Methods of Muscle Activation Onset Timing Recorded During Spinal Manipulation

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Abstract

Objective: The purpose of this study was to determine electromyographic threshold parameters that most reliably characterize the muscular response to spinal manipulation and compare 2 methods that detect muscle activity onset delay: the double-threshold method and cross-correlation method.
Methods: Surface and indwelling electromyography were recorded during lumbar side-lying manipulations in 17 asymptomatic participants. Muscle activity onset delays in relation to the thrusting force were compared across methods and muscles using a generalized linear model.
Results: The threshold combinations that resulted in the lowest Detection Failures were the "8 SD–0 milliseconds" threshold (Detection Failures = 8) and the "8 SD–10 milliseconds" threshold (Detection Failures = 9). The average muscle activity onset delay for the double-threshold method across all participants was 149 ± 152 milliseconds for the multifidus and 252 ± 204 milliseconds for the erector spinae. The average onset delay for the cross-correlation method was 26 ± 101 for the multifidus and 67 ± 116 for the erector spinae. There were no statistical interactions, and a main effect of method demonstrated that the delays were higher when using the double-threshold method compared with cross-correlation.
Conclusions: The threshold parameters that best characterized activity onset delays were an 8-SD amplitude and a 10-millisecond duration threshold. The double-threshold method correlated well with visual supervision of muscle activity. The cross-correlation method provides several advantages in signal processing; however, supervision was required for some results, negating this advantage. These results help standardize methods when recording neuromuscular responses of spinal manipulation and improve comparisons within and across investigations. (J Manipulative Physiol Ther 2016;39:279-287)
Key Indexing Terms: *Manipulation; Spinal; Chiropractic; Reflex; Electromyography; Biomechanical Phenomena; Kinetics*

Spinal manipulation (SM) is a treatment used by doctors of chiropractic, doctors of osteopathy, and physical therapists to address a wide variety of musculoskeletal conditions.[1] Although high-velocity, low-amplitude (HVLA) SM is a recognized treatment of acute and chronic low back pain,[2] questions about the underlying biomechanical mechanisms of effective treatment remain unanswered. For example, the ideal amount of relative vertebral movement, the importance of a muscular reflex response, and the role of joint cavitation (audible release) all remain unclear.[3] By developing a better understanding of how these aspects contribute to pain relief through in vivo research, improvements can be made in the pairing of specific treatments with patient and clinical condition.

In vivo research on SM has largely focused on mechanical parameters such as external thrust force, vertebral movement, and cavitation, whereas few investigations have examined the neuromuscular response to the manipulation itself. This response consists of integrated communication between the sensory system (ie, mechanoreceptors) and the motor system (ie, muscles). Sensory system responses to SM include positive action potentials in spinal nerve roots,[4] increases in central nervous system excitability,[5] and decreased sensitivity to pain.[6] The motor system response to SM includes both

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increased and decreased paraspinal muscle electromyographic (EMG) activity.[7–9] Mechanisms that may explain these effects are altered inflow of proprioceptive primary afferents (groups I and II) from the paraspinal tissues, mechanical compression of neural tissue, central nervous system sensitization, and altered motorneuron excitability.[10]

Two characteristics of the EMG response to SM are relevant for examination: *amplitude of the response* and *timing of the response*. Evidence of EMG amplitude changes after SM is conflicting,[11,12] which creates difficulty when interpreting the meaning and significance of amplitude changes in response to SM. A recent review of EMG and SM indicated that manipulation is associated with short-term changes in the amplitude response of the myoelectric signal, but that the response can be either an amplitude *increase or a decrease*, and may be specific to the proximity of the muscle to the force application and activity performed.[12] In addition, interpretation of the amplitude response across participants can be difficult as it is dependent on the type of muscle studied, the training level, and participant motivation.

