Determination of the motor unit behavior of lumbar erector spinae muscles through surface EMG decomposition technology in healthy female subjects

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Non-Technical Summary

This study describes the behavior of motor units of the lumbar spine muscles of healthy women through a non-invasive surface electromyographic decomposition technique. The subjects performed a back extension test, in a prone position, with the trunk in a neutral position. The results showed a different firing behavior of motor units at low-force contraction when comparing muscles of the dominant and non-dominant side of the trunk. This technique may improve the understanding of neuromuscular diseases and the efficacy of different interventions.

ABSTRACT

Introduction: The aims of this study were to determine the motor unit behavior of the erector spinae muscles and to assess whether differences exist between the dominant/non-dominant sides of the back muscles.

Methods: Nine healthy women, aged 21.7 years (±0.7), performed a back extension test. Surface electromyographic decomposition data were collected from both sides of the erector spinae and decomposed into individual motor unit action potential trains. The mean firing rate for each motor unit was calculated, and a regression analysis was performed against the corresponding recruitment thresholds.

Results: The mean firing rate ranged from 15.9 to 23.9 pulses per second (pps) and 15.8 to 20.6 pps on the dominant and non-dominant sides, respectively. However, the early motor unit potential s of the non-dominant lumbar erector spinae muscles were recruited at a lower firing rate.

Conclusions: This technique may further our understanding of individuals with back pain and other underlying neuromuscular diseases.

Key Words: electromyography, isometric exertion, action potential, motor units, erector spinae muscles, muscle fibers.

Running Head: Lumbar erector spinae muscles.

INTRODUCTION

The lumbar muscles play an important role in locomotion and postural control. The contractile characteristics permit the lumbar muscles to adapt to several contraction behaviors through recruitment and control of motor units (MUs).[1,2] The mechanisms of tetanic force generation and control during a voluntary contraction can be explored through the study of MUs. In 1985, De Luca[3] published a review of the rules governing the process of MU recruitment as well as firing rate behavior of active MUs. Since then the term “common drive” has been used to describe the capacity of MUs to vary firing rates with almost no time delay, as if a common excitation drives the firing behavior of all MUs in a given motoneuron pool of a muscle.[4,5]

De Luca et al. (1982)[6] used the term “common drive” to describe the behavior of the firing rates of 4 MUs in an isometric contraction of the deltoid muscle. The authors discussed how fluctuations in force output might be related to fluctuations in firing rates. More recently, De Luca and Contessa[7] reported that early recruited MUs maintain higher firing rates than later recruited MUs in voluntary constant-force contractions of the first dorsal interosseous and vastus lateralis muscles, which they referred to as an Onion Skin scheme to describe the inverse order of the hierarchy of firing rate curves.

Several studies have confirmed these findings by using surface electromyographic signal decomposition (dEMG).[8-11]This process uses artificial intelligence algorithms which have been shown to be reliable and present numerous advantages compared to invasive electrodes, such as avoiding pain, muscle lesions, and the risk of infection. The dEMG has been successfully used to assess the muscles of the upper and lower extremities of healthy individuals.[12] However, little or no information exists on the MU properties of the lumbar erector spinae muscles, with the exception of Marsden et al. (1999)[13], who investigated the degree of synchronization and coherence between MU pairs during isometric contractions in healthy subjects.

The evaluation of variables that estimate the muscle contraction such as MU behavior has great clinical value, since it allows monitoring of rehabilitation procedures and analysis of musculoskeletal disorders.[14] In addition, investigating dominance differences in back muscles is important, as the imbalance between sides can be related to the risk of back pain.[15] Thus the aims of this study were to explore the application of these methods to determine the MU behavior of the lumbar erector spinae muscles during voluntary isometric contractions, to determine if any differences exist between the dominant and non-dominant sides, and to compare the MU behavior of the erector spinae muscles with previously reported studies.

