Fatigue effect on cross-talk in mechanomyography signals of extensor and flexor forearm muscles during maximal voluntary isometric contractions

Mohamad Razif Mohamad Ismail¹, Chee Kiang Lam¹, Kenneth Sundaraj², Mohd Hafiz Fazalul Rahiman¹

¹Fakulti Teknologi Kejuruteraan Elektrik, Universiti Malaysia Perlis, Kampus Alam Pauh Putra, Perlis, Malaysia; ²Fakulti Kejuruteraan Elektronik & Kejuruteraan Komputer, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, Melaka, Malaysia

Abstract

Objective: This paper presents the analyses of the fatigue effect on the cross-talk in mechanomyography (MMG) signals of extensor and flexor forearm muscles during pre- and post-fatigue maximum voluntary isometric contraction (MVIC).

Methods: Twenty male participants performed repetitive submaximal (60% MVIC) grip muscle contractions to induce muscle fatigue and the results were analyzed during the pre- and post-fatigue MVIC. MMG signals were recorded on the extensor digitorum (ED), extensor carpi radialis longus (ECRL), flexor digitorum superficialis (FDS) and flexor carpi radialis (FCR) muscles. The cross-correlation coefficient was used to quantify the cross-talk values in forearm muscle pairs (MP1, MP2, MP3, MP4, MP5 and MP6). In addition, the MMG RMS and MMG MPF were calculated to determine force production and muscle fatigue level, respectively. Results: The fatigue effect significantly increased the cross-talk values in forearm muscle pairs except for MP2 and MP6. While the MMG RMS and MMG MPF significantly decreased (p<0.05) based on the examination of the mean differences from pre- and post-fatigue MVIC. Conclusion: The presented results can be used as a reference for further investigation of cross-talk on the fatigue assessment of extensor and flexor muscles’ mechanic.

Keywords: Cross-talk, Fatigue, Forearm Muscle, Mechanomyography

Introduction

Human forearm consists of several complex skeletal muscles particularly in close proximity and is divided into two compartmental muscles which are anterior (extensor) and posterior (flexor) muscles. From the total of 19 muscles located on the forearm, 11 of these are classified as extensor muscles, and the rest are grouped as the flexor muscles¹. During contraction, the common function of each forearm muscles varied depending on the size and proximity of the muscles². Besides, different types of forearm muscles engaged with one another during various actions such as finger movement, wrist posture, load lifting and handgrip activity. However, according to¹, the involvement of both the flexor and extensor forearm muscles in handgrip action, with increasing complexity is not yet well understood. The overworked of these muscles will cause a reduction in grip strength which later may lead to muscle fatigue.

Muscle fatigue (peripheral fatigue) is defined as the inability of a muscle or group of muscles to generate forces, power output and maximal voluntary contraction⁴,⁵ by through continuously repetitive muscle contraction. It is typically associated with a state of exhaustion and loss of muscles’ capability to perform any contraction at the desired level. This scenario reflects the decreases in muscle strength and force production, which are commonly triggered by strenuous activity or exercise⁶. Furthermore, muscles fatigue also influenced by the factors such as age⁷, different types of metabolism and fiber⁸, muscle mass⁹, accumulation of lactic acid in muscle tissue and depletion of glycogen which stored glucose¹⁰, muscle wisdom⁹, and quality of muscle to produce force¹¹. During an isometric contraction,
Muscle fatigue can be determined by using power spectral analysis in the time domain (TD) and frequency domain (FD) on both surface myographic signal: mechanomyography (MMG) and electromyography (EMG)\(^{11,12}\). Previous work as in\(^6\) recommended that the study in changes of motor recruitment (TD) and global motor unit firing rate (FD) are correlated to the MMG signals whereas muscle activation (TD) and motor unit action potential velocity (FD) are associated with the EMG signals\(^9\).

EMG signals is a non-invasive technique use to evaluate muscle contraction. It is also has been applied to evaluate muscle fatigue in TD and FD by analyzing the root mean square (RMS), median frequency (MF), and mean power frequency (MPF). However, the EMG signal has some drawbacks and is not well adopted practically since it is susceptible to high-amplitude due to the interference from the electrical stimulus from the skin impedance, motion artifacts and surrounding noise, which limits its operating environment, specifically during fatigue evaluation\(^13,14\). However, the MMG signal is a complementary approach to the EMG signal which provides information related to the muscle function, particularly for muscle fatigue\(^15,16\). Besides, the MMG signals were proven to be more reliable indicators for muscle fatigue during muscle contraction because the signals are not affected by changes in the skin impedance\(^17\) and physical postural tremor\(^18\). The MMG signals have also been demonstrated to be able to identify the individual muscle behaviors\(^8\) during fatigue. The MMG signal measures and records the low-frequency lateral oscillations of contracting muscle, which represents the muscles’ mechanical output during muscular contractions. The lateral oscillations of the contracting muscles are quantified from the gross lateral movement at the start of the contraction which is generated by the non-simultaneous stimulation of muscle fibers, and smaller subsequent lateral movement generated at the resonance frequency of muscle and dimensional changes of the active fibers\(^9\). Moreover, during and after fatiguing contractions, the MMG signals could provide more information on the changes in motor unit activity and the mechanical properties of the contracting muscle\(^20,21\). Mulla et al.\(^8\) found that the MMG signals have a significant possibility for monitoring muscle fatigue development during the isometric contraction compared to the EMG signal, and they can be used as a practical tool for muscle fatigue assessment\(^22,23\). It has been shown that the MMG amplitude (RMS) is related to motor unit (MU) recruitment, while the MMG frequency (MPF) can provide information regarding the MU firing rate\(^24,25\). MMG amplitude (RMS) is usually used to estimate muscle force production\(^26\), whereas MMG frequency (MPF) commonly utilized to indicates the level of muscle fatigue\(^27\). The reduced recruitment of MUs (MMG amplitude) or firing rate (MMG frequency) during muscle contractions indicates that muscle force production is dropping and fatigue levels are increasing, respectively. Based on the literature study, numerous researchers examined the muscle fatigue by using the features of RMS and MPF from the MMG signals\(^24,19,28-30\).

Although the myography signals have been extensively utilized to quantify muscle fatigue, most related study, however, seems to overlook the effect of cross-talk caused by fatigue on the compartmental forearm muscles. In myography signal, cross-talk refers to the contamination of the signal from the muscle of interest by the signal from another muscle or muscle group that is in close proximity\(^31\). Even though there are challenges on how to quantify the cross-talk values, prior research by\(^32-34\) agreed that the signal’s amplitude and cross-correlation-based indices are commonly employed to quantify the cross-talk values.

