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Original Article

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

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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 muscles[1]. During contraction, the common function of each forearm muscles varied depending on the size and proximity of the muscles[2]. 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 to[3], 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 contraction[4,5] 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 exercise[6]. Furthermore, muscles fatigue also influenced by the factors such as age[4], different types of metabolism and fiber[5], muscle mass[7], accumulation of lactic acid in muscle tissue and depletion of glycogen which stored glucose[8], muscle wisdom[9], and quality of muscle to produce force[10]. During an isometric contraction,

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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[6].

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[19]. 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[14,19,28–30].

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[2,39] and MMG[32–34,41,42] 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[33], 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[41], 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

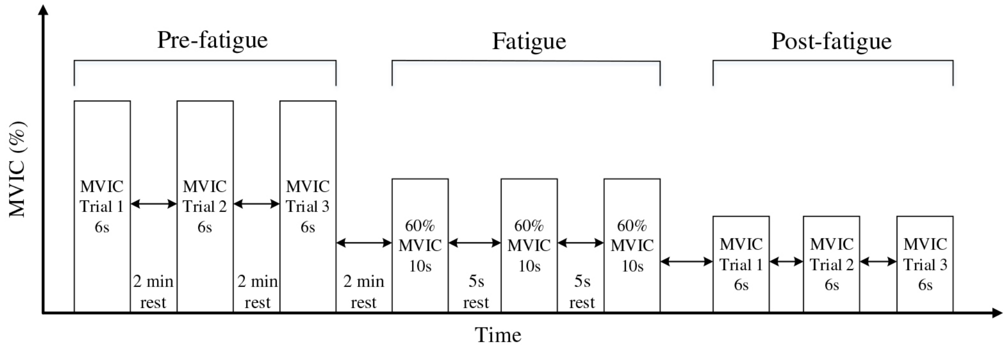

Figure 1. Schematic of the experimental protocol. The participants performed pre-fatigue MVIC, fatigue exercise at 60% of MVIC and post-fatigue MVIC during grip muscle actions.

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[44,45]. Also, the participants were limited to the age group of 19 to 28 years old because a wider range of participant age may influence the MMG signal recorded[46].

Experimental protocol

There were two orientation sessions held for each participant. During the first session, the participant familiarized with the equipment and muscle fatigue testing protocols by practicing MVIC and submaximal (60% of MVIC) isometric 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[47].

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[48] 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, including the physiologic tremor, 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[49], using double-sided adhesive tapes in a neutral arm position to ensure the applied pressure was uniform and consistent[50]. These muscles were selected based on their relevance to hand and wrist function during handgrip[51–53]. 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[54]. 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 by[34].

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 ($R^2_{x,y}$) 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).

$$R_{x,y}(\tau) = \frac{1}{a \times b \times \omega(\tau)} \sum_{n=0}^{N-1} X_t(n) * Y_t(n+\tau);\ 1-N < \tau < M \text{ , (1)}$$

where $a = \sqrt{\sum_{n=0}^{N-1} X_t^2(n)}$, $b = \sqrt{\sum_{n=0}^{M-1} Y_t^2(n)}$,

ω is the weighing factor, M and N are the length of X_t and Y_t 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

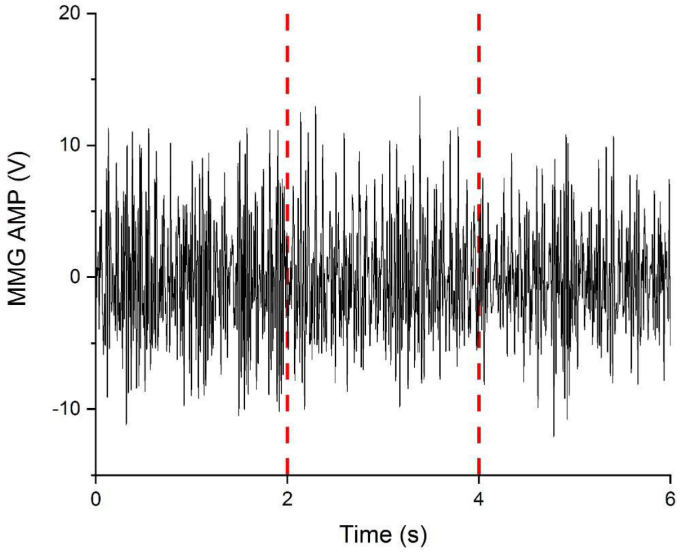

Figure 2. MMG time history data. The signals extracted between 2 to 4 seconds of the time sampling to calculate MMG RMS, MMG MPF and CT values.

