Mechanomyography responses characterize altered muscle function during electrical stimulation-evoked cycling in individuals with spinal cord injury

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\textbf{ABSTRACT}

\textbf{Background:} Investigation of muscle fatigue during functional electrical stimulation (FES)-evoked exercise in individuals with spinal cord injury using dynamometry has limited capability to characterize the fatigue state of individual muscles. Mechanomyography has the potential to represent the state of muscle function at the muscle level. This study sought to investigate surface mechanomyographic responses evoked from quadriceps muscles during FES-cycling, and to quantify its changes between pre- and post-fatiguing conditions in individuals with spinal cord injury.

\textbf{Methods:} Six individuals with chronic motor-complete spinal cord injury performed 30-min of sustained FES-leg cycling exercise on two days to induce muscle fatigue. Each participant performed maximum FES-evoked isometric knee extensions before and after the 30-min cycling to determine pre- and post-extension peak torque concomitant with mechanomyography changes.

\textbf{Findings:} Similar to extension peak torque, normalized root mean squared (RMS) and mean power frequency (MPF) of the mechanomyography signal significantly differed in muscle activities between pre- and post-FES-cycling for each quadriceps muscle (extension peak torque up to 69%; RMS up to 80%, and MPF up to 19%). Mechanomyographic-RMS showed significant reduction during cycling with acceptable between-days consistency (intra-class correlation coefficients, ICC = 0.51–0.91). The normalized MPF showed a weak association with FES-cycling duration (ICC = 0.08–0.23). During FES-cycling, the mechanomyographic-RMS revealed greater fatigue rate for rectus femoris and greater fatigue resistance for vastus medialis in spinal cord injured individuals.

\textbf{Interpretation:} Mechanomyographic-RMS may be a useful tool for examining real time muscle function of specific muscles during FES-evoked cycling in individuals with spinal cord injury.

\section{1. Introduction}

Functional electrical stimulation (FES)-evoked cycling, has reportedly improved muscle fibre histochemical adaptations and increased muscle strength (Ferrante et al., 2008; Mayson and Harris, 2014; Sabut et al., 2011). FES cycle training, when purposely embedded into rehabilitation interventions, led to improved fatigue resistance of human muscles (Decker et al., 2010; Haapala et al., 2008; Thrasher et al., 2013). However, rapid onset of muscle fatigue during FES exercise often limits its clinical benefits, because neuromuscular fatigue occurs earlier and more rapidly during FES-evoked contractions in paralyzed or paretic muscles compared to normally-innervated tissues (Binder-Macleod et al., 1995). In clinical practice, muscle fatigue can be assessed during FES-cycling as a reduction of power output over time, often counteracted by user real-time modulation of current amplitude or other neuromuscular stimulation parameters to minimize negative fatigue effects (Pincivero et al., 2001). The development of physical sensors and signal quantification software to monitor real-time fatigue at the muscle level would improve the deployment of FES systems for practical use by allowing the patient to regulate neuromuscular stimulus parameters and maintain the quality of a physical activity by reducing fatigue-related negative sequelae (Haapala et al., 2008). This would be useful both for “closed-loop” medical devices requiring real-time feedback, as well as “open-loop” systems requiring muscle status.

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monitoring. To date, fatigue assessment during FES-cycling remains poorly documented (Estigoni et al., 2011; Haapala et al., 2008).

Prior research studies have investigated muscle fatigue during FES-cycling by quantifying cycling duration or cadence, as both of these exercise parameters correlate negatively with increased muscle fatigue (Chen and Yu, 1997; Fornusek and Davis, 2004). In addition, peak torque and pedal power output have also been used as proxies of muscle fatigue during FES-cycling. However, these collectively reflect the forces from a group of muscles that are recruited during cycling, and they are influenced by the knee and ankle angular positions (Haapala et al., 2008; Szecsi et al., 2014). As such, they do not directly reflect muscle forces associated with fatigue of individual muscles within a muscle group. Surface electromyography (sEMG) has been used to characterize fatigue from individual muscles by evaluating motor unit recruitment and firing patterns, such as root mean square (RMS), M-wave amplitude and mean power frequency (MPF) of the evoked EMG signal during FES (Faller et al., 2009; Gobbo et al., 2014). While sEMG has been reported to characterize the quality of FES-evoked muscle contractions (Estigoni et al., 2014; Ibitoye et al., 2014a), its characteristics are highly susceptible to electrical stimulation artefacts. These artefacts lead to sEMG signal amplifier saturation, and while post-processing can eliminate these artefacts, the sEMG has limited use for real-time FES training (Faller et al., 2009; Haapala et al., 2008).

