

Muscle oxygenation during hybrid arm and functional electrical stimulation–evoked leg cycling after spinal cord injury

Nazirah Hasnan, MBBS, MRehabMed, PhD^{a,*}, Nurul Salwani Mohamad Saadon^b, Nur Azah Hamzaid, PhD^b, Mira Xiao-Hui Teoh^b, Sirous Ahmadi^c, Glen M. Davis, PhD^c

Abstract

This study compared muscle oxygenation (StO₂) during arm cranking (ACE), functional electrical stimulation–evoked leg cycling (FES-LCE), and hybrid (ACE+FES-LCE) exercise in spinal cord injury individuals. Eight subjects with C7-T12 lesions performed exercises at 3 submaximal intensities. StO₂ was measured during rest and exercise at 40%, 60%, and 80% of subjects' oxygen uptake (VO₂) peak using near-infrared spectroscopy. StO₂ of ACE showed a decrease whereas in ACE+FES-LCE, the arm muscles demonstrated increasing StO₂ from rest in all of VO₂ peak respectively. StO₂ of FES-LCE displayed a decrease at 40% VO₂ peak and steady increase for 60% and 80%, whereas ACE+FES-LCE revealed a steady increase from rest at all VO₂ peak. ACE+FES-LCE elicited greater StO₂ in both limbs which suggested that during this exercise, upper- and lower-limb muscles have higher blood flow and improved oxygenation compared to ACE or FES-LCE performed alone.

Abbreviations: ACE = arm cranking, ACE+FES-LCE(arm) = hybrid arm exercise, ACE+FES-LCE(leg) = hybrid leg exercise, ECG = electrocardiogram, FES-LCE = functional electrical stimulation–evoked leg cycling, H⁺ = hydrogen ions, HbO₂ = oxyhemoglobin, mVO₂ = muscle oxygen consumption, NIRS = near-infrared spectroscopy, PO = power output, SCI = spinal cord injury, StO₂ = muscle oxygen saturation, THb = total hemoglobin, VO₂ = oxygen uptake.

Keywords: arm exercise, leg exercise, near-infrared spectroscopy, neuromuscular electrical stimulation, paraplegia, tetraplegia

1. Introduction

Spinal cord injury (SCI) leads to marked muscle atrophy.^[1,2] However, induced muscle activity is believed to have the potential to prevent degeneration of the musculoskeletal system after SCI.^[3]

Functional electrical stimulation (FES) has increasingly been used to elicit rhythmic muscle contractions and purposeful movements in the paralyzed lower limbs of persons with SCI.^[4] It has been used as a rehabilitation tool that enables localized

exercise benefits to denervated muscles resulting in greater strength, enhanced circulation, and blood flow^[5,6] with concomitant adaptations in skeletal muscle mitochondrial function.^[7]

Following SCI, muscles innervated below the level of spinal lesion go through significant morphological, histological, and biochemical changes. These include reduced capillary density, lower mitochondrial concentration in the existing motor units, and a relative increase in type IIA/B motor units, which have lower oxidative capacity than type I.^[8] During prolonged exercise, effective oxygen delivery and extraction is necessary to maintain aerobic metabolism^[9] and also to prevent muscle damage during eccentric movements.^[10] As such, muscle oxidative metabolism during FES-evoked exercise is physiologically interesting (and infrequently investigated in person with SCI), because the muscle metabolic pattern during FES is dissimilar to voluntary contractions and may vary under different stimulation protocols.^[11,12]

Near-infrared spectroscopy (NIRS) is a noninvasive, real-time, continuous, and direct method to monitor oxygenation and hemodynamics in tissues. It enables evaluation of oxygen utilization in skeletal muscles.^[11] NIRS has been found to be a valid and reliable technique for measuring relative changes in tissue oxygenation both at the level of the small blood vessels, capillaries, and at the intracellular sites, and is a sensitive tool in examination of healthy and diseased states.^[13]

Literature on muscle oxygen saturation (StO₂) during FES-evoked exercise in SCI has primarily focused on the lower limbs. In this study, muscle oxygenation pattern was compared in the vastus lateralis muscles between able-bodied and SCI subjects who observed a lower muscle deoxygenation during maximal exercise, and faster changes in muscle deoxygenation during exercise oxygen uptake (VO₂) in SCI individuals when compared to their able-bodied cohort.^[14] Muscle oxygenation responses

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^a Department of Rehabilitation Medicine, Faculty of Medicine, ^b Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia, ^c Clinical Exercise and Rehabilitation Unit, Discipline of Exercise and Sport Sciences, Faculty of Health Sciences, The University of Sydney, Sydney, Australia.

* Correspondence: Nazirah Hasnan, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia (e-mail: nazirah@ummc.edu.my).

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also was investigated during prolonged FES cycling and a different pattern of muscle oxygenation was observed in FES cycling where equilibrium between oxygen demand and oxygen delivery was reached compared to voluntary leg cycling.^[12] It was found that the influence of pedaling speed on muscle oxygenation during FES leg cycling had no difference in responses at different cadences.^[15]

In terms of combined arm and leg exercise, authors compared the changes in muscle oxygenation in vastus lateralis and biceps brachii muscles simultaneously during progressive-intensity rowing in able-bodied rowers, and the authors observed that arm muscles had lower oxidative capacity than leg muscles.^[16] On the contrary, there was no additional advantages from the FES-induced leg exercise compared to hand-cycle training alone.^[17] To our knowledge, there has not been a direct comparison of voluntary arm and FES-evoked leg especially for muscle oxygenation in individuals with SCI who undertake such “hybrid” exercise.

