



Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin



Electromyographic assessment of trunk muscle activation amplitudes during a simulated lifting task using pattern recognition techniques

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ARTICLE INFO

Article history:

Received 18 July 2008

Received in revised form 9 September 2008

Accepted 9 September 2008

Available online xxxx

Keywords:

Electromyography

Pattern recognition

Lifting

Trunk muscles

Amplitude recruitment strategies

ABSTRACT

This study sought to determine the patterns of neuromuscular response from 24-trunk muscle sites during a symmetrical lift and replace task. Surface electromyograms (EMG) and kinematic variables were recorded from 29 healthy subjects. Pattern recognition techniques were used to examine how activation amplitude patterns changed with the different physical demands of the task (reach, phase of movement). The results indicated that there was very little trunk and pelvis motion during the task. Three principal patterns accounted for 95% of the total variation suggesting that the measured data had a simple underlying structure of variance. ANOVA results revealed significant differences in principal pattern scores. These differences captured subtle changes in muscle recruitment strategies that most likely reflect different stability and biomechanical demands. More balanced activations (bracing) between the abdominal and back sites were observed during the lighter demands, whereas differential recruitment among the back extensor sites was more predominant in the more demanding conditions. A pattern recognition technique offers a novel method to examine the relationships among a large number of muscles and test how different work characteristics change the relationships among the muscle sites.

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1. Introduction

In the industrial work environment, automation of the work method has reduced the call for heavy manual labour; however, it requires the worker to stand for longer periods of time and perform lighter more repetitive manual tasks (Subramanian et al., 2006). Interestingly, accumulating evidence suggests that the high incidence of occupational low back injuries, that occur while performing less demanding tasks, may be related to altered neuromuscular strategies (Cholewicki and VanVliet, 2002; Gregory and Callaghan, 2008). However, the neuromuscular responses associated with tasks requiring lighter physical efforts are poorly understood.

One of the key elements in injury prevention is to understand the neuromuscular demands associated with commonly performed work related tasks. Most of what is known about injury risk and physical demands comes from studies examining heavy dynamic lifting. Numerous studies have identified various motion parameters (ROM, velocity, acceleration), spinal loading measures (compression, shear forces) and task variables (load, asymmetry, horizontal reach) that increase the risk of suffering a low back in-

jury (Davis et al., 1998; Ferguson et al., 2005; Marras et al., 1993; Marras et al., 1995; Marras and Davis, 1998, 2003, 2004). Examination of the neuromuscular response during these activities indicates that increased agonist and antagonist activation amplitudes also occur (Davis et al., 1998; Ferguson et al., 2005; Granata and Marras, 2000; Sparto et al., 1997). Because injury risk is influenced by modulators of muscle force production that occur during dynamic motion, it is unclear if the changes in neuromuscular response reflect the dynamic effects of trunk motion or is related to the task variables (external load perturbation). To address this question other researchers have employed experimental tasks that require the subjects to maintain a static trunk while external perturbations were applied to the trunk (Lavender et al., 1993; Radebold et al., 2000; Vera-Garcia et al., 2007). While the neuromuscular responses from these tasks are related to the external perturbation, the tasks do not reflect realistic physical demands that workers experience during a typical work day. Thus, there is a need to examine the neuromuscular changes associated with realistic work demands that reflect only the task variables performed in order to begin to understand mechanisms of injury for lighter manual handling tasks.

A primary concern when performing a neuromuscular investigation is how many muscle sites are required to capture the key recruitment strategies, yet keeping the numbers low enough to manage the volume of data. Experimental and biomechanical

