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Effect of Functional Electrical Stimulation (FES) Combined with Robotically Assisted Treadmill Training on the EMG Profile

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***Abstract*—Functional electrical stimulation (FES) is used to assist spinal cord injury patients during walking. However, FES has yet to be shown to have lasting effects on the underlying neurophysiology which lead to long-term rehabilitation. A new approach to FES has been developed by which stimulation is timed to robotically controlled movements in an attempt to promote long-term rehabilitation of walking. This approach was tested in a rodent model of spinal cord injury. Rats who received this FES therapy during a 2-week training period exhibited peak EMG activity during the appropriate phase of the gait cycle; whereas, rats who received stimulation which was randomly timed with respect to their motor activity exhibited no clear pattern in their EMG profile. These results from our newly developed FES system serve as a launching point for many future studies to test and understand the long-term effect of FES on spinal cord rehabilitation.**

I. INTRODUCTION

FUNCTIONAL electrical stimulation (FES) is a biomedical technology designed to augment or supply muscle activation which is otherwise absent due to neurological damage. For example, FES is applied to the lower limbs in spinal cord injury in an attempt to assist patients to flex their ankle during the swing phase of the gait cycle [1-4]. FES has mostly been used to have an immediate effect on walking [5], and the few studies which analyzed the rehabilitative effect of FES on long-term improvements in walking did not analyze the underlying effect on EMG [5, 6].

We are engineering an FES therapy timed to robotically controlled movements in order to effect lasting changes in walking even after stimulation is removed [7]. The FES system that we are developing to implement this therapy is designed for application in a rodent model of spinal cord injury. This will allow us to perform several studies in the future to assess the long-term effect of this FES therapy and test hypotheses on the underlying mechanism of the observed effects. To implement such a therapy, FES was combined with robotically assisted treadmill training (RTT). In RTT, robotic arms guide the movements of spinal cord injured rodents' hindlimbs while the rodents perform body weight supported treadmill training (BWSTT). Only a few previous studies have examined the effect of FES combined with BWSTT [4, 8]. In the present study, our combined FES-RTT therapy was tested in spinally contused rats. One group of rats was trained with FES-RTT, and a second group received FES that was not timed to any guided motor activity; i.e., the second group received random stimulation (RS). After two weeks of training, ankle flexor EMG was compared between groups during treadmill stepping without any stimulation. The FES-RTT group was found to exhibit a more organized EMG profile with respect to the gait cycle than the RS group.

II. MATERIALS AND METHODS

A new FES therapy was developed which times stimulation according to the desired hindlimb trajectory during robotically assisted treadmill training (RTT) (See Figure 1). RTT was previously developed to study assisted treadmill training in a rodent model of spinal cord injury [9, 10]. In RTT, a rat steps on a moving treadmill while strapped into a harness which provides body weight support. The hindlimb movements are guided by robotic arms attached to the ankle. The robot applies a servomotor feedback controlled force to the hindlimbs when the ankle deviates from the pre-programmed (desired) trajectory by more than a designated window of error.

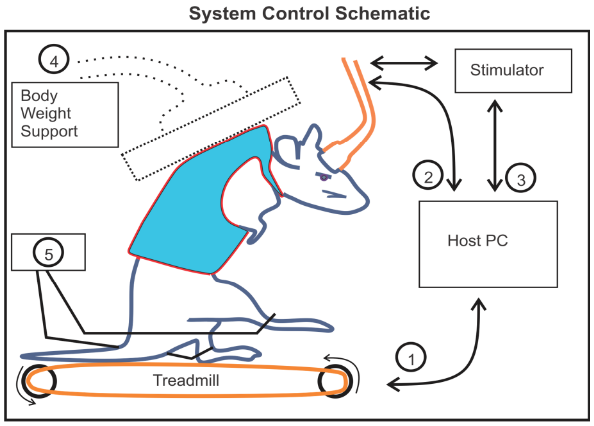

Fig. 1. System control schematic diagram. The main controller was comprised of a LabView program which integrated the robotic software program. This main controller was responsible for the following functions: 1) controlling treadmill speed; 2) recording TA EMG activity; 3) controlling the stimulator; 4) controlling BWS; 5) controlling the force applied to the hindlimbs to guide the stepping trajectory as well as sensing actual hindlimb position.

