

The Stretch Reflex and Postural Control During Disturbed Quiet Stance

Team Members

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Narration of presentation

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Motivation and Background

The global prevalence of spinal cord injury (SCI) has been estimated at 236-1009 per million people, putting the global number of people affected by SCI as high as seven million¹. Many of those with SCI have "complete" injuries. Patients with complete spinal cord injury have no motor or sensory control below the site of injury¹. An effective therapy for recovering motor control does not exist for these patients.

Recently, Angeli et. al² showed that epidural stimulation, both with an implanted stimulator and a non-invasively placed stimulator, allowed complete SCI patients to achieve voluntary movement of the lower limbs. The recovery of motor function included the ability to regulate the magnitude and timing of muscle activation and movements and showed coordination of muscle activation between the flexors and extensors. Building on this work, Rejc et. al³ showed that intensive stand training and step training with epidural stimulation led to vast improvements in standing and stepping, with patients achieving full weight-bearing standing and non-weight-bearing stepping with normal stride lengths. However, step training following stand training decreased the weight-bearing standing ability of these SCI patients³.

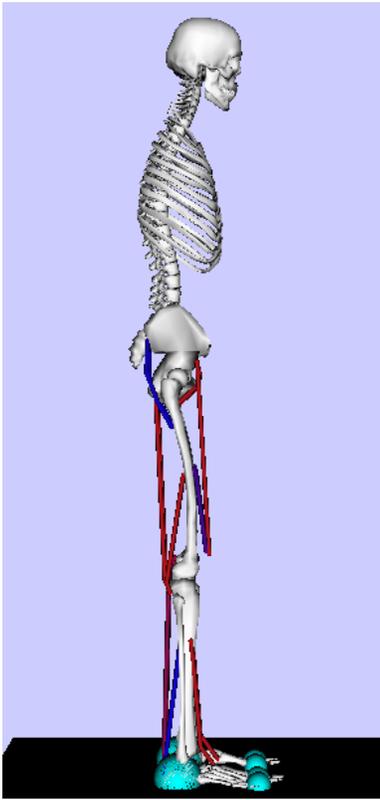
These improvements in motor function are thought to be possible because of neural plasticity in surviving neurons that cross the site of injury. In other words, "complete" spinal cord injuries that did not allow for motor control or sensory function without epidural stimulation actually were not complete. Epidural stimulation and training allows these patients to regain some motor control as long as epidural stimulation is being applied, possibly by enhancing the voluntary drive signals or by increasing the receptivity of sub-injury neurons. Improvements after task-specific training indicate growth of novel interneuronal connections.

The fact that step training after stand training reduced patients' ability to stand may evidence the limited ability of the human spinal networks for motor learning. During stepping, spinal neuronal networks called pattern generators are thought to be fundamental to achieving coordinated movements. Pattern generators can actually generate coordinated movement without any descending input⁴. During standing, a variety of peripheral and central strategies are thought to play an important role in undisturbed and disturbed quiet stance. These include reflexes driven by peripheral feedback from proprioceptive and tactile sensory neurons, as well as feedforward strategies. The stretch reflex is thought to play an important role in disturbed quiet stance, particularly in the early response from zero to one seconds after a disturbance⁵. The sensory input for the stretch reflex comes from muscle spindle neurons, which wrap around specialized muscle fibers, but the response is thought to rely on central spinal networks⁶. It is possible that step training and stand training affect the ability of the descending, voluntary signals to influence these spinal networks, in particular the central pattern generator networks and the stretch reflex networks.