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modeling evidence suggests that all trunk muscles are important (Cholewicki and VanVliet, 2002; Kavcic et al., 2004) and different segments within a muscle can respond differently to a perturbation (Butler et al., 2006a,b; Jonsson, 1970; Mirka et al., 1997; Vink et al., 1988) thus justifying the need to measure a comprehensive number of muscle sites. However, existing reports have investigated up to 14-trunk muscle sites with the majority of the studies measuring much fewer (Cholewicki and McGill, 1996; Cholewicki et al., 1997; Granata and Orishimo, 2001; Hodges and Richardson, 1997; Lariviere et al., 2000; Marras and Davis, 1998; van Dieen et al., 2003). Studies examining 8–14 trunk muscle sites (Granata and Orishimo, 2001; Lariviere et al., 2000; Marras and Davis, 1998; van Dieen et al., 2003), have used various data reduction techniques including averaging activity from different muscles and amplitude ratios. Typically, separate statistical analyses for each muscle site and assuming symmetry between right and left sides of the body are used (Cholewicki et al., 1997; Granata and Orishimo, 2001; Marras and Davis, 1998). The disadvantage of these reduction techniques is the loss of information related to changes and interactions among the different trunk muscle sites. Pattern recognition techniques, using eigenvector decomposition, can reduce the number of variables while still maintaining the salient features of the original data, and thus is an attractive alternative to the traditional univariate techniques (Daffertshofer et al., 2004; Hubley-Kozey and Smits, 1998; Hubley et al., 2005). While principal component analysis (PCA) is the most common-used term for these techniques, PCA is a multivariate statistical technique that requires the calculation of a covariance matrix that is factored (Gebrand, 1981). Other matrices have been used to determine principal patterns, and Gebrand provides a description of these techniques. In this case, the PCA allows important features from a number of muscle sites to be identified, and the interrelationships among several muscle sites to be examined by reducing the dimensionality and thus perform statistical testing of these variables. The 24 muscle sites examined have been shown to have different responses to varying perturbations and motions, therefore a comprehensive analysis of all sites was performed. Thus, the main purpose of this study was to quantify the principal activation amplitude patterns of 24-trunk muscle sites during a symmetrical lift and replace task, with the trunk maintained in an upright posture using multiple-lead surface EMG and pattern recognition techniques. The secondary purpose was to determine how these patterns were affected by changing the demands of the task (reach) and whether the movement (phase) varied for individuals with no history of LBP.

2. Methods

All subjects in this study were healthy, 20 to 50 years of age, both men and women, right hand dominant with no history of

low back pain. Subjects provided written consent, consistent with requirements of the Health Sciences Research Ethics Board at Dalhousie University. Age plus five physical anthropometric measures (mass, height, normal and maximum reaches, waist circumference) were recorded. Surface EMG was recorded from 24-trunk muscle sites and three-dimensional angular changes of the trunk and pelvis position were monitored while the subjects performed a standing symmetrical lift and replace task.

2.1. Surface electromyography

Collection and processing of the myoelectric signal was consistent with published standards (Hermens et al., 2000; Merletti, 1999). Twenty-four pairs of surface electrodes (Meditrace Ag/AgCl, 0.79 cm², 30 mm inter-electrode distance; Graphics Control Canada Ltd.) were placed along the fiber orientation of six bilateral abdominal and six back extensor muscle sites (Fig. 1). For the abdominal sites electrodes were centered on the muscle belly midway between the umbilicus and the pubis for the lower rectus abdominis site (LRA) and between the sternum and the umbilicus for the upper rectus abdominis site (URA) (Gilleard and Brown, 1994). Electrodes for the external oblique muscle, were placed over the 8th rib adjacent to the costal cartilage over the anterior fibers (EO1); 15 cm lateral to the umbilicus at a 45° angle over the lateral fibers (EO2) and at the midpoint between the lowest part of the ribcage and the iliac crest to over the posterior fibers (EO3) (Davidson and Hubley-Kozey, 2005). The electrodes for the internal oblique (IO) muscle site were placed in the center of a triangle formed by the inguinal ligament, lateral border of rectus sheath and the line between the two anterior superior iliac spines (Ng et al., 1998). Another six bilateral sites were placed over the back extensor musculature. Electrodes for the longissimus and iliocostalis muscle sites were placed at 3 and 6 cm lateral to the spinous process, at both L1 and L3 lumbar levels (Vink et al., 1988). The quadratus lumborum site was located approximately 8.5 cm lateral to the spinous process at L4. Electrodes for the multifidus muscle were placed 1–2 cm to the midline at L5 (Kavcic et al., 2004). Although, the electrode placements were standardized, minor location adjustments were made based on individual anthropometrics, palpation and a series of resistance testing exercises (see Fig. 2).

2.2. Motion measurement

The Flock of Birds™ (FOB) motion system (Ascension Technology Inc., Burlington, Vermont) was used to monitor the angular motion of the trunk and pelvis throughout the task. Sensors were placed over the spinous process of the 7th thoracic vertebrae and on the left iliac crest. Each sensor provided 6-degrees of freedom (x, y, z displacement, yaw, pitch and roll rotations) with respect to a global coordinate axis system.



Fig. 1. Muscles sites on right and left sides of the body. 1 = LRA; 2 = URA; 3 = EO1; 4 = EO2; 5 = EO3; 6 = IO; 7 = L13; 8 = L16; 9 = L33; 10 = L36; 11 = L48 and 12 = L52.

