe-off

❑ The system was trained for a 1.8m tall human using anthropometric data

Walking is Robust to Disturbances



(Left) The biped resists impacts from any direction and (Right) resists persistent forces applied to back or front of torso.

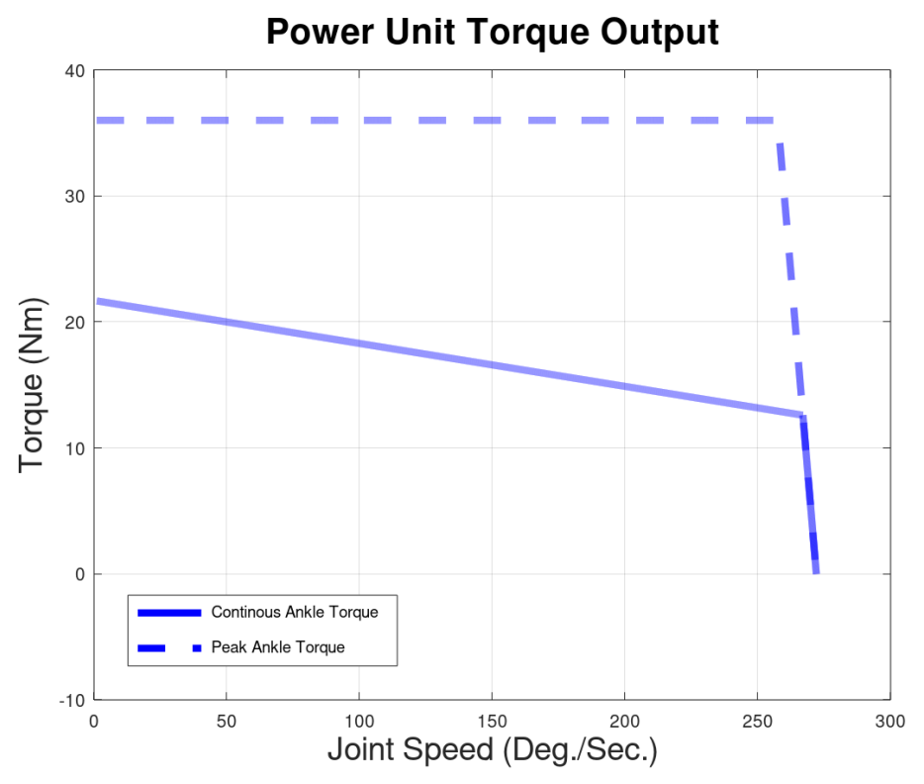
Powered Ankle Orthosis for Standing Balance

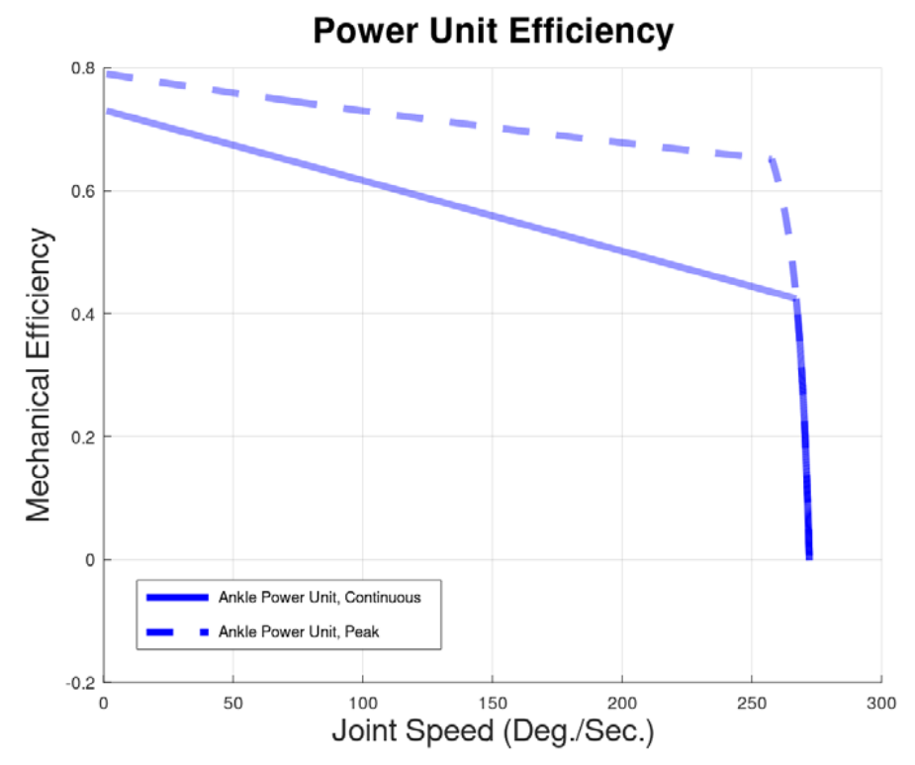
❑ **Powered, Backdrivable Ankle Joints** have been developed to facilitate standing and walking balance. While stimulated muscle is still used for propulsion, it lacks the bandwidth and controllability for fine control work. These robotic actuators have the required response time and bandwidth for balance control.

