

Amplitude threshold criteria improve surface electrode specificity during walking and functional movements

M. Elise Johanson^{a,*}, Sandra A. Radtka^b

^a VA Palo Alto Health Care System, Rehabilitation Research and Development, 3801 Miranda Avenue/153, Palo Alto, CA 94304-1200, United States

^b University of California at San Francisco/San Francisco State University, Graduate Program in Physical Therapy, San Francisco, CA, United States

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Abstract

Contamination of electromyographic (EMG) data due to crosstalk in recordings from surface electrodes can lead to misinterpretation of results. The purpose of this study was to determine if removing a portion of the EMG signal normalized to a maximum voluntary contraction (MVC) would improve the specificity of surface electrode recordings. We hypothesized that setting an amplitude threshold to define when a muscle was active would remove that part of the myoelectric signal most likely to include crosstalk, without affecting the intensity or the onset and cessation times. Surface and intramuscular electrodes recorded signals from the same muscles of adults performing cyclic ankle movements and walking at self-selected speeds. Signals identified as crosstalk were eliminated when 15% and 18% of the amplitude of the normalized signal was removed and muscle timing or intensity was not significantly changed in most cases.

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1. Introduction

When surface electrodes are used to study muscle function, the myoelectric signal recorded from the target muscle may reflect the activation of adjacent muscles as well. A contracting muscle produces an electrical signal that is dispersed throughout the tissues by volume conduction [1] that can make it difficult to distinguish individual muscle activation patterns. The potential contamination of EMG data due to crosstalk is especially problematic for studies of muscle co-activation or of muscles with synergistic actions during functional movements [3,5,11,17].

It is difficult to quantify the magnitude of crosstalk present in surface electrode recordings. Human subjects cannot *reliably* isolate a voluntary contraction of one muscle while recordings are made of volume conducted signals on nearby muscles [17]. Crosstalk has been measured in

adjacent muscles when a contraction is induced by electrical stimulation in the relaxed target muscle. De Luca and Merletti [1] demonstrated that a surface myoelectric signal detected on the peroneus brevis muscle, having a peak to peak amplitude of up to 16.6% of a signal detected over the anterior tibial muscle, may be due to crosstalk rather than to activation of the muscle below the electrode. Other studies have reported levels of crosstalk in lower extremity muscles between 11% and 18% of the maximum M-wave [10,11]. In contrast, Solomonow et al. [19] recorded from cat muscles during supramaximal stimulation of the corresponding nerve and determined crosstalk was always less than 5% for surface and less than 2.67% for wire recordings. However, supramaximal stimulation of the nerve produces unusually large signals due to synchronous recruitment of motor units and may represent a severe test for conditions that favor recording crosstalk [13].

In this study, we investigated the effect of removing the portion of the EMG signal most likely to include crosstalk during movements that did not require maximum effort and

* Corresponding author.

E-mail address: johanson@va51.stanford.edu (M.E. Johanson).

measured any resulting changes in muscle timing or intensity. Crosstalk was identified using wire electrode recordings because of their specificity [3,17,21]. In studies of voluntary movements and walking, surface electrode recordings may include low amplitude, out of phase EMG activity that is not present on the wire electrode recording from the same muscle that has been attributed to crosstalk [7]. Based on the previous studies, we hypothesized the amplitude of a surface electrode signal suspected to be crosstalk may be 5–18% of the signal recorded. The purpose of this study was to compare the duration of the EMG signal (within a movement or gait cycle) after removing 5%, 15%, and 18% of the normalized EMG signal. The EMG data were recorded during cyclic ankle movements and walking at self-selected speeds. There were four hypotheses.

H₁. The duration of the EMG activity will be significantly longer for the surface versus the wire electrode recordings at the 5% threshold level or the surface electrode recordings at the 15% or 18% threshold levels (due to the presence of crosstalk).

H₂. There will be no significant difference in the duration of the EMG activity recorded by the wire electrode recordings at 5%, 15%, and 18% threshold levels.

H₃. There will be no significant difference in the mean intensity (amplitude) of the EMG signals between the surface versus the wire electrode recordings at the 5% threshold level or the surface electrode recordings at the 15% or 18% threshold levels.