This study sought to compare localized tissue StO₂ in muscles during arm cranking, FES-assisted leg cycling, and hybrid exercise modalities during submaximal incremental exercise in persons with SCI. This study also aimed to compare the changes in muscle StO₂ between arm and leg during incremental exercise in persons with SCI.

2. Materials and methods

2.1. Subjects

Eight male subjects (aged 40.6 ± 1.1 years, stature 1.7 ± 0.01 m, body mass 73.1 ± 1.0 kg, time since injury 6.6 ± 0.4 years) with traumatic SCI, C7-T12, American Spinal Injury Association Impairment Scale A, B, and C volunteered to participate in this study. The Human Research Ethics Committee of the University of Sydney approved this study (Ref No. 09-2009/12147), and written informed consent was obtained from all subjects before their participation. Eligible subjects were aged between 18 and 65 years. All underwent a full medical screening which included a physical and neurological examination, a 12-lead resting electrocardiogram, measurement of resting blood pressure, and lower limb radiographs before the study. All subjects were healthy and neurologically stable. The subjects were recruited through a convenience sampling methodology rather than randomized sampling as they are regular FES participants who attended FES cycling exercises to complete the program for at least 8 weeks before the study.

2.2. Study protocol

The subjects were assessed on 3 different exercise modalities presented in a predefined order: arm crank ergometer (ACE), a functional electrical stimulation-leg cycle ergometer (FES-LCE), and a combined ACE and FES-LCE system [ACE+FES-LCE (arm) and ACE+FES-LCE (leg)]. The arm crank ergometer was mounted over the leg cycle ergometer for ACE and ACE+FES-LCE assessments. For all tests, the crank axle of the ACE was positioned at shoulder height with the subject in the seated posture. For FES-LCE and hybrid, the subjects transferred themselves onto the leg cycle ergometer chair and their feet were strapped and held in position by ankle-calf supports to minimize leg movements during cycling.

Gel-backed self-adhesive surface electrodes were placed over the bellies of the quadriceps, hamstrings, and glutei groups to

enable electrical stimulation muscle recruitment for FES-evoked cycling. Electrode placement was kept consistent by measurements to key anatomical landmarks to ensure that muscle fiber recruitment was similar between trials. Subject preparation and the experimental set-up were all performed by the primary investigator. During the FES cycling, electrical stimulation was delivered via biphasic rectangular pulses at a frequency of 35 Hz and pulse width of 300 μ s. The muscle stimulation “firing” angles were fixed and the timing of stimulation was pre-set by a computer program. The maximum stimulation amplitude was limited to 140 mA.

The research design involved 3 sessions of submaximal exercise testing which were performed on separate days. All assessments were separated by at least 48 hours. Before the submaximal exercise testing, all participants underwent an incremental power output (PO) test to maximal effort in the 3 exercise modes: maximal ACE, maximal FES-LCE, and maximal ACE+FES-LCE. Peak VO₂ was derived to ascertain the highest physical work capacity for each individual in all 3 exercise modalities.

2.3. Exercise protocol

During the 3 visits to the laboratory, testing was conducted in 2 stages. During the first stage, all participants underwent an incremental PO test to maximal effort in all 4 exercises modes in which VO₂ peak was obtained. For the second stage of testing, muscle oxygenation was measured during submaximal steady-state exercise at 40%, 60%, and 80% of mode-specific VO₂ peak determined from previous stage:

2.3.1. Submaximal ACE. Subjects were instructed to arm crank at 50 rev.min⁻¹ at 0 W for 3 minutes, followed by PO increases of 10 W · min⁻¹ until reaching a target PO corresponding to 40% ACE VO₂ peak. After a short recovery, wherein the heart rate and VO₂ were observed to have returned to near pre-exercise levels, subjects then continued arm cranking until reaching target PO corresponding to 60% ACE VO₂ peak. Finally, after another recovery, they continued arm cranking up to 80% ACE VO₂ peak. Each submaximal steady-state exercise bout lasted for 3 minutes.

2.3.2. Submaximal FES-LCE. Subjects performed passive leg cycling at 0 W (without FES) at 50 rev.min⁻¹ for 3 minutes, followed by PO increments of 1 to 3 W · min⁻¹ every minute until reaching target PO corresponding to 40%, 60%, and 80% of FES-LCE-specific VO₂ peak. After each exercise about lasting 3 minutes, a short recovery was commenced, followed by incremental PO to the next intensity. Increments of leg PO were achieved by deploying incrementally higher FES current amplitudes.

2.3.3. Submaximal ACE+FES-LCE. Subjects performed a combined ACE and FES-LCE cycling, incrementing both arm and leg POs until reaching a target PO corresponding to 40% VO₂ peak of ACE+FES-LCE. The subjects then continued ACE and FES-LCE until reaching target POs corresponding to 60% VO₂ peak and 80% VO₂ peak in steady-state similar to the ACE and FES-LCE protocols. Each submaximal steady-state exercise bout lasted 3 minutes.