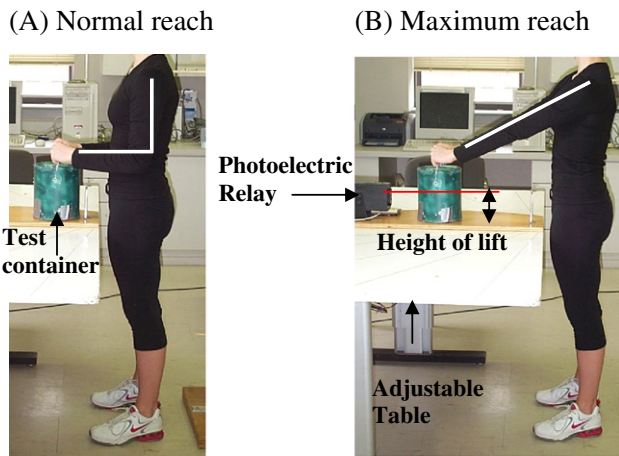


Fig. 2. Experimental set-up and posture for (A) normal reach: upper arm vertical with forearm horizontal and (B) maximum reach: upper extremities straight out in front of the body. The average time for lift, transition and replace phases were 0.5, 0.4 and 0.6 s, respectively.

2.3. Experimental trials

Three trials of lifting and replacing a test container (3.0 kg) in normal and maximum reach positions were performed (Butler and Kozey, 2003). Subjects stood in front of a height adjustable table adjusted to each subject's standing elbow height. The subjects used both hands to lift the test container vertically 4–5 cm off the table surface and replaced it in its original position in a slow and controlled manner (4 s count). The movement was subdivided into three phases defined as the lift, transition and replace phases. These phases were defined by event markers generated by a pressure sensitive switch located on the bottom of the test container and a photoelectric relay system on the table.

2.4. EMG normalization

Following the experimental trials, nine different maximum voluntary isometric contractions (MVIC) were performed to elicit the maximum activation amplitude from each muscle site (Butler et al., 2006a,b; Vezina and Hubley-Kozey, 2000). The supine sit-up and the V-sit-up (sit-up coupled with hip flexion) were used to recruit the rectus abdominis sites. Seated axial rotation (right and left) and side-lying lateral flexion (right and left coupled with an ipsilateral hip hike) were used to maximally activate the oblique muscle sites. Back extension and back extension coupled with axial rotation (right and left) were performed in a prone position, to maximally recruit the back musculature.

The exercises were performed in a randomized order with two trials of the same exercise performed in succession. Each contraction was held to a count of 3-s with a 2-min rest interval between trials. Following the completion of the normalization trials, baseline muscle activity was recorded for 0.5-s while the subjects were lying supine.

2.5. Data acquisition

Separate data collection systems were used to record the EMG and FOB data. The EMG and FOB data were synchronized with respect to the phases of movement using the event marker system. Both data collection systems used IBM Pentium computers for all collection, storage and subsequent off-line processing.

The raw myoelectric signal was preamplified (500×) and further amplified (bandpass 10–1000 Hz; CMRR = 115 db, input impedance 10 GΩ) with three AMT-8 EMG systems (Bortec Inc.,

Calgary, Alberta). The raw myoelectric and event signals were sampled at 1000 Hz using a 16-bit analogue to digital converter (National Instruments, CA-1000) using LABVIEW™. FOB data and event markers were collected using LABVIEW™ on a second computer. The output from the FOB was connected to the computer via a serial port (RS232) and event marker signal was sampled at 50 Hz using a 12-bit analogue to digital converter (National Instruments, CA-1000).

2.6. Data processing

Customized Matlab® (MathWorks Inc., Natick, MA. Version 7.3) programs were used to process the EMG and FOB data. The raw myoelectric signal was filtered with a recursive 5th order Butterworth high pass filter at 30 Hz to remove any ECG artifact (Butler et al., in press; Drake and Callaghan, 2006; Zhou et al., 2007) then corrected for bias and gain.

The root mean square (RMS) amplitude was calculated for each muscle site for each phase of the experimental trials. The normalization trials used a 500 ms moving window to determine the maximum RMS amplitude for each muscle site (Vezina and Hubley-Kozey, 2000), which was used to normalize the activation amplitude from the experimental trials to a percentage of MVIC (%MVIC) (McGill, 1991).

The FOB data were low-pass filtered at 1-Hz using a recursive 2nd order Butterworth filter. The maximum angular displacement for yaw, pitch and roll relative to the global coordinate system were calculated for the total movement duration and for each phase for each trial.

