Characterization of trunk muscle activation amplitude patterns during a simulated checkout operation with continuously changing flexor and lateral moment demands

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While the typical physical exposure to modern-day workers has changed from heavy to low level repetitive demands, there is limited research that examines light occupations. This study examined trunk muscle recruitment strategies in response to a simulated checkout operation. Surface electromyography and kinematic variables were recorded from 29 healthy subjects. Four principal patterns accounted for 95.3% of the variation. Significant differences in scores captured different strategies in response to reach conditions and external moment directions. Synergistic co-activation of ipsilateral back sites and differential activation among external oblique and erector spinae sites suggests that the central nervous system may control different regions of the trunk musculature to optimally account for asymmetrical demands. The strategy between the internal oblique and back extensor sites suggests that a specific co-activation strategy may be needed during lighter work. During low-load occupational tasks, several recruitment strategies were required to maintain spinal stability and account for changing external moments.

Statement of Relevance: Different recruitment strategies found in response to changing external moments offer new insights into neuromuscular control for lighter work. Specifically, multiple trunk muscle sites interact in a complex manner, taking into account task specificity and individual variation that are valuable in workstation design, evaluating injury risk and estimating spinal loads.

Keywords: activation amplitude patterns; checkstand operations; lifting; pattern recognition; trunk muscle

1. Introduction

Trunk muscle recruitment strategies have been studied during various tasks that attempt to simulate work demands (Lavender et al. 1992a, Vera-Garcia et al. 2006) with altered trunk muscle recruitment strategies reported for individuals with low back pain (LBP) (Ferguson et al. 2005). While research has concentrated on occupational tasks that require heavy physical effort (Marras and Davis 1998, Ferguson et al. 2004, Marras et al. 2004), surprisingly little attention has focused on how muscle recruitment strategies change during realistic simulations of lighter occupational tasks. In fact, the United States Occupational Research Agenda recently recommended that a research focus should include the assessment of muscle recruitment patterns during low-level repetitive exertions to better reflect the nature of physical exposure in the current workplace (Marras et al. 2009).

Muscle activation amplitudes often describe the simultaneous activation of both antagonist and agonist muscles as co-activation (Lavender et al. 1992b, Hubley-Kozey and Smits 1998, Thelen et al. 1995). Ergonomic studies that have examined co-activation of trunk muscles have shown it to be dependent on posture (Cholewicki et al. 1997, Granata and Wilson 2001), lifting characteristics (Granata and Orishimo 2001, van Dieen et al. 2003) and the direction and magnitude of the external moments acting on the trunk (Lavender et al. 1992a, Thelen et al. 1995, Song and Chung 2004). While it appears that co-activation is an important neuromuscular response, the activation level of the antagonist and agonists are often averaged to represent a general index of co-activation with specific co-activation strategies of individual muscle sites not identified. Furthermore, when this group scoring approach is used, important information about how individual regions within a muscle (differential recruitment) or which muscle is selectively recruited in response to different experimental conditions is lost. Recent evidence suggests that the specific recruitment strategy among the individual trunk muscle sites influences the ability to stabilise the spine in response to a sudden load release (Brown et al. 2006). Thus, it may be important to identify specific co-activation strategies among individual synergistic, agonist and antagonist muscles and examine how these strategies change in response to changing external requirements to better understand neuromuscular control during realistic occupational tasks.

Several studies have simulated individual components of occupational jobs or activities that are thought to be at high risk for a work-related low back injury. For example, trunk muscle recruitment strategies have been examined during sudden loading or quick release paradigms to simulate trips and falls that can occur in the workplace (Radebold et al. 2001, Brown et al. 2006, Reeves et al. 2006). Other studies have applied external forces to an upright trunk to simulate asymmetrical loading tasks (Lavender et al. 1992a,b, Perez and Nussbaum 2002). These examinations of individual task components are helpful in understanding pre-planned activations and muscle reflex behaviour during perturbations, but do not reflect common work demands in the current workplace. In contrast, only a few studies integrated several task components to simulate an entire job and realistic occupational demands to assess trunk muscle activation (Marras and Davis 1998, Danneels et al. 2001). In these realistic cases, the tasks required dynamic trunk motion, thereby influencing the neuromuscular response not only by changes in the external moment but also by changes in muscle length, velocity and acceleration. In the industrial work environment it is also of interest to examine the neuromuscular response without influencing dynamic factors since many jobs require the worker to maintain an upright posture while performing a variety of manual operations, such as assembly-line work, inspection and checkstand operations (Marras et al. 2009). In North America, checkstands are used for customer–clerk interactions involving the processing of items for purchase, such as groceries or items purchased in department stores. Depending on the checkstand design, the operator transfers groceries or other light items from one side of their body to the other and typically there is little or no movement of the trunk and pelvis.

In the present study, the experimental task was designed in accordance with ergonomic principles meant to reduce motion of the operator (Konz 1983) as well as represent a classification of low effort jobs that better reflects the nature of physical exposure to many modern-day workers. Healthy individuals performed a simulated checkstand operation that created continuously changing but controlled external 3-D moment demands on the trunk during different reach conditions. The main purpose of this study was to quantify how the principal trunk muscle activation amplitude patterns changed with different reach conditions (horizontal reach) and whether the pattern changed depending on the direction of the external moment (movement phase).

