ANALYZING CROSS-TALK IN MECHANOMYOGRAPHIC SIGNALS OF FOREARM MUSCLES DURING GRIP FORCE TASK AND DIFFERENT WRIST POSTURES

by

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LIST OF ABBREVIATIONS

ACC	–	Accelerometer
ANOVA	–	Analysis of Variance
CC	–	Contractile Component
cDAQ	–	Compact Data Acquisition
CMMR	–	Common Mode Rejection Ratio
dfB	–	Degrees of Freedom Between
dfE	–	Degrees of Freedom Error
dfP	–	Degrees of Freedom Participant
dfT	–	Degrees of Freedom Total
ECU	–	Extensor Carpi Ulnaris
ED	–	Extensor Digitorum
EMG	–	Electromyography
FCU	–	Flexor Carpi Ulnaris
LSD	–	Least Significant Difference
MK	–	Myokinetic
MMG	–	Mechnomyography
MMG_{FF}	–	Mechnomyographic Signal due to Fast-twitch Fibres
MMG_{SF}	–	Mechnomyographic Signal due to Slow-twitch Fibres
MMG_{TF}	–	Mechnomyographic Signal due to Force Tremor
MPF	–	Mean Power Frequency
MREC	–	Medical Research & Ethics Committee
MS	–	Mean Squared Error
MVC	–	Maximum Voluntary Contraction

MVIC	–	Maximum Voluntary Isometric Contraction
NI	–	National Instrument
PEC	–	Parallel Component
RC	–	Resistance and Capacitance
RD	–	Radial Deviation
RMS	–	Root Mean Square
SD	–	Standard Deviation
SE	–	Standard Error
SEC	–	Series Element of Passive Component
sEMG	–	Surface Electromyography
SS	–	Sum of Squares
SSB	–	Sum of Squares Between
SSE	–	Sum of Squares Error
SSP	–	Sum of Squares Participant
SST	–	Sum of Squares Total
SSW	–	Sum of Squares Within
UD	–	Ulnar Deviation
WE	–	Wrist Extension
WF	–	Wrist Flexion

LIST OF SYMBOLS

cm	–	Centimeter
dB	–	Decibel
F	–	Calculated F-ratio
F_c	–	Critical F-ratio
g	–	Gravitational acceleration
Hz	–	Hertz
k	–	Number of group
Kg	–	Kilogram
KHz	–	Kilohertz
KΩ	–	Kiloohom
L_a	–	Lateral
L_o	–	Longitudinal
m/s^2	–	Meter per second square
mm	–	Millimeter
mV	–	Millivolt
N	–	Newton
n	–	Number of participant
N	–	Total number of observation
p	–	Significant value
r^2	–	Determination of coefficient
R^2_{xy}	–	Level of cross-talk
R_{xy}	–	Cross-correlation coefficient
s	–	Second

T	–	Length of a signal
T_r	–	Transverse
X_G	–	Grand mean
X_g	–	Group mean
X_P	–	Participant mean
y	–	Year
β_0	–	Intercept of regression line
β_1	–	Slope of regression line
ε	–	Random error
η^2	–	Effect size
τ	–	Time lag

Analisa Cakap-Silang dalam Isyarat Mekanomiografi Otot Lengan semasa Aktiviti Genggaman Kuat dan Postur Gelang Tangan Berbeza

