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ORIGINAL ARTICLE

FES-rowing in tetraplegia: a preliminary report

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Study design: A training intervention study using functional electrical stimulation-rowing (FES-R) in a group of eight individuals with tetraplegia.

Objectives: To assess the feasibility of a structured progressive FES-R training programme in people with tetraplegia, and to explore the number and type of FES-training sessions required to enable continuous FES-R for 30 min.

Setting: A fully integrated sports centre, elite rowing training centre and university sport science department.

Methods: Eight participants with chronic complete and incomplete tetraplegia (C4 to C7, American Spinal Injury Association Impairment Scale A, B and C) who had not previously used any form of FES-assisted exercise, participated in the study. Participants completed a progressive FES-assisted training programme building to three continuous 30-min FES-R sessions per week at 60–80% of their predetermined peak power output. Thereafter, rowing performance was monitored for 12 months. Main outcome measures: number and type of FES-training sessions required before achieving 30-min continuous FES-R, and FES-R average power output (PO_{av}) pre and post 12 months training. Participant feedback of perceived benefits was also documented.

Results: All participants were able to continuously FES-row for 30 min after completing 13 ± 7 FES-R training sessions. Each individual PO_{av} during 30 min FES-R increased over 12 months FES-training. FES-R was found safe and well tolerated in this group of individuals with tetraplegia.

Conclusion: Individuals with tetraplegia are able to engage in a progressive programme of FES-R training. Future research examining FES-R training as an adjunctive therapy in people with tetraplegia is warranted.

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INTRODUCTION

People with spinal cord injury (SCI) are among the most inactive in society. In one of the few comprehensive cross-sectional studies, 50% of people with SCI reported no daily leisure time physical activity, and 50% less than 28 min of mild intensity activity per day.[1] Furthermore, people with tetraplegia reported significantly less activity than people with paraplegia.[1] Inactivity increases all-cause cardiovascular disease morbidity and mortality,[2] and in complete cervical injury, inactivity is compounded by autonomic disruption further increasing the risk of cardiovascular disease.[3] Poor cardiovascular health and disease reduces functional capacity and independence.[4] Accordingly, regular exercise as an adjunctive therapy has been recommended in SCI as part of a healthy lifestyle.[5]

In non-SCI and SCI populations, 30 min of moderate-intensity aerobic training at least 5 days each week, or 20 min of vigorous-intensity training at least 3 days per week, alongside resistance exercise twice a week is recommended.[6] Moreover, exercise intensities exceeding a relative oxygen consumption of 21 ml kg^{-1} min^{-1} are recommended to reduce cardiovascular disease risk.[6] However, it is unclear how these recommendations[6] can be achieved in people with tetraplegia where aerobic training typically relies on arm crank exercise (ACE) (13.6 ± 4.9 ml kg^{-1} min^{-1}),[7] using hand securing devices in injuries at or above C6.[5] Accordingly, people with tetraplegia may not confer the cardiovascular benefits associated with regular exercise training.

Metabolic demand in SCI, however, can be safely increased with the use of Functional Electrical Stimulation (FES).[8] Typically, pulsatile electrical stimulation via adhesive skin surface electrodes is used to activate paralysed musculature.[8] Proposed FES exercise modalities include FES-cycling (FES-C),[9] FES-C concurrent with ACE,[10] and although not available commercially FES-rowing (FES-R).[11] Relative peak oxygen consumption during FES-C concurrent with ACE (26.5 ml kg^{-1} min^{-1}),[12] and FES-R (35.7 ml kg^{-1} min^{-1}),[13] show the greatest metabolic cost compared with FES-C (14.3 ml kg^{-1} min^{-1}),[12] or arms-only rowing (15.7 ml kg^{-1} min^{-1}),[14] and therefore likely provide the greatest stimulus for cardiovascular health.[12] The pulling actions, involved in FES-R, may also reduce upper limb pain and discomfort habitually experienced by individuals with SCI who use manual wheelchairs, by balancing the posterior shoulder girdle musculature.[15] FES-R has also demonstrated a positive social aspect through group centre-based training and participation in elite sporting events.[13] However, the feasibility of FES-R in tetraplegia remains unclear.

