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Ventilation Limits Aerobic Capacity after FES Row Training in High Spinal Cord Injury

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Abstract

Purpose—In the able-bodied, exercise training results in increased ventilatory capacity to meet increased aerobic demands of trained skeletal muscle. However, after spinal cord injury (SCI), peak ventilation can be limited by pulmonary muscle denervation. In fact, peak ventilation may restrict aerobic capacity in direct relation to injury level. Hybrid functional electrical stimulation (FES) exercise training results in increased aerobic capacity and dissociation between aerobic capacity and injury level in those with injuries at T3 and below. However, injuries above T3 have the greatest pulmonary denervation and ventilatory capacity may restrict the increase in aerobic capacity with hybrid FES training.

Methods—We assessed relationships among injury level, peak ventilation, and peak aerobic capacity and calculated oxygen uptake efficiency slope (OUES) during hybrid FES exercise in twelve individuals (one female) with SCI at level T2 to C4 (injury duration: 0.33 to 33 yrs, age: 20 to 60 yrs), before and after 6 months of FES row training (FES-RT).

Results—Training increased peak aerobic capacity by 12% ($P=0.02$) with only a modest increase in peak ventilation (7 of 12 subjects, $P=0.09$). Both before and after training, injury level was directly related to peak ventilation ($R^2=0.48$ and 0.43) and peak aerobic capacity ($R^2=0.70$ and 0.55). Before training, the relationship of peak aerobic capacity to peak ventilation was strong ($R^2=0.62$), however, after training, this relation became almost completely linearized ($R^2=0.84$). In addition, OUES increased by 11% ($P<0.05$) after FES-RT.

Conclusion—Despite the ability to increase exercise capacity via hybrid FES exercise, the inability to increase peak ventilation beyond limits set by SCI level in those with high level injuries (above T3) appears to restrict aerobic capacity.

Keywords

ventilatory capacity; hybrid FES exercise; injury level; exercise training

INTRODUCTION

Aerobic exercise requires sufficient ventilation to provide oxygen to working muscles (22). In most able-bodied individuals, ventilatory capacity is more than adequate to meet metabolic demands for all exercise intensities (10,22). However, some highly trained individuals demonstrate a mismatch between the increased ability of the skeletal muscle to consume oxygen and ventilatory capacity (13). In contrast, those with a spinal cord injury (SCI) are unlikely to demonstrate a mismatch even after training because of significant skeletal muscle denervation which reduces O₂ demand dramatically. Even in high level injuries, the limitation to total oxygen consumption during exercise is skeletal muscle mass, despite significant respiratory muscle denervation. This is due to the proportional denervation of both skeletal and pulmonary muscle such that the respiratory system still has ample capacity to cope with the demands of arms-only exercise, even after training (27).

To augment aerobic capacity for persons with SCI, functional electrical stimulation (FES) of the legs has been combined with voluntary upper body exercise to create a hybrid FES exercise to allow engagement of more muscle mass (16,21,37). In addition, this exercise creates a leg muscle pump in synchrony with the upper body work, potentially aiding cardiac output in response to exercise (5). Moreover, arms-only exercise in SCI can be limited by the inability to vasoconstrict in the nonactive legs (31), whereas hybrid FES exercise obviates the need for this vasoconstriction (30). The normally 'wasted' blood flow to the legs serves a purpose to allow for increased oxygen consumption (6,7,29). In fact, regular FES training can result in a reduction in the normally strong inverse relationship between injury level and peak aerobic capacity (28). Our previous work showed that FES-row training (FES-RT) in individuals with low level injuries effectively improved aerobic capacity to the point that it was no longer related to injury level (28). However, for individuals with injuries above T3, respiratory capacity is much more compromised, and is proportional to the injury level (4,34). Hence, the increase in ventilatory requirements with FES training could result in an imbalance between ventilatory capacity and greater whole body skeletal muscle demand after FES-RT.

We hypothesized peak ventilation would be a key factor in determining the aerobic capacity that could be achieved with FES-RT for individuals with injuries above T3. We assessed oxygen consumption and ventilation during FES-rowing exercise in twelve volunteers with spinal cord injuries at T2 and above before and after 6 months of FES-RT and investigated the relationship between aerobic capacity, peak ventilation and injury level. In addition, we determined oxygen uptake efficiency slope (OUES), an objective and reproducible measure of cardiopulmonary reserve (1,18), to examine the integrated function of the cardiovascular, pulmonary, and musculoskeletal systems during exercise.

