

Effect of Spatially Distributed Sequential Stimulation on Fatigue in Functional Electrical Stimulation Rowing

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Abstract—Objective: A critical limitation in clinical applications using functional electrical stimulation (FES) for rehabilitation exercises is the rapid onset of muscle fatigue. Spatially distributed sequential stimulation (SDSS) has been demonstrated to reduce muscle fatigue during FES compared to conventional single electrode stimulation (SES) in single joint movements. Here we investigated the fatigue reducing ability of SDSS in a clinical application, i.e., FES-rowing, in able-bodied (AB) participants. **Methods:** FES was delivered to the quadriceps and hamstring of 15 AB participants (five female, ten male) for fatiguing FES-rowing trials using SES and SDSS, participants rowed with voluntary arm effort while endeavoring to keep their legs relaxed. Fatigue was characterized by the time elapsed until a percent decrease occurred in power output (TTF), as well as the trial length indicating the time elapsed until the complete stop of rowing. **Result:** Trial length was significantly longer in SDSS rowing than in SES (t-test, $p < 0.01$, $d = 0.71$), with an average SDSS:SES trial length ratio of 1.31 ± 0.47 . TTF_{SDSS} was significantly longer than TTF_{SES} with a median $TTF_{SDSS}:TTF_{SES}$ ratio of 1.34 ranging from 1.03 to 5.41 (Wilcoxon Ranked Sum, $p < 0.01$, $r = 0.62$). No rower experienced a decrease in TTF with SDSS. **Conclusion:** SDSS reduced fatigue during FES-rowing when compared to SES in AB individuals, resulting in a lengthened FES-rowing period by approximately 30%. Application of SDSS would increase the effectiveness of FES-rowing as rehabilitative exercise for individuals with paralyses.

Index Terms—Asynchronous stimulation, electrical stimulation therapy, exercise therapy, fatigue, functional electrical stimulation (FES), rowing.

I. INTRODUCTION

PHYSICAL activity is an important aspect of health especially for those with spinal cord injury (SCI). Individuals

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Research Ethics Board of the University Health Network, under Approval No. 18-6198, Dated June 16, 2020, and performed in line with the Declaration of Helsinki.

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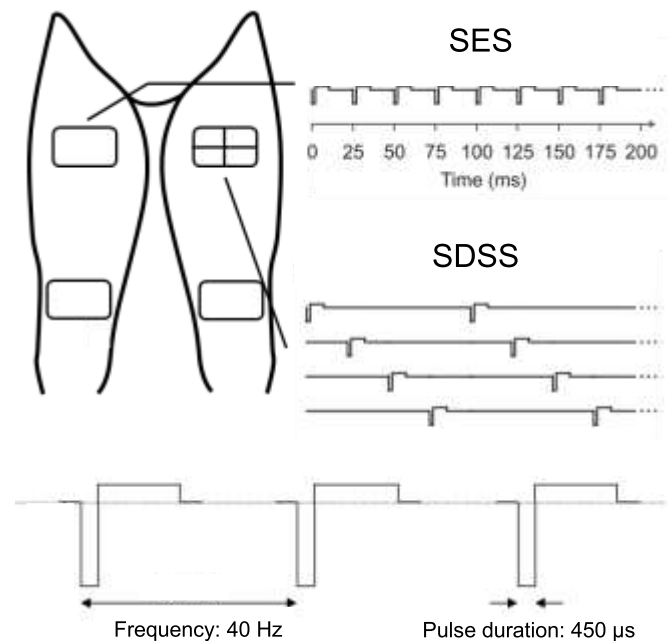


Fig. 1. Stimulation parameters used for single electrode stimulation (SES) and spatially distribute sequential stimulation (SDSS).

with SCI often lead a sedentary lifestyle due to limb paralysis that contributes to many secondary medical conditions such as increased risk of cardiovascular disease, bone density loss and metabolic complications [1]–[4]. Currently, both upper limb ergometry and wheelchair pushing exercises are frequently prescribed to increase activity level and intensity [5]–[7]. However, these upper limb interventions are not very intense and may not generate sufficient energy demand for aerobic fitness because the activity is limited to a small group of muscles. It remains unclear whether upper limb exercises are of sufficient intensity to induce positive adaptations in individuals with SCI [8].

Functional electrical stimulation (FES) exercises can be used to increase exercise intensity. In these rehabilitation exercises, FES can be used to induce functional muscle contractions in paralyzed muscles to increase active muscle mass [9], [10]. For example, FES-cycling is a FES exercise that increases exercise intensity by stimulating contractions in lower limb muscles to perform a cycling motion, which

are larger muscles compared to upper limb muscles. Hybrid FES exercise combines voluntary upper limb motion with FES of the paralyzed lower limb to perform a full body exercise that has much higher oxygen consumption (VO_2) than FES alone. For example, Hybrid FES-cycling combines arm cycling ergometry with FES-cycling of the lower limbs and is a popular form of hybrid FES exercise [11]. We intend to use hybrid FES-rowing exercise that involves coordinating voluntary rowing action using upper limbs with FES on lower limb muscles. FES-rowing exercise has been demonstrated to improve aerobic fitness, bone density, glucose tolerance, and shoulder pain in individuals with SCI [12].

Despite these beneficial effects, acute muscle fatigue is a major limitation of any FES exercises. The therapeutic effects of FES exercise depend on exercise time and intensity but both are limited by rapid onset muscle fatigue [10], [13]–[15]. One possible cause of this fatigue is that conventional electrical stimulation, which we call single electrode stimulation (SES) in this study, activates only a local subset of motor units of the stimulated muscle [16]. Furthermore, the synchronous stimulation of these motor units at the frequency required for fused muscle contraction during FES, e.g., 40 Hz, is much higher than natural nerve firing frequency and also contributes to rapid muscle fatigue [16].