Therefore, researchers have explored alternative means of muscle fatigue measurement during FES exercise. One promising strategy for assessing muscle fatigue during FES-evoked movements is based on the relationship between the muscle’s myographic signal and its contraction time, but this fundamental relationship has not received much research attention to date (Estigoni et al., 2011; Gonzalez-Izal et al., 2010a). Mechanomyography (MMG) is a mechanical alternative approach to sEMG for assessing muscle function (Gé et al., 2015; Islam et al., 2013a; Orizio, 1993). It is well documented that the RMS and MPF of MMG signals are both associated with the contractile properties of muscles during voluntary isometric and dynamic contractions (Beck et al., 2005; Islam et al., 2013b). Several previous studies (Faller et al., 2009; Gobbo et al., 2006; Yoshitake et al., 2002) have also used these MMG signal parameters to investigate muscle fatigue during involuntary contractions. However, only a limited number of such investigations have used MMG to quantify muscle fatigue during electrically-induced muscle contractions. All of these studies were performed under isometric exercise conditions in healthy humans, and they collectively concluded that MMG amplitude was a reliable tool for muscle fatigue assessment. Nevertheless, muscle fatigue in individuals with SCI as assessed by MMG during electrically-evoked dynamic exercise (e.g. FES-cycling) remains under-investigated (Ibitoye et al., 2014b; Ibitoye et al., 2014c).

The aims of this study were: i) to investigate changes in MMG responses evoked from the quadriceps muscle group comprising rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) in individuals with chronic motor-complete SCI during FES-cycling; and, ii) to quantify changes in quadriceps muscles’ MMG signals between pre- and post-fatiguing conditions. We hypothesized that the MMG might be a reliable proxy for examining muscle function during FES-evoked isometric and cycling exercises, because it is associated with muscle force output during FES-evoked isometric contraction at different knee angles in SCI individuals with high between days test-retest reliability (Ibitoye et al., 2016) and is immune to electrical stimulation artefacts during exercise (Beck et al., 2006; Orizio, 1993). In addition, as sustained FES-cycling is known to induce accelerated muscle fatigue (Agarwal et al., 2003) and the MMG signal shows decrements during sustained contractions (Orizio et al., 1989), there might be an association between FES-cycle time and MMG signal parameters.

2. Methods
2.1. Participants
Six volunteers (five males and one female) with motor-complete chronic SCI participated in this study. Their physical characteristics and clinical data are shown in Table 1. All underwent 2–3 sessions per week of FES-cycle training for muscle strength and conditioning for at least four weeks prior to participating in this study. After oral briefing and provision of written information concerning the study procedures, they gave their written informed consent to participate, and these procedures had been approved by the University Malaya Medical Centre Medical Ethics Committee, University of Malaya Medical Center (Approval No: 1003.14 (1)).

2.2. Study design
The study comprised three phases, as portrayed in Fig. 1. In the first phase, each participant underwent three trials of FES-elicted peak isometric knee extension to quantify the highest evoked peak torque (ePT) and MMG parameters of the quadriceps muscle group. These were collected at baseline [PRE] conditions. Next, each participant performed 30-min of FES-leg cycling exercise [FES-LCE] at a sufficient per-subject exercise intensity so as to induce significant muscle fatigue. In the final phase [POST], FES-elicted peak isometric knee extensions to elicit the ePT and MMG were repeated, but with a shorter inter-trial recovery period. In addition, MMG signals during the 30-min FES-cycling phase were collected to document fatigue responses of the quadriceps muscle group. Each participant underwent duplicate sessions of the study design, with a minimum of 48 h between sessions for the purpose of establishing day-to-day consistency of responses in this small sample population.