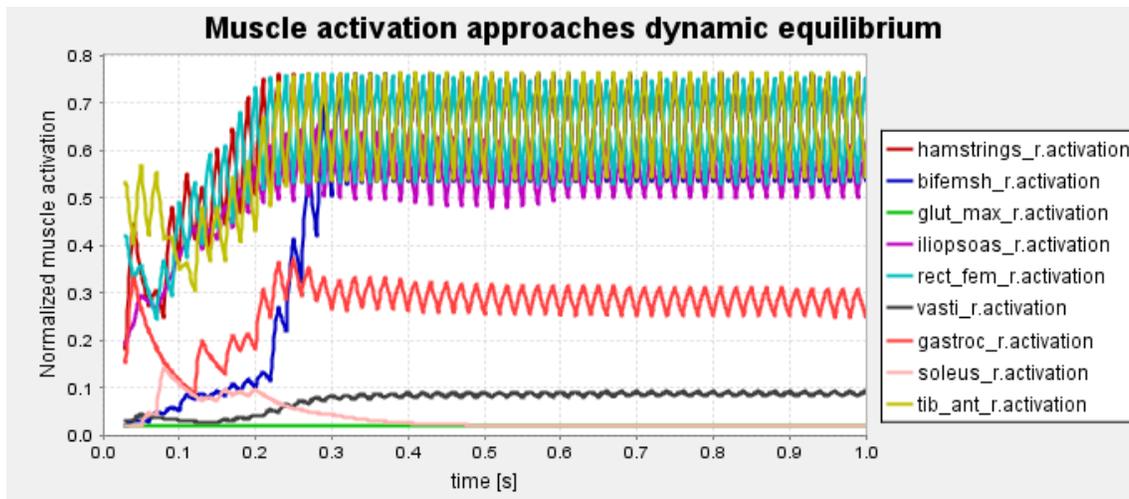
The goal of this research was to further investigate how the stretch reflex affects the ability to maintain quiet stance under disturbance. How might a reduced stretch reflex response affect the ability of a patient to withstand disturbance forces during quiet stance? The answer to this question is relevant to a patient who has a reduced ability to drive the stretch reflex response due to the nature of their specific injury, or who may have a reduced ability to drive the stretch reflex after step training. To investigate the role of the stretch reflex on maintaining quiet stance under disturbance, I applied horizontal disturbance forces in the anterior-posterior direction to the pelvis of a nine degree of freedom (DOF), eighteen muscle model confined to motions within the sagittal plane.

Methods

I used the 9 DOF, eighteen muscle model (below) developed by Ajay Seth, Darryl Thelen, Frank C. Anderson, and Scott L. Delp, which was subsequently modified by Carmichael Ong. The ankle and hip are modeled as pin joints, and the knee as a planar joint with prescribed x-y motions as a function of knee angle. Insertion of the quadriceps is handled by moving points in the tibia frame. Two contact spheres on the feet produce the ground reaction forces needed for standing support. The Hunt-Crossley contact model is used to calculate the contact force.



To determine baseline muscle activations for stance, I first locked the model's ankle, knee, and hip joints and ran a forward dynamics simulation until the model came to rest in a standing position. Starting from this pose, I unlocked the ankle and ran another forward dynamics simulation, so that the model could more evenly distribute weight between the front and rear contact spheres. Using this pose as my initial pose, I ran the computed muscle control tool to find baseline activations that could hold this stance. CMC produced activations that oscillated around an average activation for each muscle, as the algorithm alternated between choosing muscle activations that drove the contact spheres into the ground plane and compensating by reducing muscle activations (see below). I chose the average of these muscle activations as an approximation to the muscle activations that would be present in response to the average ground reaction force. These baseline activations allowed the model to stand for more than two seconds (~2.4 s) during a forward dynamic simulation.



To simulate stretch reflexes, I incorporated into the model the stretch reflex controllers developed by Matt Demers, which are [available for download on his Github repository](#). These controllers can be used to simulate both the position-based and velocity-based properties of the stretch reflex. For example, a muscle stretching beyond its optimal fiber length will develop a force proportional to the difference between the current muscle length and the optimal fiber length as well as to the muscle fiber velocity. I hand-tuned the gain k_p applied the positional error as well as the gain k_v applied to the velocity error to produce the least deviation from a vertical pose at the end of a three second forward dynamic simulation. I observed that applying stretch reflexes only to the biarticular muscles, namely the rectis femoris, hamstrings, and gastrocnemius, produced the best results. I also chose pure position and pure velocity-based gains, settling on $k_p = 2500$ in the first case and $k_v = 750$ in the second.