ABSTRAK

Dalam mekanomiografi (MMG), cakap-silang merujuk kepada pencemaran isyarat dari otot yang berkepentingan oleh isyarat dari otot lain atau kumpulan otot berdekatan. Kajian ini menganalisa cakap-silang dalam isyarat MMG yang dihasilkan oleh otot digitorum ekstensor (ED), ekstensor karpi ulnaris (ECU), dan fleksor karpi ulnaris (FCU) semasa pengecutan isometrik submaksimal kepada maksimal genggaman kuat (MVIC) dan postur gelang tangan seperti fleksi (WF), lanjutan (WE) radial (RD) dan ulnar (UD). Dua puluh lelaki sihat bertangan kanan (min ± SD: umur = 26.25 ± 3.13 y) telah mengambil bahagian dalam kajian ini. Semasa setiap tindakan otot, tiga akselerometer mikroelektromekanikal (MEMS) tiga paksi (berskala penuh = ± 3g, sambutan frekuensi = 0.5-500 Hz, kepekaan = 330 mV/g) telah digunakan untuk mendapatkan isyarat MMG dari arah membujur (L_o), sisi (L_a) dan melintang (T_r) kepada serat otot. Pekali puncak-korelasi pada susulan masa sifar telah digunakan untuk pengkuantitian cakap-silang. Analisis ukuran-berulang varians (ANOVA) diikuti dengan ujian post hoc perbezaan paling signifikan (LSD) pada tahap signifikan = 0.05 telah dijalankan untuk menganalisis cakap-silang. Tahap cakap-silang dalam isyarat MMG yang dihasilkan oleh tiga paksi otot berjulat antara R^2_{xy} = 27-70% bagi paksi-L_o, 14-53% untuk paksi-L_a, dan 9-26% bagi paksi-T_r di mana didapati isyarat cakap-silang jauh lebih rendah pada paksi-T_r MMG untuk semua postur gelang tangan ($p < 0.05$). Selain itu, postur gelang tangan, kecuali RD, tidak mempengaruhi secara ketara tahap cakap-silang antara otot ($p > 0.05$). Terdapat korelasi positif yang kuat antara tahap cakap-silang dan aktiviti genggaman kuat oleh otot ($r^2 \geq 0.857$). Cakap-silang juga terhasil di dalam isyarat MMG oleh daya menggeletar (MMG_{TF}), serat unit motor yang lambat-menembak (MMG_{SF}) dan cepat-menembak (MMG_{FF}) dengan nilai cakap-silang yang bersignifikan lebih besar dan lebih kecil untuk masing-masing MMG_{TF} dan MMG_{FF} ($p < 0.05$). Terdapat korelasi positif yang lemah antara tahap cakap-silang dan lilitan lengan semasa pengaktifan isyarat MMG yang maksima ($r^2 \leq 0.216$). Walau bagaimanapun, terdapat hubungan korelasi negatif yang lemah antara cakap-silang dan panjang lengan ($r^2 \leq 0.082$) dan antara cakap-silang dan ketebalan kulit ($r^2 \leq 0.30$). Keputusan ini boleh digunakan untuk meningkatkan pemahaman kita mengenai mekanisma otot-otot lengan semasa postur gelang tangan dan genggaman kuat dengan menggunakan teknik MMG.

Analyzing Cross-Talk in Mechanomyographic Signals of Forearm Muscles during Grip Force Task and Different Wrist Postures

ABSTRACT

In mechanomyography (MMG), cross-talk refers to the contamination of the signal from the muscle of interest by a signal from another muscle or muscle group in close proximity. This study analyzed the cross-talk in MMG signals generated by the extensor digitorum (ED), extensor carpi ulnaris (ECU), and flexor carpi ulnaris (FCU) muscles during submaximal to maximal isometric contractions of the grip force (MVIC) and wrist postures of flexion (WF) and extension (WE), and radial (RD) and ulnar (UD) deviations. Twenty, healthy right-handed men (mean ± SD: age = 26.25 ± 3.13 y) participated in this study. During each muscle action, three microelectromechanical systems (MEMS)-based tri-axial accelerometers (full-scale range = ± 3g, typical frequency response = 0.5-500 Hz, sensitivity = 330 mV/g) were used to obtain the MMG signals from the longitudinal (L_o,), lateral (L_a) and transverse (T_r) directions with respect to muscle fibres. Peak cross-correlation coefficients at zero time lags were used for quantification of the cross-talk. Repeated-measures analysis of variance (ANOVA) followed by least significant difference (LSD) post hoc tests at a significant level = 0.05 were performed to analyze the cross-talk. The level of cross-talk in the MMG signals generated by the three axes of the muscles ranged from R^2_{xy} = 27-70% for the L_o-axis, 14-53% for the L_a-axis, and 9-26% for the T_r-axis providing significantly lower cross-talk in the T_r-axis MMG signals for all the wrist postures ($p < 0.05$). Additionally, the wrist postures, except the RD, did not significantly influence the level of cross-talk between the muscles ($p > 0.05$). There were strong positive correlations between the level of cross-talk and the grip forces for the muscles ($r^2 \geq 0.857$). The cross-talk also occurred among the MMG signals due to force tremor (MMG_{TF}), slow-firing (MMG_{SF}) and fast-firing (MMG_{FF}) motor unit fibres for the muscles with significantly greater and smaller cross-talk values for the MMG_{TF} and MMG_{FF} signals, respectively ($p < 0.05$). There were weak positive correlations between the level of cross-talk and circumference of the forearm during maximally activated MMG signals ($r^2 \leq 0.216$). However, there were weak negative correlations between the cross-talk and the length of forearm ($r^2 \leq 0.082$) and the cross-talk and muscles' skin-fold thickness ($r^2 \leq 0.30$). The results may be used to improve our understanding on mechanics of the forearm muscles during the wrist postures and gripping task for using the MMG technique.