2.3. Peak evoked isometric torque
Participants were comfortably seated on a dynamometer chair (System 4; Biodex Medical System, Shirley, NY, USA) with a hip angle of approximately 90 deg and 60 deg knee angle, to assess ePT. During PRE, three trials of peak evoked isometric knee extension were developed over 4 s for each trial, separated by 5-min of inactive recovery. A further 15-min recovery period was allowed to obtain sufficient muscle recovery to reduce risk of overuse and thus produce maximum muscle

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<td>Physical characteristics and SCI-related data of the participants.</td>
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* A – complete SCI (motor and sensory); B – incomplete SCI (motor complete, sensory sparing); ASIA – American Spinal Injury Association (Kirsblum et al., 2011).
effort during FES-cycling. Following the recovery period participants performed 30-min of FES-LCE session, and then each participant repeated three trials of peak isometric knee extension developed over 4 s, but separated by 1-min of recovery period between trials (Fig. 1). During POST, a small (1-min) recovery period was deployed between trials, because previous pilot research had indicated significant recovery of post-fatigue muscle forces did not adequately characterize the post-fatigue state. For the three trials during PRE and POST, the mean score of ePT was used to characterize the highest muscle torque during each phase. If the ePT differed by more than the 5% between trials, an additional trial was undertaken. To maintain consistency between PRE and POST-cycling data, the positions of dynamometer chair were marked, documented and used in the subsequent trials and phases.

For neuromuscular stimulation during the PRE and POST phases, two 9 cm × 15 cm self-adhesive skin surface electrodes (RehaTrode, HASOMED, Germany) were affixed above and below the belly of the quadriceps muscle. The distal electrode was placed 6–8 cm proximally to the patellar border and the proximal electrode was placed approximately 1/3 of the distance between the inguinal line and the superior patellar border and slightly lateral to the muscle center line to provide stimulation coverage over the muscle bellies of VL, RF, and VM (Haapala et al., 2008; Szecsi et al., 2014). Neuromuscular stimulation was delivered at a constant frequency of 30 Hz and a biphasic pulse width of 400 μs to elicit tetanic muscle contractions. The stimulation current amplitude (range: 90–120 mA) was individually selected so that each participant reached their maximum knee extension torque that was determined via dynamometer.

2.4. FES-leg cycling exercise [FES-LCE]

All participants performed 30-min of sustained FES-LCE at a constant resistance (8/10 units of MOTOmed cycle) and a cadence of 50 rev-min⁻¹. The FES-cycling system comprised of six channels of neuromuscular stimulation (Rehasimp II, Haomed GmbH, Magdeburg, Germany) and motor-resisted cycling trainer (MOTOmed Viva 2, RECK-Medizintechnik GmbH, Betzenweiler, Germany). The feet and legs of each participant were strapped firmly and held in position by ankle-calf supports. The wheelchair was anchored firmly with the cycling system during FES-LCE.

During FES-cycling, surface stimulating electrodes were bilaterally affixed over the quadriceps and the hamstring muscles. The placement of electrodes for the quadriceps muscles was similar to that used for the peak isometric contraction. The electrode placements over the hamstring muscles were adapted from a previous study (Haapala et al., 2008) as follows: the distal electrode was placed approximately 6 cm above the superior crease of the posterior aspect of the knee joint and the proximal electrode a distance of 10 cm above the crease. The neuromuscular stimulation parameters were biphasic rectangular pulses at a frequency of 30 Hz and a pulse width of 300 μs. Stimulation intensity ranged between 60 and 120 mA for quadriceps and 58 and 90 mA for hamstrings muscle groups adjusted for each participant to maximize initial cycling power output. The stimulation intensity was gradually increased bilaterally to perform FES-cycling with a target cadence mentioned above. This was set at the beginning and remained constant for the 30-min cycling phase.