Here we present preliminary results of a progressive FES-R training programme involving complete and incomplete tetraplegia. The primary aims, designed to examine the feasibility of FES-R, were to: (1) assess the capability of people with tetraplegia to cope with and respond to a progressive structured FES-R training programme and (2) explore the number and type of FES-training sessions required to enable continuous FES-R for 30 min. The secondary aims examining

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the effect of FES-R training were to: (1) examine improvements in power output over 12 months FES-R training, (2) explore the perception of effort associated with FES-R training and (3) evaluate the practicality and safety of equipment modifications required for FES-R in tetraplegia.

MATERIALS AND METHODS

Participants

Eight participants with tetraplegia (six complete and two incomplete) were recruited for this study (Table 1). Males and females aged between 18 and 55 years, with no prior history of musculoskeletal injury or participation in FES-assisted exercise, and who were otherwise healthy, were recruited. In addition, participants had to demonstrate Medical Research Council (MRC) grade 4 elbow flexion,[16] and an MRC grade 1 or 2 response and tolerance to electrical stimulation in the quadriceps, with limited susceptibility to autonomic dysreflexia.[17] Brunel University Research Ethics Committee approved the study and all participants provided written informed consent before start.

Equipment modifications

The FES-R prototype (Figure 1) used in this study was based on the Concept2 Model D ergometer with adaptations for FES-rowing originally developed by our group.[13,18–21] In paraplegia, this prototype uses four channels of electrical stimulation and an external control switch with stimulation parameters set at a frequency of 50 Hz, a pulse width of 450 μs, and an output current manually adjusted by the participant between 0–115 mA. A momentary-acting push-button switch is used to change over the electrical stimulation between quadriceps and hamstrings to produce the rowing action. Electrical stimulation is delivered via self-adhesive skin surface electrodes (Pals Ultraflex Platinum 7 cm round; Axelgaard Manufacturing Company Ltd, Fallbrook, CA, USA) placed over the muscle motor points.

For this study, a four-channel stimulator (Odstock O4CHS; Odstock Medical Ltd, Salisbury, UK) was used with a 7 Ah sealed lead-acid battery pack, incorporating a 9 V regulator, to ensure a stable stimulus output over the experimental sessions. In addition, on the basis of pilot work, the return to catch (recovery phase of rowing) was optimised by inclining the Concept2 ergometer monorail by 4° for injuries up to C5, and 5° for injuries at C4. The air damper drag factor was set at 100 (C4) or 110 (C5 to C7). The custom seat-base and backrest was inclined 10–15° from the vertical, depending on monorail inclination, to prevent skin shear to the buttocks. In addition, a rubber seat pad (Concept2, Morrisville, VT, USA) was used as the interface to reduce the risk of skin breakdown. A telescoping leg stabiliser prevented mediolateral movement whilst offering no resistance in the sagital plane. A shoulder harness (Bodypoint, Seattle, WA, USA) was adapted to prevent abrasion of the contact areas around the shoulder and axillia by distributing the loading to the pectoral region (Figure 2a). For participants with weak or no hand-grip strength and dexterity, velcro-fastened gloves (Active Hands Company Ltd, Birmingham, UK) were used to secure participants hands to the rowing ergometer handle (Figure 2b). In addition, carers were trained to operate the push-button switch in synchrony with the rower's voluntary arm flexion movements (Figure 2c), and to manually adjust the stimulator output currents to maintain optimum knee extension without hyperextension when FES-leg conditioning (FES-LC) or when FES-R.