2.4. Muscle oxygenation

NIRS was used to continuously record changes in muscle oxygenation in the exercising arm and leg. Dual-channel

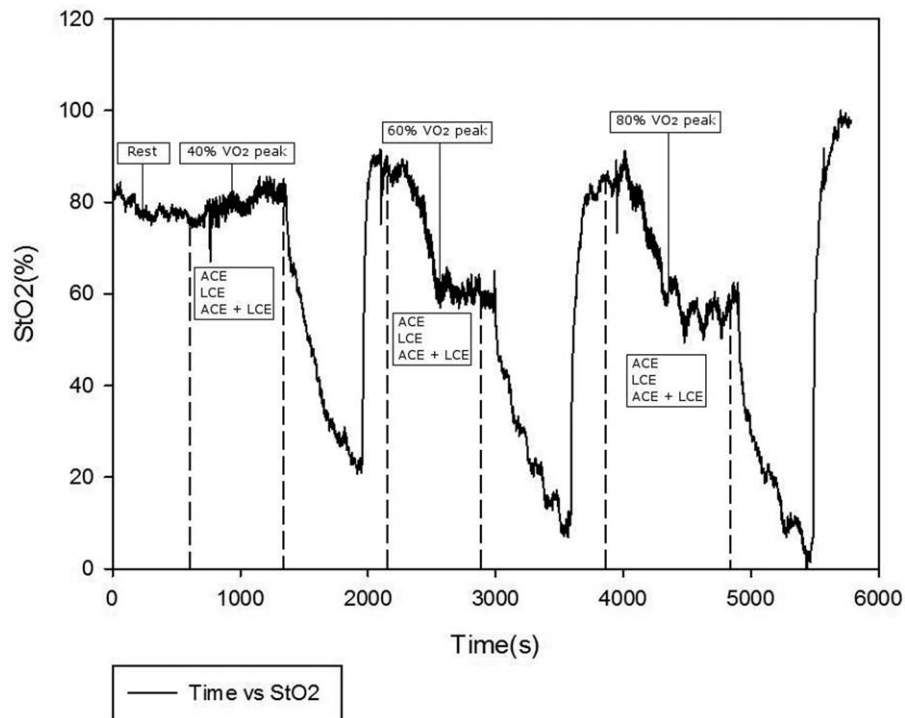


Figure 1. A sample of near-infrared spectroscopy (NIRS) muscle oxygen saturation (StO₂) measurements obtained during each exercise. Arterial occlusion was done after 40%, 60%, and 80% of oxygen uptake (VO₂) peak, respectively.

frequency-domain NIRS system (ISS OxiplexTS Oximeter, Model 96208, ISS Inc, Champaign, IL) was deployed, comprising 2 probes each consisting of 8 laser diodes operating at 2 wavelengths (690 and 830 nm) and a photomultiplier tube. This system measured separately the absorption (μ_a) and the reduced scattering (μ'_s) coefficients in large muscles. This enabled the absolute values of oxyhemoglobin (HbO₂), deoxyhemoglobin, total hemoglobin (THb), and percentage of StO₂, because the ratio of oxygenated to total hemoglobin concentration.

The NIRS sensors were placed on the right vastus lateralis muscle (on the point between the electrodes placed for electrical stimulation) and the right biceps brachii. The skin of each subject was cleaned with alcohol wipes and to prevent slipping and the influence of perspiration on the probes, an optically neutral double-sided adhesive waterproof tape (Shimadzu, Kyoto, Japan) was applied between the skin and the probes. A light blocking material was used to wrap the limbs, which held the NIRS probe to prevent contamination from ambient light.

NIRS measurements were made continuously during rest, and incremental exercise (40%, 60%, and 80% VO₂ peak). In addition, measurements were also made during super-systolic arterial occlusion of the arm and thigh immediately upon cessation of exercise at the each intensity and also during recovery following release of the occlusion. The super-systolic arterial occlusion was produced and maintained at 260 mm Hg using a rapid-inflating blood pressure cuff (Hokanson E20, Bellevue, WA). The occlusion was maintained for up to 9 minutes for the thigh and 3 minutes for the arm or until the decreasing thigh muscle StO₂ had stabilized. A schematic diagram of the protocol employed in this study which shows StO₂ measurements during rest, occlusions and exercise (Fig. 1).

For 40%, 60%, and 80% of VO₂ peak, muscle oxygen consumption (mVO₂) was measured (Table 1). It is calculated by

the rate of change in HbO₂ during brief arterial occlusions in NIRS signals using linear regression. Hemoglobin and myoglobin both contribute with the changes in NIRS signals in which its signal changes are proportional to mitochondrial oxygen consumption due to relative changes in hemoglobin and myoglobin saturation.^[18]

Physiological calibration is very important because it is the most practical comparisons of oxygenation levels between different people and different muscle build and thus providing accurate interpretation of NIRS data. The physiological range provides functional scaling from 0% oxygen saturation until reached nadir (after 5–6 minutes ischemia) to 100% oxygen saturation during reactive hyperemia at 250 to 280 mm Hg of pressure.^[18,19] From the 3 occlusion curves, all data were calibrated using lowest nadir point and highest point of hyperemia from the 3 curves.

Table 1

Mean muscle oxygen consumption during graded submaximal arm and leg exercise.

Exercise intensity	40% VO ₂ peak	60%VO ₂ peak	80% VO ₂ peak
mVO ₂ (mLO ₂ ·min ⁻¹ ·100 g ⁻¹)			
ACE	0.02 ± 0.01	0.04 ± 0.06	0.02 ± 0.01
ACE+FES-LCE (arm)	0.08 ± 0.07	0.07 ± 0.03	0.07 ± 0.07
FES-LCE	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.02
ACE+FES-LCE (leg)	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01

ACE+FES-LCE(arm) = hybrid arm exercise, ACE+FES-LCE(leg) = hybrid leg exercise, FES-LCE = functional electrical stimulation–evoked leg cycling, mVO₂ = muscle oxygen consumption, VO₂ = oxygen uptake.