We proposed spatially distributed sequential stimulation (SDSS) as a method to reduce this rapid muscle fatigue by distributing the stimulation location sequentially and spatially via multiple electrodes [17]–[23]. In SDSS, multiple electrodes are placed on a stimulation site and lower frequency stimulation pulses are sent one after another sequentially “rotating” across the electrodes. We have been using a typical stimulation setting with a frequency of 40 Hz delivered as a summation of 90° phase-shifted 10 Hz pulses to each of the four electrodes clustered at the same location as one electrode for SES. Multiple studies including ours have shown the effectiveness of SDSS in reducing muscle fatigue in isometric and isokinetic tasks in the thigh and shank muscles for both able-bodied (AB) individuals and individuals with SCI [17]–[23]. Compared to SES, SDSS uses 4 smaller electrodes clustered at a common location that has a total area similar to one SES electrode in clinical settings [17]–[25]. Similar variations of SDSS used in other studies include using multiple SES-sized electrodes as SDSS electrodes [26]–[28] or distributing the electrodes over multiple motor points within agonist muscles [29], [30], for clarity, these variations are referred to as sequential stimulation. These studies show the positive effects of sequential stimulation in single joint movements [26]–[29] and FES-cycling [30].

Although previous studies have shown that SDSS is effective at reducing acute muscle fatigue in single joint movements, few studies show the effect of SDSS on muscle fatigue in a dynamic exercise context. Thus, the purpose of this study was to investigate the fatigue reducing ability of SDSS in FES-rowing by comparing muscle fatigue and rowing performance with SDSS versus conventional SES in AB rowers. This was motivated by the need to make FES exercises more effective for individuals with SCI and testing the effectiveness of SDSS in able-bodied FES-rowing is an important first step

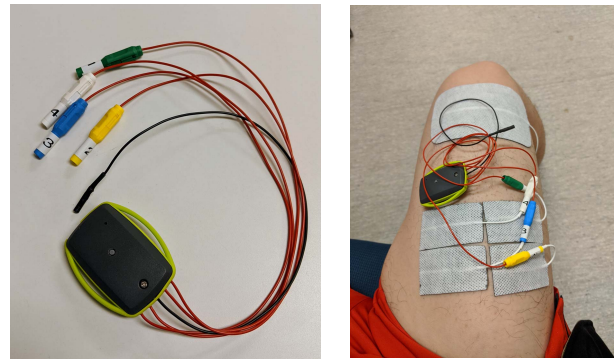


Fig. 2. Proprietary in-line adapter (left) for spatially distributed sequential stimulation attached to electrode array over quadriceps (right).

in translating this method to clinical applications where fatigue is a major limiting factor.

II. IMPACT OF COVID-19 ON DATA COLLECTION

The original plan for this study’s data collection was to collect VO_2 data from all recruited participants. However, we were concerned with the possibility of spreading COVID-19 via the portable spirometer used for VO_2 data collection. As a result, VO_2 data for analysis was available from only 5 out of the 15 recruited participants.

III. METHODS

A. Participants

Fifteen AB individuals with no history of neurological disorders (aged 24.8 ± 3.2 years, height of 170.3 ± 12.2 cm, and weight of 67.4 ± 11.9 kg, five females) participated in this study (Table I). Each participant gave informed written consent to the experimental procedure. This study (18-6198) was approved by the Research Ethics Board of the University Health Network on June 16, 2020 in accordance with the Declaration of Helsinki on the use of human subjects in experiments.

B. Rowing Ergometer

A commercially available rowing ergometer (Concept2 model D, Concept2 Inc., Morrisville, Vermont, USA) was modified with custom-made back and leg rests, and sensors for FES-rowing. The ergometer was instrumented with 5 load cells (GS1240-250 and SML-300, Interface Advanced Force Measurement Durham Instruments, Arizona, USA) and 2 linear string potentiometers (Measurement Specialties, Durham Instruments, Arizona, USA) to measure rowing force and rower position, respectively. One load cell was connected in series with the rowing handle, the other four load cells were mounted under the left and right foot plate providing both normal and shear force measurement along the foot plate. One string potentiometer was mounted to the back of the rower rail and connected to the back of the seat, the other potentiometer was mounted to the front just above the attachment point of the chain to the flywheel and connected to the handle by a metal hook. The Concept2 ergometer has a 10-level damper setting. We set the damper level of the rowing ergometer at 8 across all participants and conditions.

TABLE I
PARTICIPANT DEMOGRAPHICS

Participant	Age	Height (cm)	Weight (kg)	Sex	FES Naïve	Rowing Naïve	VO ₂ data
1	25	185	70	M	N	N	N
2	24	178	72	M	N	N	N
3	24	152	57	F	N	N	N
4	25	178	65	M	N	Y	N
5	35	187	79	M	Y	Y	N
6	23	152	43	F	Y	Y	N
7	24	152	57	F	Y	Y	N
8	22	180	64	M	N	N	N
9	27	172	75	M	Y	N	N
10	25	187	90	M	Y	N	N
11	25	174	80	M	N	N	Y
12	22	165	61	F	Y	N	Y
13	20	172	79	M	Y	N	Y
14	27	162	66	M	Y	N	Y
15	24	158	53	F	N	N	Y
Mean	24.8	170.3	67.4	F=5	Y=8	Y=4	Y=5
SD	3.2	12.2	11.9				

C. Electrical Stimulation

A programmable 4 channel neuromuscular electrical stimulator (Compex Motion, Compex SA, Switzerland) was used to deliver FES to the quadriceps and hamstring through self-adhesive gel electrodes (ValuTrode, Axelgaard Manufacturing Co. Ltd., USA). In both of SDSS and SES, the cathodes were placed over the proximal ends of the quadriceps and hamstrings, while the anodes were placed distally. SDSS stimulation was delivered via a custom-made proprietary adapter in-line with the stimulator and electrodes (Fig. 1).

The SDSS electrode array was placed over the same area as the cathode of single large electrode in SES by outlining the electrode area on the legs. Electrical stimulation was delivered manually by the participant with a push button on the handle; holding down the button stimulates the quadriceps and releasing the button stimulates the hamstrings.

A custom-made coaching system assisted the rower to indicate the timing of the button push to initiate the patterned FES with visual cues [31], [32]. The coaching system consisted of a laptop computer (Dell XPS 9830, Texas, USA) and a data acquisition system (USB-6002 Multifunction I/O Device, National Instruments, South Portland, ME, USA) (Appendix Fig. 9.). The optimal stimulation range was between 100-150mm before returning to the front of the stroke [31]. Seat position movement was shown in real-time and a symbol on screen turned green when the participant was within the optimal range. When the participants depressed the push button, the electrical stimulator delivers FES to the quadricep muscles to execute the drive phase and a specific sound was played for buttons presses within the optimal range and a different sound was played for incorrect presses. The stimulation waveform parameters were a biphasic asymmetric pulse with pulse duration of 450 μ s. The stimulation frequency was 40 Hz for SES and was split into 4 phase-shifted 10 Hz pulses to each electrode for SDSS (Fig. 2).

