Cross-correlation analysis of isometric contraction for mechanomyography signals on forearm muscle

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Abstract. This study examines the cross-correlation coefficient of Mechanomyography (MMG) signals recorded from Palmaris Longus (PL), Flexor Digitorum Superficialis (FDS), Extensor Digitorum (ED) and Extensor Carpi Ulnaris (ECU) of forearm muscles during isometric muscle action. Nine healthy participants using dominant hand (mean±SD: age=24.78±1.79 year) volunteered in this study to perform submaximal to maximal (25%, 50%, 75% and 100%) isometric muscle actions with maximal voluntary contraction force of hand exercise gestures (grip strength supinated, grip strength pronated, finger flexion and pinch grip). During each isometric contraction, four-separated VMG sensor (TSD250A)-sensitive accelerometer type was used to record MMG signals on flexor and extensor side of forearm muscles. Maximum cross-correlation coefficients at zero time lags were analyzed between flexor (PL & FDS) and extensor (ED & ECU) sides for each subject and force level to determine which sides show high level of association during isometric muscle action of forearm with different hand exercise gestures. The results showed maximum cross-correlation coefficients that range from $R_{x,y} = 0.801 - 0.943$ for all hand exercise gestures performed. In addition, from the results obtained between flexor and extensor side indicates that the maximum range of cross-correlation coefficient for extensor side muscle groups were slightly higher than the flexor side muscle groups.

1. Introduction
Recently, the relationship between muscle activities and generated force during muscle contraction is becoming a popular case study among researchers. Various recording techniques have been developed to measure muscle activities from different aspects especially on forearm and leg muscles. Most popular techniques used includes electromyography (EMG) and mechanomyography (MMG) signals. EMG is composed of electrical contribution made by the active motor units during muscle contraction. Meanwhile, MMG is a recording of the low-frequency lateral oscillations of active motor units considered as mechanical contribution during muscle contraction [1]. Several studies are working with both EMG and MMG responses during isometric muscle action on forearm and leg muscles with cross-correlation coefficient to determine the amount of common signal (cross-talk). For example Mogk and Keir [2] used cross-correlation function to determine amount of cross-talk with forearm postures: pronation, neutral and supination. According to the cross-correlation

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values presented, peak cross-correlation values were not significantly different between target force levels and between grasp and pinch trials. The authors found that the maximum grasp forces were reduced when the forearm was deviated from the mid-prone position, significantly in pronation. In addition, similar effect was not found for pinch forces. As expected, cross-correlation magnitude decreased as the distance between electrode pairs increased.

In addition, T. W. Beck, M. A. Dillon, J. M. DeFreitas, and M. S. Stock [3] examined the cross-correlation of MMG signals detected from rectus femoris muscle in perpendicular and transverse axis during isometric muscle actions. Two MMG sensors used which, one of the sensor was oriented in an axis that was perpendicular to the muscle surface and the other sensor was oriented in an axis that was transverse to the muscle surface. The signal recorded from both axis were correlated to each other obtain the maximum cross-correlation coefficients that are ranged from $R_{xy} = 0.273 - 0.989$. The present results indicate, a high level of association between the MMG signals detected in both axis based on COHEN interpretation [4].

In other research [5], the authors quantified the level of crosstalk in the MMG signals from the longitudinal, lateral and transverse with different isometric wrist posture: wrist flexion, wrist extension, radial and ulnar deviations. The results indicate, transvers axis of MMG signals between the muscle groups showed significantly less crosstalk for each wrist posture. However, cross-correlation does not always referred to cross-talk. There is evidence that the cross-correlation method used to determine motor unit synchrony as common neural input between two muscles [6]. If two muscles receive common input and response similarly with the muscle action, then it is reasonable to expect that they would demonstrate high correlation. Therefore, cross-correlation can also represent other appliances instead of cross-talk.

Through literature study, more information of isometric contraction are found on leg muscle compared to forearm muscles. Forearm consists of numerous small muscles separated with flexor and extensor side that is in close proximity and contracted to each other when perform muscle actions [7]. Therefore, the purpose of this research was to examine the maximum cross-correlation coefficient of MMG signals recorded from flexor (PL & FDS) and extensor (ED & ECU) side muscles of forearm during isometric muscle action for maximum voluntary isometric contraction of force with multiple hand exercise gestures.