2.7. EMG pattern recognition

Pattern recognition techniques were applied to the discrete normalized activation amplitudes from 24-trunk muscle sites (averaged across trials) to reduce the multidimensional nature of the EMG amplitude data and extract important features of variability for physiological and biomechanical interpretation. The first step in this analysis was to construct a data matrix $X_{[n \times p]}$ with p -variables ($p = 24$ -trunk muscle sites) and n -observations. The order of the trunk muscle sites was fixed and created a unique pattern: RLRA, LLRA, RURA, LURA, REO1, LEO1, REO2, LEO2, REO3, LEO3, RL13, LL13, RL16, LL16, RL33, LL33, RL36, LL36, RL48, LL48, RL52 and LL52. The observations included reach and phase for each subject yielding a data matrix $X_{[174 \times 24]}$ (two reach positions, three phases by 29 subjects).

The pattern recognition technique is described elsewhere (Hubley-Kozey and Smits, 1998). Briefly, a cross product matrix of X was calculated $CP_{[p \times p]}$. Next, an eigenvector decomposition was performed on CP . The eigenvectors or principal patterns (PP) represent specific features of the measured activation amplitude patterns. The eigenvalues represent the variance explained from each corresponding principal pattern and are ranked in order of descending magnitude of explained variance. The eigenvalues were scaled to the percentage of the total generalized variation in the data for each principal pattern to provide an estimate of relative importance of each PP to the measured variables. The PP matrix was then used to transform the original observations (X) into new uncorrelated observations called PP_i scores $[174 \times 24] = X \times PP$. Since the goal of this study was to simplify a multidimensional problem, only those principal patterns (k) that together explain 95% of the total variability in the data were retained for further analysis (Johnson and Wichern, 1998; Johnson, 1998). The PP_i scores for k principal patterns were then used as dependent measures for traditional inferential statistical testing.

To aid in the interpretation of each principal pattern, the mean from a subsample of activation amplitude patterns corresponding

279 to high and low scores for PP_1 scores and high positive and high
 280 negative scores for PP_2 scores and PP_3 scores were presented. In
 281 addition, the *Scaled Percent Variance Explained*, between the i th PP
 282 and the variance associated with the j th original variable (muscle
 283 site) and associated standard deviation (s_j) was calculated to identify
 284 the muscle site(s) in the amplitude pattern where the PP explained
 285 the greatest amount of variance (Jackson, 2003).

286 2.8. Statistical analysis

287 Separate two-factor ANOVA with repeated measures were performed
 288 on the PP_i scores for each k principal pattern to test the effects
 289 of reach and phase on activation amplitude patterns. Means, standard
 290 deviations and range of maximum angular displacement for the trunk
 291 and pelvis were calculated throughout the total movement. Bonferroni
 292 adjustments on the $\alpha = 0.05$ were made to test for the multiple
 293 comparisons. Minitab™ (Minitab Inc., State College, PA. Version 14)
 294 was used to perform the statistical analyses.
 295

296 3. Results

297 Twenty-nine individuals (15 males, 14 females) participated in this
 298 study. Based on reported occupational experience, the subjects did not
 299 have extensive experience with manual material handling tasks (Table
 300 1).

Table 1
 Average (standard deviation) subject demographic variables ($n = 29$).

Variable	Mean	SD
Age (years)	30.9	9.1
Height (cm)	171.3	8.6
Mass (kg)	69.2	13.6
Body mass index (kg/m ²)	23.5	3.6
Waist circumference (cm)	77.4	9.8
Normal reach (cm)	31.7	2.8
Maximum reach (cm)	50.2	3.6

The activation amplitude pattern consisted of discrete normalized
 301 activation amplitudes from 24-trunk muscle sites averaged
 302 across trials. Fig. 3 shows that the general shape of the amplitude
 303 pattern was similar among the experimental conditions. Specifically,
 304 the amplitude pattern demonstrated higher activation amplitudes
 305 for the back extensor and internal oblique sites (6.2–21.0%
 306 MVIC) compared to the remaining abdominal sites (2.6–4.5%
 307 MVIC). For the back extensor sites, mean activation amplitudes
 308 from the medial back extensor sites (L13, L33, L52; 15.3% MVIC)
 309 were higher than the more lateral sites (L16, L36, L48; 10.3%
 310 MVIC).
 311

Three principal patterns explained 95% of the variability in the
 312 measured data. Principal pattern one represented the general
 313 shape and magnitude and accounted for 91.7% of the total variation.
 314 This pattern is essentially the mean pattern. Principal patterns
 315 two and three captured 1.9% and 1.6% of the variability, respectively,
 316 and represented subtle differences in shape of the activation
 317 amplitude patterns during the symmetrical lift and replace task.
 318 For interpretation purposes, positive PP_i scores associated with
 319 principal patterns two or three resulted in the pattern being added
 320 to the mean pattern, where negative PP_i scores resulted in the pattern
 321 being subtracted from the mean pattern.
 322