CHAPTER 1

INTRODUCTION

1.1 Background

Researchers are exploring to set suitable methods to examine muscles' activities noninvasively; these methods for example, include surface electromyogram (sEMG) (Cho & Kim, 2012; Simoneau, Longo, Seynnes, & Narici, 2012), , sonomyogram (SMG) (Chen *et al.*, 2011; Shi, Chang, & Zheng, 2010) and mechanomyogram (Cooper, Herda, Vardiman, Gallagher, & Fry, 2014; Ibitoye, Hamzaid, Zuniga, & Abdul Wahab, 2014). Of these techniques, the sEMG, measures electrical activity from superficial muscle, has been widely accepted as a reliable tool to examine the condition of muscle function for kinesiological and rehabilitation purposes. However, the sEMG is also observed sensitive to skin impedance changes due to sweating and electrode placement over muscle, which is a problem in certain applications of wearable sensor fields such as prosthetics (Anderson, Wybo, & Bartol, 2010; Ma, 2009; Orizio, 1993). In addition, the sEMG is very sensitive to power line and external electrical noise interferences (Mercer, Bezodis, DeLion, Zachry, & Rubley, 2006; Wollaston, 1810). The sEMG is also observed susceptible to motion artefacts and thus provides very low Signal-to-Noise Ratio (SNR), which demands for a low noise and high gain acquisition system to record a useable sEMG signal (Anderson, *et al.*, 2010; Galiana-Merino, Ruiz-Fernandez, & Martinez-Espla, 2013). Thus, researchers have been trying to find alternative to sEMG technique and discovered the surface mechanomyogram (MMG). Several terms including soundmyography (Orizio & Veicsteinas, 1992), phonomyography (Guillaume, Guillaume, Denis, François, & Thomas, 2002 ; Hemmerling, Babin, & Donati, 2003), acoustic-myography (Rodriguez, Agre, Franke, Swiggum, & Curt, 1996), accelerometermyography (Lammert, Jorgensen, & Einer-Jensen, 1976), and vibromyography (Matheson *et al.*, 1997; Mealing, Long, & McCarthy, 1996) have been used initially to describe MMG. In 1995, the CIBA Foundation Symposium suggested a common term "surface mechanomyogram" to distinguish the MMG signal from other mechanical signals that are unrelated to muscle activity (Orizio, Gobbo, Diemont, Esposito, & Veicsteinas, 2003).

According to a research published by (Beck, 2010), the MMG was first discovered in 1663 by Francesco Grimaldi, who claimed hearing a rumbling sound while he placed his thumbs tending to his ears and clenched his fists. In 1810, William Hyde Wollaston also observed the sound signal from a muscle during contraction (Wollaston, 1810). Gordon and Holbourn in 1948 made the first step in order to record MMG signal with a microphone. Consequently, they concluded that the surface MMG signal is the mechanical counterpart of the motor unit electrical activity as measured by sEMG (Gordon & Holbourn, 1948). Due to the advancements of electronic devices and digital signal processing tools, Oster and Jaffe first ensured that MMG signal was generated by muscle activity and the amplitude of the MMG signal increased with the level of muscle activity (Oster & Jaffe, 1980).

The MMG has several potential advantages over sEMG technique. The MMG is less sensitive to sensor placement over muscle and provides clearer picture of motor unit recruitment and its firing rate for both superficial and deeper muscles (Orizio, 1993; Orizio, *et al.*, 2003). The MMG, due to its mechanical nature, is insensitive to skin impedance changes caused by perspiration, and is very less sensitive to electrical cross-talk between sensors caused by external noise (Barry, Leonard, Gitter, & Ball, 1986;

Posatskiy & Chau, 2012). Additionally, since the MMG acquisition system is simpler (because it uses only one transducer compared to bipolar sEMG that uses three electrodes), this technique is very useful for muscles that are in close proximity and with limited surface area for placing recording sensors (Anderson, *et al*., 2010; Beck, 2010). Several studies claimed that the MMG provides higher SNR value compared to sEMG (C. Murphy, Campbell, Caulfield, Ward, & Deegan, 2008; M. Nolan, 2013; Y. Nolan & dePaor, 2004). Particularly, Murphy *et al*., 2008 reported that an accelerometer based MMG signal showed better SNR than sEMG signal (C. Murphy, *et al*., 2008).

