Quadriceps oxygenation during steady state FES-rowing in persons with spinal cord injury

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Abstract

Functional electrical stimulation (FES) rowing is an effective and well-tolerated type of cardiovascular exercise for persons with spinal cord injury (SCI). However optimal health and fitness benefits can only be achieved if the exercise time is sufficient. Due to the consequences of paralysis and the nature of surface FES, muscular fatigue is a common problem in electrically stimulated muscles, which restricts exercise time. One of the possible underlying reasons for this fatigue is inadequate muscle perfusion and oxygenation.

Muscle oxygenation was monitored in the rectus femoris by near-infrared spectroscopy in five SCI volunteers during 10 min of steady state FES-rowing. The results show that muscle deoxygenation reached a steady state in the FES-rowers and in two rowers oxygenated haemaglobin and total haemaglobin even increased. Furthermore, long-term follow data in one subject showed that the ability to reach a steady state in perfusion during FES-rowing was correlated with fatigue resistence.

The results suggest that muscle perfusion is a limiting but trainable factor for persons with SCI involved in FES-exercise.

1 Introduction

Persons with spinal cord injury (SCI) can benefit greatly from functional electrical stimulation (FES) exercise since it reduces the load on the upper body musculature and increases the amount of active muscle mass. This results in a high intensity exercise modality that avoids or decreases repetitive stress on the upper body as seen during wheelchair exercise. However optimal health and fitness benefits can only be expected if the exercise time is sufficient. This can be problematic in FES-exercise since paralysed muscles have a low fatigue resistance [1]. Muscular fatigue in this context is defined as a significant drop in power generation in the muscle resulting in an inability to continue the exercise (e.g. cycling or rowing). Although long-term training has shown to result in more fatigue resistant muscle fibres, in our experience muscular fatigue remains one of the main reasons to stop an FES-exercise session, especially in novice users. One of the possible reasons for this fatigue is inadequate muscle perfusion and oxygenation [1].

Electrically stimulating muscles is different from the normal activation pattern in the sense that all fibres are activated simultaneously instead of a more selective and gradual activation pattern. This massive fiber contraction results in muscle ischemia, which may contribute to fatigue.

Secondly, it has been reported that paralyzed muscles have a higher proportion of Type II fibers, a reduced capillary capacity and a lower mitochondrial density. All these factors contribute negatively to muscle oxygenation and subsequently muscle ischemia might explain the early onset of muscular fatigue.

Bhambhani *et al*. reported in SCI FES-cyclists a rapid decrease in oxygenation of the vastus lateralis at the onset of the exercise followed by a steady state at levels below the resting value [2]. In FES-rowing this might be more pronounced since the power output of the leg muscles determines the overall exercise intensity (if the knees buckle due to insufficient leg strength, the rowing cycle cannot be completed). However at the present no data is available on muscle oxygenation during FES-rowing in SCI and it is subsequently unknown how this relates to muscular fatigue.

2 Methods

Five SCI volunteers participated in steady state FES-rowing tests. All participants had been using the FES-rowing machine for at least 6 months (2-3 sessions per week) and in addition all had performed leg strengthening exercise for at least 6 months (2-3 sessions per week). One volunteer (participant 1) also completed a FES-rowing test in the early stages of his FES-rowing training period.

Table 1: Subject characteristics.

	1	2	3	4	5
Sex	M	M	M	M	F
Age (yrs)	52	23	46	37	25
Level of lesion	T4	T12	T2/3	T6	C5/6
ASIA	A	A	A	A	C
Time since injury (yrs)	6	2	9	8	12
Power output during FES-rowing (W)	55	50	38	57	9