FES-training programme

Once familiarised with safe operation of the Odstock O4CHS, participants followed a progressive structured FES-assisted training programme leading to continuous FES-R for 30 min (Figure 3). The programme involved three phases: Phase 1 FES-LC. Phase 2 Initial FES-R training building to continuous FES-R for 30 min. Phase 3 Chronic FES-R training for 12 months. Heart rate (HR; Polar Electro Oy, Kempele, Finland), blood pressure (Omron MX2, Kyoto, Japan), and symptom recognition were used to assess susceptibility to autonomic dysreflexia during initial researcher supervised FES-LC.[17] In addition to operating the push-button switch, carers were taught how to operate the seat brake, assist with transfer on and off the FES-rower, and securing the shoulder harness. Participants were also instructed to inform the lead researcher of any associated adverse events.

Phase 1 FES-leg conditioning

Initially supervised, seated FES-LC was used to progressively increase quadriceps fatigue resistance and force-generating capacity. This consisted of stimulating a concentric quadriceps contraction to extend a lower leg (against gravity from 90° of knee flexion), while concurrently stimulating an isometric hamstring contraction of the contralateral leg every 12 s. This resulted in five cycles of an alternating kicking action every minute. Importantly, during the first 5 min of FES-LC, stimulation current was manually adjusted to a level that limited knee movement to 45° flexion. This was to prevent any FES-induced muscle spasm imposing additional knee joint loads.[22] Thereafter stimulation intensity was adjusted sufficiently to produce an alternate knee extensor exercise (KEE) without hyperextension. Generally, as the quadriceps fatigued, stimulation current was incrementally increased to 115 mA. Importantly, as quadriceps conditioning improved, the maximum stimulation current was reduced to prevent potential joint damage. Maximum stimulation current used with the isometric hamstring contraction was 75 mA.

Phase 2 Initial FES-rowing

Systematic evaluation of quadriceps conditioning cycles to the onset of muscle fatigue (defined as knee extensor exercise below 45° flexion) revealed that 150 cycles of continuous alternate knee extensor exercise were required before

Table 1 Individual participant characteristics

No.	Gender	Injury level	AIS	Aetiology	TPI (year)	Age (year)	Height (m)	Mass (kg)	BMI (kg m^{-2})
1	F	C4	A	RTA	8	36	1.82	56.1	16.9
2	F	C5	C	RTA	11	25	1.72	55.1	18.6
3	F	C6	A	RTA	13	30	1.69	51.5	18.0
4	F	C7	B	RTA	12	28	1.74	55.0	18.2
5	M	C4	A	Sport	1.5	19	1.72	50.0	16.9
6	M	C5	C	Fall	11	56	1.87	88.6	25.3
7	M	C5	A	RTA	8	25	1.82	94.0	28.4
8	M	C6	A	RTA	3	25	1.87	82.1	23.5
Maximum					13	56	1.87	94.0	28.4
Minimum					1.5	19	1.69	50.5	16.9
Mean					8.4	30.5	1.78	66.6	20.7
s.d.					±4.2	±11.4	±0.07	±18.3	±4.4
Range		C4–C7							

Abbreviations: AIS, American Spinal Injury Association Impairment Scale (A, complete motor and sensory; B, complete motor and incomplete sensory; C, incomplete motor and sensory); BMI, body mass index; F, female; M, male; RTA, road traffic accident; TPI, time post injury.