Timing of the muscle response is quantified as the muscle activity onset following the application of the thrust force. Pickar and Kang[13] demonstrated that the frequency of muscle spindle firing increases in response to forces consistent with SM, which may incite timing changes in efferent motoneuron activity. The muscle activity onset delay measured after a manual posterior to anterior SM in the thoracic spine was 50 to 200 milliseconds, a range that suggests a muscle spindle pathway reflex.[8] In contrast, the muscle activity onset delay measured after an SM performed with a mechanical device applied directly to L1 and L3 spinal vertebra in a posterior to anterior direction was 2.4 to 18.1 milliseconds.[4]

Two common methods are available to calculate the muscle activity onset delay: double-threshold detection and cross-correlation. It is currently unclear which method is most appropriate for calculating onset delays in response to SM. Considering the wide range of onset delays reported in the literature (≈2-200 milliseconds), and that forces are applied by practitioners in variable settings, there is a need to facilitate comparison between investigations by standardizing methodologies. The double-threshold method, which is more commonly used, requires identification of an amplitude threshold and a duration threshold over which EMG activity is considered muscle “active.”[14] The cross-correlation method uses the cross-correlation function to identify the temporal shift (or time lag) between 2 time-varying signals, and has been used in human movement and rehabilitation sciences to evaluate muscle activity.[15]

Specific details of how muscle activation onset delays are calculated within each investigation are sometimes sparse, and a comparison of methodologies does not exist. Therefore, the objectives of this investigation were as follows: (1) to determine the threshold parameters that most reliably characterize the muscular response to SM using the double-threshold method of EMG onset detection, and (2) to evaluate the advantages and disadvantages of the double-threshold method and cross-correlation methods when applied to HVLA SMs in healthy participants. This information will help develop methodological standards on which to compare the EMG responses in research on SM and assist interpretation and applications of EMG in research and clinical practice.

Table 1. *Mean ± SD Participant Anthropometric Information*

	Male (n = 9)	Female (n = 8)
Age (y)	31.6 ± 13.4	28.8 ± 5.2
Height (cm)	179.4 ± 7.7	165.0 ± 3.3
Weight (kg)	79.9 ± 6.4	59.0 ± 4.7
Dominant hand (right/left)	(8/1)	(6/2)

Methods

Participant Information

Seventeen participants with no history of low back pain during the previous 4 years (Table 1) visited the laboratory for 1 session lasting 3 hours in which lumbar muscle activity was collected during SM. Each participant was screened for contraindications to SM by performing an orthopedic and neurologic examination. Participants were excluded from the investigation if their current level of pain exceeded a 7 of 10 on a verbal pain scale, they experienced radicular pain below the knee during orthopedic testing, or neurologic examination revealed absent reflexes, decreased sensation, or weakness below the knee. Each participant provided written, informed consent in accordance with the Colorado Multiple Institutional Review Board prior to the start of the experimental session.

Application of SM

Two doctors of chiropractic, each with more than 10 years of clinical experience, performed HVLA SM at the L3 and sacroiliac spinal level with a hypothenar contact in the side-lying position. The order of manipulations was randomized, the time between manipulations was between 1 and 3 minutes, and only data from the manipulation at L3 were used in this analysis.

EMG and Thrust Force Instrumentation

Each participant was instrumented with surface EMG over the left erector spinae at the L2 level and indwelling EMG (50 mm, 25-gauge needle with a pair of 0.051 mm, insulated, hooked wires, and 200 mm tail with 5 mm bare-wire terminations) in the left multifidus at the L2 spinal level (Fig 1) according to the insertion protocol

