ELSEVIER

Journal of Electromyography and Kinesiology 13 (2003) 63–71

JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY

www.elsevier.com/locate/jelekin

Crosstalk in surface electromyography of the proximal forearm during gripping tasks

Jeremy P.M. Mogk, M.Sc., Peter J. Keir, Ph.D. *

School of Kinesiology and Health Science, York University, 4700 Keele St., Toronto, ON M3J 1P3, Canada

Received 19 April 2002; received in revised form 28 August 2002; accepted 9 September 2002

Abstract

Electromyographic (EMG) crosstalk was systematically analyzed to evaluate the magnitude of common signal present between electrode pairs around the forearm. Surface EMG was recorded and analyzed from seven electrode pairs placed circumferentially around the proximal forearm in six healthy individuals. The cross-correlation function was used to determine the amount of common signal, which was found to decrease as the distance between electrode pairs increased, but was not significantly altered by forearm posture (pronation, neutral, supination). Overall, approximately 40% common signal was detected between adjacent electrode pairs (3 cm apart), dropping to about 10% at 6 cm spacing and 2.5% at 9 cm. The magnitude of common signal approached 50% between adjacent electrode pairs over the extensor muscles, while over 60% was observed between neighbouring sites on the flexor aspect of the forearm. Although flexor and extensor EMG amplitude was similar, less than 2% common signal was present between flexor and extensor electrode pairs during both pinch and grasp tasks. Maximum grip force production was not affected by forearm rotation for pinch, but reduced 18% from neutral (mid-prone) to pronation during grasp (p=0.01). In spite of differences in grip force, mean muscle activity did not vary between the three forearm postures during maximum pinch or grasp trials. While this study improved our knowledge of crosstalk and electrode spacing issues, further examination of forearm EMG is required to improve understanding of muscle loading, EMG properties and motor control during gripping tasks.

Keywords: EMG; Crosstalk; Forearm; Gripping; Cross-correlation

1. Introduction

Surface electromyography (EMG) is a powerful tool for examining the biomechanics and motor control of the human body. EMG signals are affected by changes in muscle force and muscle length, and the relationship may be further complicated by changes in electrode–muscle configuration. The forearm provides a prime example of many EMG collection pitfalls. The forearm consists of many muscles in close proximity, with varying degrees of common function, and a relatively small surface area on the overlying skin to place recording electrodes. The potential for surface electrodes to record signal common to multiple muscles is a concern [1,2]. The size and proximity of the forearm muscles not only create concern regarding which muscle is being recorded, but forearm rotation may also cause the electrodes on the skin to shift relative to the muscle. This could potentially result in recording activity from additional or new muscles, creating a potential source of error [3]. The smaller pick-up volume and greater specificity of fine wire electrodes has been offered as a solution for crosstalk issues, however, these electrodes have been shown to shift within the muscle and alter the activity recorded [4]. There is a need to evaluate crosstalk and common signal using surface EMG to examine issues regarding electrode placement and forearm rotation.

Varying levels of accuracy have been used to report electrode location in the literature, possibly leading some readers to infer that accuracy in electrode placement is not important. Studies in occupational settings have described electrode placement using terms such as “common flexor muscle mass,” “finger and wrist flexor musculature” and “forearm flexor and extensor muscles”

---

* Corresponding author. Tel.: +1-416-736-2100; fax: +1-416-736-5774.

E-mail address: pjkeir@yorku.ca (P.J. Keir).

1050-6411/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S1050-6411(02)00071-8

[5,6,7]. While it may be of interest to record “flexor” activity during various tasks in the workplace, and report a statistical analysis of effort, the use of a “common muscle mass” makes it difficult to know which muscles are contributing to the recorded signal.

Several methods have been used to quantify the amount of common signal (or crosstalk) present between neighbouring muscles, the most common being the cross-correlation function (CCF) [8,9,10,11,12,13]. Key features of the cross-correlation function include the peak correlation value, the value at zero phase shift, and the timing of zero crossings [12,14]. The cross-correlation value at zero phase shift (or peak), or its square, is often used to quantify the magnitude of common signal [11,13,14]. Winter et al. (1994) [13] reported that the amount of common signal present between seven adjacent electrode sites on the quadriceps muscle decreased as the distance between electrode pairs increased (from 22–24% at 2.5 cm to 1–2% at 7.5 cm). The equation used to cross-correlate two signals, $x(t)$ and $y(t)$, is as follows:

$$R_{xy}(\tau) = \frac{1}{T}\int_{0}^{T} x(t)y(t+\tau)\mathrm{d}t \qquad (1)$$

where T is the length of the signals being cross-correlated.

The normalized form of the equation, resulting in values between -1 and +1, is:

$$R'_{xy}(\tau) = \frac{R_{xy}(\tau)}{\sqrt{R_{xx}(0)R_{yy}(0)}} \qquad (2)$$

where $R_{xx}(0)$ is the auto-correlation of $x(t)$ at τ=0, $R_{yy}(0)$ is the auto-correlation of $y(t)$ at τ=0, τ is the time shift and R'_{xy} is the normalized cross-correlation value [13]. In the context of this paper, “crosstalk” is synonymous with “common signal” and is defined as $R'_{xy}{}^{2}$, which may also be referred to as the relative common power between two signals, x and y. It should be noted that, based on this method using surface EMG, one cannot discriminate between the individual contributions of motor unit synchrony, common neural input and electrode crosstalk.