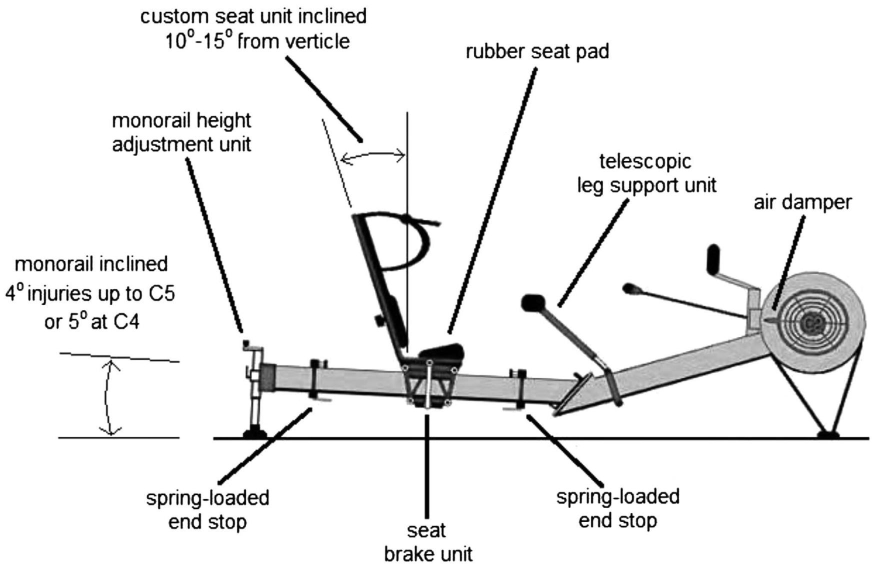

Figure 1 The FES-rowing prototype.

Figure 2 Equipment modifications to enable FES-rowing in tetraplegia. (**a**) Shoulder harness; (**b**) neoprene gloves; (**c**) attendant switching.

commencing FES-R training (Figure 3). Initial FES-R involved an interval training regime to progressively increase muscle strength and endurance sufficient to complete 30 min of continuous FES-R while maintaining a cadence of 30 strokes per minute. This involved 30 s FES-R followed by 30 s arms-only rowing. The latter was accomplished with the seat locked with the knees at ~10° of flexion and the stimulation switched OFF. During FES-R training, the maximum 115 mA quadriceps stimulation current was typically reached within 5 min rowing time, while maintaining up to 86 mA hamstring stimulation current. This stimulation current protocol remained unchanged throughout the training programme. When the average power output (PO_{av}) decrease during the 30 s FES-R period was <20%, the FES-R interval was increased to 40 s, resulting in a 40:20 interval split. A 50:10 interval split was occasionally required before participants' were then able to continuously FES-R for 30 min. The number and type of FES-training sessions required to reach 30 min of continuous FES-R was recorded. PO_{av} was continuously recorded throughout all FES-R training using the Concept2 performance monitor, and HR was recorded via telemetry (Polar Electro Oy, Kempele, Finland).

Graded exercise testing and exercise prescription

Once continuous FES-R for 30 min was possible, a graded exercise test was used to determine peak power output (PO_{peak}) at the start of Phase 3 (Figure 4). The test involved a standardised 5 min warm-up[6] at a modest self-selected power output, followed by up to six incremental stages of 2 W (C4) or 5 W (C5 to C7)

