Original Research

Aerobic Capacity With Hybrid FES Rowing in Spinal Cord Injury: Comparison With Arms-Only Exercise and Preliminary Findings With Regular Training

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Objective: To determine the magnitude and range of increases in peak aerobic capacity with hybrid–functional electrical stimulation (FES) rowing versus arms-only rowing in persons with spinal cord injury.

Design: Comparison of graded exercise tests for peak responses during FES rowing and arms-only rowing. Preliminary data on adaptations to FES row training were gathered in a subset of individuals.

Setting: Outpatient cardiovascular research laboratory.

Participants: Six male patients with spinal cord injury (T4-T9, American Spinal Injury Association class A).

Methods or Intervention: Arms-only rowing was compared with FES rowing, in which the person who is exercising synchronizes the voluntarily controlled upper body movement with the FES-controlled leg movement via stimulation to the paralyzed leg muscles. A subgroup (n = 3) completed at least 6 months of a progressive FES row training exercise program with graded exercise tests every 6 months.

Main Outcome Measurements: Peak oxygen consumption, peak ventilation, peak respiratory exchange ratio, peak heart rate, and peak oxygen pulse.

Results: Peak oxygen consumption was greater during FES rowing than during arms-only rowing (20.0 ± 1.9 mL/kg/min versus 15.7 ± 1.5 mL/kg/min, $P = .01$). Peak ventilation was similar, whereas peak respiratory exchange ratio and peak heart rate tended to be lower ($P = .14$ and $P = .19$, respectively). As a result, oxygen pulse was greater by 35% during FES rowing. Two of the three persons who completed at least 6 months of FES row training demonstrated increases in aerobic capacity greater than those previously observed in able-bodied individuals.

Conclusions: FES rowing may provide a more robust exercise stimulus for persons with spinal cord injury than most options currently available because of the greater aerobic demand.

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INTRODUCTION

Ample evidence indicates that aerobic exercise in persons with spinal cord injury (SCI) is greatly beneficial to health [1-3], improves one's quality of life [4], and affects outcomes after SCI [5]. Moreover, active voluntary exercise may be an effective rehabilitation technique to target potential neuroplasticity by eliciting functional ranges of joint motion, activation of muscles, and multiple modes of afferent stimulation [6,7]. However, in all persons, able-bodied or not, aerobic exercise must meet certain intensity and volume criteria to induce significant benefits across multiple systems [8]. For example, sustained aerobic exercise greater than 21 mL/kg/min, or 6 metabolic equivalents (METs), is needed to significantly reduce the risk of coronary disease [9], and greater exercise intensity is associated with lesser prevalence of multiple disorders [10]. Hence more vigorous exercise results in greater benefits. Patients with SCI can have difficulty achieving sufficient exercise intensities because the paralyzed muscles cannot contribute to overall oxygen consumption, and thus the hemodynamic responses to most forms of exercise that can be performed are compromised.

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The solution could be "hybrid" functional electrical stimulation (FES) exercise involving both innervated upper body and electrically stimulated lower body muscles. Although hybrid FES can produce greater aerobic power and oxygen consumption than either upper body or FES exercise alone [11], not all hybrid FES exercise modes can provide the appropriate exercise stimulus; the hemodynamic profile during exercise is critical to achieve sufficient intensities for attendant adaptations [12]. Sustained, coordinated movement directly comparable with that in an able-bodied person would minimize hemodynamic limitations imposed by SCI (ie, sufficient active muscle mass, a dynamic "muscle pump," and constriction of non-active muscle) and thereby provide the optimal stimulus.

Laskin et al [13] proposed hybrid FES rowing as a form of exercise for persons with SCI that is closest to the large-muscle exercise performed by able-bodied individuals. Simultaneous and coordinated engagement of both upper innervated and lower non-innervated limbs results in a unique form of aerobic exercise for the population with SCI. The non-innervated legs initiate the stroke and create a force vector that is completed with the arm pull [14]. Contraction of the lower limb muscles creates a muscle pump for venous return and contributes to the exercise load, so there is no need for vasoconstriction in this region [12].

