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Hybrid Functional Electrical Stimulation Exercise Training Alters the Relationship Between Spinal Cord Injury Level and Aerobic Capacity

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Abstract

Objective—To test the hypothesis that hybrid Functional Electrical Stimulation Row Training (FES-RT) would improve aerobic capacity but that it would remain strongly linked to level of spinal cord lesion due to limited maximal ventilation.

Design—Longitudinal before-after trial of 6 months FES-RT.

Setting—Exercise for persons with disabilities program.

Participants—Fourteen volunteers with complete SCI T3_T11, >2 years post-injury, aged 21–63 years.

Interventions—Six months of FES-RT preceded by a variable period of FES 'strength training.'

Main Outcome Measures—Peak aerobic capacity, and peak exercise ventilation before and after 6 months of FES-RT

Results—FES_RT significantly increased VO_2peak and Vepeak (both $p<0.05$). Prior to FES-RT, there was a close relationship between level of spinal cord injury and VO_2peak (adj $r^2=0.40$, $p=0.009$) that was markedly reduced after FES-RT (adj $r^2=0.15$, $p=0.10$) . In contrast, the

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Suppliers List
Rowing ergometer: Concept 2, Morrisville, Vt. http://www.concept2.com/
Functional electrical stimulation unit: Odstock, Salisbury, England. http://www.odstockmedical.com/
Metabolic cart: ParvoMedics, Sandy, Ut. http://www.parvo.com/

relationship between level of injury and $V_E$peak was comparable before and after FES-RT (adj r^2=0.38 vs. adj r^2=0.32, both $p<0.05$).

Conclusions—The increased aerobic capacity reflects more than increased ventilation; FES_RT effectively circumvents the effect of the spinal cord injury on peak aerobic capacity by engaging more muscle mass for training, independent of level of injury.

Keywords

chronic spinal cord injury; exercise; oxygen uptake; training

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After a spinal cord injury (SCI), the ability to perform aerobic exercise at high levels of oxygen demand is largely limited by loss of innervated skeletal muscle. As a result, those with an SCI typically demonstrate low aerobic capacities compared to the able-bodied.[1] Although regular exercise (e.g., arm crank exercise) can increase aerobic capacity, the magnitude of effect depends upon a number of factors, including the level and the completeness of the lesion.[2] In fact, a direct relation between higher level of lesion and lower aerobic capacity is seen in individuals regardless of whether they are untrained[1;3–6] or trained.[7;8] This may not be surprising simply because higher lesions result in lesser innervated skeletal muscle for whole body aerobic exercise. In addition, higher level lesions result in more pronounced limitations to peak ventilation.[5] In fact, peak ventilatory capacity can play an important role in limiting aerobic capacity in those with an SCI.[3;5] Hence, any increase in aerobic capacity with regular training may be circumscribed not only by the amount of metabolically active muscle mass available but also by impaired respiratory muscle function in those with an SCI.

One approach to augment increases in aerobic capacity with exercise training in those with an SCI is to incorporate functional electrical stimulation (FES) of the lower limbs with voluntary exercise of the upper limbs (3; 18), termed hybrid training. .[9;10] This may enhance exercise training effects in two ways: increasing the active whole body muscle mass and increasing upper body limb blood flow during exercise. For example, although the magnitude of work produced by the stimulated leg muscles during FES-cycling can be small (e.g., usually less than 20 watts) and the mechanical efficiency is low,[11] the leg muscles do demonstrate a training effect that increases whole body aerobic capacity.[10] In addition, the leg muscle contractions may enhance venous return during exercise and effectively increase the capacity to perform arm exercise. In those with an SCI, leg compression decreases heart rate and increases stroke volume during submaximal exercise[12;13] and can increase peak oxygen consumption.[14] Hence, training via hybrid FES exercise may effectively obviate the effect of lesion level on aerobic capacity. On the other hand, hybrid FES exercise does not ameliorate significantly lower minute ventilation during exercise in those with an SCI compared to uninjured controls.[5] Restrictive pulmonary changes consequent to SCI impair ventilation during exercise and may therefore mean that lesion level remains a significant determinant of peak oxygen consumption regardless of any benefit in training from hybrid FES exercise.