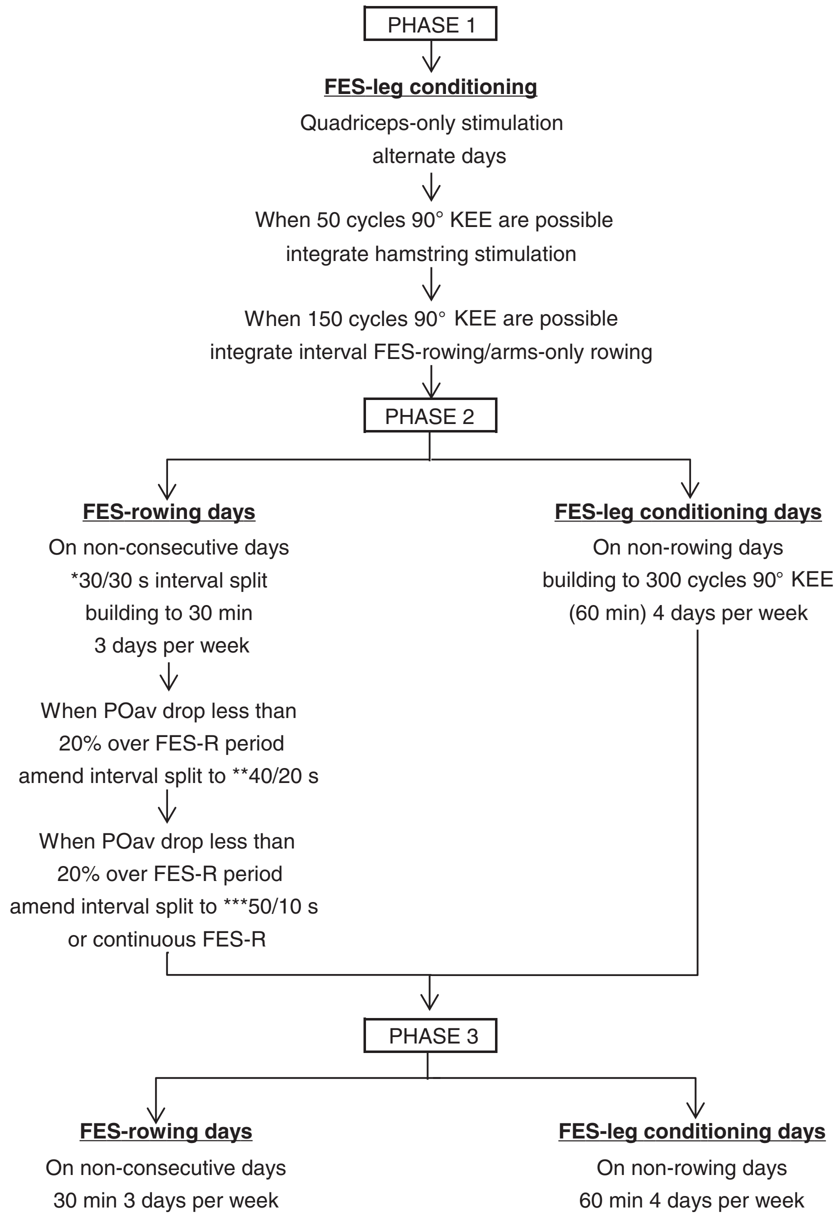

Figure 3 FES-training programme schematic. Abbreviations: KEE, knee extension exercise; FES-R, FES-rowing. *30/30, 30 s FES-row/30 s arms-only row. **40/20 s, 40 s FES-row/20 s arms-only row; ***50/10 s, 50 s FES-row/10 s arms-only row. Note, the FES-rowing interval was increased by 10 s when the average FES-rowing PO was less than 20%.

every minute to volitional termination. HR was recorded throughout the test, and the Borg CR10 rating of perceived exertion scale (RPE; Borg's Perceived Exertion and Pain Scale, Champaign, IL, USA) was used to assess subjective effort; specifically arm and shoulder muscle fatigue and breathing discomfort were both recorded. In line with previous research,[23] PO_{peak} and associated RPE were used to prescribe target exercise intensity during Phase 3. Graded exercise tests were repeated at 6 and 12 months to monitor any changes to PO_{peak}.

Phase 3 Chronic FES-rowing training

Participants were encouraged to FES-train daily for at least 12 months during Phase 3, consisting of three centre-based continuous 30 min FES-R sessions, and four home-based 60 min FES-LC sessions per week (Figure 3). During FES-R, participants were instructed to maintain an exercise intensity equivalent to an overall RPE rating of 6–8 on the Borg CR10 scale. This equated to 60–80% of peak power determined from the first and subsequent graded exercise tests (Figure 4). FES-R training adherence was confirmed using data from the Concept2 performance monitor.

Outcome measures

To determine the feasibility of FES-rowing in tetraplegia, the number, type and duration of individual FES-training sessions were recorded throughout the study. During Phase 3, individual PO_{av} values were averaged over the first and last six 30-min FES-R training sessions. Peak HR response to the graded exercise tests at 0, 6 and 12 months was also recorded. In addition, participant perception of arm and shoulder muscle fatigue and breathing discomfort during the final min of each FES-R training session were recorded. Participants were also encouraged to report any changes in their quality of life over the course of the study. Due to the small sample size and heterogeneous population, individual data are reported.

RESULTS

In line with our primary aims, we found that all participants were able to cope with and respond to the progressive structured FES-R training programme. Furthermore, continuous FES-rowing for 30 min was possible three times per week following 7 ± 4 weeks of FES-training. Participants with complete injury required 19 ± 10 FES-LC training sessions plus 16 ± 3 FES-R interval training sessions to achieve 30 min of continuous rowing. In contrast, individuals with motor incomplete injury only required 3 ± 1 FES-R interval training sessions.