However, despite its potential, very little work has been done to define the magnitude of oxygen consumption that can be achieved with this form of exercise. In fact, since Laskin and colleagues defined the paradigm more than 15 years ago, only 4 publications have appeared in the literature in which the authors described aerobic capacity [15-18], and in 3 of these publications, the authors present data from an essentially identical group of subjects. Moreover, limitations inherent in the studies preclude clear interpretation of the potential exercise capacity with FES rowing versus arms-only exercise. The level of injury and time since injury varied greatly (from C7 to T12 and from 2 to 36 years), and the age range also was great (from 24 to 68 years).

Although persons with SCI are a heterogeneous group, the large range of injury level, injury duration, and age could confound the responses to exercise. In addition, exercise testing to determine peak aerobic capacity requires rigorous control to ensure that a true maximum is achieved [19,20] and a reliable value is obtained [21]. However, it appears that the previous work did not use standardized end points [15] and/or precise metrics [16]. As a result, previous comparisons of aerobic capacity between FES rowing and arms-only exercise, as well as responses to training, may have misestimated the magnitude of effect.

Therefore we set out to determine the magnitude and range of increases in peak aerobic capacity with FES rowing versus arms-only rowing in persons with SCI. We restricted our population to minimize potential confounds of lesion level, injury duration, and age. In addition, we used a standardized protocol that followed widely accepted guidelines to ensure achievement of true peak oxygen consumption (ie, achievement of ≥85% age-predicted maximal heart rate, maximal respiratory exchange ratio ≥1.10, plateau in oxygen consumption despite increasing workload, and Borg [22] rating of perceived exertion ≥17) [19,20]. Finally, we adopted a reliable data-processing approach consistent with recommendations for time-averaged indirect calorimetry [21]. Thus we limited potential confounds to interpretation to better delineate the differences in aerobic capacity of hybrid FES rowing versus arms-only rowing. We hypothesized that the greater muscle mass engaged with FES rowing would result in greater peak aerobic capacity and oxygen pulse despite similar peak ventilation, respiratory exchange ratio, and heart rate. In addition, we present preliminary data on the effects of 6-18 months of exercise training with FES rowing.

METHODS

Participants

Subjects (N = 6) were recruited via mailings to former patients in the Spaulding Rehabilitation Hospital SCI program. All subjects had a complete medical history and physical examination, including an American Spinal Injury Association neurological examination performed by an experienced physician. All subjects were neurologically stable and were approved to participate by a physiatrist specializing in SCI. All subjects were male, had complete injuries below the T3 level, were within 18 years of injury, and were younger than 40 years (Table 1). All procedures were approved by the Institutional

Table 1. *Subject characteristics*

Participant	Lesion Level	ASIA Classification	Age (y)	Time Since Injury (y)	Weight (kg)	Height (in)
1	T8	A	33	17.5	74.8	73
2	T4	A	35	15.3	57.5	71
3	T4	A	22	1.6	68.0	70
4	T9	A	36	6.1	77.1	71
5	T4	A	35	5.5	89.8	73
6	T5	A	37	5.1	99.8	68

ASIA = American Spinal Injury Association.

Review Board at Spaulding Rehabilitation Hospital, and all participants provided written informed consent.

All subjects achieved the initial stage of FES row training and could perform continuous progressive FES rowing to peak capacity. Three of 6 subjects completed at least 6 months of FES row training. Data will be presented for all 6 subjects for continuous progressive FES rowing to peak capacity. Preliminary data for the 3 trained individuals also will be presented.