2.5. MMG setup

Three MMG sensors (Sonostics VMG BPS II Transducer, operational frequency response = 20–200 Hz, sensitivity 50 V/g) were placed over the bellies of the VL, RF, and VM muscles using double sided adhesive tape. Quadriceps muscles were elicited during FES-evoked isometric contraction to identify the bulky position of each muscle, of which the center position was used to place the MMG sensor and maintained the position for FES-evoked cycling exercise. For VL muscle, the sensor was placed at approximately 66% of the distance from the anterior-superior iliac spine to the lateral border of the patella. For RF, the sensor was placed at approximately 50% of the distance from the anterior superior iliac spine to the superior aspect of the patella. For VM, the sensor was placed at 70–80% (based on subject’s muscle belly elicited by the stimulation) of the distance from the anterior superior iliac spine to the medial border of the patella. The greatest thickening of the VM muscle belly was determined through a FES-evoked isometric contraction. The placements of the MMG sensors over the muscle groups remained unchanged, performed and/or monitored by the same investigator(s), amongst the trials in each testing day, and between PRE and POST phases to provide consistency of MMG signals.

2.6. Data acquisition and processing

The raw data of each MMG sensor during isometric muscle contractions and the output of ePT from the dynamometer were recorded at a sampling rate of 2 kHz and 100 Hz, respectively. These data were synchronously recorded and stored. Additionally, the output of each MMG sensor during FES-LCE was recorded at a sampling rate of 2 kHz and the data stored for the entire 30-min cycling period for later analysis of muscle fatigue during exercise. The acquisition unit (BP150 and HLTI00C, BIOPAC System Inc., USA) and software (AcqKnowledge 4.3.1, BIOPAC System Inc., USA) were used in both cases to record and store the raw data on a computer for off-line analyses.

The raw data detected by the sensors were digitally bandpass-filtered (fourth-order Butterworth) at 20–200 Hz to obtain the MMG signals for RMS in the time domain and MPF in the frequency domain. The lower cut-off of the MMG signal was set so that movement and other low frequency artefacts could be filtered out (De Luca et al., 2010) and the higher cut-off of the MMG signal was set to capture greater ‘signal density’ from fast firing motor unit fibres, which are in much higher proportion in muscles of chronic SCI individuals (Burnham et al., 1997; Higashino et al., 2013). All signal processing was performed with custom programs written in LabVIEW programming software (Version 12.0, National Instruments, Austin, TX, USA).
2.7. Data analysis

The MMG signals and ePT of the two isometric conditions (PRE and POST phases on each day) were extracted for 2 s corresponding to the middle of each 4 s isometric trial to produce the RMS and MPF. MMG signals (RMS and MPF) and ePT during PRE were normalized to their respective peak values considering all the participants and trials and during POST condition these signals were normalized to their respective peak values of the PRE condition. The MMG signals during FES-cycling were partitioned into six consecutive 5-min of cycling epochs. A middle 10 s of each 5-min epoch was extracted to determine the MMG RMS and MPF for later analysis. In addition, the first and last 10 s of the entire 30-min of FES-LCE were also included for analysis to represent early and final response of the muscles. For each of these data segments, the RMS and MPF were normalized to their respective peak values obtained at PRE condition.

2.8. Statistical analysis

Linear regression was performed between FES-cycling time and normalized MMG signals to determine the degree of association between them, and this was the criterion to investigate fatigue-state of the quadriceps muscle group during FES-LCE. This analysis was based on previous studies that had employed linear regression to estimate measures of muscle fatigue during dynamic contractions (Gonzalez-Izal et al., 2010a; Gonzalez-Izal et al., 2010b). Due to the heterogeneous characteristics of the participants, such as sex, age, weight, level and year of injury that might influence FES-cycling fatigue differently between the muscles, we performed participant basis regression analysis between MMG signal and FES-cycling duration. Note that the prolonged phenomenon was investigated to determine if there was any decrease of MMG signal intensity during the 30-min FES-LCE exercise. Additionally, the slope and intercept indices of the MMG-time regression analysis were used for repeated measures one-way ANOVA analyses with LSD post-hoc tests to quantify the fatigue rate of the quadriceps muscle group. According to the Cohen’s interpretation for behavioral science (< 0.14 is poor, between 0.14 and 0.36 is fair, between 0.37 and 0.50 is medium and > 0.51 is large), the regression correlation was determined (Cohen, 1988). Paired t-tests between PRE and POST FES-cycling phases were performed to determine fatigue using the MMG signals. The two-way mixed mode intraclass correlation consistency (ICC) test of the MMG signal and ePT between Day 1 and Day 2 were performed. The between days ICC categories were defined according to the Cicchetti’s interpretation of consistency correlation (< 0.4 is poor, between 0.4 and 0.59 is fair, between 0.6 and 0.74 is good and > 0.75 is high) (Cicchetti, 1994). All statistical analysis was performed using SPSS software (IBM SPSS Statistics, version 20, New York, USA). Statistical significance was determined at an alpha of 0.05 (p < 0.05).

