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

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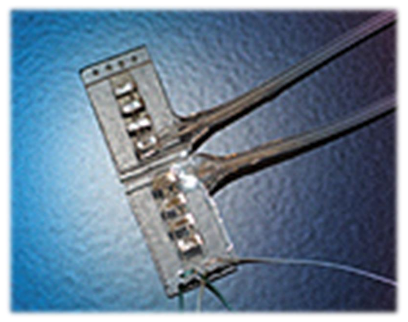
Objective and Motivation

Motivation

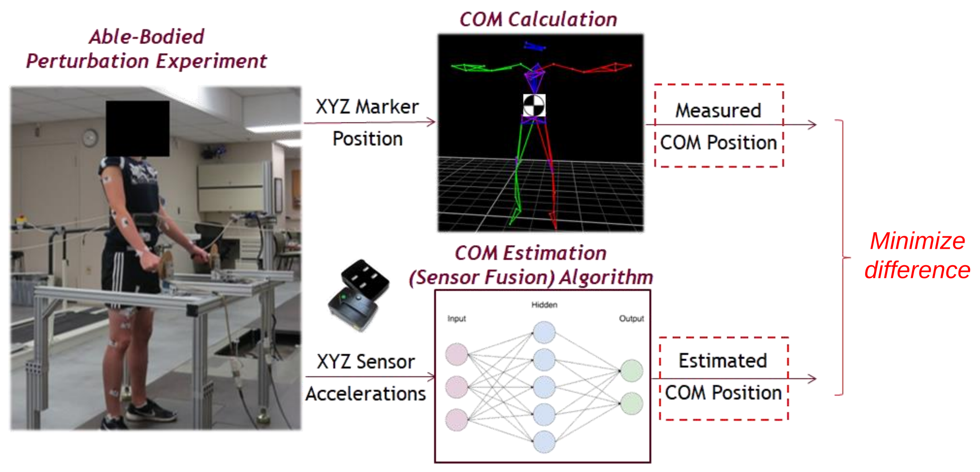
- Paralysis due to spinal cord injury
  - limits mobility
  - threatens overall health
  - compromises a productive lifestyle
- Commercially available powered exoskeletons:
  - lack balance control
  - passively move the user's muscles

Objective

- Develop a cyber-physical walking system (CPWS) that integrates:
  1) ***person*** with spinal cord injury (SCI) and neuro-muscular implants to stimulate their muscles to provide most of the torque for walking
  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.



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.

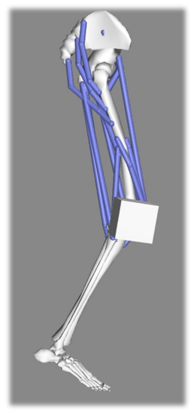


ABOVE: Center-of-mass (COM) estimation algorithm, where a trained neural network uses accelerometers to estimate COM as feedback for a balance controller

RIGHT: Fully assembled CPWS with electric motors at the hip, knee, and ankle joints. The design minimizes overall mass and mass moment of inertia, supplementing the user's biomechanics and assisting the user's stimulated muscles. Distributed electronics and control architecture allows for real time low-level joint control while balance algorithms run at higher level.

LEFT: Individual with thoracic level SCI with implanted stimulating electrodes stands and walks while wearing the CPWS. In this walking experiment, the pilot's muscles are controlled by a typical walking pattern while ballistic control at the motors assists with completing the movement.

