Electrically evoked wrist extensor muscle fatigue throughout repetitive motion as measured by mechanomyography and near-infrared spectroscopy

Abstract: Repetitive electrically-evoked muscle contraction leads to accelerated muscle fatigue. This study assessed electrically-evoked fatiguing muscle with changes to mechanomyography root mean square percentage (%RMS-MMG) and tissue saturation index (%TSI) in extensor carpi radialis. Forty healthy volunteers (n = 40) performed repetitive electrical-evoked wrist extension to fatigue and results were analyzed pre- and post-fatigue, i.e. 50% power output (%PO) drop. Responses of %PO, %TSI and %RMS-MMG were correlated while the relationships between %RMS-MMG and %TSI were investigated using linear regression. The %TSI for both groups were negatively correlated with declining %PO as the ability of the muscle to take up oxygen became limited due to fatigued muscle. The %RMS-MMG behaved in two different patterns post-fatigue against declining %PO whereby; (i) group A showed positive correlation (%RMS-MMG decreased) throughout the session and (ii) group B demonstrated negative correlation (%RMS-MMG increased) with declining %PO until the end of the session. Regression analysis showed %TSI was inversely proportional to %RMS-MMG during post-fatigue in group A. Small gradients in both groups suggested that %TSI was not sensitive to the changes in %RMS-MMG and they were mutually exclusive. Most correlation and regression changed significantly post-fatigue indicating that after fatigue, the condition of muscle had changed mechanically and physiologically.

Keywords: fatigue; functional electrical stimulation; muscle oxygenation; muscle strength; rehabilitation; upper limb.

List of non-standard abbreviations: ATT, adipose tissue thickness; ECR, extensor carpi radialis; EMG, electromyography; FES, functional electrical stimulation; Hb, deoxyhemoglobin; MMG, mechanomyography; NIRS, near infrared spectroscopy; O₂Hb, oxyhemoglobin; PO, power output; RMS, root mean square; StO₂, oxygen saturation; TSI, tissue saturation index; VMG, vibromyography.

Introduction

Neuromuscular electrical stimulation therapies including functional electrical stimulation (FES) training, are often prescribed to individuals with paralysis/paresis arising from central nervous system injury. Colson et al. have concluded that FES might be more efficient than voluntary isometric training in order to improve the strength of muscle [1]. However, muscle contractions elicited by FES are more susceptible to rapid-onset fatigue than voluntary contractions due to their synchronous pattern of motor unit recruitment and the preferential stimulation of large diameter neurons innervating fast-fatiguing muscle fibers [2].

Muscle fatigue has been understood to be a decline in muscle ability to generate force or power output (PO) [3] as well as a reduction in movement speed [4] of voluntary contractions [5]. Packman-Braun proposed a fatigue criterion as a 50% decrease from the muscle’s initial force output [6]. Researchers have investigated muscle fatigue under various conditions involving numerous muscles to understand the characteristics of different muscles since they may be relatively dissimilar among individuals [7].

Electromyography (EMG) is one approach to understand muscle activity and its pathological changes for both diagnostic and therapeutic purposes. It is also often...
used during electrically-stimulated exercise [8] to evaluate motor units firing patterns, through root mean square (RMS), M-wave amplitudes, median frequency [9, 10] and mean frequency analyses.

While EMG represents muscle activation, another approach to describe muscle fatigue is through muscle oxygenation measured using near-infrared spectroscopy (NIRS) [11, 12]. NIRS has been widely used to assess muscle oxygen consumption, blood flow and oxygen saturation (StO2) within muscle [13, 14]. It has been also used in the clinical setting to assess circulatory and metabolic abnormalities in tissues and muscles [15]. Previous studies have reported muscle oxygenation pattern using NIRS during upper limb voluntary exercises such as wrist extension [16] and handgrip [17, 18] in healthy subjects as well as during FES-evoked exercise [8] using NIRS. It has been reported that the fatigue resulting from repetitive exercise is related to a decrease in oxygenated blood and blood volume in the muscle [8, 19]. Noninvasive muscle oxygenation measurement using NIRS could be an alternative method for identifying onset of muscle fatigue during repetitive movements.