Our preliminary work with hybrid FES exercise (i.e., rowing) has shown an almost 30% increase in aerobic capacity when coordinated leg contractions are engaged and suggests

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that regular training can lead to improvements in aerobic capacity.[9] However, we have also found an important determinative relation of spinal cord lesion level to aerobic capacity via effects on peak ventilation.[3] Hence, even though FES_row training (FES-RT) circumvents the spinal lesion to increase the exercising muscle mass, we hypothesized that FES-RT would improve aerobic capacity but that it would remain strongly linked to level of spinal cord lesion due to limitations in peak ventilation. Therefore, we assessed peak oxygen consumption during FES_rowing in fourteen volunteers and assessed the relationships among lesion level, aerobic capacity, and peak ventilation before and after six months of FES-RT. Contrary to our hypothesis, the increase in aerobic capacity with FES-RT resulted in peak oxygen consumption levels that were no longer related to lesion level, but remained strongly related to peak ventilation.

METHODS

Subjects

Fourteen individuals (one female) with American Spinal Injury Association class A, T3_T11, >2 years post-injury participated in this research. Age ranged from 21 to 63 and averaged 39.2 ± 3.3 years; body mass index averaged 27.0 ± 4.5 (average height of 1.76 ± 0.07 meters and weight of 83.5 ± 11.5 kilograms) and ranged from 18.9 to 33.9. Mean time since injury ranged from 2 to 38 years and averaged 9.7 ± 2.6 years. All subjects completed a medical history and physical examination, performed by an experienced physician prior to participation. Individuals were excluded if they were on cardioactive medications or had any cardiovascular or pulmonary disease, diabetes, neurological disorders (other than SCI), current pressure sore(s), lower extremity contractures, or peripheral nerve compressions or rotator cuff tears that would limit the ability to row. All procedures were approved by the Institutional Review Board at Spaulding Rehabilitation Hospital and all participants provided written informed consent.

FES-Row Training (FES-RT)

FES_rowing requires adaptations to an existing rower (Concept 2, Morrisville, Vt.) that involve a seating system that provides trunk stability and constrains leg motion to the sagittal plane. In addition, there is a button on the handle of the rower that provides a command signal to an electrical stimulator (Odstock, Salisbury, England) to initiate rowing and control the timing of leg muscle stimulation (no ramp, pulse width of 450ms, frequency of 40 Hz). The exercising individual synchronizes upper body movement with the FES controlled leg movement via a voluntary thumb press to control the timing of stimulation to the paralyzed leg muscles. The specifics of this device have been described elsewhere.[9]

To perform FES_RT, leg muscle strength and endurance is first developed via preliminary FES_strength training for the quadriceps and hamstring muscle groups. Electrodes over the motor points of the quadriceps (rectus femoris, vastus medialis, vastus lateralis), and hamstrings (biceps femoris and semitendinosus) attached to the four channel stimulator provided alternating contractions of the quadriceps and hamstrings (6 second per contraction) for full knee extension and hamstrings isometric contraction. Frequency of training was 3 to 5 days/week and the duration increased to the point where repetitive full knee extension for 30 minutes could be achieved. At this point, participants began FES_RT 3 days/week, consisting of multiple short intervals of FES_rowing interspersed with intervals of 3_5 minutes arms_only rowing (cumulative arms_only and FES_rowing of 30 minutes per session). The duration of the intervals of arms_only rowing provided a rest period for the leg muscles as they fatigued and was individualized based on the responses to FES. Once sufficient muscle strength and endurance developed to allow continuous FES_rowing for >10 minutes (range 2_ 6 weeks), peak graded exercise tests were performed.

Thereafter, participants were encouraged to participate in the lab-based FES_RT 3 days/week for the next 6 months. The training consisted of intervals of FES_rowing that continually increased with the goal of 30 minutes of continuous FES_rowing 3 days/week at an intensity of 75_85% of peak heart rate. Training data was monitored on a weekly basis.

Aerobic Capacity Testing

Graded FES_rowing exercise tests were performed pre and post 6 months of FES_RT. Exercise tests were performed at approximately the same time of day. Individuals had not eaten for two hours prior to testing and had refrained from caffeine and alcohol for 24 hours, and from vigorous physical activity for 48 hours. Aerobic power was determined from on_line computer_assisted open circuit spirometry (ParvoMedics, Sandy, Ut). Ventilation and expired O_2 and CO_2 were measured to determine O_2 consumption (VO_2), CO_2 production, respiratory exchange ratio, ventilation (V_E), and oxygen pulse. Expired O_2 and CO_2 gas fractions were measured with paramagnetic O_2 and infrared CO_2 analyzers. Ventilation was measured via a Hans Rudolph 3813 pneumotachograph. A heart rate monitor (Suunto, Vantaa, Finland) was used throughout the tests. The baseline graded FES_row test protocol was based on each individual’s initial FES_row response and 1_2 minute work loads were selected to achieve test protocols of 8_12 minutes of incremental exercise. The protocol from the pre-test was used for the 6 month post-test unless the subject had progressed to the point where the initial workload was too low to allow proper FES_rowing technique. In these cases, the protocol was initiated at the second workload from the pre-test. To ensure attainment of peak exercise capacity, at least 3 of the following criteria were met: 1) 85% of age_predicted maximal heart rate (220_age), 2) respiratory exchange ratio >1.10 at end exercise, 3) plateau in O2 consumption despite increasing workload, 4) perceived exertion of at least 17 on the Borg scale of 6_20, and, 5) precipitous decline in power >20 watts during maximal leg stimulation.