METHODS

Subjects

Twelve individuals (one female) with incomplete and complete SCI at T2 and above participated in this study. The mean age was 33.3 ± 3.8 yr (22 to 60), and mean body mass index (BMI) was 23.5 ± 1.1 kg·m⁻² (18.1 to 29.7). Time since injury ranged from 0.33 to 33

yr and averaged 8.3 ± 3.3 yr. Three individuals were over the age of 35, six had BMI in the category of overweight, and eight had a time since injury less than 10 years. None of the subjects smoked, had a history of any cardiovascular or pulmonary disease, or were taking cardioactive medications. Each subject gave written informed consent as approved by the Institutional Review Board at Spaulding Rehabilitation Hospital. Before the study, all participants completed a healthy history and were classified by an experienced physician according to the American Spinal Injury Association impairment scale.

FES-RT Protocol

To be able to perform functional movements for rowing, subjects underwent preliminary FES strength training prior to FES-RT. Pairs of electrodes placed over the motor points of the right and left quadriceps and hamstring muscles were attached to the 4-channel electrical stimulator (Odstock, Salisbury, United Kingdom). Stimulation parameters were set at a one second contraction with a 6-s rest for alternating muscles with an electrically stimulated knee extension followed by knee flexion. The intensity of stimulation to the quadriceps was increased to a level producing full knee extension; if full extension was not produced, the stimulation intensity was increased up to maximal (110mA). Subjects trained 3 times weekly and only advanced to FES-RT when 30 min of full knee extension was achieved (2 to 12 wk of strength training). Subsequently, subjects underwent FES-RT 3 times weekly. A detailed explanation of the FES-rowing device has been described previously (29). Basically, an existing rower (Concept, Morrisville, VT) with a seating system for stability was used with an electrical stimulator (Odstock, Salisbury, United Kingdom). The stimulator was connected to a button on the handle of the rower, allowing the exercising individual to synchronize the voluntarily controlled upper body with the FES-controlled legs to produce a rowing stroke. Participants began with short intervals of FES-RT interspersed with rest intervals and/or arms-only rowing depending on fitness level and the response to the FES, for a training session of 30 min. Each individual was expected to engage in 3 sessions per week for 6 months with the goal of reaching an exercise intensity of 75-85% of peak heart rate (HR_{peak}) for a continuous 30 min. Training data were monitored on a weekly basis.

Aerobic Capacity Testing

Once individuals were able to perform more than 10 min of continuous FES rowing, the first graded exercise test was performed. This test was repeated after 6 months of training. Subjects refrained from food for two hours prior to testing, from caffeine and alcohol for 24 h prior, and from vigorous physical activity for 48 h prior. The FES-rowing protocol was individualized to the fitness level of each individual with work progression specific to each subject. In general, work output increased every 1 to 2 min until volitional exhaustion with a total testing time between 8 and 12 min. On-line computer-assisted open circuit spirometry (ParvoMedics, Sandy, UT) was used to determine O_2 consumption (VO_2), CO_2 production, and respiratory exchange ratio (RER). Expired O_2 and CO_2 gas fractions were measured with a paramagnetic O_2 and infrared CO_2 analyzers. Ventilation (V_E) was measured via a Hans Rudolph 3813 pneumotachograph. Tidal volume (V_T) was obtained by integration of the flow signal. A heart rate monitor (Suunto, Vantaa, Finland) was used throughout the test. To determine that maximal exercise capacity was reached, at least 3 of the following criteria had to be met: 1) respiratory exchange ratio of 1.1 or higher, 2) a plateau in VO_2 despite

increasing workload, 3) 85% of age-predicted maximal heart rate (220-age), 4) a subjective rating of perceived exertion with a Borg scale of 17 or higher, and 5) precipitous decline in power >20 W during maximal leg stimulation. Since there are no explicit peak heart rate parameters for those with higher level injuries, we used the standard approach to exercise testing of 220-age. In fact, only those with SCI at level T2 achieved this peak heart rate.

Data and Statistical Analysis

Values for peak aerobic capacity ($\text{VO}_{2\text{peak}}$), peak ventilation (V_{Epeak}), peak tidal volume (V_{Tpeak}), peak breathing frequency (BF_{peak}), peak respiratory exchange ratio (RER_{peak}), and HR_{peak} were derived from the highest average 30s value obtained during the exercise test, usually the final 30s or within the final work load. In addition, breath-by-breath VO_2 and V_E were averaged over 10s periods to derive the OUES for each individual. This measure has been established in healthy subjects (2,17), children (3), and adult patients with cardiac or other metabolic diseases (11,32,33). OUES was calculated as follows:

$\text{VO}_2 = \text{OUES} \cdot \log_{10} \text{V}_{\text{E}} + \text{constant}$. OUES represents the rate of increases in VO_2 in relation to increasing V_E . Thus, a steeper slope indicates greater oxygen uptake for any given amount of ventilation during exercise. To determine the effect of 6 months of FES-RT, a paired Student's t-test was used to compare pre- and post-training values. Relations among injury level, V_{Epeak} , V_{Tpeak} , and $\text{VO}_{2\text{peak}}$ were determined via linear regressions. The injury score was derived from the injury level (C4-5, C5-6, C6-7, C7-8, and T2-10) and did not account for grade of injury. Rowing sessions per week across training months were analyzed by one-way repeated-measures analysis of variance (ANOVA). Two-way repeated-measures ANOVA was used to assess the effects of 6 months of FES-RT on the tidal volume and breathing frequency responses to the graded maximal exercise test as a function of relative exercise intensity (% $\text{VO}_{2\text{peak}}$). Significance was set at $P < 0.05$. All results are presented as mean $\pm$ standard error of the mean (SE).

RESULTS

Body mass did not change from pre- to post- training periods, averaging 72.5 ± 3.89 versus 73.3 ± 4.19 kg. Compliance to the 6-month training program averaged 1.8 ± 0.2 rowing sessions per week which corresponded to 59% of planned rowing sessions. There was no significant change in rowing sessions per week across training months ($F = 0.13$, $P = 0.99$). Though subjects were all encouraged to attend 3 sessions per week, this population, in particular, is subject to a number of secondary health complications, as well as transportation issues that gave rise to cancellations during the training period. Training intensity progressed, on average to 86% of HR_{peak} (range from 76 to 94%) by the end of 6 months, but this increase in intensity was not consistent across all subjects (7 of 12). Figure 1 shows one subject's training performance on a weekly basis over the 6 months. This subject was consistent in FES-RT (83% planned training session attended) and demonstrated a 34% relative increase in aerobic capacity from 16.2 to 21.7 $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$.

For all participants, $\text{VO}_{2\text{peak}}$ increased on average by 12% with 6 months of FES-RT, from 15.3 ± 1.5 to 17.1 ± 1.6 $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ($P = 0.02$; Fig. 2). This was accompanied by a 28% increase in peak wattage (34.6 ± 4.4 vs. 44.4 ± 5.7 W, $P < 0.01$). Average V_{Epeak} did tend to

be higher after FES-RT (37.5 ± 4.4 vs. 40.7 ± 3.0 L·min⁻¹, $P = 0.09$), but an increase was demonstrated in only 7 individuals. This modest increase in V_{Epeak} result from slight increases in V_{Tpeak} (1.23 ± 0.1 vs. 1.28 ± 0.12 L, $P = 0.18$) and BF_{peak} (38.4 ± 2.6 vs. 40.0 ± 1.5 min⁻¹, $P = 0.20$). There were no significant differences between pre- and post-training RER_{peak} and HR_{peak} . The magnitude of the increases in VO_{2peak} did not relate to exercise compliance ($P = 0.72$).

Prior to FES-RT, there was a close relationship between injury level and VO_{2peak} ($y = 0.17x - 0.15$, adjusted $R^2 = 0.70$, $P = 0.0004$; Fig. 3). In addition, there was a significant relationship between injury level and V_{Epeak} ($y = 3.85x + 8.97$, adjusted $R^2 = 0.48$, $P = 0.0076$). Although these relations remained after the 6 months of FES-RT, they were somewhat weaker (injury level and VO_{2peak} : $y = 0.17x - 0.03$, adjusted $R^2 = 0.55$, $P = 0.0035$; injury level and V_{Epeak} : $y = 4.26x + 9.14$, adjusted $R^2 = 0.43$, $P = 0.0126$). In contrast, 6 months of FES-RT markedly enhanced the relationship of VO_{2peak} to V_{Epeak} (Fig. 4). Before training, the relation of VO_{2peak} to V_{Epeak} was similar to its relation to injury level ($y = 0.03x - 0.03$, adjusted $R^2 = 0.62$, $P = 0.0014$; Fig. 4). However, after training, the relation of VO_{2peak} to V_{Epeak} became almost completely linearized (VO_{2peak} to V_{Epeak} : $y = 0.03x - 0.12$, adjusted $R^2 = 0.84$, $P < 0.0001$). Underscoring the importance of ventilation in determining the VO_{2peak} after training was its relationship to V_{Tpeak} . Prior to FESRT, VO_{2peak} and V_{Tpeak} were modestly related ($y = 0.616x + 0.33$, adjusted $R^2 = 0.34$, $P = 0.03$). However after training, the explained variance doubled such that ~75% of VO_{2peak} across these individuals could be predicted by V_{Tpeak} : $y = 0.79x + 0.21$, adjusted $R^2 = 0.74$, $P = 0.0002$). A likelihood ratio test between the regression models for all four variables showed that the pre- and post- FES-RT regressions were significantly different (Chi-squared < 0.01). The breathing pattern during the graded exercise tests before and after FES-RT is presented in Figure 5. As expected, both V_T and BF increased with exercise intensity ($P < 0.05$), and the magnitude of response was unchanged after FES-RT ($P = 0.15$).