Table 2**Mean muscle oxygen saturation, oxyhemoglobin deoxyhemoglobin, and total hemoglobin during graded submaximal arm and leg exercise.**

Exercise intensity	Rest	40% VO ₂ peak	60% VO ₂ peak	80% VO ₂ peak
StO ₂ , %				
ACE	65.12 ± 7.30	61.96 ± 7.81	61.47 ± 6.54	61.59 ± 15.66
ACE+FES-LCE (arm)	63.16 ± 11.83	62.75 ± 8.90	64.69 ± 11.76	68.82 ± 7.99
FES-LCE	79.29 ± 6.87	79.00 ± 6.40	85.01 ± 10.57	90.74 ± 9.67
ACE+FES-LCE (leg)	67.30 ± 23.44	71.08 ± 14.83	80.51 ± 18.75	77.71 ± 22.85*
HbO ₂ , μM				
ACE	33.06 ± 15.42	31.30 ± 10.41	32.66 ± 12.08	34.53 ± 14.72
ACE+FES-LCE (arm)	21.04 ± 8.12	19.62 ± 6.91	21.76 ± 9.55	23.86 ± 10.51
FES-LCE	50.85 ± 14.77	53.40 ± 13.73	57.48 ± 18.41	60.76 ± 16.40
ACE+FES-LCE (leg)	24.74 ± 12.99	25.44 ± 15.29	27.02 ± 15.09	27.66 ± 16.75*
HHb, μM				
ACE	17.93 ± 8.42	17.09 ± 6.79	17.62 ± 7.43	17.81 ± 6.86
ACE+FES-LCE (arm)	20.56 ± 10.33	22.36 ± 10.64	22.46 ± 11.16	23.15 ± 12.99
FES-LCE	7.45 ± 1.93	7.03 ± 2.01	6.48 ± 2.42	6.04 ± 1.85
ACE+FES-LCE (leg)	10.65 ± 6.74	9.70 ± 5.51	7.06 ± 4.36	8.29 ± 3.63*
THb, μM				
ACE	51.00 ± 23.02	47.52 ± 14.18	50.34 ± 18.99	52.44 ± 21.06
ACE+FES-LCE (arm)	71.42 ± 20.76	75.74 ± 21.72	79.90 ± 24.40	83.97 ± 24.64
FES-LCE	28.45 ± 9.79	26.72 ± 8.53	28.24 ± 11.40	29.89 ± 11.60
ACE+FES-LCE (leg)	35.36 ± 19.10	35.15 ± 20.50*	34.10 ± 18.52	35.96 ± 19.67*

Data refers to StO₂, HbO₂, HHb, and THb of bicep brachii and vastus lateris muscle during each VO₂ peak. Paired *t* test was done to compare resting value with each VO₂ peak.

ACE+FES-LCE(arm) = hybrid arm exercise, ACE+FES-LCE(leg) = hybrid leg exercise, FES-LCE = functional electrical stimulation–evoked leg cycling, HbO₂ = oxyhemoglobin, HHb = deoxyhemoglobin, StO₂ = muscle oxygen saturation, THb = total hemoglobin, VO₂ = oxygen uptake.

* Significant difference between resting value with 40%, 60%, and 80% VO₂ peak (*P* < .05).

2.5. Data analysis

All data were obtained during exercise and were examined using paired *t* test by IBM SPSS Statistics 24 (SPSS Inc) by percentage of VO₂ peak. The results were divided into 4 parts: during ACE, FES-LCE, ACE+FES-LCE (arm), and ACE+FES-LCE (leg). Resting value was obtained as a mean of the rest period before the exercise. During each VO₂ peak, a value for each parameter was computed as the average of the all the data points. Changes relative to baseline (rest) were computed as the difference between the average baseline value and the average contraction value, that is, ΔStO₂ and ΔHbO₂, and these data were used for further analyses.

In each exercises, paired *t* test were also used to compare differences from resting state (ΔStO₂ and ΔHbO₂) with each mode-specific 40%, 60%, and 80% of VO₂ peak measurement while mVO₂ was compared with the VO₂ before them. All statistical analyses were performed using the SPSS 21 statistical package. Data are presented as mean ± standard error, and the level of statistical significance was set to the 95% confidence limit (*P* < .05).

3. Results

This study compared muscle oxygenation during arm cranking, FES-assisted leg cycling and combined arm and leg (“hybrid”) exercise modalities during graded submaximal incremental exercise. Data from ACE+FES-LCE exercise were separated for arm and leg, termed ACE+FES-LCE (arm) and ACE+FES-LCE (leg), respectively. There were 10 eligible subjects, but 2 of them could not be included in the study due to upper body exercise issues.

The resting and submaximal data during ACE, FES-LCE, ACE+FES-LCE (arm), and ACE+FES-LCE (leg) during all exercise

intensities are presented in Table 2. All 8 subjects completed their submaximal test at 40%, 60%, and 80% mode-specific VO₂ peak of exercise intensities. In this section, the results are represented as ACE versus ACE+FES-LCE (arm) and FES-LCE versus ACE+FES-LCE (leg). Percentage StO₂ and HbO₂ were quantified during 4 different exercises modalities and plotted in Figures 2 and 3. Figures 4 and 5 show detailed analysis in which Δ%StO₂ is plotted against VO₂ peak for each subjects.