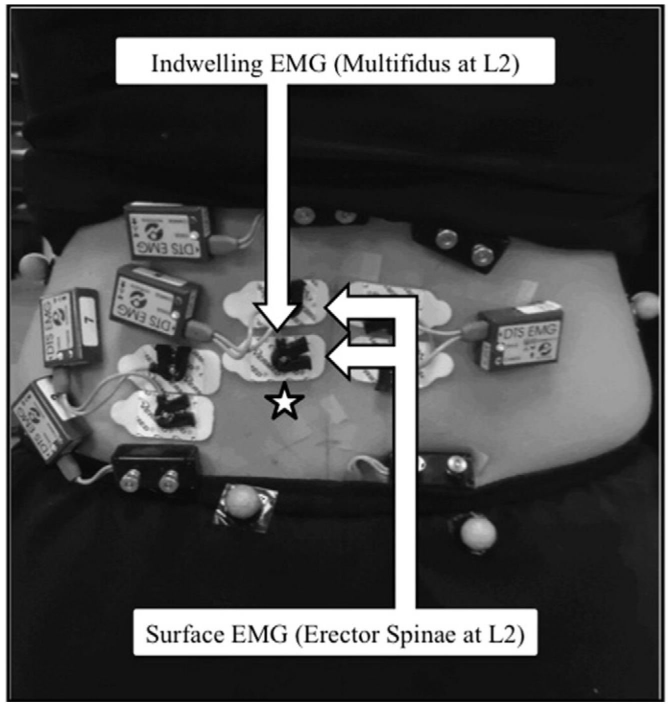

Fig 1. *Instrumentation included indwelling and surface EMG. The indwelling EMG recorded information from the multifidus and the surface EMG from the erector spinae. Star indicates manipulation site at the L3 spinal level on the left.*

defined by Haig et al.[16] These recording sites were a subset from a larger protocol in which multiple levels of the lumbar multifidi and erector spinae were similarly instrumented (Fig 1). Recordings at L2 were chosen to analyze in this investigation for their close proximity to the site of manipulation (L3). A Noraxon TeleMyo DTS (Noraxon USA, Scottsdale, AZ) system was used to record both surface and indwelling EMG signals. The thrust force from the contact hand was estimated using an optimized algorithm that combines measurements from a force plate (Bertec Corporation, Columbus, OH) embedded in the treatment table and force transducers attached to the practitioner while maintaining natural contact between the practitioner and the participant.[17]

EMG Signal Processing

The raw EMG signals were sampled at 2000 Hz, bandpass filtered to remove movement artifact and high-frequency noise (fourth-order Butterworth, 15-350 Hz), and transformed using the Teager-Kaiser Energy Operator (TKEO)[18,19]:

$$\Psi[x(n)] = x^2(n) - x(n+1)x(n-1) \tag{1}$$

where *x* is the EMG amplitude and *n* is the sample number. Following TKEO transformation, linear envelopes of the erector spinae and multifidus EMG signals were created by applying full-wave rectification and low-pass filter (fourth-order Butterworth, 50-Hz cutoff).

Onset Delay Calculations

Onset delay between the thrust force and muscle activation was calculated using the double-threshold method,[20] with varying threshold parameters and the cross-correlation method.[15]

Onset Delay Using Double-Threshold Method

Muscle activation onset was determined using 3 different amplitude thresholds and 3 different duration thresholds (9 combinations total). The amplitude thresholds were 3, 8, and 13 SDs above the mean baseline amplitude recorded 1 second prior to manipulation. The duration thresholds chosen were 0, 10, and 20 milliseconds. The muscle was considered “active” if the signal passed the amplitude threshold for the given duration threshold. The onset of thrust force application was determined by the initiation of positive rate of force. Muscle activation onset delay was recorded as the difference between these times (Fig 2).