D. Oxygen Consumption

Oxygen consumption (Table I) was measured via portable spirometry (K4b2, COSMED, USA) in 5 out of the 15 recruited participants (cf. Section II). Expired O₂ was

measured throughout the entire experimental procedure to determine oxygen consumption rate and metabolic demand. The spirometer was attached to participants via a chest harness.

E. Experimental Protocol

The exercise protocol consisted of FES-rowing performed across two sessions separated by at least 48 hours. All participants were asked to refrain from strenuous exercise 24 hours prior to and in between sessions. The order of SES and SDSS rowing sessions was counterbalanced.

The participant was first instructed on proper rowing technique consisting of an initial drive and recovery phase [33]. Then the maximum tolerable stimulation for SES and SDSS was determined by increasing FES intensity in 1 mA increments until maximum tolerable intensity was identified. The stimulation intensity used for the rowing trials were 80% of tolerable maximum and the stimulation intensity was matched across SES and SDSS sessions. Then, the participant performed 5 minutes of warm up rowing at a self-selected intensity and stroke rate. After a 2-minute rest, the participant then performed 1 minute of maximal effort voluntary rowing without FES (Voluntary Maximal Rowing). After another 2-minute rest, the participant then performed 1 minute of maximal effort rowing with FES, this was achieved by combining voluntary arm rowing in maximal effort with FES driven leg contraction with voluntarily relaxed legs (FES Maximal Rowing). Participants were asked to avoid voluntarily contracting leg muscles during FES. Reducing voluntary leg contraction allowed us to use AB rowing as an approximate model of SCI rowing.

Following a 15- to 20-minute rest, the participant started fatiguing trials. The participant rowed at a self-selected arm rowing intensity and FES driven leg contraction at 80% of maximal stimulation intensity (Fatiguing Rowing). Participants were instructed to use only the minimum upper limb strength necessary to complete the rowing stroke. There were three endpoints for Fatiguing Rowing: voluntary exhaustion, leg collapse, or pain. Voluntary exhaustion occurred when the participant felt too tired to continue rowing but were still able to complete the rowing motion. Leg collapse occurred when legs could no longer support the rowing motion despite continuous FES. Pain as the endpoint occurred when the stimulation

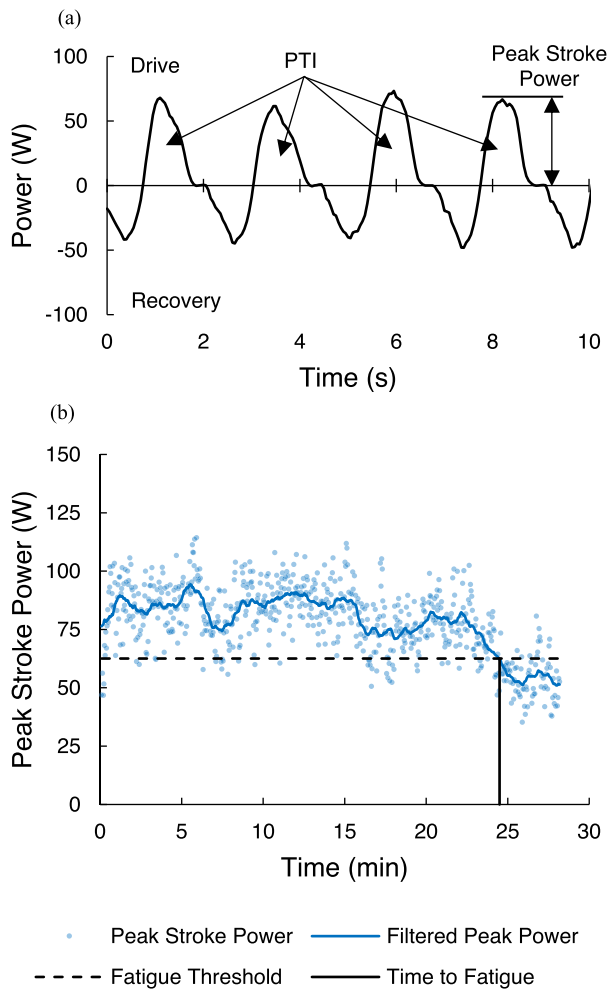


Fig. 3. Outcome measures of FES-rowing exercise. (a) Power time integral (PTI) is calculated by integrating positive power over time for drive phase and negative power for recovery phase PTI. Peak stroke power was used to calculate time to fatigue (TTF). (b) Peak stroke power of fatiguing rowing was extracted and filtered with a 30-point moving average. The fatigue threshold was determined as 80% of the average of the first 10 filtered peak power data points. TTF was then determined as the point in time at which the filtered peak power crossed below this threshold.

was causing too much discomfort or pain to continue rowing. The participant was encouraged to maintain a steady stroke rate. Again, the participant was reminded to avoid voluntarily contracting leg muscles throughout the fatiguing trial.

The experimental procedure for second session was identical to the first except SES electrodes were replaced by SDSS electrodes or vice versa. Since maximum tolerable stimulation intensity was measured for both SES and SDSS in the first session, the stimulation intensity of second rowing session was matched with the first.

F. Data Collection and Analyses

The kinetic data from the load cells and string potentiometers were recorded from a data acquisition system (PowerLab 16SP, ADInstruments Inc., Colorado Springs, CO, USA) at 2 kHz. VO_2 data were recorded on a portable spirometer system (K4b2, COSMED, USA). The raw kinetic data were filtered with a 10 Hz low-pass filter and raw VO_2 data were filtered with a 30 second moving average filter [34].