Regardless of the criticisms of using cross-correlation in the past studies\(^35,36\), it is now the most effective method for quantifying cross-talk\(^37,38\). In theory, signals from two independent muscles should not have a high cross-correlation coefficient (cross-talk) as it is computed from two different sources and has received dissimilar waveform shape. Also, cross-correlation is more practical to be employed because it can measures the proportion of a common signal shared by any two different muscles without having information regarding an uncontaminated signal\(^39,40\) despite fatigue was induced.

In the previous studies, the cross-correlation function has been used to investigate the cross-talk in both EMG\(^2-29\) and MMG\(^22-34,41,42\) signals. According to\(^2\), cross-correlation can be used to look at the cross-talk in sEMG signals on the proximal forearm (flexor and extensor) during gripping tasks. They observed that cross-talk values between adjacent muscles remained between 50% to 60% during the task. Besides, the authors\(^39\) examined the effect of cross-talk using cross-correlation in sEMG signals during static grip task on the forearm flexors. The cross-talk values obtained varied from 32% to 50% in the wrist-dedicated flexors. As mentioned in\(^13\), the authors have investigated cross-talk using cross-correlation coefficient in MMG signals from the extensor and flexor muscles during grip muscle contractions and reported that the cross-talk values ranged from 2.45% to 62.28%. The same authors have also examined cross-talk using the same procedures but in different wrist postures\(^31\), resulting in cross-talk values ranged from 1.69% to 64.05%. In addition, the studies on upper arm muscles\(^34,42\) and leg muscles\(^32\) during the isometric contraction shows that the cross-talk values ranged from 0.92% to 21.57% and 1.54% to 50.98%, respectively. To summarize, none of these literature studies has been conducted to look into the cross-talk of MMG signals during muscle fatigue on forearm muscles, specifically between the extensor and flexor muscles. Moreover, it is unclear whether muscle fatigue has any significant influences on the cross-talk between the MMG signals of these muscles. The analyses involved between extensor and flexor muscles caused by muscle fatigue could be valuable in clinical applications such as monitoring muscle force and activities, rehabilitation tool in the reconstructions of muscles, and development and control of an externally powered prosthesis\(^43\). Therefore, the objective of this study is to analyze the effect of muscle fatigue on the cross-talk values in MMG signals generated by the extensor (ED and ECRL) and flexor (FDS and FCR) of forearm muscles during cross-talk.
pre- and post-fatigue MVIC. Our hypothesis proposed that, as the muscles force production from each proximity muscles that interacted due to induced muscle fatigue decreases, the generated cross-talk will be increased.

**Materials and Method**

**Ethics approval**

This study was approved by the local Medical Research & Ethics Committee (MREC), Ministry of Health, Kuala Lumpur, Malaysia via Ref No.: KKM/NIHSEC/P14-1197. The guidelines were followed according to the Declaration of Helsinki due to the involvement of human as the subject in the experiment.

**Participants**

There were 20 healthy right-handed male (mean ± SD: age= 25.54±2.30 years, weight= 63.92±6.80 kg, height= 170.31±6.24 cm) volunteers participated in this study. All participants were informed about the purpose of the research as well as the experimental protocol of the study through a consent form. Before the testing and familiarization session, each participant was required to complete a health history questionnaire and submit their written consent form to participate. Participants with a history of neuromuscular or musculoskeletal disorder specific to the elbow, wrist and/or finger joints injury were excluded from the investigation. The signals were recorded on dominant right-handed male participants in order to exclude the variability of the MU firing rate due to the hand domination. The participant was required to produce grip muscle actions on the forearm muscles. The participants visually tracked the torque production using a real-time torque displayed on the hand dynamometer screen. The participant was informed not to perform any upper body physical exercise 72 hours prior to the second session. During the second session, the participant was required to start with a set of warmup exercise, which included fingers and arm stretching and few repetitions practiced of low-force grasp activity. The participant was seated comfortably on a chair that has two adjustable arms supports attached to the chair arm. Following that, the participant was required to complete a muscle fatigue contraction protocol, which includes the pre-fatigue MVIC, fatigue protocol and post-fatigue MVIC. The contraction protocols were measured using an electronic hand dynamometer (EH101; Camry, Guangdong Province, China) with a digital display and a standard adjustable hand for ideal grasp.

**Pre-fatigue MVIC**

The participants performed 3 trials of 6 seconds MVIC of grip muscle contractions. The participant was verbally instructed to produce as much grip muscle contractions as possible. The highest isometric contraction from the three trials was selected as pre-fatigue MVIC. Each trial contraction was separated by 2 minutes of rest.

**Fatigue protocol**

Following the determination of the pre-fatigue MVIC, the participant was required to perform isometric contractions at 60% of their MVIC. Each isometric muscle contraction was performed for 10 seconds followed by 5 seconds of rest in order to induce muscle fatigue as illustrated in Figure 1. These fatiguing contractions were performed continuously to increase the amount of fatigue generated within the forearm muscles and so to maximize the central changes that occurred in reaction to the muscle changes.

The participant was required to produce grip muscle
contractions until they could no longer maintain the targeted force. Throughout fatigue protocol, the participant was verbally encouraged to maintain their grip force production at 60% MVIC, which was visually indicated on the hand dynamometer screen display. The fatigue protocol was stopped when the grip force production dropped to approximately 40% of MVIC, which indicate that the muscles were exhausted. The exhausted level was decided when the muscle contraction failed to reach the designated target (60% MVIC) on three consecutive attempts.

The ratings of perceived exertion (RPE) were recorded using the Borg CR10 Scale to determine the muscle fatigue during 60% of MVIC. Every 20 seconds, the participant was asked to rate their perceived exertion on a scale of 0–10 where 0 represented the resting state and 10 represented the strongest contraction that participants could grip. The fatigue protocol was terminated either: (i) Borg number reached or surpassed a score (RPE ≥8), (ii) the participant failed to reach the designated target for three consecutive attempts or (iii) the participants could no longer maintain the grip muscle actions position. However, these terminating conditions have remained undisclosed to the participant.

Post-fatigue MVIC

As soon as the fatigue protocol dismissed, the participant was requested to perform three trials of MVIC as the pre-fatigue procedure. The highest grip force production of MVIC (i.e. isometric contraction) from the three trials was selected as the post-fatigue MVIC and used for further analysis. The real-time torque was displayed on the hand dynamometer screen for the participant’s indicator.