The relation of VO_2 and $\log V_E$ from one typical case is shown in Figure 6. The relation shifted upward with an increased slope from pre- to post- training periods. Thus, after FES-RT, this subject had a larger increase in VO_2 for a given increase in V_E . For all twelve subjects, average OUES was higher after 6 months of FES-RT (1.24 ± 0.11 vs. 1.38 ± 0.12 , $P < 0.05$). Hence, FES-RT improved the efficiency of oxygen uptake in these individuals with SCI.

DISCUSSION

Consistent with prior research (8,28,34), we found that both peak aerobic capacity and ventilatory capacity were related to injury level. Higher level injuries cause greater skeletal muscle denervation, resulting in lower peak aerobic capacities. One might surmise that the accompanying pulmonary muscle denervation contributes to this lower capacity (4), however previous work suggests that even well-trained individuals with cervical spinal cord injuries rarely demonstrate ventilatory constraint during high-intensity arms-only exercise (27). Nonetheless, arms-only exercise engages a small muscle mass, and in those with SCI the amount of denervated skeletal muscle and denervated pulmonary muscle would be directly proportional. Hence, it might be difficult to create a mismatch between even highly

trained skeletal muscle and pulmonary capacity. We found that hybrid FES exercise, which effectively trains both innervated upper body and denervated leg skeletal muscles results in the restricted ventilatory capacity becoming a key limitation to aerobic capacity.

Individuals with SCI have significantly lower peak aerobic capacity and peak ventilation than the able-bodied (18,34,36). Moreover, peak aerobic capacity decreases as injury level moves up the spinal cord (4,28). Thus, active muscle mass has a profound effect on aerobic capacity, and is a significant challenge to achieve high level exercise in the SCI population. Hybrid FES exercise can overcome the limitations of limited muscle mass (20,35) and results in higher peak aerobic capacity than arms-only or FES legs-only exercise (6,7,15,37). Our previous work demonstrated an almost 30% greater peak aerobic capacity with FES-rowing exercise as compared to arms-only rowing (29). Regular training with FES-rowing will increase aerobic capacity (12,16), but adequate ventilation is critical to provide sufficient oxygen to working muscles during aerobic exercise. Those with SCI above T7 have the greatest functional reduction in respiratory capacity (14,25). Hence, for individuals with high level injuries, the greater muscle mass engaged during hybrid FES exercise as compared to arms-only exercise could potentially tax ventilatory ability. In fact, prior to training, we did find a strong relation between peak aerobic capacity and peak ventilation. However, peak ventilation contributed less than injury level to the prediction of peak aerobic capacity so that injury level might be considered to play a more important role in limiting peak aerobic capacity. Our previous work reported FES-RT in those with injuries at T3 and below improved not only aerobic capacity but also ventilatory capacity (28). In these individuals, ventilatory capacity appeared to be sufficient for the exercise demand and aerobic capacity was no longer related to injury level after training. However, the current work shows that those with higher level injuries and greater pulmonary denervation demonstrate a strikingly different response to training. The relationship of aerobic capacity to injury level remained and the relative role of peak ventilation in determining aerobic capacity increased. Moreover, after 6 months of FES-RT, the relationship between aerobic capacity and peak tidal volume was markedly stronger and hence it contributed more to the prediction of aerobic capacity. Thus, the inability to sufficiently increase tidal volume limited peak ventilation and hence restricted the increase in aerobic capacity. This suggests that the improvements in muscle metabolism and cardiovascular function and potentially greater active muscle mass after FES-RT outstrips the ability of the pulmonary musculature to generate higher levels of ventilation. This might be considered as analogous to highly trained elite athletes. During maximal exercise, highly trained elite athletes can reach the mechanical limits of the lung and respiratory muscles for producing alveolar ventilation (13). Similarly, in these FES-row trained individuals, the pulmonary system may not be able to meet the demands of muscular exercise and hence limit further training induced increases in aerobic capacity. In the able-bodied, the pattern of increasing ventilation is an initial increase in both tidal volume and breathing frequency followed by a plateau in tidal volume and further increases in breathing frequency (24). Our data showed linear increases in both tidal volume and breathing frequency throughout graded maximal exercise testing in those with high level SCI. Hence, these individuals do not reach the mechanical limit for tidal volume during exercise, suggesting that respiratory insufficiency limits exercise.