MATERIALS AND METHODS

Subjects. Nine healthy women, mean age 21.7 years (SD=0.7), BMI = 21.3 kg/m^2 (SD=1.9), volunteered to participate in this study. The exclusion criteria were low back pain, intervertebral disc protrusion, history of abdominal or spine surgery, evidence of scoliosis, neurological or muscular disorders, inflammatory diseases, cancer, or pregnancy. All subjects signed a written informed consent document, which had been previously approved by the Universidade Estadual de Londrina Ethics Committee (#073/13). After being accepted for inclusion, the volunteers were asked not to perform any physical activity for 24 hours prior to data collection.

EMG Measurement. The surface electromyography equipment consisted of a 16-channel Bagnoli dEMG System (Delsys Inc., Natick, USA), 2 surface EMG array sensors, and a 16-bit A/D converter, which was used to record muscle activity of the lumbar erector spinae muscles. Two array sensors with 5 protruding blunted pins each (0.5 mm diameter each), located at the corners and in the middle of a 5x5mm square, were placed on the erector spinae muscles (iliocostalis lumborum, which originates from the extremities of the lumbar transverse processes and adjacent middle layers of the thoracolumbar fascia and inserts onto the ventral border of the iliac crest)[16], 3 cm either side of the spinal process of L-3. Four channels of single differentiated EMG were recorded between the 4 outer pins and the central pin. Potentials were collected at a sampling rate of 20 KHz, amplified, and filtered at a band-pass of 20-450 Hz.[4] A 4 cm diameter adhesive gel reference electrode (Dermatrode®) was placed on the dorsal aspect of the non-dominant hand. Prior to data collection, the skin was prepared for both EMG sensors by shaving, cleaning with alcohol wipes, and removing the superficial layer of dead skin cells using multiple applications of hypoallergenic tape. Baseline noise was assessed, and values < 4.8 µV RMS (root mean square) were considered acceptable. If this value was exceeded, the skin preparation procedure was repeated, and the sensor was re-located. EMGworks 4.1.7 Acquisition (Delsys Inc., Natick, USA) was used for data collection.

Isometric Testing. Subjects were placed in the prone position with their arms alongside their bodies. This position was fixed using 3 rigid straps, which maintained the spinal column in a neutral position; one at half the distance between the popliteal fossa and the malleolus, one at the level of the greater trochanter, and the third in the scapular region (Figure1).

A maximum voluntary isometric contraction (MVIC) was recorded by asking the subjects to extend their spine against the resistance of the straps. This was performed 3 times for 5 seconds with a rest interval of 60 seconds between contractions. The MVIC was filtered using an RMS with a window length of 0.125s directly from 1 channel of the decomposition array sensor; the highest value was recorded. Verbal encouragement were given to the participants.

Subjects were then asked to track a trapezoidal force trajectory, during which, according to the muscle contraction, feedback was shown on a monitor. The trajectory started with 3s of initial rest or a quiescent region, which allowed the algorithm to establish baseline noise. This was followed by a 2s increase up to a 40% MVIC, which was sustained for 20s, a downward ramp of 2s, and finally a 3s quiescent region, giving a total time of 30s. Forty percent of MVIC was chosen, as this has been shown to produce substantial recruitment of motor unit action potentials (MUAPs) and avoid significant fatigue.[10] If the participant could not adequately follow the trajectory, the test was repeated.Before the data collection, all subjects performed a familiarization, and before each trial, a minimum rest of 60 seconds was given.

Decomposition. The constituent motor unit action potential trains (MUAPTs) were established using the surface EMG signal decomposition algorithm described by De Luca et al.[17] and Nawab et al.[9] This algorithm identifies individual action potentials in the signal through artificial intelligence techniques which resolves superpositions and allocates action potentials to individual motor unit trains.[4] This was conducted using

EMGworks 4.1.7 Analysis (Delsys Inc., Natick, USA). An accuracy assessment was performed to quantify motor unit action potential trains that were decomposed to determine the accuracy of the identified firing instances, referred to as the Decompose Synthesize-Decompose-Compare (DSDC) test.[19] MUAPTs with a firing accuracy > 90% were considered for Mean Firing Rate and Motor Unit Recruitment Thresholds, and a firing accuracy > 95% was considered for cross-correlation.