Other methods of quantifying crosstalk, not directly comparable to the cross-correlation function, have drawn comparisons between EMG amplitudes. De Luca and Merletti (1988) [15] electrically stimulated the tibialis anterior and found that up to 16.6% of the tibialis anterior amplitude appeared in the surface EMG signal of the peroneal muscles. Comparing surface and indwelling EMG amplitudes in a cat preparation, Solomonow et al. (1994) [16] determined crosstalk magnitude by calculating how much signal from a neighbouring active muscle was detected in a denervated leg muscle. Crosstalk did not exceed 5% of the maximum value recorded by the surface electrodes positioned over areas of limited subcutaneous fat, but reached levels of 15–20% when a substantial layer of fatty tissue covered the muscles. Greater skinfold thickness has also been shown to increase cross-correlations in humans, effectively decreasing selectivity of the electrode [17]. Comparisons between surface and intramuscular recordings have been made in humans [18], however, determining crosstalk using EMG amplitude measures may leave room for misinterpretation, except for truly isolated specimens [16]. Using the cross-correlation function with surface EMG has also been criticized due to the potential confounds of tissue filtering and motor unit synchronization between coactivated muscles [19]. With fine wire EMG, analyses examining synchronization and common input to single motor units have included the cumulative sum procedure (CUSUM) followed by various synchronization indices [20]. However, this procedure is untested with surface EMG, and with full consideration of its limitations, the cross-correlation function provides a powerful technique by which to study common signal content in surface EMG.

The purpose of this study was to determine the common signal, or crosstalk, present between electrode pairs placed circumferentially around the proximal forearm. Adapting the protocol from a previous study [13], we included the effects of forearm rotation, force level and grip type. A secondary purpose was to determine the effect of forearm rotation on grip force normalization and the associated effect on muscle activity.

2. Methods

2.1. Participants

Six healthy male volunteers participated in this study (mean age: 23.7 years; range: 22–25 years). All participants were pain free in the forearm at the time of testing, and reported no history of hand, wrist or forearm dysfunction. Pilot work involved two additional male participants, and although statistical outcomes were no different with their data included, they were omitted to maintain experimental integrity due to slight modifications in protocol and collection parameters. Therefore, all data presented are based on six participants. In addition to each participant’s height (mean: 178.2 cm; range: 165.0–187.5 cm) and mass (mean: 93.0 kg; range: 57.6–123.0 kg), forearm circumference was also measured (mean: 30.2 cm; range: 25.5–33.3 cm).

2.2. Apparatus/set-up

Each participant sat upright in a chair with his back supported at a 15° incline from the vertical, and the right forearm supported on a horizontal platform with the hand and wrist beyond the end of the platform and unsupported. Platform height was adjusted to standardize elbow and shoulder posture and to limit lateral flexion of the trunk. The upper arm was aligned with the trunk at 0° shoulder abduction and an elbow angle of 105°. Maximum voluntary pinch (thumb opposing index and long fingers) and power grasp (full grip with all fingers and the thumb) efforts were performed with the wrist in a neutral posture and the forearm in mid-prone (neutral) using a grip dynamometer (MIE Medical Research Ltd., Leeds, UK). Neutral wrist posture was defined as the anatomical position of the wrist, such that the dorsal surfaces of the hand and forearm formed a straight line and the 3rd metacarpal was parallel to the lateral border of the radius. Uniform pinch and grasp spans were used for all participants (3.1 and 5.0 cm, respectively). The grip dynamometer was supported during pinch efforts to standardize finger and wrist postures between participants, but not during grasp efforts. During grasp, hand position was standardized by aligning the radial border of the index finger with a marker on the handle of the dynamometer. Participants were instructed to maintain a neutral wrist with the desired forearm posture throughout each trial, during all target force exertions. Each trial was videotaped and simultaneously monitored on a television screen to ensure proper posture was achieved and maintained throughout the effort. A mirror apparatus, angled at 45°, allowed for the measurement of radio–ulnar deviation and wrist flexion–extension from a single videotape view in all postures (Fig. 1(a)). To aid in posture analysis, a pointer was taped to the back of the hand, between the 3rd and 4th metacarpal bones, and aligned with a line drawn on the forearm parallel to the radius (Fig. 1(b)). Alignment of the pointer in each posture required that three lines be drawn (i.e. one on the dorsal surface for pronation, and two on the ventral surface for neutral and supination). Two lines were needed on the ventral surface due to skin movement with forearm rotation. The dorsal surface of the hand and wrist were placed against a wooden board to help regulate wrist posture and forearm rotation during all neutral trials.

EMG signals were differentially amplified to maximize the raw signals (gain up to 10 k, and a common mode rejection rate of 90 dB) and were bandpass filtered (10–500 Hz) prior to A/D conversion (12 bit, Model PCI-MIO-16E-4; National Instruments Corp., Austin, TX). Raw EMG and force were recorded using collection software created in LabVIEW (National Instruments Corp., Austin, TX) with a sampling rate of 2000 Hz. EMG and force data were stored on a computer for later analysis. After forearm hair was shaved and the skin of the recording sites was scrubbed with alcohol, a total of 7 disposable Ag–AgCl surface electrode pairs (recording surface: 1 cm diameter, area 0.79 cm^2) were placed around the circumference of the right forearm (Fig. 2). A landmark electrode pair was placed over the flexor carpi radialis (FCR, channel 5, Fig. 2), one third of the distance from the proximal end of a line from the medial epicondyle to the distal head of the radius, with the forearm supinated. The position over FCR was confirmed by