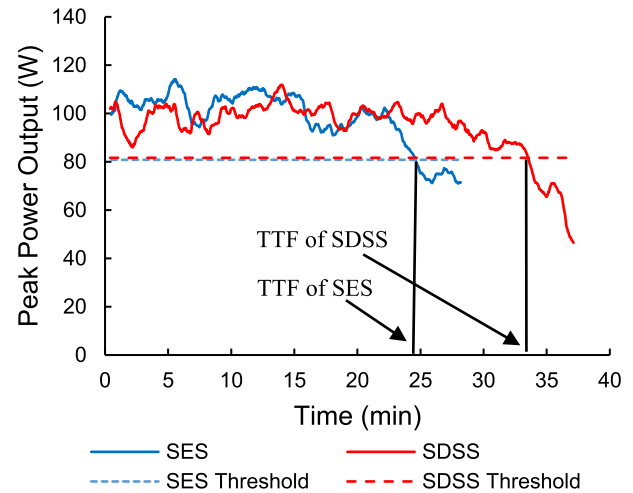


Fig. 4. A representative time course of filtered peak power output that shows for both single electrode stimulation (SES) and spatially distributed sequential stimulation (SDSS) fatiguing rowing. Fatigue thresholds of SES and SDSS rowing were set at 80% of the initial power output. Initial power output was determined as the average power output of the first 10 strokes.

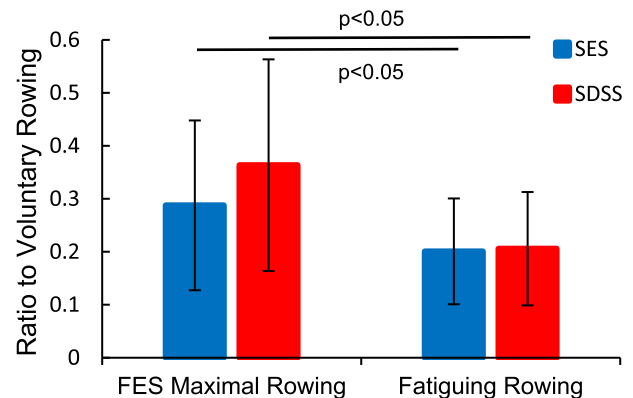


Fig. 5. Ratio of peak power output of maximal rowing with functional electrical stimulation (FES) and fatiguing rowing to voluntary rowing power output for both single electrode stimulation (SES) and spatially distributed sequential stimulation (SDSS).

Fatigue was defined by (1) the trial length and (2) time to fatigue (TTF). TTF was defined as the time elapsed from the first stroke to when rowing performance drops below a predetermined threshold. Thresholds in previous isometric knee extension FES studies have been defined as a 60% drop of initial torque output over 2 consecutive contractions [35] or as a 20% drop in peak torque output [26]. For this study, peak power was used to quantify rowing performance because it has been shown to be the most reliable measure of rowing performance [36], [37], and then TTF was defined as time elapsed until 20% drop in peak power output from initial peak power. Peak power per stroke was extracted (Fig. 3a) and filtered by a 30-point moving average filter to reduce stroke to stroke variability (Fig. 3b). To ensure that only steady state rowing was included for analysis, the first 5 strokes were excluded, and the initial peak power was defined as the average peak power of the subsequent 10 strokes. If peak power output recovered above and then subsequently dropped below the threshold, TTF was determined as the last point in time when filtered peak power output remains below the fatigue threshold (Fig. 3b). The trial length was defined as the time elapsed until

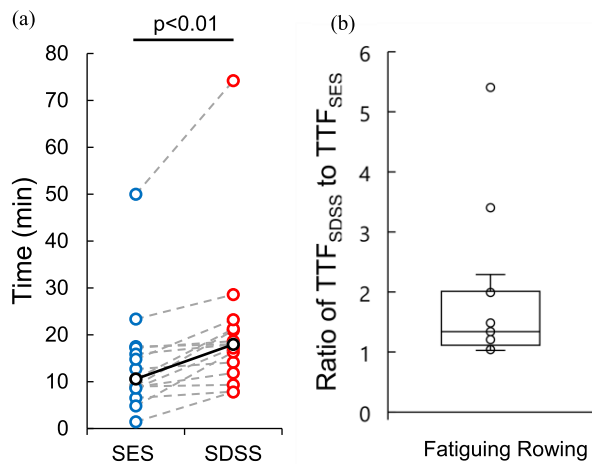


Fig. 6. Time to fatigue (TTF) of single electrode stimulation (SES) rowing and spatially distributed sequential stimulation (SDSS) rowing. (a) Time in minutes of TTF_{SDSS} and TTF_{SES} , with median in black. TTF for both SES and SDSS were not normally distributed, statistical significance was calculated with a wilcoxon signed rank test. (b) Box and whisker plot of ratio of TTF_{SDSS} to TTF_{SES} , the box contains the 25th and 75th percentile with the center line denoting the median value. Whiskers extend above and below the box to data elements that are not outliers. Outliers are shown as an open circle and are more than or equal to 1.5 times the interquartile range.

one of three endpoints was reached during Fatiguing Rowing (i.e., voluntary exhaustion, leg collapse, or pain).

Power output of both FES Maximal Rowing and Fatiguing Rowing was compared to Voluntary Maximal Rowing. The average peak power of the first minute of rowing in FES Maximal Rowing and Fatiguing Rowing was extracted and calculated as a ratio to Voluntary Maximal Rowing for each participant.

The kinetic energy exerted during rowing was used to quantify the exercise intensity and energy demand. For the 5 participants who had the oxygen consumption recording, the exercise intensity and the energy consumption were also quantified by (1) metabolic equivalents of task (METs) and (2) MET-minutes, respectively. VO_2 data collected by spirometry were converted to METs based on participant weight. Kinetic energy exerted during rowing was calculated as the integral of the power-time series of fatiguing rowing. The power time integral (PTI) until TTF quantified energy exerted of rowing until fatigue occurred. Drive phase PTI was determined as the area above the x-axis whereas recovery phase PTI was determined by the area below the x-axis (Fig. 3a).

G. Statistical Analyses

Data were analyzed using programmable computation software packages (MATLAB 2019, MathWorks, Natick, USA and Microsoft Excel, Microsoft Corporation, USA). To identify differences in outcomes during SDSS and SES, Wilcoxon signed-rank tests were performed for non-normally distributed data and two-tailed paired t-tests were performed for normally distributed data. Data normality was tested using the Shapiro-Wilk test. Significance and effect size of non-parametric tests were described by p - and r -values, respectively. Significance and effect size for parametric tests were described by p - and

d -values, respectively. A p -value less than 0.05 ($p < 0.05$) indicated statistical significance.