❑ Each prototype joint contains a frameless, brushless DC motor, chain drive, and 50:1 harmonic drive gearbox.

❑ These actuators are capable of 35 Nm peak torque, with less than 7 Nm of static friction

Actuator Performance



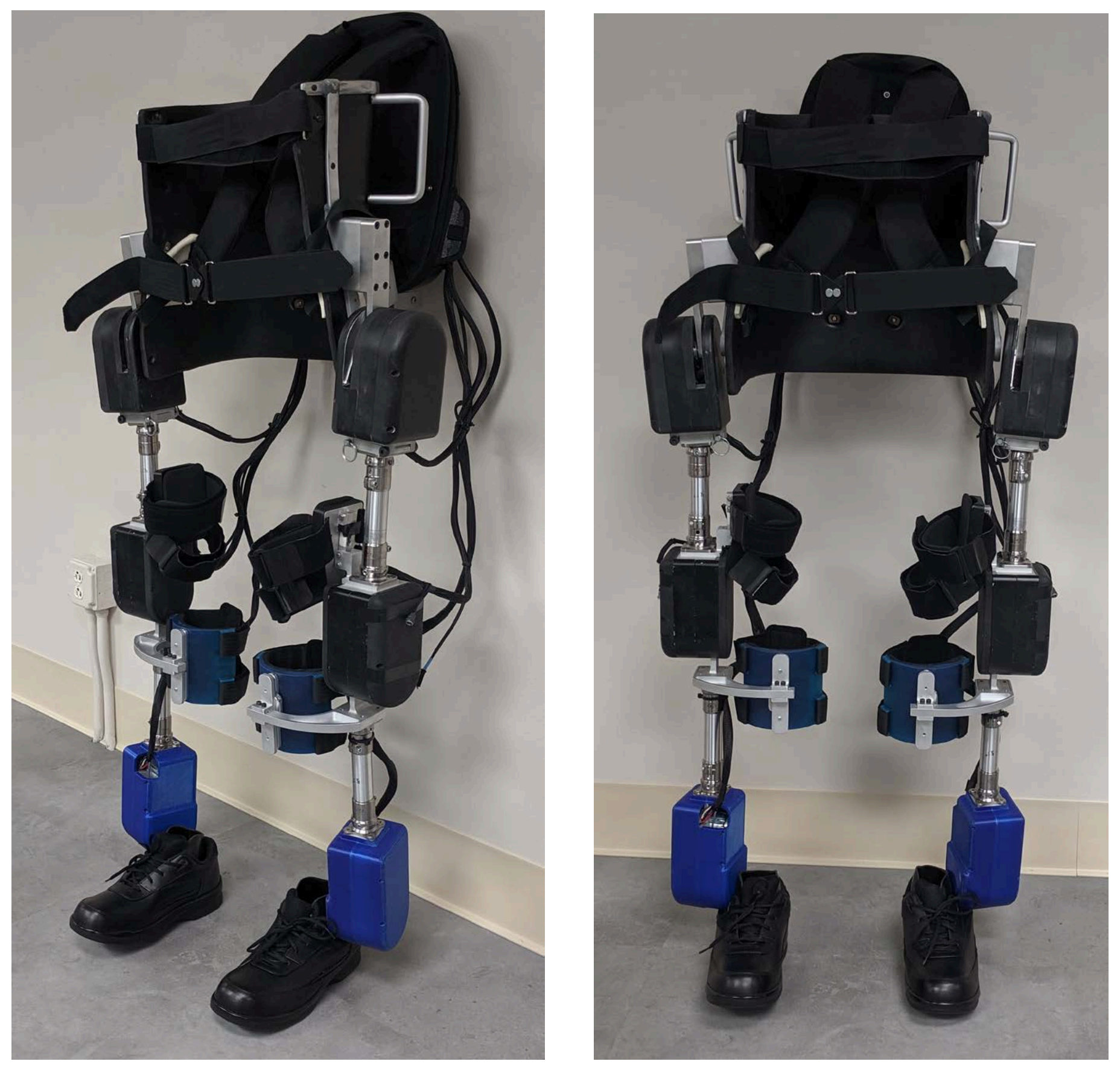


❑ At low speeds, ankle actuators are capable of over 20 Nm continuous torque, and 35 Nm peak

❑ High efficiency and backdrivability allow for unit to be passively moved by stimulated muscle during gait.

❑ Future work aims to decrease size, mass, and increase efficiency through use of custom planetary gearboxes.

System Integration



❑ Powered Ankle Joints have been integrated into a lower body exoskeleton.

❑ Minimalist exoskeleton supplements the user's biomechanics and assists the user's stimulated muscles.

❑ Design minimizes overall mass and mass moment of inertia about the hip joint.

❑ Distributed Electronics and Control architecture allows for real time low-level joint control while balance algorithms run at higher level

References

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