H₄. There will be a significant correlation between the size of the extremity and the frequency of crosstalk.

2. Methods

2.1. Subjects

Nineteen adult subjects without neurological or orthopaedic impairment in lower extremity function participated in this study. There were 15 females and 4 males with an average age of 31 years (range 24–50). Informed consent was obtained prior to participation in the study.

2.2. Recording procedures

Surface and wire EMG signals were recorded from peroneus longus (PL), lateral head of the gastrocnemius (GS), and anterior tibialis (AT). Sterile, paired, nylon-shielded 50 μ m stainless steel wire electrodes (2 mm exposed tip) were inserted via 25 gauge needles into each muscle according to Delagi and Perotto [2]. Placement was confirmed by electrical stimulation. An active surface electrode (B & L Engineering, Santa Fe Springs, CA) was

placed on the skin adjacent to the wire electrode. The electrodes were stainless steel pads, 1.14 cm in diameter, with a fixed inter-electrode distance of 1.97 cm, center to center. A ground electrode was attached to the head of the fibula.

All signals were recorded with a bandpass of 30–500 Hz, 2500 Hz sampling rate and amplified by a gain factor of 5000. For the walking tests, contact closing footswitches were taped to the subject's feet and used to define one gait cycle during the walking trial. EMG signals were differentially amplified and transmitted with the footswitch signals via FM telemetry. During the ankle movements, the footswitches were used by the examiner as an event marker to identify the beginning and ending of each movement cycle. A cycle was defined as the time to complete one movement of dorsi-plantarflexion or one gait cycle and was divided into phases: dorsiflexion or plantarflexion during the functional movements and swing or stance during walking. Fig. 1 is an example of raw (unprocessed) EMG data and the events describing each cycle of movement.

2.3. Protocol

The subject's leg length and girth were measured. While sitting, subjects performed a MVC, resisted by the examiner, of the AT and the PL with the ankle maintained in a neutral position. The MVC for the GS was recorded when the subject plantarflexed the ankle during a single limb standing heel rise. The subjects practiced each isometric contraction and the trial with the highest EMG was used for normalization.

The ankle movements tested each muscle in gravity resisted and gravity assisted positions and with the knee flexed and extended. Subjects performed the following movements: ankle plantarflexion and dorsiflexion/inversion in sitting (Test 1); ankle plantarflexion/eversion and dorsiflexion/inversion in sitting (Test 2); ankle plantarflexion and dorsiflexion with the knee extended in prone (Test

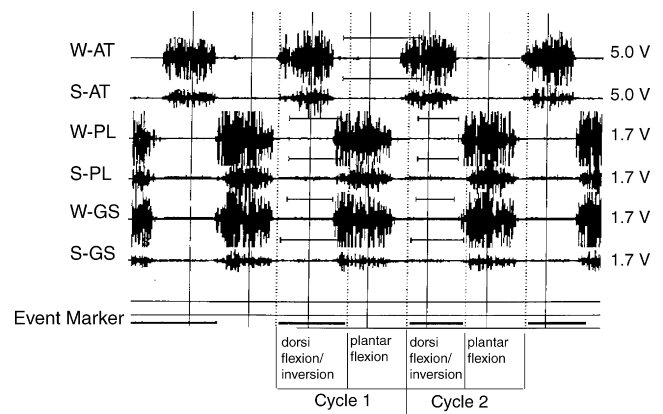


Fig. 1. Raw (unprocessed) surface (S) and wire (W) recordings from the AT, PL, and GS muscles from one subject during Test 1. Multiple cycles from one trial are averaged and presented as mean% EMG normalized to a maximum voluntary contraction (see text for abbreviations).

3); and ankle plantarflexion and dorsiflexion with the knee flexed in prone (Test 4). The mean cycle times for ankle movements in tests 1–4 were similar (mean = .21 s, S.D. = .04 s). For Test 5, subjects walked at a self-selected speed along an 8 m walkway. The mean walking speed was 72.8 m/min (S.D. = .41 s).

