Peak and submaximal physiologic responses following electrical stimulation leg cycle ergometer training

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Abstract—Eight males with spinal cord injury (SCI) participated in an exercise training program using neuromuscular electrical stimulation (NMES) leg cycle ergometry. Each subject completed a minimum of 24 (mean±SD=38.1±17.2) 30-minute training sessions over a 19-week period. The initial work rate (WR) of 0 watts (W) of unloaded cycling was increased when appropriate with subjects exercising at 11.4±3.7W (range=6.1W–18.3W) at the end of the training program. Randomized block repeated measures ANOVA was used to compare pretraining and posttraining peak physiologic responses during graded NMES leg cycle tests and subpeak physiologic responses during 10 minutes of NMES leg cycle exercise at an absolute WR (0 W). A significant (P≤0.05) increase was observed for peak VO$_2$ (+10%, 1.29±0.30 to 1.42±0.39 l·min$^{-1}$). No other statistically significant differences were noted for any other peak variable (VCO$_2$, VO$_2$ ml·kg$^{-1}$·min$^{-1}$, $V_{E}$, WR, HR, RER) pre- to posttraining. During submaximal NMES leg cycle testing, a significant decrease was noted for RER (−9.2%, 1.19±0.14 to 1.08±0.09). No other submaximal variable (VO$_2$ l·min$^{-1}$, ml·kg$^{-1}$·min$^{-1}$, VCO$_2$, HR, $V_{E}$) showed significant changes as a result of the training. Although the improvement in peak VO$_2$ was not as dramatic as those reported in previous studies, it appears that NMES leg cycle training performed two times per week can significantly enhance cardiopulmonary fitness.

Key words: aerobic fitness, exercise, oxygen consumption, paraplegia, quadriplegia, rehabilitation, spinal cord injury.

INTRODUCTION

Neuromuscular electrical stimulation (NMES) leg cycle ergometers for persons with spinal cord injury (SCI) were formally introduced almost 11 years ago (1,2). There has since been much speculation as to their potential for improving and/or maintaining cardiopulmonary fitness in such persons. Studies have reported either nonsignificant (3,4) or significant (5) effects upon resting physiology, physiologic responses to submaximal work rates (5), and peak exercise performance and cardiopulmonary fitness (4,6–8).

The training programs adopted in these studies have been based on recommendations from the primary manufacturer of NMES leg cycle ergometers. The exercise prescription has entailed NMES leg cycling 3 times per week for 12 weeks (36 total exercise sessions). Exercise training work rates are increased as tolerated to provide continuous overload to the musculoskeletal and cardiopulmonary systems. This regimen is structured similar to exercise programs derived to provide aerobic fitness enhancement in healthy persons without SCI (9).
Moderately to severely deconditioned persons without SCI are known to exhibit substantial increases in cardiopulmonary fitness after exposure to exercise programs using minimal training frequencies and durations (9). Persons with SCI are predisposed to a sedentary lifestyle, have little remaining active muscle mass, and display autonomic dysfunction. In combination, these factors contribute to low levels of aerobic fitness in such persons (10,11). However, it is not known whether an NMES leg cycle exercise program utilizing less than the suggested training frequency would be effective for promoting physiologic adaptations in persons with SCI. Therefore, the purpose of this study was to determine the effects of an NMES leg cycle training program with a training frequency of two times per week upon the maximal and submaximal aerobic capacities of persons with SCI. This was accomplished by evaluating pretraining and postraining peak and submaximal physiologic responses to NMES leg cycle exercise.

METHODS

Subjects

The study was approved by the Research and Development Committee at the West Los Angeles VA Medical Center. Each subject gave written informed consent prior to participation. Subjects underwent medical screening which included: a physical exam including a sensory/motor neurological assessment; blood chemistry and urinalysis; x-rays of the chest, spine, and lower limbs; 12-lead resting electrocardiogram (ECG); and an arm crank ergometer stress test with 12-lead ECG. Individual degree of impairment was based on the ASIA Impairment Scale (12).

Eight males with SCI were involved in the training program. None of the subjects had been involved in any regular endurance exercise or NMES leg cycle ergometry prior to the training program. All eight subjects used manual wheelchairs. Subject characteristics are listed in Table 1.