Data and Statistical Analysis

Injury score was derived from the level of complete neurologic injury and ordanalized, with T3 corresponding to a value of 11 and values increasing as injury level moved down the spinal column. Values for peak aerobic capacity (VO_2peak), peak minute ventilation ($V_E$peak), peak respiratory exchange ratio, and peak heart rate were derived from 30 second averages during the graded exercise tests. Compliance was derived from the weekly compliance (percent of scheduled exercise sessions attended) and the average weekly work was derived from the product of exercise minutes and average wattage. Differences were determined via a Students paired t_test. Relations among values were determined via linear regressions. Significance was set at $p < 0.05$. All values are presented as mean +/− standard error of the mean.

RESULTS

Over the 6 months of FES_RT, compliance averaged 1.7 ± 0.5 rowing sessions per week which corresponded to attendance of 55% of planned rowing sessions (range from 22 to 85%). (It should be noted that those with an SCI have a range of barriers to regular, assisted exercise, including accessibility, transportation, and health issues - e.g., chronic pain, urinary infections, and fractures.) Average training intensity when expressed as percentage of peak heart rate ranged from 62 to 89%. In addition, the average weekly work calculated from average power and duration was highly variable, ranging from 269 to 3238 watts*minutes and averaging 1826 ± 976 watts*minutes. Nonetheless, over the six months, the training stimulus increased by 25%, on average.

Despite the wide range in training stimulus, the six months of FES_RT modestly increased VO_2peak (19.6 ± 6.0 ml/kg/min pre_training vs. 21.4 ± 6.6 ml/kg/min post_training, p=0.02; Fig. 1). Ten out of the fourteen subjects increased VO_2peak and the increase ranged from as little as 3% to as much as 37%. $V_E$peak was also increased by FES-RT (54.1 ± 13.5 L/min vs. 60.3 ± 13.5 L/min, p=0.01; Fig.1). Peak heart rate (169 ± 17 vs. 172 ± 12, p=0.12) and peak wattage (54 ± 20 vs. 60 ± 20, p=0.07) were slightly but not significantly higher after training. Interestingly, the magnitude of the increases in VO_2peak did not relate to exercise adherence (Fig 2). Neither weekly compliance nor average weekly work were correlated to the percent increase in VO_2peak.

Prior to FES-RT, there was a close relationship between level of spinal cord injury and VO_2peak (y=0.10x + 0.08, adj r^2=0.40, p=0.009; Fig. 3). In addition, there was a significant relationship between level of injury and $V_E$peak (y =3.41x + 4.87, adj r^2=0.38, p=0.01; Fig. 3) and between $V_E$peak and VO_2peak (y =0.02x + 0.43, adj r^2=0.48, p=0.004; Fig. 3). However, after training VO_2peak no longer related to level of injury (Fig. 4). That is, prior to FES_RT, almost 50% of the variance in VO_2peak across these subjects was explained by level of injury, but after FES-RT, the relation provided only 20% of explained variance and did not achieve significance (p=0.12). A statistical ANOVA comparison between the two linear regressions showed that the two models were significantly different from each other with an F value of 20.42, which provides a $p<0.01$ at 0.90 power. In contrast, there remained significant relations between level of injury and $V_E$peak (y = 3.17x + 14.6, adj r^2=0.32, p=0.02; Fig. 4) and between $V_E$peak and VO_2peak (y =0.02x+0.39, adj r^2=0.58, p=0.001; Fig. 4). Stepwise multiple regression supported these differences before versus after FES-RT. Prior to FES-RT, both level of injury and peak exercise ventilation contributed to the prediction of VO_2peak (r^2=0.59, p=0.008). After FES-RT, level of injury no longer contributed to the prediction of VO_2peak. Peak exercise ventilation remained a significant predictor, but in addition, we found that average weekly work also contributed to the prediction of VO_2peak (r^2=0.70, p=0.001).

