

Short Communication

Cross-correlation as a method for comparing dynamic electromyography signals during gait

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Abstract

Current clinical interpretation of dynamic electromyography (EMG) data is usually based on qualitative assessments of muscle timing. Cross-correlation may provide a method for objectively comparing the timing and shape of EMG signals. This study used cross-correlation to compare EMG signals from different walking trials, different test sessions, and different individuals in able-bodied adults. Cross-correlation results (R -values) for different walking trials within a single test session were high, averaging ≥ 0.90 for all muscles tested ($R = 1.0$ indicates exact agreement). Cross-correlation values were also high among trials from different test sessions conducted by the same and different examiners (average $R \geq 0.78$ for all muscles). R -values were much more variable when comparing different subjects (average 0.40–0.81, range 0.00–0.91). R -values were lower for the medial hamstrings and rectus femoris compared with the other muscles tested. These results suggest that cross-correlation may be useful for evaluating changes in an individual patient's muscle activation patterns, such as before and after surgery, but not for comparing EMG patterns among different individuals, such as between patients and normative data. This is especially true for biarticular muscles such as the hamstrings and rectus femoris, which may have variable activation patterns and/or increased sensitivity to electrode placement. Cross-correlation may also be useful for identifying appropriate muscles for transfer, identifying “outlier” trials within a test session, and selecting representative EMG curves for a given patient. The advantages of cross-correlation are that it considers shape of the EMG signal in addition to timing and that the assessments it provides are objective, rather than subjective.

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1. Introduction

Dynamic electromyography (EMG) is used to measure muscle activity during gait analysis testing. Clinically, EMG is used to describe deviations from normal motor unit firing patterns, to identify muscles for transfer, and to evaluate surgical outcomes (Perry et al., 1976; Perry and Hoffer, 1977; Gueth et al., 1985; Hoffer et al., 1990; Kleissen et al., 1998). These applications currently focus on comparisons of muscle

timing and overall muscle activity. Muscle timing can be quantified by defining signal onset and cessation times (Bogey et al., 1992; Buurke et al., 2004), and overall muscle activity can be quantified in terms of EMG amplitude relative to either a maximal volitional contraction or a maximum during gait. However, muscle activity is most often assessed subjectively through visual examination of EMG data. This approach has two major limitations. First, the comparisons are largely subjective. Second, information about the shape of the EMG signals (changing magnitude across the gait cycle) is ignored. To address these limitations, a simple, objective method is needed for analyzing EMG data taking into account both timing and shape of the EMG signal.

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Cross-correlation is a well-established approach for comparing signals. It is used in many fields including audio-signal processing and image processing. In the field of EMG, cross-correlation has been used to assess myoelectric cross talk (Morrenhof and Abbink, 1985; Lowery et al., 2003), synchronization of motor unit firing (Person and Kudina, 1968; Loeb et al., 1987), mechanical positions (Lee and Wong, 2002), and EMG amplitudes (Li and Caldwell, 1999). To our knowledge, cross-correlation has not been used to compare EMG signal amplitudes between different individuals or at different time points in the same individual, such as before and after surgery. This paper examines whether cross-correlation may be useful for these purposes.

2. Materials and methods

Five able-bodied female adult subjects gave written informed consent to undergo dynamic EMG testing following standard clinical procedures. Surface EMG electrodes with built-in pre-amplifiers were placed over five muscles on each leg: rectus femoris, lateral quadriceps, medial hamstrings, anterior tibialis, and medial gastrocnemius. The electrodes were round with 11 mm diameter and an inter-electrode distance of 8 or 22 mm. The electrodes were aligned in the longitudinal direction of the muscle fibers and taped over the largest muscle bulk palpated with contraction or stretch. Electronic foot switches were taped under the subject's feet to detect events such as initial contact, which define the gait cycle. Subjects walked down a 15-m-walkway four times at a self-selected speed. An MA-300-10 ten channel EMG system (Motion Lab Systems, Inc., Baton Rouge, LA) recorded EMG and foot-switch data at 2500 Hz during each walking trial and during a 5 s "resting" trial that established baseline noise levels for the system. The data were filtered with a high-pass setting of 120 Hz and a low-pass setting of 350 Hz. Each subject participated in three test sessions within a two-week period. Two sessions were conducted by the same physical therapist and the third session was conducted by another therapist. In some cases, multiple tests were performed on the same day. When this occurred, the tests were separated by several hours so electrode placement locations from prior tests were not evident during later tests.

The EMG data were processed using EMG Analyzer 1.97 (B & L Engineering, Tustin, CA). The raw signals were rectified and smoothed using a 50-sample window moved successively through the data in 20-sample increments (Perry et al., 1993). The resulting data were time normalized to the gait cycle and amplitude normalized to the peak signal recorded for each muscle during the test session. Four to six strides within a trial underwent ensemble averaging to produce an "average"

gait cycle representing the trial (Bogey et al., 1992). This "average" EMG curve had 100 data points, each representing 1% of the gait cycle.