Biologically Inspired Optimal Terminal Iterative Learning Control (BIOTILC)

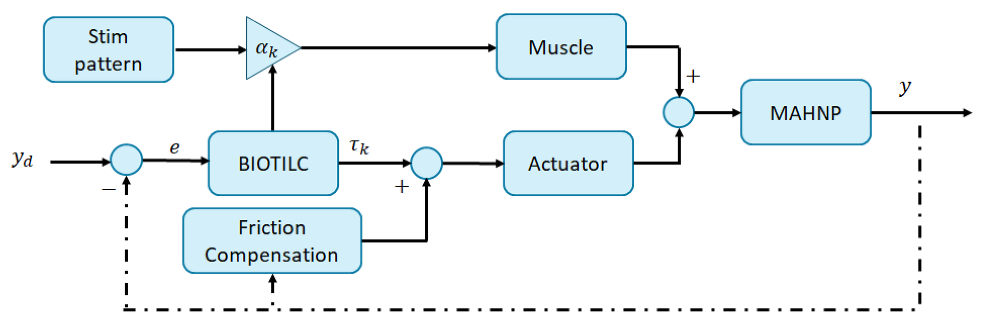


Key Features:

- ❑ Trajectory-free ballistic walking paradigm
- ❑ Model-free ILC optimization updates both muscles and motors over each step
- ❑ Enforces "muscles-first" philosophy – muscles produce majority of torque required for walking while motors at joints assist as needed

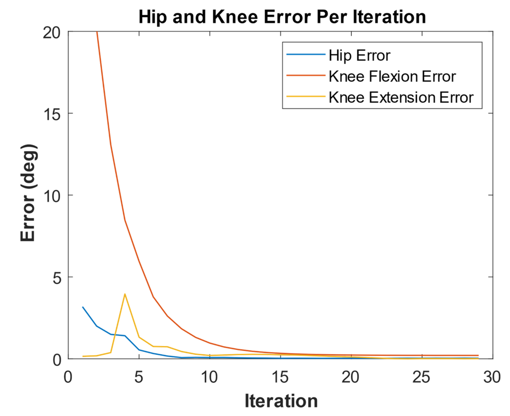
Controller Architecture:

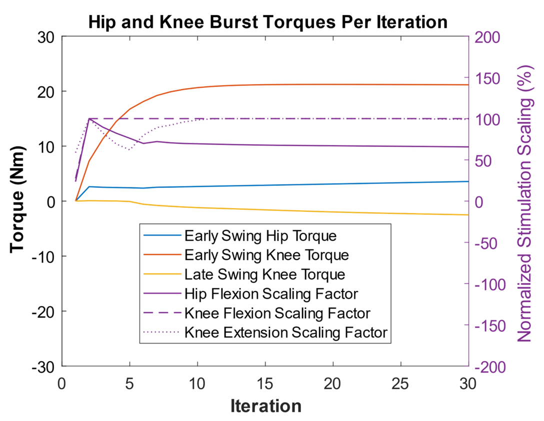
- ❑ BIOTILC scales a predetermined stimulation pattern and modulates the amplitude of a motorized burst.
- ❑ Update laws:
- ❑ $\hat{\Psi}_k = \hat{\Psi}_{k-1} + \frac{\eta(\Delta y_{k-1} - \hat{\Psi}_{k-1}\Delta u_{k-1})\Delta u_{k-1}^T}{\mu + ||\Delta u_{k-1}||^2}$
- ❑ $u_k = u_{k-1} + \frac{\rho(\hat{\Psi}_k^T e_{k-1})}{||\hat{\Psi}_k||^2 + \lambda} - \frac{\gamma(x_{mot}\mathrm{sgn}(x_{mot} \cdot u_{k-1}))}{2(||\hat{\Psi}_k||^2 + \lambda)} + \frac{\beta(x_{mus})}{x_{mus} \cdot u_{k-1}|x_{mus} \cdot u_{k-1}|} \cdot \frac{1}{2(||\hat{\Psi}_k||^2 + \lambda)}$



Simulations Prioritize Muscles over Motors:

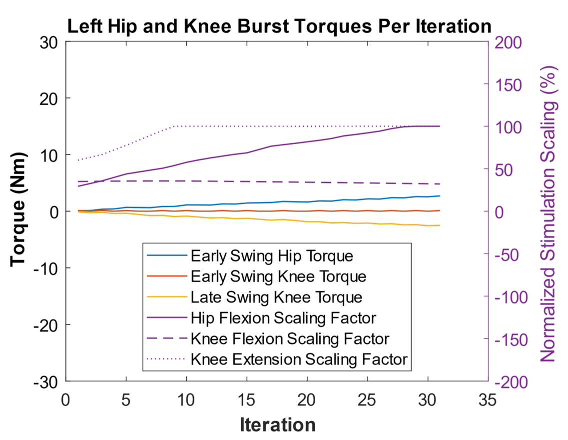
- ❑ (Below) Muscle recruitment (purple lines) maximized in early steps. (100% on right axis)
- ❑ Motor burst torques make up for deficit
- ❑ (Right) Error converges before 30 iterations.