Exercise Test Procedures

Subjects completed the following tests pretraining and postraining: 1) Graded NMES leg cycle ergometry to fatigue, 2) 10 minutes of steady rate NMES leg cycle ergometry at 0 Watts (W) (unloaded cycling), and 3) Graded arm ergometry to fatigue (Monark Rehab Trainer). The REGYS1 (Therapeutic Alliances, Inc., Fairborn, OH) NMES leg cycle ergometer was used for all NMES tests. NMES exercise was induced by attaching carbon-filled silastic surface electrodes to quadriceps, hamstring, and gluteal muscles. These muscles were stimulated sequentially at 30 Hz with a current (10–132 mA) that varied to maintain a pedalling cadence of 50 revolutions per minute (rpm).

The graded NMES leg cycle exercise test consisted of an initial 2-minute assisted warm-up followed by 5-minute stages of increasing work rates to fatigue. The initial work rate of 0 W was increased by 6.1 W (1/8 kiloponds at 50 rpm) every 5 minutes. Fatigue occurred when NMES could not maintain a pedalling cadence of \( \geq 35 \) rpm. The steady-rate NMES leg cycle test included a 2-minute assisted warm-up followed by 10 continuous minutes at 0 W. The graded arm ergometry test consisted of an initial warm-up period of arm cycling at 0 W followed by 1-minute stages of increasing work rates to fatigue. The initial work rate of 0 W was increased by 5 W every minute.

Expired gas was collected with a Collins triple “J” valve (Warren E. Collins, Braintree, MA) and analyzed using a Medical Graphics CPX metabolic cart (Medical Graphics Corporation, Minneapolis, MN). Gas analyzers and pneumotach were calibrated before and after each test, and breath-by-breath data of ventilation and pulmonary gas exchange were measured using standard techniques. Oxygen consumption (\( \dot{V}O_2 \)), carbon dioxide production (\( \dot{V}CO_2 \)), pulmonary ventilation (\( \dot{V}E \)), and

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yr)</th>
<th>Ht (cm)</th>
<th>Wt (kg)</th>
<th>Lesion Level</th>
<th>TSI (yr)</th>
<th>Frankel Class</th>
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<tr>
<td>1#</td>
<td>33</td>
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<td>63.5</td>
<td>C5–6</td>
<td>15</td>
<td>A</td>
</tr>
<tr>
<td>2*</td>
<td>37</td>
<td>182.9</td>
<td>104.4</td>
<td>C6–7</td>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td>3*</td>
<td>33</td>
<td>177.8</td>
<td>72.6</td>
<td>T4</td>
<td>11</td>
<td>A</td>
</tr>
<tr>
<td>4*</td>
<td>46</td>
<td>180.3</td>
<td>99.4</td>
<td>T5</td>
<td>4</td>
<td>A</td>
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<tr>
<td>5@</td>
<td>31</td>
<td>178.8</td>
<td>62.6</td>
<td>T6</td>
<td>13</td>
<td>A</td>
</tr>
<tr>
<td>6*</td>
<td>42</td>
<td>175.3</td>
<td>79.4</td>
<td>T6–7</td>
<td>9</td>
<td>A</td>
</tr>
<tr>
<td>7#</td>
<td>37</td>
<td>172.7</td>
<td>68.1</td>
<td>T9</td>
<td>12</td>
<td>A</td>
</tr>
<tr>
<td>8*</td>
<td>29</td>
<td>182.9</td>
<td>63.5</td>
<td>T12–L1</td>
<td>11</td>
<td>A</td>
</tr>
<tr>
<td>Mean</td>
<td>36.0</td>
<td>179.7</td>
<td>76.7</td>
<td></td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>5.4</td>
<td>4.6</td>
<td>15.5</td>
<td></td>
<td>4.0</td>
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</tbody>
</table>

* = motor vehicle accident; # = trauma; @ = inflammatory disease; TSI = time since injury.
respiratory exchange ratio (RER) were calculated and recorded at 15-second intervals during each test. The highest VO₂ level was considered VO₂ peak for both graded tests: NMES leg cycle and arm ergometry. Values for VO₂, VCO₂, VE, RER, and HR were averaged during the last 2 minutes of the steady rate submaximal NMES leg cycle test and used for data analysis. Heart rate (HR) and rhythm were continuously monitored via 3-lead ECG and recorded during the final 15 seconds of each exercise stage during the graded test and each minute of the steady rate test. Blood lactate (BLa) samples were evaluated in duplicate from the same capillary samples (finger prick), which were taken before and within 2 minutes of stopping the steady rate submaximal NMES leg cycle test using a YSI 1500 Sport Lactate Analyzer (Yellow Springs Instruments, Yellow Springs, OH).