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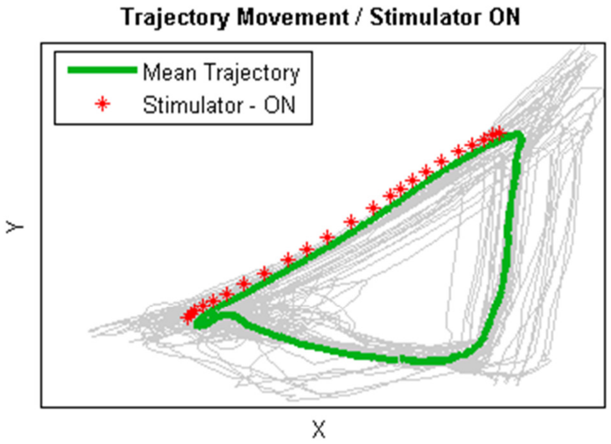

Fig. 2. Ankle trajectory and period of stimulation during training: Thin gray traces in the background show the trajectory of all the steps in one sample training session of an FES-RTT rat. *y* is the vertical position and *x* the horizontal position of the ankle. The green solid trace is the average trajectory. The portion of the gait cycle during which stimulation was applied is indicated on the average trajectory by red asterisks.

The program which controls the RTT device was modified to output a trigger for stimulation to occur during the upswing of the gait cycle (See Fig. 2). A main controller for the stimulator (Grass Instruments, S88x) was developed in LabView (National Instruments). The LabView virtual instrument (VI) monitored the trigger signal from the robot program and accordingly turned the stimulator on and off through a USB interface (Figure 1).

Eleven rats were spinally contused and implanted with wire electrodes in the tibialis anterior (TA), an ankle flexor muscle, in each leg for both stimulation and EMG recording. The rats were divided into two groups: 1) a robotic treadmill training-based FES (**FES-RTT**) group (N=6); and 2) a random stimulation (**RS**) group (N=5). FES-RTT animals received stimulation which was timed to the robotically detected swing phase of the gait cycle. The rats received this FES-RTT training over 1000 gait cycles per training session. RS animals received electrical stimulation while in their cages. Stimulation was applied for a total of four minutes of stimulation each day for 2 weeks during treadmill training (FES-RTT) or in cages (RS).

Testing was performed at the conclusion of the 2 weeks of training. Rats in both groups were placed in the body weight support harness while the treadmill was turned on at 8 cm/s. EMG was recorded from the rats while they were performing the treadmill stepping. The hindlimb position was simultaneously acquired through the robot. Each rat was tested for a total of 2 minutes. During testing, the ability to perform independent stepping without any assistance (i.e. no robotic forces and no stimulation were applied to the hindlimbs) was assessed.

III. DATA ANALYSIS

Raw EMG was amplified by 1000x, bandpass filtered (0.1-3 kHz), and stored for offline analysis in MATLAB (Mathworks, Natick, MA). Envelope detection was then performed on these digitized EMG using full-wave rectification and a moving average filter (window length = 25 ms). The average EMG profile during a gait cycle was computed for each rat as follows: Negative peaks in the horizontal position signal (*x*) were detected based on zero-crossings of the first-order difference with a step size of 5 (i.e., $x[k+5] - x[k]$). This demarcated the beginning of the swing phase, also known as "toe off" (TO). Stance phase is defined as the time from "paw contact" (PC) to "toe off". Typically PC can be defined as the time at which *x* reaches its maximum; i.e. time of the positive peak in *x*. However, because of the abnormal trajectory of the rats (Figure 2), PC was determined by finding the first point at which *y* reached 0 after a positive peak in *x*. The continuous *x* and *y* signals were divided into step cycles, defined between consecutive TO events. The PC within each step cycle demarcated the boundary between swing phase and stance phase. These TO and PC times were then used to also define steps, as well as the swing and stance phases, in the synchronously acquired EMG. Steps which did not reach a height of 30 mm (i.e., the *y* range within a given step did not reach a certain threshold) were not considered valid steps and were excluded from analysis. Most of the steps excluded were from the RS group because they often exhibited dragging rather than proper stepping during testing.

The duration of each step varied a lot between individual subjects (mean ± s.d. = 945 ± 637 ms), so to compare the EMG profile across a single gait cycle, the duration of each EMG segment for a given step was normalized to the longest step duration [11-13]. In order to carry out this normalization, the EMG segments during each gait cycle were linearly interpolated (using MATLAB's predefined function interp1); i.e., if the longest step in duration had a length of L samples, each EMG segment length was normalized to L samples. The individual EMG profiles for all the extracted steps were averaged to create the average EMG profile for a given rat.