Response to FES-rowing training

Throughout Phase 3, training compliance was maintained above 80% of the maximum intended FES-training sessions and all participants demonstrated a progressive increase in PO_{av} and PO_{peak} during FES-R training (Figures 4 and 5). In addition, PO_{av} was consistently within 80% of predetermined PO_{peak} in all participants throughout Phase 3.

Graded exercise test duration was 8 min in C4 injury (5 min rest followed by three incremental stages) and 8–10 min in the lower injuries. The peak HR response to the three graded FES-R exercise tests during Phase 3 was heterogeneous across the group (Table 2). Four participants showed a low HR response ⩽120 b.p.m., and four showed a high HR response ⩾120 b.p.m.

Effect of FES-training

During FES-R training, participants consistently rated arm and shoulder muscle fatigue above breathing discomfort (RPE 7 ± 0.9 versus 6 ± 0.5, respectively). In addition, three participants reported improved upper limb comfort and reduced pain during activities of daily living following long-term FES-R training. Improvements in cough, breathing ease and sleep patterns were noted by five participants.

Importantly, it was noted that the FES-R equipment modifications were safe, reliable and well tolerated, and no health related issues were

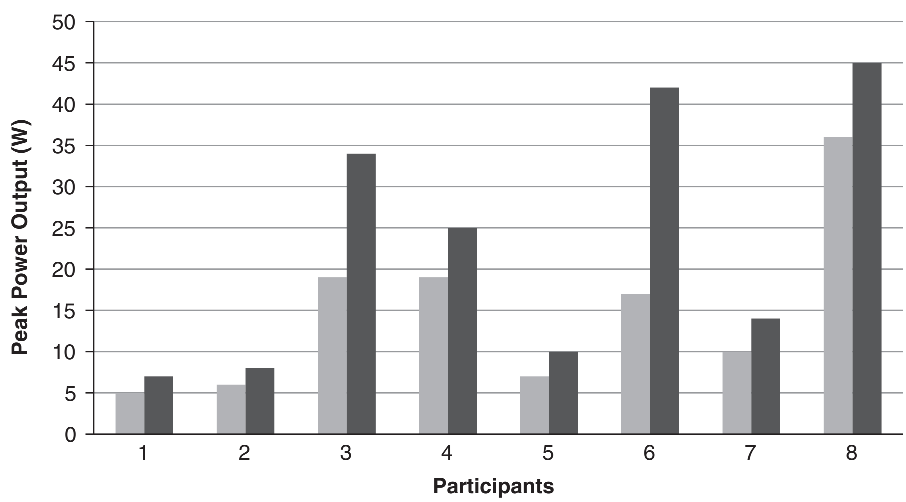

Figure 4 Individual peak power outputs (PO_{peak}) before starting and on completion of Phase 3 FES-rowing training. Female participants, 1–4; male participants, 5–8. Light grey columns, PO_{peak} at the start of Phase 3; dark grey columns, PO_{peak} on completion of Phase 3. Note, participants 2 and 6 have American Spinal Injury Association Impairement Scale C incomplete tetraplegia.