DISCUSSION

Like others before us,[1;3–8] we found a strong relation between level of spinal cord injury and aerobic capacity. Moreover, despite the fact that our subjects were highly heterogenous in age and injury duration, the relationship was comparable to that reported in more homogenous groups.[4;6] Hence, level of spinal cord injury appears to be an important determinative of aerobic capacity, regardless of other factors that can impact it. Some of our previous work suggested that a key component of the relation between spinal cord injury level and aerobic capacity is the restricted pulmonary response to exercise. These current data support this postulate, but more importantly they demonstrate that training skeletal muscle below the lesion level via hybrid FES exercise effectively overcomes a key limitation to aerobic capacity in those with a spinal cord injury.

Peak aerobic capacity is limited in persons with SCI (as it is in the able-bodied) by cardiac output and active muscle oxygen extraction. However, in those with SCI, both are compromised. The paralyzed muscles are unable to contribute to oxygen extraction and the restricted muscle mass available for exercise is generally insufficient to elicit volume loading of the heart that helps increase cardiac output during aerobic exercise. Moreover, there is absent or impaired sympathetic vasoconstriction in paralyzed muscles, precluding efficient redistribution of blood from inactive tissues to active muscle during exercise.[15] As a result, even elite athletes with an SCI have aerobic capacities that decrease as the level of lesion moves up the spinal cord.[8]

Functional electrical stimulation for exercise has been in use for over 30 years[16] and although FES leg exercise alone has only modest effects on peak aerobic fitness in people with SCI,[17] hybrid FES exercise has been used to overcome the limitations of both upper body ergometry and FES cycling. Our own previous work[9] demonstrated an almost 30% increase in peak aerobic capacity during FES_row exercise as compared to arms only rowing. Only two previous longitudinal studies explored the effects of FES_RT[18;19] and both reported significant increases in aerobic capacity after 12 weeks of training of 8–11%. Our current results from six months of FES_RT in 14 subjects show a comparable increase in aerobic capacity (~9%). However, it should be noted that half of our 13 subjects showed a greater than 10% increase in peak aerobic capacity and five showed a greater than an 18% increase. On the other hand, despite the increase the aerobic capacity remained lower than age-predicted average at ~55% of population norms. Of note, Brurok et al.[10] found a 24% increase in VO2peak in six individuals with SCI after only 8 weeks of hybrid FES-bike training (i.e., concurrent arm cycling and stationary FES cycling). Their approach utilized high intensity training intervals and had 100% compliance, hence, it is possible that even greater increases in aerobic capacity could be achieved with more intense and more consistent training. However, the practicality of greater exercise frequency can be difficult in this population[20]; the FES-rowing equipment is not available for home use and transportation can be a significant barrier in those with an SCI. Moreover, as others have reported,[21] we found that invariably, health issues over the six months impact the ability to consistently train in some individuals with an SCI. Nonetheless, our current work suggests that FES-RT provides a form of regular aerobic exercise that provides an unique exercise stimulus that circumvents a primary limitation to vigorous exercise those with an SCI - compromised innervation of skeletal muscle mass.

Surprisingly, the change in aerobic capacity after 6 months of FES_RT did not correlate with measures of adherence. Compliance ranged widely and only averaged less than 60% of sessions, or slightly less than twice per week. Nonetheless, we did not find that either compliance or the average work performed bore a relation to the increase in aerobic capacity. This could reflect variances in the atrophy and fatiguability of the denervated muscle.[22] That is, for example, an individual with lesser atrophy and lesser shift to type II fiber type might require be more trainable and hence respond more with a lesser exercise stimulus. Hence, it may be that responses to FES-RT are not uniform and one cannot generalize the expected adaptations to this exercise stimulus across the range of SCI. However, our data did evidence an important adaptation in that six months of FES_RT markedly decreases the association between level of spinal cord injury and aerobic capacity. Similar to prior work,[1;3–8] we found a strong relationship between level of injury and peak oxygen consumption prior to training. However, after training, the relationship was markedly reduced and this did not derive from increased peak ventilation. The relationship of peak ventilation to injury level shifted upward to higher ventilation volumes, but otherwise remained essentially unchanged with a similar slope and comparable explained variance. In contrast, the relationship of injury level and peak aerobic capacity shifted upward with a reduced slope and strikingly lower explained variance. This reflects more than increased ventilation and is likely due to the training effect of FES_rowing on leg skeletal muscle. That is, FES_RT effectively circumvents the effect of the spinal cord injury on peak aerobic capacity by engaging more muscle mass, independent of level of injury.