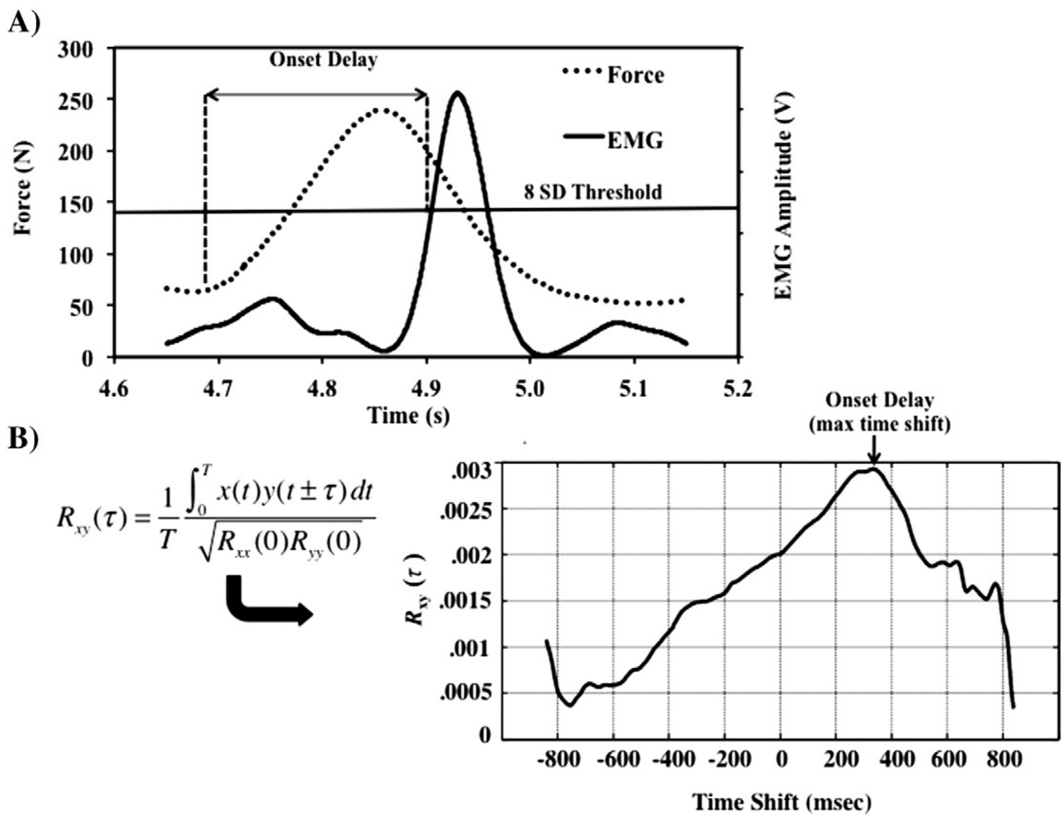

Fig 2. *Illustration of 2 methods used to determine EMG onset delay. A, Onset delay as calculated by the double-threshold method using the difference between the onset of positive force rate and muscle activity that crossed the threshold. B, Onset delay as calculated using the cross-correlation function lag plot. The time at which the maximum value occurs represents the time shift between the 2 signals.*

Onset Delay Using Cross-Correlation Method

The cross-correlation function is given by

$$R_{xy}(\tau) = \frac{1}{T}\frac{\int_0^T x(t)y(t \pm \tau)\mathrm{dt}}{\sqrt{R_{xx}(0)}R_{yy}(0)} \quad (2)$$

where T is the duration of the record. The numerator is the integration of the products of the 2 signals at each point, where $x(t)$ (force signal) is held stationary and $y(t)$ (EMG signal) is shifted by time (τ). The denominator is the square root of the product of the autocorrelations (R_{xx}, R_{yy}) of the signals with no time shift, which removes the units and results in a cross-correlation value constrained between −1 and 1. The cross-correlation function between the thrust force and EMG linear envelope was evaluated using the *xcorr* function in Matlab (The MathWorks Inc, Natick, MA). Muscle activation onset delay was defined as the time shift that corresponded with the maximum value of the cross-correlation function lag plot (Fig 2).

Selection of Thresholds and Comparison to Cross-Correlation Method

The combination of amplitude threshold and duration threshold that minimized 2 error variables (number of signal dropouts, number of false positives) was chosen for comparing the muscle activation onset delays to those calculated by the cross-correlation method. A signal dropout in the double-threshold method was defined as any instance in which the EMG activity did not meet both thresholds. A false positive in the double-threshold method was defined as EMG activity that crossed the threshold but was not visually different from baseline (Fig 3). The collective effect of the dropout rates and false positives was considered the total detection failures. To choose the parameter combination, we emphasized minimizing false positives over minimizing dropouts.

$$\text{Detection Failure} = \text{Signal Dropouts} + \text{False Positives} \quad (3)$$

The onset delays calculated using the previously chosen double-threshold parameters were compared for both muscle groups to the onset delays calculated using the cross-correlation method using a generalized linear model. Level of significance of all comparisons was set at $\alpha = .05$.