MMG recording

On the second visit, four accelerometer-based TSD250A, single-axis MMG sensors (Sonostics VMG BPS II Transducer, Biopac System Inc., Goleta, CA, USA; operational frequency response 20–200 Hz; sensitivity 50 V/g; maximum range 2000 g; dimension = 32.64 mm (octogonal) × 9.14 mm (sidewall) to 12.57 mm (dome) and weight = 10 g) were used to record the MMG signals. TSD250A was used for measuring absolute muscle force from substantial muscle groups, such as forearm and leg muscles and was utilized in advanced signal analysis algorithms to monitor the small muscle vibrations that occur when a muscle is triggered or contracted. In order to eliminate the most motion artifacts, the sensor used in this study comprised band-pass filtering. Four sensors were affixed to the skin surface over the belly of the forearm muscles (ED, ECRL, FDS and FCR) according to the anatomical guide by using double-sided adhesive tapes in a neutral arm position to ensure the applied pressure was uniform and consistent. These muscles were selected based on their relevance to hand and wrist function during handgrip. The ED muscle is located at the extensor side, one-third of the distance from the proximal end of a line from the lateral epicondyle of the humerus to the distal head of ulna; the ECRL muscle is located at the extensor side, two fingerbreadths distal to the lateral epicondyle; the FDS muscle is located at flexor side, in the middle third of the forearm along a line drawn from the middle of the wrist to the biceps tendon; and FCR muscle is located at flexor side, one-third of the distance from the proximal end of a line from the medial epicondyle to the distal head of the radius.

Signal processing and data analysis

The output of each MMG signal direction was amplified at a gain (G=200) using an amplifier (DA100C, BIOPAC Systems) that connected with a data acquisition unit (MP160 & HLT100C, BIOPAC Systems) and then interfaced with AcqKnowledge 5.0 software, which separately recorded and stored the data in a computer for off-line analyses. The input voltage range of the analogue-to-digital converter was ±10 V. The raw MMG signal were sampled at 2 kHz as recommended by the manufacturer. The raw MMG signals were digitally filtered by a band-pass fourth-order Butterworth filter with a pass-band of 5-100 Hz because the main signal component of the MMG signal is widely adapted between 5 and 100 Hz. The MMG signals were recorded for 6 seconds during each trial. In order to quantify the cross-talk, MMG RMS, and MMG MPF values, only 2 out of 6 seconds of the isometric contraction corresponded to the middle 33% was selected as shown in Figure 2. This MMG signal portion was selected to remove the effect of signal transition during muscle contraction, as recommended by a previous study.

The cross-talk between two muscles was measured using the peak cross-correlations. There are total of 6 muscle pairs employed in the present study, namely ED & ECRL (MP1), ED & FDS (MP2), ED & FCR (MP3), ECRL & FDS (MP4), ECRL & FCR (MP5) and FDS & FCR (MP6). The cross-correlation coefficients between the two signals $x(t)$ and $y(t)$ were determined using Equation (1). The cross-talk value was then determined from the squared ($R_{xy}^2$) value of the peak cross-correlation coefficient between two signals. Theoretically, cross-correlation coefficient (CCC) at zero phase shift (or peak) often used to quantify the magnitude of common signal (CT).

$$ R_{xy}(τ) = \frac{1}{a \times b \times ω(τ)} \sum_{n=0}^{N} X_i(n) \ast Y_i(n+τ); 1−N <τ< M, \quad (1) $$

where $a = \sqrt{\sum_{n=0}^{N} X_i^2(n)}$, $b = \sqrt{\sum_{n=0}^{N} Y_i^2(n)}$, $ω$ is the weighing factor, $M$ and $N$ are the length of $X_i$ and $Y_i$ respectively, and $τ$ represents the time lag between the two signals. Figure 3 shows the example of a correlogram of the peak cross-correlation coefficient between two signals. The cross-correlation results indicated that most of the peak coefficients were observed at time lag (τ) of approximately 0 second.

The MMG RMS value was determined by taking the absolute RMS of the signal epoch from each forearm muscle and then normalized against the maximum RMS from the pre-fatigue.
MVIC of the MMG signals. The pretest MVIC with the highest isometric contraction was used as the standard normalizing factor and has been uniquely normalized for each participant. Whereas, for the MMG MPF, each signal epoch was processed with a Hamming window and Fast Fourier transform (FFT) algorithm. The MMG MPF value was calculated from the obtained periodograms and used to represent the power spectrum\(^5\). MMG MPF were calculated on the obtained periodograms. In this study, all signal processing and data analysis were performed using custom programs written in MatLAB programming software.

**Statistical analysis**

The Shapiro-Wilk test is used to determine if a variable in a population is normally distributed. The statistical results of the Shapiro-Wilk test show that all data for cross-talk,
MMG RMS, and MMG MPF have a normal distribution with homogeneity of variances (p>0.05). Hence, parametric statistical tests were used for further analysis of the data. The paired sample t-test was performed to compare the effect of fatigue on the cross-talk values between pre- and post-fatigue MVIC for all the forearm muscle pairs investigated. Post-hoc analysis was performed using a Bonferroni-adjusted for multiple comparisons of muscle pairs between pre- and post-fatigue MVIC. Furthermore, the effect sizes for the paired sample t-tests were interpreted using Cohen’s (d) as follow: <0.2 (small), 0.2-0.5 (medium) and >0.5 (high)\(^7\). In addition, a repeated-measures two-way (time [pre vs post] x 4 muscles [ED vs. ECRL vs. FDS vs. FCR]) ANOVA were used to determine the effect of fatigue on the MMG RMS and MMG MPF values during pre- and post-fatigue MVIC. If any interaction was significant, simple main

![Figure 4. Raw MMG signals from ED, ECRL, FDS, and FCR muscles of a participant during pre- and post-fatigue MVIC grip muscle action.](image-url)
Effects were conducted using one-way repeated-measures ANOVA. Partial eta squared effect sizes ($\eta^2_p$) were calculated for the ANOVA. The statistical analysis was performed using IBM SPSS v. 21 (Armonk, NY) and an alpha of $p<0.05$ was considered statistically significant. All data are provided as mean (SD).

### Results

Figure 4 shows the raw MMG signal during pre- and post-fatigue MVIC of ED, ECRL, FDS and FCR forearm muscles. The cross-talk, MMG RMS and MMG MPF values were analyzed independently to determine the effect of muscle fatigue during pre- and post-fatigue MVIC of grip muscle actions.