A few studies have related EMG with muscle StO2 during isometric exercises in the upper limb muscles where these have revealed a strong relationship between NIRS and EMG characteristics in healthy individuals [20, 21]. Most of these studies used voluntary exercise instead of FES-evoked muscle contractions. However, EMG is very susceptible to high-amplitude electrical currents from skin-surface FES electrode [7] besides there being technical and physiological limitations especially during FES-evoked contractions in spinal cord injury (SCI) individuals [22]. Therefore, researchers have explored alternative approaches to quantify muscle fatigue during FES-elicted exercise especially in the smaller muscles of the upper limb, in which mechanomyography (MMG) is appropriate.

MMG has been used and validated in quantifying muscle fatigue [23] during isometric as well as dynamic contractions [2, 24] and clinical applications [25]. It employs different types of transducers to measure the mechanical property of muscle derived from the motor unit’s activity [26] and it is not easily influenced by skin impedance or artefacts from other probes [27–29]. Few studies had verified that MMG is a reliable tool to measure the development of muscle fatigue when torque output is not, or hardly, detectable such as during FES-evoked rehabilitation for individuals with paralysis or paresis [7, 30]. It has been well documented that the amplitude and frequency of MMG signal are both related to muscle force [30, 31] and torque in the SCI population population during electrical stimulation [32, 33]. Muscle fatigue from lower back pain using EMG, MMG and NIRS has also been investigated, and the authors concluded that a simultaneous recording system of multiple signals might be a more promising approach with regards to quantifying muscle fatigue [34] and such system that could predict and detect onset and rate of fatigue might be clinically efficacious for rehabilitation purposes. However, there have not yet been any studies that have co-recorded real-time MMG and NIRS to assess the state of fatiguing muscle during FES, especially in the upper limbs.

This study investigated the relationship between MMG and NIRS against changes in PO during repetitive electrically-evoked wrist extension exercise. It was hypothesized that a fatiguing muscle would show a clear relationship between MMG and NIRS after fatigue onset or at pre-defined decrease of muscle force output during repetitive FES-elicted exercise task.

**Materials and methods**

**Subjects**

Forty subjects (n = 40: 12 male, 28 female; age: 21.55 ± 1.4 years) participated in the study after providing their informed written consent. The Medical Ethics Committee, University Malaya Medical Center approved this study (MECID.NO: 20166-2552). Skinfold thickness over the muscle was measured using a skinfold caliper to determine the adipose tissue thickness (ATT) (4.09 ± 1.56 mm). All subjects were right hand dominant and were in good health with no history of upper extremity musculoskeletal disorder or surgeries.

**Fatigue measurement**

PO was the primary outcome, a measurement of fatigue [6] and it was calculated from Equation 1. A pilot session was conducted with six subjects to determine the amount of load to be used in the experiment. The maximum load was set at 0.8 kg and it was determined using the binary method. All subjects were able to lift 0.8 kg of load until they reached maximum angle of wrist extension with FES-elicted muscle contraction, thus 0.8 kg was used for all individuals.

\[
\text{Power (N·ms}^{-1}\text{)} = \frac{\text{Force (N)} \times \text{Displacement (m)}}{\text{Time (s)}}
\]  

(1)

A strap attached to a 0.8 kg weight was placed on the dorsal part of the hand during the exercise task. Time and displacement during lifting of the load were recorded using a video camera and Kinovea 0.8.15, a free software application for movement analysis. The exercise task was performed until a subject was either unable to lift the load indicating zero PO or a pre-set limit of 15-min exercise.
Functional electrical stimulation

An Ottobock STIWell med4 surface stimulator (MED-EL Elektro- medizinische Geräte GmbH, Innsbruck, Austria) was used to provide electrical stimulation to the muscles with stimulation frequency of 30 Hz, pulse width of 250 µs evoking full wrist extension and on/off duty cycle 4 s/4 s. The stimulation amplitude ranged from 10 to 30 mA was adjusted according to the subjects’ tolerance.