Principal pattern one consistently accounted for 70% to 96% of the
 323 *Scaled Variance Explained* across the muscle sites (Fig. 4A). Since
 324 PP_1 scores were positive, a subsample of 15 activation amplitude
 325 patterns were averaged based on their high and low PP_1 scores
 326 (Fig. 4B). As shown in Fig. 4C there was a significant interaction effect
 327 for reach-by-phase for the PP_1 scores ($\rho < 0.000$). Pair wise
 328 comparisons revealed statistically higher PP_1 scores associated with
 329 the maximum reach compared to the normal reach for the lift
 330 ($\rho < 0.000$), transition ($\rho < 0.000$) and replace ($\rho < 0.000$) phases.
 331 For maximum reach, the lift phase PP_1 scores were significantly
 332 higher than the transition ($\rho < 0.000$) and replace ($\rho < 0.000$)
 333 phases with the transition phase significantly higher than the re-
 334 place ($\rho < 0.000$) phase. Similar findings were observed for the normal
 335 reach with the exception that the patterns were similar
 336 between the lift and transition phase ($\rho = 0.472$). In other words,
 337 the decrease in PP_1 scores across the three phases was greater for
 338

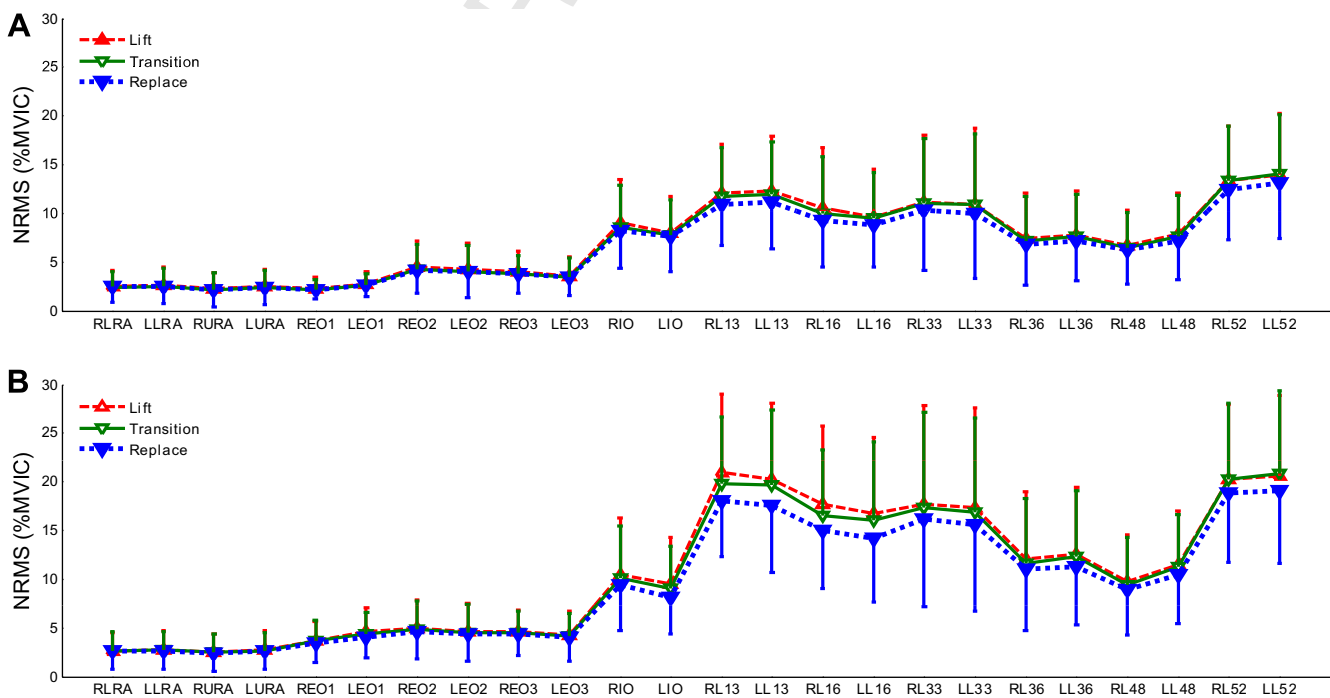


Fig. 3. Mean and standard deviation for the activation amplitude patterns for (A) normal and (B) maximum reaches across movement phases.