Mean Firing Rate. The MFR of each motor unit was computed through low-pass filtering of the impulse train with a 3 sec Hanning window; the MFRs were expressed as pulses per second (pps). For each MU the average value of the MFR was calculated over a 5 sec period within the constant force region.[4,6]

Motor Unit Recruitment Threshold. The RMS values from each back extension contraction were computed and normalized against the MVIC RMS. This allowed the percentage MVIC value to be determined for each MU at the point of recruitment. Data were extracted through the software EMGworks 4.1.7 Analysis (Delsys Inc., Natick, USA). The MFR was plotted as a function of the MU recruitment threshold for each participant and muscle. The slope and intercept values of the regression lines were then identified.

Cross-Correlation. A cross-correlation between the mean firing rates of pairs of concurrently active MUs was established. The highest value function in pairs of MUs within a ±100 ms window was calculated and used to explore the common drive.[6,19] These procedures were performed using the software EMGworks 4.1.7 Analysis (Delsys Inc., Natick, USA).

Statistics. The data were tested for normality using the Shapiro-Wilk test. The descriptive values are presented as mean, standard deviation, and/or 95% confidence interval. The peaks of cross-correlation values (R_{xy}) are presented comparing all values of the dominant and non-dominant sides. To avoid bias due to different numbers of MU pairings being identified in each side of the muscle, a normalization procedure was performed by dividing the total number of MU pairs that showed a peak in the cross-correlation function by the total number of cross-correlated MU pairs and then expressing these as a percentage (*Lindley S, 2014, unpublished Thesis*). Differences between the dominant and non-dominant sides were explored using a paired-samples student *t*-test.

The average MFR (dependent variable) and recruitment thresholds (independent variable) of each MU, for both the dominant and non-dominant sides, were extracted, and a linear regression line was drawn using the stepwise method. Least squares were used to estimate the parameters. Slopes and intercepts generated from the 2 regressions were compared. Results are presented using plots, confidence intervals, and prediction intervals. The statistical significance adopted was 5%.

RESULTS

The characteristics of the MUs and their respective firing rates are presented in Table 1. The MU yields (mean and 95% CI) on the dominant and non-dominant sides were similar [total = 217; 24.1 95% CI (17.3;30.8) and total = 252; 28 95% CI (21.1;34.8), respectively]. The mean firing rate varied from 15.9 to 23.9 pps on the dominant side, while the non-dominant side presented similar behavior, from 15.8 to 20.6 pps.

The accuracy of the MUAPT is presented as the number of MU, percentage of accuracy, and number of errors per second.[11] The data had a high degree of accuracy of MU identification, reaching up to 98.5% for the dominant side and 98.7% for the non-dominant side. Fifteen MUs (7% of total) on the dominant side and 30 MUs (11% of total) on the non-dominant side were discarded due to accuracy values below 90%.

The mean value of the peak cross-correlation function, during a time lag of ±100ms window, for the dominant side was R_{xy} =0.39 [95% CI (0.37;0.41)] and R_{xy}=0.46 [95% CI (0.43;0.50)] for the non-dominant side when the analysis was executed, taking into account the total sample. The difference between sides was R_{xy} = 0.07 [95% CI (-0.10;-0.19)]; P = .007. The non-dominant side demonstrated a slightly higher cross-correlation value when compared to the dominant side, but both can be considered as moderate correlations. When analyzed by subject, the values were distributed between R_{xy} = 0.38 and 0.62 (dominant side) and R_{xy} = 0.32 and 0.53 (non-dominant side).

Figure 2 shows the normalized data, which were achieved by dividing the total number of MU pairs that showed a peak in the cross-correlation function by the total number of cross-correlated MU pairs from all subjects. The highest proportion (20%) of cross-correlated MU pairs fitted the values of R_{xy} = 0.40 - 0.49 (61 pairs) for the dominant side and R_{xy} = 0.30 - 0.69 (17%), with 20 pairs for the non-dominant side. There was a reduced proportion of the number of MU correlated pairs for the dominant side from 0.70 - 0.79 (3.4%) to 0.80 - 0.89 (1.7%) when compared to the non-dominant side. In the lower stratum this behavior was inverted, with 10% against 4.2% in the 0 -.09 and 12% against 5.9% (dominant and non-dominant side).

