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# Modulation of Ankle EMG in Spinally Contused Rats Through Application of Neuromuscular Electrical Stimulation Timed to Robotic Treadmill Training

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*Abstract*— **While neuromuscular electrical stimulation (NMES) has enabled patients of neuromotor dysfunction to effectively regain some functions, analysis of neuromuscular changes underlying these functional improvements is lacking. We have developed an NMES system for a rodent model of SCI with the long term goal of creating a therapy which restores control over stepping back to the spinal circuitry.**

**NMES was applied to the tibialis anterior (TA) and timed to the afferent feedback generated during robotic treadmill training (RTT). The effect of NMES+RTT on modifications in EMG was compared with that of RTT alone. A longitudinal study with a crossover design was conducted in which group 1 (n=7) received 2 weeks of RTT only followed by 2 weeks of NMES+RTT; group 2 (n=7) received 2 weeks of NMES+RTT followed by RTT only. On average, both types of training helped to modulate TA EMG activity over a gait cycle, resulting in EMG profiles across steps with peaks occurring just before or at the beginning of the swing phase, when ankle flexion is most needed. However, NMES+RTT resulted in concentration of EMG activation during the initial swing phase more than RTT only. In conjunction with these improvements in EMG activation presented here, a more complete analyses comparing changes after NMES+RTT vs. RTT is expected to further support the notion that NMES timed appropriately to hindlimb stepping could help to reinforce the motor learning that is induced by afferent activity generated by treadmill training.**

## I. Introduction

One approach to assist spinal cord injury (SCI) patients with walking is to apply neuromuscular electrical stimulation (NMES) to nerves which innervate the leg muscles predominantly used in walking [1-3]. NMES has been used to strengthen muscles which are weakened by stroke [4-6]. To assist with walking, NMES is typically applied to artificially replace muscle activation that is missing due to SCI with externally induced activation [1, 7-9]. One question that still remains is how peripheral nerve stimulation might alter spinal cord circuitry, rather than serve primarily as a muscle strengthening tool or as an artificial prosthesis, and assist with long-term rehabilitation after spinal cord injury. Inducing activity in the spinal cord either directly or indirectly (as with locomotor training) has long been observed to help shape spinal cord circuitry and its ability to control motor behavior [10, 11]. It has been suggested that such spinal plasticity could be encouraged with NMES by a Hebbian mechanism [12]. In this scenario, timing electrically induced motor activity with sensory activity might be an important factor in encouraging synaptic potentiation.

We have developed an NMES system for a rodent model of SCI by which stimulation can be timed to robotically controlled treadmill stepping. This system was engineered to enable research and development of an NMES therapy such that nervous pathways would be activated at appropriate times to promote the necessary spinal plasticity that would enable patients to eventually walk without the artificial assistance of NMES. This approach contrasts with the conventional use of NMES, in which stimulation is applied at the time that muscle activation is expected in the normal (healthy) gait cycle [7, 13]. Stimulation is typically delivered for a fixed duration and at a fixed time interval relative to the beginning of a step cycle, which is usually detected by some external trigger, such as a mechanical foot switch.

The long term effect of conventional NMES combined with treadmill training on walking speed has already been measured in humans [14, 15]. We are developing an NMES system integrated with a robotic treadmill training (RTT) device that could be used for studying how to appropriately stimulate peripheral nerves in order to invoke spinal plasticity in the rehabilitation of stepping. Thus, we developed our system for a rodent model of SCI and we analyzed the effect our NMES therapy has on the EMG produced by the rat after a period of training, in addition to kinematic measures.

Jung et al. have already developed a system for studying the mechanisms of rehabilitation of stepping through spinal plasticity in a rodent model of SCI [16]. They applied NMES to rats which were suspended so that their limbs could move freely, as opposed to our system which applies stimulation while the rats undergo treadmill stepping during training periods. The aim of our work thus differs in that we focus on how to appropriately time stimulation to stepping in order to strengthen spinal cord circuitry involved in walking and thereby encourage normal autonomous stepping.

In our combined NMES and RTT system, stimulation was timed to hindlimb position during treadmill training. We

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have previously presented our system design and shown the tendency for NMES+RTT to improve the EMG step profile more than patterned stimulation alone [17, 18]. Here, we compare the effect of NMES+RTT on modifications in EMG with that of RTT alone.