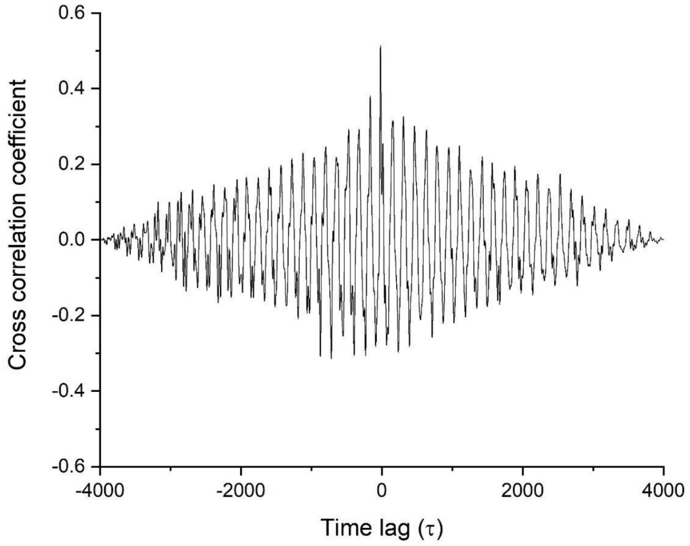

Figure 3. Correlogram of MMG signal analyzed from the fatigue assessment of MP1 (ED & ECRL) during MVIC grip force performed by a participant. The figure showed level of correlation for entire time lags but the peak correlation is approximately at 0-time lag for the muscle pair.

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[55,56]. 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,

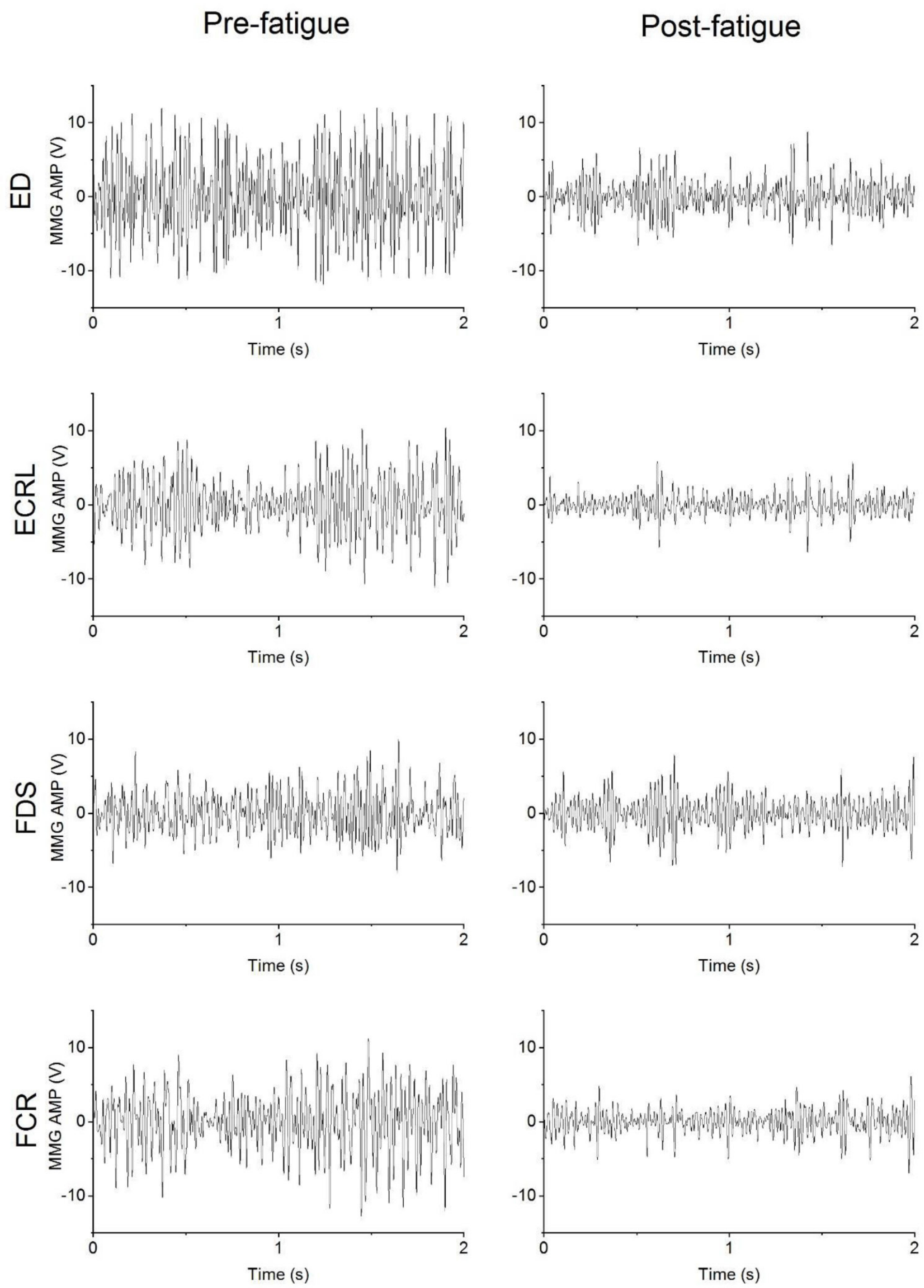

Figure 4. Raw MMG signals from ED, ECRL, FDS, and FCR muscles of a participant during pre- and post-fatigue MVIC grip muscle action.

