Spinal Cord Stimulation with Activity-Based Training: Effect on Spasticity

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***Abstract*— Spasticity is common after a spinal cord injury (SCI). Pharmacological treatments for spasticity often have adverse effects on neurorehabilitation. Spinal cord transcutaneous stimulation (scTS) and activity-based training (ABT) have been shown to be useful tools for neurorehabilitation which can lead to improved function for people with SCI. Our preliminary data suggests that neuromodulation of the spinal circuitry may result in attenuating spasticity.**

***Clinical Relevance*— Spasticity effects 65-70% of individuals following SCI, this technique of using ABT with scTS may allow for improvements in limiting spasticity.**

I. INTRODUCTION

Spinal-cord transcutaneous stimulation (scTS) can be applied to segments of the spinal cord following spinal cord injury (SCI) to provide neuromodulation and improve motor control [1]. Variations of stimulation intensity and choice of spinal segment for scTS have been shown to allow for preferential recruitment of neuromodulation [2]. It has also been shown that scTS in addition to activity-based training (ABT), specifically exoskeleton walk training, can lead to improved function for both complete and incomplete SCI participants [3].

Spasticity is a prevalent movement disorder with an annual incidence of 54 per million [4], [5] that develops in 65-70% of individuals after SCI [6]. A recent large cohort study showed 37% were prescribed anti-spasticity medication during hospital admission, 55% at 6 months post-injury, and 71% at one year [7]. Current treatment of severe spasticity by pharmacological treatments are associated with several concomitant side effects that have consequences including limiting the ability to participate in and respond to neurorehabilitation [8], [9].

In this study we evaluated the effect of scTS with ABT on muscle activation in the lower limbs for one incomplete SCI participant.

II. METHODS AND PROCEDURES

A. Study Participants

One female participant, with incomplete C5/6 spinal cord injury, participated in this study following informed consent – approved by the institutional review board of Kessler Foundation.

B. Spinal Cord Transcutaneous Stimulation

Targeted scTS was applied to participants as they performed ABT. The parameters for stimulation were decided based on systematic spinal mapping sessions in which parameters were modulated to assess optimal stimulation for therapeutic effect. Amplitude and frequency mapping sessions modulated their respective parameters at specific spinal roots of the cervical, thoracic, lumbar, and sacral spinal cord. One-inch transcutaneous electrical nerve stimulation (TENS) surface electrodes were placed over spinal roots and connected to a Neuro-Recovery Technology (NRT) stimulator (Onward, Eindhoven, the Netherlands). Specific, individualized, subthreshold stimulation parameters and locations were then selected for use during training.

C. Participant Training

The longitudinal training intervention consisted of ABT, in this case robotic exoskeleton gait and overground training, 3-4 days/week, 5 hours of training/week, using the EksoGT™ (Ekso Bionics, Richmond, CA) with the guidance of a trained physical therapist and a trained technician. For 60 training sessions, participant trained without stimulation. Following the conclusion of 60 sessions, participant then trained for an additional 34 training sessions with scTS in addition to ABT. During ABT, spinal cord transcutaneous stimulation was applied to various spinal roots of the cervical, thoracic, and lumbar spinal cord. Over the course of ABT, the participant progressed assistive devices: first walker, then crutches, then canes. Data was collected prior to exoskeleton training after 60 sessions of training, and once all training was completed.

D. EMG Data Collection Setup

Surface electromyography (sEMG) data were collected at 2520Hz pre-ABT, and 10kHz post ABT (MA400, Motion Lab Systems, Baton Rouge, LA, USA). Skin was shaved, cleansed with alcohol, and lightly abraded. Surface electrodes were placed [10] bilaterally on semitendinosus (MH), bicep femoris (BF), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), medial gastrocnemius (MG), soleus (S), and tibialis anterior (TA). Reference electrode was placed on clavicles.