NMES Leg Cycle Training
The training program was performed in two phases. Phase I (pedalling progression) consisted of applying NMES to the quadriceps, gluteal, and hamstrings sequentially in order to achieve a rhythmical cycling motion. Initially, subjects pedalled against a resistance of 0 W for a period of 5–15 minutes or until they could no longer maintain 35 rpm. Rest periods of 2–5 minutes were incorporated between exercise bouts. The duration of each successive exercise period was progressively increased until the subject was able to pedal for 30 minutes continuously. After 2 consecutive 30-minute sessions of NMES leg cycling at 0 W, the subject performed the aforementioned test protocols.

Phase I training sessions were scheduled to be performed three times per week. However, due to scheduling conflicts and other time constraints, it was decided to reduce the training frequency to two times per week to accommodate the subjects. This decision was made in lieu of eliminating subjects from participation in a program that could potentially be of substantial benefit.

Phase II consisted of a minimum of 24 30-minute sessions of NMES leg cycle exercise. The training frequency was maintained at two times per week. The training protocol consisted of each subject starting with a resistive load of 0 W and progressively increasing the work rate (if possible) over the duration of the training program. After the subject was able to complete 3 consecutive 30-minute sessions at a given work rate, the work rate was increased by 6.1 W. If the patient was unable to complete 30 minutes of NMES leg cycling at the higher work rate, the work rate was reduced to the previous level (without a rest period), and a total of 30 minutes was completed.

Statistical Procedures
A randomized block analysis of variance (ANOVA) with repeated measures was used to compare pretraining and posttraining work rate and peak physiologic responses during the graded NMES leg cycle test, and metabolic and cardiopulmonary responses during the steady rate submaximal NMES leg cycle exercise. All data are presented as mean ± standard deviation (SD).

RESULTS
Training. Subjects completed 14.6±7.4 sessions of Phase I pedalling progression in 7.3±4.1 weeks for an average of 2.3±0.64 sessions per week. During the training program (Phase II), subjects completed 38.1±17.2 sessions in 19.6±12.2 weeks corresponding to 2.1±0.42 training sessions per week. At the end of the training program, the training work rate increased from 0 W to an average of 11.4±3.7 W (range=6.1 W–18.3 W). There were no reported incidents of either autonomic dysreflexia or exertional hypotension during the training program.

Testing. Results for each variable during the pre- and posttraining graded and submaximal NMES leg cycle tests are identified in Tables 2 and 3. During the graded NMES leg cycle test, a significant (P<0.05) difference existed between pre- and posttraining for VO₂ (l·min⁻¹): 1.29±0.30 to 1.42±0.39, +10 percent. Although peak work rate increased 25 percent (12.2±5.6 W to 15.3±4.6 W), this was not statistically significant. There were no significant differences noted for any other variables. Pre- and posttraining values for graded arm ergometry tests were 1.28±0.41 l·min⁻¹ and 1.26±0.57 l·min⁻¹, respectively. This represented 112 and 92 percent of the peak VO₂ achieved during the pre- and posttraining graded NMES leg cycle tests, respectively. This indicated a greater increase in the NMES peak VO₂, which was expected based on the training protocol.

During submaximal steady rate NMES leg cycle ergometer testing, a significant (P<0.05) decrease in RER was observed from pre- to posttraining (1.19±0.14 to 1.08±0.09, −9.2 percent), VE and VCO₂ decreased (13.6 and 12.3 percent, respectively); however, these
Table 2.
Peak physiologic responses to graded electrical stimulation leg cycle ergometry to fatigue (mean ± SD).