Near infrared spectroscopy

NIRS (PortaMon, Artinis Medical Systems, Gelderland, The Netherlands) is a non-invasive, non-ionizing, real-time monitoring and portable system that generates infrared light at two wavelengths of 760 and 850 nm with three transmitters and a receiver (Figure 1B), which is transmitted through body’s skin, muscle and adipose tissue. Based on the amount of light that is absorbed at respective wavelengths into the device, they were then converted to concentration changes of oxyhemoglobin (ΔO2Hb), deoxyhemoglobin (ΔHHb) and total hemoglobin (ΔtHb) from its baseline using a modified Lambert-Beer Law. With these concentrations changes, tissue saturation index (TSI) can be calculated. TSI, on the other hand, quantifies the average saturation of the underlying muscle tissue and is calculated as [O2Hb]/([O2Hb] + [HHb]) × 100. It reflects the dynamic balance between oxygen supply and oxygen demand in the tissue microcirculation [35–37]. Previous studies have shown that TSI reflects muscle oxygenation more accurately than HHb [35, 38]. %TSI therefore shows muscle oxygen utilization more precisely than ΔO2Hb and ΔHHb, and was the primary outcome representing muscle metabolism.

Physiological calibration was performed before starting the experiment to normalize NIRS signals as it provided a range of NIRS optical density unit changes, and thus gave an accurate interpretation of change in raw NIRS data. It was an important and the most practical comparisons of oxygenation levels between different subjects and muscle builds. The physiological calibration during 5–8 min vascular occlusion (250 mm Hg) provided the minimum value during ischemia and maximum value during reactive hyperemia (or highest point observed during the experiment), and these minimum and maximum values were used as a scaling factor (0% and 100%) for further measurements [13, 39].

The subcutaneous or fat layer overlying the muscle of interest may have influenced NIRS measurements. The influence was due to different muscle builds of each individual. To control this, ATT was measured using skinfold callipers. ATT was defined as skinfold thickness divided by 2. The maximum penetration depth of NIRS was calculated as half the distance between source and detector probes. This means that individuals with a high adiposity might prevent sufficient infrared light transmission through the muscle and, thereby affecting the NIRS measurement [40]. For individuals with high adiposity, the signals may be less accurate due to a lower metabolic and blood flow rates within adipose tissue [41], infrared signal scattering and light absorption. This was proved by a study that showed that when ATT increased from 5 to 10 mm, there was a decrease of 50% in absorbance of the NIRS light while a decrease of 25% was observed when fat layer thickness was increased from 2.5 to 5 mm [42].

Mechanomyography

The accelerometer-based MMG sensor, Sonostics VMG BPS II Transducer (Biopac System, Inc., Goleta, CA, USA) was used to record contractions elicited by mechanical activity within the muscle using different types of sensors, where it could be used to monitor and examine mechanical activity of the muscle and showed a strong impact in muscle fatigue detection. MMG signals were collected at 2 kHz sampling frequency and were digitally band-pass filtered at 20–200 Hz as has been recommended by Biopac for assessment of muscle effort. All MMG signals recorded were obtained from the vibration of muscle that caused wrist extension movement. MMG-RMS was extracted from the raw MMG signal and was normalized to %RMS-MMG.

Figure 1: (A) The setup diagram for the experiment. (B) Closer look at the schematic view of a TSI measurement. Light through tissue with three transmitters (T1, T2 and T3) and receiver (R). A transmitter and receiver together form an optode combination. d (40 mm) is the total distance between the receiver and transmitters and is called the source-detector distance. Δd (5 mm) is the distance between two subsequent transmitters. T1 is at 30 mm, T2 is at 35 mm and T3 at 40 mm distance. The light travels in a “banana shape” form from T1, T2 and T3 to R and its maximum penetration depth is approximately half the distance between receiver and transmitters.
Study procedure