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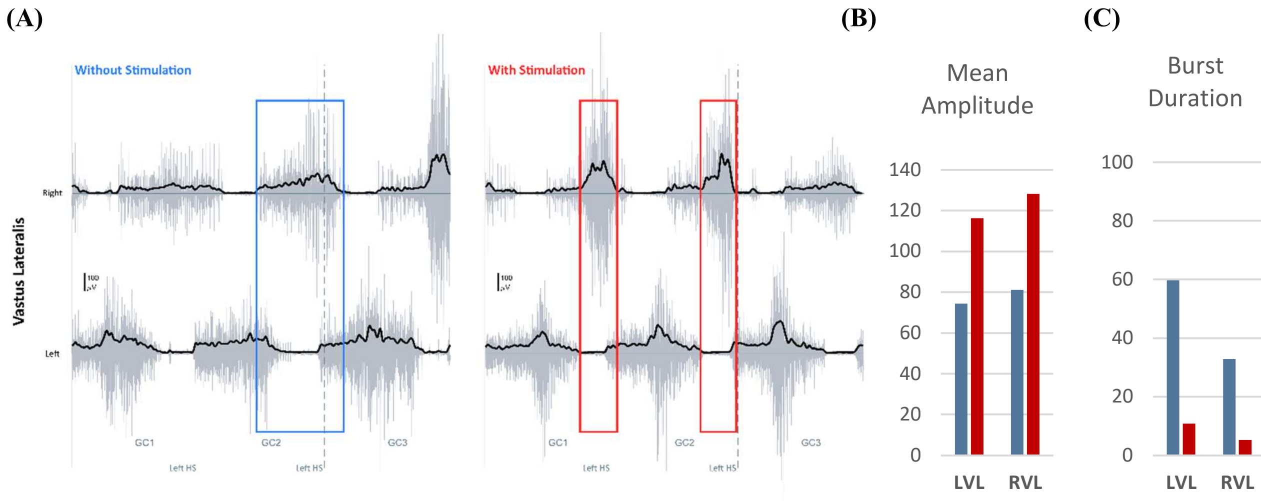


Figure 1. **A)** Single session muscle activation comparison for overground gait without stimulation (left panel) versus with stimulation (right panel) of Vastus lateralis sEMG. The immediate effect (same day) of stimulation decreased interlimb coactivation to show more reciprocal interlimb gait and increased amplitude of sEMG with stimulation. Grey represents filtered sEMG; Black represents RMS of the filtered sEMG. **B)** The mean amplitude of the VL when muscle is active, per gait cycle, without and with stimulation. **C)** The burst duration – percent of gait cycle in which VL muscle is 'On', without and with stimulation.

E. EMG Post-processing

Processing of sEMG data was performed using programs written in MATLAB (MathWorks™, Natick, MA, USA). A 4th order Butterworth bandpass filter (cutoffs: 20Hz and 450Hz) and a 4th order Butterworth notch filter for 60Hz noise were both applied to sEMG data. Data was then split up into gait cycles based on kinematic event markers for bilateral heel-strikes and toe-offs.

Fast Fourier Transform (FFT) was applied to the EMG data. Peak power was used as a measure in the frequency