2.4. Signal processing

The EMG signals were processed using software developed and distributed by B & L Engineering, Santa Fe Springs, CA. A noise level was established by quantifying a resting trial. In subsequent trials, the EMG signal was rectified and summed only when the signal exceeded the noise level. All MVC trials were quantified to find the greatest amplitude of EMG during a .5 s segment. The absolute values of EMG were summed in discrete intervals of 1/50 s and a moving window of 25 intervals was averaged to identify the maximum segment. This value was chosen as the normalization factor for all tests. The intensity of the functional task EMG exceeded the MVC value in 28% of the data so these trials were normalized to the trial with the highest EMG amplitude.

Walking and ankle movement EMG were expressed as a percentage of the maximum signal for each muscle and normalized to the gait or movement cycle times. All of the recorded signals were at least 5% of the cycle in duration with an average amplitude greater than 5% of the MVC. Fig. 2A shows data processed at the 5% threshold level.¹ Each trial was re-processed using 15% (Fig. 2B) and 18% (Fig. 2C) of the MVC. Changes in the duration or intensity of activity were calculated.

2.5. Data analysis

Trials were excluded from the analysis if noise, motion artifact, or poor wire electrode signals were present. Final data analyses were conducted on the 215 useable recordings. EMG recordings were coded into two categories, presence or absence of crosstalk, based on visual inspection of the raw data. Crosstalk was defined as out of phase, low amplitude EMG activity recorded by the surface electrode that was not present on the recording from the wire electrode from the same muscle. In Fig. 2A, the duration of EMG recorded by the surface and wire electrodes was the same from the AT muscle during Test 1. But the duration of the EMG activity recorded by the surface electrodes for the GS and PL muscles exceeds that of the wire electrodes due to the “out of phase” activity recorded during ankle dorsiflexion with inversion. In this case, the AT recordings were coded as absence of crosstalk while the GS and PL recordings were coded as presence of crosstalk.