Preliminary SCI Implementation

- ❑ Knee extension and knee flexion muscular recruitment maximized.
- ❑ Motor torques slowly make up for deficit



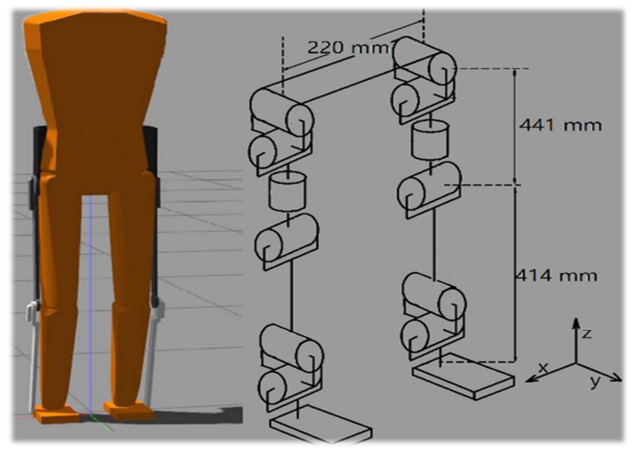
Future Work

- ❑ Free pelvis and add heel-strike in simulation
- ❑ Extend BIOTILC with robustness against initial states
- ❑ Learn unique stimulation patterns instead of scaling a premade pattern
- ❑ Adjust timing of motorized bursts through the gait cycle
- ❑ Additional SCI Testing

Reinforcement Learning for Controlling Dynamic Walking

3D biped model in GAZEBO simulation environment

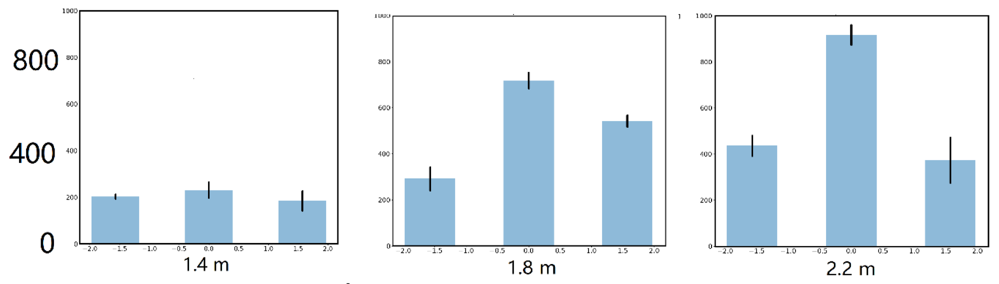
Core control system developed for 1.8m tall human/exo, then enhanced using a reinforcement learning algorithm.



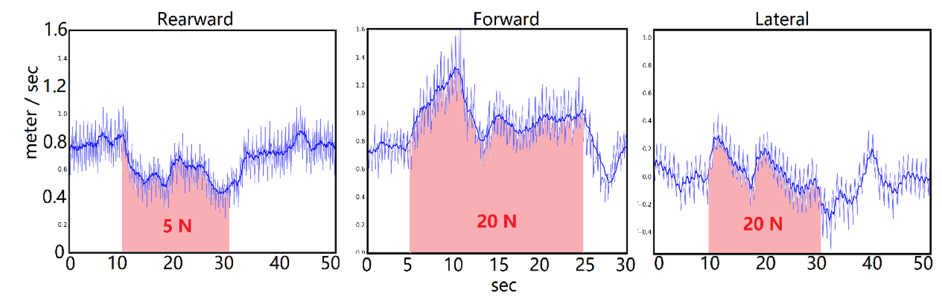
- ❑ Separate controllers for swing and stance reduce the dimensionality of the problem.
  - ***Stance leg:*** Torso stability task
  - ***Swing leg***: Optimal foot-placement task
- ❑ The core controller was robust to impact and persistent disturbances, but it failed if the model was changed (e.g. if another person used the system or the user picked up an object).