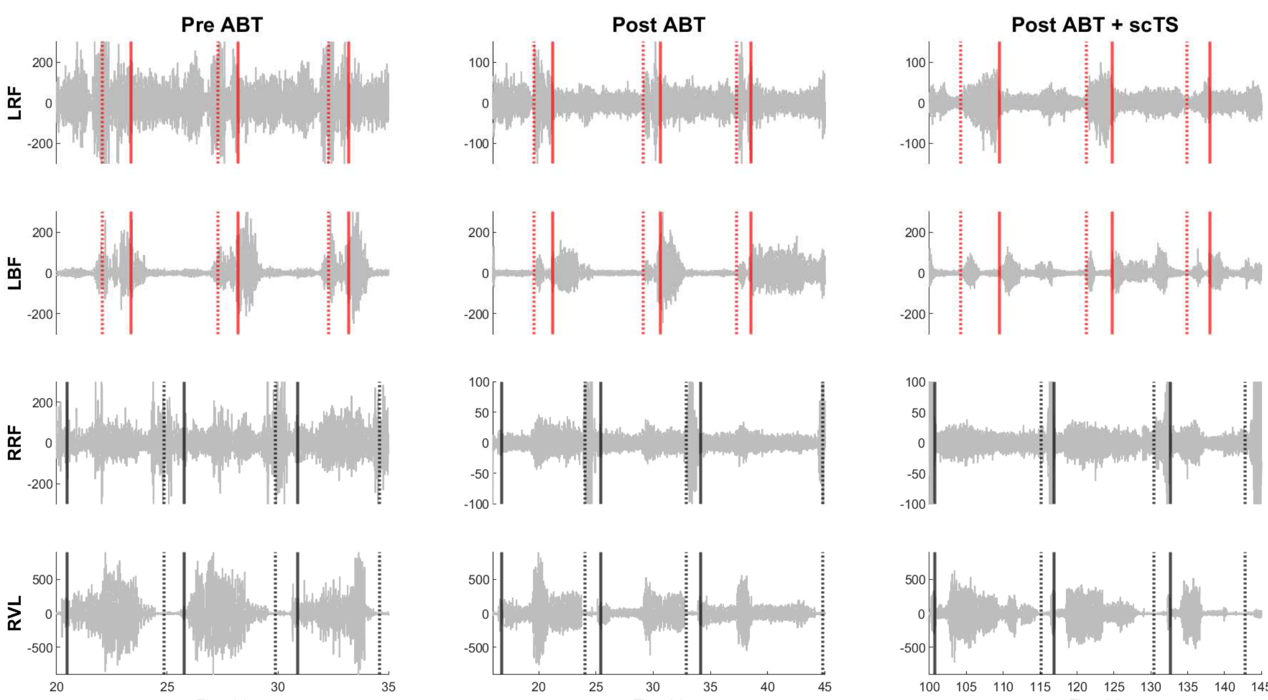
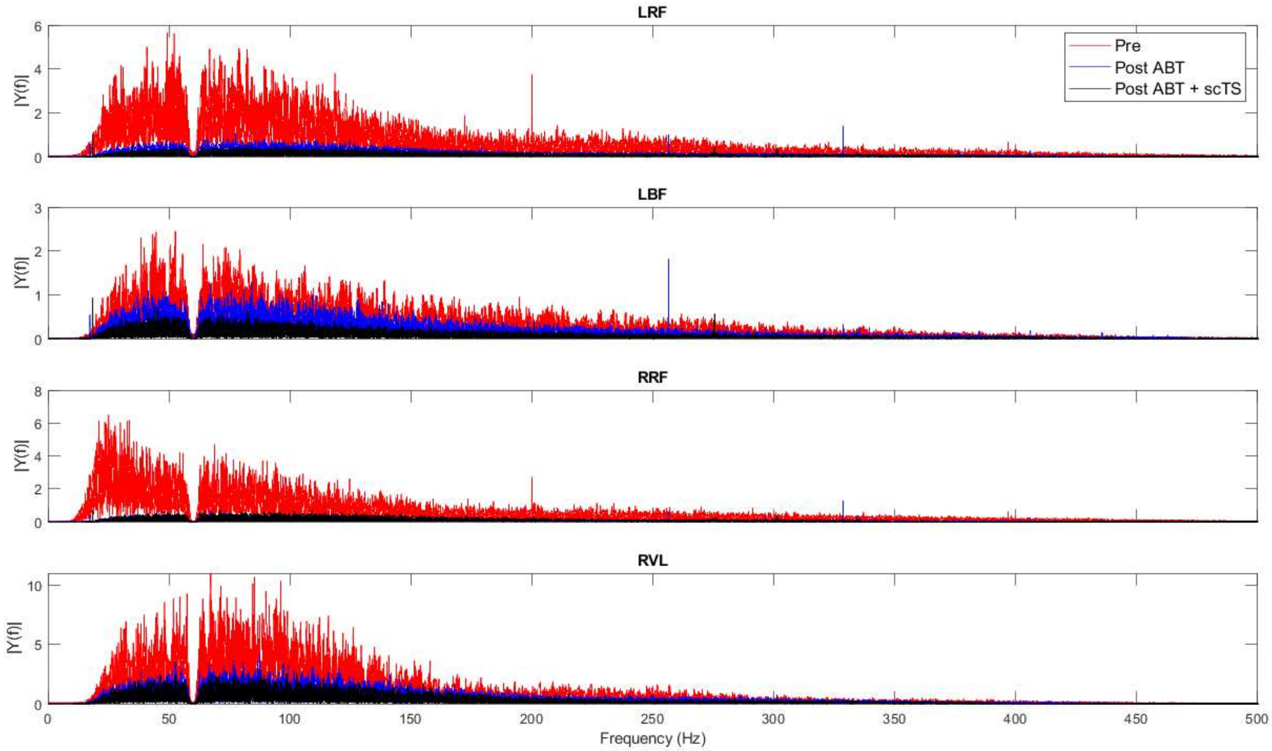


Figure 2. Filtered sEMG for 4 muscles: Left Rectus Femoris (LRF), Left Biceps Femoris (LBF), Right Rectus Femoris (RRF), Right Vastus Lateralis (RVL). Each column of plots is from a different data collection session. 'Pre ABT' is when the participant first joined the study before they began ABT, 'Post ABT' is following 60 hours of ABT only, and 'Post ABT+scTS' is following 34 hours of ABT with scTS active. All EMG data within this figure is without stimulation and with the participant using a walker overground. The vertical lines are gait events, with red referring to left side and black referring to right side. The solid lines are heel-strikes, and the dotted lines are toe-offs. Three gait cycles are shown for each data collection session.