The recruitment threshold and mean firing rate were calculated for each participant and also for the whole sample. The corresponding %MVIC of the RMS was defined (illustrative example of a participant in Figure 3).

Figure 4 shows the recruitment threshold regression lines of both erector spinae muscles. The R^2 for each muscle was retrieved, presenting values of 26% and 45% for the dominant and non-dominant sides respectively, while the intercept and slope values (followed by the standard errors - SE) were: 24.9 [95% CI (23.7;26.2)], (SE = 0.63) and -0.35 [95% CI (-0.44;-0.26)] (SE = 0.04) for the dominant side and 23 [95% CI (22.3;23.6)], (SE = 0.31) and -0.33 [95% CI (-0.38;-0.28)], (SE = 0.02) for the non-dominant side.

There was a statistically significant difference between the intercepts (P<.00001), but not the slope, demonstrating that the early recruited MUs of the non-dominant lumbar erector spinae muscles were recruited with a lower firing rate (difference of 2 pps) when compared with the dominant side of the lumbar erector spinae muscles. This behavior presented an inverse pattern throughout the contraction, when the values of the %MVIC increased. Moreover, for every reduction in MU firing rate (1 pps), the MVIC increased by 0.35 percent for the dominant side and 0.33 percent for the non-dominant side.

During the individual analysis, only 2 participants had an opposing pattern regarding these general results; the early recruited MUs of the dominant side were recruited with a lower firing rate and the variance explained (R^2) presented from 32% to 79% on the dominant side and from 31% to 74% on the non-dominant side.

DISCUSSION

This study describes the motor unit behavior of the back extensors in healthy female subjects through a non-invasive EMG decomposition technique. Although Marsden et al. (1999)[13] described the use of the degree of MU synchronization/common-drive coefficient (through spectral and coherence analysis) between MU pairs of paraspinal muscles, no studies were found related to erector spinae muscles using surface EMG decomposition. Over the last decade, there have been significant advances in the decomposition of EMG signals. A review of dEMG in 2012[12] included 79 studies, which analyzed 26 muscles, with the first dorsal interosseous and vastus lateralis muscles being the most commonly assessed. This technique has been used to demonstrate the relationship between muscle MU firing rates, recruitment, and common drive; however, no similar studies have been conducted in the erector spinae muscles.

The submaximal reference of 40% of MVIC, based on a value of maximal EMG activity (RMS), was chosen due to wide acceptance of the characteristics of this postural muscle and because sufficient numbers of MUs were likely to be activated during lower exertion (10-20%) of maximal muscle force.[20-23] The study by Mannion et al.,[24] also reported relative stability up to 30-40% MVIC when assessing fatigue. In addition, the value of 40% is within 0-60% MVIC, where the majority of functional activities and tasks occur.[7]

Westgaard et al.[25] investigated the trapezius muscle up to 5% MVIC, although using different dEMG protocols. The authors reported that it might be a disadvantage to use these procedures to establish the common drive rationale when assessing postural muscles, since the low-threshold motor units are required to maintain elevated firing rates over a long time period. Our results, which utilized the latest decomposition approach, seem to be similar to other studies, which used upper/lower limb muscles. However, discussion of the differences between appendicular and axial muscles is worthy of future exploration.