As a result, the MMG technique has recently been extensively used to examine the conditions of muscle functions in the clinics and rehabilitation centers. The applications for example include examination of muscle dystrophic process (Barry, Gordon, & Hinton, 1990; Orizio *et al*., 1997), muscle fatigue (Armstrong, 2011; Barry, Geiringer, & Ball, 1985; Cè, Rampichini, Limonta, & Esposito, 2013; Hendrix *et al*., 2010; Xie, Guo, & Zheng, 2010), muscle stiffness (Dobrunz, Pelletier, & McMahon, 1990; Jarocka, Marusiak, Kumorek, Jaskólska, & Jaskólski, 2012), muscle strength (Marek *et al*., 2005; Matta *et al*., 2005), muscle fibre composition (Herda *et al*., 2010; Šimunic *et al*., 2011), exercise trainings (Cramer *et al*., 2007; Esposito, Limonta, & Cè, 2011; W. McKay, Vargo, Chilibeck, & Daku, 2013; W. P. McKay, Chilibeck, & Daku, 2007), neuromuscular disorders (Madeleine & Arendt-Nielsen, 2005; Marusiak, Jaskólska, Kisiel-Sajewicz, Yue, & Jaskólski, 2009; Tian, Liu, Li, Fu, & Peng, 2010) and balance (Armstrong *et al*., 2010). In addition, several researchers also reported that the MMG may be used in movement classification (Kawakami *et al*., 2012; Scheeren, Krueger-Beck, Nogueira-Neto, Nohama, & Button, 2010), prosthesis device and binary switch control (Alves, 2010; Alves & Chau, 2010; Alves, Sejdic, Sahota, & Chau, 2010; Barry, *et al*., 1986; Woodward, Gardner, Angeles, Shefelbine, & Vaidyanathan, 2014), muscle-machine interface (M. Nolan, 2013) communication channel for disabled patients (Narayanan, Irfan, Geethanjali, & Kumar, 2012; Y. Nolan & dePaor, 2004) and monitoring neuromuscular blockade (Claudius & Viby-Mogensen, 2008; G. S. Murphy *et al*., 2011; Trager, Michaud, Deschamps, & Hemmerling, 2006). However, cross-talk between adjacent muscles limits using the MMG technique for comprehensive examination of muscle function (Beck, DeFreitas, & Stock, 2010; Ebersole, Housh, Johnson, Evetovich, & Smith, 2001). Hence, the cross-talk in the MMG signals will be analyzed in this study and is elaborated in the next chapter.

1.2 Problem Statement and its Significance

As mentioned previously, the MMG technique has been applied in both clinics and rehabilitation centers. By this time, many investigators have addressed some technical factors such as sensor type (Beck *et al*., 2006), sensor orientation and fixation over muscle (Barry, 1987; Bolton, Parkes, Thompson, Clark, & Sterne, 1989; Farina, Li, & Madeleine, 2008), sensor weight (Watakabe, Mita, Akataki, & Ito, 2003), contact pressure between the sensor and muscle (Bolton, *et al.*, 1989), sensor location on muscle (Alves, *et al*., 2010; Zuniga *et al*., 2010), and temperature effect on muscle's mechanical properties (W. McKay, *et al*., 2013; Orizio, 1993). These studies have put great practical importance for establishing the validity of MMG technique.

However, many questions regarding MMG signal contamination still remains to be answered to use the technique for a comprehensive examination of muscle function. For example, the cross-talk that occurs between adjacent muscles is one of the more important concerns associated with both MMG (Beck, *et al*., 2010; Ebersole, *et al*., 2001) and sEMG techniques (Hagg & Milerad, 1997; Kong, Hallbeck, & Jung, 2010).