STUDY LIMITATIONS

Though these results are encouraging for a FES-rowing as an effective exercise intervention to improve health in those with an SCI, there are limitations to this work. From a physiologic perspective, although our data clearly show an increase in peak aerobic capacity after 6 months of FES_RT, we cannot say what accounts for the increase. Future measurements of cardiac output during peak exercise could determine whether the ability to generate greater systemic flow contributes to the increase in aerobic capacity. In terms of generalizability, we did not have any individuals with injuries above the T3 level or any with incomplete injuries. The magnitude of effect may not be similar in those without complete paraplegia. Implementation was limited in that the current FES device is only four channels and only stimulates the quadriceps and hamstrings with a standardized stimulation pattern. The use of more channels or optimized stimulation parameters could enhance contribution of the denervated muscle mass and could provide a more vigorous exercise stimulus. Lastly and practically, further refinement of the apparatus could lead to an in_home device. Home_based exercise programs for the non_SCI population can be expected to have adherence as high as 75% of the planned number of sessions. [23] This would be of even greater impact for the population of individuals with an SCI given their limitations to regular exercise training.

CONCLUSIONS

We found that FES_RT in those with SCI improved aerobic capacity over 6 months of training. This improvement was associated with an increase in peak ventilation and resulted in aerobic capacities that were no longer related to level of injury. Surprisingly, we found that the improvements in aerobic capacity did not correlate to the exercise stimulus, providing some evidence that this mode of exercise may be broadly efficacious. Our data suggests that the benefits of FES_RT may lie in effectively circumventing the effect of spinal cord injury by engaging more muscle mass, independent of level of injury.

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Abbreviations

SCI	spinal cord injury
FES	functional electrical stimulation
FES-RT	FES_row training
VO_2peak	peak aerobic capacity
$V_E$peak	peak minute ventilation

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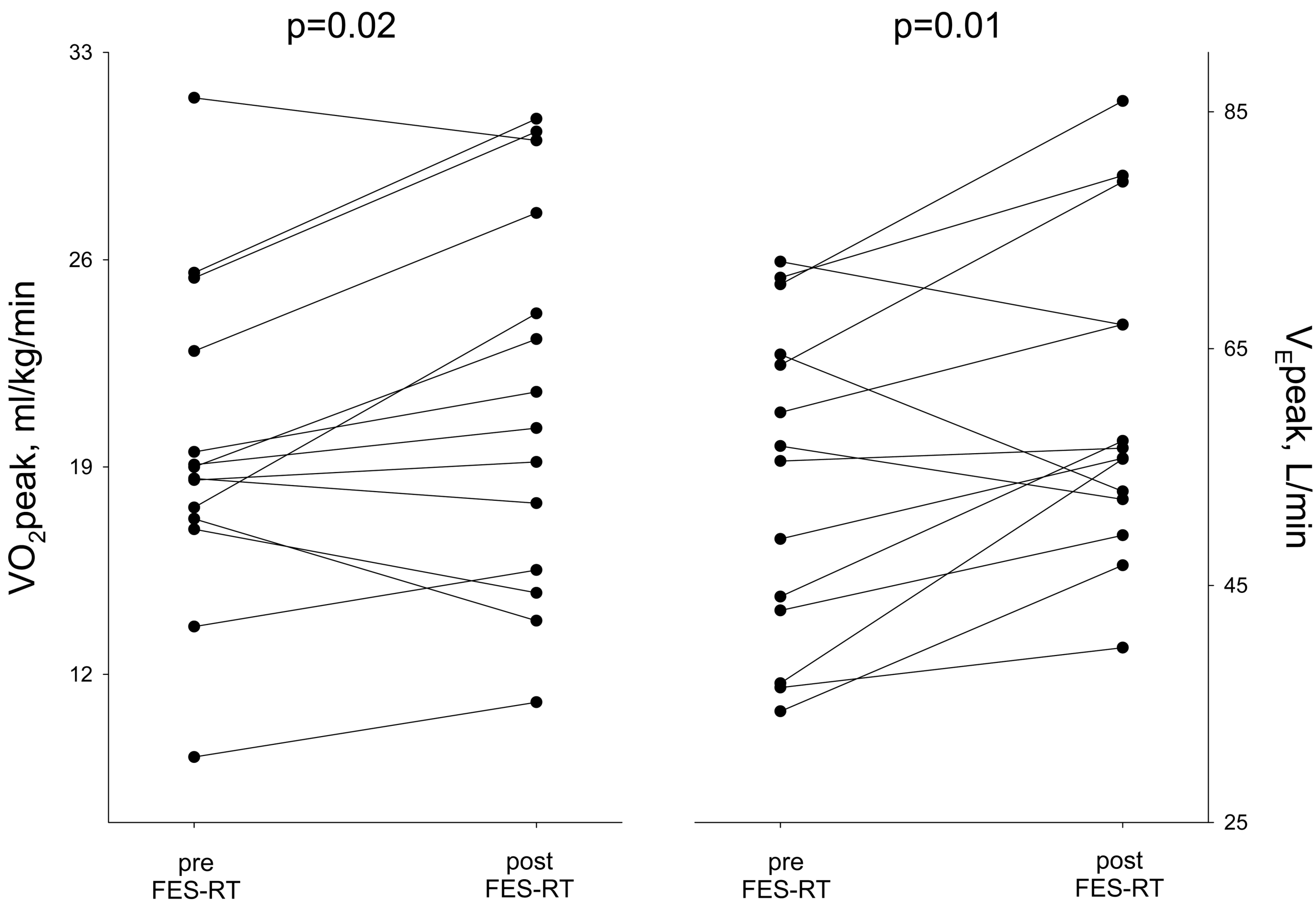