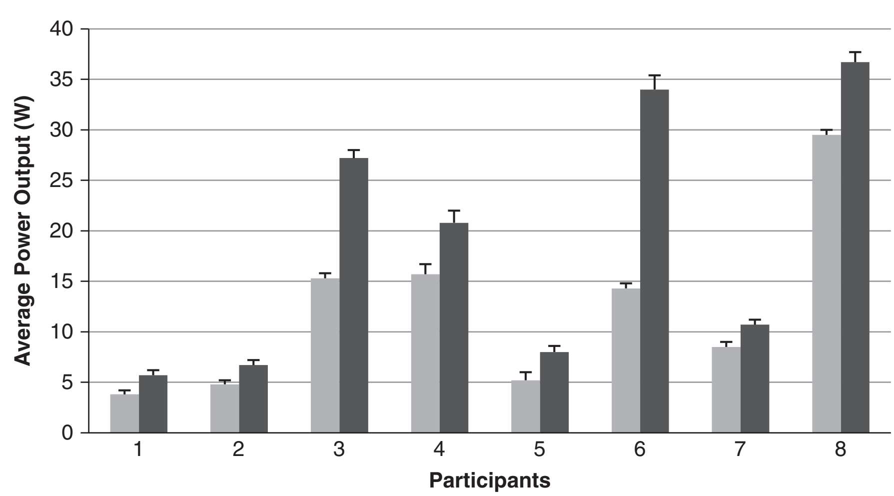

Figure 5 Individual average power outputs (PO_{av}) before starting and on completion of Phase 3 FES-rowing training. Female participants, 1–4; male participants, 5–8. Light grey columns, average power outputs (PO_{av}) at the start of Phase 3; dark grey columns, PO_{av} on completion of Phase 3. Data are mean ± standard deviation and averaged over six consecutive 30-min FES-rowing sessions. Note, participants 2 and 6 have American Spinal Injury Association Impairement Scale C incomplete tetraplegia.

Table 2 Individual peak heart rate responses to graded FES-rowing exercise tests during Phase 3 training

Participant	SCI and AIS	Peak heart rate response (b.p.m.)			Age-predicted peak heart rate (b.p.m.)
		0 months	6 months	12 months	
1	C4 A	**142**	**142**	**165**	184
2	C5 C	80	90	100	195
3	C6 A	**150**	**136**	**162**	190
4	C7 B	117	116	119	192
5	C4 A	**146**	**152**	**158**	201
6	C5 C	**131**	**150**	**162**	164
7	C5 A	90	108	112	195
8	C6 A	100	113	116	195

Abbreviations: AIS, American Spinal Injury Association Impairment Scale (A, complete motor and sensory; B, complete motor and incomplete sensory; C, incomplete motor and sensory); SCI, spinal cord injury. High heart rate responders are in bold. Age-predicted peak heart rate calculation: 220 – participant age.

reported. However, transfer on and off the FES-rowing machine was challenging in those with higher-level injuries.

DISCUSSION

We set out to assess the feasibility of FES-rowing in people with tetraplegia. The primary findings were that continuous FES-R for 30 min was possible in a group of male and female participants with both complete and incomplete tetraplegia up to C4 AIS A who were able to elbow flex.

Response to FES-rowing training

The more rapid response to FES-training seen in motor incomplete injury is likely due to preserved voluntary active muscle. Unfortunately we did not assess preservation of motor function, so cannot ascertain the contribution to total PO between the upper and lower limbs when FES-rowing. However, the neuromuscular response to FES-training appears to be affected by completeness rather than level of injury as reflected by the lower number and type of FES-training sessions required to continuously FES-R for 30 min in participants with motor incomplete injury. In addition, we observed a modified technique in the two participants with complete C4 injury who used lateral elbow abduction during arm flexion in late drive. Unlike the participants with lower lesions who employed a more traditional arm flexion technique,[13] it appears that those with C4 lesions may rely on scapula retraction.

In the absence of sympathetic activity, increased HR in tetraplegia is primarily achieved by vagal tone withdrawal resulting in an HR of ~100–120 b.p.m. intrinsically set by the sinoatrial node.[24] In non-SCI, increments in HR beyond ~100–120 b.p.m. are related to increased sympathetic activity. Therefore, the high HR response observed in some individuals, despite significant spinal cord damage, may reflect an element of preserved sympathetic control.[25] This hypothesis warrants further investigation before it can be fully explained.

It is important to note that although the volume of FES-R training provided a significant increase over activities of daily living, it is possible that the intensity of exercise did not meet that recommended for cardiovascular health.[6] This requires further investigation with greater participant numbers, and measures of metabolic response during FES-R training. However, it is interesting to note that while five participants were unable to energetically propel themselves in their wheelchair, and three participants relied on being pushed, all were able to continuously FES-row for 30 min. Furthermore, participant 6 was able to ambulate and row without FES following 7 months of FES-R training.