IV. RESULTS

A. Fatiguing Rowing Compared to Voluntary Maximal Rowing

Power outputs of FES Maximal Rowing and Fatiguing Rowing were different from Voluntary Maximal Rowing. Fig. 4 shows that the ratio of average peak power of FES Maximal Rowing to Voluntary Maximal Rowing was significantly different from the ratio of Fatiguing Rowing to Voluntary Maximal Rowing for SES (0.29 ± 0.16 for FES Maximal Rowing, group mean \pm standard deviation, 0.20 ± 0.10 for Fatiguing Rowing, $p < 0.05$, $d = 0.98$) and SDSS (0.36 ± 0.20 for FES Maximal Rowing, 0.21 ± 0.11 for Fatiguing Rowing, $p < 0.05$, $d = 0.91$). There was no significant difference between SES and SDSS conditions for both FES Maximal Rowing ($p > 0.05$, $d = 0.38$) and Fatiguing Rowing ($p > 0.05$, $d = 0.25$).

B. Fatiguing Rowing Trial Length

Fig. 5 shows a representative time course of filtered peak power output for SES and SDSS rowing trials of one participant. The total trial length (indicated by the length of traces) of SDSS rowing was longer than SES. Furthermore, the time at which SDSS power output crossed the fatigue threshold was longer than that of SES, resulting in a longer TTF for SDSS rowing.

Table II shows the trial length and the reason for stopping for each participant. Trial length for SDSS was significantly longer than SES (28.8 ± 15.9 minutes for SDSS, 22.6 ± 11.4 minutes for SES, $p < 0.01$, $d = 0.71$). The ratio of SDSS to SES rowing trial length averaged across all participants was 1.31 ± 0.47 ($p < 0.01$, $d = 0.70$). Voluntary exhaustion was the endpoint for 7 participants. Leg collapse was the endpoint for 6 participants. One participant stopped the SDSS trial due to pain; another participant stopped both trials due to pain.

C. Peak Power and TTF

Fig. 6 shows the TTF result, indicating that the median TTF for SES and SDSS conditions were 10.6 and 17.9 minutes, respectively. TTF_{SDSS} was significantly longer than TTF_{SES} ($p < 0.01$, $r = 0.62$) (Fig. 6a). The ratio of TTF_{SDSS} to TTF_{SES} had a median of 1.34, ranging from 1.03 to 5.41 (Fig. 6b). There was large variation in the ratio of TTF_{SDSS} to TTF_{SES} likely due to individual difference, however, no participant experienced a decrease in TTF with SDSS rowing (i.e., a ratio less than 1.0).

Stroke rate of Fatiguing Rowing was not significantly different between SES and SDSS conditions (22.1 ± 5.6 strokes per minute for SES, 23.0 ± 5.8 strokes per minute for SDSS, $p > 0.05$). Arm power output generally decreased alongside leg power (Fig. 10).

D. Energy of Rowing

Fig. 7 shows PTI until fatigue of the drive and recovery phase and the ratio of PTI of SDSS to SES. Drive phase PTI_{SES} until fatigue had a median of 16.3 kNm^*s and ranged from 0.7 to 164.4 kNm^*s whereas PTI_{SDSS} until fatigue had a median of 24.5 kNm^*s and ranged from 4.5 to 269.2 kNm^*s . PTI_{SDSS} until fatigue was significantly larger than PTI_{SES} until fatigue by $14.7 \pm 25.6 kNm^*s$ ($p < 0.01$, $r = 0.53$) (Fig. 7a). The ratio of drive phase PTI_{SDSS} to PTI_{SES} had a median of 1.42 and ranged from 0.83 to 6.78 (Fig. 7b). One participant experienced a decrease in PTI_{SDSS} until fatigue whereas the other participants all experienced an increase.

Recovery phase PTI_{SES} until fatigue had a median of 10.0 kNm^*s and ranged from 0.5 to 79.7 kNm^*s whereas PTI_{SDSS} until fatigue had a median of 16.0 kNm^*s and ranged from 2.9 to 127.4 kNm^*s . PTI_{SDSS} until fatigue was also significantly higher than PTI_{SES} until fatigue ($p < 0.01$, $r = 0.61$) (Fig. 7c). The ratio of recovery PTI_{SDSS} until fatigue to PTI_{SES} had a median of 1.42 and ranged from 1.00 to 6.33 (Fig. 7d).

Exercise intensity as measured by METs was recorded for 5 participants for both SES and SDSS fatiguing rowing. The average METs of Fatiguing Rowing was 4.4 ± 1.5 METs for SES rowing and 4.6 ± 1.9 METs for SDSS rowing. MET-minutes was calculated to quantify energy expenditure throughout the rowing trial by integrating the area under the MET-time curve. The group average for total MET-minutes during SES rowing was 115.0 ± 66.3 MET-minutes whereas the average total MET-minutes for SDSS rowing was significantly larger ($p = 0.04$, $d = 1.33$) at 143.3 ± 73.6 MET-minutes. Average MET-minutes until TTF for SES rowing was 81.2 ± 45.5 MET-minutes and average MET-minutes for SDSS rowing until fatigue was significantly larger ($p < 0.01$, $d = 1.71$) at 106.1 ± 51.1 (Fig. 8).

V. DISCUSSION

We investigated the effect of SDSS on muscle fatigue in dynamic exercise for AB individuals in FES-rowing exercise. The main findings of this study are: (1) Trial length was longer for SDSS rowing than SES rowing by 31%, (2) SDSS improves fatigue resistance as rowing performance measured by TTF can be maintained for longer with SDSS than with SES by 34%, (3) because of a longer TTF, more energy was consumed during the drive phase before fatigue is reached in SDSS rowing by 42%.