The FES-Rowing Paradigm

FES rowing requires adaptations to an existing rower (Concept2, Morrisville, VT) that involves a seating system that provides trunk stability and constrains leg motion to the sagittal plane. The low-pressure seating system has a high back, adjustable lumbar support, and an adjustable seat belt to stabilize the trunk when necessary. To protect the knee joints against hyperextension and hyperflexion, the range of the seat motion is limited by 2 adjustable safety stops with springs installed on the rail. A button on the handle provides a command signal to the electrical stimulator to initiate rowing and control the timing of leg muscle stimulation. The 4-channel electrical stimulator (Odstock, Salisbury, United Kingdom) activates the quadriceps and hamstrings in drive and recovery phases of the rowing cycle, respectively. Thus the exercising individual synchronizes the voluntarily controlled upper body movement with the FES-controlled leg movement via a voluntary thumb press to control the timing of the stimulation to the paralyzed leg muscles. Figure 1 shows a schematic of the rowing set-up.

Initial FES Strength Training

To perform the aforementioned FES row technique, a certain level of leg muscle strength and endurance is needed; however, most persons with SCI have pronounced atrophy.

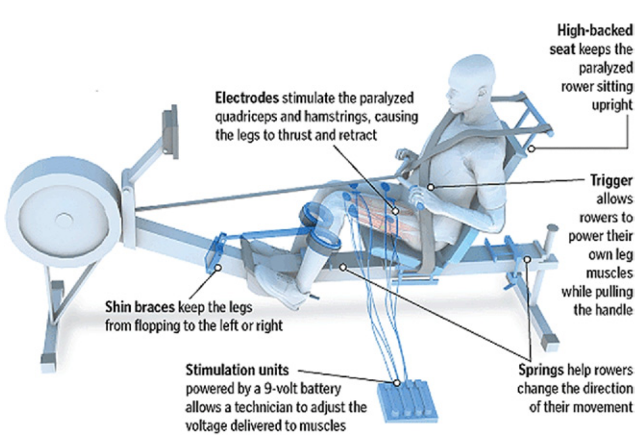

Figure 1. Schematic of adapted rower.

Therefore, before FES row training, patients underwent initial preliminary FES strength training for the quadriceps and hamstring muscle groups. This strength training was intended to allow the patient to complete a rowing stroke wherein the force of the arm pull can be counteracted by a sustained quadriceps contraction and the return can be affected by a hamstring contraction.

The electrodes were placed over the motor points [23] of the quadriceps (rectus femoris, vastus medialis, and vastus lateralis) and hamstrings (biceps femoris and semitendinosus) and attached to the 4-channel electrical stimulator. While seated, individuals used the stimulator to generate a dynamic knee extension through concentric activation of the quadriceps muscle in one leg while the opposite knee remained in a fixed position at approximately 90° of flexion and was stimulated to generate a mild isometric contraction of the hamstrings (6 seconds per contraction, no ramp, pulse width of 450 ms, frequency of 40 Hz). Stimulation was applied to each leg in an alternating pattern (concentric right quadriceps with isometric left hamstring contractions alternating with concentric left quadriceps with isometric right hamstring contractions) at a rate of 5 cycles per minute. The intensity of the stimulus to the quadriceps was set to the level that produced full knee extension.

As the quadriceps fatigued, the intensity of the stimulation was increased to maintain full knee extension, up to the maximal intensity of the device if necessary (approximately 110 mA). The intensity of the stimulus to the hamstrings also was increased as needed to maintain a mild isometric contraction. Frequency of training was 3-5 days per week, and the duration increased to the point at which repetitive full knee extension for 30 minutes could be achieved. At this point, FES row training was initiated. Duration of FES strength training varied from 2 to 12 weeks.

Transition to FES Rowing

After FES strength training, participants began FES row training 3 days per week, consisting of multiple short intervals of FES rowing interspersed with intervals of 3-5 minutes of arms-only rowing (cumulative arms-only and FES row training 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 on the basis of the responses to FES. Individuals were trained in the FES row technique to ensure proper timing of the stimulation in the rowing stroke. On days that rowing was not performed (4 days per week), individuals continued to perform FES strength training. 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.