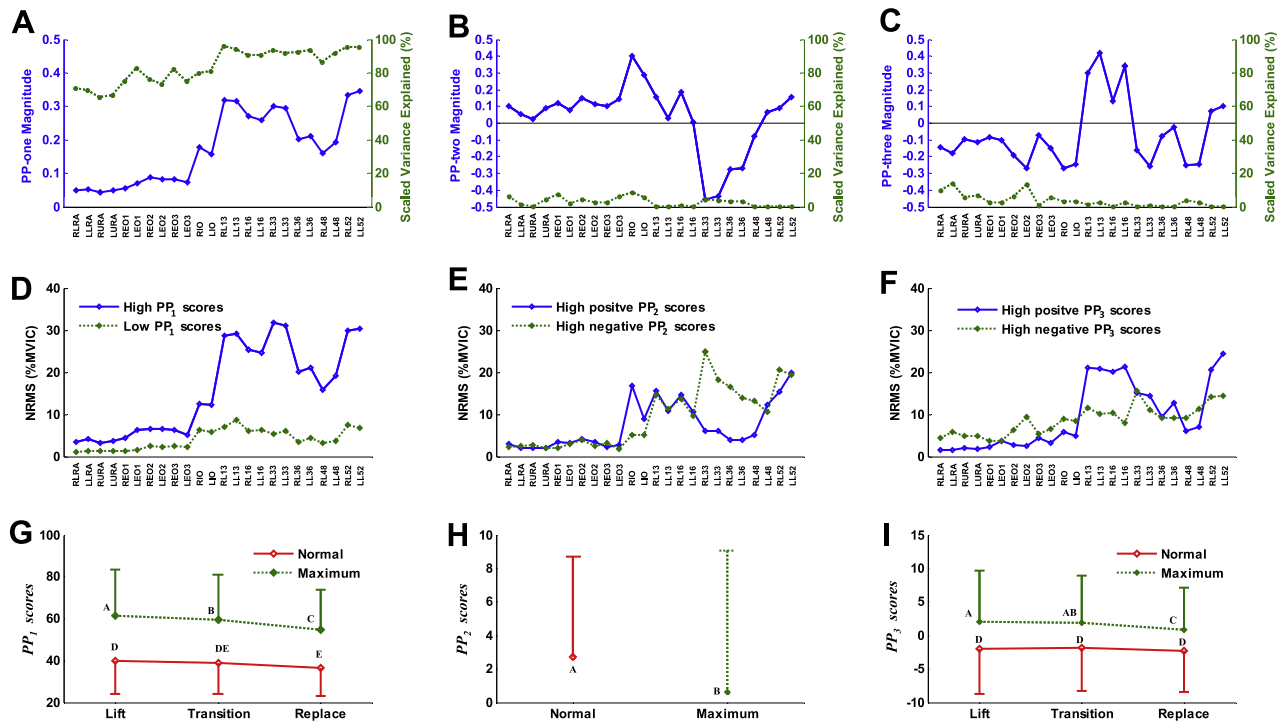


Fig. 4. Figure 4: Principal pattern (solid) and scaled variance explained (dashed) across the muscle sites for (A) principal pattern one (PP-one), (B) principal pattern two (PP-two), and (C) principal pattern three (PP-three). Mean normalized activation amplitude pattern for high PP_1 scores and low PP_1 scores for (D) PP-one, (E) PP-two, and (F) PP-three. Mean and standard deviation for 20 (G) PP_1 scores (H) PP_2 scores (I) PP_3 scores with significant pair wise comparisons indicated with different capital letters.

the maximum reach compared to the normal reach. Overall, principal pattern results showed that the physical demands related to the lift produced slightly different patterns of activation across the phases for the different reaches.

Since principal patterns are uncorrelated and the first pattern represented the overall magnitude, the subsequent patterns characterized subtle differences in activation amplitude patterns that resulted from different experimental conditions. While principal pattern two accounted for only 1.9% of the total variation, it accounts for 3–9% of the variation for the oblique muscle sites and 4–5% of the variation in the L3 muscle sites (Fig. 4D). There was a significant reach main effect ($\rho = 0.001$), where the normal reach had significantly higher ($\rho < 0.000$) PP_2 scores compared to maximum reach (Fig. 4F). For maximum reach, the mean PP_2 score was close to zero, meaning this feature had little influence on the maximum reach conditions. Principal pattern two had a positive magnitude for the abdominal sites and negative magnitude for the L3 back sites. Since normal reach was associated with positive PP_2 scores, principal pattern two featured the similarity in activation amplitudes between the IO and back extensor sites in normal reach across the phases. To highlight this feature, Fig. 4E illustrates the effect of positive and negative scores for this pattern.