3. Results

MMG RMS was sensitive to fatigue-induced changes of both static and dynamic FES-evoked exercise conditions similar to ePT. The knee extension normalized ePT of POST condition revealed significantly smaller values compared to the PRE condition for the duplicate Day 1 (by 64%) and Day 2 (by 69%) assessments (Fig. 2). Similar to ePT, normalized RMS and MPF of MMG signal decreased significantly between PRE and POST conditions for all the muscles in both days (p < 0.05).

The normalized MMG RMS of post-fatigued muscles decreased significantly from their pre-fatigued state for all muscle groups both Day 1 and Day 2 repeated assessments with VL by 63% on Day 1; by 46% on Day 2, RF by 80% on Day 1; by 60% on Day 2, and VM by 50% on Day 1; by 65% on Day 2 (p < 0.05 for all three muscles; Fig. 2). In addition, the MMG MPF after fatigue decreased significantly from the pre-fatigue condition for VL (by 13% on Day 1; by 14% on Day 2), RF (by 8% on Day 1; by 19% on Day 2), and VM (by 7% on Day 1; by 8% on Day 2) muscle groups. This fatigue measure was further validated by examining the relationship between changes in ePT and changes in MMG RMS and MPF between PRE and POST conditions. There were moderate to strong linear relationships between changes in ePT and changes in MMG RMS between PRE and POST conditions on both days for the three muscles within the quadriceps group with R2 between 0.24 and 0.68 (VM: 0.34 Day 1, 0.44 Day 2; VL: 0.68 Day 1, 0.24 Day 2; RF: 0.39 Day 1, 0.23 Day 2; all p < 0.05). The linear relationships of changes in MMG MPF and ePT between PRE and POST conditions were moderate to strong on Day 1 for all the muscles with R2 from 0.24 to 0.70. However, this relationship was poor on Day 2 for VL (R2 = 0.11) and VM muscles (R2 = 0.11) (Supplementary 1 and 2).

Fatigue analysis during FES-LCE presented changes in MMG signals as a function of FES-cycling time for VL, RF, and VM muscles on Day 1 and Day 2 repeated assessments. Moderate to high consistency observed between days in case of MMG RMS for VL (ICC = 0.45–0.76), RF (ICC = 0.71–0.84), and VM (ICC = 0.69–0.91) muscles were reported and hence the data for each participant between Day 1 and Day 2 were pooled to perform the regression analyses between the MMG RMS and FES-cycle time. Fig. 3 shows that the MMG RMS decreased significantly over time of FES-cycling for all the muscles (p < 0.05). In addition, repeated measures one-way ANOVA was performed on slope and intercept indices of each muscle to determine the fatigue rate during FES-cycling. There was a significant difference in fatigue rate (slope and intercept) for the VL, RF, and VM muscles (p < 0.05, Fig. 4). LSD post-hoc tests in the VL, VM, and RF muscles further confirmed that the RF muscle revealed significantly greater slope, implying faster fatigue rate, followed by the VL and VM muscles. The intercept of VM muscle was
significantly smaller than the VL and RF muscles. Although there was no significant difference between intercepts of RF and VL muscles (p = 0.061), the overall effect size of the significance was 52%, a high difference.

In contrast to the MMG RMS findings, there were poor consistency observed between days for MMG MPF during FES-cycling for VL (ICC = 0.09–0.13), RF (ICC = 0.08–0.09) and VM (ICC = 0.13–0.23) and hence the data for each participant were used separately for Day 1 and Day 2 repeated assessments to perform the regression analyses between the MMG MPF and FES-cycle time. In almost all cases, there was poor relationship (i.e. “flat” or unchanging MPF-time slope indices) between the MMG MPF and FES-cycle time on both Day 1 and Day 2 (Supplementary 3 & 4).