Only three previous longitudinal studies have explored the effects of FES-RT, reporting increases in aerobic capacity from 8% to 11% (19,28,37). However, there appears to have been only one subject with high level injury in these studies, and no separate data were reported. Our current results are the first to show a comparable increase in aerobic capacity in 12 individuals with injuries at T2 and above after 6 months of FES-RT (~12%). In fact, 5 of our 12 subjects showed a >20% increase in peak aerobic capacity. Although participants achieved high training intensity by the end of 6 months, compliance ranged widely and averaged only <60% of sessions. We did not find a close relation between compliance and the increase in aerobic capacity which may simply reflect variances in the degree of atrophy and fatigability of the denervated muscles (23). Nonetheless, our current work suggests that FES-RT provides a form of regular aerobic exercise that circumvents the compromised innervation of skeletal muscle mass in those with high level injuries.

We used OUES as a composite value for the efficiency of the cardiopulmonary system to provide sufficient oxygenated blood to active muscle to perform exercise. In essence, it reflects the integrated function and health of the pulmonary, cardiovascular and skeletal muscle systems during aerobic exercise (11,23). Prior to training, the OUES in this group of spinal cord injured individuals was 61% less than that observed in able-bodied individuals of similar age (9). This is likely due to the lesser and untrained skeletal muscle mass, although pulmonary and cardiovascular limitations could also have played a role. After training, there was an 11% increase, however the increase was as great as 58%, and 5 individuals showed a >22% increase. Interestingly, the change in OUES with FES-RT was unrelated to the change in peak ventilation (adjusted $R^2 = 0.09$, $P = 0.20$) yet strongly related to the change in peak aerobic capacity (adjusted $R^2 = 0.72$, $P < 0.05$). Thus the change in OUES with FES-RT may be due mainly to cardiovascular and skeletal muscle adaptations.

Our subjects included both tetraplegic and paraplegic individuals and since they can demonstrate quantitatively different exercise responses, they could be considered as different groups. However, we were focused on compromised respiratory capacity. With injuries at T2 and above, vital capacity can be less than 30% of normal respiratory function and as the injury level moves down from T4 and below, vital capacity improves greatly. Therefore, we studied individuals with injuries at T2 and above to provide a range of respiratory impairment. If we only examine the 10 subjects with cervical spinal cord injury, our findings remain. Although the sample size was small, it was sufficient to answer our primary hypothesis. Future measurements of arterial oxyhemoglobin saturation during exercise could provide a direct indicator of effective pulmonary gas exchange and determine the extent of inadequate ventilation during intense exercise.

In conclusion, we found that 6 months of FES-RT increased aerobic capacity with only a modest increase in ventilatory capacity in those with SCI at T2 and above. However, we found that this increased aerobic capacity resulted in trained individuals who appeared to be at their ventilatory constraint for maximal exercise. Hence, improvements of cardiopulmonary reserve appear to derive from cardiovascular and skeletal muscle adaptations and not from any improvement in ventilatory capacity. This suggests that aerobic adaptations in response to high-intensity FES-RT in those with high level injuries are limited by the amount of pulmonary muscle denervation. If this ventilatory limitation could be

overcome, high level injuries may experience greater improvements in aerobic capacity with hybrid FES exercise training.

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Figure 1.
Weekly FES-RT performance in one subject over 6 months.

Figure 2.

Peak responses to graded FES-rowing exercise tests pre- and post- training. Data refer to VO₂peak, peak wattage, and V_Epeak. Data are presented in a scatter plot with mean ± SE. * *P* < 0.05 compared with pre- and post- training.

Figure 3.
Relations of peak aerobic capacity and peak ventilation to injury level pre- and post-FES-RT.
Linear regressions with 95% confidence intervals are presented.

Figure 4.

Relations of peak aerobic capacity to peak exercise ventilation and peak tidal volume pre- and post- FES-RT. Linear regressions with 95% confidence intervals are presented.

Figure 5.
Comparison of V_T and BF pre- and post- FES-RT to the relative exercise intensity (%VO₂peak) during graded FES-RT tests. Data are presented as mean ± SE.

Figure 6.

The relationship between oxygen uptake and ventilation during graded FES-rowing exercise tests in one individual with SCI (left). Comparison of OUES pre- and post- FES-RT (right). Data are presented as mean $\pm$ SE. * $P < 0.05$ compared with pre- and post- training.