Subjects were comfortably seated on a chair, with the right hand positioned on a thermoplastic arm rest placed on the table with Velcro strapped along their forearm for limb stabilisation (Figure 1A). The arm rest supported and secured their hands while minimizing other unintended movements throughout the experiment. A Hokanson vascular occlusion cuff was strapped around the forearm just above the elbow. One 4 × 4 cm electrode was placed at the extensor carpi radialis (ECR) muscle belly, just above the wrist on the dorsal surface of the forearm and the other electrode was placed close to the lateral epicondyle of the humerus for FES. By using small FES electrodes, the NIRS probe was able to fit in between the electrode while the MMG probe was affixed over the proximal FES electrode (Figure 1A). The measurement from receiver to transmitter located under the NIRS probe was only 40 mm when it was placed on the muscle according to the location of the receiver and transmitter. NIRS and MMGs probes were placed along the muscle belly of the extensor muscle and double-sided optically-neutral tape was used to ensure consistent contact pressure between the sensor and the skin over the ECR area. Both probes were wrapped with an elastic bandage to secure them during the exercise. Large unintended movements were avoided by restricting other movements using a thermoplastic arm rest with Velcro strapped around the proximal of the wrist. A maximum load was attached and strapped around their palm while doing the exercise task. The setup for the experiment was as shown in Figure 1A. After a 5-min rest period, a super-systolic arterial occlusion was performed where the cuff was inflated to a high pressure of 250 mm Hg until the %TSI reached a nadir lasting at least 5 s, then the cuff was released immediately to evoke reactive hyperaemia. The subjects’ muscles were then FES recruited to non-voluntarily performed repetitive wrist extension. The duty cycle (contraction: non-contraction ratio) for the exercise task was set at 4-s contraction and 4-s rest to induce rapid muscle fatigue. The NIRS with MMG signals throughout the entire period of each wrist extension exercise were collected during rest, arterial occlusion and exercise until the load could not be lifted anymore, indicating zero PO which was the fatigue point or a maximum of 15 min exercise. A schematic diagram of the protocol employed in this study is shown in Figure 2.

Data analysis

The number of contractions successfully completed was converted to percentage of total contractions per subject to normalize analysis across the participant pool. Percentages of power output (%PO) were calculated using Equation (1) while mean percentages %TSI from NIRS were obtained during each 4-s contraction to fatigue. The %RMS-MMG were also normalized and the mean amplitude for every 4-s contraction was computed using epoch analysis. All subjects’ mean of %PO, %TSI and %RMS-MMG for each 10% increment percentage of contractions were plotted and data are presented as mean ± standard deviation.

Statistical analyses

All data of %PO, %TSI from NIRS and %RMS-MMG were obtained during exercise for all subjects and were examined using bivariate correlation by IBM SPSS Statistics 24 (SPSS Inc., Chicago, IL, USA). Pairwise correlations (%PO, %TSI and %RMS-MMG) were done on two groups which were pre-fatigue and post-fatigue, whereby the pre-defined fatigue point was a 50% drop of PO. The correlations were done by pairs: %PO and %TSI, %PO and %RMS-MMG, %TSI and %RMS-MMG. Correlation coefficient (r) measured the degree of association (scatter) and the direction of a linear relationship between any two primary outcomes. The interpretations of correlations were based on these criteria; r > 0.5 is a good correlation, r = 0.3–0.5 is a moderate correlation, and r < 0.3 is a poor correlation [43]. A relationship between %TSI and %RMS-MMG was obtained from a regression analysis to determine their relationship with each other during exercise.

Results

Figure 3 presents sample data from the experiment where both NIRS and MMG signals were shown. NIRS data was recorded throughout the experiment while MMG data was only recorded during wrist extension exercise. Figure 4 portrays %PO, %TSI and %RMS-MMG plotted over the percentage of contractions. One of the subjects was excluded because the muscle did not reach the pre-defined fatigue point during the experiment, i.e. %PO did not reach 50%. A primary finding during this muscle fatigue experiment, was that %PO progressively fell over the increasing number of contractions while %TSI behaved in the opposite direction and rose during the exercise. In contrast, %RMS-MMG changes over time were inconsistent did not demonstrate a clear pattern during exercise. Figure 5 on the other hand, shows the concentration changes and pattern of ΔO₂Hb and ΔHHb derived from NIRS during exercise. Concentration of ΔO₂Hb increased over time, which was similar with %TSI while ΔHHb did not reveal clear changes throughout the exercise.

