The Effects of Stimulating Lower Leg Muscles on the Mechanical Work and Metabolic Response in Functional Electrically Stimulated Pedaling

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***Abstract*—Functional electrical stimulation (FES) pedaling with the muscles of the upper leg has been shown to provide benefit to spinal cord injured (SCI) individuals. FES pedaling with electrical stimulation timing patterns that minimize the stress-time integral of activated muscles has been shown to increase the work individuals can perform during the exercise compared to existing FES stimulation timing patterns. Activation of the lower leg muscles could further enhance the benefit of FES pedaling by increasing the metabolic response to the exercise. For SCI individuals, the objectives of this study were to experimentally determine whether FES pedaling with the upper and lower leg muscles would affect the work generated and increase the physiological responses compared to pedaling with the upper leg muscles alone. Work, rate of oxygen consumption ($\dot{V}O_2$), and blood lactate data were measured from nine SCI subjects (injury level T4–T12) as they pedaled using upper leg and upper and lower leg muscle groups on repeated trials. The subjects performed 6% more work with the upper and lower legs than with the upper legs alone, but the difference was not significant ($p = 0.2433$). The average rate of oxygen consumption associated with the upper leg muscles (441 ± 231 mL/min) was not significantly different from the corresponding average for the upper and lower legs (473 ± 213 mL/min) ($p = 0.1176$). The blood lactate concentration associated with the upper leg muscles (5.9 ± 2.3 mmoles/L) was significantly lower than the corresponding average for the upper and lower legs (6.8 ± 2.3 mmoles/L) ($p = 0.0049$). The results indicate that electrical stimulation timing patterns that incorporate the lower leg muscles do increase the blood lactate concentrations. However, there was not enough evidence to reject the null hypothesis that stimulating the lower leg muscles affected the work accomplished or increased the rate of oxygen consumption. In conclusion, incorporating the lower leg muscles in the exercise does not lead to negative effects and could result in enhanced exercise outcomes in the long term.**

***Index Terms*—Electrical stimulation, energy, functional electrical stimulation (FES), muscle, pedaling, recumbent, rehabilitation, simulation.**

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I. Introduction

FUNCTIONAL electrically stimulated (FES) leg cycle ergometry is an exercise modality that provides therapeutic benefit to individuals with spinal cord injury. Pedaling with the muscles of the upper leg has lead to improved circulation [1]–[5] and capillarization of the activated muscles [6], muscle hypertrophy [7], elevated cardiorespiratory activity [2], [8], [9], and an improved sense of well being [10].

Although FES leg cycle ergometry using upper leg muscles has been shown to provide a method of exercise and a means to maintain good health for spinal cord-injured (SCI) individuals, incorporating more muscle mass in the exercise activity could enhance the benefit of FES pedaling. In a comparison of the metabolic, pulmonary, and hemodynamic responses of SCI individuals as they used a voluntarily controlled arm crank ergometer (ACE) and FES pedaling both separately and concurrently, the hybrid exercise resulted in increased cardiorespiratory responses, blood flow, and oxygen delivery to the active muscles [3], [11]–[13]. Similarly, prior studies using empirically derived stimulation timing patterns for the lower leg muscles demonstrated that incorporating more muscle mass in FES pedaling provides metabolic and cardiopulmonary benefit [14]–[17]. However, the direct effects of activating the lower leg muscles in the FES pedaling studies were confounded by modifications made to the electrical stimulation amplitude and timing.

In addition to increasing the muscle mass, another means of enhancing the benefit of FES pedaling is to increase endurance and work performed. In a previous paper, we used a forward dynamic simulation of FES pedaling to compute the stimulation timing patterns that minimized the muscle stress-time integral and the difference in the muscle stress-time integral across the upper leg muscles [18]. Subsequently we conducted experiments which showed that the work accomplished by SCI subjects while pedaling increased significantly compared to existing stimulation timing patterns thus indicating that the endurance of the muscles working together increased [19].