Reinforcement Learning with Proximal Policy Optimization (PPO) trained a neural net controller for enhanced robustness. The parameters for the neural net swing leg foot-placement controller were optimized after the stance controller was tuned.

Controller trained for 1.8m tall human/exo is robust for humans 1.4 – 2.2 m tall.



0.1 second impact disturbances in Newtons vs. direction of disturbance: rearward, lateral and forward. 1.4m tall (left), 1.8m tall (middle) and 2.2m tall (right) human/exo models. In each case the controller resists impacts in rearward, lateral, and forward directions.



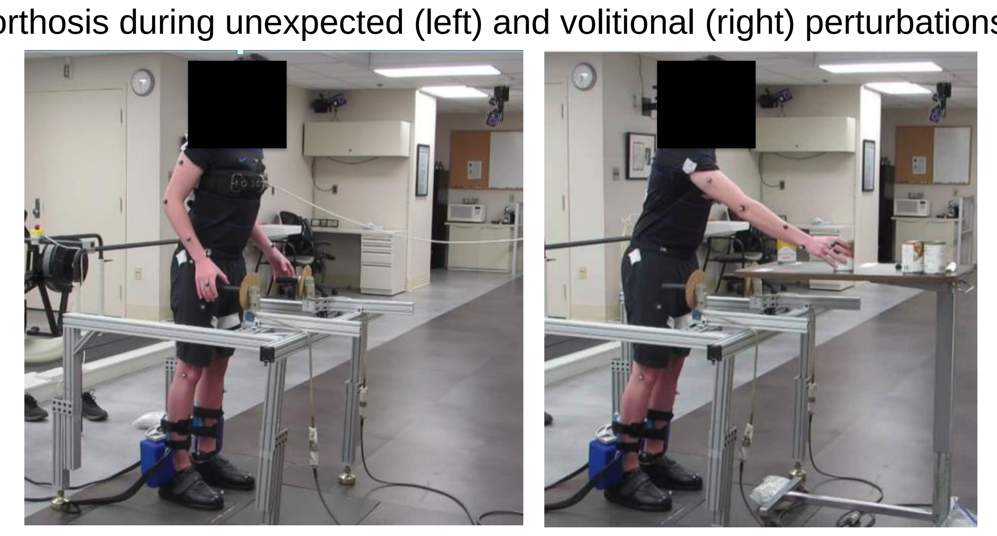
Speed of the biped vs. time with a persistent force. From left to right, force on torso is rearward, forward and lateral. In the left and middle, the speed is in the forward direction. In the right, the speed is in the direction of the lateral force. The controller adapts to stabilize the speed.

Powered Ankles for Standing Balance

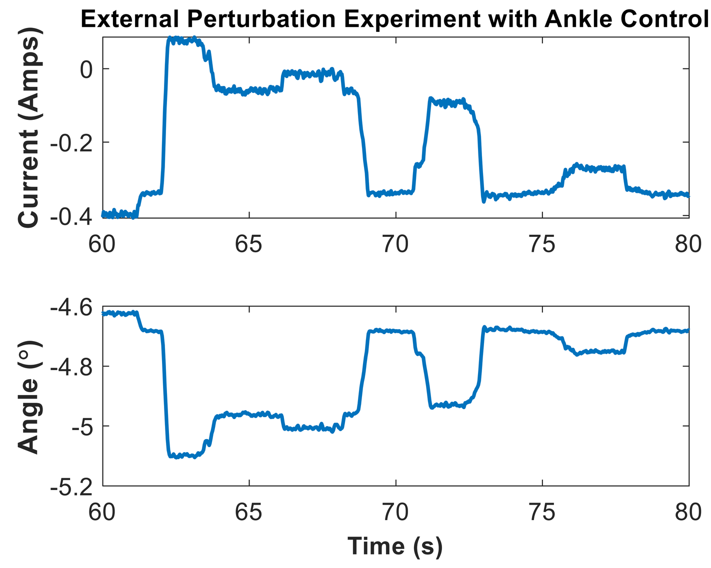
Perturbation Experiments Destabilized Participant