Stimulation during training was applied from 0% to approximately 50% of the swing cycle. The concentration of EMG activity during the corresponding period during testing was quantified, as described by Equation 1.

$$\gamma = \frac{\int_0^{50\%\sigma} \bar{s}(\tau)\,d\tau}{\int_0^{100\%} \bar{s}(\tau)\,d\tau} \times 100 \tag{1}$$

Where *s* is the EMG profile of a given rat, and "*s*-bar" is the average EMG profile for a given group, τ is the percent gait cycle, σ is the proportion of the gait cycle represented by the swing phase, and γ is the percentage of EMG activity concentrated from 0 to 50% of the swing cycle.

IV. RESULTS

Figure 3b shows a sample of average EMG profiles from the RS group during testing. Peaks in EMG were observed to occur unpredictably at different points in the gait cycle and could often have multiple peaks. In contrast, the EMG profile of FES-RTT (Figure 3a) exhibited a much more organized and predictable pattern; namely, there was generally one or two peaks in the profile, and the peak(s) generally occurred at the beginning of the swing phase.

Figure 4c and d show the overall average EMG profile from the left and right legs, respectively, of the RS group. The corresponding average trajectories are also shown (Fig. 4 a and b). The green circle indicates where the start of the swing phase was detected (i.e., TO), while the red x indicates the start of the stance phase (i.e., PC). Analogously, Fig. 5 illustrates the overall average EMG profile and trajectory from left and right legs of the FES-RTT group. The overall average EMG profile of RS group has multiple peaks, and the left and right side do not have much consistency with one another aside from a large peak toward the end of stance; whereas that of the FES-RTT group has generally one large peak, which occurs at the beginning of the swing phase. This peak in the FES-RTT profile occurs approximately in the same period during which stimulation was applied during training (Fig. 5 e and f); i.e., during the upswing of the swing phase (Fig. 2). A comparison of γ between groups is shown in Table 1. The FES+RTT group had significantly greater γ values on average than the RS group (one-way ANOVA F(1, 26) = 35.7, $p<<0.01$).

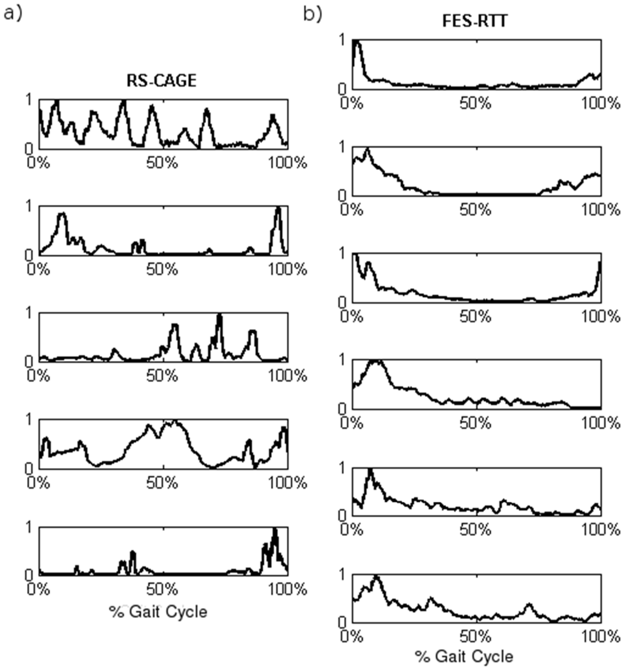

Fig. 3. a) Sample EMG profiles from each of the rats in the RS group during testing. b) Sample EMG profiles from each of the rats in the FES+RTT group during testing.

TABLE I

A COMPARISON OF EMG CONCENTRATION (γ) BETWEEN GROUPS

	RS	FES-RTT
Mean γ	**26 %**	**55 %**
Std. Dev. γ	13%	12 %

V. DISCUSSION

The results presented here demonstrate the lasting effect of a new biomedical therapy which combines FES and robotic treadmill training on muscle activity. For rats which received the position-based FES therapy during a 2-week training period, peak EMG activity was found to occur most often during a window from 0% of the gait cycle (start of the swing phase) until roughly halfway through the swing phase during treadmill stepping even when stimulation was off. This corresponded to approximately the same period during which stimulation was applied during training. In contrast, when RS rats performed treadmill stepping without stimulation, the EMG profile exhibited peaks inconsistently at random times with respect to the gait cycle. As can be seen by comparing Figure 4 a and b with Figure 5 a and b, the swing and stance phases cover similar portions of the overall trajectory in both groups; hence, any differences in

