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A Framework for Modeling and Simulation of Neuromuscular Control of Walking

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Abstract

Our walking gait is a result of coordinated activations of different muscle groups controlled by the central nervous system (CNS). High degrees of freedom of our muscular system and our articulated lower limb kinematic chain, i.e. motor abundance, allows CNS to orchestrate an optimal walking gait while enables performing secondary tasks and dealing with unexpected perturbations. Gait optimality can be examined and modeled using model-based and model-free optimal control approaches. To stabilize walking, CNS vastly benefits from co-activation of agonist-antagonist muscles to modulate the joint mechanical impedance, which enables rejecting perturbations and return to desired trajectories. This work presents our achievements in neuromuscular modeling of gait on i) modeling variable joint impedance in lower limbs, ii) identifying optimal cost functions of natural walking and iii) using these findings along in generating dynamic simulations of gait, which enabled us to test adaptive control of assistive robotics systems such as lower limb exoskeletons.

To obtain accurate joint impedance models, we used perturbation experiments and developed techniques to account for gait variability, which can worsen our joint impedance estimates. Our proposed method employs a clustering of unperturbed gait to identify a set of equilibrium trajectories allowing us to find the best baseline for each perturbed trajectory. We used our technique in simulations and experiments, and the results demonstrate its superiority over the conventional techniques. Our method showed decreased expected error upper bound in simulated ankle stiffness by five folds and obtained more accurate experimental apparent hip impedance during swing phase on two subjects with an increased variance accounted for up to 7.5%.

To investigate the optimal cost function for walking, we used deep reinforcement learning (DRL) for interactive learning of walking in a musculoskeletal model. While we did not use any human gait data in the training of DRL agent, a natural walking gait emerged that demonstrated Pearson correlation of 0.95 and 0.83 with human gait hip and knee trajectories, respectively. DRL walking showed similar spatiotemporal parameters to those of healthy walking. This study showed that cubed muscle activation penalty and jerk penalty should be gradually increased during learning to walk to obtain natural walking efficiently.

Finally, we developed a dynamic musculoskeletal simulation of individuals with incomplete spinal cord injury and tested our exoskeleton adaptive controller on that. Our preliminary results showed the effectiveness of the adaptive controller in detecting the intent of the user and helped them achieve their desired gait pattern.