A. SDSS Increased Fatigue Resistance in FES-Rowing

Fatiguing Rowing trial length was significantly longer in SDSS rowing by approximately 31%, i.e., the ratio of SDSS to SES trial lengths showed that SDSS trial lengths were 1.31 ± 0.47 times longer than SES on average. Although trial length increased overall, 4 participants experienced a shorter trial length with SDSS, ranging from 5.7 to 18.6% shorter. This decrease in trial length could explain the large deviation seen in the group data since the increase in trial length with SDSS of the other 10 participants ranged from 2% to 279% of the SES time (Table II). Although participants were verbally

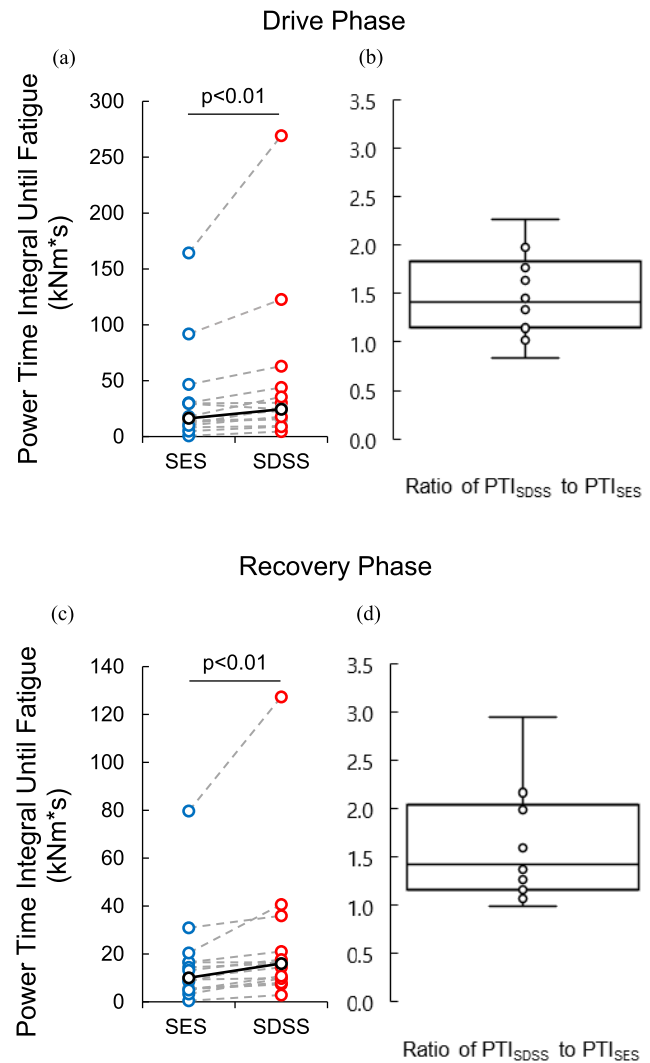


Fig. 7. Power time integral until fatigue (PTI) (a) and ratio of spatially distributed sequential stimulation (SDSS) PTI to single electrode stimulation (SES) PTI during drive phase (b). Recovery phase PTI (c) and ratio (d) are also shown. PTI of both conditions were not normally distributed, medians of PTI are displayed in black. Statistical significance was calculated with a wilcoxon signed rank test. Box and whisker plots of PTI ratios for both drive (b) and recovery (d) phases of rowing are shown. The box contains the 25th and 75th percentile with the center line denoting the median value. Whiskers extend above and below the box to 1.5 times the interquartile range and data points outside the whiskers were considered outliers and are not shown. PTI ratios were not normally distributed and not statistically significant between drive and recovery phase.

encouraged throughout the trial to continue rowing until leg collapse, the endpoint of Fatiguing Rowing for 8 participants was either voluntary exhaustion or pain, not leg collapse (Table II). Therefore, trial length was dependent on individual endurance and is relatively subjective. The subjective nature of trial length was why we also measured TTF, TTF indicated a quantitative decrease in performance and was more objective as measure of fatigue resistance.

Our results showed that a median ratio of TTF_{SDSS} to TTF_{SES} of 1.34 suggests that SDSS increased fatigue resistance by about 34%. Furthermore, despite the large variation in TTF, no rower experienced a decrease in TTF when using SDSS over SES.

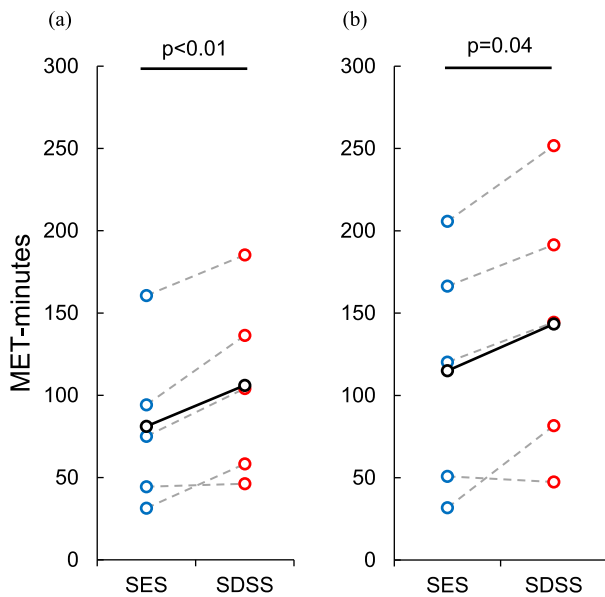


Fig. 8. Energy consumption of FES-rowing exercise with single electrode stimulation (SES) and spatially distributed sequential stimulation (SDSS) measured by MET-minutes of rowing exercise. (a) MET-minutes until fatigue and (b) total MET-minutes of exercise are calculated with the mean in black.