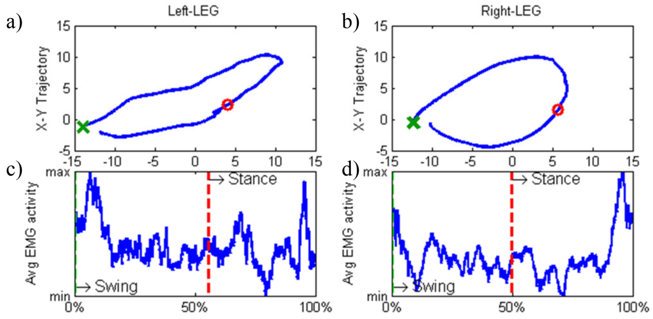

Fig. 4. Overall average trajectory and EMG profile of RS rats during testing: a and b) The average trajectory across all RS rats; green 'x' marks toe off; red 'o' marks paw contact. c and d) The average EMG envelope across all RS rats during a complete gait cycle, defined as toe off to toe off. Swing phase occurs from toe off (green dashed line) until paw contact (red dashed line). Stance phase occurs from paw contact to the next toe off (green dashed line to 100% of the gait cycle).

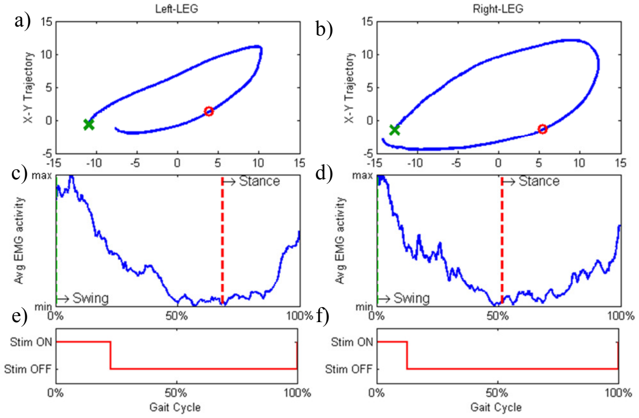

Fig. 5. Overall average trajectory and EMG profile of FES-RTT rats during testing: a and b) The average trajectory across all FES-RTT rats; green 'x' marks toe off; red 'o' marks paw contact. c and d)The average EMG envelope across all FES-RTT rats during a complete gait cycle, defined as toe off to toe off. Swing phase occurs from toe off (green dashed line) until paw contact (red dashed line). Stance phase occurs from paw contact to the next toe off (green dashed line to 100% of the gait cycle). e and f) Stimulation profile showing when stimulation would have been applied within each gait cycle during *training*.

when stance and swing phase occur in the two groups are not likely to explain the obvious differences in EMG profiles.

These results are consistent with the concept of activity-dependent plasticity, by which recovery of a particular function post-injury is enhanced by consistently performing that function. In comparison with rats who received randomly timed stimulation, rats who received stimulation appropriately timed to their stepping activity over a significant training period more reliably produced the EMG profile that matched the stimulation pattern during training. Production of such an EMG profile is an indication that FES-RTT rats were better enabled to perform proper stepping even without stimulation than RS rats, and that rehabilitation of stepping was enhanced in FES-RTT rats. Kinematic analysis of stepping will be conducted to further test this hypothesis.

The present work was conducted as part of a pilot study testing our new FES+RTT therapy. The focus of the pilot work was to test the effect of synchronizing the timing of stimulation to stepping. Although resources were limited in this study to add a third (control) group which had robotic treadmill training alone without FES, we are planning a study to compare FES+RTT therapy to RTT alone. Other studies have already shown the benefits of RTT in helping injured rodents to regain stepping ability after injury but we expect FES+RTT will actively enhance the rehabilitation.

VI. CONCLUSION

Results from this study indicate that FES appropriately timed to robotically controlled treadmill stepping encourages EMG activity to occur at the appropriate stage of the gait cycle; whereas randomly timed stimulation does not encourage any distinct pattern of EMG during the gait cycle. These results provide us with an impetus toward further developing our FES therapy to tap into spinal plasticity as a way of generating lasting rehabilitative effects following spinal cord injury.

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