2. Methods

Participants for the study were recruited using advertisements and electronic notices posted at Dalhousie University. In total, 29 right-hand dominant individuals (15 males and 14 females) with a mean age of 30.9 + 9.1 years and BMI 23.5 + 3.6 kg/m2 participated in this study. These subjects reported no previous injury that resulted in pain to their low back region. In addition, they had no known cardiovascular, neurological or orthopaedic conditions. With regard to work experience, none of the participants reported extensive experience with manual material handling tasks. Prior to testing, the subjects signed an informed consent that was approved by the Health Sciences Research Ethics Board at Dalhousie University.

2.1 Sensor Placement

Disposable Ag/AgCl surface electrodes with 30 mm inter-electrode distance (Meditrace; Graphics Control Canada Ltd., Ganaoque, Ontario, Canada) were placed over 24-trunk muscle sites (right and left sides of the body) with reference electrodes placed at three locations on the right iliac crest (Butler et al. 2008). Surface electromyography (EMG) was used to collect myoelectric signals from 12 abdominal muscle sites using standard electrode placements: lower rectus abdominis site (LRA: midpoint between the pubis symphysis and umbilicus); upper rectus abdominis site (URA: midpoint between the umbilicus and the sternum); external oblique muscle that represented the anterior (EO1:over the eighth rib), lateral (EO2:approximately 15 cm lateral to the umbilicus at a 458 angle) and posterior fibres (EO3: halfway between the iliac crest and lower portion of the ribcage) and internal oblique (IO: centred in the triangle formed by the inguinal ligament, lateral border of rectus sheath and the line between the two anterior superior iliac spines). A total of 12 muscle sites represented the back musculature and electrodes were placed over the following muscles at four lumbar levels using standard electrode placements: lumbar erector spinae at L1 and L3 at 3 and 6 cm from the midline to represent the longissimus and iliocostalis muscle sites, respectively (L13, L16, L33, L36); quadratus lumborum at L4 (L48: 8 cm from the midline) (McGill et al. 1996); multifidus at L5 (L52: 1–2 cm from the midline). The muscle sites were chosen to represent the different components of the abdominal wall musculature and the lumbar back extensor muscles known to have differential functions during both motion and stabilising tasks (Bogduk et al. 1992). To validate electrode placements and minimise signal cross talk among neighbouring muscles (Winter et al. 1994), a series of validation exercises aimed at isolating specific muscle sites based on manual muscle testing principles (Kendall and McCreary 1983) and the literature (Richardson et al. 1999) were performed (trunk flexion, extension, lateral bend, rotation, hip hiking and abdominal hollowing). Based on these activations and subject anthropometrics, in some cases minor adjustments were made to ensure the electrodes were over the muscle of interest. In the case of deeper muscles, evidence supports that appropriately placed surface electrodes adequately represent the activation amplitude of the quadratus lumborum and IO muscles (McGill et al. 1996).

The raw myoelectric signal was pre-amplified (5006) and further amplified using three AMT-8 EMG systems (Bandpass 10–1000 Hz; common mode rejection ratio (CMRR) ¼ 115 db, input impedance 10GO, Bortec Inc., Calgary, Alberta, Canada). The raw myoelectric and event signals were sampled at 1000 Hz using a 16-bit analogue to digital converter (CA-1000; National Instruments, Austin, TX, USA) and stored on a personal computer using LABVIEWTM. In addition, two electromagnetic sensors were placed over the seventh thoracic vertebrae and left iliac crest and monitored angular motion of the trunk and pelvis throughout the task using Flock of BirdsTM (FOB) motion system (Ascension Technology Inc., Burlington, VT, USA). The FOB signal and event markers were collected using LABVIEWTM on a second computer. The output from the FOB was connected to the computer via a serial port (RS232) and the raw signal was sampled at 50 Hz using a 12-bit analogue to digital converter (CA-1000; National Instruments). The EMG and FOB data were synchronised with regard to the phases of movement using the event marker system.

2.2 Experimental Trials

To simulate a checkstand operation task the subjects were required to perform three trials of transferring a load (3.0 kg) in the frontal plane at two reach distances (normal, maximum) while minimising trunk and pelvis motion. Typically, minimal trunk motion occurs during the performance of this task; however, the constraint was also necessary to control factors that could alter the neuromuscular responses in addition to the two manipulated variables (reach and movement phase). The mass of the load was chosen based on previous work and on the need to produce a measurable neuromuscular response, but that was safe with regard to spinal loading (Butler et al. 2009a). For normal reach, the upper arm was vertical and the forearm horizontal, whereas for maximum reach the upper extremity was straight (Butler and Kozey 2003). During the task, the subjects stood with their midline aligned with the centre of the table, which was adjusted to their measured standing elbow height. The simulated movement required the subjects to first lift the load positioned at 608 to their body midline with their right hand, then move the load toward their midline, transfer the load to the left hand at their midline and then move the load away from the midline and replace it on the other side of their body midline at 7608 (Figure 1). During this movement the subjects were required to follow each reach path while maintaining the load approximately 4–5 cm above the table surface while transferring the load in a slow and controlled manner. Using a standard 5-s count and an event marker system, the lifting movement was divided into three phases: right-hand transfer phase; hand transition phase; left-hand transfer phase (Figure 1a–c). While subjects were asked to control motion at the trunk and pelvis, only in the case of clearly observable motions of the trunk and pelvis were the trials repeated.