In our previous paper where we used a forward dynamic simulation of FES pedaling [18], we also computed timing patterns with both the upper and lower leg muscles activated in FES pedaling using the same stress-time integral minimization criterion. The resulting computed timing patterns for the upper and lower leg muscles resulted in small increases in the net mechanical energy generated by the quadriceps and gluteals, 3% and 2%, re-

spectively, and insufficient mechanical energy produced by the lower leg muscles to reduce the net energy contributions of the upper leg muscles. Thus, our first objective was to test whether FES pedaling with both upper and lower leg muscles would affect the amount of work generated by an individual with SCI pedaling with upper leg muscles alone. Our second objective was to determine whether increasing the number of activated muscles by using the computed stimulation patterns would improve the efficacy of FES pedaling by increasing the muscle metabolic responses as seen in the studies where the stimulation patterns were determined empirically.

II. Methods

A. Forward Dynamic Simulation

To satisfy these objectives, the electrical stimulation on and off times that minimized the muscle stress-time integral and the difference in the stress-time integral of the quadriceps (QUADS), gluteus maximus (GMAX), and hamstrings (HAMS) muscle groups (referred to as Stim3) and the QUADS, GMAX, and HAMS plus the triceps surae (TRI) muscle group (referred to as Stim5) were tested in a clinical setting. Stim5 also included the electrical stimulation on and off times for the tibialis anterior (TA), which were synchronized with the TRI muscle group to stabilize the ankle joint. Both Stim3 and Stim5 electrical stimulation on and off times were computed previously by means of a forward dynamic simulation of FES pedaling with the ankle joint fixed in the neutral position (the foot at a 90° angle with the shank). Detailed information on the forward dynamic simulation can be found in Hakansson and Hull [18]. In brief, a forward dynamic simulation representative of FES pedaling on a commercial ergometer (ERGYS 2, Therapeutic Alliances, Inc., Dayton, OH) was developed. The muscle excitation on and off times that satisfied the performance criterion were computed and programmed into the FES ergometer controller. The performance criterion, J, was as follows:

$$J = \sum_{i=1}^{p} \int_{t_{0i}}^{t_{fi}} \left(\frac{F_i}{A_i}\right) dt + \sum_{i=1}^{p} \sum_{j=1}^{p} \left| \int_{t_{0i}}^{t_{fi}} \left(\frac{F_i}{A_i}\right) dt - \int_{t_{0j}}^{t_{fj}} \left(\frac{F_j}{A_j}\right) dt \right| \tag{1}$$

for $i \neq j$ and only different combinations of i, j where F_i is the force of the ith muscle, A_i is the physiologic cross-sectional area of the ith muscle, t is the time, t_{0i} and t_{fi} are the on and off times, respectively, of the ith muscle, and p is the number of activated muscles. The physiologic cross-sectional area was determined by normalizing the maximum isometric strength of the muscle by the maximum active muscle stress (i.e., specific tension). A maximum active stress of 250 kPa was used [20]. The optimal electrical stimulation amplitudes and on and off times were obtained by converting the optimal control problem into a parameter optimization problem [21] and using a simulated annealing optimization algorithm [22] to compute the excitation parameters that both minimized the cost, J, and satisfied a time constraint requiring an average pedaling rate within 1 rev/min of the target 50 rev/min pedaling rate (Fig. 1). The cost, J, as given above minimized the stress-time integral and the difference in the stress-time integral across activated muscles that could generate work to drive the crank.