Pre-planned correlation analyses were done at pre- and post-fatigue where the fatigue point was defined as a 50% drop of PO [6] from initial values. Pairwise correlations during pre-fatigue did not demonstrate any
significant associations while during post-fatigue, %PO and %TSI revealed weak negative relationships to each other ($r = -0.16$, $p = 0.00$) while %TSI and %RMS-MMG were positively correlated ($r = 0.36$, $p = 0.00$) and both were statistically significant. %PO and %RMS-MMG, on the other hand, showed a weak positive correlation of $r = 0.05$, $p = 0.04$. 

Figure 3: Actual data from NIRS and MMG during the experiment. 
(A) NIRS signals are recorded throughout the experiment including occlusions and (B) MMG signals are recorded during exercise only as MMG detects muscle vibrations during contraction. (C) and (D) are a closer look at the signals for one separate contraction from NIRS and MMG.

Figure 4: Mean of %TSI, %RMS and %PO plotted against % of contractions for all subjects. Data are presented as mean and standard deviation. Dashed vertical lines denote the point of fatigue (50% drop of PO) where correlations were done at two parts; pre- and post-fatigue.

Figure 5: Mean of ΔO$_2$Hb and ΔHHb plotted against % of total contractions for all subjects. Data are presented as mean and standard deviation.
As the overall group correlation of %PO and %RMS-MMG was weak, further correlation analysis between %PO and %RMS-MMG was done pre- and post-fatigue for each individual to elucidate any patterns more clearly. These analyses revealed that %RMS-MMG behaved in two different ways post-fatigue, which were either in positive correlation against declining %PO, i.e. both parameters decreasing throughout the session ($r = 0.26$, $p = 0.00$) or negatively correlated with %PO, whereby the %RMS-MMG increased with decreasing %PO ($r = -0.23$, $p = 0.00$). Due to this unexpected finding, secondary analyses were conducted whereby all subjects were divided into two groups; group A ($n = 23$) with positive correlation and group B ($n = 16$) with negative correlation, respectively.

Figure 6 shows an overall plot of group A for %PO, %TSI and %RMS-MMG against the percentage of contractions. A clearer pattern of decreasing %RMS-MMG was observed along with declining %PO and increasing %TSI over increasing contractions. Correlation during pre-fatigue did not portray any significant value (Table 1) while at post-fatigue the correlation of %PO and %TSI with %PO and %RMS-MMG showed a significant negative and positive correlation, respectively ($r = -0.10$, $r = 0.30$). As for the overall trend shown by group B (Figure 7), %RMS-MMG increased with %TSI while %PO declined as contractions progressed. During pre-fatigue, significant positive correlations were observed for %RMS-MMG and %PO with %TSI and %PO, respectively ($r = 0.25$, $r = 0.12$). During post-fatigue, a total opposite pattern was observed where %RMS-MMG and %TSI were in different direction of decreasing %PO with significant and negative correlation ($r = -0.14$, $r = -0.11$).

The relationship between %TSI and %RMS-MMG was investigated by regression analysis whereby two regression lines fitted to each other over decreasing %PO. Using %PO as the independent variable and %TSI or %RMS as the dependent variables, while $a_2$ and $a_3$ were statistically determined regression coefficients, their relationship are represented by Equations (2) and (3).

$$\%\text{TSI} = a_0 + a_1 \%\text{PO} \quad (2)$$

$$\%\text{RMS} = a_0 + a_1 \%\text{PO} \quad (3)$$

$a_2$ and $a_3$ are the new constants calculated from Equation 4 describing the relationship between %TSI and %RMS-MMG.

$$\%\text{TSI} = a_2 \%\text{RMS} + a_3 \quad (4)$$

Table 2 shows regression equations for group A and group B at pre- and post-fatigue, respectively.