The cross-talk issue is particularly relevant in cases where the timing of activation of different muscles is of importance, such as in movement analysis (Sasidhar, 2013). The problem becomes even more critical for muscles those are in close proximity with each other (Farina, Merletti, Indino, Nazzaro, & Pozzo, 2002). For instance, the human forearm consists of several muscles in close proximity, and thus there is a relatively small surface area on the forearm for placing the recording devices.

Therefore, analyzing cross-talk from the forearm muscles is an intriguing issue for certain clinical applications such as prosthesis control and pre-and -post operative units for monitoring the activity of muscle of interest, because cross-talk can modify the activity of the muscle, which may misinterpret the intended muscle function. In particularly, most of the clinic relies on the muscle on/off activity that may be altered by the cross-talk (Merlo & Campanini, 2010). Thus, this study focused to understand on cross-talk between the MMG signals recorded from muscles in the forearm.

1.3 Motivation of the Research

To the best of our knowledge, a limited number of studies have investigated the cross-talk in sEMG signals from the forearm muscles (Kong, *et al.*, 2010; Mogk & Keir, 2003; Yung & Wells, 2013). However, it is unclear whether the cross-talk occurs in the forearm muscle as a result of wrist posture and different levels of the gripping tasks. Since the forearm muscle group plays an important role for the finger and wrist movements and gripping an object in our daily activities, the activities from an individual muscle of the forearm need to be ensured for comprehensive examination of muscle function in rehabilitation centers and controlling prosthesis devices precisely in the clinics. However, the sEMG signal generated by an individual muscle of the forearm is very challenging, because sEMG requires two electrodes to place over a muscle whereas the muscle consists of very limited surface area for the recoding electrodes (Kong, *et al*., 2010; Riek, Carson, & Wright, 2000). Additionally, the volume of conductor in sEMG signal of a muscle may be changed as a movement, which may also recruit geometrical artifact to sEMG signals (Rainoldi *et al*., 2000). In view of this, MMG may be a better selection for the muscles that have limited surface area and close to each other like the forearm, because the MMG needs only single transducer to place over a muscle. However, before applying the MMG technique over forearm muscles convincingly, the cross-talk between adjacent muscles needs to be revealed out. Although some studies (Beck, *et al*., 2010; Cramer *et al*., 2003) have examined the crosstalk of MMG signals from quadriceps, those studies did not examine the propagation axes of the muscle. This is important because crosstalk is highly associated with the propagation properties of muscle fibre oscillation and becomes even more critical for muscles that in close proximity with each other (Jaskólska *et al*., 2004). Therefore, crosstalk in MMG signals from quadriceps muscles may not hold true for the muscles in the forearm, because quadriceps muscle group consists of larger surface area for placing sensor than the forearm. Unfortunately, no previous study to date has examined cross-talk between the MMG signals detected from the forearm muscles. This gap motivates the current study to answer some interrelated research questions.

1.4 Research Questions

i) Does cross-talk occur for MMG signals generated by the different axes of the forearm muscles during all wrist postures?

ii) Do the wrist postures influence the level of cross-talk in the MMG signals generated by the forearm muscles?

iii) Is there any relationship between the level of cross-talk in the MMG signals generated by the forearm muscles and the submaximal to maximal isometric muscle contractions of the grip force?

iv) Does cross-talk occur for MMG signals due to: force tremor (MMG_{FT}) in the limb, the signal component of intramuscular pressure waves produced by the muscle fibres geometrical changes of fast-twitch fibres (MMG_{FF}) and slow-twitch fibres (MMG_{SF})?

1.5 Research Objectives and Hypotheses

The overall objective of this thesis was to analyze the cross-talk in the MMG signals generated by the longitudinal (L_o), lateral (L_a) and transverse (T_r) axes of the extensor digitorum (ED), extensor carpii ulnaris (ECU), and flexor carpii ulnaris (FCU) muscles during the isometric wrist postures of wrist flexion (WF) and extension (WE) and radial (RD) and ulnar (UD) deviations. Additionally, the effect of the wrist postures and different levels of grip force on the cross-talk values was also analyzed. Specifically the objectives are:

i) To quantify and analyze the level of cross-talk in the MMG signals from the L_o, L_a and T_r axes of the ED, ECU, and FCU muscles during the WF, WE, RD, and UD wrist postures.

Our hypothesis suggests that the multi-axis MMG signals from forearm muscles may show different levels of cross-talk due to the effects of the propagation properties of muscle fibres forming the MMG signal. Therefore, any of these axes may accumulate