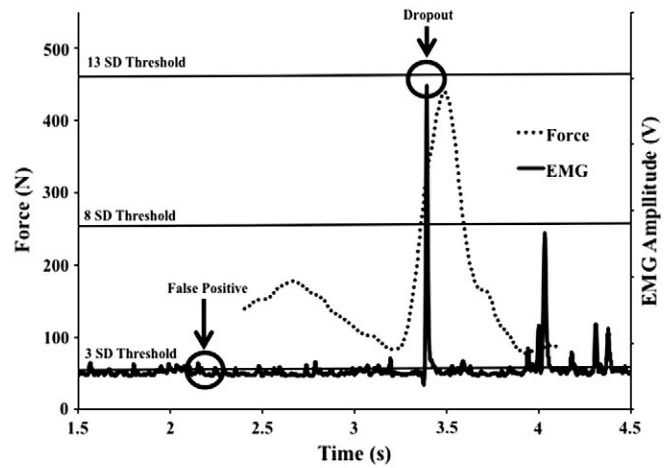

Fig 3. *Illustration of the 2 errors (false positives and dropouts) in onset delay calculation using the double-threshold method. A false positive occurred when EMG activity crossed the threshold but was not different from baseline and a dropout occurred when the activity did not meet the threshold criteria.*

Table 2. *Mean (95% CI) Onset Delays (in Milliseconds) for 9 Combinations of Double-Threshold Parameters for Both Multifidus and Erector Spinae*

	Multifidus			Erector Spinae		
	Duration Thresholds (ms)					
	0	10	20	0	10	20
Amplitude thresholds (SD)						
3	19 [−743, 781]	13 [−145, 171]	127 [13, 242]	−100 [−1301, 1100]	−99 [−334, 136]	218 [120, 316]
8	**137 [73, 202]**	**149 [65, 233]**	171 [85, 258]	**185 [80, 289]**	**252 [106, 397]**	252 [106, 397]
13	164 [77, 251]	188 [101, 275]	193 [91, 294]	304 [79, 530]	365 [149, 600]	292 [129, 455]

Negative values indicate EMG activity that occurred prior to the onset of positive force rate. Parameters with the lowest *Detection Failures* are bolded.

All statistical analyses were conducted using MINITAB (version 16.0; Minitab Inc., State College, PA) and Microsoft Excel (Redmond, WA).

Results

Thrust Force During SM

The peak thrust force applied by the thrusting hand of the practitioner during the manipulation was 529.5 ± 152.4 N and ranged from 242.2 to 940.2 N. The time between onset of thrust force application and peak force was 243 ± 80 milliseconds.

Double-Threshold Parameter Selection

Higher-amplitude thresholds and higher-duration thresholds both corresponded with higher muscle activation onset delays (Table 2). The 2 parameter combinations of amplitude and duration thresholds that resulted in the lowest *Detection Failures* were the "8 SD–0 milliseconds" (Detection Failures = 8) and the "8 SD–10 milliseconds" (Detection Failures = 9) combinations (Fig 4).

We chose the 8-SD–10-millisecond threshold combination for comparison to the cross-correlation method. The 8-SD–10-millisecond parameter combination was chosen because it resulted in 0 false positives compared with 6 false positives for the 8-SD–0-millisecond combination.

Comparison Between Methods and Muscles

The mean EMG muscle activation onset delay for the 8-SD–10-millisecond double-threshold method across participants was 149 ± 152 and 252 ± 204 milliseconds for the multifidus and erector spinae, respectively. The EMG onset delay for the cross-correlation method was 26 ± 101 for the multifidus and 67 ± 116 for the erector spinae (Fig 5).

There was no interaction between muscle and method (F = 0.61, P = .44). There was no main effect for muscle (F = 3.28, P = .08); but there was a main effect for method (F = 14.88, P = .00). There were no statistical difference between the 2 muscle groups (t value = −1.41, P = .166); however, a trend of smaller onset delays across methods in the multifidus (85 ± 140) compared with onset delays in the erector spinae (151 ± 183) was noted. Onset delays were significantly different for the double-threshold method and the cross-correlation method (t value = 3.57, P = .001).