4. Discussion

The present study was undertaken to examine whether MMG signals (RMS in time domain and MPF in the frequency domain) derived from VL, RF, and VM of the quadriceps muscle group changed during FES-cycling induced fatiguing conditions in SCI participants. In addition, the MMG signals between pre- and post-fatiguing conditions derived from these muscles were analyzed in relation to the ePT. To the authors’ knowledge, this is the first study that has investigated these MMG relationships during muscle fatigue induced by sustained FES-cycling in individuals with chronic SCI. Normalized MMG RMS showed a significant association with the ePT and as such, the normalized MMG RMS was altered significantly between the PRE and POST conditions for VL, RF and VM on repeated Day 1 and Day 2 trials. The normalized MMG MPF of POST condition reduced significantly from the PRE counterpart in Day 1 and Day 2 for all the muscles. However, the association in changes of normalized MMG MPF with the changes in ePT between PRE and POST was inconsistent between Day 1 and Day 2 for the VL and VM muscles. While the MMG RMS showed good promise for measuring the muscle fatigue during FES-cycling with moderate-to-strong consistency between days for quadriceps, the MMG MPF-based measures revealed poor day-to-day consistency between days. Clearly, there is a need for further research on the reliability of muscle fatigue.
The knee extension ePT of the post-fatiguing condition was significantly reduced from the pre-fatiguing state on Day 1 and Day 2. These findings are similar to previous studies on able-bodied volunteers who performed exercise (Çè et al., 2008; Faller et al., 2009), whereby similar decrements of MMG amplitude for evoked fatiguing muscle contractions was reported. This reduction in MMG amplitude can be attributed to numerous physiological changes concomitant with muscle fatigue, such as muscle fiber and deoxygenation that could likely alter the mechanical properties (Hogan et al., 1994) and hence the MMG RMS, which reflects the dimensional changes of muscle fibers. We found significant association between changes of MMG RMS with reduced ePT between the PRE and POST conditions for the three muscles in Day 1 and Day 2 trials. This finding also concurs with previous studies that have revealed a significant relationship between the ePT and MMG RMS from leg muscles (medial gastrocnemius and soleus) in healthy volunteers (Yoshitake and Moritani, 1999) and RF in SCI individuals at different knee angles (Ibitoye et al., 2016). Another study (Faller et al., 2009), however, reported no significant alterations of MMG frequency between pre- and post-fatiguing conditions of electrically stimulated muscle of able-bodied participants. The authors performed sustained stimulated isometric contraction of 120 s in healthy population, which may be one of the factors that might explain the difference in MMG MPF results between pre- and post-fatiguing conditions in their study and ours. The reduction in ePT, MMG RMS and MPF between pre-and post-conditions in SCI individuals was possible because the electrically stimulated sustained contraction impairs both low- and high-threshold motor units contributing to the muscle force and firing frequency and also lose the ability to return muscle's initial level even after long recovery time (150 min) following sustained FES-evoked contractions in SCI (Shinohara and Sogaard, 2006). The changes in MMG MPF showed significant association with the changes in ePT between the PRE and POST conditions for the RF muscle in Day 1 and Day 2 duplicate trials.

During FES-cycling, the MMG RMS reduced significantly with FES-cycling time for the VL, RF, and VM muscles in individuals with motor-complete SCI with a moderate to strong consistency between Day 1 and Day 2. This is possible because FES motor recruitment is synchronous thus muscle fibers are activated in reverse recruitment order (Binder-Macleod et al., 1995). This causes rapid reduction of muscle force which was reflected in the MMG RMS during sustained FES-cycling. This finding is similar to other works (Faller et al., 2009; Heasman et al., 2000), in which the MMG amplitude reduced with continuous FES stimulation. The decline in MMG amplitude may have occurred due to the development of muscle fiber where the high discharge rate of motor units greatly decreased the dimensional changes in muscle fibers. The increased discharge rate of motor units with sustained contraction of FES-cycling under fatigue might naturalize the occurrence of fusion and thus would decrease the MMG amplitude (Yoshitake et al., 2002). Another potential factor other than a motor unit strategy that could also alter the MMG signal is an increase in the intramuscular pressure during sustained electrically evoked contraction. The sustained fatigue contracting impairs the oxygenation of muscle, which changes the intramuscular pressure of muscle fibers. This phenomenon indirectly alters the mechanical properties that reduce muscle force and consequently declines the MMG signal (Shinohara and Sogaard, 2006).