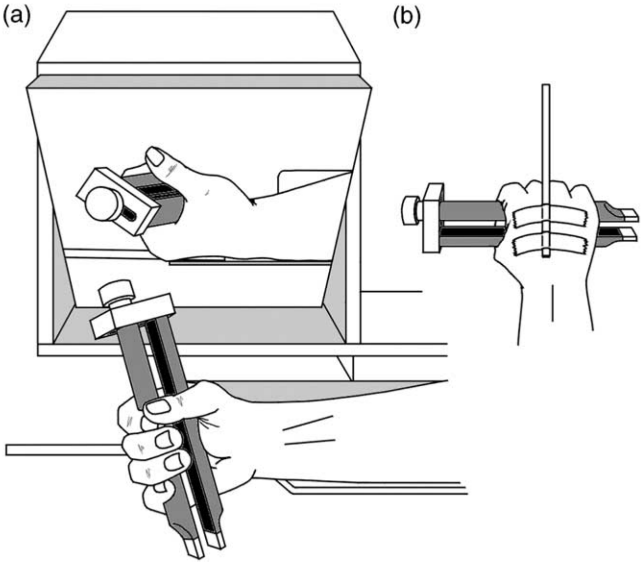


Fig. 1. (a) Schematic of the mirror apparatus designed to monitor and measure wrist angles, as seen from the video camera. Illustrated is the neutral wrist and forearm posture, with wrist flexion–extension angle apparent in the mirror image. Radio–ulnar deviation was measured as the angle of the pointer relative to the line drawn on the forearm. Inset, (b) pointer affixed to the back of the hand, with the line used for radio–ulnar deviation measurements in pronation.

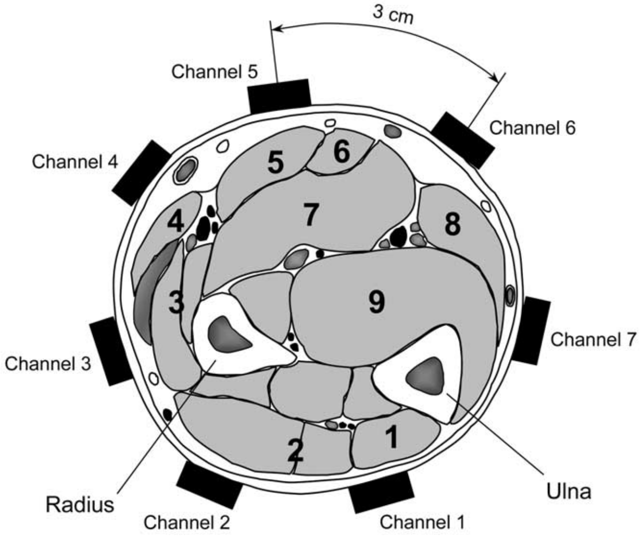


Fig. 2. Cross-section of right forearm indicating approximate electrode locations (adapted from Perotto, 1994 [29]). Muscles are as follows: 1. extensor carpi ulnaris (ECU); 2. extensor digitorum communis and extensor digiti minimi (EDC/EDM); 3. extensor carpi radialis longus and brevis (ECRL/B); 4. brachioradialis (BR); 5. flexor carpi radialis (FCR); 6. palmaris longus (PL); 7. flexor digitorum superficialis (FDS); 8. flexor carpi ulnaris (FCU); 9. flexor digitorum profundus (FDP). Channel 5 was positioned over FCR.

palpation and signal response during specific FCR tasks involving wrist flexion with radial deviation. The inter-electrode spacing was 2.5 cm (centre-to-centre) for each differential pair. The six remaining electrode pairs were aligned around the forearm starting immediately medial and lateral to the landmark pair at a centre-to-centre distance of 3 cm between each pair. This arrangement resulted in a natural gap across the ulnar border, which varied in size depending on forearm circumference.

2.3. Protocol

A summary of the protocol is shown in Table 1. After determining the participant's maximum grip force in a neutral forearm posture, four grip force target levels relative to maximum voluntary grip force (25%, 50%, 70% and 100%), were performed with a straight wrist in three forearm postures (full pronation, neutral and full supination). Maximal grip force was determined separately for both pinch ("Pinch$_{\text{max}}$") and grasp ("Grip$_{\text{max}}$"), and target force levels were calculated (12 pinch and 12 grasp trials, for a total of 24 exertions). Pilot tests revealed that although their objective was to reproduce the maximum pinch and grasp forces achieved during calibration, not all participants attained the 100% target force in all postures. Therefore, three additional target forces were calculated, based on the maximum pinch and grasp forces achieved in pronated and supinated postures (referred to as 25, 50, and 70% "Pinch$_{\text{max-p}}$" and "Grip$_{\text{max-p}}$", for pinch and grasp, respectively). These additional trials were performed only in pronation and supination, using the respective posture-specific maximum grip force only (resulting in an additional 6 pinch and 6 grasp trials). No additional trials were performed in neutral since all target force levels were originally calculated relative to neutral forearm values. Participants were asked to attain each relative target force level and hold it for 5 seconds. Visual feedback of the force level was given via an oscilloscope to help the participants maintain the desired target force level during each trial. Trials were randomized with a minimum rest of 1 minute between each effort.