#### Cross-talk

Figure 5 shows the mean (SD) of the cross-talk values for each muscle pair before pre- and post-fatigue MVIC. The results of mean differences show that the cross-talk values increased for MP1, MP3, MP4 and MP5 as the induced muscle fatigue for post-fatigue MVIC, except for MP2 and MP6. The statistical analysis of paired sample $t$-test of cross-talk values between the pre- and post-fatigue MVIC were detailed in Table 1. The results show that there were significant mean differences of cross-talk values for the muscle pairs MP3 ($t= -3.586, p<0.008$) and MP5 ($t= -3.263, p<0.008$), which is caused by fatigue. However, the muscle fatigue did not significantly influence the cross-talk values in the MMG signal for muscle pairs: MP1 ($t= -2.241, p=0.037$); MP2 ($t=0.284, p=0.780$); MP4 ($t= -2.646, p=0.016$) and MP6 ($t=1.085, p=0.291$). The results of mean differences show that the cross-talk values increased by 28.72%, 44.40%, 32.39% and 44.68%, respectively for MP1, MP3, MP4 and MP5 as the induced muscle fatigue during the transition from pre- to post-fatigue MVIC. The cross-talk values, however, decreased by 2.81% and 16.20% for MP2 and MP6, respectively. Based on the results of mean differences of muscle pairs

### Table 1. Paired samples t-test of cross-talk between pre- and post-fatigue MVIC.

| Cross-talk (%) | Pre-fatigue | Post-fatigue | $t$ - test | $p$ - value | Effect size, $d$ |
|----------------|-------------|--------------|-----------|------------|----------------|
| MP1            | 18.00 ± 5.68| 23.17 ± 7.66 | -2.241    | 0.037      | 0.501          |
| MP2            | 7.83 ± 2.14 | 7.61 ± 2.06  | 0.284     | 0.780      | 0.063          |
| MP3            | 5.54 ± 1.48 | 8.00 ± 2.87  | -3.586    | 0.002*     | 0.802          |
| MP4            | 6.36 ± 3.16 | 8.42 ± 2.88  | -2.646    | 0.016      | 0.592          |
| MP5            | 6.20 ± 2.56 | 8.97 ± 2.66  | -3.263    | 0.004*     | 0.730          |
| MP6            | 18.33 ± 11.60| 15.36 ± 5.75 | 1.085     | 0.291      | 0.243          |

* Bold font indicates statistical significance, $p<0.008$
Table 2. The marginal mean (±SD) for the pre- and post-fatigue MVIC.

|                | Pre-fatigue MVIC | Post-fatigue MVIC |
|----------------|------------------|-------------------|
| **MMG RMS (V)**|                  |                   |
| ED             | 3.45 ± 1.31      | 2.03 ± 1.40       |
| ECRL           | 2.47 ± 1.13      | 1.64 ± 1.49       |
| FDS            | 3.12 ± 1.17      | 1.77 ± 1.35       |
| FCR            | 3.96 ± 1.21      | 2.26 ± 1.53       |
| **MMG MPF (Hz)**|                 |                   |
| ED             | 50.23 ± 6.09     | 46.27 ± 7.43      |
| ECRL           | 47.91 ± 9.06     | 44.17 ± 7.28      |
| FDS            | 40.66 ± 6.93     | 38.39 ± 7.55      |
| FCR            | 39.50 ± 7.56     | 36.48 ± 5.60      |

Figure 6. MMG RMS of pre- and post-fatigue MVIC of extensor (ED & ECRL) and flexor (FDS & FCR) muscles.

Figure 7. MMG MPF of pre- and post-fatigue MVIC of extensor (ED & ECRL) and flexor (FDS & FCR) muscles.
between pre- and post-fatigue MVIC (see Table 1), it can be concluded that fatigue effect significantly increased the cross-talk values in the MMG signal for all the forearm muscle pairs except for MP2 and MP6. Besides, according to Cohen’s interpretation of effect size mentioned, there were small effect sizes (MP2 and MP6), medium effect sizes (MP1, MP4 and MP5) and large effect sizes (MP3) of CT values in the pre- and post-fatigue test.

**MMG RMS and MMG MPF**

A repeated-measures two-way (time: pre- vs post-fatigue MVIC) × (muscle: ED vs ECRL vs FDS vs FCR) ANOVAs exhibited no significant interaction for time × muscle MMG RMS ($F_{1,152}=0.756$, $p=0.520$, $n^2_p=0.015$), which indicates that there was no change in MMG RMS values due to fatigue effect. However, there were significant main effects on time ($F_{1,152}=39.617$, $p<0.05$, $n^2_p=0.207$) and muscle ($F_{3,152}=4.501$, $p<0.05$, $n^2_p=0.082$) showing that there were change in MMG RMS values due to induced muscle fatigue. On the examination of mean differences, both results for extensor and flexor muscles show a consistent decrease of MMG RMS values during pre- and post-fatigue MVIC that caused by fatigue. The results presented 41.16% and 36.60% declines in MMG RMS between pre- and post-fatigue MVIC for ED and ECRL (extensor) muscles, respectively. Likewise, 43.27% and 42.93% of FDS and FCR (flexor) muscles declines in MMG RMS due to induced muscle fatigue (see Figure 6 and Table 2).

Similarly, the two-way ANOVA analysis revealed no significant interaction for time × muscles for MMG MPF ($F_{1,152}=0.110$, $p=0.954$, $n^2_p=0.002$). But there were significant main effects on time ($F_{1,152}=8.015$, $p<0.05$, $n^2_p=0.050$) and muscle ($F_{3,152}=18.763$, $p<0.05$, $n^2_p=0.270$) indicating that there were changes in MMG MPF values due to induced muscle fatigue. On the same examination of mean differences, both extensor and flexor muscles results show a consistent decreasing of MMG MPF during pre- and post-fatigue MVIC caused by muscle fatigue. The results presented 7.88% and 7.81% decreased in MMG MPF between pre- and post-fatigue MVIC for ED and ECRL (extensor) muscles, respectively. Also, 5.58% and 7.65% of FDS and FCR (flexor) muscles decreased in MMG MPF due to the fatigue effect (see Figure 7 and Table 2).

**Discussion**

The objective of this study was to analyze the effect of fatigue forearm muscles (extensor and flexor) on the cross-talk in MMG signals during pre- and post-fatigue MVIC. It was hypothesized that when the force production during repetitive submaximal (60% MVIC) isometric contractions decreases, the cross-talk in MMG signals will increase. To test this hypothesis, the mean cross-talk values were quantified and analyzed from pre- and post-fatigue MVIC in 6 muscle pairs investigated. Additionally, the current study also observed the behavior of MMG signals related to motor unit recruitment (RMS) and motor unit firing rate (MPF) for both extensor and flexor forearm muscles to see whether they can provide significant results on the contraction mechanics during pre- and post-fatigue MVIC. These observations aimed to examine the effect of induced muscle fatigue on the MMG RMS and MMG MPF of forearm muscles. The MMG RMS and MMG MPF values were compared to each of the extensor (ED & ECRL) and flexor (FDS & FCR) muscles during pre- and post-fatigue MVIC.