Discussion

This investigation is the first to quantify multifidus and erector spinae muscle activity during a side-lying SM, with

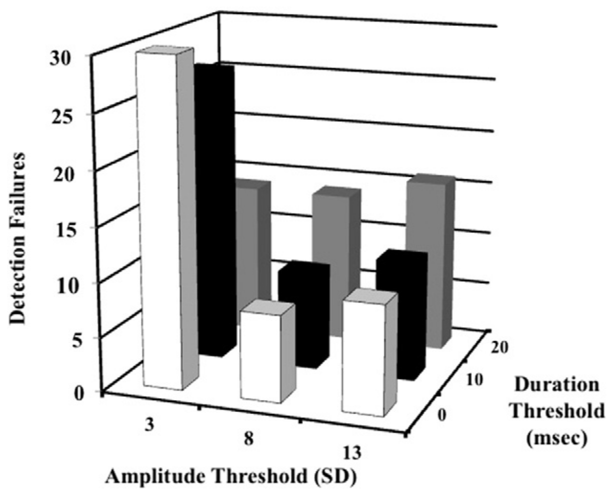

Fig 4. *Plot of the Detection Failures for the amplitude threshold (3, 8, and 13 SDs) and the duration threshold criteria (0, 10, and 20 milliseconds). The number of Detection Failures is the sum of the number of dropouts and the number of false positives. The lowest values represent the best minimization of false positives and dropouts. The total number of observations was 34 (17 multifidus onset delays and 17 erector spinae onset delays).*

the goal of developing a common method to detect muscle activation onset delay. We chose the 8-SD amplitude threshold and the 10-millisecond duration threshold as the combination that most accurately and reliably detected onset delay in response to SM. Onset delays using cross-correlation were also calculated and compared with the double-threshold method. The large differences between methods and threshold parameters illustrate the importance of accurately reporting timing methods. The cross-correlation method has advantages in processing time and simplicity requiring less supervision, but introduced complexities when interpreting onset delays in some signals. The double-threshold method had the advantage of confirming the relation of muscle activity to thrust force during supervision, but required more processing time and was subject to more human influence.

For the double-threshold method, we chose the combination of 8 SD for the amplitude threshold and 10 milliseconds for the duration threshold as parameters that allowed for confident calculation of muscle activity onset delays. These parameters minimized both the dropouts and false positives and allowed for the identification of activity with confidence that it was not baseline activity or noise. The duration threshold of 10 milliseconds corresponds with previous work that identified 25 samples (sampled at 1000 Hz) as a good parameter when EMG data are transformed using the TKEO.[19] We also considered the 8-SD–0-millisecond parameter combination, but it would have resulted in a large number of false positives. Little consensus exists for the threshold criteria for determining EMG onset, and visual inspection remains the standard against which new algorithms are tested.[14]

A change in amplitude threshold or duration threshold systematically changes the number of Detection Failures as a result of increasing False Positives or Dropouts. Changing the amplitude threshold from 8 SD to 3 SD increases the number of False Positives, and changing the SD from 8 SD to 13 SD increased the number of Dropouts. By eliminating the duration threshold (8 SD–0 milliseconds), muscle activation onset was identified when the threshold criterion was met; however, they occurred far in advance of the thrust force and were not discernible from baseline activity in some cases (Fig 3). False Positives are highest for the 3-SD amplitude parameter; therefore, inclusion of these data as true muscle activation would result in inaccurate onset delay. The importance of visualizing all data before comparisons are made cannot be overemphasized.

The cross-correlation method may be most appropriate for evaluating the timing of the peak EMG response rather than the onset of the response as measured in this study. Although the cross-correlation function uses every data point from both signals, the function is most related to identifying peak-to-peak differences between signals. The peak EMG often occurred when the rate of force was greatest, which follows the initiation of positive rate of force and results in a smaller activation onset delay than the double-threshold method. Contrasted with timing and muscle "on" measures, the peak EMG response may represent a summation of the neuromuscular response. Because the amplitude of the EMG signal is used as a measure of neural drive to the muscle and is proportional to the number of motor units activated,[20] the peak amplitude of the EMG response may be an indicator of the aggregate physiological response to the perturbation of manipulation.