2.4. Data analysis

After removing DC-bias, EMG levels were normalized to maximum voluntary electrical activation (MVE) from the maximum pinch and grasp force trials and a series of contractions used to elicit maximal activation. Trials performed to calibrate EMG included maximal grasp exertion with voluntary isometric wrist extension and forceful voluntary wrist circumduction. A "quiet" trial was recorded for each participant to determine baseline activity and for quantification of any system bias. Average EMG (AEMG) was calculated from

Table 1

Summary of the protocol, including all trials performed. The order of both posture and grip type was randomized. All trials within a particular posture, for the given grip type, were performed before changing postures. The order of the target levels was randomized within each posture, with Pinch$_{\text{max-p}}$ and Grip$_{\text{max-p}}$ trials always following the 100% Pinch$_{\text{max}}$ and Grip$_{\text{max}}$ target trials for that posture

Calibration:
- Quiet
- Maximum voluntary grip (determining "Pinch$_{\text{max}}$" and "Grip$_{\text{max}}$")
- Maximum grip force with forceful isometric wrist extension
- Forceful voluntary wrist circumduction

Forearm posture	Pinch		Grasp	
	% Pinch$_{\text{max}}$	% Pinch$_{\text{max-p}}$	% Grip$_{\text{max}}$	% Grip$_{\text{max-p}}$
Pronation	25	25	25	25
	50	50	50	50
	70	70	70	70
	100 ("Pinch$_{\text{max-p}}$")* ↗		100 ("Grip$_{\text{max-p}}$")* ↗	
Neutral	25	+	25	+
	50	+	50	+
	70	+	70	+
	100		100	
Supination	25	25	25	25
	50	50	50	50
	70	70	70	70
	100 ("Pinch$_{\text{max-p}}$")* ↗		100 ("Grip$_{\text{max-p}}$")* ↗	

*Pinch$_{\text{max-p}}$ and Grip$_{\text{max-p}}$: 100% force was generally not achieved, thus target levels were calculated relative to the maximum grip force for that specific posture. +By definition, Pinch$_{\text{max-p}}$ and Grip$_{\text{max-p}}$ in neutral are equal to Pinch$_{\text{max}}$ and Grip$_{\text{max}}$, respectively, therefore no additional trials were performed.

the linear envelope (3 Hz) signal over the plateau period of each contraction.

The raw EMG signal from each channel was cross-correlated with the corresponding signal from each of the three adjacent channels, where applicable, with the distance between electrode pairs ranging from 3–9 cm. For example, the signal from channel 6 was cross-correlated with channels 3, 4 and 5 on the one side, but only with channel 7 on the other side due to the gap between channels 1 and 7. Hence, by definition channel 4 was the only signal to be cross-correlated with three channels on either side. To further test potential crosstalk between the flexor and extensor musculature, the signals from the two electrode pairs immediately on either side of the ulnar border were also cross-correlated (i.e. channel 1 versus channel 7). This cross-correlation was not included in the data for 3 cm spacing since the gap between these electrode pairs varied with forearm circumference. A total of 16 cross-correlations were performed within each trial. Wrist flexion and extension and radio–ulnar deviation angles were manually measured from the videotape.

2.5. Statistics

Repeated measures ANOVAs and planned comparisons and contrasts (Least Significant Difference or LSD) were performed using STATISTICA (Version 6.0, StatSoft, Inc., Tulsa, OK) to determine levels of significance for cross-correlation, AEMG and grip force values. Unless otherwise stated, all *p*-values reflect those determined by planned comparisons.

Due to the arbitrary placement of the electrode pairs, with the exception of channel 5 being positioned over FCR, there was no guarantee that electrodes were located over the same muscles in all individuals. Therefore, statistical analyses were not performed on changes in AEMG amplitude of individual channels. Instead, the recorded activity levels were pooled to represent the extensor (i.e. channels 1–3) and flexor (i.e. channels 5–7) musculature before performing planned comparisons. This made AEMG data comparable to previous studies that reported electrode placements over “flexor” and “extensor” muscle masses. Pooled channels 1–3 will be referred to as “extensor” activity and channels 5–7 as “flexor” activity throughout the remainder of this paper.

3. Results

3.1. Grip force

There was no significant main effect of forearm posture on the maximal absolute pinch grip force produced (Table 2). However, in the grasp trials, forearm posture significantly affected maximum grip force ($F_{3,15}$=4.204, $p<0.05$) with more force produced in neutral than in pronation (p=0.01) or supination, although not significant in supination (Table 2). Since not all participants were able to achieve the desired 100% target force in all postures, further statistical analysis confirmed that significantly greater force was produced with each increasing target level, in each forearm posture ($p<0.001$). Of interesting note, during the trials in which participants attempted 100% force in a neutral forearm posture, they produced only 90% of maximum (i.e. 90% $\text{Pinch}_{\text{max}}$) in pinch and 86.6% of maximum in grasp (Grip_{max}).

Table 2
Mean peak force (standard deviation) in Newtons for 100% ($\text{Pinch}_{\text{max}}$ and Grip_{max}) trials in each of the three forearm postures. Forces for the neutral forearm posture reflect the maximum force attained during calibration trials and represent the reference force of 100% $\text{Pinch}_{\text{max}}$ and Grip_{max} for pinch and grasp, respectively

	Pronation	Neutral	Supination
Pinch	97.7 (7.9)	97.3 (7.8)	85.7 (4.9)
Grasp	319.8 (31.9)	391.0 (41.1)	326.0 (26.6)

3.2. Cross-correlation of raw EMG

All cross-correlation values presented in this paper reflect those observed at zero phase shift of the cross-correlation function. Peak cross-correlation values were also analyzed but were not significantly different from those at zero-lag nor was the lag time significantly different from zero. R'_{xy} values did not differ significantly between target force levels, nor did they differ significantly between grasp and pinch trials. As expected, cross-correlation magnitude decreased as the distance between electrode pairs increased (Table 3). Comparison of the signals recorded from each side of the ulnar border revealed little correlation (i.e. channel 1 vs. channel 7; Table 3). Since there were no significant differences between the R'_{xy} values in any of the three forearm postures, the results from all three positions were combined. Grip type interacted with target level ($F_{3,15}$=4.265, $p<0.05$). During pinch grip trials, R'_{xy} values tended to be largest at 25% $\text{Pinch}_{\text{max}}$ and smallest at 100% $\text{Pinch}_{\text{max}}$ for all electrode spacings, while the opposite trend tended to be true during grasp trials (%Grip_{max}).