Based on the stated results, the mean differences of muscle pairs for cross-talk values between pre- and post-fatigue MVIC were found to be statistically significant, as shown in Table 1. Apparently, the induced muscle fatigue increased the cross-talk values in all the forearm muscle pairs except MP2 (ED & FDS) and MP6 (FDS & FCR), as shown in Figure 5. These results support the finding reported by Kong et. al. where the number of cross-talk values increased due to the contamination signals that correlated between two adjacent muscles. However, the decreased in cross-talk values for MP2 and MP6 muscle pairs might possibly due to the larger distance in both muscles as the cross-talk in myography signal is a function of muscle proximity. This finding supported our hypothesis that the amount of cross-talk would increase as the muscle fatigue induced, due to the contamination signals of proximity muscles.

In addition, this study also analyzed the effect of muscle fatigue on the cross-talk in two different groups, which are within-muscles (extensor muscle, MP1 and flexor muscle, MP6) and between-muscles (MP2, MP3, MP4 and MP5) during pre- and post-fatigue MVIC. The recorded cross-talk values for within and between compartmental of adjacent muscle pairs ranged from 15.36% to 23.17% and 5.54% to 8.97%, respectively. The cross-talk values for the group of within-muscles (MP1 and MP6) are higher compared to the value obtained for the group of between-muscles (MP2, MP3, MP4 and MP5), demonstrating that the cross-talk value increased as the distance between sensors placed on the targeted muscle pairs decreased. The finding is parallel with a previous study by, where the cross-talk values for within compartmental muscles (27.46%-55.17%) was higher than between compartmental muscles (13.21%-35.53%). Additionally, the presented results indicate that the extensor muscle pair (MP1) shows the highest cross-talk values compared to the flexor muscle pair (MP6) which were ranged from 18.98%-29.94% and 11.85%-18.65%, respectively, during pre- and post-fatigue MVIC. This result was supported by De Luca, which conclude that cross-talk decreased with the increase of distance between two muscles location. However, the current finding was contradicted to those published by Mogk and Keir, who discovered the amount of cross-talk values were up to 50% for extensors and 60% for flexors muscles during gripping tasks. The contradiction could be related to differences in the fascicle structure of muscle fibers, muscle size and number of proximity muscle, which contribute to cross-talk changes in MMG signals.

Despite the proximity muscle that correlates high contamination on cross-talk, the range of amplitude...
signals recorded also affected the cross-talk value. The attenuated low signal amplitudes signified a reduction in the force capability of muscle contractions and this scenario also influenced the motoneuron firing rate which occurred when the fatigue changes the intrinsic muscles. During fatiguing maximal contraction, the motoneuron firing rate decreases because of repetitive activation (repeated firing), resulting in less force being generated on the active muscles. As the large muscle voluntary contractions decreased, the signal amplitude dropped to an almost a similar range as the signal amplitude for small muscles. During pre-fatigue MVIC, ED has a higher amplitude signal dedicated on the extensor muscle whereas for the flexor muscle, FCR has higher amplitudes compared to FDS (see Figure 4). The present results were supported by previous researchers which revealed that ED and FCR muscles exhibited large effect sizes during handgrip and wrist exertion. However, during post-fatigue MVIC, the current results observed that induced muscle fatigue significantly affected these muscles (ED and FCR) with minimal activity and low variability of muscle activity (lower in amplitude) compared to other muscles (ECRL and FDS) as shown in Figure 4. This finding agreed with our understanding that the cross-talk increased as the amplitude signal of muscles (ED and FCR) decreased to a similar range of the other muscles signal (ECRL and FDS) during post-fatigue MVIC due to induced muscle fatigue. Consequently, no significant differences recorded on MP2 (ED and FDS) and MP6 (FDS and FCR) muscle pairs were related to the FDS muscle due to lower activation of muscle activity, which decreased the cross-talk values when correlated to the ED and FCR muscles.

As shown in Table 1, the overall mean for cross-talk values were ranged from 5.54% to 23.17% for all the forearm muscle pairs. The cross-talk values observed in this study can be compared with the finding reported by researchers where the authors examined cross-talk of MMG signals on forearm muscles (ED, ECU and FCU) during submaximal to maximal isometric grip muscle actions. The cross-talk values were reported to range from 2.45% to 62.28% which slightly higher than the current study. The difference in related findings might be due to the number and selection of forearm muscles, type of accelerometer used and anthropometric parameters of participants. The presence of cross-talk in this study supported the observation that, a diverse range of activities on the forearm muscle will increase the chances of receiving contaminated signals from the examined muscle even after induced muscle fatigue.

Fatigue is generally associated with the ability to maintain and perform any muscular contraction at the desired target, which reflects decreases in muscle strength, force production and shifting power spectrum. As mentioned before, MMG RMS is referred to the muscle strength and force production during muscle contraction, whereas MMG MPF denotes the shifting power spectrum towards frequency levels. In this study, the development of muscle fatigue was spotted correlated to changes in the MMG RMS and MMG MPF values during pre- and post-fatigue MVIC. The MMG RMS was analyzed to observe the strength and force production capacity of forearm muscles during fatigue assessments. In the present work, the statistical mean differences indicate that, MMG RMS decreased from pre-fatigue to post-fatigue MVIC for both extensor and flexor muscles. The results show that the decrease of MMG RMS at 60% of MVIC may reflect the de-recruitment of the fast fatiguing motor unit due to a high level of muscle contractions. The MMG RMS for ED and ECRL muscles decreased by 41.16% and 36.60%, whereas FDS and FCR muscles decreased by 43.27% and 42.93%, respectively due to induced muscle fatigue. The results demonstrated that flexor muscles significantly decreased in MMG RMS compared to extensor muscles, which indicates that low muscle strength and force production were generated. These findings further support the theory that during exercise the muscles voluntary force-producing lose their capacity throughout the time. In addition, the MMG RMS depends on the muscle fiber activation and it is generally increasing simultaneously with increasing muscle force and vice versa.

In the present result, MMG RMS decreased drastically on the post-fatigue MVIC for all investigate muscles (see Figure 6). This finding agrees with Gobbo et al., who discovered changes in muscle fiber activity at different muscular forces during muscle fatigue. The MMG RMS results indicated that the strength and force production capacity drastically decreased, especially FDS muscle due to fatigue protocols carried out in this study. The results agreed with the previous study in which the authors demonstrated post-fatigue MVIC decreases the muscle strength and force production through the changes of amplitude signals. Moreover, induced muscle fatigue in the present results concurs with the findings, where the correlation between the fatigue simulation versus time course illustrated decreased trend in MMG RMS values. In this work, the induced muscle fatigue significantly affects the muscles' physiology, as a result of the fatigue protocol's procedure. These finding supported the conclusion made by Salwani et al., where the RMS-MMG values decreased as muscle force decreased due to the muscle fatigue.