Cross-correlation between pairs of processed EMG curves was performed as follows. Consider two series x_i and y_i where $i = 0, 1, 2, \dots, N-1$. The normalized cross-correlation function with zero time lag is calculated, with $N = 100$, as

$$R = \frac{\sum x_i y_i}{(\sum x_i^2)^{1/2} (\sum y_i^2)^{1/2}}.$$

The cross-correlation measures the similarity in shape between two curves as a scalar between 0 and 1, analogous to the dot product of two vectors. Two curves with exactly the same shape will have a cross-correlation of 1.0. Uniform scaling (changing the amplitude of the curve without changing its shape) does not affect the cross-correlation results. R -values are most sensitive to similarities and differences in timing; when timing is similar, they are also sensitive to similarities and differences in shape (Fig. 1).

Cross-correlation was used to compare different trials, different test sessions, and different subjects (Table 1). Comparisons of trials within a single test session examined variability due to inconsistent walking patterns and variability inherent in the EMG signal. Comparisons between different sessions with the same examiner examined the effects of electrode placement

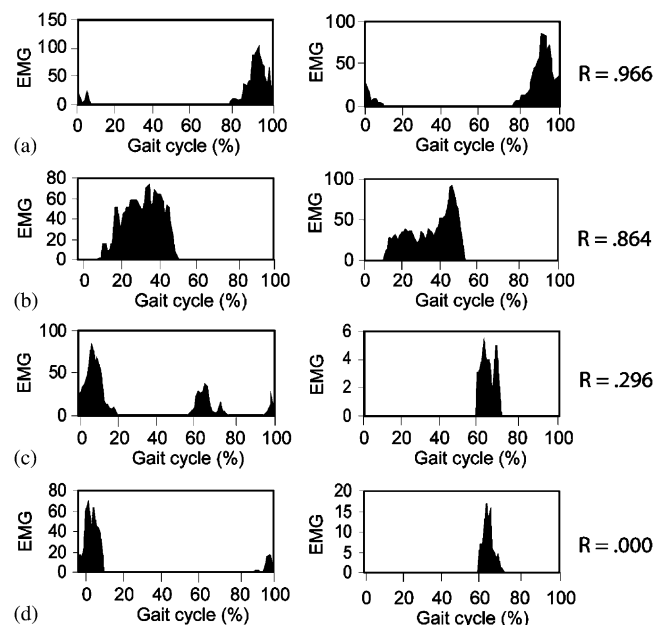


Fig. 1. Cross-correlation between average rectified EMG signals with (a) similar timing and shape; (b) similar timing but different shape; (c) some similarities in timing and possibly shape; and (d) different timing but similar shape. R -values are most sensitive to similarities and differences in timing; when timing is similar, they are also sensitive to similarities and differences in shape.

Table 1
Comparisons performed

Comparisons	Test conditions			Analysis	
	Session	Therapist	Subject	# Trials per session	Total # comparisons (all subjects)
(1) Trials within a single session	Same	Same	Same	4	24
(2) Different sessions (same therapist)	Different	Same	Same	2	16
(3) Different therapists	Different	Different	Same	2	16
(4) Different subjects	Different	Same	Different	1	6

Number of trials indicates trials per session per subject that were included in the analysis. For comparisons involving fewer than four trials, the first available trials were used in the analysis.

and day-to-day variability in gait patterns. Comparisons between sessions conducted by different therapists examined differences due to the examiner. Finally, comparisons between different subjects examined the variability in EMG patterns among able-bodied individuals.

For some comparisons, fewer than four trials were used per session to make the number of comparisons more manageable (Table 1). For example, two trials per session were used for each subject when evaluating inter-session variability. In these cases, the first available trials from each session were used, and each of the two trials from the first session was compared with each of the two trials from the second session (four comparisons per subject).

3. Results

Cross-correlation results for different trials within a single test session were extremely high, averaging ≥ 0.90 for all muscles (Table 2). Cross-correlation values for most muscles were also high among trials from different test sessions conducted by the same and different examiners (Table 2). However, lower R -values and greater variability in R -values were observed for the medial hamstrings and rectus femoris compared with the other muscles. R -values were also lower for all muscles when comparing different subjects (Table 2).

4. Discussion

Current interpretation of dynamic EMG data is usually based on qualitative visual assessments of muscle timing. Methods have been proposed to quantify the timing and overall intensity of EMG activity (Bogey et al., 1992; Buurke et al., 2004). However, these methods do not consider the shape of the EMG response. Since the shape of the EMG signal reflects the pattern of muscle activation and force output

throughout the gait cycle (Coggshall and Bekey, 1970; Hof and van den Berg, 1977; Crosby, 1978; Perry and Bekey, 1981), an objective method is needed to compare EMG signals taking both timing and shape into account. The results of this study suggest that cross-correlation provides such a method.