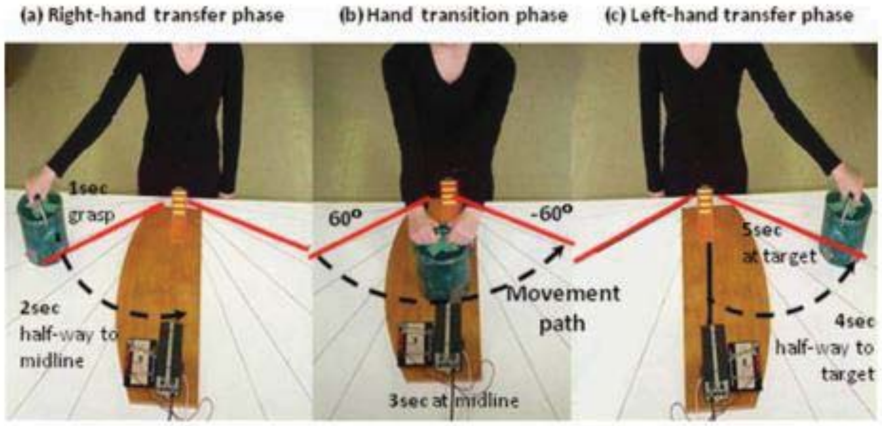

Figure 1. Experimental set-up, subject position and movement path in maximum reach. Event marker system consisted of a pressure transducer on the bottom of the can and a photoelectric relay system. The average times for (a) right-hand transfer, (b) hand transition and (c) left-hand transfer phases were 1.4, 0.8 and 1.5 s, respectively.

2.3 Electromyographic Normalisation

Nine different maximum voluntary isometric contraction (MVIC) exercises were performed following the lifting trials. These exercises were based on previous research and while they target specific muscles, maximum voluntary activation amplitudes can occur from the different abdominal and back extensor sites for different exercises (McGill 1991, Butler et al. 2008). The subjects performed a supine sit-up and V-sit-up, sitting axial rotation to the right and to the left, sidelying lateral flexion to the right and left with contralateral hip hike, prone back extension and prone back extension coupled with axial rotation to the right and to the left. The order of exercises was randomised with two trials performed in succession. During each exercise standardised verbal encouragement and feedback was provided to ensure maximum effort and correct performance of the exercise. To avoid fatigue the subjects were given at least a 2-min rest period between trials. After the normalisation exercises, baseline muscle activity was recorded for 0.5 s with the subject lying supine.

2.4 Data Processing

Customised programs in Matlab1 (version 7.3; MathWorks, Inc., Natick, MA, USA) were used to process the EMG and FOB data. For the EMG data, the raw myoelectric signal was first filtered using a recursive fifth order Butterworth high pass filter to remove the electrocardiogram artefact (Drake and Callaghan 2006, Zhou et al. 2007, Butler et al. 2009b). Next, it was corrected for bias and adjusted by the true gain of the channel to mV at the skin–electrode interface. The root mean square (RMS) amplitude was calculated for each phase of the test trials. For the normalisation trials, a 500 ms moving window was used to identify the maximum RMS amplitude for each muscle. Within each subject, the normalisation exercise that produced the maximum RMS amplitude was then used to normalise the activation amplitude from the test trials as a percentage of MVIC (%MVIC) (Vezina and Hubley-Kozey 2000). For the FOB data, the 3-D rotation data were filtered at 1 Hz with a recursive second order Butterworth filter and the maximal angular displacement was calculated for yaw, pitch and roll of the trunk and pelvis for the duration of the movement.

2.5 Electromyographic Data Analyses

A detailed description of the pattern recognition techniques used in the present study is found elsewhere (Gerbrands 1981, Hubley-Kozey and Smits 1998, Jackson 2003). For data analysis purposes, the mean amplitude for each muscle from the repeated trials was used to create the data matrix X[nxp], which consisted of n ¼ 174 observations (29 subjects, two reaches, three phases) and p ¼ 24 variables (normalised activation amplitude pattern). The primary features were extracted using eigenvector decomposition of the cross product matrix. The number (k) of eigenvectors or principal patterns (PP) retained was established as the number required to account for 95% of the total variance in the measured patterns. PPi scores were calculated for each subject and condition. The PPi scores provide a measure of how close the individual measured pattern corresponds to the features captured in each PP. The PPi scores that represented the extracted PPs were then statistically tested to identify the differences associated with reach and movement phase conditions during the simulated checkstand operation. To assist with interpretation of these PPs: 1) the location where the greatest variation occurred within each PP was determined (scaled percent variation explained) (Johnson and Wichern 1998, Astephen and Deluzio 2005); 2) the mean from a subsample of measured amplitude patterns that corresponded to high (positive) and low (negative) PPi scores were presented; these measured patterns were best-case representations of the feature captured in each PP. In the case of high and low PPi scores, the amplitude patterns associated with specific experimental factors that have similar PPi score magnitude and the same polarity reflect a similar recruitment strategy among the muscle sites. However, the opposite polarity indicates that a different muscle recruitment strategy is utilised.

2.6 Statistical Analysis

For each ANOVA test, the assumptions of normality and homogeneity of variance were examined. For each PP, a two factor ANOVA with repeated measures tested for differences in PPi scores to determine the effect of reach and movement phase on the activation amplitude pattern. All statistical tests were performed using MinitabTM (version 14; Minitab Inc., State College, PA, USA), all main and interaction effects were tested at a ¼ 0.05. When applicable, post-hoc analyses were performed using Bonferroni corrections.