The amount of crosstalk, or common signal, may also be reported in terms of R_{xy}^2 (or R'^2_{xy} in this case). Mean R'^2_{xy} values, pooled across postures, for adjacent electrode pairs ranged from 33.1–38.6% in pinch and 36.8–41.3% in grasp; at 6 cm, R'^2_{xy} ranged from 8.0–10.5% in pinch and 8.6–10.7% in grasp; at 9 cm, R'^2_{xy} ranged from 2.4–4.0% in pinch and 2.1–2.5% in grasp. R'^2_{xy} between channels 1 and 7 ranged from 0.9–1.8% in pinch and 0.7–1.0% in grasp, indicating a lack of com-

Table 3
Mean peak cross-correlation ($R'_{xy}{}^2$) and explained variance ($R'_{xy}{}^2$), with standard error in parentheses, for each electrode spacing pooled across posture and effort level. The comparison between channels 1 and 7 has also been included. The *n* values represent the number of cross-correlations performed

Electrode Spacing	Pinch		Grasp	
	Peak R'_{xy}	$R'_{xy}{}^2$	Peak R'_{xy}	$R'_{xy}{}^2$
3 cm	0.601 (0.196) n=438	0.361 (0.038)	0.623 (0.197) n=438	0.388 (0.039)
6 cm	0.307 (0.186) n=365	0.094 (0.035)	0.314 (0.216) n=365	0.099 (0.047)
9 cm	0.182 (0.146) n=292	0.033 (0.021)	0.152 (0.162) n=292	0.023 (0.026)
1 vs. 7	0.111 (0.153) n=73	0.012 (0.023)	0.089 (0.071) n=73	0.008 (0.005)

mon signal between electrode pairs on opposite sides of the ulnar border.

Statistical analyses were performed on each of the defined electrode spacings as a whole (i.e. correlations for 3, 6 and 9 cm spacing were not differentiated according to electrode placement), however, visual inspection of the correlations between electrode pairs positioned over the common flexor and extensor muscle masses (channels 5 and 6, and channels 2 and 3, respectively) revealed some interesting trends. Mean $R'_{xy}{}^2$ of channel 2 versus 3 and channel 5 versus 6 were somewhat higher than the overall means reported for electrode pairs 3 cm apart (as high as 52.5% and 51.8% in pinch, and 57.8% and 64.0% in grasp, respectively), depending on forearm posture and force exerted. While the correlations between channels 1 and 3 were similar to the overall mean for 6 cm spacing, as much as 15.9% and 29.8% common signal was observed for channel 5 versus 7 (in pinch and grasp, respectively). Although channels 2 and 5 were 9 cm apart, the magnitude of common signal between them was similar to that found between channels 1 and 7.

3.3. Average EMG (AEMG)

An interaction was present between grip type and target level ($F_{3,15}$=43.1, $p<0.001$), with significantly more activity during grasp trials than pinch trials ($p<0.001$) and significantly greater activity with increased force level for both pinch and grasp trials ($p<0.001$; Figs 3 and 4). Average muscle activity did not vary between the three forearm postures during 100% target force trials for either pinch or grasp. Despite the 10–15% difference in absolute grip force attained between the neutral 100% target force and maximum grip force calibration trials, there was no significant difference in overall AEMG between these trials for either pinch or grasp.

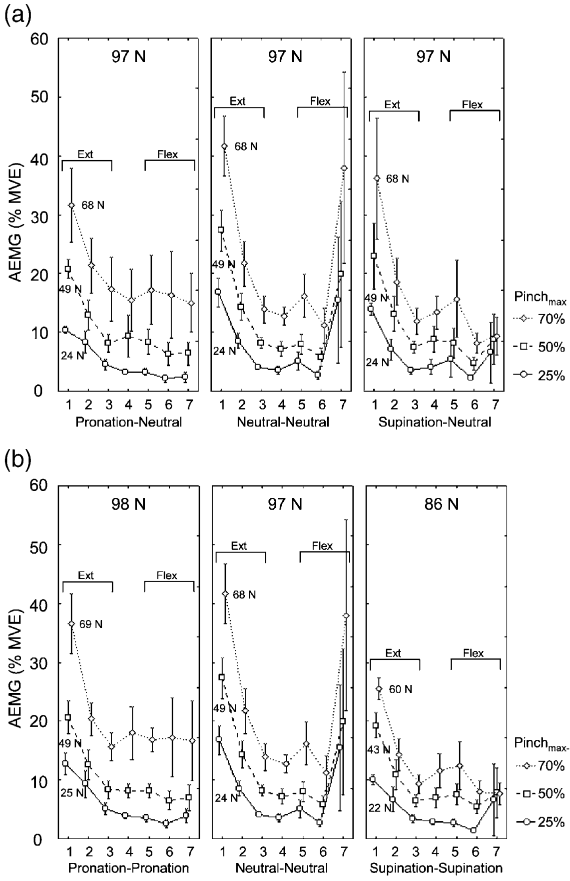


Fig. 3. Pinch: mean normalized activation levels for each channel at each submaximal effort level. (a) AEMG for each channel with target force levels relative to maximum in neutral (Pinch$_{max}$). (b) AEMG for target force levels relative to the postural maximum (Pinch$_{max-p}$). Each panel includes the mean force value (from Table 1) and the mean relative force levels (shown above each line). Both middle panels are identical, as no additional trials were performed in neutral. The “extensors” (ch. 1–3) and “flexors” (ch. 5–7), which were pooled for analysis, are indicated.