In this study, the participants were tested in the prone position, with their trunks horizontal and fixed to the plinth, and the traditional Biering-Sorensen test was not used. This option was chosen not only to avoid changes in lordosis (which could have created higher EMG activity) and because intra-disc pressure is lower than when standing, but also due to the possible error or variability caused by manual resistance applied to the shoulders/trunk by an assessor.[25]

Studies of lumbar muscle architecture have demonstrated that the greatest cross-sectional area is found in L-3, and this contributes to the following muscles: iliocostalis lumborum, longissimus thoracis, and multifidus (although the lumbar multifidus is more than twice that of either the longissimus thoracis or the iliocostalis lumborum). Moreover, the erector spinae is 1 of the main muscles that contracts to stabilize and mobilize the lumbar spine. For this reason, investigation of these muscles in healthy individuals may have greater clinical importance for understanding MU behavior, so that assessment and planning of rehabilitation protocols can be conducted with more information and relevance.[14,26]

Zaheer et al.[10] investigated the influence of the sensor site, including skinfold thickness, on the number of identifying MUAPs in lower and upper limb muscles. The authors concluded that although the data indicate the presence of preferred sensor sites on the muscle, associated with lower skinfold thicknesses, the relationship is not completely consistent and not statistically robust. Moreover, it appears that there are other factors that influence the MU yield, for instance the muscle innervation zone. The BMI mean in our study was 21.3 kg/m^2 (SD=1.9), which is considered within the normal limits (Cole, 1991)[27]. In the study of Zaheer, et al the mean was 22.8kg/m^2.[10]

Additionally, MUs were extracted with greater than 90% accuracy, obtained using the reconstructed signal decomposition method for MU firing rates. The algorithm for the accuracy test proposed by Nawab et al.[12] takes into consideration any amplitude (high or low) and the overlapping rates. This could explain the high accuracy rate found in this study and the reduction in multiple superimposed MUAPs and noise contamination. Nawab et al.[9] also achieved an accuracy range of between 92.5% and 97%, and other studies have found accuracy values close to or above 90%.[19,28]

The cross-correlation calculation, as well as the mean firing rate extracted from the individual MUAPTs explored in this study, is a step towards explanation of the control of motor units in the lumbar erector spinae muscles. The degree of correlation between the mean firing rate fluctuations of pairs of concurrently active MUs was obtained (only MUs higher than 95% accuracy were considered). One-hundred thirteen MU pairs and 70 MU pairs were cross-correlated for the dominant and non-dominant sides, respectively, and the correlation (among time-varying firing rates of 2 MUs) can be described as moderate. Individually the results varied from low to high correlation. Indeed, the cross-correlation demonstrated the presence and large degree of common drive in the lumbar erector spinae muscles.

The recruitment threshold seen on both sides of the trunk and represented by the linear regression was explored. This indicated that the number of motor units was inversely correlated with the mean firing rate, demonstrating the hierarchical scheme of motor unit recruitment. The pooled results differed only in the intercept, which demonstrated that the early recruited MUs of the non-dominant lumbar erector spinae muscles appeared to be recruited with a lower firing rate (difference of 2 pps) when compared to the dominant side of the trunk. Although this difference might be considered small and without physiological significance, the results indicate that MUs recruited at the same force fire at lower rates on the non-dominant side.

Recruitment and firing rate characteristics are determined by the physical proprieties of the motoneurons. The earlier recruited fibers have a smaller diameter, and the firing rate increases faster as a function of time. These fibers are more sensitive to the influence of rising excitation.[17,29] On the other hand, the velocity of firing rate is inversely proportional to the recruitment threshold.[17] This control scheme has been shown previously and is reported in this study, demonstrating the characteristic of energy economy of the erector spinae muscles to generate the MUAPs when the force increases. This gives this muscle a feature of avoiding fatigue, which is expected in postural muscles.

When the data were explored for each participant, a similar intercept pattern was found in 7 subjects. The explained variance when observing all participants presented low/moderate values; 78% and 55% of all variances between the mean firing rate and the %MVIC could not be explained in the dominant and non-dominant sides, respectively. When the values were observed individually, there was an improvement in the explained variance, for both sides ranging from 32 to 79% (dominant side) and 31 to 74% (non-dominant side). In any case, lower variability in the individual analysis is expected, since the variability increases when data from multiple subjects are aggregated.[29]

Some thought should be given to this isometric tracked trapezoidal force trajectory at 40% of the maximal voluntary contraction protocol for future experiments, particularly involving low back pain patients. The application of the decomposition tool in clinical studies could be useful for understanding the morphology, recruitment, and firing behavior of MUs during this specific protocol. It could also be used in controlled studies as a possible explanation for changes in the behavior of motor units after training, mainly for each condition/diagnosis.