3. Results

Figure 2 shows the mean activation amplitude pattern for the normal (Figure 2a) and maximum (Figure 2b) reaches across movement phases. While the bilateral back muscle sites were more symmetrically activated during the hand transition phase, the muscle sites contralateral to the load were selectively recruited to a higher activation level when handling the load with one hand. Interestingly, both the left and right internal oblique muscle sites were recruited to similar amplitudes to the back sites ipsilateral to the handled load. In maximum reach the amplitudes of the EO1 sites were higher than the RA sites and similar in magnitude to the EO2 and EO3 sites with changing activation level depending on the movement phase.

3.1 Activation Amplitude Pattern Analysis

The results from the pattern recognition analysis revealed that 95.3% of the total variance was explained by four PPs. The first PP represented the mean activation pattern and accounted for the majority (87.3%) of the total variation in the data. PPs 2, 3 and 4, respectively, captured 4.4%, 2.3% and 1.3% of the total variance in the data and reflect the changes in shape of the activation amplitude patterns.

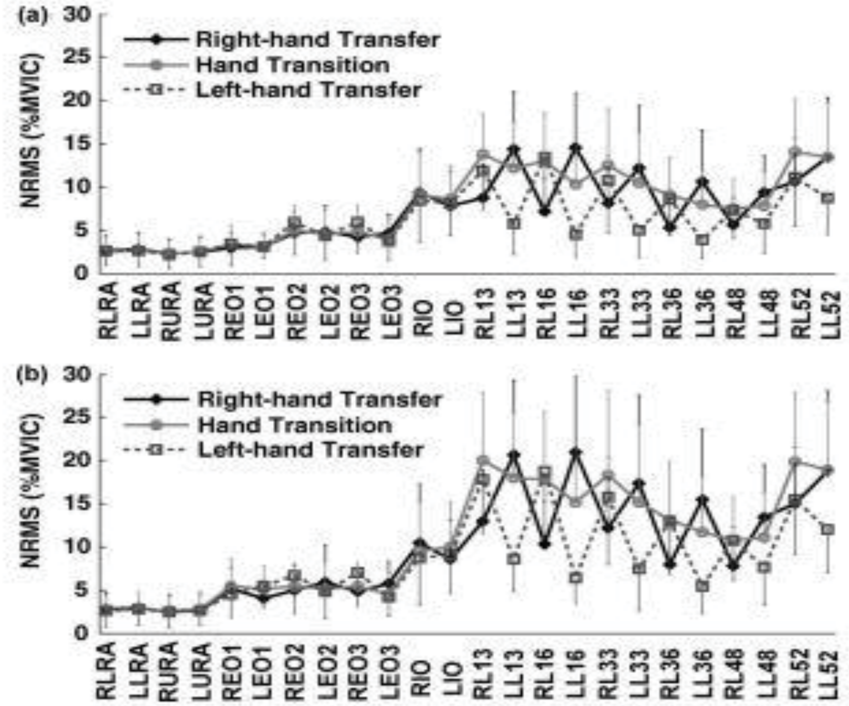

Figure 2. Mean normalised activation amplitude pattern (%MVIC) for each phase for (a) normal reach and (b) maximum reach. NRMS = normalised root mean square activation amplitude.

The first PP consistently accounted for 70–95% of the variation across the muscle sites (Figure 3a). The results from the ANOVA showed significant main and interaction effects (Table 1). As indicated in Figure 3b the interaction revealed statistically significant effects among all pairwise comparisons (p 5 0.001). Consistent across movement phases, higher PP1 scores were observed for maximum reach, reflecting overall higher muscle activation amplitudes compared to the normal reach condition. The PP1 scores for the hand transition phase were the highest, whereas the scores for the left-hand transfer phase were lowest for both reaches. The greater reduction in PP1 scores between the hand transition and left-hand transfer phase in maximum reach compared to normal reach resulted in the significant interaction effect; however, the difference as %MVIC was small (Figure 2). These changes in magnitude reflect different physical demands associated with reach and movement phase as illustrated in different activation amplitude patterns corresponding to high and low PP1 scores (Figure 3c).