Data during submaximal exercise for ACE was compared with the arm component during hybrid exercise, that is, ACE+FES-LCE (arm). For ACE, ΔStO₂ kept on decreasing with increasing percentage VO₂ peak; −3.16%, −3.65%, and −3.53%, respectively. ΔHbO₂ was seen declined during 40% and 60% of VO₂ peak with 60% value of decrease was lower (−0.40 μM) than 40% (−1.50 μM). During 80%, an increase by 1.61 μM was seen in ΔHbO₂. As for ACE+FES-LCE (arm), 0.41% decrease of ΔStO₂ was seen during 40% of VO₂ peak and kept on increasing by 1.53% and 5.67% during 60% and 80% of VO₂ peak of exercise, whereas ΔHbO₂ value increased throughout the exercise 2.55, 6.63, and 9.91 μM, respectively. Altogether, ACE showed more decreasing value compared to ACE+FES-LCE (arm) during submaximal exercises. mVO₂ pattern for both ACE and ACE+FES-LCE (arm) showed a nonconsistent pattern with no significant results.

FES-LCE was compared with the leg component of the hybrid exercise, that is, ACE+FES-LCE (leg) for all exercise intensities. FES-LCE showed the same pattern for ΔStO₂ and ΔHbO₂ in which both values initially dropped by 0.29% and 1.42 μM, respectively during 40% of VO₂ peak and as for 60% and 80%, both values of ΔStO₂ and ΔHbO₂ increased steadily; 5.72% to 11.45% and 0.72 to 2.82 μM, which the value significantly increase at 80%. As for ACE+FES-LCE (leg), a steady increase of ΔStO₂ was seen during 40% and 60% of VO₂ peak; 3.78 and

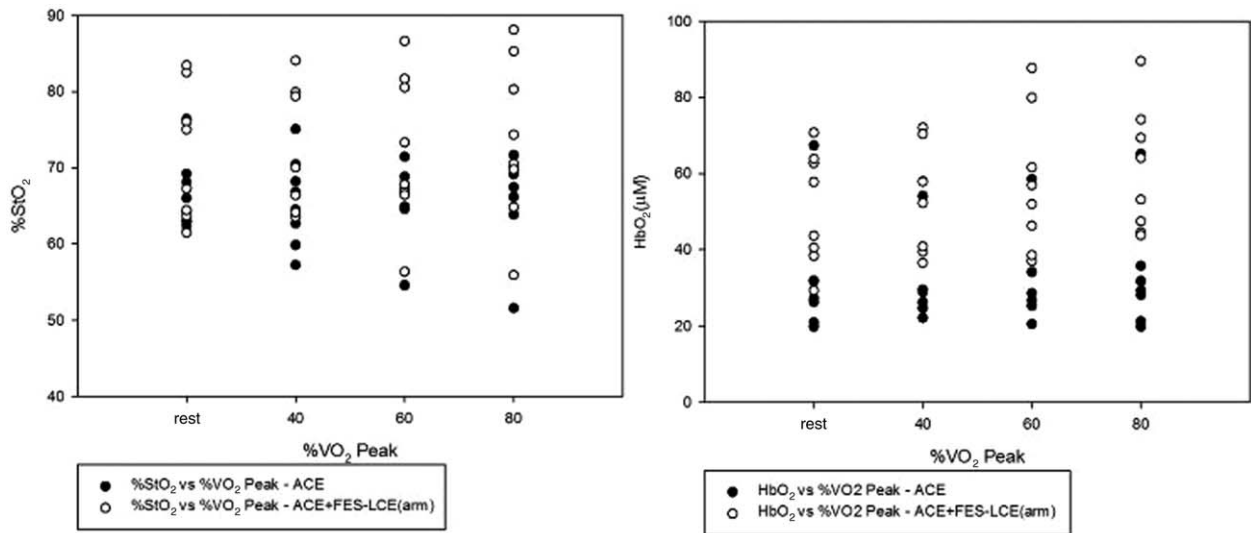


Figure 2. Scatter plot of %StO₂ (left) and HbO₂ (right) for both ACE and ACE+FES-LCE (arm) exercise. ACE+FES-LCE (arm) = hybrid arm exercise, HbO₂ = oxyhemoglobin, StO₂ = muscle oxygen saturation, VO₂ = oxygen uptake.

13.21%, respectively. However, during 80% of VO₂ peak, the ΔStO₂ value dropped to 10.41% but the decrease was not significant. ΔHbO₂ on the other hand portrayed a consistent increase throughout the exercise with 0.71, 2.28, and 2.93 μM for 40%, 60%, and 80% of VO₂ peak, respectively. Overall, ACE+FES-LCE (leg) were at higher values compared to FES-LCE for most of the parameters especially for ΔStO₂ and ΔHbO₂. mVO₂ pattern for both FES-LCE and ACE+FES-LCE (leg) also showed a nonconsistent pattern with no significant results.