Graded Exercise Testing

Exercise tests were performed at approximately the same time of day, at least 2 days apart, and in random order. Individuals received nothing by mouth (ie, their status was NPO) for 2 hours before testing; in addition, they had refrained from ingesting caffeine and/or alcohol for 24 hours and had refrained from vigorous physical activity for 48 hours. All individuals were required to void their bladder before testing to avoid a dysreflexic response and/or involuntary voiding. Aerobic power was determined from online computer-assisted open circuit spirometry (ParvoMedics, Sandy, UT). Ventilation and expired O_2 and CO_2 were measured while subjects performed arms-only rowing or FES rowing to determine O_2 consumption, CO_2 production, respiratory exchange ratio, ventilation, and oxygen pulse. Expired O_2 and CO_2 gas fractions were measured with a paramagnetic O_2 and infrared CO_2 analyzers. Ventilation was measured via a pneumotachograph (model 3813; Hans Rudolph Co., St. Louis, MO). A heart rate monitor (Suunto, Vantaa, Finland) was used throughout the tests.

The arms-only rowing test was performed with the adapted rowing seat locked in a fixed position with subjects belted securely across the shoulders to ensure trunk stability. Subjects rowed with arms only at an initial workload of 10 watts for 2 minutes and with increasing workload by 10 watts every 2 minutes. The FES row test was performed similarly. 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 beats/min − age) was achieved; (2) the respiratory exchange ratio was ≥1.10 at the end of exercise; (3) a plateau in O_2 consumption occurred despite increasing workload; (4) perceived exertion was rated at least 17 on the Borg scale of 6-20; and (5) a precipitous decline in power of ≥20 watts occurred during maximal leg stimulation (FES row test only).

FES Row Training

All patients continued to FES row train 3 days per week and to perform the FES strength training on non-rowing days. The training consisted of intervals of FES rowing that continually increased, with the goal of 30 minutes of continuous FES-rowing. After 30 minutes of continuous FES rowing was possible, FES row training progressed to 30-40 minutes of exercise 3 days per week at an intensity of 75%-85% of maximal heart rate. However, only 3 persons achieved the ability to perform the minimum prescribed exercise duration and intensity. Each of these 3 persons trained for at least 6 months or longer. High compliance was ensured by having all exercise sessions on site; missed scheduled exercise sessions were followed by phone contact with the subjects to ensure a swift return to FES row training. Graded FES rowing exercise tests were performed at 0, 6, 12, and 18 months.

Data Analysis

Peak values for aerobic capacity, minute ventilation, respiratory exchange ratio, and heart rate were derived from 30-second averages during the graded exercise tests. Peak oxygen pulse was derived from peak oxygen consumption (mL/min) divided by heart rate (beats/min). The amount of average weekly exercise was derived from the product of exercise minutes and average wattage for each exercise training bout. To test the hypothesis that FES rowing resulted in greater peak aerobic capacity and oxygen pulse despite similar peak ventilation, respiratory exchange ratio, and heart rate, comparisons were made for baseline data via a Student paired t-test. With a Bonferroni correction, a P value of .01 was considered significant.

RESULTS

Differences in peak aerobic capacity for arms-only rowing versus FES rowing at baseline can be seen in Figure 2. Peak aerobic capacity averaged 15.7 ± 1.5 mL/kg/min for arms-only rowing and was greater for FES rowing (20.0 ± 1.9 ml/kg/min, $P = .01$). Only one subject demonstrated no increase in aerobic capacity with the addition of FES leg stimulation to the rowing. For the other 5 subjects, the increase ranged from 12% to more than 50%. Peak ventilation was similar for the 2 forms of exercise. However, peak respiratory exchange ratio tended to be higher for arms-only rowing (1.28 ± 0.16 versus 1.17 ± 0.03, $P = .14$). In addition, peak heart rate tended to be somewhat lower (179 versus 170, $P = .19$), and as a result of both this phenomenon and the greater peak oxygen consumption, peak oxygen pulse was, on average, 35% greater during FES rowing versus arms-only rowing (6.90 versus 9.08, $P = .0007$).