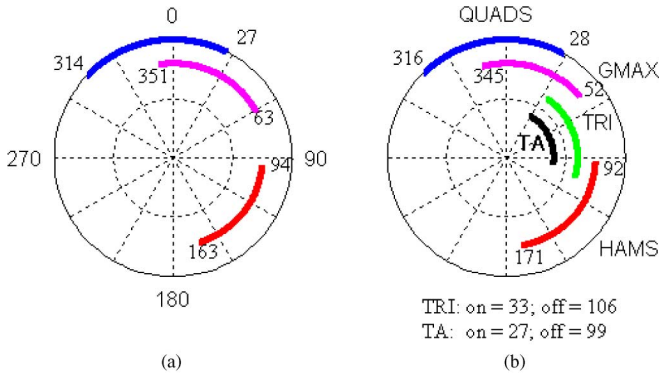

Fig. 1. Plot of muscle electrical stimulation on and off timing as a function of crank angle for the minimized stress-time integral for the (a) quadriceps (QUADS), gluteal (GMAX), and hamstring (HAMS) (Stim3) and (b) QUADS, GMAX, HAMS, triceps surae (TRI), and tibialis anterior (TA) muscle groups (Stim5). Top-dead-center indicates 0° and the beginning of the crank cycle. The on and off timing angles are listed at the beginning and end of the stimulation for the QUADS, GMAX, and HAMS muscle groups. The on and off timing angles for TRI and TA are tabulated below (b).

B. Experiments

Experimental data were collected from subjects to test their performance using the computed electrical stimulation timing patterns for the upper leg muscle groups, Stim3, compared to the stimulation timing patterns for the upper and lower leg muscle groups, Stim5. Written informed consent was obtained from nine individuals (seven male, two female) with a complete spinal cord injury (American Spinal Injury Association (ASIA) A impairment classification) who volunteered for the eight-week study. The age of the subjects ranged from 18 to 48 years (mean 28±10 years), the heights ranged from 1.55 to 1.85 m (mean 1.73±0.10 m), the weights ranged from 49 to 89 kg (mean 68±14 kg), and the injury level T4–T12. All of the subjects were at least one year post spinal cord trauma (Table I). None of the subjects had pedaled an FES ergometer prior to the study. The experimental protocol was approved by the Institutional Review Board of the University of California at Davis.

Functional electrically stimulated pedaling was performed on a computer-controlled leg cycle ergometer (ERGYS 2, Therapeutic Alliances, Inc., Dayton, OH). The subjects' feet were secured in padded boots connected to the pedals. The boots also served to fix the ankle joint in the neutral position (i.e., the foot and tibia form a 90° angle). The ergometer seat was positioned to limit the knee angle to 45° of extension (full extension equals 0°) with the ankle in the neutral position (ERGYS 2, Therapeutic Alliances, Inc., Dayton OH, manufacturer recommendations). Pairs of self-adhesive 2 × 4 inch oval electrodes (TENS products, Grand Lake, CO) were placed on the skin over each of the QUADS, HAMS, and GMAX muscle groups on both legs for Stim3. The same electrodes were used for the TRI, but smaller electrodes, 2.5 × 1.5 inch oval, were used on the smaller tibialis anterior muscle (TA) with Stim5. Electrode placements were based on the ergometer manufacturer recommendations (Therapeutic

TABLE I
DESCRIPTIVE CHARACTERISTICS OF THE SUBJECTS. AVERAGE PEDALING TIME FOR THE TWO TRIALS WITH EACH STIMULATION TIMING PATTERN IS TABULATED. THE 1-MINUTE TIME PERIOD DURING WHICH THE METABOLIC MEASURES USED IN THE ANALYSIS WERE RECORDED IS ALSO TABULATED

	Age (years)	Height (m)	Weight (kg)	Level of Injury	Time Since Injury (years)	Gender	Average Pedaling Time (sec) Stim3	Stim5	Metabolic Measurement time (min)
Subject 1**	48	1.65	89	T4	6	M	414	336	**
Subject 2*	18	1.85	57	T6	3.75	M	*	*	27-28
Subject 3*	20	1.65	64	T10	1.5	M	*	*	41-42
Subject 4**	30	1.73	55	T9	11	F	373	434	**
Subject 5	27	1.73	74	T10	6.5	M	2347	2682	34-35
Subject 6	35	1.78	85	T6	1.25	M	2324	2540	27-28
Subject 7*	20	1.80	60	T10	2	M	*	*	48-49
Subject 8	22	1.55	49	T8	3.5	F	923	910	13-14
Subject 9	36	1.83	78	T7	17	M	515	583	6-7

* denotes subjects who chose to end at least one test session prior to reaching the 35 rpm termination criterion and were not included in the analysis indicated
** denotes subjects who did not pedal long enough to achieve steady state metabolic response and were not included in the analysis indicated

Alliances, Inc., Dayton, OH) and muscle motor point locations [23]. Electrode placement positions were measured with respect to bony landmarks to ensure that the electrodes were placed in the same position during each session.