- ❑ Powered ankle joints have been implemented for standing and walking balance (right)
- ❑ External perturbations: A linear actuator randomly pulled the test subject in the forward direction, with three perturbation magnitudes at 3-5% bodyweight.
- ❑ Internal perturbations: the participant moved 2 weighted jars between 4 locations on a table

BELOW: Able-bodied participant wearing the powered ankle orthosis during unexpected (left) and volitional (right) perturbations.



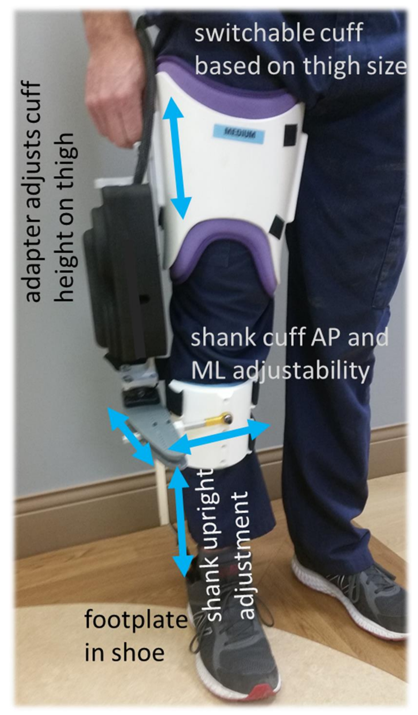
- ❑ A proportional-derivative controller helped the user maintain an upright posture to counteract the perturbations (below)



Unilateral Adaptation for Stroke Survivors

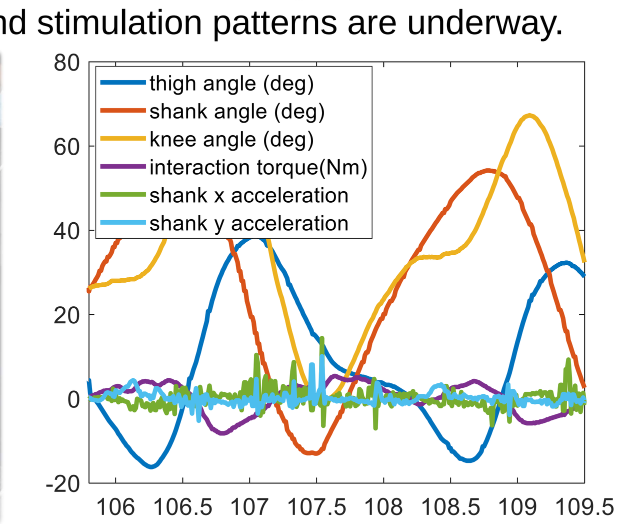
Modular Hardware Allows Adaptation for Other Neurological Conditions

- ❑ Orthosis mounted sensor signals are sampled by the controller to determine phase of gait and coordinate exoskeletal knee assistance motor burst torques make up for deficit
- ❑ Surface stimulation applied to muscles in the thigh and shank
- ❑ Stimulation drives improvements in gait speed while the motor ensures toe clearance in swing and knee stability in stance.



ABOVE: Unilateral adaptation for stroke survivors requiring knee assistance.

RIGHT: BELOW: (Left) Stroke survivor shown wearing the device during fitment. (Right) Preliminary walking experiments with hip, knee, and ankle angle. Refinements to the motor control and stimulation patterns are underway.



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