When selecting a method for determining activation onset, there are distinct advantages and disadvantages of the double-threshold and the cross-correlation methods. A key advantage of the double-threshold method is that the muscle activity onset delay in relation to force onset is easily visualized and confirmed during the supervision process. However, the steps require more processing time and inherently contain a higher potential for human influence than the cross-correlation method. Two advantages of the cross-correlation method are as follows: (1) an absence of a seemingly arbitrary threshold to be defined and (2) less supervision and therefore less influence to human error. A disadvantage of the cross-correlation method is that it accounts for all data points in the trial and can be more sensitive to extraneous noise in the signal than the double-threshold method. In addition, a 0 value that results from the cross-correlation method can be difficult to interpret. When a 0 value occurs, the data must be examined to determine if the 0 truly indicates no time shift between the 2 signals (ie, the peaks of the signals were coincident), or if the data are completely uncorrelated. In this data set, we obtained 6 zero values of 34 data points (17 onset delays for the multifidus, 17 onset delays

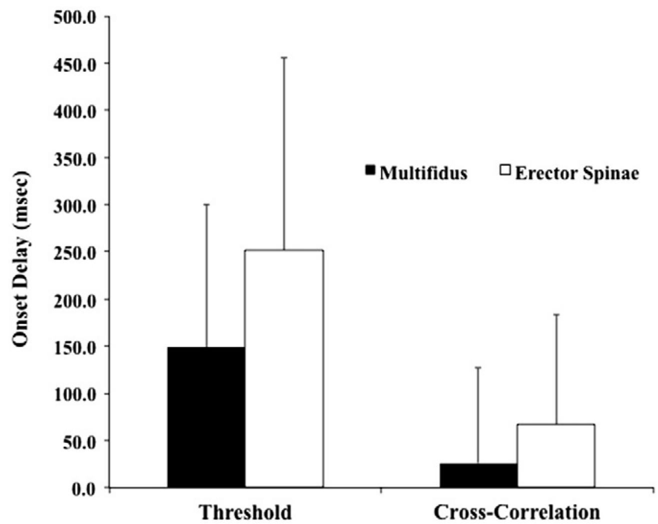

Fig 5. *Mean ± SD muscle activation onset delays for multifidus and erector spinae are compared using the double-threshold method and the cross correlation method.*

for the erector spinae) from the cross-correlation function. We visually inspected these signals and determined that each of these did not correspond with coincident peak thrust force and peak muscle activity, and they were excluded. The results that were obtained using both methods highlight the necessity of validating quantitative results, regardless of method chosen, by qualitatively examining the raw data alongside the analysis.

Selecting the time at which the force onset occurs can greatly change the activation onset delays values and underscore the importance of reporting the specific methods used to determine all timing variables. The first increase beyond the preload force[7] and estimates of thrust acceleration [4] have been used to define the instant of thrust force onset in relation to EMG activity. The duration of the thrust phase time (time between the onset of positive thrust force and peak force) has been reported as 150 milliseconds for thoracic and lumbar manipulations.[3] The duration of this force profile could result in calculated muscle activity onset delays that vary by 150 milliseconds depending on which point during the thrust is selected as the onset of force. We defined force onset as the time at which the rate of force became positive which placed the force onset early in the thrust. If instead, the time at which the peak force magnitude occurred was chosen as the onset of force, the delays would shift by an average of 236 ± 77 milliseconds. Because mean onset delay was 149 milliseconds for the multifidus and 252 milliseconds for the erector spinae, this shift could result in negative onset delays (EMG activity *before* force onset), which represents a substantial and clinically meaningful shift. The onset of EMG activity after manipulation in this study most often occurred after the initiation of the thrust and prior to the peak force—at some point during the steepest slope of the force profile.