The experimental protocol was designed to take eight weeks to complete. Subjects pedaled the ergometer three times per week with a target of 30 min total per session during the first three weeks to acclimate to FES pedaling and once per week during the last five weeks for the experimental data collection. Because the subjects were not experienced with metabolic tests, the data from the first experimental session for each subject was not used in the analyses. The last four weeks of the experimental data collection were divided into two two-week time blocks. The order of the electrical stimulation timing patterns, Stim3 and Stim5, was randomly assigned during the first two-week time block. The order was then reversed during the second two-week time block (e.g., week 1: Stim3, week 2: Stim5, week 3: Stim5, week 4: Stim3).

During the acclimation period, subjects pedaled using both the computed and existing ergometer stimulation patterns assigned randomly. The FES ergometer computer controller applied a biphasic sinusoidal waveform (500-μs pulse duration and 30 Hz frequency) to each of the electrode pairs. When the crank reached the stimulation on angle, the electrical stimulation ramped up linearly to the set stimulation amplitude. Similarly, the electrical stimulation amplitude ramped down linearly from the ergometer controlled amplitude to the off angle. The ramp up and down portions of the applied electrical stimulation each covered 21° of the crank cycle. The maximum stimulation amplitude was set at 140 mA, which was the maximum output of the FES ergometer computer controller for the QUADS, HAMS, GMAX, and TRI muscle groups. The maximum stimulation amplitude was set at 70 mA for the TA to provide a similar current per electrode area for the smaller electrodes.

At the beginning of each pedaling session, an assistant manually turned the cranks on the ergometer for the subject at 44 rev/min for 1 min. After the 1 min of manual pedaling, the stimulation amplitude was increased to a level such that the subject's muscles were able to pedal the ergometer at the 50 rev/min target pedaling rate. The stimulation amplitude was increased (up to the maximum 140 mA or 70 mA for the TA) or decreased by the ergometer controller as needed to maintain the target pedaling rate. As the muscles fatigued, the stimulation amplitude was increased to the maximum current so as to maintain the target pedaling rate. The controller ended the exercise session if the pedaling rate dropped below 35 rev/min. Resistance was applied to the ergometer flywheel by means of an electromagnetic brake. During the acclimation sessions, flywheel resistance was increased by small increments (0.06 Kp or approximately 3 W at 50 rev/min) every 7 min once the subjects were able to pedal the ergometer for 15 min continuously without applied resistance during the prior acclimation session. Upon completion of each pedaling run, the ergometer was manually pedaled for the subject for 2 min to permit the subject to cool down.

Tests for the experimental data collection began a week after the final acclimation session. After positioning the ergometer seat and the electrodes, the subject was fit with a low dead-space mask for breath-by-breath respiratory gas analysis (MedGraphics CPX/MAX/D, Medical Graphics Corporation., St. Paul, MN). The metabolic cart gas oxygen and carbon dioxide analyzers and volume flow pneumotachometer were calibrated prior to each testing session. Baseline breath-by-breath respiratory gas data were collected for 5 min. Respiratory gases data were recorded continuously for the duration of the session. After 5 min of quiet sitting, baseline blood lactate (Lactate-Pro, Fact Canada, Quesnel, BC, Canada) measurements were made from the subject's earlobe. The subject then experienced 1 min manual pedaling by an assistant at 44 rev/min. After the 1 min of manual pedaling, the stimulation was gradually increased over the first minute until the stimulation amplitude was high enough to permit the subject to pedal under his own power. The pedaling rate, stimulation amplitude, and applied resistance were continuously recorded via custom written software (Matlab, The Mathworks, Natick, MA). No external resistance was applied during the first 7 min. The resistance to the flywheel was increased by 0.06 Kp (approximately 3 W) at the end the first 7-min period and every 7-min period thereafter until the sessions were stopped due to the 35 rev/min cutoff or the subject's request. At the end of the pedaling session, the subject was manually pedaled for 2 min to cool down. The 7-min time step was chosen to account for the mean response time of oxygen consumption kinetics ($\dot{V}O_2$) to reach steady-state [24], [25].