4. Discussion

Since the earliest utilization of NIRS in muscle physiology studies during exercise in the mid-1980s, the technique has become

popular for estimation of relative changes in muscle tissue oxygenation.^[13,20] Neurophysiological control of muscle blood flow, muscle oxygen uptake, and tissue oxygen saturation during exercise are titrated by descending adrenergic sympathetic vasoconstrictor stimulation and intrinsic vasodilator control, and the “balance” of these determines StO₂ both at the level of the small blood vessels, capillaries, and at the intracellular sites.^[21] In people with spinal cord lesions (depending upon of their degree of sensorimotor “complete” injury) the descending vasoconstrictor control is attenuated or absent, so local vasodilator factors predominate. Yet how these altered neuro-humoral factors after SCI may lead to an approximately 50% lower muscle metabolic rate in this population or altered StO₂ has only been speculated.^[2,3,15] It is likely that, as in able-bodied

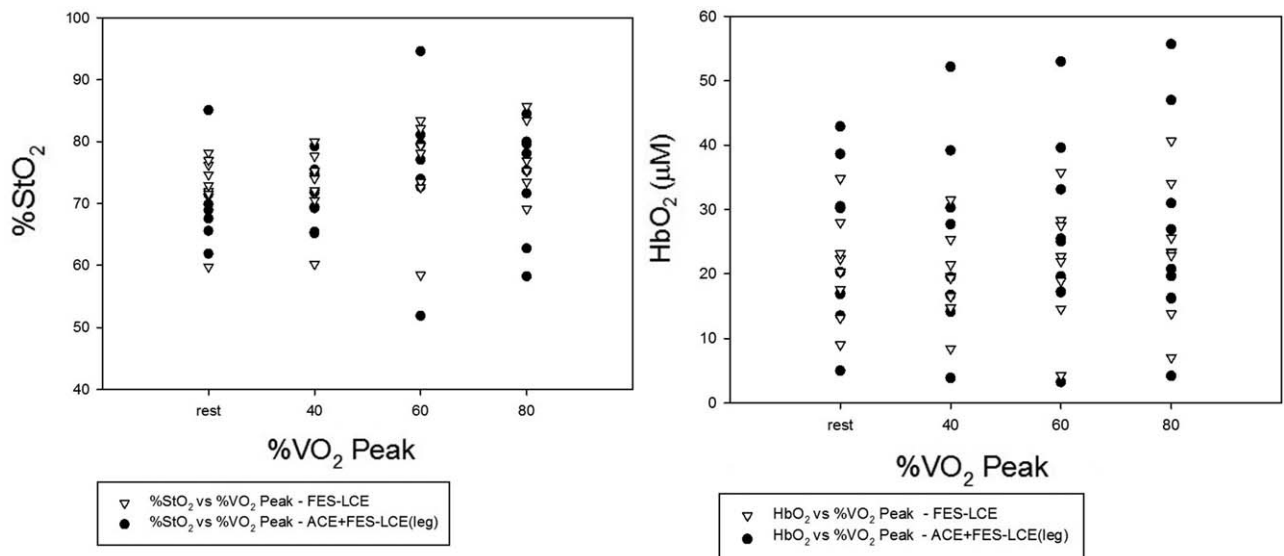


Figure 3. Scatter plot of %StO₂ (left) and HbO₂ (right) for both ACE and ACE+FES-LCE (leg) exercise. ACE+FES-LCE (leg) = hybrid leg exercise, HbO₂ = oxyhemoglobin, StO₂ = muscle oxygen saturation, VO₂ = oxygen uptake.

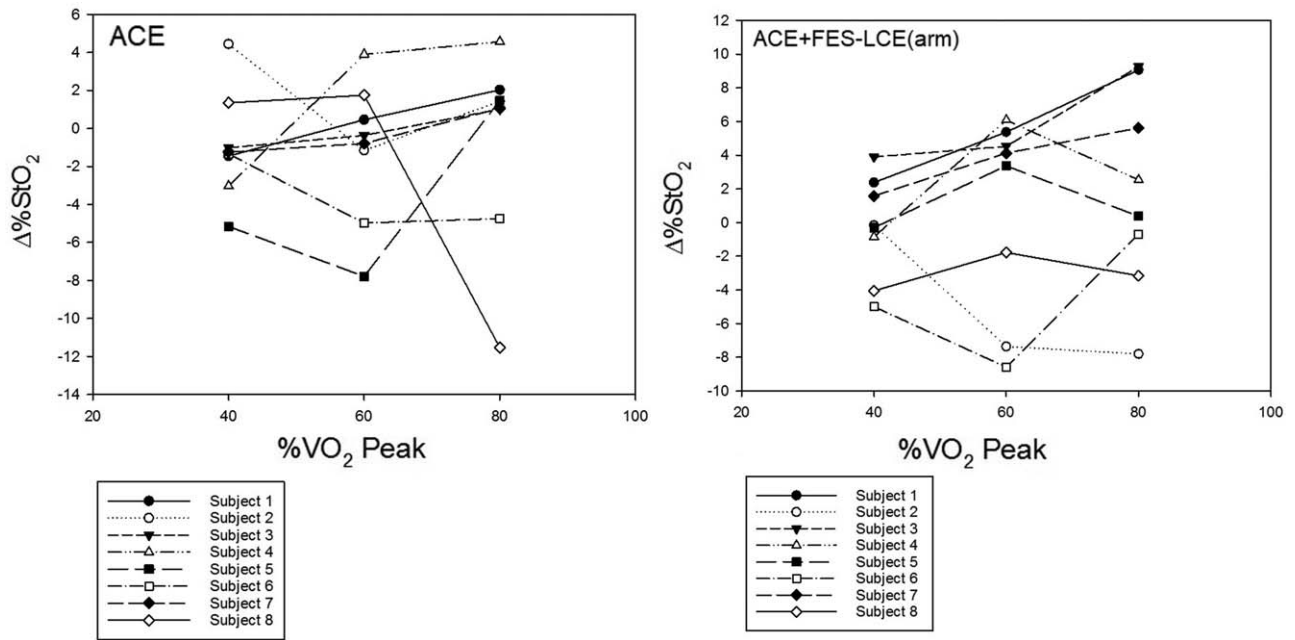


Figure 4. Data of ΔStO_2 for both ACE and ACE+FES-LCE (arm) exercise plotted by subjects. ACE+FES-LCE (arm) = hybrid arm exercise, StO_2 = muscle oxygen saturation, VO_2 = oxygen uptake.

humans in which local vasodilator factors prevail, the same is true in a population with attenuated or absent descending spinal neural command. Thus, any differences in NIRS parameters are largely driven by differences of muscle morphology, histochemistry and humoral adaptations after SCI.^[22] The role of central neurological control during FES-evoked exercise in this population remains unclear.