2. Materials and Methods

2.1. Participants
Nine participants, healthy dominant handed male (mean±SD: age=24.78±1.79 y; height= 170.67±5.92 cm; weight= 65.89±6.77) were volunteered with specific criteria for the measurement of the signal. Written consent forms were given to the participants for their participation in this experiment. All volunteered participants were clinically healthy and in good physical condition with no previous or ongoing history of neuromuscular or musculoskeletal disorder specific to the elbow, wrist and/or finger joints.

2.2. Ethical 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 individuals in experiment.

2.3. Isometric Contraction Protocols
Subject were required to seat comfortably on a chair with adjustable arm support attached to the chair arm. Specifically, participants were required to execute three muscle contraction with three trials for every 4 seconds of interval and each contraction is held for 4 seconds for isometric contraction. The isometric contraction was repeated with four maximal voluntary isometric contractions (25%, 50%,
There was 3-4 minutes of rest before executing next hand exercise gestures as shown in Figure 1 to avoid fatigue issue.

![Images of hand gestures](image1)

**Figure 1.** (a) Grip Strength Supinated, (b) Grip Strength Pronated, (c) Flexion Finger (FF) and (d) Flexion Finger (FF)

### 2.4. MMG Measurements

During isometric contraction of forearm muscles, two sides of forearm muscles (extensor and flexor) placed with VMG sensor (TSD250A) to record MMG signals. The TSD250A VMG Transducer is a sensitive accelerometer (32.64 mm diameter) for use with BIOPAC Vibromyography Systems. TSD250A used for measuring absolute muscle force from substantial muscle groups, such as forearm and leg muscles. Four VMG sensors were attached on the skin surface over the muscle bellies of the extensor side (ED and ECU) and flexor side (PL and FDS) with double-sided adhesive tape.

### 2.5. Data Acquisition and Signal Processing

The output of each direction of the four VMG sensors were connected to the data acquisition unit (BIOPAC VMG System) using an MP160 and HLT100C. It was set to record four channel of VMG raw signals as four muscles has been selected. The signals from each muscle were amplified at gain equals to 200, sampled at a rate of 2000 samples/s and stored in a personal computer for subsequent analysis. The filtered signals were selected for a 2-s time period corresponding to the middle 50% of each 4-s muscle contraction as shown in Figure 2. The filtered signals were then cross-correlated between each other (palmaris longus versus flexor digitorum superficialis and extensor digitorum versus extensor carpi ulnaris) by using the cross-correlation with normalization formula as shown below. According to Cohen [4], maximum cross-correlation coefficients between 0.1-0.3 were considered small, those between 0.3-0.5 were considered moderate and those between 0.5-1.0 were considered large.

\[
R_{xy}(\tau) = \frac{1}{a \times b \times \omega(\tau)} \sum_{n=0}^{N-1} X_x(n) \ast Y_y(n + \tau) ; 1 - N < \tau < M
\]

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where \( a = \sqrt{\sum_{n=1}^{N-1} X_t^2(n)} \), \( b = \sqrt{\sum_{n=1}^{M-1} Y_t^2(n)} \) and \( \omega \) is weighting factor, \( M \) and \( N \) are the length of \( X_t \) and \( Y_t \), respectively, \( \tau \) represent time lag between the signals.

\[ \frac{X_t^2(n)}{N-1}, \frac{Y_t^2(n)}{M-1}, \sqrt{\sum_{n=1}^{N-1} X_t^2(n)}, \sqrt{\sum_{n=1}^{M-1} Y_t^2(n)} \]

Figure 2. An example of segmented MMG signals from PL muscle during isometric contraction

3. Results and Discussions

Table 1 - 4 show the result of maximum cross-correlation coefficients of isometric contraction for four different hand exercise gestures (GSP, GSS, FF and PG) that range from \( R_{x,y} = 0.801 - 0.943 \) for all gestures performed. According to the results obtained, for each of muscle comparisons, the maximum cross-correlation coefficients increase with force level for some of the participants, but the trend was not consistent. For each cross-correlation that was performed, the maximum cross-correlation coefficient occurred at a time-shift of 0 s (i.e., \( \tau = 0 \) s).