<table>
<thead>
<tr>
<th></th>
<th>Pretraining</th>
<th>Posttraining</th>
<th>%Δ</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work Rate (W)</td>
<td>12.2 ± 5.6</td>
<td>15.3 ± 4.6</td>
<td>+25%</td>
<td>0.17</td>
</tr>
<tr>
<td>( \dot{V}O_2 ) (l·min(^{-1}))</td>
<td>1.29 ± 0.30</td>
<td>1.42 ± 0.39*</td>
<td>+10%</td>
<td>0.04</td>
</tr>
<tr>
<td>( \dot{V}O_2 ) (ml·kg·min(^{-1}))</td>
<td>17.7 ± 5.8</td>
<td>19.4 ± 7.5</td>
<td>+9.6%</td>
<td>0.07</td>
</tr>
<tr>
<td>( \dot{V}CO_2 ) (ml·kg·1·min(^{-1}))</td>
<td>1.47 ± 0.35</td>
<td>1.52 ± 0.33</td>
<td>+3.4%</td>
<td>0.42</td>
</tr>
<tr>
<td>Heart Rate (bpm)</td>
<td>133.1 ± 29.6</td>
<td>131.5 ± 25.5</td>
<td>-0.4%</td>
<td>0.07</td>
</tr>
<tr>
<td>( \dot{V}_E ) (l·min(^{-1}))</td>
<td>56.5 ± 16.5</td>
<td>58.0 ± 13.6</td>
<td>+2.7%</td>
<td>0.42</td>
</tr>
<tr>
<td>RER</td>
<td>1.14 ± 0.11</td>
<td>1.09 ± 0.08</td>
<td>-4.4%</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Significant differences (P ≤ 0.05) between pretraining and posttraining values.

Table 3.
Physiologic responses to submaximal steady rate electrical stimulation leg cycle ergometry (Mean ± SD).

<table>
<thead>
<tr>
<th></th>
<th>Pretraining</th>
<th>Posttraining</th>
<th>%Δ</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{V}O_2 ) (l·min(^{-1}))</td>
<td>0.96 ± 0.19</td>
<td>0.91 ± 0.20</td>
<td>-5.2%</td>
<td>0.37</td>
</tr>
<tr>
<td>( \dot{V}O_2 ) (ml·kg·min(^{-1}))</td>
<td>13.1 ± 3.5</td>
<td>12.3 ± 3.4</td>
<td>-6.1%</td>
<td>0.42</td>
</tr>
<tr>
<td>( \dot{V}CO_2 ) (ml·kg·1·min(^{-1}))</td>
<td>1.14 ± 0.23</td>
<td>1.00 ± 0.29</td>
<td>-12.3%</td>
<td>0.09</td>
</tr>
<tr>
<td>Heart Rate (bpm)</td>
<td>98.0 ± 14.9</td>
<td>102.3 ± 18.6</td>
<td>+4.4%</td>
<td>0.27</td>
</tr>
<tr>
<td>( \dot{V}_E ) (l·min(^{-1}))</td>
<td>41.2 ± 12.0</td>
<td>35.6 ± 13.5</td>
<td>-13.6%</td>
<td>0.06</td>
</tr>
<tr>
<td>RER</td>
<td>1.19 ± 0.14</td>
<td>1.08 ± 0.09</td>
<td>-9.2%</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Significant differences (P ≤ 0.05) between pretraining and posttraining values.

were not statistically significant. No other differences were noted for any other variable. In 5 subjects, BLA values were obtained pretraining (6.7±1.5) and posttraining (6.3±2.9 mM). At pretraining, the \( \dot{V}O_2 \) (l·min\(^{-1}\)) during the steady rate NMES leg cycle test represented 77.5 percent (mean) of the subjects’ NMES leg cycle peak \( \dot{V}O_2 \), and after training this value was reduced to 68 percent.

**DISCUSSION**

Persons with SCI are usually at the lower end of the spectrum with regard to exercise tolerance and aerobic fitness (10,11). Adopting exercise prescription guidelines known to be effective for improving aerobic capacity in moderately to severely deconditioned persons without SCI and applying those guidelines to SCI subjects performing an NMES leg cycle training program was a major objective of this study. The exercise prescription variable of interest became training frequency as a two-time per week frequency was incorporated to better accommodate the subjects’ schedules. Training mode, duration and “intensity” guidelines previously used by several investigators were implemented without modifications.

Our subjects exhibited a 10 percent increase in peak absolute and relative \( \dot{V}O_2 \) (graded NMES leg test), a 25 percent increase in peak work rate and a 4 percent decrease in peak heart rate from pre- to post NMES leg cycle training. The increase in peak \( \dot{V}O_2 \), although statistically significant, was not as dramatic as previously reported for persons with SCI completing similar training regimens with a training frequency of 3 times per week (36 sessions in 12–14 weeks). Published reports indicate 45–100, 23–35, and 8–11 percent increases in peak work rate, \( \dot{V}O_2 \), and HR, respectively, after 3-time per week NMES leg cycle training (6-8). The smaller improvement in peak \( \dot{V}O_2 \) experienced in this study may have been due to the reduced training frequency and/or to initially testing subjects after several weeks of progressive NMES cycling exercise (Phase I).