To disturb the model, I applied a sinusoidal positive half cycle disturbance force to the model. The disturbance force had a duration of 0.2 seconds and a peak magnitude of either 2 Newtons or 10 Newtons. The force was directed in the anterior-posterior direction and was applied to the center of mass of the model's pelvis. The model had either the pure position or pure velocity stretch reflex controllers applied to the biarticular muscles. I also ran two additional trials with pure velocity stretch reflex controllers applied to the soleus and tibialis anterior as well as to the biarticular muscles. The performance metric of the disturbance trials was fall time. I approximated fall time as the time until one of the foot contact spheres lost contact with the ground, i.e. until the vertical component of the ground reaction force on that sphere dropped to zero.

Results

The results of the disturbance trials are shown below. Neither the pure velocity nor the pure position stretch reflex controllers improved time to fall relative to just the baseline activations without stretch reflex controllers. Additionally, applying stretch reflex controllers to the soleus and tibialis anterior either did not improve time to fall or reduced time to fall relative to the trials where stretch reflexes were applied only to biarticular muscles.

Discussion

The results of this study indicate that stretch reflexes with a static gain tuned for undisturbed stance do not in and of themselves reduce the time to fall due to a disturbance. While these results may be surprising, they agree with prior research. Fitzpatrick et. al displaced subjects' limbs while collecting EMG muscle activation data to measure the gains associated with the stretch reflex. The authors concluded that the gain was too low for standing to be attributed to this feedback mechanism. This implies that muscle activations attributable to stretch reflexes do not make up the most significant component of muscle activations during quiet undisturbed stance. However, observation of the disturbance trials led to the conclusion that the stretch reflex controllers did help keep joint angles close to their initial angles throughout the fall, even at very low gain values (data not shown). It's possible that the baseline gains of the stretch reflex help maintain joint angles during the early response to the disturbance, which puts the body in a more favorable position for middle and late latency feedforward responses. Indeed, subjects who undergo anterior-posterior floor translations maintain relatively constant knee and hip angles while rotating about the ankle and rocking onto the heels and toes to maintain balance. With larger disturbances, subjects rotate at the waist to reposition their center of mass to be above their center of pressure⁵. Mansouri et. al used baseline activations with a stretch reflex controller that chose optimal gains at each timestep, and were able to achieve balance and return to resting position under a variety of disturbance forces. This demonstrates the viability of a continued role for the stretch reflexes even after feedforward mechanisms begin, as the gains of the stretch reflex can be tuned via supraspinal inputs.

Downloads

Read me (how to use the files below): [readme.txt](#)

Modified model with stretch reflex controllers: [2_wDefaults_gait9dof18musc_Thelen_BigSpheres_20170403.osim](#)

Reserve actuators with added disturbance force actuator: [quietStance_Reserve_Actuators_withDisturbance.xml](#)

MATLAB file to generate a controls file with a disturbance force: [Generate controls file with disturbance force.m](#)

Input file which the MATLAB file opens to obtain excitation values (already averaged from results of CMC): [quietStance_initialStates.sto](#)

Example controls file with a disturbance force: [quietStance_desiredControls_withDisturbance.sto](#)

References

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- 2.) Angeli, Claudia A., et al. "Altering spinal cord excitability enables voluntary movements after chronic complete paralysis in humans." *Brain* 137.5 (2014): 1394-1409.
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- 7.) Mansouri, Misagh B., and Jeffrey A. Reinbolt. "A platform for dynamic simulation and control of human movement." (2011).

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