Figure 3 shows the changes in aerobic capacity in the persons who completed 18, 12, and 6 months of FES row training and the corresponding amount of exercise performed. Compliance varied from 67% to 86% of planned rowing exercise sessions. Subject 1 had inconsistencies in the amount of training performed (75% planned training sessions attended) but demonstrated a 30% increase in aerobic capacity during the 18 months of training (from 24.4 to 32.2 mL/kg/min). Subject 2 was more consistent in FES row training (82% planned training session attended) and demonstrated an almost 50% relative increase in aerobic capacity, from 18.3 to 27.1 mL/kg/min. In contrast, Subject 3, who trained for only 6 months, had no change in peak aerobic capacity. However, this person rarely achieved the average weekly exercise intensity of either subject 1 (1878 ± 157 watts*min) or subject 2 (2986 ± 185 watts*min). In fact, the maximum exercise

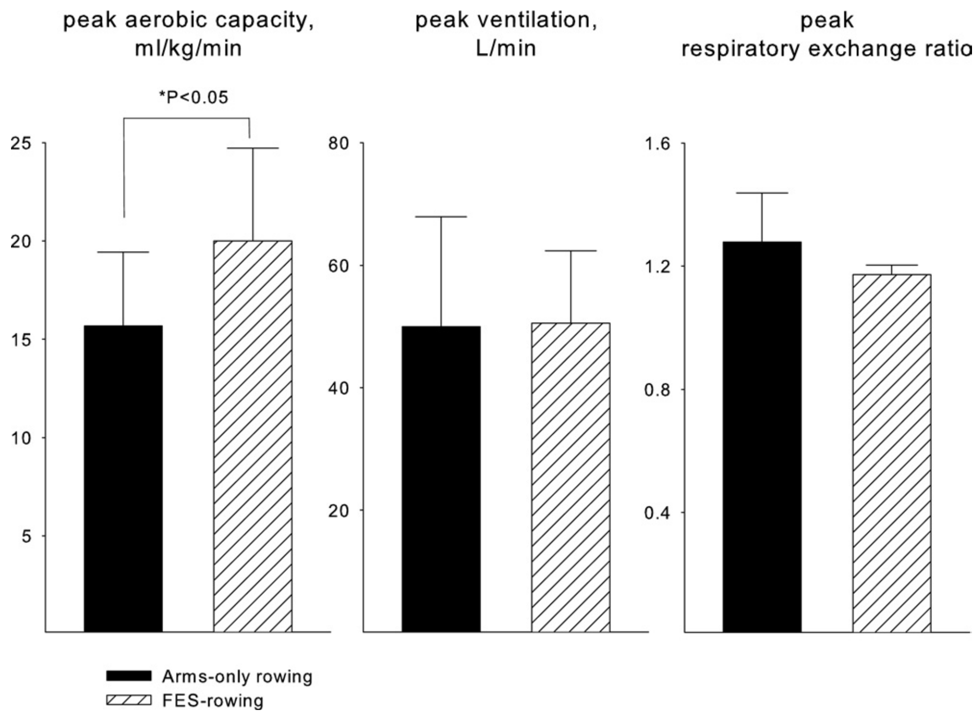

Figure 2. Peak responses to arms-only rowing and functional electrical stimulation rowing graded exercise tests. Data are mean ± standard error. FES = functional electrical stimulation.

performed during a single week by subject 3 (1698 watts*min) was well below these averages.

DISCUSSION

The demands of producing aerobic work require integrated responses in a number of body systems, but most importantly, adequate blood flow must be directed to the active muscle under sufficient perfusion pressure. In fact, the functional limit of aerobic work, maximal oxygen consumption, is by definition the product of maximal systemic flow (ie, cardiac output) and active muscle oxygen extraction (ie, arteriovenous oxygen difference). On