Figure 1.

Pre and Post 6 months FES-RT aerobic capacity and peak ventilation in all subjects.

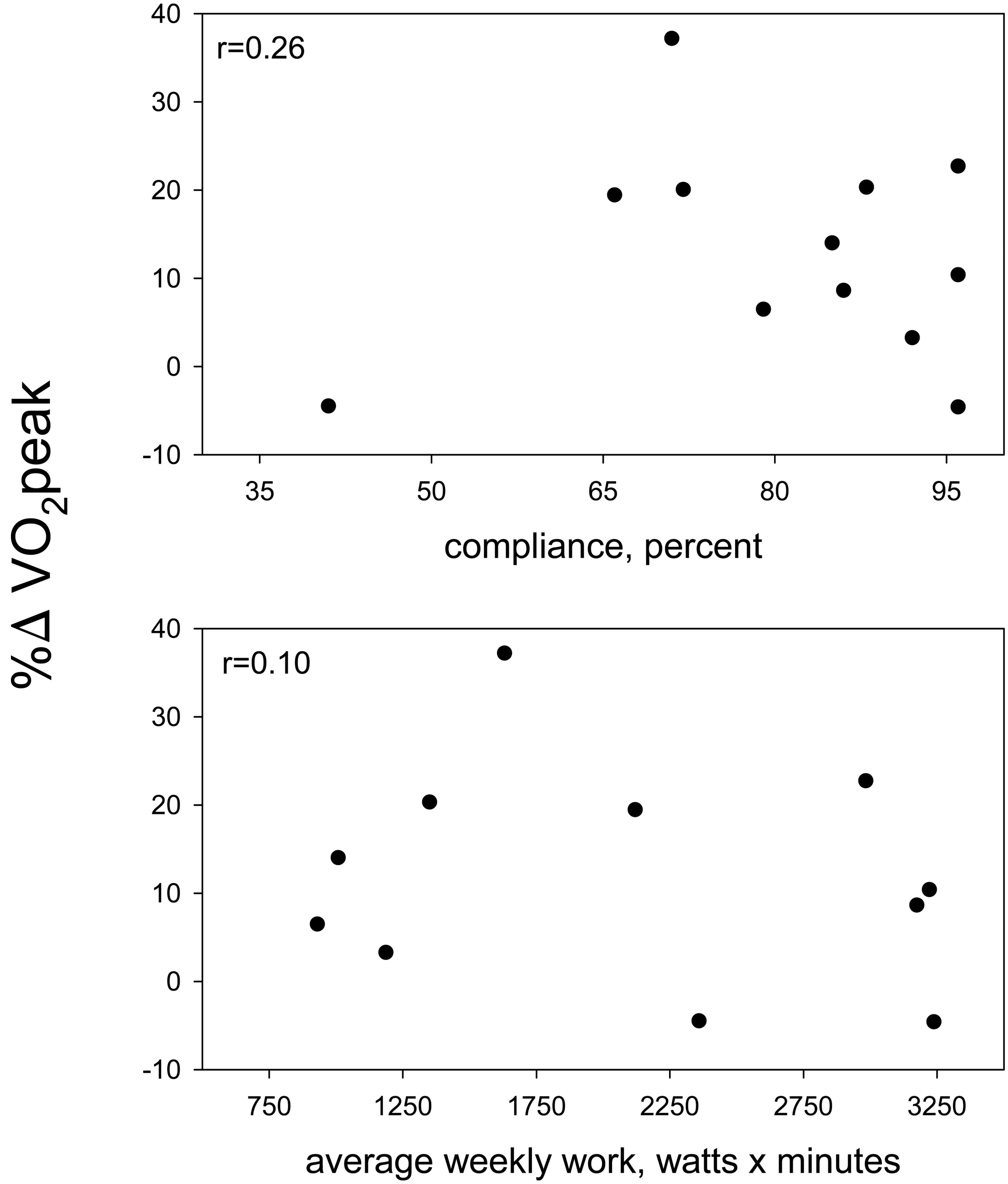

Figure 2.