## II. Methods

### A. Animal experiments

All procedures with rats were carried out in accordance with protocols approved by the Institutional Animal Care and Use Committee at California State University, Los Angeles. Twenty rats were spinally contused with a force impactor (Precision Systems & Instrumentation, Lexington, KY) at the mid-thoracic (T9) level to model severe spinal cord injury. Two weeks later, a pair of Teflon-coated multistranded stainless steel wire electrodes was implanted in the tibialis anterior (TA) muscle of each hindlimb, across the muscle fibers for EMG acquisition and a pair along the muscle fibers for electrical stimulation. Seventeen rats survived the spinal cord injury long enough to complete training; electrode implants remained intact in 14 animals out of those 17 for the course of the study. Group 1 ($n$=8) received 2 weeks of RTT only followed by NMES+RTT, while Group 2 ($n$=6) received therapies in the reverse order (Fig. 1). During testing, neither robotic assistance nor electrical stimulation was provided.

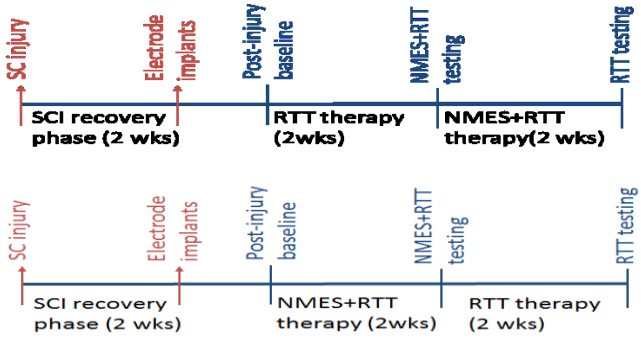


Figure 1. Study timeline for Group 1 (a) and Group 2 (b)

For RTT therapy, 85% of the rat's body weight is supported while robotically controlled arms guide the rat's ankle according to a pre-programmed trajectory to step on a treadmill moving at 6cm/s. A previous study [19] showed providing low levels of assistance was more beneficial to rehabilitating stepping than rigid robotic control. Thus, the robot was programmed to apply forces only if the rat deviated more than 1cm from the desired trajectory. During NMES+RTT therapy, biphasic current pulse trains (70pps, 100μs pulse width, and 1.5 times the animal's motor threshold) are delivered to the TA while the rat is performing RTT. The stimulation is timed occur, according to optically sensed ankle position, during the first 50% of the swing phase, as shown in Fig. 2. However, if the rat's ankle position did not follow the programmed pattern sufficiently, as defined by the correlation coefficient between desired and actual trajectory in the past 50ms, then the stimulation is aborted. In contrast to conventional FES systems which apply stimulation for a fixed duration at every gait cycle, the stimulation in NMES+RTT can be of variable duration depending on the step trajectory from gait cycle to gait cycle and only occurs during gait cycles in which the step trajectory is deemed sufficiently worthy of reinforcing.

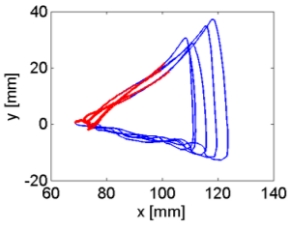


Figure 2. Stimulation coordinated to the step trajectory of rat hindlimb. The robot guides the rat ankle along a pre-programmed trajectory (solid blue trace), and then electrical stimulation is applied during the 1st 50% of the swing phase (dotted red trace) unless the rat's actual trajectory is deviating from the desired trajectory according to a correlation measure.

### B. EMG Analysis

The EMG profile during a gait cycle for each rat was created by rectifying raw EMG, applying a moving average filter using a 25-ms window to extract the EMG envelope, performing step detection on the simultaneously recorded position signals, and averaging the EMG envelope across steps. We also defined γ (1) to be a measure of how well the EMG profile matched the normal EMG profile obtained from one rat from which pre-injury EMG during stepping was obtained (this also was corroborated by our previous study showing a similar EMG profile for rats who stepped well). This normal EMG profile typically rises from about 10% of the gait cycle before the beginning of the swing phase peaking near the beginning of the swing phase, and decreasing until about 50% of the swing cycle; we defined γ to measure the concentration of EMG energy during this portion of the gait cycle at which the normal EMG profile tends to peak.

$$\gamma = \frac{\int_{-10\%}^{50\%\sigma} \bar{s}(\tau)\, d\tau}{\int_{0}^{100\%} \bar{s}(\tau)\, d\tau} \times 100\,, \qquad (1)$$

where $s$ is the EMG profile of a given rat, and the bar represents the average across steps in a given test; τ represents the percent gait cycle and σ represents the proportion of the gait cycle during which the swing phase occurs.