### Discussion

#### Overview

This study sought to investigate the relationship between %TSI, %RMS-MMG and %PO during repetitive wrist

![Figure 6: Mean of %TSI, %RMS and %PO plotted against % of contractions for group A. Data are presented as mean and standard deviation. Dashed vertical lines denote the point of fatigue (50% drop of PO) where correlations were done at two parts; pre- and post-fatigue.](image)
extension exercise to fatigue. Muscle fatigue was defined as a decline in the ability of ECR muscle to produce PO [3] and in this study, %PO decreased continuously as the percentage of contractions increased. While %PO decreased, %TSI, on the other hand, rose slightly throughout the exercise.

%TSI is an estimate of the StO2 in the tissue or muscle and it changed during exercise in different direction to %PO especially during post-fatigue, where they were significantly negative correlated with each other (Table 1). %TSI gradually increased along with ΔO2Hb throughout exercise and our findings showed similarities to those of Muraki et al. where during exercise, StO2 started to increase along with total hemoglobin and O2Hb [44]. Similar results were also observed in the current study wherein ΔO2Hb increased to a plateau with ΔHHb relatively unchanged.

The interpretation is that during the repetitive task, blood flow was increased due to arteriolar vasodilation with the amount of blood supply (and oxygen saturation) exceeding the metabolic demand [45]. These results suggested that the ability of the muscle to take up oxygen may be limited during the middle of the FES-evoked exercise task even with sufficient oxygen supply because the muscles had become increasingly fatigued. It might also be due to poor oxygen uptake of the ECR itself, and not because of poor oxygen supply into the muscles as ΔO2Hb increased [44]. As with %StO2, the general trend was an initial drop with a steady increase during exercise, and this trend has been reported often found in healthy subjects [46].

**Two distinct trends in %RMS-MMG progression**

Based on the relationship between %PO and %RMS in group A, %RMS-MMG was positively associated with %PO, where both of them declined with increasing percentage of contractions post-fatigue. The RMS amplitude from the MMG signal depends on the muscle fiber activation and it generally increase with increasing muscle force. Additionally, the RMS signal varies and depends on the degree of muscle fiber activation and therefore is highly associated with muscle effort and was considered the most reliable parameter in the time domain [7]. %RMS-MMG showed a consistent decline pattern throughout the exercise with the declining of %PO. However, during FES-evoked exercise, larger (fast-firing) motor units with lower excitability threshold are generally recruited first before the slow twitch muscle units, which is the ‘normal’ physiological voluntary recruitment order. That was why FES evoked exercise evokes a higher rate of fatigue in muscles compared to voluntary exercise and resulted, in the current study, in a more rapidly decreasing %RMS-MMG [47].

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**Figure 7:** Mean of %TSI, %RMS and %PO plotted against % of contractions for group B.

Data are presented as mean and standard deviation. Dashed vertical lines denote the point of fatigue (50% drop of PO) where correlations were done at two parts; pre- and post-fatigue.