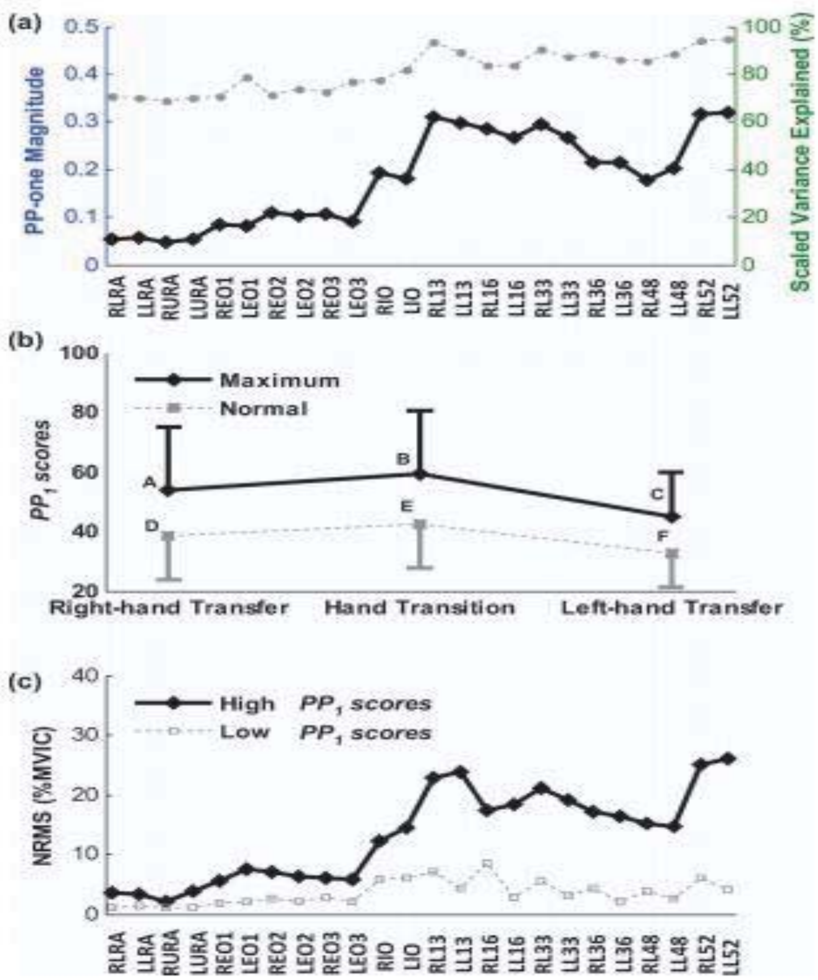

Figure 3. (a) Principal pattern (PP) 1 (solid) and the scaled variation across the muscle sites (dashed); (b) mean and SE bars for PP_1 scores with significant pairwise comparisons indicated by different capital letters; (c) mean normalised activation amplitude pattern with a high PP_1 score and a low PP_1 score.

Table 1. Descriptive data for statistically significant effects ($p < 0.05$) for PP_i scores.

Scores	Mean (SD)	Main effects	p value	Interaction effects	p value
PP_1	45.2 (18.8)	Reach	0.000	Reach * Phase	0.000
		Phase	0.000		
PP_2	1.0 (11.0)	Reach	0.365	Reach * Phase	0.000
		Phase	0.000		
PP_3	1.2 (7.8)	Reach	0.000	Reach * Phase	0.000
		Phase	0.000		
PP_4	−0.3 (6.0)	Reach	0.028	Reach * Phase	0.445
		Phase	0.003		

PP = principal pattern.

The alternating positive and negative values of PP 2 represent the asymmetrical loading associated with handling the load with one hand. The greatest amount of variability was featured in three anatomical regions: specific abdominal sites (LEO1, REO2, REO3) accounting for 3–6% of variation; L1 muscle sites (4– 12% of variation); L3 sites (5–10% of variation) (Figure 4a).

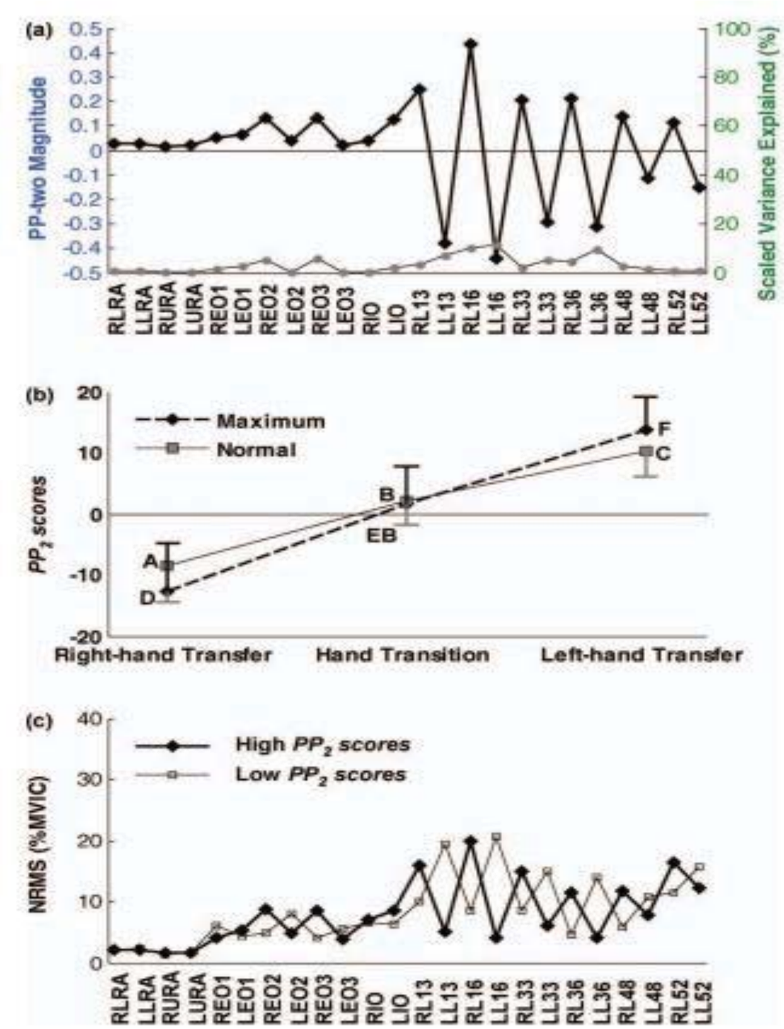

Figure 4. (a) Principal pattern (PP) 2 (solid) and the scaled variation across the muscle sites (dashed); (b) mean and SE bars for PP_2 scores with significant pairwise comparisons indicated by different capital letters; (c) mean normalised activation amplitude pattern with a high PP_2 score and a low PP_2 score.