C. Data Processing and Analysis

The respiratory and pedaling data recorded from each of the subjects were time synchronized. The recorded pedaling rate and workload data were used to calculate the instantaneous pedaling workrate. The instantaneous pedaling workrate was then integrated over the duration of the testing session to compute the total mechanical work performed. Breath-by-breath $\dot{V}O_2$ data collected over the final minute of each 7-min period (i.e., between minutes 6 and 7, 13 and 14, and so on) were averaged. Blood lactate concentrations were measured during the last minute of each 7-min period for the duration of the testing session. Resting baseline values collected during the 5-min rest period were averaged and subtracted from the $\dot{V}O_2$ measures. Similarly, the resting blood lactate concentration was subtracted from the values collected while the subject actively pedaled.

Statistical analyses were performed to address the two objectives of the study. A two-factor repeated measures ANOVA analysis was used to test whether the electrical stimulation timing patterns that minimize the stress-time integral and the difference in the stress-time integral across activated muscles affected the mechanical work generated by individuals pedaling with the upper leg muscle groups, Stim3, versus both the upper and lower leg muscle groups, Stim5. The two factors were the electrical stimulation timing patterns at two levels (Stim3 and Stim5) and the two-week time block the electrical stimulation factor was tested (first half and second half). The dependent variable was the log transformation of the total work generated prior to cessation of the test (35 rev/min cutoff pedaling rate). The log transformation was used to account for the increased variance associated with larger work values [26]. To determine whether Stim5 increased the metabolic demand of the pedaling task, one-tailed two-factor repeated measures ANOVA tests were performed on two metabolic measures, $\dot{V}O_2$ and blood lactate concentration [27]. The two factors in these analyses were the electrical stimulation timing patterns and the two-week time blocks. The dependent variables in these analyses were the 1-min averaged $\dot{V}O_2$ and the blood lactate concentration. The 1-min average occurred over the same minute across all sessions for an individual subject and corresponded to the last minute of the highest 7-min period reached by the subject in all of his or her experimental testing sessions (Table I). The criterion level of significance was $p < 0.05$ for the statistical analyses. SAS (Release 9.1.3, Cary, NC) was used for all statistical calculations.

III. Results

For the six subjects who pedaled until the 35 rev/min termination criterion was reached (Table I), there was no significant difference in mechanical work performed ($p = 0.2433$). Based on the difference of the within subject averages normalized to the average work for all four trials, 6% more mechanical work was accomplished with Stim5 than Stim3. The average work for the six subjects pedaling with Stim3 was 20.8 ± 19.8 kJ while the average for Stim5 was 22.8 ± 22.5 kJ (Fig. 2). There was no significant interaction between the electrical stimulation timing patterns and the time blocks ($p = 0.9471$).

For the seven subjects who could pedal long enough for gas exchange kinetics to reach steady-state during the first 7-min period (i.e., no applied flywheel resistance) for each of the four testing sessions (Table I), the electrical stimulation timing patterns did not have a significant effect on $\dot{V}O_2 (p = 0.1176)$ (Fig. 3). The average $\dot{V}O_2$ for the seven subjects pedaling with Stim3 was 441 ± 231 mL/min while the average for Stim5 was 473 ± 213 mL/min.