Table 1. Maximum cross-correlation coefficients for grip strength supinated

| Subject | 25% | 50% | 75% | 100% | 25% | 50% | 75% | 100% |
|---------|-----|-----|-----|------|-----|-----|-----|------|
| 1       | 0.867 | 0.890 | 0.919 | 0.883 | 0.921 | 0.883 | 0.867 | 0.878 |
| 2       | 0.895 | 0.860 | 0.873 | 0.907 | 0.864 | 0.889 | 0.926 | 0.841 |
| 3       | 0.858 | 0.837 | 0.851 | 0.882 | 0.855 | 0.838 | 0.893 | 0.837 |
| 4       | 0.884 | 0.876 | 0.884 | 0.880 | 0.877 | 0.864 | 0.906 | 0.900 |
| 5       | 0.871 | 0.875 | 0.875 | 0.883 | 0.826 | 0.880 | 0.835 | 0.856 |
| 6       | 0.865 | 0.913 | 0.876 | 0.857 | 0.854 | 0.838 | 0.875 | 0.898 |
| 7       | 0.897 | 0.906 | 0.869 | 0.846 | 0.859 | 0.884 | 0.861 | 0.834 |
| 8       | 0.857 | 0.833 | 0.857 | 0.886 | 0.891 | 0.884 | 0.845 | 0.882 |
| 9       | 0.866 | 0.864 | 0.900 | 0.842 | 0.866 | 0.874 | 0.879 | 0.880 |
Table 2. Maximum cross-correlation coefficients for grip strength pronated

| Subject | 25% | 50% | 75% | 100% | 25% | 50% | 75% | 100% |
|---------|-----|-----|-----|------|-----|-----|-----|------|
| 1       | 0.896 | 0.859 | 0.832 | 0.843 | 0.877 | 0.877 | 0.864 | 0.866 |
| 2       | 0.830 | 0.866 | 0.859 | 0.899 | 0.837 | 0.910 | 0.897 | 0.882 |
| 3       | 0.843 | 0.865 | 0.899 | 0.838 | 0.892 | 0.882 | 0.911 | 0.894 |
| 4       | 0.868 | 0.850 | 0.899 | 0.882 | 0.862 | 0.865 | 0.897 | 0.906 |
| 5       | 0.879 | 0.885 | 0.870 | 0.896 | 0.834 | 0.874 | 0.872 | 0.865 |
| 6       | 0.889 | 0.881 | 0.892 | 0.886 | 0.857 | 0.890 | 0.891 | 0.851 |
| 7       | 0.858 | 0.868 | 0.858 | 0.846 | 0.869 | 0.849 | 0.862 | 0.893 |
| 8       | 0.877 | 0.853 | 0.886 | 0.878 | 0.860 | 0.888 | 0.861 | 0.880 |
| 9       | 0.801 | 0.839 | 0.877 | 0.843 | 0.876 | 0.874 | 0.875 | 0.861 |

Table 3. Maximum cross-correlation coefficient for finger flexion

| Subject | 25% | 50% | 75% | 100% | 25% | 50% | 75% | 100% |
|---------|-----|-----|-----|------|-----|-----|-----|------|
| 1       | 0.893 | 0.868 | 0.870 | 0.849 | 0.901 | 0.874 | 0.851 | 0.870 |
| 2       | 0.890 | 0.901 | 0.891 | 0.873 | 0.861 | 0.886 | 0.894 | 0.901 |
| 3       | 0.921 | 0.819 | 0.871 | 0.921 | 0.849 | 0.861 | 0.872 | 0.869 |
| 4       | 0.818 | 0.889 | 0.874 | 0.898 | 0.877 | 0.886 | 0.852 | 0.836 |
| 5       | 0.837 | 0.879 | 0.887 | 0.826 | 0.877 | 0.837 | 0.886 | 0.824 |
| 6       | 0.827 | 0.876 | 0.849 | 0.826 | 0.826 | 0.844 | 0.865 | 0.885 |
| 7       | 0.851 | 0.849 | 0.866 | 0.852 | 0.894 | 0.871 | 0.871 | 0.866 |
| 8       | 0.848 | 0.842 | 0.900 | 0.878 | 0.943 | 0.831 | 0.859 | 0.886 |
| 9       | 0.859 | 0.852 | 0.884 | 0.906 | 0.849 | 0.868 | 0.838 | 0.876 |