MMG MPF was analyzed to observe the effect of muscle fatigue related to shifting power spectrum towards frequency levels during fatigue assessment. The current findings revealed that the fatigue protocol had a significant effect on post-fatigue MVIC, where MMG MPF decreased as induced muscle fatigue. Based on Figure 7 and Table 2, the statistical mean differences, indicates that the fatigue protocols significantly shifted the power spectrum of the MMG MPF values for both extensor and flexor muscles toward the lower frequency range (global firing rate of the motor units decreases). The results agreed with previous research, which found that MPF pattern during repeated muscle actions on quadriceps femoris muscles decreased in the global firing rate of active motor units due to fatigue tasks. The current study observed that MMG MPF for ED and ECRL muscles decreased by 7.88% and 7.81%, whereas FDS and FCR muscles decreased by 5.58% and 7.65%, respectively due to induced muscle fatigue. Moreover, the fatigue effect...
on the extensor muscles in the present results show a significant declined trend compared to flexor muscles (see Figure 7 and Table 2), indicating that the fatigue level has a greater effect on the extensor muscles. This may be due to the specific influences of different components of muscle mechanical of the forearm during grip muscle actions. These results appeared to be consistent with the research by 68, signifying that the extensor muscles were more sensitive to muscles fatigue compared to the flexor muscles. A consistent decrease in MMG MPF values was also been reported previously by 21, during intermittent (30% MVIC, increment by 5%) and continuous static (100% MVIC, increment by 25%) contractions of maximal voluntary contractions.

Despite the overall discussion, several potential limitations should be highlighted. Firstly, this study did not consider the skin-fold thickness of the forearm muscles which influences the cross-talk values in MMG signals 69. Second, this study was carried out only on male volunteers. It has been suggested that males may experience greater muscle fatigue than females for contraction at 40%-60% MVIC, as investigated by sex-related differences 70. Therefore, it is reasonable to hypothesize that the MMG RMS, MMG MPF and cross-talk values could be slightly different in female participants.

Conclusion

The cross-talk in MMG signals from extensor and flexor forearm muscle was influenced by the induced muscle fatigue for all the forearm muscle pairs during pre- and post-fatigue MVIC. These results indicate that the fatigue effect increased cross-talk values in all the forearm muscle pairs except for MP2 (ED & FDS) and MP6 (FDS & FCR). The contradiction found in MP2 and MP6 muscle pairs is associated with the lower activation of FDS muscle activity, which decreased the cross-talk values when correlated to the ED and FCR muscles. The overall mean cross-talk values ranged from 5.54%-23.17% in all the forearm muscle pairs. The study has found that the cross-talk in extensor muscle is always higher than the flexor muscle, where the recorded data in extensor muscle was from muscle pair MP1 with the percentage of 18.98%-29.94%, while for the flexor muscle, muscle pair MP6 reported the highest percentage at 11.85%-18.65%. These findings indicate that cross-talk values increased with the decrease of distance between two adjacent muscles. In conclusion, the findings in the present work offering a new understanding of the mechanics of the forearm muscles during induced muscle fatigue, and the comprehensive information can be used as further reference for future development of hand prosthesis control 71, neuromuscular response 79, the assessment of arm function in the fields of sports 72 and rehabilitation monitoring systems 73. Last but not least, the demonstrated results on the trend of MMG RMS and MMG MPF values for each muscle might be useful in the motor recruitment pattern and global firing rate of the motor units during muscles fatigue.

Authors’ contributions

All authors contributed to the study conception and design and in particular: Conception and design of the study: Mohamad Razif Mohamad Ismail, Chee Kiang Lam. Kenneth Sundaraj. Mohd Hafiz Fazalul Rahman. Generation, collection and integrity of the data: Mohamad Razif Mohamad Ismail, Chee Kiang Lam. Assembly, analysis and/or interpretation of the data: Mohamad Razif Mohamad Ismail, Chee Kiang Lam. Drafting and revising the manuscript: Mohamad Razif Mohamad Ismail, Chee Kiang Lam.

Funding

The authors would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2015/TK04/UNIMAP/02/5 from the Ministry of Higher Education Malaysia.

References

1. Rodrigues J, Santos-Faria D, Silva J, Azevedo S, Tavares-Costa J, Teixeira F. Sonoanatomy of anterior forearm muscles. J Ultrasound 2019;22:401–5.
2. Mogk JPM, Keir PJ. Crosstalk in surface electromyography of the proximal forearm during gripping tasks. J Electromyogr Kinesiol 2003;13:63–71.
3. Forman DA, Forman GN, Robathan J, Holmes MWR. The influence of simultaneous handgrip and wrist force on forearm muscle activity. J Electromyogr Kinesiol 2019;45:53–60.
4. Kent-Braun JA, Ng AV, Doyle JW, Towe TF. Human skeletal muscle responses vary with age and gender during fatigue due to incremental isometric exercise. J Appl Physiol 2002;93:1813–23.
5. Ebersole KT, O’Connor KM, Wier AP. Mechanomyographic and electromyographic responses to repeated concentric muscle actions of the quadriceps femoris. J Electromyogr Kinesiol 2006;16:149–57.
6. Hill EC, Housh TJ, Smith CM, Cochrane KC. Jenkins NDM, Cramer JT, et al. Effect of sex on torque, recovery, EMG, and MMG responses to fatigue. J Musculoskeletal Neuronal Interact 2016;16:310–7.
7. AllenDG, LambGD, WesterbladH. Skeletal muscle fatigue: Cellular mechanisms. Physiol Rev 2008;88:287–332.
8. Al-Mulla MR, Sepulveda F, Colley M. A review of non-invasive techniques to detect and predict localised muscle fatigue. Sensors 2011;11:3545–94.
9. Smith CM, Housh TJ, Jenkins NDM, Hill EC, Cochrane KC, Miramonti AA, et al. Combining regression and mean comparisons to identify the time course of changes in neuromuscular responses during the process of fatigue. Physiol Meas 2016;37:1993–2002.
10. Gonzalez-Izal M, Cadore EL, Izquierdo M. Muscle conduction velocity, surface electromyography variables, and echo intensity during concentric and eccentric fatigue. Muscle and Nerve 2014;49:389–97.
11. Bilgin G, Hindistan IE, Özkaya YG, Köklükaya E, Polat Ö, Çolak ÖH. Determination of Fatigue Following Maximal Loaded Treadmill Exercise by Using Wavelet Packet Transform Analysis and MLPNN from MMG-EMG Data
12. Smith CM, Housh TJ, Herda TJ, Zuniga JM, Camic CL, Bergstrom HC, et al. Time Course of Changes in Neuromuscular Parameters During Sustained Isometric Muscle Actions. J Strength Cond Res 2016;30:2697–702.