4.1. ACE versus ACE+FES-LCE (arm)

StO_2 of local tissue is determined by the amount of oxyhemoglobin present in the tissue. In this study, a decrease of StO_2 from rest was observed as a decrease in ΔHbO_2 during submaximal 40% VO_2 ACE by $1.50 \mu\text{M}$. The same pattern was discovered by Muraki et al,^[9] whereby arm cranking showed earlier decrease in oxygen saturation (at 20% of VO_2 peak) compared to leg cycling.

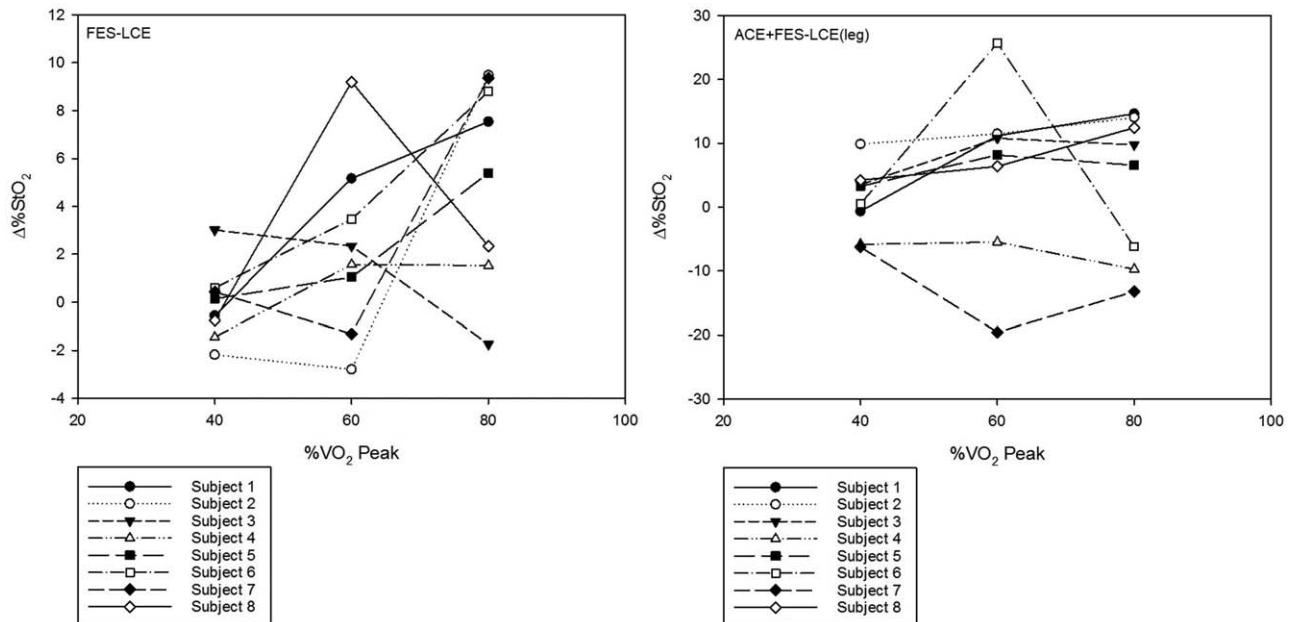


Figure 5. Data of ΔStO_2 for both ACE and ACE+FES-LCE (arm) exercise plotted by subjects. ACE+FES-LCE (arm) = hybrid arm exercise, StO_2 = muscle oxygen saturation, VO_2 = oxygen uptake.

At 40% of VO_2 peak, ACE showed lower value of StO_2 compared to ACE+FES-LCE (arm) because with increasing work, StO_2 tends to decrease below their resting baseline.^[14] In this case, muscle deoxygenation was observed more in ACE compared to ACE+FES-LCE (arm) and this was probably due to a greater need for oxygen release in order to meet the demands of the bicep brachii muscle in ACE.

The greater StO_2 decrease in ACE also may be due to a decrease in the ability of oxygen to bind with hemoglobin caused by a decrease in pH in the blood known as Bohr effect.^[9] Increasing ACE intensity accelerates the production of lactic acid and thus releases hydrogen ions (H^+) into the blood^[23] where the H^+ is buffered by bicarbonate ions which then increased carbon dioxide output. So, the quick decrease in the early state of ACE might not be from metabolic demand from the body, but due to a greater release of oxygen from hemoglobin as part of the metabolic acidosis process.

After decrease in ΔStO_2 at the onset of exercise, the cessation of the decrease from resting state was clearly observed at 60% of VO_2 peak where ΔStO_2 of ACE+FES-LCE (arm) exercise showed a steady increase compared to ACE. ACE on the contrary showed a continuous decrease in ΔStO_2 as exercise intensity increases due to relative poor oxygen uptake compared to ACE+FES-LCE (arm). This explains why the decreasing ΔStO_2 values for ACE. In ACE alone, ΔHbO_2 were seen decreased until 60% of maximal exercise intensity, and increased slightly at 80% maximal exercise intensity while ΔStO_2 decreased. This might suggest that it was due to poor oxygen supply into the bicep brachii muscle with increase in exercise intensities.