Principal pattern three, accounted for 1.6% of the overall variation capturing the greatest amount of variability in three regions of the activation amplitude pattern; 6–15% for the RA sites, 6–14% for the EO2 sites and 0.4–2.9% for the L1 sites (Fig. 4G). As shown in Fig. 4I there was a significant reach-by-phase interaction for principal pattern three ($\rho = 0.001$). The results from the multiple comparisons revealed significantly higher PP_3 scores during the maximum reach for lift ($\rho < 0.000$), transition ($\rho < 0.000$) and replace ($\rho < 0.000$) phases compared to normal reach. There was no phase effect for the normal reach ($\rho = 1.000$). However, for maximum reach, the replace phase was significantly lower than both the lift ($\rho < 0.000$) and transition ($\rho < 0.000$) phases, but no differences were observed between the lift and transition phases

($\rho = 1.000$). When the influence of positive versus negative PP_3 scores was examined, together with principal pattern three, it became apparent that a negative PP_3 score represented the decreased amplitude for L1 sites and increased amplitude for select abdominal sites (RA and EO2), whereas a positive PP_3 score had the opposite effect. High positive and negative PP_3 scores for two subsamples of activation amplitude patterns are presented in Fig. 4H. This featured how the changes in activation amplitude patterns for normal and maximum reaches were a function of movement phases.

3.1. Motion assessment

Motion analysis revealed that there was slightly more motion in the trunk than in the pelvis. The measure of roll produced the greatest mean motion for the pelvis (1.0°), whereas the yaw was the greatest change for the trunk (1.5°). Based on the minimal observed motion, it could be suggested that the activation amplitude patterns were the result of accounting for the external moment and spinal stability and not due to dynamic trunk motion.

4. Discussion

Using pattern recognition techniques, this study characterized the pattern of 24-trunk muscle activation amplitudes in individuals with no history of LBP during a symmetrical lift and replace task. Only three principal patterns were needed to accurately reflect the salient features of the measured data. This highlights a simple underlying structure to the variability in the EMG amplitude patterns. Principal pattern one accounted for the majority of the variability of the data reflecting the general magnitude and shapes of the activation amplitude patterns, which is unique to the order of muscle sites. The order chosen allowed for a visual comparison of symmetry between sides (left and right) and for differences between abdominal and back extensor sites. Principal

patterns two and three revealed subtle changes in the recruitment of the muscle sites in response to realistic work demands (horizontal reach and movement phases).

The results from the present study need to be interpreted recognizing that the pattern analyzed consisted of discrete normalized amplitudes from 24-trunk muscle sites averaged within phases of movement. The merit of this approach has already been demonstrated with a pattern consisting of activation amplitudes from six lower leg muscle sites during plantar flexion at different velocities (Hubley-Kozey and Smits, 1998) and 14-trunk muscle sites during static flexion/extension, lateral bending and twisting exertions (Perez and Nussbaum, 2003). However, in these studies, biomechanical interpretations of the principal patterns were limited since statistical analysis was not performed on the scores associated with the different experimental conditions. At this time, no other study has used this technique to examine the relationships among trunk muscle sites during a simulated occupational task. Nor have there been studies to document the subtle changes that occur in the recruitment strategies with different work demands as demonstrated in this study.

It has been shown that antagonistic co-activation is necessary to maintain the mechanical stability of the spine (Cholewicki and McGill, 1996; Granata and Orishimo, 2001; Granata and Wilson, 2001; Vera-Garcia et al., 2007). This is particularly true for tasks that require little physical effort, such as standing (Cholewicki and McGill, 1996; Cholewicki et al., 1997). The results from the present study revealed two antagonistic recruitment strategies. First, a specific synergistic strategy among all abdominal muscle sites was observed and was consistent across the experimental conditions. This strategy showed that the IO sites were recruited to higher amplitudes compared to both the EO and RA sites, where the EO sites were slightly higher than the RA (Fig. 3). This was captured by principal pattern one. A similar recruitment strategy has been observed in studies where the abdominals were acting as antagonists during symmetrical lifting (Butler et al., 2007; Marras and Davis, 1998; de Looze et al., 1999), in preparation to posteriorly applied sudden loads (Brown et al., 2006; Vera-Garcia et al., 2006) and during static back extension efforts (Perez and Nussbaum, 2002). A second recruitment strategy observed was co-activation between the IO and L3 sites during the less demanding tasks in the normal reach position (Fig. 3) and was captured by principal pattern two. It appears that when the trunk was under light loads the IO and L3, along with the other back extensor sites, were activated to similar amplitudes. The general description of similar activation levels has been called "bracing" in the biomechanical literature and has been shown to reduce lumbar displacement and increase lumbar spinal stability when posteriorly loading the trunk (Vera-Garcia et al., 2006, 2007). Given this information, the recruitment strategy observed in the present study indicates that the CNS may specifically selectively recruit the IO to initial amplitudes that is independent of the physical demands used in this study and perhaps reflects its unique role during lighter work tasks.