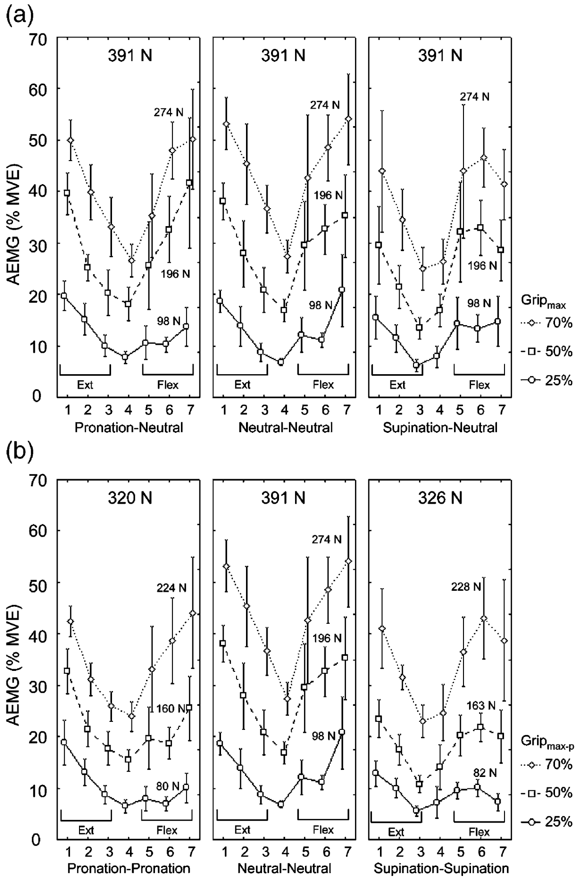


Fig. 4. Grasp: mean normalized activation levels for each channel at each submaximal effort level. (a) AEMG for each channel with target force levels relative to maximum in neutral (Grip$_{max}$). (b) AEMG for target force levels relative to the postural maximum (Grip$_{max-p}$). Each panel includes the mean force value (from Table 1) and the mean relative force levels (shown above each line). Both middle panels are identical, as no additional trials were performed in neutral. The "extensors" (ch. 1–3) and "flexors" (ch. 5–7), which were pooled for analysis, are indicated.

3.4. AEMG with target grip force relative to neutral maximum trials

Pooled flexor and pooled extensor activity were not significantly affected by posture within a given target pinch or grasp force level. However, it should be noted that some differences in AEMG amplitude were evident between postures at specific electrode sites, as well as between adjacent electrode pairs in certain postures, during both pinch and grasp trials (Figs 3(a) and 4(a), respectively). In some individuals, these differences were as much as 20–30% MVE.

3.5. AEMG with posture specific grip target forces

The maximal grasp forces in pronation and supination (i.e. Grip$_{max-p}$) were approximately 20% less than neutral, while maximal pinch force (Pinch$_{max-p}$) was 12% less in supination and no different in pronation compared to neutral (Table 2). Using these posture-specific maxima to calculate target forces, we found that overall AEMG was not affected by forearm posture, with some exceptions. During pinch trials, significantly more extensor activation occurred at all relative submaximal levels (i.e. 25, 50 and 70% Pinch$_{max-p}$) in neutral than in supination ($p<0.01$; Fig. 3(b)). Similarly, more flexor activation was recorded in a neutral posture during 25% and 70% Pinch$_{max-p}$ efforts ($p<0.05$) compared to supination. During grasp trials (Grip$_{max-p}$), significantly less flexor activation was observed in pronation than in neutral ($p<0.05$), regardless of target level (Fig. 4(b)). Extensor activation was significantly greater in neutral than in pronation for the 70% Grip$_{max-p}$ trial ($p<0.05$). This may be attributed to the lower absolute grip force in pronation (i.e. 70% of 320 N) compared to neutral (70% of 391 N). Again, differences in AEMG amplitude were evident between postures at specific electrode sites, as well as between adjacent electrode pairs in certain postures, during both pinch and grasp trials (Figs 3(b) and 4(b), respectively).

4. Discussion

This is the first study to examine the effects of forearm rotation and target force level on forearm EMG with specific reference to crosstalk (common signal) as determined by the cross-correlation function. We found that maximum grasp forces were reduced when the forearm was deviated from the mid-prone position, significantly in pronation. A similar effect was not found for pinch forces. While grip forces were altered by forearm rotation, EMG amplitude did not always reflect the changes in force. As expected, common signal decreased as the distance between electrode pairs increased. Overall, the percentage of common signal ranged from about 33–41% between adjacent electrode pairs, 8–10% at 6 cm and 2–4% at 9 cm. However, 50% common signal was detected between adjacent electrode pairs placed over the extensor muscles, while over 60% was observed between flexor electrode sites. About 1–2% common signal was found for comparisons made between flexor and extensor electrode pairs. Forearm rotation did not significantly affect the observed correlation values.

Overall, the correlation values of this study were similar to Winter et al. (1994) [13], in spite of differences in musculature (forearm versus thigh) and greater electrode spacing (3 cm versus 2.5 cm). Closer examination of the $R'_{xy}{}^2$ values revealed common signal to be slightly higher in the forearm than those reported previously for the thigh (33–41% versus 22–24% for adjacent pairs and 2–4% versus 1–2% at the largest spacing, respectively) [13]. Consistent with previous surface EMG findings [9], we found grasp trials to have slightly higher R'_{xy} values than pinch trials, perhaps due to a more concerted effort of the musculature to stabilize the wrist while producing force in grasp than in pinch. Additionally, the highest percentages of common signal (50–60%) were detected between adjacent electrode sites on either the extensors or the flexor muscles. Despite similar activity levels, we found virtually no common signal between the flexors and extensors ($<2\%$), whether from either side of the ulnar border or any other flexor and extensor sites, as could be expected from muscles of differing function and innervation. This likely reflects minimal crosstalk between the flexor and extensor muscle compartments and an inability of surface EMG to reflect motor unit firing rates, which may be moderately correlated between antagonists during isometric tasks [21]. There is also evidence that anatomical antagonists may be strongly coupled in the amplitude domain without motor unit synchronization [10]. Although motor unit synchronization has been examined with surface EMG using cross-correlation [9,12] and other techniques [22], its effectiveness is debatable [23,24].