Habituation protocols have been used previously by many investigators to increase leg muscle strength and endurance prior to actual NMES leg cycle training programs for persons with SCI (4–8). Both NMES leg extension (quadriceps training) and leg cycle ergometry have been utilized during habituation periods. However, rarely have changes in peak \( \dot{V}O_2 \) been reported prior to and following a habituation phase. Pollack et al. (6) noted a mean increase of 30 percent in peak \( \dot{V}O_2 \) in their subjects with SCI following 1–15 weeks of habituation with NMES leg cycling. Twelve weeks of additional NMES leg cycle training was associated with only an additional 4 percent increase in peak \( \dot{V}O_2 \).

Considering the established criteria and highly demanding nature of the habituation stage of the present study (Phase I), subjects may have experienced improvements in their aerobic fitness capacity during this segment of the project. The time required to attain the criteria for advancement to Phase II varied among subjects ranging from one to 13 weeks. Unfortunately, physiologic responses to graded and submaximal NMES leg cycle exercise were not obtained before and after Phase I. Thus, the respective 10 and 25 percent increases in peak \( \dot{V}O_2 \) and work rate during the twice weekly NMES leg cycle training protocol appear
substantial. This is noteworthy since the scheduling and staffing of NMES exercise training sessions is difficult at times, and a two-time per week training frequency may foster better adherence to the training program.

The ability to exercise longer at the same work rate (0 W) during Phase I indicated improved muscle endurance and strength and, perhaps, cardiorespiratory fitness. This early progression in exercise tolerance is probably due to peripheral (muscle) training adaptations (13). Indeed, peripheral adaptations have previously been speculated as being responsible for the enhancement of exercise tolerance in persons with SCI exposed to regular NMES leg cycle exercise (4—7,14,15). The increases in Phase II training work rates from 0 W to 11.4 W and peak VO₂ following Phase II training are also likely due to peripheral training adaptations since these improvements occurred without a change in arm ergometry peak VO₂ (7).

In the only other study to evaluate changes during submaximal exercise (unloaded cycling) following NMES leg cycle training, Faghri et al. (5) noted a significant decrease in HR (—6—7 percent) with no changes in VO₂ or VE. The current study recorded 13.6 percent lower VE and 4.4 percent higher HR levels during steady state submaximal NMES leg cycle testing after training. However, submaximal VO₂ was also lower (5.2 percent) indicating that a change in work efficiency was likely responsible for the lower VE responses. It remains unclear as to why a decrease in HR was not observed during submaximal NMES leg cycling after training.

A significant decrease (—9.2 percent) was also observed in posttraining RER (VCO₂/VO₂) during the submaximal NMES leg cycle test. The decrease in RER from pre- to posttraining may represent a greater reliance on lipid metabolism (16), recruitment of more Type I fibers, and/or enhanced peripheral adaptations in the skeletal muscle (e.g., increased oxidative capacity, mitochondrial content, or capillarization). The RER values (i.e., RER≥1.00) are usually associated with non-steady state exercise conditions. However, the current subjects reached and attained steady state VO₂ and VE during the last 5 minutes of submaximal exercise. These results are similar to Hooker et al. (17) whose subjects performed 30 minutes of steady state NMES leg cycle ergometry with RER values greater than 1.00.

Blood lactate levels remain low during submaximal (<55 percent peak VO₂) steady state exercise (16). Subjects in the current study performed NMES leg cycle exercise at 68—77 percent peak VO₂. Although samples were not obtained on all tests, five subjects attained BLA levels of 6.3—6.7 mM. The relatively high BLA concentrations may indicate that Type II muscle fibers are primarily used to perform NMES cycling. Neuromuscular electrical stimulation is known to preferentially recruit large Type II motor units (18). Nonetheless, the high BLA levels and associated hydrogen ion concentration would increase VCO₂ and VE, which may be responsible for the high RER values observed during NMES leg cycle ergometry (16).

CONCLUSION

Previous studies suggest that prolonged (30 minutes), submaximal NMES leg cycle exercise should be conducted at least 3 times per week for optimal gains in cardiorespiratory fitness in persons with SCI. The current study indicated that a two-time per week NMES leg cycle training program will also result in significant increases in exercise tolerance and cardiorespiratory capacity in persons with SCI. These results have direct implications for those who participate in and/or supervise NMES leg cycle training programs.

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REFERENCES