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**Table 2:** Equations for regression lines from (i) %PO and %TSI, (ii) %PO and %RMS and (iii) %TSI and %RMS.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Pre-fatigue</th>
<th>Post-fatigue</th>
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<tbody>
<tr>
<td><strong>Group A</strong></td>
<td></td>
<td></td>
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<tr>
<td>(i) %PO and %TSI</td>
<td>%TSI = −0.03 %PO + 57.25</td>
<td>%TSI = −0.05 %PO + 64.18*</td>
</tr>
<tr>
<td>(ii) %PO and %RMS</td>
<td>%RMS = −0.04 %PO + 49.64</td>
<td>%RMS = −0.36 %PO + 19.96*</td>
</tr>
<tr>
<td>(iii) %TSI and %RMS</td>
<td>%TSI = 0.70 %RMS + 22.36</td>
<td>%TSI = −0.15 %RMS + 67.22</td>
</tr>
<tr>
<td><strong>Group B</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i) %PO and %TSI</td>
<td>%TSI = 0.09 %PO + 53.77*</td>
<td>%TSI = −0.09 %PO + 68.44*</td>
</tr>
<tr>
<td>(ii) %PO and %RMS</td>
<td>%RMS = 0.33 %PO + 2.52*</td>
<td>%RMS = −0.24 %PO + 52.57*</td>
</tr>
<tr>
<td>(iii) %TSI and %RMS</td>
<td>%TSI = 0.27 %RMS + 53.10</td>
<td>%TSI = 0.35 %RMS + 50.22</td>
</tr>
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*Regression is significant (p < 0.05).
In order to investigate the relationship between %TSI and %RMS-MMG, regression analysis was performed and their equations are presented in Table 2(iii). In group A, the gradient changes in regression analysis from positive gradient during pre-fatigue to negative gradient during post-fatigue. This change indicated that %TSI and %RMS-MMG are inversely proportional to each other post-fatigue such that when %TSI increased, %RMS-MMG decreased. The gradient changes agree with the discussion above where %TSI increased due to an inability of muscle to take up oxygen [44] while %RMS-MMG decreased as muscle effort decreased to fatigue [7].

On the contrary, %RMS-MMG in group B was significantly negatively correlated to %PO where %RMS-MMG increased as %PO declined. This pattern was especially evident during post-fatigue part of the exercise in this group. The increase of %RMS-MMG may be due to the probable recruitment of a new single motor unit, at low levels of effort [48], suggesting that when the fresh muscle started to fatigue, new muscle unit recruitment occurred during exercise [7]. This is possible as FES-evoked contractions accelerated muscle fatigue and as muscle started to become fatigued, a new muscle unit will be recruited thus increasing %RMS-MMG. An increase in %RMS-MMG may also be due to higher intramuscular pressure leading to impairment of the active muscle fibre dimensions [49] in addition to swollen muscle fibers caused by an osmotic phenomena and physiologic vibration during the prolonged exercise [50]. Healthy subjects in this study might have faster muscle recovery rate. Muscle recovery will affect the %RMS-MMG because the fatigued muscle had already recovered during the 4-s rest period throughout the repetitive 4-s contraction 4-s rest exercise. This viewpoint agreed with a study from Clarkson and Tremblay that an adaptation may happen where the muscle was more resistant to damage and was repaired at a faster rate among healthy subjects during eccentric exercises [51].

Ultimately, the physiological mechanisms responsible for different responses between muscle performance (%PO and %RMS-MMG) and its metabolic concomitants (%TSI) during the fatiguing exercise task for group A and group B are open to speculation. The muscle adaptation and recovery can also explain the lack of change in the gradient of the regression line during pre- and post-fatigue as %TSI and %RMS-MMG were proportional to each other in group B. The proportionality suggested that as the muscle was unable to take up oxygen [44], probable recruitment of a new single motor unit also occurs [48] resulting in an increasing pattern for both. From the equations in Table 2(iii), small gradients in pre-fatigue and post-fatigue in both groups A and B suggested that %TSI was not sensitive to the changes in %RMS. A small gradient supported that %RMS-MMG and %TSI were mutually exclusive.

To the best of our knowledge, this is the first study to examine wrist extensor muscle fatigue during FES in terms of mechanical and metabolic response recorded simultaneously in healthy subjects. It was found that there were two different trends in RMS-MMG behavior throughout fatigue, whereby one increases after the point of fatigue while another continuously decreases with the drop in PO. As the correlations were done at pre- and post-fatigue point, most correlations were significant at the post-fatigue point of the exercise. This showed that after fatigue in healthy subjects, the condition of a muscle may change mechanically or physiologically.

Author Statement

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Conflict of interest: Authors state no conflict of interest.

Informed consent: Informed consent has been obtained from all individuals.

Ethical approval: The research related to human use complied with all the relevant national regulations and institutional policies, was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the Medical Ethics Committee, University Malaya Medical Center approved this study (MECID.NO: 20166-2552).

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