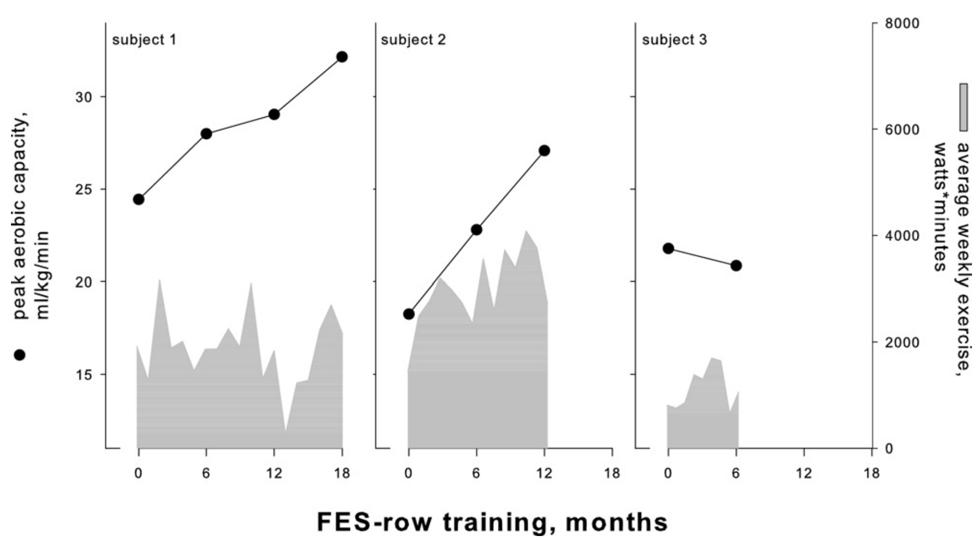

Figure 3. Changes in peak oxygen consumption and weekly total work with functional electrical stimulation row training. FES = functional electrical stimulation.

both fronts, persons with SCI have much greater obstacles to overcome to maintain high levels of aerobic fitness.

We have established that a form of hybrid FES exercise that combines a modified rowing ergometer with FES of the lower extremities can produce greater aerobic capacity than arms-only exercise. Moreover, this mode of exercise has several advantages that make it possible to achieve greater exercise intensities for longer periods. This unique form of exercise for the SCI population requires the non-innervated legs to initiate the rowing stroke and create a force vector that is then completed with the arm pull. This approach has the advantages of increasing the active muscle mass, creating a muscle pump in synchrony with the upper body work, and eliminating the need for vasoconstriction in the legs. We observed an almost 30% increase in aerobic capacity when the legs were engaged in the rowing exercise. In fact, in some persons with SCI, the absolute magnitude of increase in oxygen consumption was greater than that previously observed in able-bodied persons after 20 weeks of exercise training [24].

Most aerobic exercise options for persons with SCI are limited to some form of arm exercise. Although arm exercise can increase maximal aerobic capacity and power output [25], it is insufficient to produce high levels of aerobic work. The small active muscle mass used during arm exercise does not elicit "volume loading" of the heart. In part, this volume loading may be lacking because of a decreased peak heart rate due to reduced central (ie, central command) and peripheral (ie, muscle afferent) cardioacceleratory drive [12]. In addition, the arms produce minimal "muscle pump," that is, the propulsion of blood from the skeletal muscle vasculature back to the heart induced by muscle contractions [12].

Moreover, a major hemodynamic challenge to arm exercise in persons with an SCI is lack of sympathetic vasoconstriction in the inactive leg muscles, leading to further inadequate redistribution of blood flow to the active muscle. Indeed, the limitations to integrative exercise responses in persons with an SCI were clearly shown in work by Pitetti et al [26]. They found marked increases in both aerobic capacity and peak work rate in persons with an SCI when lower body positive pressure was applied to redistribute blood from the lower extremities during either arm ergometry or wheel chair exercise. This finding relates both to the magnitude of muscle pump and to the issue of impaired sympathetic vasoconstrictor responses in the legs during arm exercise. Thus active muscle mass has a profound effect on the oxygen consumption, and sustained power output that can be achieved during exercise and is therefore a significant challenge to achieving high levels of exercise in the SCI population.