In contrast, the electrical stimulation timing patterns did have a significant effect on blood lactate concentration ($p = 0.0049$) (Fig. 4). The blood lactate concentration was greater with Stim5 than Stim3 for six of the seven subjects. Consequently the average blood lactate concentration for the seven subjects pedaling with Stim5 (6.8 ± 2.3 mmoles/L) was significantly greater than that for Stim3 (5.9 ± 2.3 mmoles/L). The interactions between the electrical stimulation timing patterns and the time blocks were not significant for either the $\dot{V}O_2 (p = 0.4864)$ or the blood lactate concentration ($p = 0.1306$).

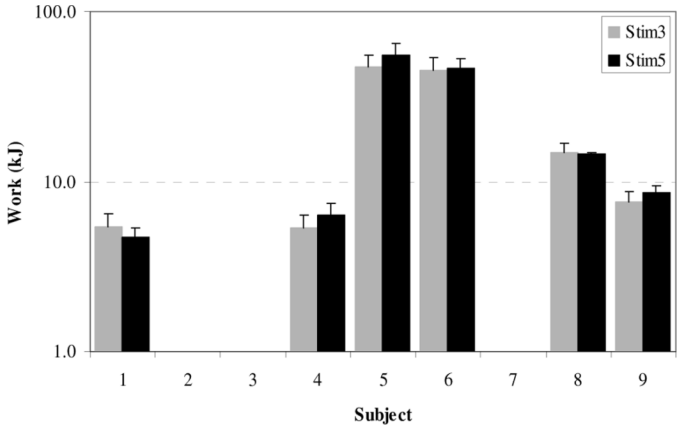

Fig. 2. Bar chart of the mechanical work generated by the six subjects who pedaled the FES ergometer to the 35 rev/min cutoff pedaling rate with the Stim3 and Stim5 electrical stimulation timing patterns. Each bar is the average of the two time blocks. The error bars denote one standard deviation.

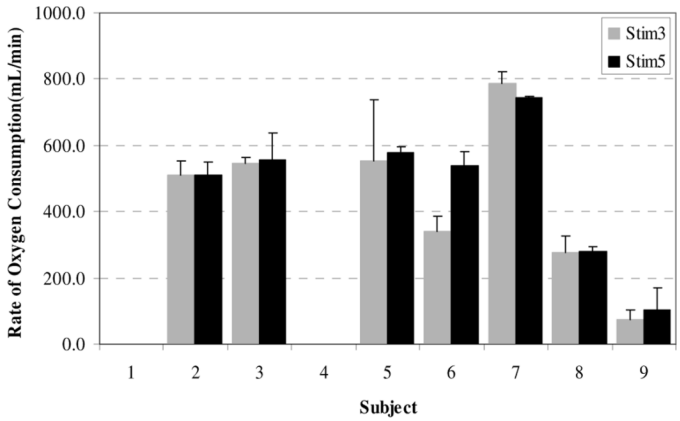

Fig. 3. Bar chart of the rate of oxygen consumption ($\dot{V}O_2$) recorded from the seven subjects who were able to pedal long enough with both the Stim3 and Stim5 electrical stimulation timing patterns to achieve steady-state $\dot{V}O_2$ kinetics. Each bar is the average of the two time blocks. All values represent the change above resting baseline values. The error bars denote 1 standard deviation.

IV. Discussion

To advance the beneficial outcomes of FES pedaling for SCI individuals, it is desirable to increase the physiologic response

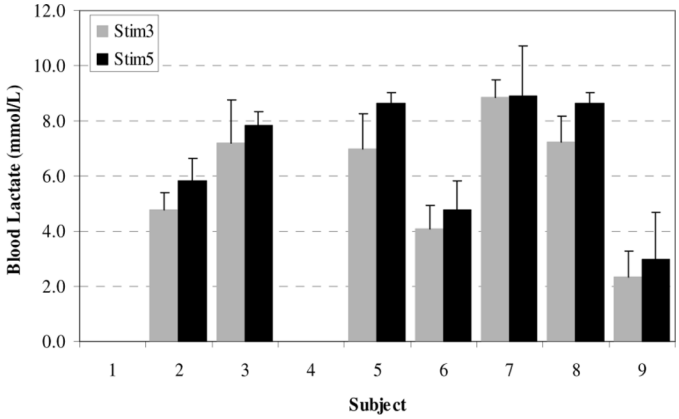

Fig. 4. Bar chart of the blood lactate concentrations recorded from the seven subjects who were able to pedal long enough with both the Stim3 and Stim5 electrical stimulation timing patterns to achieve steady-state metabolic responses. Each bar is the average of the two time blocks. All values represent the change above resting baseline values. The error bars denote 1 standard deviation.