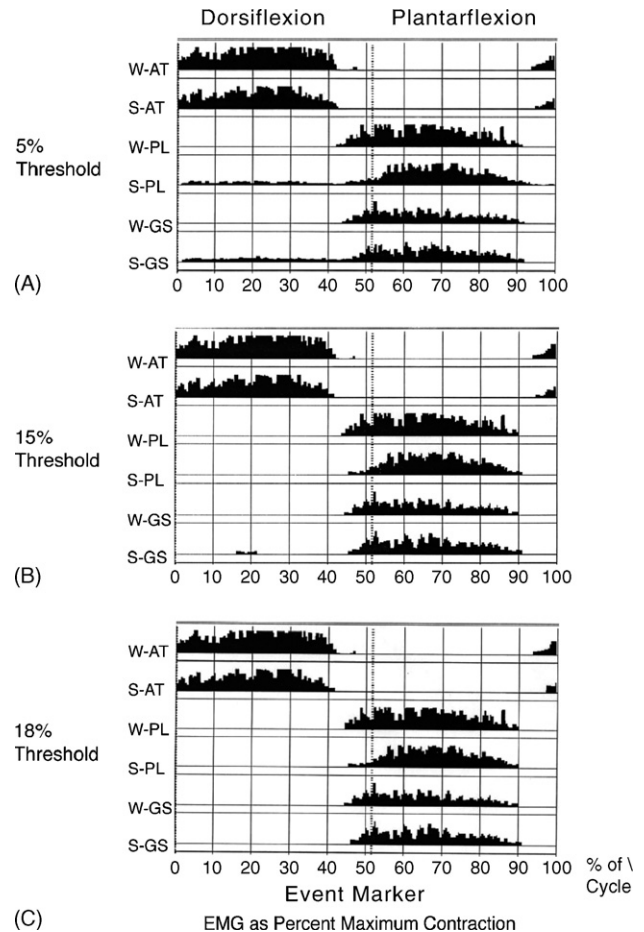


Fig. 2. (A) Surface (S) and wire (W) recordings from the AT, PL, and GS muscles from one subject during Test 1. In (A) 5% of a maximum EMG signal was used as a threshold to define the significant EMG level. Crosstalk is present on the surface electrode recordings of the PL and the GS muscles during dorsiflexion with inversion. (B) is the same trial as (A) with 15% of a maximum EMG signal used to define the threshold for a significant EMG level. Crosstalk has been removed from the surface recording of PL. Nearly all of the crosstalk was removed from the surface recording of the GS during dorsiflexion with inversion. (C) is the same trial as (A) with 18% of a maximum EMG signal used to define the threshold for a significant EMG level. Crosstalk has been removed from the surface recordings of both the PL and the GS muscles during dorsiflexion with inversion (see text for abbreviations).

The mean duration and intensity of muscle activity from all electrode recordings were calculated for each threshold level. Analysis of variance (ANOVA) with one independent factor (crosstalk presence or absence), and two repeated factors (electrode type and threshold level) was used to test for the effects of crosstalk and its interaction with electrode type and threshold level on duration and intensity of muscle activity at $p \leq .05$. For the trials with crosstalk, 15 ANOVAs (three muscles and five tests) with two repeated factors (electrode type and threshold level) were used to test for the interaction effects of the repeated factors on both duration and intensity of muscle activity. The alpha level of .05 was divided by 15 ($p \leq .003$) to account for the multiple ANOVA tests [18]. Five post hoc pairwise comparisons

¹ Fig. 2 shows the processed EMG signals from the same trial shown in Fig. 1 as raw data.

using Tukey's Honestly Significant Difference Test addressed the specific hypotheses for significant ANOVA tests: (1) wire electrodes at 5% (W5%) versus surface electrodes at 5% (S5%); (2) W5% versus surface electrodes at 15% (S15%); (3) W5% versus surface electrodes at 18% (S18%); (4) W5% versus wire electrodes at 15% (W15%); and (5) W5% versus wire electrodes at 18% (W18%). The alpha level of .05 was divided by five ($p \leq .01$) to account for the five comparisons [18]. Point biserial correlation coefficients ($p \leq .05$) were used to determine the relationships between lower leg girth and length and presence of crosstalk.

3. Results

Muscle activity defined as crosstalk was present in 59% (126/215) of the recordings. The presence of crosstalk had a significant ($p \leq .05$) effect on the recordings of the muscle duration between groups, and the interaction of crosstalk and electrode type, and the interaction of crosstalk and threshold level on muscle duration within groups (Fig. 3). Crosstalk was present most often in the signals from the PL (53%), from the GS in (28%), and least often from the AT (19%). There was no evidence of crosstalk in 41% (89/215) of the recordings.

There was a significant ($p \leq .003$) effect on the interaction of electrode type and threshold level on muscle duration for 9 of the 15 analyses on the trials with crosstalk listed in Table 1 (Wire 5% versus surface comparisons). Muscle duration was significantly longer ($p \leq .01$) for the S5% threshold level compared to the W5% threshold level due to the presence of crosstalk in the surface electrodes. The mean duration of the EMG signal for W5% threshold level ranged from 37% to 56% of the movement cycle, indicating muscle activity in one phase of the movement. The mean duration of the EMG signal recorded by the S5% threshold ranged from 80.6% to 92.6% of the movement cycle, indicating nearly continuous activity throughout both phases of the cycle. These findings result in

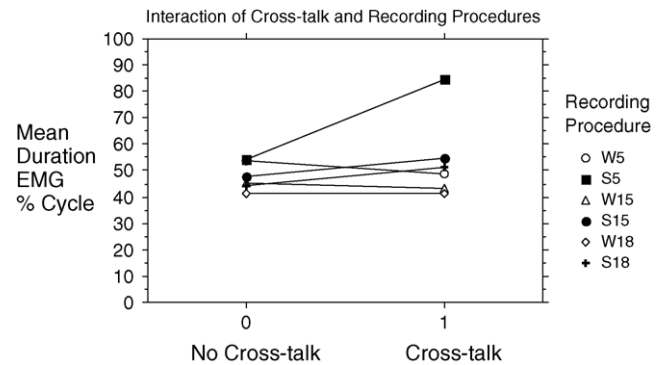


Fig. 3. Mean duration of recorded EMG expressed as a percentage of the movement or gait cycle. Recording procedures include wire (W) and surface (S) electrode recordings at 5%, 15%, and 18% threshold levels (see text for abbreviations).

different interpretations of the timing of muscle activation from the surface compared to the wire electrodes. The duration of EMG activity was not significantly different between the W5% threshold and either the S15% or S18% threshold levels (Table 1).