Our findings in the arm component of the hybrid exercise showed similarities with findings by Muraki et al^[9] where around 60% of peak exercise intensity, the ΔHbO_2 started to increase and ΔStO_2 in normal subject. These results suggest better oxygen uptake during hybrid exercise compared to ACE alone.

4.2. FES-LCE versus ACE+FES-LCE (leg)

Throughout the exercise duration and increasing exercise intensities, increase in ΔHbO_2 was observed in both cases. At the onset of FES-LCE, the ΔHbO_2 showed a decreased by $1.4 \mu M$ from rest, but following that kept on increasing with increasing exercise intensity. On the contrary, ACE+FES-LCE (leg) showed a consistent increase of ΔHbO_2 throughout the exercise duration. The decrease in FES-LCE is may be due to an initial poor blood flow in the muscles.

In FES-LCE, value of ΔHbO_2 was at lower values than ACE +FES-LCE (leg) across all exercise intensities. This may be due to insufficient oxygen supply secondary to poor blood flow, in which Davis et al^[24] had concluded in their findings that the lower oxygen saturation observed in FES-LCE suggested that there was inadequate oxygen supply to the muscle during exercise.

An increase in ΔHbO_2 during exercise also was observed in previous study in which the response might imply an increased supply of oxygen and other nutrients to the exercising muscle. FES-LCE displayed a gradual steady increment of ΔStO_2 during all the submaximal exercise intensities except a small drop during exercise increment from 40% to 60% of VO_2 peak. However, the drop is not statistically significant. As ΔStO_2 increases, this showed that ACE+FES-LCE (leg) has better aerobic gains compared to FES-LCE alone during exercise. In order to reduce the risk of cardiovascular disease in SCI population, exercise that can improve leg muscle's aerobic capacity such as ACE+FES-LCE exercise will be very helpful for SCI patients.

There are some limitations in this study in which all subjects were 8 male subjects around the age of 40 years. In the future, the outcome might be extended to other age groups and female patients as well. Previous studies have investigated muscle oxygenation on both men and women and concluded that muscle oxygenation observed was not significant and was independent of sex.^[25-28] These studies also required regular FES users to be recruited as subjects and therefore, we had limited sample. This could have been overcome by recruiting novice FES users and putting them on habituation program before the study.

Overall, ACE+FES-LCE exercise showed higher ΔStO_2 and ΔHbO_2 value compared to ACE and FES-LCE alone. Better cardiovascular output improves oxygenation to muscle for ACE +FES-LCE exercise. It provides many other benefits such as activation of more muscle mass. This might be due to the larger muscle mass involvement with the addition of FES-LCE to the ACE. This study suggested that especially in SCI population, ACE alone might be not as effective as lower limb exercise due to the smaller muscle in the upper limbs. Therefore, ACE+FES-LCE exercise which combines ACE and FES-LCE in paralyzed SCI population has shown a significantly higher peak oxygen uptake, heart rate, cardiac output, and stroke volume than ACE or FES-LCE alone.^[29-32] Bakkum et al^[33] also expected ACE+FES-LCE to be more effective in avoiding secondary health problems (e.g., osteoporosis and cardiovascular disease) as well as to increase physical fitness.^[34]

In conclusion, this study demonstrated better oxygenation by the muscles during submaximal exercise intensities of ACE +FES-LCE, that is, ACE+FES-LCE (arm) and ACE+FES-LCE (leg) exercise compared to just ACE or FES-LCE alone, demonstrated by higher values of ΔStO_2 and ΔHbO_2 during ACE+FES-LCE exercise. These findings suggest that combined arm and leg training may lead to increased gains in muscle oxygenation compared to arm or leg exercise training alone. As this study provides information regarding muscle capacity, endurance, and fatigue during exercise, it can contribute in increase of understanding in rehabilitation and exercise program in SCI.

Author contributions

Conceptualization: Nazirah Hasnan, Nur Azah Hamzaid.

Data curation: Nazirah Hasnan, Nurul Salwani Mohamad Saadon, Mira Xiao-Hui Teoh, Sirous Ahmadi.

Formal analysis: Nazirah Hasnan, Nurul Salwani Mohamad Saadon, Mira Xiao-Hui Teoh, Sirous Ahmadi, Glen M. Davis.

Funding acquisition: Nazirah Hasnan, Nur Azah Hamzaid, Glen M. Davis.

Investigation: Nazirah Hasnan, Nur Azah Hamzaid.

Methodology: Nazirah Hasnan, Nur Azah Hamzaid, Glen M. Davis.

Project administration: Nazirah Hasnan.

Resources: Nazirah Hasnan.

Software: Nazirah Hasnan.

Supervision: Glen M. Davis.

Validation: Nazirah Hasnan, Sirous Ahmadi, Glen M. Davis.

Visualization: Nazirah Hasnan, Glen M. Davis.

Writing – original draft: Nazirah Hasnan, Nurul Salwani Mohamad Saadon, Nur Azah Hamzaid, Mira Xiao-Hui Teoh, Glen M. Davis.

Writing – review and editing: Nazirah Hasnan, Nurul Salwani Mohamad Saadon, Nur Azah Hamzaid, Mira Xiao-Hui Teoh, Glen M. Davis.

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