Our cross-correlation results indicated that EMG patterns for an individual subject are consistent across different walking trials and test sessions even with re-positioning of the electrodes by different examiners. Cross-correlation should therefore be a useful method for comparing muscle activity for a given subject at different time points, such as before and after surgery. Although the hamstrings and rectus femoris exhibited more variability than the other muscles, R -values were still reasonably high (>0.7) suggesting that cross-correlation would be useful for these muscles. R -values comparing different individuals were generally lower than R -values within the same individual, especially for certain biarticular muscles. This suggests that cross-correlation may be less useful for comparisons between different individuals, at least for some muscles.

The lower R -values for the hamstrings and rectus femoris compared with the other muscles may reflect greater variability in the activation patterns of these muscles during walking at self-selected speeds. It may also reflect increased sensitivity of these muscles to electrode placement due to the muscles' length and greater overlying fat mass. If this were the case, it would demonstrate a possible limitation of using surface EMG to evaluate these biarticulate muscles. The cross-correlation results also highlight potential problems with averaging EMG signals across multiple subjects as is sometimes done to define normative data or "typical" muscle activation patterns.

One limitation of cross-correlation is that it does not identify specific differences between EMG signals. It also does not consider the absolute magnitude of the signal and therefore would not detect uniform changes in muscle activation level. In addition, we did not consider all possible pairs of trials for the inter-session

Table 2
Cross-correlation results (*R*-values)

Muscle	Cross-correlation, mean \pm SD (range)			
	Different trials, same test session	Different sessions, same examiner	Different sessions, different examiner	Different subjects
L rectus femoris	0.90 \pm 0.05 (0.78–0.99)	0.86 \pm 0.07 (0.67–0.99)	0.84 \pm 0.09 (0.61–0.99)	0.62 \pm 0.17 (0.35–0.81)
R rectus femoris	0.92 \pm 0.04 (0.80–0.99)	0.87 \pm 0.05 (0.73–0.94)	0.88 \pm 0.06 (0.73–0.97)	0.68 \pm 0.19 (0.43–0.92)
L lateral quadriceps	0.97 \pm 0.02 (0.89–0.99)	0.94 \pm 0.05 (0.82–0.98)	0.96 \pm 0.02 (0.91–0.99)	0.89 \pm 0.07 (0.78–0.98)
R lateral quadriceps	0.96 \pm 0.02 (0.92–0.99)	0.93 \pm 0.04 (0.83–0.99)	0.94 \pm 0.03 (0.82–0.99)	0.91 \pm 0.05 (0.82–0.97)
L medial hamstrings	0.92 \pm 0.04 (0.80–0.99)	0.84 \pm 0.14 (0.52–0.97)	0.86 \pm 0.14 (0.58–0.97)	0.56 \pm 0.18 (0.32–0.92)
R medial hamstrings	0.93 \pm 0.05 (0.84–1.00)	0.78 \pm 0.15 (0.53–0.96)	0.85 \pm 0.10 (0.68–0.97)	0.65 \pm 0.15 (0.46–0.81)
L anterior tibialis	0.95 \pm 0.02 (0.92–0.98)	0.90 \pm 0.08 (0.59–0.98)	0.95 \pm 0.03 (0.89–0.98)	0.87 \pm 0.05 (0.79–0.97)
R anterior tibialis	0.95 \pm 0.02 (0.90–0.98)	0.93 \pm 0.04 (0.85–0.98)	0.94 \pm 0.02 (0.91–0.98)	0.85 \pm 0.06 (0.78–0.95)
L gastrocnemius	0.96 \pm 0.02 (0.92–0.99)	0.92 \pm 0.07 (0.79–0.98)	0.96 \pm 0.02 (0.87–0.99)	0.84 \pm 0.06 (0.74–0.94)
R gastrocnemius	0.96 \pm 0.01 (0.91–0.98)	0.92 \pm 0.07 (0.78–0.99)	0.95 \pm 0.02 (0.86–0.99)	0.82 \pm 0.08 (0.71–0.93)

analyses, although the results should be accurate given the consistency of trials within a test session. Finally, this study involved a limited number of healthy subjects. Children and disabled subjects may exhibit more inconsistent muscle firing patterns than healthy subjects. To examine this limitation, we applied cross-correlation to EMG data from three randomly selected children with cerebral palsy and found that they had trial-to-trial *R*-values similar to the able-bodied subjects (0.95 \pm 0.04; range 0.75–0.99). We also found similar results in a test using a lower high-pass cutoff value of 40 Hz (0.96 \pm 0.03; range 0.86–0.99).

Dynamic EMG is primarily used for two clinical applications: evaluating changes in function after surgery and comparing a patient's muscle activity with normative data to identify appropriate muscles for transfer or lengthening. This study suggests that cross-correlation should be most useful in evaluating changes in an individual patient's muscle activation patterns, either after surgery or at different points in time during an intervention. Cross-correlation may also be useful in identifying muscles for transfer if the desired EMG pattern of the transferred muscle is defined. Finally, cross-correlation may provide an efficient means for identifying "outlier" trials within a test session and for selecting a representative EMG curve for inclusion in reports. The advantages of cross-correlation in these applications are that it considers shape of the EMG signal in addition to timing and that the assessments it provides are objective, rather than subjective.

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