The increased threshold levels at 15% and 18% changed the duration of some of the signals recorded by the wire electrodes. Muscle duration was significantly decreased ($p \leq .01$) in five of the tests that recorded from the PL, indicating that the processing had eliminated signals (Table 1 (Wire comparisons)). In the tests demonstrating significant differences between the threshold levels for the wire electrode recordings, the mean differences in the duration of the EMG ranged from 4.3% to 6.9% of the movement cycle.

The mean (normalized) intensity of all three muscles at the 5% threshold levels ranged from 15.7% to 49.4% MVC (Table 2). The mean intensity of the EMG signals for muscles with crosstalk was not significantly reduced in any of the five pairwise comparisons, indicating that when the threshold level was increased from 5%, 15% to 18% for

Table 1
Mean differences in duration for post hoc pairwise comparisons of electrode recordings^a

Muscle and test	Wire 5% vs. surface comparisons				Wire comparisons	
	N ^b	W5–S5	W5–S15	W5–S18	W5–W15	W5–W18
AT Test 2	8	–32*	0	1	5*	6
AT Test 4	4	–36*	2	2	4	5
GS Test 1	10	–36*	10	15	14	14
GS Test 2	6	–33*	–6	6	3	4
PL Test 1	16	–38*	–6	–5	5	7
PL Test 2	15	–31*	–3	–1	5*	6*
PL Test 3	11	–43*	–19	–12	5	7*
PL Test 4	15	–37*	–7	–3	4*	7*
PL Test 5	10	–48*	–16	–8	7	9

See text for abbreviations.

* Significant at $p \leq .01$.

^a For the wire 5% vs. surface comparisons, a negative value indicates the duration of the surface EMG was greater. For the wire electrode comparisons a positive value indicates the W5% recordings were longer duration.

^b Number of recordings.

Table 2

Mean intensity of wire and surface electrode recordings at 5% threshold levels^a

Muscle and test position	N ^b	W5	N ^b	S5
AT Test 1	3	44 (18)	4	49 (9)
AT Test 2	6	36 (14)	4	45 (8)
AT Test 3	2	29 (21)	2	18 (2)
AT Test 4	3	27 (15)	2	42 (0)
AT Test 5	4	18 (8)	4	25 (11)
GS Test 1	8	39 (15)	4	35 (14)
GS Test 2	5	33 (7)	2	19 (3)
GS Test 3	7	37 (20)	2	27 (7)
GS Test 4	4	17 (9)	2	16 (7)
GS Test 5	5	25 (9)	3	25 (5)
PL Test 1	14	34 (15)	10	30 (8)
PL Test 2	14	45 (17)	10	41 (16)
PL Test 3	10	26 (17)	7	23 (10)
PL Test 4	14	30 (15)	7	27 (8)
PL Test 5	9	20 (14)	7	21 (8)

See text for abbreviations.

^a Standard deviation in parenthesis.

^b N varies due to limitations in the processing software, mean intensities could not be calculated for any of the trials that used maximum gait EMG for normalization.

surface and wire electrodes the magnitude of the EMG signal was not significantly affected. The intensity of each muscle increased during the appropriate test, indicating the subjects were performing the functional movements correctly.

The subjects had a mean lower leg girth of 36.4 cm (S.D. = 2.89) and a mean lower leg length of 31.1 cm (S.D. = 2.28). There were no significant correlations between leg girth and the presence of crosstalk (coefficients ranged from $-.33$ to $.35$) or between leg length and the presence of crosstalk (coefficients ranged from $-.10$ to $.53$).