Scatterplots of percent increase in aerobic capacity and exercise compliance and average weekly work.

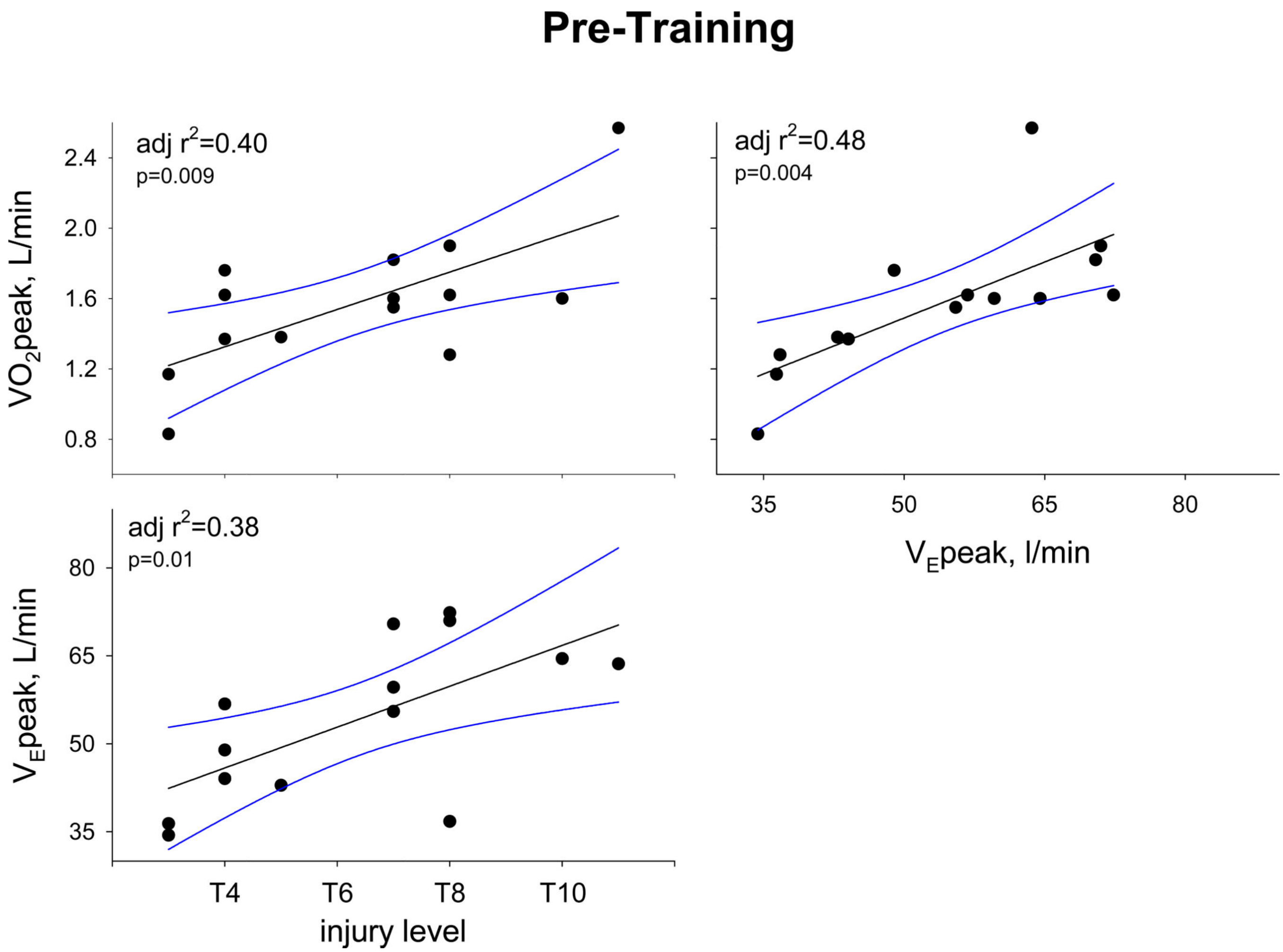

Figure 3.