Table 4. Maximum cross-correlation coefficient for pinch grip

| Subject | 25% | 50% | 75% | 100% | 25% | 50% | 75% | 100% |
|---------|-----|-----|-----|------|-----|-----|-----|------|
| 1       | 0.911 | 0.848 | 0.879 | 0.871 | 0.901 | 0.918 | 0.889 | 0.882 |
| 2       | 0.886 | 0.863 | 0.890 | 0.892 | 0.904 | 0.860 | 0.859 | 0.921 |
| 3       | 0.854 | 0.890 | 0.865 | 0.881 | 0.867 | 0.879 | 0.898 | 0.843 |
| 4       | 0.896 | 0.819 | 0.854 | 0.862 | 0.864 | 0.885 | 0.899 | 0.878 |
| 5       | 0.866 | 0.907 | 0.859 | 0.892 | 0.834 | 0.858 | 0.879 | 0.889 |
| 6       | 0.858 | 0.851 | 0.848 | 0.882 | 0.893 | 0.857 | 0.903 | 0.872 |
| 7       | 0.868 | 0.877 | 0.868 | 0.904 | 0.919 | 0.914 | 0.888 | 0.906 |
| 8       | 0.887 | 0.881 | 0.877 | 0.863 | 0.919 | 0.858 | 0.858 | 0.873 |
| 9       | 0.905 | 0.827 | 0.866 | 0.845 | 0.857 | 0.890 | 0.839 | 0.872 |

Based on the summary of maximum cross-correlation function in Table 5, the results indicate that the range level of cross-correlations for extensor side muscle group were higher than flexor side muscle groups for all hand gestures exerted for isometric contraction increment of force (25%, 50% 75% and 100%). This finding is in agreement with the finding of [2] and [5] where extensor muscles group showed high cross-correlation coefficient compared to flexor muscle even for difference of hand gestures or exercise motions specifically on forearm muscle contractions.

In addition, this study found that extensor side muscles were most convenient in determining the cross-talk level of isometric contraction on forearm muscles for MMG signal compared to flexor side muscles based on results obtained. Furthermore, the obtained results show the maximum cross-correlation coefficients did not increase with isometric contraction and force level for both flexor and
extensor side muscles for many of the participants. Finally, based on summary on Table 5 it can be concluded that cross-correlations coefficient performed were classified as large based on the recommendations by COHEN since the maximum cross-correlation coefficients for all muscle groups and hand exercise gestures were in the 0.8 to 0.9 range.

| Gestures | Flexor Side (PL & FDS) | Extensor Side (ED & ECU) |
|----------|------------------------|--------------------------|
| GSS      | 0.883 – 0.919          | 0.826 – 0.926            |
| GSP      | 0.801 – 0.899          | 0.834 – 0.9.11           |
| FF       | 0.818 – 0.921          | 0.824 – 0.943            |
| PG       | 0.819 – 0.911          | 0.834 – 0.921            |

4. Conclusion

In this work, maximum cross-correlation coefficient was analyzed for different hand exercise gestures with various force level exerted (25%, 50%, 75% and 100%) to determining which compartmental muscle groups shows high level of association between MMG signals detected in flexor (PL & FDS) and extensor (ED & ECU) side muscles during isometric muscle action of forearm. Presented results of cross-correlation coefficient between flexor and extensor side muscles indicates that the maximum range value of cross-correlation coefficient for extensor side muscle groups were slightly higher than the flexor side muscle groups for all hand exercise gestures exerted. Further studies should examine the cross-talk level quantification of isometric contraction using cross-correlation function as well as isometric contraction during fatiguing muscle actions since cross-talk value can be analysed from the maximum value of cross-correlation coefficient.

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