## III. Results

Fig. 3 shows an example of the EMG profile at each testing time point (baseline, 2-week testing, and 4-week testing) for a rat in Group 1 (A) and Group 2 (B). Above each EMG profile plot is a plot of the average trajectory (bold solid red) as well as the trajectory for a sampling of individual steps (dashed gray) at regular intervals during the course of the test.

The EMG profile of the rat from Group 1 (Fig. 3) at baseline did not show much of a peak and was relatively flat through the gait cycle (γ =37.9%). Correspondingly, the rat

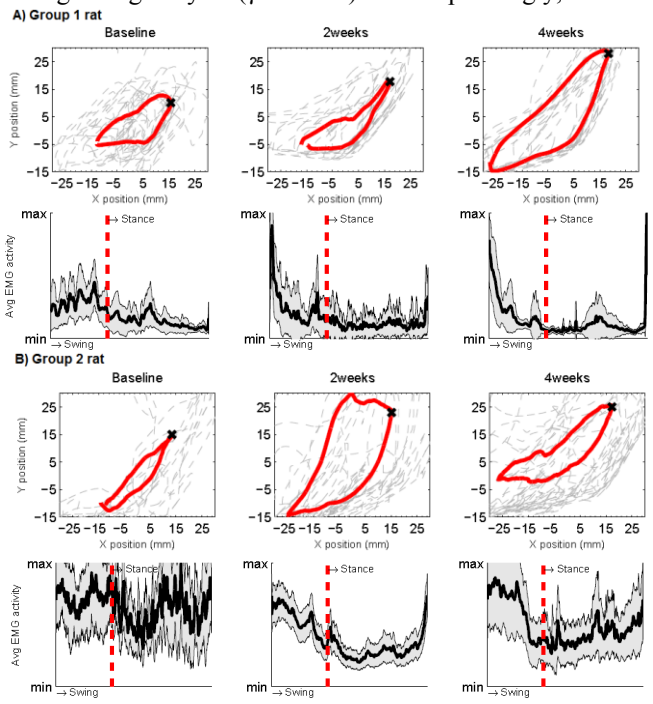


Figure 3. Sample EMG profiles, and corresponding trajectory plots, for a rat from Group 1 (A) and one from Group 2 (B) at baseline, after 2 weeks of RTT only (A) or NMES+RTT (B), and after a subsequent 2 weeks of NMES+RTT (A) or RTT only (B). The dashed traces in the trajectory plots show a random sampling of individual steps, while the solid bold trace shows the average trajectory. In the EMG profile plots, the gray outline indicates the 90% confidence interval; the dashed vertical line shows the end of the swing phase / beginning of stance.

produced a very disorganized stepping pattern. After two weeks of RTT only, the rat exhibited a sharper EMG profile (γ=46.7%) accompanied by more organized stepping patterns which more closely matched the desired trajectory. The peak, starting from a short preparation period before the swing phase through the early portion of the swing phase, became even sharper by the end of two weeks of NMES+RTT (γ =56.1%); in conjunction, the rat was still stepping with consistency and additionally producing longer steps. The rat from Group 2 (Fig. 3B) exhibited a very disorganized EMG profile (γ =27.0%) accompanied by dragging and poor stepping at baseline. The EMG profile improved to a much more organized EMG profile (γ =47.5%) and the steps more closely matched the desired trajectories (with the ankle being lifted higher and farther throughout the swing phase) with two weeks of NMES+RTT. Two additional weeks of RTT only did not lead to improvements in the step trajectories and led to more variable EMG profile with a lower γ value (γ =35.6%).

This trend was observed more generally across rats in each group (Fig. 4 and 5). Fig. 6 shows that average γ for Group 1 increased by 3.5% with 2 weeks of RTT and an additional 2.6% after 2 weeks of NMES+RTT; whereas the average Group 2 γ increased by 4.5% after 2 weeks of NMES+RTT and when followed by 2 weeks of RTT γ only improved by 0.8%. The increase in the concentration of EMG activity during the early portion of the swing phase,