The MMG RMS revealed that the RF muscle showed significantly greater fatigue rate followed by the VL and VM muscles. This observation is also in line with another study (Camata et al., 2011) that found the greater fatigue rate in RF muscle followed by VL and VM muscles detected by the EMG signal during abed-boded cycling. The RF muscle consists of the greatest proportion of fast-twitch type II fibers that is recruited first during FES-evoked contraction, which may cause faster fatigue in RF muscle during prolonged contraction. Moreover, the RF is one of the biarticular muscles, which dictates the torque between joints during a task, and has major contribution in the hip flexion during the recovery phase of the pedaling cycle (Takaishi et al., 1998). The greater the contribution of the uniarticular muscle group (VL and VM) and the hip extensor muscles are, the greater activity RF requires to re-coordinate torque and power distribution between joints during cycling exercise (So et al., 2005). There is also evidence that this re-coordination strategy may be triggered by the central nervous system that is impaired by SCI population thereby causing more impact on the RF muscle to be active during FES-LCE (Dorel et al., 2009). Collectively, these factors may contribute to a greater exertion of the RF muscle, leading to early recruitment of the fast-twitch type II fibres during FES-LCE and hence causing faster fatigue.

This study showed that the relationships between the MMG MPF and sustained FES-cycling duration were very week in most cases for the VL, RF and VM muscles in Day 1 and Day 2. Although there were some cases where the MMG MPF declined with the FES-cycling duration, this result did not show consistency between Day 1 and Day 2. While one previous study showed a reduction in the MMG MPF with sustained contraction time for the biceps brachii muscle (Madeleine et al., 2006), the authors did not report the correlation between the MMG MPF and contraction time. The present study observed a week correlation between the MMG MPF and FES-cycling time for all the electrically evoked muscles in almost all participants. This was also reported by another study that claimed a very low correlation between the MMG MPF and sustained evoked contraction time (Faller et al., 2009). Hence, the explanation for the use of MMG MPF in assessing muscle fatigue during FES-cycling would require further investigation.

Our results have practical implications as these showed the sensitivity on MMG responses to muscle function during FES-cycling and isometric contractions for individuals with motor-complete SCI. The MMG RMS based approach showed good promise as a proxy to monitor the mechanical aspects of the muscle performance in rehabilitation. The limitation of this study was that this study was performed on six SCI participants amongst whose two could not perform FES-cycling in Day 2. As two of them only participated in one trial, their data did not contribute to the reliability calculation. The difference of participation in duplicate days may not have altered our main findings as the analysis was performed on participant by participant basis. This study however recommends further comprehensive investigation with higher number of SCI individuals under various types of contractions i.e. static and dynamic. This study had to permit a small inter-trial time (≤ 5 min) in determining fatigue after FES-cycling as transferring time of each participant from FES-cycling to FES-isometric condition (Fig. 1). This could be an issue for the quantitative measure of MMG signals difference between the pre-and post-fatiguing conditions. In addition, while this study allowed a small recovery time after FES-cycling, other studies suggested that even long recovery time (up to 150 min) cannot improve muscle force after sustained electrically stimulated contractions (Blangsted et al., 2005; Shinohara and Sogaard, 2006). Our results also showed that there was a significant difference in MMG signals between the pre-and post-fatiguing conditions for the quadriceps muscle group.

5. Conclusion

This study demonstrated MMG signals (RMS and MPF), similar to ePT, were significantly altered between the pre- and post-fatiguing states in SCI individuals after FES-evoked cycle exercise. The MMG RMS showed good promise in determining muscle function between pre- and post-fatigue FES-evoked conditions as well as in characterizing muscle fatigue during FES-cycling with an acceptable consistency between days. However, the MMG MPF based measures warrant additional research in assessing muscle function during FES-cycling. One potential observation in this study is the RF muscle showed greater fatigue rate compared to the VL and VM, which may play a vital role in limiting FES-cycling in SCI individuals.
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Competing interests

There is no competing interest to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clinbiomech.2018.06.020.

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