The reduced maximal force from neutral to pronation during grasp, and the similar force levels in all three forearm postures during maximal pinch trials are comparable to previous investigations of grasp [25,26,27] and pinch [28]. However, we found grasp strength in supination to be lower than neutral, which is contrary to previous reports [26,27]. Also, our participants produced only 86–90% of maximal grip force in the mid-prone (neutral) test trials, perhaps indicating a slight difference in task between calibration and test trials. Participants concentrated on maintaining the neutral posture while gripping maximally during calibration, but had to concentrate on both posture and maintaining the 100% target force level during test trials. We also used the peak value from the maximum force calibration trial but reported mean forces over the test trials, likely contributing to this observation. Additional maximum grip force trials may have assisted in determining a truer maximum force. The effect of forearm posture on grip strength for grasp but not pinch likely reflects the difference in muscular contributions, specifically the greater involvement of the intrinsic hand muscles during pinch.

When target grip forces were based on the maximum force in a neutral forearm posture ($\text{Pinch}_{\text{max}}$ and Grip_{max}), there were no differences between flexor and extensor AEMG amplitudes within any given force level. However, when force was normalized to the postural grip maximum ($\text{Pinch}_{\text{max-p}}$ and $\text{Grip}_{\text{max-p}}$), some differences in muscle activity were apparent between the three forearm positions. These differences were attributed to the different absolute target forces required in each posture indicating that the posture used to determine grip force is likely important. Visual inspection of individual channels indicated differences in AEMG as large as 20–30% MVE between adjacent sites, as well as between forearm postures for specific electrode sites. Differences in forearm circumference did not appear to account for this variance. Overall results suggest that electrode position variation by 3 cm or less did not significantly affect AEMG amplitude. Therefore, the use of a standardized common muscle mass electrode site may be reasonable when a statistical representation of muscle activity is of interest over an extended period of time.

While visual inspection of individual cross-correlation data and specific AEMG comparisons suggested the presence of a rotational effect, a main effect of forearm posture was not found across participants. This was somewhat unexpected, as the electrodes could be expected to move 1–2 cm relative to the muscle with forearm rotation, depending on the amount of forearm rotation and forearm circumference. The circumferential placement of the electrode pairs likely contributed to the lack of a postural effect, as well as individual physiological and anatomical differences in muscle size, although we found forearm circumference not to be a factor. Crosstalk between specific flexor and extensor muscles of the wrist and fingers in a number of combinations of forearm and wrist posture is currently being investigated in another experiment.

There are several limitations to the present study. Due to the large number of contractions required within the protocol, only one trial per condition was performed. Although we randomized trials to minimize its effects, fatigue was not monitored and therefore cannot be ruled out as a contributing factor to observed differences in force and AEMG amplitudes. However, based on similar studies in our laboratory, in which we did monitor fatigue, we are confident that the rest breaks and randomization prevented fatigue in the present study. Manual goniometric measurements were chosen over those of an electrogoniometer to avoid compression of the device against the supporting platform. While similar measurement error has been reported for both methods, the combination of compression and forearm rotation could result in increased error. And, although we found that forearm position did not affect the correlation values, the common signal detected in each condition should be viewed as from a changing pool of motor units rather than a constant pool based on the likelihood that recording volume was altered with rotation of the arm.

This was the first study to systematically evaluate crosstalk in forearm EMG during gripping tasks in three forearm postures. We found that forearm posture had little effect on pinch forces, but deviation from neutral resulted in decreased power grasp forces. While grasp forces changed with forearm rotation, EMG amplitudes were relatively invariant to posture. Although similar flexor and extensor EMG amplitudes were observed, small cross-correlation values suggest that this is not a function of signal crosstalk as they represented only 1–2% common signal. Within a functional muscle group, common signal was as high as 60%. Using the amplitude of the EMG signal to determine common muscular function should be done with caution or avoided entirely, particularly between antagonist muscles. While this study has provided important information regarding crosstalk and electrode spacing issues, the electrode arrangement limited its generalizability. Further examination of forearm EMG is required to improve our understanding of muscle loading, EMG properties and motor control during gripping tasks.

Acknowledgements

This study was supported by an NSERC research grant (217382-00) awarded to P.J. Keir.

References

[1] G.M. Hägg, E. Milerad, Forearm extensor and flexor muscle exertion during simulated gripping work—an electromyographic study, Clin Biomech 12 (1) (1997) 39–43.

[2] G.M. Hägg, J. Öster, S. Byström, Forearm muscular load and wrist angle among automobile assembly line workers in relation to symptoms, Appl Ergon 28 (1) (1997) 41–47.

[3] Jonsson B., Kinesiology—with special reference to electromyographic kinesiology. Contemporary clinical neurophysiology (EEG Suppl. #34), Elsevier Scientific Publishing Company, Amsterdam, 1978, pp. 417–428.

[4] B. Jonsson, P.V. Komi, Reproducibility problems when using wire electrodes in electromyographic kinesiology, in: J.E. Desmedt (Ed.), New developments in electromyography and clinical neurophysiology, vol. 1, Karger, Basel, 1973, pp. 540–546.