The statistical results indicated a significant reach-by-phase interaction (Table 1). The multiple comparisons revealed that PP2 scores showed no differences between reaches during the hand transition phase (p ¼ 1.000), whereas significant differences were observed for all other comparisons (p 5 0.001). Specifically, higher absolute PP2 scores were found for maximum reach compared to normal reach and slightly higher during the right-hand transfer phase compared to the left-hand transfer phase (Figure 4b), indicative of highest back muscle site recruitment during the right-hand transfer phase in maximum reach. The abdominals had a slightly higher activation during the left-hand transfer phase with the contralateral EO2 and EO3 sites selectively recruited. The changes in asymmetrical activation of back muscle sites and differential recruitment among external oblique sites that were captured in PP 2 are illustrated in the measured activation amplitude patterns corresponding to high and low PP2 scores (Figure 4c).

The third PP represented differences between the abdominal and back sites. This pattern of variability accounts for 5–15% of the variation for the abdominal sites and 1–4% variation for the right L3 sites (Figure 5a). As indicated in Table 1, results from the ANOVA revealed a significant interaction between reach and movement phase. Significant differences were found among all comparisons (p 5 0.001) except between left-hand transfer phase in normal reach and righthand transfer phase in maximum reach (p ¼ 1.000) (Figure 5b). When the effect of a high vs. a low PP3 score was assessed, it became apparent that a high score represented the reduction in amplitude difference between the abdominal and back sites (Figure 5c). Specifically, the activation level in the EO2 and IO sites was increased and there was a slight reduction in activation level for the L3 sites. This resulted in more similar activation amplitudes between the abdominals and back sites during normal reach across the movement phases. Due to the multi-dimensionality of the PPs and the small variance associated with PP 3, this effect is not easily observed for the right-hand transfer in maximum reach (Figure 2). In contrast, a low PP3 score was associated with a greatest amplitude difference between the abdominals and the L3 sites during the hand transition phase in maximum reach.

PP 4 explained 1.3% of the total variation in the data and represented a difference operator between the muscle sites at L1 and L3 sites (Figure 6a). The statistical results revealed significant reach and phase main effects (Table 1). Lower PP4 scores were found for maximum reach than normal reach (p 5 0.001) (Figure 6b), while the hand transition phase was significantly lower than right and left transfer phases (p 5 0.001) with no difference between the transfer phases (Figure 6c). Because the magnitude of PP4 scores associated with normal reach and the transfer phases were close to zero and therefore not associated PP 4, this pattern captures the changes in muscle activation amplitudes during the hand transition phase in maximum reach. Specifically, the L1 muscle sites were selectively recruited to higher activation amplitudes compared to the L3 and L4 sites with corresponding greater magnitude differences with the abdominal sites. The activation amplitude pattern associated with low PP4 scores features this differential recruitment between L1 and L3 levels of the erector spinae muscle that is featured during the hand transition phase in maximum reach (Figure 6d).

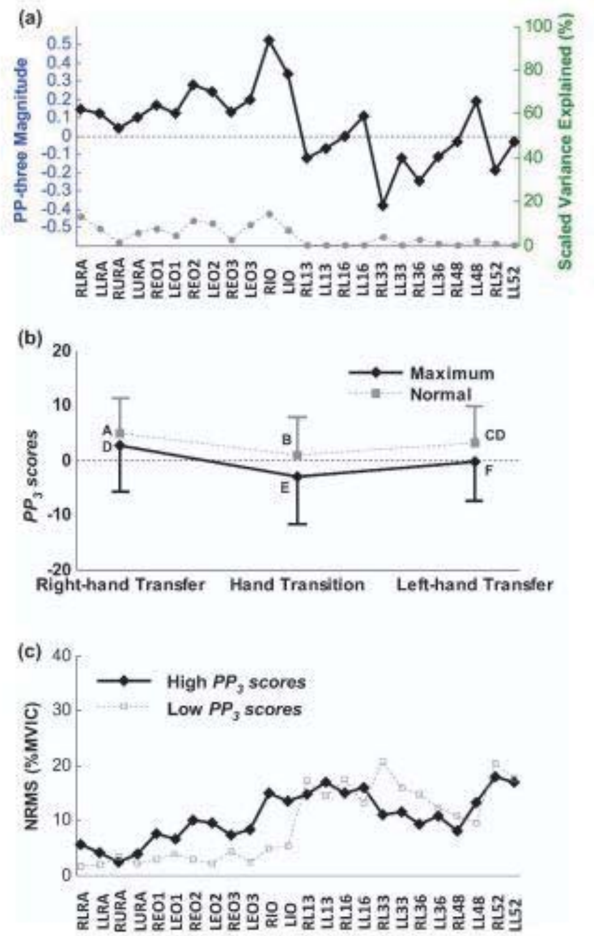

Figure 5. (a) Principal pattern (PP) 3 (solid) and the scaled variation across the muscle sites (dashed); (b) mean and SE bars for PP_3 scores with significant pairwise comparisons indicated by different capital letters; (c) mean normalised activation amplitude pattern with a high PP_3 score and a low PP_3 score.