All participants used an adapted Concept 2 rowing ergometer that was fitted with leg stabilisers and a special seat with back rest and straps to provide adequate postural support. The leg action during FES-rowing was achieved by surface stimulation of the quadriceps and hamstrings muscles. An ODS 4-channel stimulator (Odstock Medical, Salisbury UK), controlled by a switch mounted on the handle bar of the rowing machine, delivered 50Hz, 250 ms unramped stimulation.
Muscle oxygenation was monitored by near-infrared spectroscopy (NIRS). This technique is based on the different absorption properties of haemaglobin and myoglobin in the near-infrared spectrum. This allows for monitoring of oxygenated haemaglobin [HbO_2] and reduced haemaglobin [Hb], as well as total haemaglobin [Hbt]. The latter can be used to estimate blood flow in the muscle.
For these experiments a Hamamatsu NIRO500 system was used. The laser probe was placed on the (shaven and cleaned) skin over the rectus femoris at approximately half-way between the knee joint and the hip. The signal from the NIRO system was converted by a Mico 1401 (CED, Cambridge UK) and imported into Spike software (CED, Cambridge UK). Sample frequency was 2 Hz.
Participant 1 completed a NIRS test after approximately 3 months of FES-rowing training. At that stage muscle fatigue prevented him from continuously FES-rowing and he conducted intervals of 30s of FES-rowing followed by 30s of arms only rowing. All five participants conducted the test consisting of 3 min of rest, followed by 10 min of FES-rowing at a self-chosen steady state intensity (see Table 1). After the FES-rowing interval a 3 min rest period was included.

3 Results

Figures 1-6 are the NIRS graphs for all completed tests. Each graph consists of three lines. The top line is [Hbt], the middle line is [HbO_2] and the bottom line is [Hb].

Figure 1 shows the FES-rowing session of subject 1 in the initial phases of his FES-rowing training. The area between the two vertical lines is the first 30 seconds of FES-rowing, followed by 30 seconds of arms only rowing, etc.

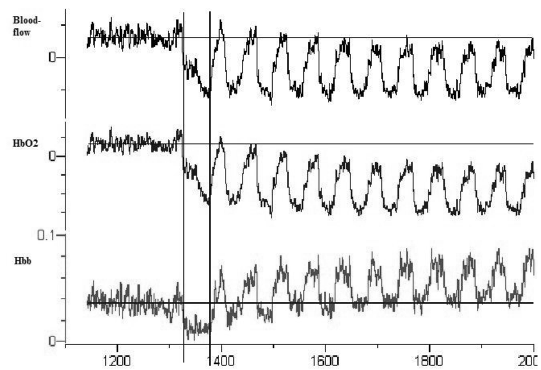

Figure 1: NIRS data of participant 1 during steady state FES-rowing in initial stages of FES-rowing training.

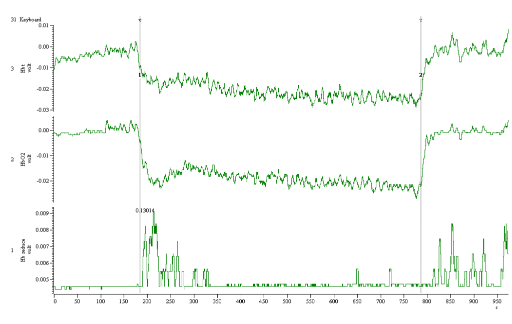

Figure 2: NIRS data of participant 1 during 10 minutes of steady state rowing in advanced stages of FES-rowing training.

Figures 2-6 are NIRS data from participants 1-5 during 10 minutes of steady state FES-rowing.

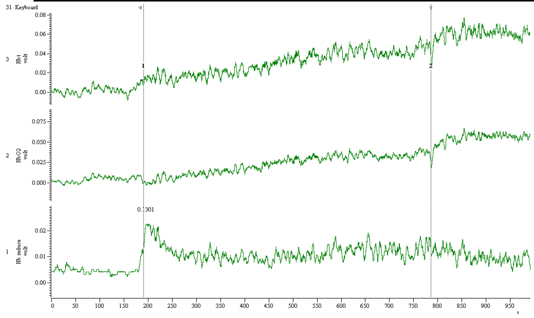

Figure 3: NIRS data of participant 2 during 10 minutes of steady state FES-rowing.