Peak thrust forces measured in this investigation (529.5 ± 152.4 N) are comparable with previous investigations that manipulated the lumbosacral area. Triano and Shultz[21] recorded mean peak forces of 495.0 ± 142.5 N with experienced clinicians, whereas Triano et al[22] recorded mean peak forces of 321.0 ± 112.6 N with experienced students. The slightly higher peak forces recorded in this study may have been a result of the experimental set up in which forces from the thrusting hand were estimated using a combined optimized algorithmic method which allows for accurate prediction of thrust force (3.6 ± 9.1 N, 95% limits of agreement, −21.9 to 14.7 N), while maintaining natural contact between the practitioner and the patient[17], whereas previous studies reported forces recorded by the force plate in the treatment table. We expected that the forces applied by the thrusting hand would be higher than the forces recorded by an embedded force plate after transmission through the patient.

There are 3 novel approaches used in this investigation. First, EMG timing was measured during a side-lying diversified lumbar manipulation as opposed to a prone thoracic maneuver or instrumented manipulation. Second, this is the first investigation that recorded EMG directly from the multifidus *during* the HVLA manipulation. A recent case study used needle EMG to demonstrate a decrease in amplitude after SM,[23] but the recording occurred after the manipulation and did not address timing. Because surface EMG recordings are more susceptible to mechanical artifact and confounding crosstalk than indwelling EMG recordings, surface EMG may not represent the activity of the muscle under investigation with complete accuracy,[24] and it has been recommended that the use of indwelling electrodes is necessary[25] to measure the multifidus. Last, the thrust force of the practitioner was estimated using an optimized estimation technique described by Myers et al.[17] Three-dimensional quantification of side posture thrust kinetics is complex, which is why most of thrust kinetics studies have used a prone thoracic technique.[26] This

technique allows the thrust force to be estimated accurately while allowing clinical contact with the thrusting hand.

Two limitations should be considered when interpreting the results of this study. First, the double-threshold parameter recommendations and comparison of methods and results are generalizable only to muscle activity during SM. Second, the L3 manipulations analyzed in this study were part of a larger treatment data set that included a sacroiliac manipulation. Although the order of treatments was randomized, there may be an effect of treatment order on muscle activity. Future work using these data will compare painful and nonpainful participants, additional deep and superficial lumbar muscles, treatment locations, and different manual treatment types, and further establish the neuromuscular relation of muscle activity to thrust force during these procedures.

Conclusion

A comparison of 2 methods for onset detection, double-threshold and cross-correlation, is presented that combines optimized thrust force estimation with EMG recordings. We recommend the use of the double-threshold method with an 8-SD amplitude and a 10-millisecond duration threshold as the method that best represents the EMG timing response to manipulation. The interpretation of onset delays is critically dependent on criteria used to determine the onset of the force application and should be reported in future studies. These methods improve upon previous applications, add to the current catalogue on muscle activation, and can provide a basis for standardizing timing calculations across investigations and gain further insight into the neuromuscular effects of the SM.

Funding Sources and Potential Conflicts of Interest

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Contributorship Information

Concept development (provided idea for the research): B.D., B.E.

Design (planned the methods to generate the results): B.D., B.E.

Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): B.D., B.E.

Data collection/processing (responsible for experiments, patient management, organization, or reporting data): B.D., S.C., C.M.

Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): B.D., S.C., A.K.

Literature search (performed the literature search): B.D., B.E., S.C., C.M.

Writing (responsible for writing a substantive part of the manuscript): B.D., B.E., S.C., C.M.

Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): B.D., B.E., S.C., C.M., A.K.

Practical Applications

- Neuromuscular responses to SM as measured by muscle activity onset delays were measured during a lumbar SM.
- For the first time, 2 methods to calculate the neuromuscular response to SM were compared (double-threshold method and cross-correlation method).
- The muscle onset delays as calculated by the cross-correlation method were significantly shorter than the delays calculated by the double-threshold method.
- The cross-correlation method had signal processing advantages, but significant supervision was required resulting in the double-threshold method being the method of choice.
- The parameters that most reliably characterized the neuromuscular response to SM were an "8-SD, 10-millisecond" double-threshold.

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