The addition of a load cell could also be used for feedback and data normalization. Other positions could be tested, for instance, “semi-standing”, sitting, and functional task simulations; in addition, genders could be compared. These findings have the potential to provide information over and above standard EMG methods already published in the back pain literature. In particular, this technique should be able to give information on motor unit behavior in fatigue states, muscle imbalance, and response to pain.

CONCLUSION

Characteristics of MU behavior in lumbar erector spinae muscles in healthy women were demonstrated. These presented properties consistent with those reported in the literature. Similar mean firing rates were found between the dominant and non-dominant sides, and moderate values were observed across the MU pairs in the cross-correlation analyses. The recruitment threshold demonstrated that the earlier MUs of the non-dominant lumbar erector spinae muscles are recruited with a lower firing rate when compared to the dominant side. This technique enables understanding of MU behavior of erector spinae muscles by means of a non-invasive method and may increase our understanding of individuals with back pain and other underlying neuromuscular diseases and the efficacy of different interventions, which may alter MU behavior.

Abbreviations

dEMG, decomposition of surface electromyography; EMG, electromyography; MFR, mean firing rate; MU(s), motor unit(s); MVIC, maximal voluntary isometric contraction; MUAP, motor unit action potential; MUAPT; motor unit action potential train; PPS; pulse per second; R_{xy} = cross-correlation and RMS, root mean square.

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Figure legends

Figure 1. Illustration of the isometric testing.

Figure 2. The numbers of motor units distributed by peak cross-correlation values of the dominant and non-dominant sides of the erector spinae.

Figure 3. Example of the root mean square trajectory of a participant during 40% of maximal voluntary isometric contraction. B. The Onion Skin scheme for both sides of the erector spinae muscles.

Figure 4. Regression plot of both muscles showing the behavior of the recruitment threshold.

Table 1 – Individual numbers of motor units and respective firing rates.

Sub	Dominant Side				Non-Dominant Side				MD_{MFR} [95% CI]
	MU	MFR	[95% CI]	MFRmin-max	MU	MFR	[95% CI]	MFRmin-max	
1	15	21.7	[20.4;22.9]	16.4-28.5	18	18.6	[17;19.8]	14.7-23.4	3.1 [2.1;4.2]
2	16	15.9	[14.9;16.9]	13.8-17.8	26	19.1	[18;20.2]	16.2-28.5	3.2 [2;4.7]
3	27	19.6	[18.7;20.5]	16.2-24.9	23	17.7	[16.7;18.6]	13.1-23.8	1.9 [1;2.8]
4	31	19.8	[18.7;20.9]	12.2-22.9	25	18.9	[18.1;19.7]	14.6-22.2	0.98 [0.34;1.6]
5	12	19.6	[18.2;21.1]	17.2-25	19	15.8	[14.9;16.6]	12.6-19.4	3.8 [2.4;5.2]
6	35	22	[21.2;22.9]	17.4-26.7	47	18.6	[17.9;19.2]	13.5-22.3	3.4 [2.8;3.9]
7	36	20.7	[19.8;21.5]	16.1-25	34	20.5	[19.6;21.4]	14.9-25.2	0.14 [-0.4;0.7]
8	22	17	[16.1;17.9]	13.6-20.9	33	17.6	[16.8;18.4]	11.7-21.2	0.6 [-0.1;1.2]
9	23	23.9	[22.7;25]	18.2-28.6	27	20.6	[19.7;21.6]	16-25.2	3.3 [2.4;4.2]

Sub = subjects; MU = Number of motor units; MFR= Average of the time-varying mean firing rate in pulses per second; 95% Confidence interval of the MFR; $MFR_{min-max}$ = Average minimum and maximum of the time-varying firing rates in pulses per second and Dominant-Non-Dominant side mean difference of mean firing rate; MD = Mean difference.