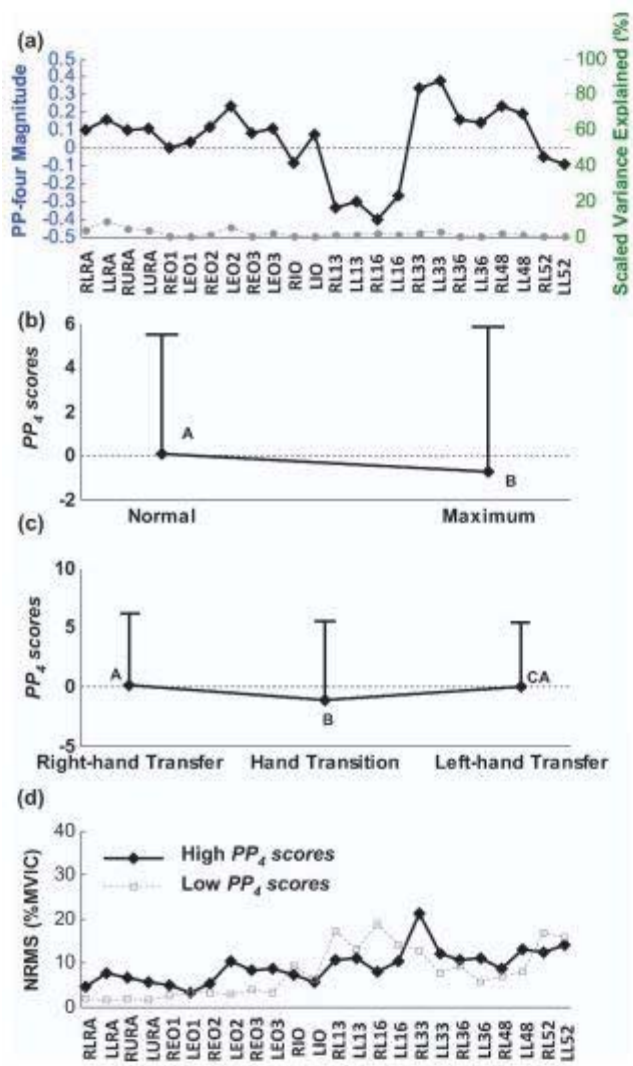

Figure 6. Principal pattern (PP) 4 (solid) and the scaled variation across the muscle sites (dashed). Mean and SE bars for PP_4 scores with significant pairwise comparisons for (b) reach and (c) phase as indicated by different capital letters; (d) mean normalised activation amplitude pattern with a high PP_4 score and a low PP_4 score.

3.2 Motion Assessment

In absolute terms, there was slightly more motion in the trunk than in the pelvis. The yaw motion produced the greatest motion for the pelvis (2.48) and for the trunk (5.48). In addition, more motion occurred during the maximum reach than normal reach; however, the differences were small (0.2–1.58).

4. Discussion

Coordinated muscle recruitment strategies are required to account for the 3-D external moments placed on the trunk during occupational tasks. In this study, activation amplitude recruitment was examined during a simulated checkstand operation. Since the subjects performed the simulated task with very little movement in the trunk and pelvis, the recruitment strategies reflect the combined spinal stability demands and the symmetrical/asymmetrical loading of the trunk that is characteristic of industrial assembly-line work and checkstand operations. The major finding was that only four PPs were needed to characterise the important features of the EMG amplitude patterns. While the first PP represented the overall magnitude of the muscle sites, PPs 2–4 reflected different muscle recruitment strategies in response to the changing external moment demands. Specifically, a number of co-activation strategies as well as differential and selective recruitment strategies were observed, depending on the reach conditions and the direction of the external moment.

4.1. *Co-activation strategies*

The results from the present study identified three specific co-activation strategies during the simulated checkstand operation. The first co-activation strategy described the order of abdominal site amplitude recruitment with the rectus abdominis sites as the lowest, followed by the external oblique sites and the IO was selectively recruited to the highest amplitude (PP 1). Similar antagonist co-activation strategies have been observed during a variety of experimental tasks: light symmetrical and asymmetrical lift and replace tasks (Butler et al. 2008, 2009a); dynamic onehanded lifting (Marras and Davis 1998); higher effort sagittal and frontal plane trunk exertions (Perez and Nussbaum 2002); low level abdominal stabilising manoeuvres (Brown et al. 2006, Vera-Garcia et al. 2006). In addition, the relative co-activity among the abdominal sites changed depending on the experimental conditions. While the rectus abdominis and IO sites remained constant across the experimental conditions, the amplitude of the external oblique site was dependent on the magnitude and direction of the external moment (PP 2). Determining whether the observed abdominal recruitment strategy was optimal for spinal stability was beyond the scope of this paper. However, it is reasonable to suggest that given the consistent findings across different experimental tasks this strategy may be a common motor programme used by the central nervous system. The specific order of abdominal recruitment amplitudes and that individual abdominal sites responded differently to the changing demands of the simulated checkstand operation suggests that average scoring approaches describing co-activation may miss out on important information about individual muscle responses limiting understanding of neuromuscular control during occupational tasks.