associated with the activity. One potential approach to achieve this goal is to increase the muscle mass involved in the exercise. Because an increase in the muscle mass activated in the exercise can increase the metabolic response to FES exercise, the objectives of this study were to determine whether FES pedaling with the upper and lower leg muscles would affect the amount of work accomplished by an individual with SCI and increase metabolic responses relative to pedaling with the upper leg muscles alone. One key finding was that the work generated was unaffected by the electrical stimulation timing patterns for the upper and lower leg muscles versus those for the upper leg muscles alone. Another key finding was the blood lactate concentration was significantly higher for pedaling with the upper and lower leg muscles whereas the rate of oxygen consumption was the same for both pedaling conditions.

Before addressing the importance of our findings, a discussion of the methodological limitations of our study is warranted. The forward dynamic simulations used to determine the optimal electrical stimulation amplitudes and on and off times were developed based on a generic human musculoskeletal model and not subject-specific musculoskeletal models. Subject-specific simulations would have accounted for the muscle-tendon properties (e.g., maximum muscle force, fiber type distribution, fiber lengths, and tendon slack lengths) of the individual subjects in the calculation of the electrical stimulation amplitudes and on and off times and could have led to improved pedaling outcomes. However, the electrical stimulation amplitude-to-force relationship varies greatly among SCI individuals [28]–[30] and depends on many stimulation variables including electrode placement, muscle strength, fiber-type distribution, and skin impedance. Because the aforementioned stimulation variables would have been difficult to measure and control in the experimental tests and unrealistic to measure in most clinical or home settings, the generic model was used. Additionally, because the stimulation amplitude-to-force relationship for the individual subjects was not determined, only the electrical stimulation on and off timing was tested in this study.

A second methodological limitation was associated with the control of the subjects' pedaling rate. The ERGYS 2 adjusted the electrical stimulation amplitude applied to the subjects to elicit the pedaling motion. As the muscles fatigued, the electrical stimulation amplitudes delivered to the muscle groups were increased up to the maximum delivered by the ERGYS 2 controller to best maintain the 50 rev/min pedaling rate. During three trials—one trial each for three subjects—the sustained pedaling rate was below the 50 rev/min target for at least 1 min of the final 7-min period. The forward dynamic simulation was designed to replicate steady-state pedaling at 50 rev/min and did not account for pedaling rates below 50 rev/min because we did not foresee that subjects would maintain a pedaling rate below the 50 rev/min target. There were no observable negative effects (e.g., jerky pedaling motion or pedaling motion stoppages) as a consequence of pedaling below 50 rev/min.

The result that activation of the lower leg muscles did not lead to a difference in the mechanical work is not surprising for two reasons. First, in a previous study of low workrate recumbent pedaling by able-bodied cyclists, it was observed that the triceps surae generated little power [31]. Instead, the triceps surae muscles transferred power from the limbs to the crank primarily through isometric contractions despite the ability of the able-bodied cyclists to flex and extend the ankle joint. Second, in the current study with the ankle joint fixed, the biarticular gastrocnemius muscle was the only one of the lower leg muscles with the potential to generate mechanical work. The computer simulation used to determine the electrical stimulation timing patterns including the lower leg muscles, Stim5, indicated that the gastrocnemius activity did not result in a net gain in mechanical work to drive the crank [18].