13. Naeem J, Hamzaid NA, Islam A, Azman AW, Bijak M. Mechanomyography-based muscle fatigue detection during electrically elicited cycling in patients with spinal cord injury. Med Biol Eng Comput 2019;57:1199–211.

14. Mohamad Saadon NS, Hamzaid NA, Hasnan N, Dzulkiﬁ MA, Davis GM. Electrically evoked wrist extensor muscle fatigue throughout repetitive motion as measured by mechanomyography and near-infrared spectroscopy. Biomed Tech 2019;64:439–48.

15. Tosovic D, Than C, Brown JMM. The effects of accumulated muscle fatigue on the mechanomyographic waveform: implications for injury prediction. Eur J Appl Physiol 2016;116:1485–94.

16. Hussain J, Sundaraj K, Low YF, Lam CK, Sundaraj S, Ali MA. A systematic review on fatigue analysis in triceps brachii using surface electromyography. Biomed Signal Process Control 2018;40:396–414.

17. Orizio C. Muscle Sound: Bases for the Introduction of a Mechanomyographic Signal in Muscle Studies. Biomed Eng (NY) 1993;3:201–43.

18. Marusiak J, Jaskólska A, Kisiel-Sajewicz K, Yue GH, Jaskólski A. EMG and MMG activities of agonist and antagonist muscles in Parkinson’s disease patients during absolute submaximal load holding. J Electromyogr Kinesiol 2009;19:903–14.

19. Hill E, Housh T, Smith C, Schmidt R, Johnson G. Muscle-and Mode-Speciﬁc Responses of the Forearm Flexors to Fatiguing, Concentric Muscle Actions. Sports 2016;4:47.

20. Beck TW. Surface mechanomyographic responses to muscle fatigue. Transw Res Netw 2010;37:p51.

21. Madeleine P, Jorgensen LV, Segard K, Arendt-Nielsen L, Sjoggaard G. Development of muscle fatigue as assessed by electromyography and mechanomyography during continuous and intermittent low-force contractions: Effects of the feedback mode. Eur J Appl Physiol 2002;87:28–37.

22. Kimura T, Fujibayashi M, Tanaka S, Moritani T. Mechanomyographic responses in quadriceps muscles during fatigue by continuous cycle exercise. Eur J Appl Physiol 2008;104:651–6.

23. Itoh Y, Akataki K, Mita K, Watakabe M, Itoh K. Time-Frequency Analysis of Mechanomyogram during Sustained Contractions with Muscle Fatigue. Syst Comput Japan 2004;35:26–36.

24. Lei KF, Tsai WW, Lin WY, Lee MY. MMG-torque estimation under dynamic contractions. Conf Proc - IEEE Int Conf Syst Man Cybern 2011;585–90.

25. Malek MH, Coburn JW, Tedjasaputra V. Comparison of mechanomyographic amplitude and mean power frequency for the rectus femoris muscle: Cycle versus knee-extensor ergometry. J Neurosci Methods 2009;181:89–94.

26. Perry-Rana SR, Housh TJ, Johnson GO, Bull AJ, Berning JM, Cramer JT. MMG and EMG responses during fatiguing isokinetic muscle contractions at different velocities. Muscle and Nerve 2002;26:367–73.

27. Yoon SH, Jung MC, Park SY. Evaluation of surgeon’s muscle fatigue during thoracoscopic pulmonary lobectomy using interoperative surface electromyography. J Thorac Dis 2016;8:1162–9.

28. Madeleine P, Ge HYHY, Jaskólska A, Farina D, Jaskólski A, Arendt-Nielsen L. Spectral moments of mechanomyographic signals recorded with accelerometer and microphone during sustained fatigue contractions. Med Biol Eng Comput 2006;44:290–7.

29. Han H, Jo S, Kim J. Comparative study of a muscle stiffness sensor and electromyography and mechanomyography under fatigue conditions. Med Biol Eng Comput 2015;53:577–88.

30. Hendrix CR, Housh TJ, Camic CL, Zuniga JM, Johnson GO, Schmidt RJ. Comparing electromyographic and mechanomyographic frequency-based fatigue thresholds to critical torque during isometric forearm flexion. J Neurosci Methods 2010;194:64–72.

31. Koh TJ, Grabiner MD. Cross talk in surface electromyograms of human hamstring muscles. J Orthop Res 1992;10:701–9.

32. Beck TW, DeFreitas JM, Stock MS. An examination of cross-talk among surface mechanomyographic signals from the superficial quadriceps femoris muscles during isometric muscle actions. Hum Mov Sci 2010;29:165–71.

33. Islam A, Sundaraj K, Ahmad RB, Sundaraj S, Ahamed NU, Ali MA. Cross-Talk in Mechanomyographic Signals from the Forearm Muscles during Sub-Maximal to Maximal Isometric Grip Force. PLoS One 2014;9:e96628.

34. Talib I, Sundaraj K, Lam CK. Analysis of the crosstalk in mechanomyographic signals along the longitudinal, lateral and transverse axes of elbow flexor muscles during sustained isometric forearm flexion, supination and pronation exercises. J Musculoskelet Neuronal Interact 2020;20:194–205.

35. Farina D, Merletti R, Indino B, Nazzaro M, Pozzo M. Surface EMG crosstalk between knee extensor muscles: Experimental and model results. Muscle and Nerve 2002;26:681–95.

36. Lowery MM, Stoykov NS, Kuiiken TA. A simulation study to examine the use of cross-correlation as an estimate of surface EMG crosstalk. J Appl Physiol 2003;94:1324–34.

37. Winter DA, Fuglevand AJ, Archer SE. Crosstalk in surface electromyography: Theoretical and practical estimates. J Electromyogr Kinesiol 1994;4:15–26.
39. Kong YK, Hallbeck MS, Jung MC. Crosstalk effect on surface electromyogram of the forearm flexors during a static grip task. J Electromyogr Kinesiol 2010; 20:1223–9.

40. Winter DA, Fuglevand AJ, Archer SE. Crosstalk in surface electromyography: Thoretical and practical estimates. J Electromyogr Kinesiol 1994;4(1):15–26.

41. Islam A, Sundaraj K, Ahmad B, Ahamed NU, Ali MA. Analysis of crosstalk in the mechanomyographic signals generated by forearm muscles during different wrist postures. Muscle and Nerve 2015;51:899–906.