Relations among injury level, peak aerobic capacity, and peak exercise ventilation prior to FES-RT.

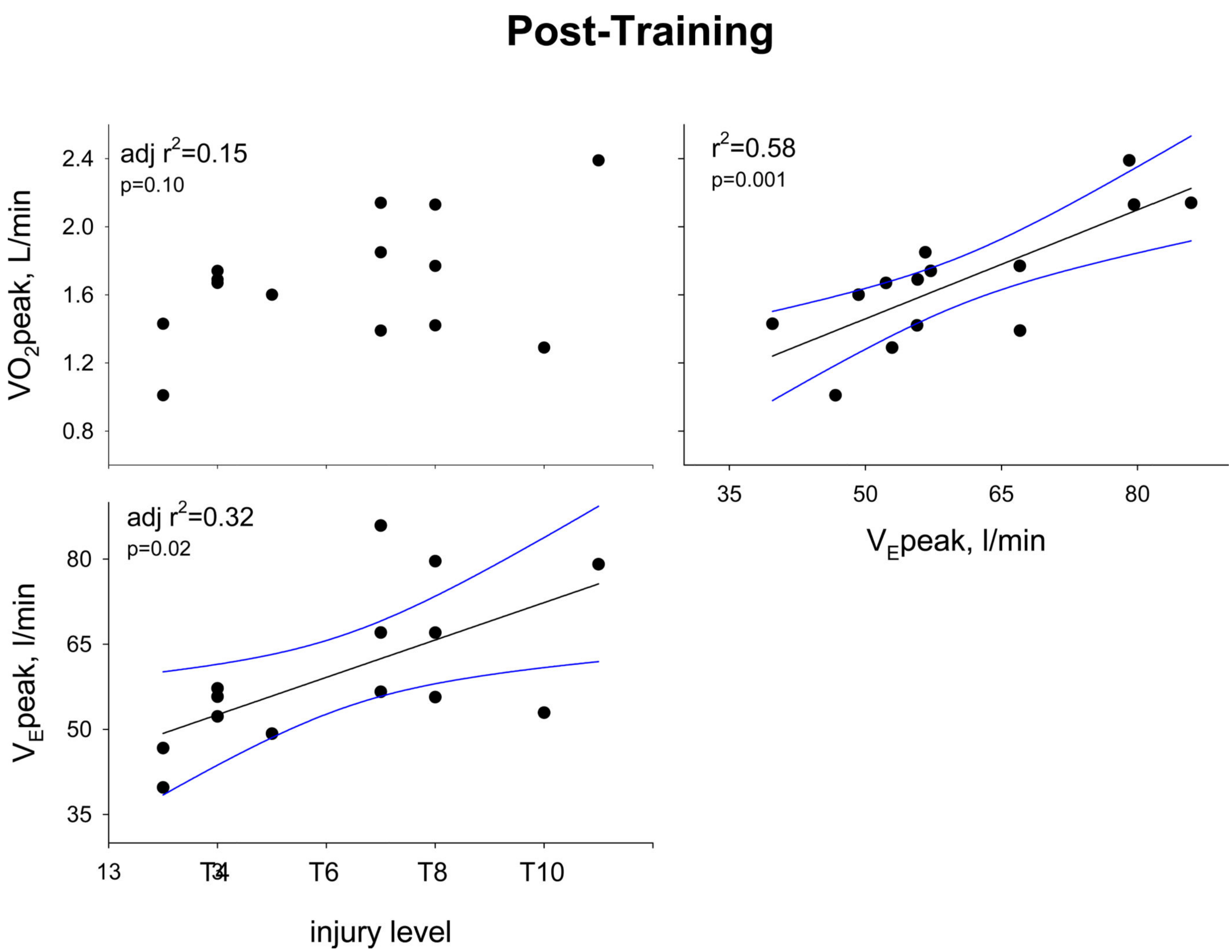

Figure 4.
Relations among injury level, peak aerobic capacity, and peak exercise ventilation after 6 months of FES-RT.