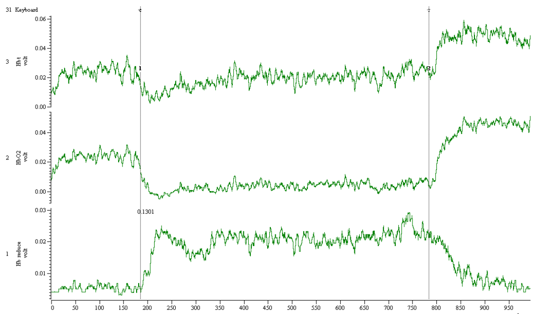

Figure 4: NIRS data of participant 3 during 10 minutes of steady state FES-rowing.

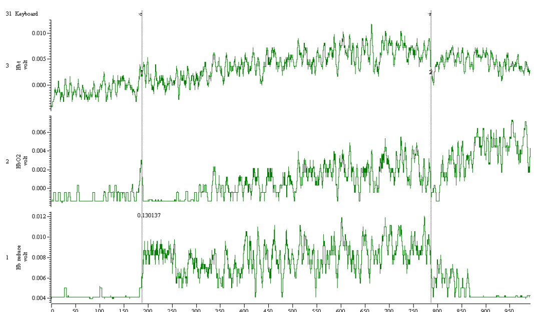

Figure 5: NIRS data of participant 4 during 10 minutes of steady state FES-rowing.

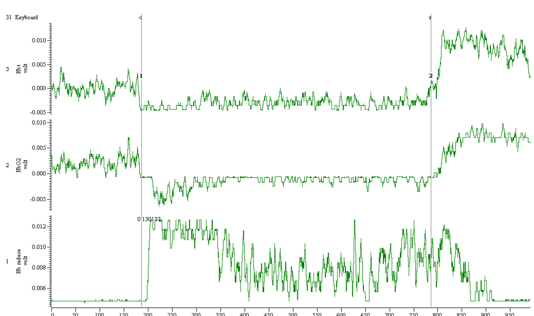

Figure 6: NIRS data of participant 5 during 10 minutes of steady state FES-rowing.

4 Discussion and Conclusions

The NIRS results in five SCI FES-rowers showed two different responses (Fig 2-6). In two subjects (Fig 3 and 5) a hyperaemic response was seen (i.e. increases in [HbO_2], [Hbt] and [Hb] during FES-rowing). In the other three FES-rowers (Fig 2, 4 and 6) and 5) [Hbt] and [HbO_2] decreased and [Hb] increased. An increase in [Hbt] and [HbO_2] during exercise is a preferred response as this implies an increased supply of O2 and other nutrients to the exercising muscle. The other three participants showed a decrease in [Hbt] and [HbO_2] although a steady state was achieved within minutes of starting the exercise. This is in contrast to the results of participant 1 in the early phases of his FES-rowing training (Fig 1), when no steady state in any of the Hb parameters could be achieved. Even although the arms only rowing intervals results in a recovery of [HbO_2], [Hb] and [Hbt], during the session there was a gradual increase in [Hb] and decrease in [HbO_2] and [Hbt]. After long-term FES-rowing training, participant 1 was able to complete 10 min of continuous FES-rowing and the NIRS data show a rapid decrease in [HbO_2] and [Hbt] and increase in [Hb], but all three reached a steady state within minutes. All participants displayed a hyperaemic response after the exercise bout, although the current study only measured up to 3 minutes after the exercise. A more long-term carry over effect would be of value for persons with SCI who often have impaired circulation in the lower extremities.

Although further research is needed, the results suggest that muscle oxygenation is related to muscular fatigue in FES-rowing. Experienced FES users showed a steady state in muscle oxygenation while a novice FES-rower could not achieve such a steady state. However long-term FES-rowing training resulted in improved fatigue resistance and muscle oxygenation.

References

[1] Mizrahi J. Fatigue in muscles activated by functional electrical stimulation. Crit Rev Phys Rehabil Med, 9: 93-129, 1997.

[2] Bhambhani Y, Tuchak C, Burnham R, et al. Quadriceps muscle deoxygenation during fundtional electrical stimulation in adults with spinal cord injury. Spinal Cord, 38: 630-8, 2000.

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