Co-activation to similar amplitudes (bracing) was observed between the IO and back extensor sites during the asymmetrical loading phases in normal reach conditions only (PP 3). Previous work also observed this co-activation strategy in normal reach during both symmetrical and asymmetrical lift and replace tasks (Butler et al. 2008, 2009a). It appeared that during tasks requiring lower muscular forces, the neuromuscular system creates a more balanced strategy with similar activation amplitudes among the IO and back sites. Interestingly, Brown and colleagues observed enhanced spinal stability when the activation of the trunk muscles was balanced (bracing) compared to selective recruitment of a muscle site with lower activations in the remaining sites (Brown et al. 2006). In addition, results from modelling studies estimate that for a given compressive force on the spine, the IO was the most effective abdominal muscle in maintaining the stability of the spine without generating additional spinal loads (Grenier and McGill 2007, Arjmand et al. 2008). Given this information and with the findings of the present study, which showed IO and back extensor co-activity, suggests that coordinated muscle activation may be critically important to prevent unstable spinal behaviour (Cholewicki and McGill 1996), especially while performing lighter asymmetrical occupational demands.

Evidence suggests that increased activation of ipsilateral trunk muscle sites plays an important role in spinal stability (Kavcic et al. 2004). Co-activity of the ipsilateral back sites represented the third co-activation strategy observed in the present study. Higher coactivation among the ipsilateral back sites was associated with the lifting requirement of the righthand transfer phase compared to those found when lowering the load in the left-hand transfer phase (Butler et al. 2008). In addition, greater ipsilateral back sites co-activation was found during the horizontal load transfer in the present study compared to a previous work examining an asymmetrical vertical lift and replace task (Butler et al. 2009a). Differences in loading and task demands between the simple asymmetrical lift and replace task and the more comprehensive simulation of an occupational task, examined in the present study, may explain these findings. The continuously changing external moments may have created a greater dynamic challenge to the stability of the spine compared to the lift and replace task, where the external moment remained constant. In fact, evidence indicates that activities that involve greater stability demands result in higher co-activation among the trunk musculature (Cholewicki and McGill 1996, Granata and Orishimo 2001, Granata and Wilson 2001). Along this line of reasoning, the multidirectional challenge to the spine associated with the checkstand task may have required increased coactivation of the ipsilateral back sites to prevent unstable behaviour of the spine, whereas the lift and replace task required less complex motor programmes for the less challenging task, representing only one component of the simulated job.

4.2. Differential recruitment strategies Different regions of the abdominal and back extensor muscles were recruited to different levels of activation depending on the magnitude and direction of the external moment. First, the contralateral lateral (EO2) and posterior (EO3) fibres were recruited to higher activation amplitudes during the right- and left-hand transfer phases in normal and maximum reach conditions (PP 2). Differential recruitment of regions of the external oblique muscle have been found during asymmetrical lift and replace tasks (Butler et al. 2009a), asymmetrical supine leg extension exercise (Davidson and Hubley-Kozey 2005) and axial moment exertions (Mirka et al. 1997). The role of differential recruitment of trunk muscles is not clearly understood. In this study, it appears that the control of these muscle sites may be to oppose the external lateral flexion moment since the orientation of these fibres has a large vertical vector component and the highest amplitudes when contralateral to the load. Regardless of the mechanism, the specific external oblique sites were responsive to the changing lateral bending external moments created during the simulated checkstand operation, suggesting that the external oblique functions as an antagonist and as a synergist.

Second, the differential recruitment was observed for the erector spinae sites between lumbar L1 and L3 during the hand transition phase in maximum reach (PP 4). This feature occurred during a symmetrical lift and replace task in maximum reach (Butler et al. 2008) and suggests that higher activation at the L1 muscle site is necessary due to the lower moment capability found at L1 (Bogduk et al. 1992). The differential recruitment of the erector spinae at different levels was similar to those found by others in the iliocostalis muscle (Vink et al. 1988). These findings suggest that different portions of the erector spinae can be recruited to best suit the demands of the task. Further investigations are required to fully address the mechanism of differential recruitment and its influences on spinal loading and injury risk.

4.3. *Limitations*

The experimental task was designed to reflect realistic demands placed on checkstand workers and at the same time limit the influence of motion effects on the neuromuscular response. The results reflect the true muscle activation in response to the perturbation (phase and reach), although it is recognised that the patterns may be slightly different in field experiments. However, the nature of the checkstand operation suggests minimal trunk and pelvis motion and, thus, it is expected that the observed results may be generalised to workers performing similar tasks.

Discrete measures of amplitude were used to examine the neuromuscular response during a task where the external moments change continuously throughout. Although this is a common approach used to assess muscular effort (Marras and Davis 1998, de Looze et al. 1999, Danneels et al. 2001), assessing the temporal activation profiles could provide additional information on neuromuscular control of these muscles (Hubley-Kozey and Vezina 2002). Also, it is recognised that without assessing the 3-D moments of force and spinal loading variables, the interpretation of the EMG is limited to addressing the function of the trunk muscles measured. Furthermore, since the present study did not quantify spinal stability, the authors cannot comment on which muscle recruitment strategies are optimal for the stability of the spine. However, because subjects did not have a history of LBP it is reasonable to assume that the recruitment strategies observed in the present study reflected healthy activation amplitude patterns in response to realistic work demands. It is important to understand the healthy neuromuscular response during realistic work demands so that the results can be generalised to the workforce that performs similar tasks and have implications for safe return to work.

5. Conclusions

Different muscle recruitment strategies found in response to continuously changing external moments offer new insights in neuromuscular control for lighter work. Specifically, multiple trunk muscle sites interact in a complex manner that takes into account the important factors related to task specificity and individual variation that can be valuable in workstation design, as well as for evaluating low back injury risk and estimating biomechanical spinal loads.

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