Effect of FES-rowing training

The increase in PO_{av} seen in all participants following 12 months FES-training, suggests that FES-R provided an effective training stimulus. Direct PO comparisons between FES-R and previously conducted FES-C studies are problematic due to differences in study design; however, the peak and subpeak PO values observed in the present study are some of the largest recorded in the SCI population.[26] It is possible that the increase in PO_{av} observed may be due to increased lower limb muscle mass in response to overall leg conditioning and might be associated with a concurrent increase in metabolic cost. Furthermore, it is highly likely that muscle strength also increased in line with the increases in average and peak POs.[27] These hypotheses require further investigation with measures of metabolic cost and skeletal loading during and following FES-R training.

Participant perceived effort and health benefits

The fact that all participants assessed arm and shoulder muscle fatigue above breathing discomfort may suggest that the cardiorespiratory response did not limit exercise capacity. This contrasts with data from individuals with paraplegia who report greater breathing discomfort in response to FES-R.[13] This difference may be explained by the greater voluntary muscle mass and therefore metabolic demand in people with paraplegia.

All participants in our study reported cross-over improvements in upper limb comfort and reduced pain during activities of daily living, this suggests that the pulling actions associated with FES-R offer some therapeutic benefit.[15] In addition, the improvements reported in respiratory symptoms and sleep patterns are likely due to the increased activity levels following FES-R training relative to activities of daily living.[5]

FES-R training appears to provide a safe method of increasing activity level relative to ACE or FES-C, and was well tolerated in this group of individuals with tetraplegia who reported no adverse medical complications. However, further equipment development is required to enable participants with tetraplegia to transfer on and off the FES-rower with greater ease. Training compliance and dropout are also challenging in longitudinal training studies in SCI due to the effort and time commitment required in attending training sessions. FES-assisted training also requires additional preparation compared with conventional exercise modalities; in particular electrode placement and connection of stimulator leads. However, high compliance was maintained with the combination of more convenient home-based FES-leg conditioning and centre-based FES-rowing training.

It is important to note that over the course of training, participant 4 was diagnosed with bilateral calcific trochanteric bursitis, which appears to be unrelated to rowing in SCI or non-SCI.[28] Only mild symptoms of autonomic dysreflexia were observed over the course of the study; all were managed by an initial reduction in stimulation. We recommend that all individuals starting an FES-R training programme are monitored carefully for any adverse affects.

Study limitations and future directions

Unfortunately the small participant numbers and heterogeneous injury characteristics precludes statements on the statistical significance of our findings. Nevertheless, the variability in participant characteristics provides preliminary evidence that this form of FES-assisted training is a potential exercise option for a wide range of people with SCI who are able to elbow flex.

Further cardiorespiratory and biomechanical studies are required to determine the relative contribution of upper and lower limbs to total metabolic cost and mechanical power in response to FES-R training in both complete and incomplete tetraplegia. In addition, the simple four-channel FES-rowing system used in this study may limit the potential for physiologic adaptation. Increasing the number of muscle groups being stimulated may result in even greater therapeutic benefit as well as improvement in rowing performance. Further development is also required to provide an automatic control system, which would enable participants with injuries at or above C6 to FES-row autonomously.[19] For people with injuries at or above C3 where functional elbow flexion is not possible, it is possible that FES-cycling provides a more suitable option than FES-R for improving lower limb health and function.[29]

In conclusion, individuals with tetraplegia up to C4 AIS A, who are able to elbow flex, are capable of participating in a structured FES-rowing programme and increasing overall physical activity using this exercise modality. However, large variability exists in the volume and type of training sessions required to enable individuals to continuously FES-row for 30 min. Future research should focus on the impact of increasing the number of muscle groups stimulated, and whether this results in the modification of cardiovascular disease risk factors and improvement in skeletal loading[27] in people with SCI following FES-rowing training.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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