An unanticipated result was the lack of a difference in the measured rate of oxygen consumption for the subjects pedaling with the Stim3 and Stim5. It was expected that the increase in stimulated muscle groups would lead to increased metabolic activity. The increase in $\dot{V}O_2$ observed in previous studies of FES pedaling with the lower leg muscles [14]–[17] could provide some insight into the current result. These prior studies confounded the effect of the lower leg muscles in FES pedaling because they activated the upper leg muscles with a higher maximum stimulation amplitude (300 mA versus 140 mA) over a wider range of the crank cycle (approximately one-third of the crank cycle) when the lower leg muscles were activated. The higher stimulation amplitude and longer duty cycle would have recruited more muscle fibers for a longer period of time, respectively, resulting in a greater metabolic response most likely due to the upper leg muscles. In our study, the maximum stimulation amplitude was the same for Stim3 and Stim5 and the stimulation on and off timing for the upper leg muscles was nearly identical for Stim3 and Stim5 (Fig. 1). Therefore, the 32 mL/min difference in the average $\dot{V}O_2$ measured for Stim3 (441 mL/min) and Stim5 (473 mL/min) would have been due to the lower leg muscle metabolic activity. Because of muscle atrophy, fiber type conversion associated with disuse from the spinal cord injury, and the non-physiological recruitment of muscle fibers with surface electrical stimulation, the rate of oxygen consumption by the lower leg muscles was too low to register a statistically significant difference.

Whereas the inclusion of the lower leg muscles did not change the work performed or $\dot{V}O_2$ during FES pedaling, it did lead to an increase in blood lactate concentration. Activation of the lower leg muscle groups in FES pedaling caused the blood lactate concentration to increase for six of the seven subjects who pedaled through the first 7-min period. There was no change in the blood lactate for the remaining subject (Fig. 4). Because more muscle groups were activated and because surface electrical stimulation of muscles is associated with the recruitment of type II fibers and, consequently, anaerobic metabolism, the lower leg muscle groups activated with Stim5 were the likely source of the increased blood lactate concentration. The relationship between the blood lactate measurements and the experimental protocol design supports this assertion. The blood lactate concentration measures included in the analysis for each subject were taken over the same minute of the last 7-min period completed for all trials by that subject. Thus, the blood lactate concentrations were measured after the subjects had performed similar work at the same workload. Because the addition of the lower leg muscles did not increase the work performed and because the stimulation timing patterns for the upper leg muscles were nearly the same for both Stim3 and Stim5, the lower leg muscles were the most probable source of the increase in the blood lactate.

Taken together, the results indicate that FES pedaling with the lower leg muscle groups holds promise for improving the outcome of the exercise. Because there was no evidence of a difference in the work and the $\dot{V}O_2$ when pedaling with Stim3 and Stim5, activation of the lower leg muscle groups would not have a negative effect on the exercise outcomes. In light of previous research that has demonstrated that FES training by individuals with SCI yields gains in work performed, gas exchange kinetics, and cardiovascular responses [2], [6], [8] as well as muscle hypertrophy and capillarization of the muscles that received stimulation [32], [33], including the lower leg muscles in FES pedaling would be beneficial in the long term. The result that blood lactate concentration increased with Stim5 signifies the potential for more muscle mass to benefit from the training effects of the exercise. The incorporation of more muscles in the exercise would increase the number of muscle fibers activated and presumably allow the benefits of FES training to be realized in more muscles of the leg.

In summary, the results of this study demonstrated that the addition of the lower leg muscles in FES pedaling did increase the measured blood lactate concentration. There was not enough evidence to reject the null hypothesis that the addition of the lower leg muscles affected the work accomplished or increased the rate of oxygen consumption. There was no evidence of negative effects associated with the incorporation of the lower leg muscles in the exercise. Collectively the results indicate that stimulating the lower leg muscles in FES pedaling could lead to enhanced exercise outcomes over time.

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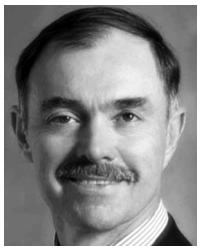

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