Engaging the lower body might be one solution to overcome the limitations of arms-only exercise, and FES cycling has recently become more popular as a form of exercise for persons with an SCI. However, the mechanical efficiency of this exercise is estimated as ~8% [27], less than one third of that for cycling in able-bodied individuals. Moreover, this type of training does not achieve high levels of aerobic work, and a plateau in training effect is quickly reached [28]. In an attempt to overcome the limitations of both upper body ergometry and FES cycling in persons with an SCI, the 2 modalities have been performed simultaneously in what is called hybrid FES exercise. Very few studies have been performed in which the authors examined oxygen consumption with this type of exercise, but results seem to indicate that the hybrid exercise can achieve greater aerobic capacities and workloads than during either component alone [11]. However, it appears that the ability to sustain hybrid FES exercise at a level that will induce benefits could be difficult; peak aerobic capacity has been reported as equal to [29] or less than [30] the 21 mL/kg/min (6 METs) intensity of sustained exercise necessary to reduce risk.

Our data also show that the average peak aerobic capacity of FES rowing can be less than this threshold, although one third of those who could perform FES rowing demonstrated peak capacities greater than this. Thus a period of consistent training may be required to achieve even peak aerobic capacities greater than 6 METs, although this would still preclude individuals from maintaining a 6-MET intensity during training. The only previous report of FES row training suggests that 12 weeks of training induces an 11% increase in peak aerobic capacity [15]. This increase resulted in a peak value of ~25.4 mL/kg/min, which means that these persons would need to maintain an intensity equivalent of 83% of maximum to achieve the 6-MET threshold.

For most persons other than well-trained athletes, this relative intensity would require a strenuous effort to maintain. However, our preliminary training data suggest that with longer FES row training of sufficient magnitude, aerobic capacity can increase substantially more in persons with an SCI. In the 2 persons who demonstrated increases in aerobic capacity, peak values were 32.2 and 27.1 mL/kg/min, representing improvements of 31% and 48%. Moreover, for the person who has trained the longest, the threshold exercise intensity for risk reduction now represents a reasonable 65% of peak capacity. Furthermore, in response to regular FES row training, the person who trained the longest increased aerobic capacity to a level within the range of normative values for able-bodied individuals of his age [31].

LIMITATIONS AND FUTURE DIRECTIONS

Although our data clearly delineate an increase in peak aerobic capacity with FES rowing compared with arms-only rowing, we cannot say what accounts for this increase. Peak oxygen pulse increased significantly, indicating that stroke volume and/or arteriovenous oxygen difference was greater with FES rowing. Given that the leg muscles were active, it is highly likely that arteriovenous oxygen difference played some role in this increase. However, it remains unclear whether the greater muscle pump may have led to greater stroke volumes during FES rowing. Future measurements of cardiac output during peak exercise could determine whether the ability to generate greater systemic flow contributes to the greater response.

In addition, our population was limited by design. Persons with higher lesions may respond differently given that caudal lesions lead to cardiac sympathetic denervation [32]. This could limit or even enhance the magnitude of difference between FES rowing and arms-only rowing. Moreover, our preliminary training data are suggestive but incomplete. More subjects will be required to define the potential of regular FES row training in persons with SCI.

CONCLUSIONS

Whole-body aerobic training at a sufficient intensity to induce adaptations across multiple physiologic systems in persons with SCI is achievable with this form of hybrid FES exercise. The age-adjusted mortality from heart diseases is higher in all adults with an SCI compared with the general population [33], and aerobic exercise training is a key intervention to reduce cardiovascular risk [10]. In addition, obesity, dyslipidemia, increased blood pressure, proinflammatory conditions, and insulin resistance may be of especial concern in persons with an SCI [34-37], considering the lack of access to appropriate exercise. Studies also indicate that osteoporosis develops below the level of the injury in 100% of persons with an SCI d [38] and that exercise that involves impact, even a modest amount, appears to be most efficient for enhancing bone mass [39]. Finally, even passive exercise in persons with an SCI has been proposed as a route to promote neuroplasticity caudal to the injury, but active exercise may provide a broader stimulus that promotes plasticity both rostral and caudal to the injury [7]. FES row training represents a unique approach to exercise that can enhance health and even promote recovery in persons with an SCI.

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