In biomechanical terms, changing the physical (mechanical) demands associated with performing tasks indeed alters the loading environment of the spine. The increased physical demands associated with lifting the load in maximum reach not only increased the magnitude of the activation amplitude pattern as shown in Fig. 3 and confirmed by the statistical analysis of principal pattern one, but produced a different recruitment strategy in response to the greater physical demands as shown by the differences in principal pattern three. Specifically, differential recruitment was observed between the L1 and L3 back extensor sites with L1 sites recruited to higher amplitudes during the more physically demanding conditions. This finding supports other studies that have observed differential recruitment among the sites within the longissimus and

iliocostalis muscles at different lumbar levels (Jonsson, 1970; Vink et al., 1988). One explanation for this finding is that load bearing capabilities may differ between the different lumbar segments. It has been shown using a detailed anatomical model, that the muscle moment capability at L1 is less than at L3 (Bogduk et al., 1992). Based on this model, the increased activation of the fascicles at L1 observed in the present study would be necessary given a constraint of a constant moment across the lumbar spine. These findings further support the necessity to record from multiple trunk muscles as well as from multiple sites within a muscle in order to fully understand the neuromuscular control strategies used for work related tasks. This data may be necessary to accurately characterize spinal loading and the corresponding risk estimates from biomechanical models.

The findings from this study must be interpreted within the limitations of the study. The normalization method used (maximum voluntary isometric contraction) in the present study has the potential to influence the relative activation amplitude of the muscle sites. For example, if the muscle cannot produce a 'true' maximum voluntary contraction then the resulting normalized amplitudes would provide an overestimation of muscle activation. However, numerous studies provide evidence that the MVIC is a reproducible standard for comparison despite criticisms of its limitations (Burden and Bartlett, 1999; Dankaerts et al., 2004; Knutson et al., 1994). Furthermore, the evidence-based procedures employed in the present study, which included using a series of exercises (McGill, 1991), feedback and motivation (Baratta et al., 1998; McNair, 1996) as well as motor learning principles (Moritani, 1996) increased the probability that the maximum voluntary activation was achieved. Thus, it is believed that the maximum voluntary values represented consistent and valid measures to use as the standard reference method.

In addition, a reasonable assumption was made that minimal changes occurred in the temporal waveform for each muscle site within each phase of the task since the external moment remained constant and lifting height was small (5-cm). The unique order of the data used in the present study created the shape of the principle patterns, but does not have a physiological meaning in the sense of a 'time varying' pattern. Thus, the single measure of the RMS amplitudes provided a comprehensive picture of the muscular responses to the demands of the task, which allowed for comparisons of the activation amplitudes of the abdominal and back extensor sites and between bilateral sites.

In summary, the present study demonstrated that a clear, relatively simple pattern of activation amplitudes is responsible for providing the neuromuscular responses to a symmetrical lifting perturbation. The sample included both men and women and still a large percentage of the variation was explained by the three patterns. The pattern shows low activation amplitudes for the abdominal sites, with higher IO activation, that changes very little with increasing physical demands of the task. The antagonist co-activation strategy observed in the present study may serve to support the spine while minimizing loading of the spine during more demanding tasks. For the back extensors, selective recruitment of the more medial back sites suggests that the CNS may control different regions of the back musculature to optimally account for the biomechanical demands of the task. These patterns can be described with three numbers (i.e. scores) with a high degree of accuracy. This allows researchers to better examine the relationships among a large number of muscles and test how different work characteristics change the relationships among the muscle sites compared to the limitations associated with the traditional methods of analyzing multiple muscle sites. This ability to capture the neuromuscular demands from a large number of muscles offers new insights into ergonomic initiatives and workstation layout to optimize the work method and the physical demands placed on the worker.

537 **Conflict of interest statement**

538 There were no conflicts of interest associated with this study.
539 There were no financial or personal relationships involved in this
540 work which could have biased the work.

541 **5. Uncited reference**

542 Q3 Hubley-Kozey et al. (2006).

543 **Acknowledgements**

544 The Natural Sciences and Engineering Research Council of Can-
545 ada (NSERC) and the Nova Scotia Health Research Foundation
546 (NSHRF) supported this study. We would like to thank J. Crouse
547 for his technical assistance, M. Abbott, J. Boulay and C. Cameron
548 for their assistance in data collection as well as the subjects for
549 their time and effort.

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