[5] T. Cook, J. Rosecrance, C. Zimmerman, D. Gerleman, P. Ludewig, Electromyographic analysis of a repetitive hand gripping task, Int J Occup Safety Ergon 4 (2) (1998) 185–198.

[6] J.B. Dahalan, J.E. Fernandez, Psychophysical frequency for a gripping task, Int J Ind Ergon 12 (1993) 219–230.

[7] M.G. Klein, J.E. Fernandez, The effects of posture, duration, and force on pinching frequency, Int J Ind Ergon 20 (1997) 267–275.

[8] C.J. De Luca, Z. Erim, Common drive in motor units of a synergistic muscle pair, J Neurophysiol 87 (4) (2002) 2200–2204.

[9] E.J. Huesler, M.C. Hepp-Reymond, V. Dietz, Task dependence of muscle synchronization in human hand muscles, NeuroReport 9 (10) (1998) 2167–2170.

[10] M.A. Maier, M.C. Hepp-Reymond, EMG activation patterns during force production in precision grip, II. Muscular synergies in the spatial and temporal domain, Exp Brain Res 103 (1) (1995) 123–136.

[11] J.W. Morrenhof, H.J. Abbink, Cross-correlation and cross-talk in surface electromyography, Electromyogr Clin Neurophysiol 25 (1985) 73–79.

[12] R.S. Person, L.N. Mishin, Auto- and cross-correlation analysis of the electrical activity of muscles, Med Elec Biol Eng 2 (1964) 155–159.

[13] D.A. Winter, A.J. Fuglevand, S.E. Archer, Crosstalk in surface electromyography: theoretical and practical estimates, J Electromyogr Kinesiol 4 (1) (1994) 15–26.

[14] D.A. Winter, A.E. Patla, Signal processing and linear systems for the movement sciences, University of Waterloo, Ontario, 1997.

[15] C.J. DeLuca, R. Merletti, Surface myoelectric signal cross-talk among muscles of the leg, Electroencephalogr Clin Neurophysiol 69 (1988) 568–575.

[16] M. Solomonow, R. Baratta, M. Bernardi, B. Zhou, Y. Lu, M. Zhu, S. Acierno, Surface and wire EMG crosstalk in neighbouring muscles, J Electromyogr Kinesiol 4 (3) (1994) 131–142.

[17] E.J. De la Barrera, T.E. Milner, The effects of skinfold thickness on the selectivity of surface EMG, Eletromyogr Clin Neurophysiol 93 (1994) 91–99.

[18] J. Perry, C. Schmidt Easterday, D.J. Antonelli, Surface versus intramuscular electrodes for electromyography of superficial and deep muscles, Phys Ther 61 (1) (1981) 7–15.

[19] C.J. De Luca, The use of surface electromyography in biomechanics, J Appl Biomech 13 (1997) 135–163.

[20] M.A. Nordstrom, A.J. Fuglevand, R.M. Enoka, Estimating strength of common input to human motoneurons from the cross-correlogram, J Physiol 453 (1992) 547–574.

[21] C.J. De Luca, B. Mambrito, Voluntary control of motor units in human antagonist muscles: coactivation and reciprocal activation, J Neurophysiol 58 (3) (1987) 525–542.

[22] H.S. Milner-Brown, R.B. Stein, R. Yemm, The contractile properties of human motor units during voluntary isometric contractions, J Physiol 228 (1973) 285–306.

[23] J.G. Semmler, M.A. Nordstrom, A comparison of cross-correlation and surface EMG techniques used to quantify motor unit synchronization in humans, J Neurosci Meth 90 (1999) 47–55.

[24] G. Yue, A.J. Fuglevand, M.A. Nordstrom, R.M. Enoka, Limitations of the surface electromyography technique for estimating motor unit synchronization, Biol Cybern 73 (1995) 223–233.

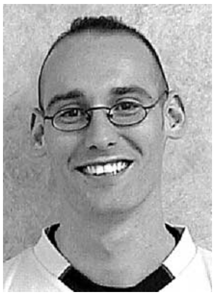
[25] L. Claudon, Evaluation of grip force using electromyograms in isometric isotonic conditions, Int J Occup Safety Ergon 4 (2) (1998) 169–184.

[26] L. De Smet, B. Tirez, K. Stappaerts, Effect of forearm rotation on grip strength, Acta Orthop Belg 64 (4) (1998) 360–362.

[27] L. Richards, B. Olson, P. Palmiter-Thomas, How forearm position affects grip strength, Amer J Occup Ther 50 (2) (1996) 133–138.

[28] C.A. Halpern, J.E. Fernandez, The effect of wrist and arm postures on peak pinch strength, J Human Ergol 25 (2) (1996) 115–130.

[29] A.O. Perotto, Anatomical guide for the electromyographer: the limbs and trunk, 3rd ed, Charles C. Thomas, Springfield, 1994.



Jeremy Mogk has a B.Kin. degree from McMaster University and an M.Sc. from York University in 2002. He is currently working towards his Ph.D. at York University. His research interests include modeling and motor control of the upper extremity as it pertains to predictions of muscle response and injury mechanisms.

Peter J. Keir received his B.Sc. and Ph.D. degrees from the University of Waterloo. After receiving his Ph.D. in 1995, he spent two years as a post-doctoral fellow in the University of California Ergonomics Program (UC San Francisco and UC Berkeley). Since 1998, he has been an Assistant Professor in the School of Kinesiology and Health Science at York University in Toronto. His research is dedicated to modeling the upper extremity to ultmately determine the mechanisms of work-related musculoskeletal disorders, with emphasis on carpal tunnel syndrome and muscle related injuries of the arm and hand.