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)[57]. 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

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*

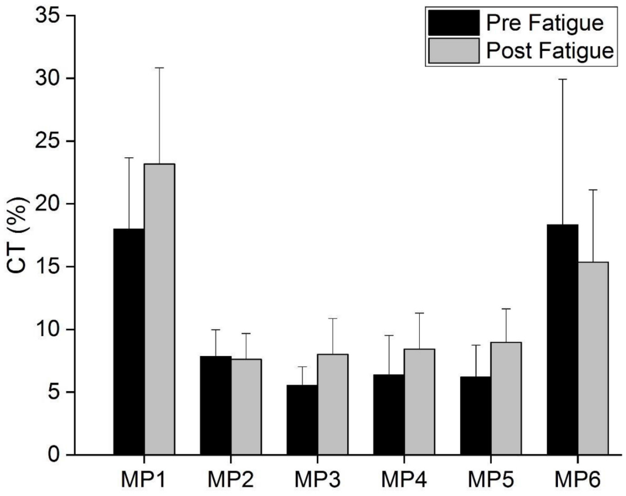

Figure 5. Cross-talk of the six muscle pairs (MP1: ED & ECRL, MP2: ED & FDS, MP3: ED & FCR, MP4: ECRL & FDS, MP5: ECRL & FCR and MP6: FDS & FCR) of pre- and post-fatigue MVIC.

effects were conducted using one-way repeated-measures ANOVA. Partial eta squared effect sizes (n^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 pos-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 between 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 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

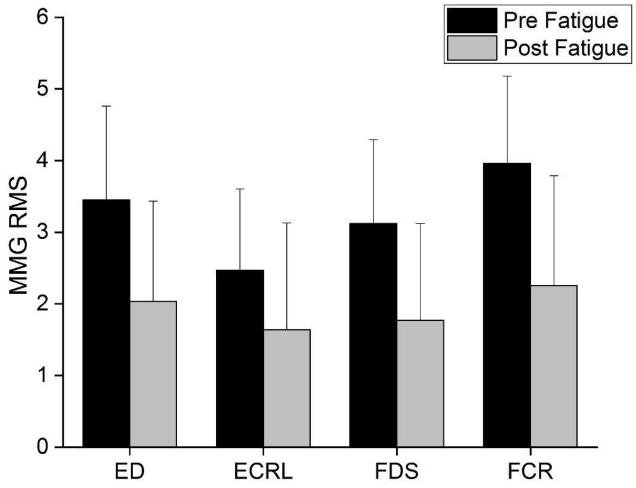

Figure 6. MMG RMS of pre-and post-fatigue MVIC of extensor (ED & ECRL) and flexor (FDS & FCR) muscles.

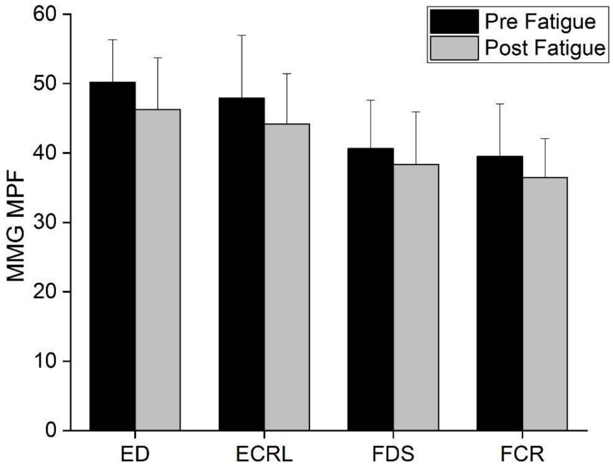

Figure 7. MMG MPF of pre- and post-fatigue MVIC of extensor (ED & ECRL) and flexor (FDS & FCR) muscles.

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 ($F_{3,152}$=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 ($F_{3,152}$=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.[39] 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[58]. 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[33], 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[59], 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[2], 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[32], which contribute to cross-talk changes in MMG signals.

Despite the proximity muscle that correlates high contamination on cross-talk[39], 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[60]. 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[3,61] 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[33], 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 were 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[62] 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 a to high level of muscle contractions[63]. 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[64] throughout the time[29]. 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.[65], 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 by[66], 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 by[67], 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.[14], 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 by[5], 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[19], 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 Rahiman. 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.

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