(A)



(B)

Session	Peak Power LRF	Peak Power LBF	Peak Power RRF	Peak Power RVL
Pre	5.6558	2.4458	6.4854	10.9969
Post ABT	1.3856	1.8086	1.2675	4.2609
Post ABT + scTS	1.0020	0.9297	0.7411	2.5439

Figure 3. **A**) The power spectrum plots for the EMG walking data from three data collection sessions: Pre – before beginning ABT (red), Post – following completion of 60 sessions of ABT only (blue), and Post ABT +scTS – following 34 sessions of ABT with scTS active (black). **B**) The Peak power in the frequency domain for the 4 muscles (LRF, LBF, RRF, and RVL) in the three sessions.

domain to allow for quantitative comparison of the power of the signals [11].

III. Results

A. Single Session – Co-Activation of sEMG due to scTS

Figure 1A shows the immediate effect of stimulation on the sEMG of the vastus lateralis. With stimulation VL amplitude increased and burst duration decreased to improve interlimb coordination, as displayed in Figures 1B and 1C.

B. Longitudinal Testing – Effects of ABT and scTS on sEMG

Data was collected for three sessions, at various stages of the study as outlined in Figure 2 – 'Pre ABT' before starting ABT, 'Post ABT' after 60 hours of ABT without stimulation, and 'Post ABT + scTS' after 34 hours of ABT with scTS active. All sessions were collected without stimulation. Participant used a walker as an assistive device. The sEMG data for 4 muscles of the lower extremity during gait testing are reported in Figure 2. The four muscles shown are LRF, LBF, RRF, and RVL. Visually, there was a decrease in spasticity recorded in sEMG following post only ABT (60 sessions), and a further decrease post ABT + scTS (34 sessions)

C. Longitudinal Training – Effects of ABT alone and scTS + ABT in Power Spectrum

The power spectrum plots for the same 4 muscles are shown in Figure 3A for the three sessions collected. Figure 3B shows the peak power for each of the signals in the frequency domain. For all muscles, the peak power decreased from the 'Pre' session to both the 'Post' and 'Post ABT + scTS' sessions. This same change is also noticeable visually in the plot of the overlapping power spectrums.

For the LRF, there was a 75% drop in peak power from 'Pre' to 'Post ABT', and an additional 27% drop in peak power from 'Post ABT' to 'Post ABT + scTS'. There were similar drops of 26%, 80%, and 61% respectively, for LBF, RRF, and RVL from 'Pre' to 'Post ABT'. From 'Post ABT' to 'Post ABT + scTS', the power also dropped 48%, 41%, and 40%, respectively.

IV. Discussion

Exoskeleton gait training for 60 sessions decreased power (>25%), and with the addition of stimulation, there was a further decrease in power (>25%). These results are concomitant with the decrease in spasticity. Figures 2 and 3 illustrate this decrease in observed spasticity, in amplitude, and in burst duration from ‘Pre ABT’ to ‘Post ABT’. From ‘Post ABT’ to ‘Post ABT + scTS’, the repeated training sessions with both scTS and ABT decreased spasticity further and reflected a more intralimb (RRF and RBF) and interlimb (RRF and LRF) reciprocal firing pattern. These results indicate similar drops in the peak power of the sEMG in the frequency domain, suggesting that the addition of scTS decreased spasticity and the peak power in the power spectrum.

Neuromodulation of the spinal circuity via ABT gait training alone or with scTS stimulation to enhance the spinal-motor activation pools of activity has an inhibitory effect on the spasticity within the lower limb. Of note is the effect of ABT – gait training alone decreased the amplitude of LRF and RRF and potentially the reciprocally firing pattern of agonist/antagonist (LR/LB). Both these LRF and RRF muscles established a decrease in Peak Amplitude. The addition of scTS to ABT continued this inhibitory effect on spasticity. ScTS + ABT training also had an excitatory effect of increasing the burst duration (LRF) to reflect an increase in reciprocal gait.

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