42. Talib I, Sundaraj K, Lam CK. Crosstalk in Mechanomyographic Signals From Elbow Flexor Muscles During Submaximal to Maximal Isometric Flexion, Pronation, and Supination Torque Tasks. J Biomech Eng 2021;143:1–8.

43. Islam A, Sundaraj K, Ahmad B, Ahamed NU, Ali A. Mechanomyography sensors for muscle assessment: A brief review. J Phys Ther Sci 2012;24:1359–65.

44. Novák P, Zacharová G, Soukup T. Individual, age and sex differences in fiber type composition of slow and fast muscles of adult lewis rats: Comparison with other rat strains. Physiol Res 2010;59:783–801.

45. Adam A, De Luca CJ, Erim Z. Hand dominance and motor unit firing behavior. J Neurophysiol 1998;80:1373–82.

46. Tian SL, Liu Y, Li L, Fu WJ, Peng CH. Mechanomyography is more sensitive than EMG in detecting age-related sarcopenia. J Biomech 2010;43:551–6.

47. Noakes TD, St. Clair Gibson A, Lambert E V. From catastrophe to complexity: A novel model of integrative central neural regulation of effort and fatigue during exercise in humans: Summary and conclusions. Br J Sports Med 2005;39:120–4.

48. Borg G, Hassmén P, Lagerström M. Perceived exertion related to heart rate and blood lactate during arm and leg exercise. Eur J Appl Physiol Occup Physiol 1987;56:679–85.

49. Perotto A & Delagi EF. Anatomical Guide for the Electromyographer: The Limbs and Trunk: Charles C Thomas., 2005.

50. Abd Aziz M, Hamzaid NA, Hasnain N, Dzulkifli MA. Mechanomyography-based assessment during repetitive sit-to-stand and stand-to-sit in two incomplete spinal cord-injured individuals. Biomed Tech 2019.

51. Mogk JPM, Keir PJ. Prediction of forearm muscle activity during gripping. Ergonomics 2006;49:1121–30.

52. Roman-Liu D, Bartuзи P. The influence of wrist posture on the time and frequency EMG signal measures of forearm muscles. Gait Posture 2013;37:340–4.

53. Ngo BPT, Wells RP. Evaluating protocols for normalizing forearm electromyograms during power grip. J Electromyogr Kinesiol 2016;26:66–72.

54. Ibitoye MO Iusola, Hamzaid NA, Zuniga JM, Hasnain N, Wahab AK hairi A. Mechanomyographic parameter extraction methods: an appraisal for clinical applications. Sensors (Basel) 2014;14:22940–70.

55. Diemont B. Spectral Analysis of Muscular Sound at Low and High Contraction Level. Int J Biomed Comput 1988;23:161–75.

56. Kwatny E, Thomas DH, Kwatny HG. An Application of Signal Processing Techniques to the Study of Myoelectric Signals. IEEE Trans Biomed Eng 1970;BME-17:303–13.

57. Jacob C. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale: Lawrence Erlbaum Associates Inc.; 1988.

58. Talib I, Sundaraj K, Lam CK. Association of anthropometric parameters with amplitude and crosstalk of mechanomyographic signals during forearm flexion, pronation and supination torque tasks. Sci Rep 2019;9:1–12.

59. De Luca CJ, Kuznetsov M, Gilmore LD, Roy SH. Inter-electrode spacing of surface EMG sensors: Reduction of crosstalk contamination during voluntary contractions. J Biomech 2012;45:555–61.

60. Wan JJ, Qin Z, Wang PY, Sun Y, Liu X. Muscle fatigue: General understanding and treatment. Exp Mol Med 2017;49:e384-11.

61. Keir PJ, Mogk JPM. The development and validation of equations to predict grip force in the workplace: Contributions of muscle activity and posture. Ergonomics 2005;48:1243–59.

62. Stephan Riek, Richard G. Carson, Anthony Wright b. A new technique for the selective recording of extensor carpi radialis longus and brevis EMG. J Electromyogr Kinesiol 2000;10:249–53.

63. Orizio C, Gabbo M, Diemont B, Esposito F, Veicsteinas A. The surface mechanomyogram as a tool to describe the influence of fatigue on biceps brachii motor unit activation strategy. Historical basis and novel evidence. Eur J Appl Physiol 2003;90:326–36.

64. Zwarts MJ, Bleijenberg G, van Engelen BGM. Clinical neurophysiology of fatigue. Clin Neurophysiol 2008; 119:2–10.

65. Gabbo M, Cè E, Diemont B, Esposito F, Orizio C. Torque and surface mechanomyogram parallel reduction during fatiguing stimulation in human muscles. Eur J Appl Physiol 2006;97:9–15.

66. Blangsted AK, Sjøgaard G, Madeleine P, Olsen HB, Søgaard K. Voluntary low-force contraction elicits prolonged low-frequency fatigue and changes in surface electromyography and mechanomyography. J Electromyogr Kinesiol 2005;15:138–48.

67. Cè E, Rampichini S, Monti E, Venturelli M, Limonta E, Esposito F. Changes in the electromechanical delay components during a fatiguing stimulation in human skeletal muscle: an EMG, MMG and force combined approach. Eur J Appl Physiol 2017;117:95–107.

68. Larivièrè C, Plamondon A, Lara J, Tellier C, Boutin J, Dagenais A. Biomechanical assessment of gloves. A study of the sensitivity and reliability of electromyographic parameters used to measure the activation and fatigue of different forearm muscles. Int J Ind Ergon 2004;34:101–16.
69. Jaskólska A, Brzenczek W, Kisiel-Sajewicz K, Kawczyński A, Marusiak J, Jaskólski A. The effect of skinfold on frequency of human muscle mechanomyogram. J Electromyogr Kinesiol 2004;14:217–25.
70. Demura S, Nakada M, Nagasawa Y. Gender difference in subjective muscle-fatigue sensation during sustained muscle force exertion. Tohoku J Exp Med 2008;215:287–94.
71. Smith CM, Housh TJ, Hill EC, Keller JL, Johnson GO, Schmidt RJ. A biosignal analysis for reducing prosthetic control durations: A proposed method using electromyographic and mechanomyographic control theory. J Musculoskelet Neuronal Interact 2019;19:142–9.
72. Macgregor LJ, Hunter AM, Orizio C, Fairweather MM, Ditroilo M. Assessment of Skeletal Muscle Contractile Properties by Radial Displacement: The Case for Tensiomyography. Sport Med 2018;48:1607–20.
73. Begovic H, Can F, Yağcioğlu S, Ozturk N. Passive stretching-induced changes detected during voluntary muscle contractions. Physiother Theory Pract 2020;36:731–40.