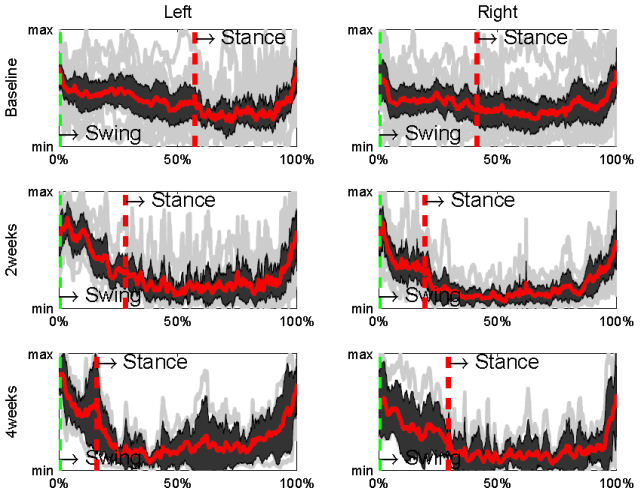


Figure 4. Group 1 average EMG profiles of the left and right hindlimbs at baseline, 2-week testing (after RTT), and 4-week testing (after NMES+RTT), plotted vs. % gait cycle. EMG profiles of individual rats (faint gray), group mean (bold solid red), and 90% CI (black shadow).

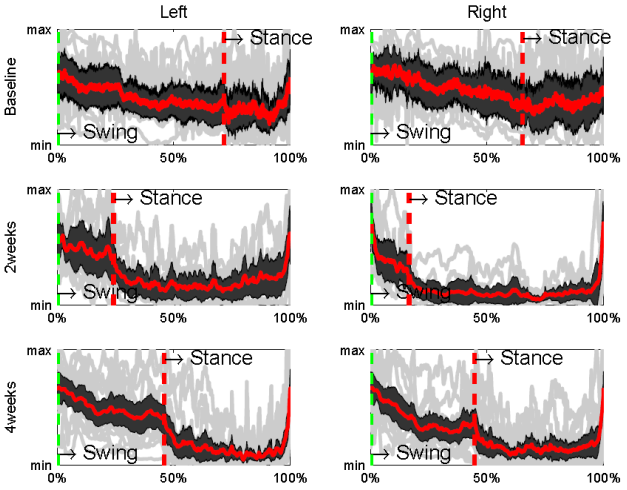


Figure 5. Group 2 average EMG profiles at baseline, 2-week testing (after NMES+RTT), and 4-week testing (after RTT), plotted vs. % gait cycle.

relative to baseline gamma values, was statistically significant after two weeks of NMES+RTT (paired t-test on all rats; i.e., from both groups, $p < .01$) but not after RTT training ($p$=.10). The amount of improvement achieved by each type of training appears to be state-dependent in that it depended on the order in which the two therapies were applied.

## IV. Discussion

In a previous study, NMES+RTT was shown to help improve step kinematics and underlying EMG patterns more than the same patterned stimulation alone, suggesting that timing the stimulation to afferent feedback generated during

stepping promotes long-term changes in neuromotor control of stepping. We have also observed that NMES+RTT leads to greater improvements in stepping and burst activity than RTT alone when the robotic assistance provided is quite

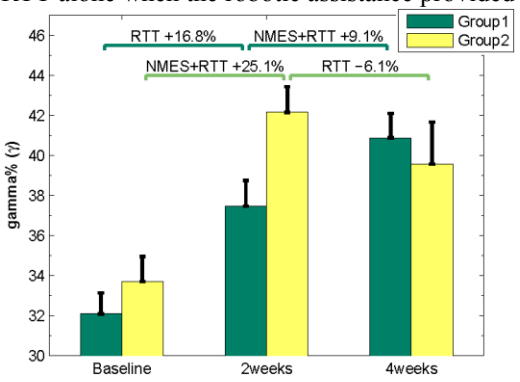


Figure 6. Changes in the shape of the EMG profile (according to the γ measure) from baseline to 2 weeks of RTT followed by 2 weeks of NMES+RTT (Group 1) and from baseline to 2 weeks of NMES+RTT followed by 2 weeks of RTT (Group 2).

rigid and does not allow for much deviation from the desired trajectory (unpublished results). In the present study, the effect of NMES+RTT and RTT alone on EMG profiles were compared when the robotic assistance was provided at gradually decreasing levels such that the rat had more control over their own stepping and lesser forces were imposed to allow for greater flexibility in the actual trajectory as training progressed. Afferent activity, as generated during treadmill training, is believed to promote spinal plasticity and resulting improvements in stepping [10]. Our results indicate that RTT is beneficial in organizing EMG activation patterns during step cycles but NMES+RTT further increased the benefit. These improvements are consistent with the notion that NMES timed appropriately to hindlimb stepping could help to reinforce the motor learning that is induced by afferent activity generated by treadmill training. We are presently analyzing the variability of EMG activation patterns across steps as well as developing a correlation measure between these activation profiles and a healthy (pre-injury) activation profile. One major question that remains outstanding is whether the stimulation could be timed differently or applied at different amplitudes, pulse width, and frequencies to further improve the effects of NMES+RTT.

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