Fatigue resistance from SDSS is well documented in isometric and isokinetic tasks with a large range in performance improvement with SDSS [17]–[25]. Nguyen *et al.* found similar results in isometric ankle torque where SDSS improved fatigue resistance by 280% in one individual with SCI [17]. Sayenko *et al.* measured fatigue index instead of a TTF-like measure to quantify fatigue resistance in both AB and individuals with SCI. Fatigue index compared the difference between the torque values at the beginning and end of the stimulation to indicate the ability to maintain torque with a higher fatigue index indicating higher fatigue resistance [19]. Sayenko *et al.* found that SDSS improved fatigue index by 28% in 17 individuals with SCI and 26% in 11 AB individuals. Similarly, Laubacher *et al.* found that SDSS improved fatigue index in isokinetic knee extension by 31% in AB individuals [21] and improvement ranging from 10% to 34% in 3 of 4 individuals with SCI where 1 individual with SCI experienced a decrease in fatigue resistance by 23% [22]. Previous publications utilizing sequential stimulation also show similar gains in fatigue resistance. Downey *et al.* found that SDSS improved isometric knee TTF by an average of 253% in 4 individuals with SCI; additionally, when stimulation frequency of SDSS was lowered, the stimulated muscle did not even reach fatigue threshold over the course of the trial [26]. However, Downey *et al.* used a different stimulation frequency of 32 Hz instead of the 40 Hz used in our study and each SDSS electrode was the same size as a SES electrode. Malesevic *et al.* found that sequential stimulation of electrodes distributed over agonist thigh muscles resulted in 26% more fatigue resistance in isometric knee extension compared to SES [29]. Findings from Sayenko *et al.* [19] show that fatigue resistance was similar when SDSS was applied to both AB and SCI groups. Fatigue resistance was similar in single joint tasks including knee extension, knee flexion, plantarflexion

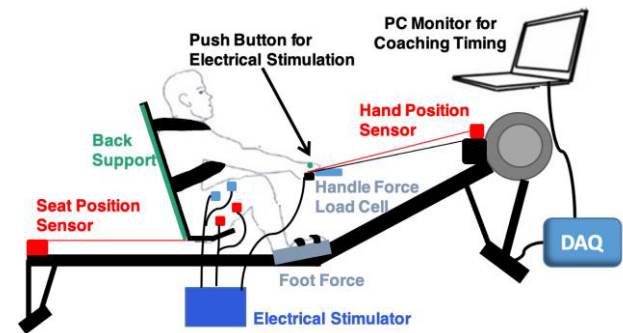


Fig. 9. Schematic of rowing ergometer data collection and coaching set-up.

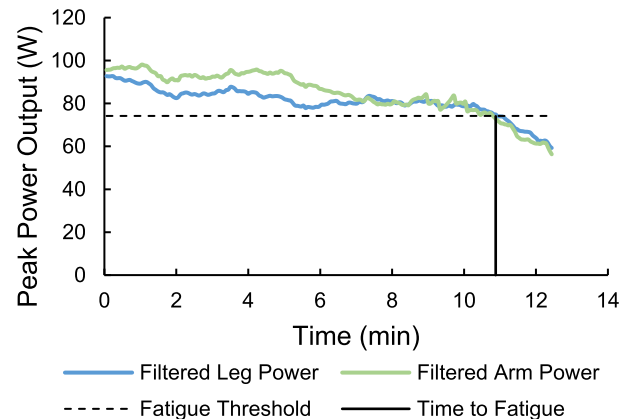


Fig. 10. A representative time course of filtered peak power output that shows power output of both the arms and legs in spatially distributed sequential stimulation (SDSS) fatiguing rowing. Fatigue threshold of rowing was 80% of the initial power output. Initial power output was determined as the average power output of the first 10 strokes.

and dorsiflexion. These results across groups suggest that it would be viable to use an AB group to model SCI rowing with SDSS.

As far as we are aware, this study is the first to report improved fatigue resistance with SDSS in a dynamic exercise context where an active upper body is coupled with stimulated lower limbs, a previous publication has reported improved fatigue resistance with sequential stimulation in FES-cycling [30]. Specifically, we found that with matched stimulation intensity, the time elapsed until fatigue occurred with SDSS was significantly longer than with SES. Our results suggest that SDSS should be able to extend FES exercise times by 31% percent and maintain a high power output for 34% longer in clinical settings. Previously, it was unknown whether the improved fatigue resistance found in single joint SDSS studies would be observed if SDSS was applied in a dynamic exercise setting. However, our results show that SDSS significantly improved fatigue resistance, in similar amounts as single joint studies, in a dynamic FES-exercise context meaningful for SCI rehabilitation.

B. Energy Expenditure Was Larger With SDSS

Energy expenditure was evaluated with two methods; (1) the mechanical energy exertion, PTI, and (2) the metabolic energy consumption, MET-minutes, the latter evaluation was limited to 5 participants out of 15 due to COVID-19 restrictions.

TABLE II
TRIAL LENGTH OF FATIGUING ROWING

Participant	Trial Length (min)			Reason for Stopping	
	SES	SDSS	SDSS:SES	SES	SDSS
1	13.6	15.8	1.16	Leg collapse	Leg collapse
2	14.2	13.1	0.92	Leg collapse	Leg collapse
3	5.0	8.5	1.71	Leg collapse	Leg collapse
4	27.2	38.1	1.40	Voluntary	Voluntary
5	15.3	12.5	0.81	Voluntary	Voluntary
6	28.2	37.1	1.32	Leg collapse	Leg collapse
7	17.9	27.9	1.56	Leg collapse	Leg collapse
8	31.8	32.5	1.02	Leg collapse	Pain
9	15.3	22.6	1.48	Voluntary	Voluntary
10	30.7	42.5	1.40	Voluntary	Voluntary
11	50.0	75.3	1.51	Voluntary	Voluntary
12	20.8	18.7	0.93	Pain	Pain
13	36.7	34.6	0.94	Voluntary	Voluntary
14	24.4	27.8	1.14	Voluntary	Voluntary
15	8.8	24.7	2.79	Leg collapse	Leg collapse
Mean	22.6	28.8	1.31		
SD	11.4	15.9	0.47		

PTI was quantified for the drive phase and recovery phase separately. While the drive phase provides energy to the ergometer load (i.e., the flywheel), the recovery phase provides energy to reset the rowing stroke. In both phases, we observed clear increases of mechanical energy exertion by applying SDSS in FES-rowing. This increase of mechanical energy exertion was approximately 42% for both drive phase and recovery phase, which was similar to the increase in exercise time. This result implies that the efficiency of rowing was similar between SDSS and SES conditions as the increase of the mechanical energy exertion was heavily influenced by exercise time (i.e., TTF). The metabolic energy consumption was evaluated for 5 participants. Spirometry is commonly used to measure VO_2 and METs where METs are used to express the energy intensity of exercises. The average METs of FES-rowing was 4.4 ± 1.5 METs for SES rowing and 4.6 ± 1.9 METs for SDSS rowing, putting FES-rowing within the 3.0-6.0 METs range as a moderate intensity exercise. Hettinga *et al.* reported METs of previous FES-rowing studies with SES where the METs of maximal FES-rowing across two studies averaged 6.9 METs whereas average METs of submaximal rowing was 5.4 METs [38]. Given that participants in the submaximal rowing studies were also instructed to row at a self-selected pace, the results of this study may underestimate previously reported FES-rowing exercise intensities. [39], [40].