4. Discussion

Defining the criterion for significant EMG to be at least 15% of the amplitude level of the MVC performed by the subject was effective for reducing signals attributed to crosstalk in this study. Using the 15% or the 18% threshold level removed the signals that were identified as crosstalk and the important phasing (onset and cessation) and intensity information during a functional movement was not misrepresented. There were significant changes in the duration of the wire signals when the threshold amplitude was increased. However, a 4–7% difference in the duration of EMG signal would not likely result in a misinterpretation of the data. The magnitude of the crosstalk signals recorded in this study was consistent with the findings reported by De Luca and Merletti [1], Koh and Grabiner [11] and Knaflitz et al. [10] but higher than the findings reported by Solomonow et al. [19] evidenced by the threshold level that was effective in removing the signals attributed to crosstalk.

For studies of unresisted ankle movements or walking, the PL recordings most often included crosstalk. Recordings from the PL may be particularly susceptible to crosstalk because of the relative intensity of the EMG signals and the anatomical orientation of the muscles to each other [16]. The PL, is separated from the anterior compartment muscles by only thin fascia [17]. The AT muscle is partially shielded from the peroneal muscles by the extensor digitorum longus and more distally by the extensor hallucis longus. Muscle activation of the PL is often recorded for clinical gait studies and if surface electrodes are used, a 15% threshold level for processing EMG data may prevent misinterpretation of data.

Wire electrodes were used in this study as a reference signal to make judgements about the selectivity of the surface recordings. There is little disagreement that the small detection volume of the wire electrodes makes them less sensitive to volume conducted signals than surface electrodes. Nonetheless their small detection area has raised concern about their ability to represent muscle activation and use to identify crosstalk [8]. The recent studies that report evidence of functional compartments within a muscle has restated the concern that signals recorded by surface electrodes (we identified as crosstalk) could be due, instead, to activity recorded from a different “functional compartment” of the target muscle. These studies propose there are different motor unit territories that are active during different functional tasks of the same muscle [15,20]. In contrast, other investigators have demonstrated the ability of wire electrodes to represent the activation of even large muscles confirming the EMG signal is equally distributed throughout the muscle [6,9,14]. In the present study, the functional task was the same and the close proximity of the surface and wire electrodes minimized the possibility that the two electrodes were sampling from entirely different motor unit pools. These findings are consistent with data that show the muscle fibers associated with each motor unit are dispersed throughout the muscle [12,16]. In the absence of any conclusive evidence demonstrating the signals from wire electrodes are not representative a muscle contraction, we conclude the signals from the wire electrodes represented the activation of the target muscle and the EMG activity classified as crosstalk was due to volume conducted signals from adjacent musculature.

Other signal processing procedures have been reported for quantifying or reducing crosstalk. Spatial filtering, such as the double differential recording technique described by De Luca and Merletti [1], both reduced and helped to identify signals due to crosstalk, but required specific recording procedures and equipment that may not be available in all settings. Temporal (high-pass) filtering to remove crosstalk assumes that the signals have a lower frequency content because their source is distant to the recording electrode [22]. However, recent studies have demonstrated the non-propagating potentials from distant muscles can produce high frequency signals corresponding to the termination of the potentials at the tendon.

These signals are not removed by high-pass filtering or mathematical differentiation and appear as crosstalk on surface electrode recordings [4]. Variability across subjects, testing protocols, and available technology makes it difficult to predict when volume conducted signals will contaminate the surface electrode signal and measurement technology makes it difficult to selectively remove only the volume conducted signals. This presents a dilemma for determining the most effective recording procedures.

This study demonstrated that deleting up to 15% of the normalized EMG signal is one method for improving the specificity of surface electrode recordings of muscle activation. This method was effective for studies of functional movements and walking because the timing and intensity information are not significantly altered. Determination of a threshold amplitude that represents a significant EMG signal can be made independent of subject characteristics, level of effort and specialized equipment. The method presented here is intended to be a practical solution for reducing crosstalk that will improve the ability to correctly interpret surface electrode recordings until our technical expertise includes the elimination of signals attributed to crosstalk. This method is appropriate for clinical gait analysis and for use in kinesiology studies.

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