One possible reason for our relatively lower MET values could be that we used 80% of maximum tolerable stimulation intensity instead of 100%. It may be possible to reach similar MET values as reported by Hettinga *et al.* if stimulation intensities were increased to maximum and participants instructed to row as hard as possible. In the clinic, individuals with SCI often require a high level of stimulation to row with SES,

therefore many would require more than 80% of maximum tolerable intensity for FES-Rowing. It is possible that stimulation intensity would need to be increased further in SDSS given lower stimulation frequency at each pad. However, increasing intensity to maximum tolerable levels may not be possible in participants with intact sensory function but may be feasible in participants with SCI to elicit a stronger cardiovascular response. Further investigations in individuals with SCI may achieve previously reported MET values if stimulation intensity is at maximum. Given that the participants in this study were not paralyzed, it may be difficult to suppress voluntary contractions during FES-rowing if participants were instructed to row as hard as possible.

Guidelines for cardiovascular health usually recommend performing moderate intensity exercise 90 minutes a week for individuals with SCI and 150 minutes for AB individuals [41]. At an intensity of 3.0-6.0 METs, this corresponds to 270-540 MET-minutes per week for individuals with SCI and 450-900 MET-minutes per week for AB individuals. Group results showed that average total MET-minutes for SDSS rowing was 143.3 ± 73.6 MET-minutes versus 115.0 ± 66.3 MET-minutes for SES. MET-minutes until TTF for SDSS rowing was 106.1 ± 51.1 MET-minutes versus 81.2 ± 45.5 MET-minutes for SES. Based on the total amount of MET-minutes achieved, SDSS rowing would reach the 540 MET-minute requirement in 3.7 sessions whereas it would require 4.7 for SES. Even if participants do not complete the entire trial and only row until the fatigue threshold, the 540 MET-minutes guideline for individuals with SCI can be completed in 5.1 sessions with SDSS rowing sessions versus 6.7 with SES. SCI rowers would need one to two fewer rowing session per week with SDSS versus SES to achieve recommended exercise amounts.

SDSS rowing would improve rehabilitation effectiveness by reducing the number of exercise sessions required to reach weekly exercise goals.

C. Limitations

Our results were from AB participants who mimicked FES-rowing in individuals with SCI by relaxing their legs during stimulation. We planned to include individuals with SCI but were not able to do so due to COVID-19 restrictions. This AB model of SCI may not completely mimic FES-rowing in individuals with SCI as AB participants might have exerted voluntary force unknowingly. An EMG analysis of voluntary contraction during FES-rowing is a potential topic for future study. Furthermore, our AB group was relatively homogenous in age and given the wide range of age in individuals with SCI, future investigations reflecting these patient demographics are required. However, even if the participants exerted some voluntary force exertion, it may be a good model of performance in individuals with incomplete SCI where we expect some voluntary contribution to FES-rowing as we see a similar percent change in fatigue resistance with SDSS when compared to trials conducted with SCI.

Another consideration is the amount of muscle in the legs of individuals with SCI. Because individuals with SCI have a large amount of compromised muscle mass [42], their cardiovascular ability and number of fatigue resistant muscle fibers would be much less than an AB individual [15], [43]. Variation in these factors in individuals with SCI could lead to different outcomes compared to those seen our AB model. Even in our AB model, there was large variation in the response to SDSS. Although we did not find any relation in sub-group analyses, factors such as leg muscle strength or cardiovascular fitness may influence the response to SDSS and warrants further investigation.

Another limitation was that the metabolic energy consumption was measured for only 5 participants which limited the power of the results. While the results were promising, further investigation, especially with individuals with SCI, is required. Future studies with participants with SCI are required to verify the advantage of the proposed method in FES rowing.

VI. CONCLUSION

Our study has revealed that the SDSS stimulation strategy improves fatigue resistance in FES-rowing for AB individuals by increasing total exercise time and time elapsed until fatigue occurs. SDSS significantly increased trial length of FES-rowing by 31% and TTF of FES-rowing by 34%. The kinetic energy exerted as measured by PTI was also significantly higher for SDSS rowing than it was for SES rowing by 42%. Since trial length was a primary factor in determining kinetic energy consumption, similar increases in trial length and PTI indicates that SDSS rowing was just as efficient as SES rowing. Metabolic energy consumption of SDSS rowing was higher than SES to where individuals with SCI would reach recommended exercise guidelines in fewer rowing sessions with SDSS than SES.

SDSS has been previously shown to improve fatigue resistance in isometric and isokinetic studies, our study is the first to showcase this effect of SDSS in a dynamic FES-rowing exercise setting relevant to SCI rehabilitation. Since fatigue is a major limitation for any FES application, it means that SDSS would improve fatigue resistance for any FES application as well. Although results from AB models of SCI are very promising, future research should repeat this study with individuals with SCI.

APPENDIX A

The coaching system used raw data from the load cells and string potentiometers and was processed in real-time in software written in Python on the connected laptop computer (Python Software Foundation, Python Language Reference, Version 3.5). Because the participants delivered stimulation manually through a push button attached to the ergometer handle, the primary function of the coaching system was to provide real-time visual and auditory feedback to the participant on the timing of button presses. Furthermore, the coaching system also displayed a score of correct and incorrect button presses (Fig. 9).

APPENDIX B

The contribution of the upper limbs could be evaluated with force and power output at the handle load cell and potentiometer. In general, we saw that power output at the handle was similar in magnitude to power output at the foot plate and thus upper limb power output decreased with lower limb power output. Given that the participants were instructed with the minimum power necessary to complete the upper limb portion of the rowing stroke, the output measured at the handle should closely mimic the output at the foot plate (Fig. 10).

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