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# Temporal Coactivation of Abdominal Muscles During Dynamic Stability Exercises

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## Abstract

Hubley-Kozey, CL, Hatfield, GL, and Davidson, KC. Temporal co-activation of abdominal muscles during dynamic stability exercises. *J Strength Cond Res* 24(5): 1246-1255, 2010-The purpose of this study was to determine abdominal muscle temporal responses to a leg-loading exercise protocol and if differences exist between those able and unable to minimize lumbar-pelvic motion during this protocol. The focus was a supine bilateral leg-loading task that incorporated a slide (level 4) or no slide (level 5). Thirty-three healthy subjects (mean age 24 years) completed the task while surface electromyograms (EMG) from 5 abdominal muscle sites were recorded. Subjects were assigned to stable or unstable groups based on their ability to minimize lumbar-pelvic motion. After time and amplitude normalization, electromyography waveforms were entered into a pattern recognition procedure and scores for each principal pattern were calculated. Four principal patterns explained 90% of variance in the waveform data, with these principal patterns capturing the mean pattern, the relative amplitude change during the leg-extension phase, and subtle changes in shape throughout the exercise. Significant interactions ( $p < 0.05$ ) were found for principal patterns; 1, 2, and 4 scores; and significant main ( $p < 0.05$ ) effects for principal pattern 3 scores. These results illustrate temporal synchrony among the abdominal wall muscle activation during the bilateral leg-loading tasks; however, there was less variability in the activation patterns during the leg-lift and leg extension-phases for those who were able to minimize lumbar-pelvic motion compared to those who were unable to perform the task correctly. These results illustrate the need to focus on coordinated recruiting of the abdominal wall muscles in an organized manner and not simply increasing the intensity of activation for stabilization training.

## Introduction

Dynamic spinal stabilizing exercise protocols have become regular additions to fitness, athletic, and rehabilitation training regimens ([3,8,10,12,14,18](#)). Although strength and endurance components are included, the main focus is on improving neuromuscular control strategies such as synergist and antagonist coactivation and coordination of the muscles responsible for controlling spinal stability and minimizing lumbar spine and pelvic motion. These protocols include upper- and lower-extremity loading in supine ([4,19,20](#)) and prone kneeling postures ([1,19](#)) that challenge the spinal stabilizing muscles.

The present study focused on an exercise protocol that uses an initial abdominal hollowing maneuver and aims to maintain the lumbar spine in a neutral position while performing “leg-loading” tasks in the sagittal plane in a supine position (18). The challenge to the abdominal muscles is altered through a 5-level progression by including single- and double-leg extensions with and without sliding. Even for the highest level-5-the average amplitudes reported for the abdominal muscles of healthy young adults were 40% of maximal voluntary isometric contraction amplitudes or lower (4). Therefore, the abdominal muscles are not recruited to intensities necessary to elicit a strengthening response, although repeating the exercises should train endurance (4). Second, although the protocol incorporates an initial abdominal hollowing, all muscles were recruited to similar amplitudes for the higher loading tasks (i.e., those leg extensions that do not incorporate a slide) indicative of a bracing activation pattern (4). The demands placed on the abdominal muscles of healthy individuals are known for this exercise protocol (4), but the relationships among muscles with respect to temporal firing during the entire exercise have not been studied. To maintain lumbar-pelvic stability during the performance of any dynamic task, the muscles must constantly respond to the continual changes to the 3-dimensional torques associated with the forces acting on the system (16). Hence, evaluating the time-varying responses of the electromyographic (EMG) waveforms to the changing dynamics associated with this exercise protocol should improve our understanding of coordination (temporal synergies) and coactivity among the abdominal muscles. Only 1 study evaluated the time-varying responses of the stabilizing muscles using pattern recognition techniques applied to the EMG waveforms for level 1 of this protocol (9). A temporally synchronized pattern among the abdominal and back extensor muscles was found for asymptomatic controls but not for those with chronic low back pain (9). Whether this temporal synchrony is maintained throughout the higher levels of this protocol for asymptomatic individuals is unknown. Furthermore, it is unknown whether there are differences in symptomatic individuals who are able to control lumbar-pelvic motion and those that cannot. Therefore, the purpose of the present study was 3-fold: (a) to determine if there are differences in the temporal patterns among the abdominal wall muscle sites during performance of a common exercise protocol, (b) to determine if the temporal patterns change in response to the changing demands of this protocol, and (c) to determine whether there were differences between asymptomatic controls who were able to and those who were not able to minimize lumbar-pelvic motion during levels 4 and 5 of the protocol.

## **Methods**

### **Experimental Approach to the Problem**

To address the purpose of the study, 3 questions were asked: (a) Do the abdominal wall muscles activate with a synchronized temporal response to a dynamic challenge to spinal stability? (b) Are differences in the muscle responses dependent on the demand of the challenge (i.e., level of the exercise?) and (c) Are the temporal patterns of muscle responses similar between those who are able to minimize lumbar-pelvic motion and those who cannot? A pattern recognition technique applied to the EMG waveforms was chosen to generate the dependent variables of this study. This technique was chosen because it has the advantage of being able to evaluate time-varying responses of EMG waveforms, rather than just amplitude characteristics.

## Subjects

This study was approved by the faculty of the Graduate Studies Ethics Committee at Dalhousie University. Thirty-three healthy men and women volunteers between the ages of 19 and 35 years participated. Subjects were informed of the experimental risks and signed a written informed consent document prior to the investigation. Subjects were included if they had no history of low back pain or abdominal or back surgery or any other neuromuscular, orthopedic, or cardiorespiratory problems as determined through a health-screening questionnaire.

Height (cm), mass (kg), age (y), and activity level (defined as the number of exercise sessions participated in per week, constituting at least 30 minutes of cardiovascular activity) (6) were recorded. The groups were similar for age, mass, height, and activity level ( $p > 0.05$ ), as indicated in [Table 1](#).

	US ( $n = 14$ )	S ( $n = 19$ )	$p$
Age (y)	24 (2.4)	24 (3.4)	0.82
Mass (kg)	66 (10.5)	69 (12.8)	0.55
Height (m)	1.71 (.08)	1.72 (.09)	0.65
Activity	3.1 (1.7)	4 (1.4)	0.06

US = unstable group; S = stable group.

Activity = number of 30-minute aerobic exercise sessions each week.

Data are presented as mean (SEM).

Table 1: Subject demographics

## Procedures

Subjects were instructed on how to perform all 5 levels of the exercise protocol using verbal instruction (18) and video demonstration. This study focused on the results of the bilateral leg extension exercises (i.e., levels 4 and 5). Subjects were placed into a stable or an unstable group based on their ability to minimize lumbar-pelvic motion and maintain a neutral spine while performing levels 4 and 5 of the exercise progression. The criteria were if he or she could not successfully complete levels 4 and 5 without excessive lordosis or anterior pelvic tilt (18). The exercise protocol is described in detail elsewhere (4), and a brief description is provided in [Figure 1](#). None of the subjects had prior experience with this exercise progression. Subjects were taught the exercise at 1 session and the test session took place within 2 weeks of the initial session. Nineteen subjects made up the stable group and 14 made up the unstable group.

One reflective marker was placed on the iliac crest and 1 was placed as a reference on the exercise table. These 2 markers were aligned at the beginning of the exercise and the change in iliac crest marker compared to the table reference marker was used to help estimate pelvic motion during the exercises. A strip of metal tape was placed on the sole of the right foot to complete a circuit used to identify the start and end of the exercise (right foot off and right foot on) to synchronize the EMG ([Figure 1](#)).

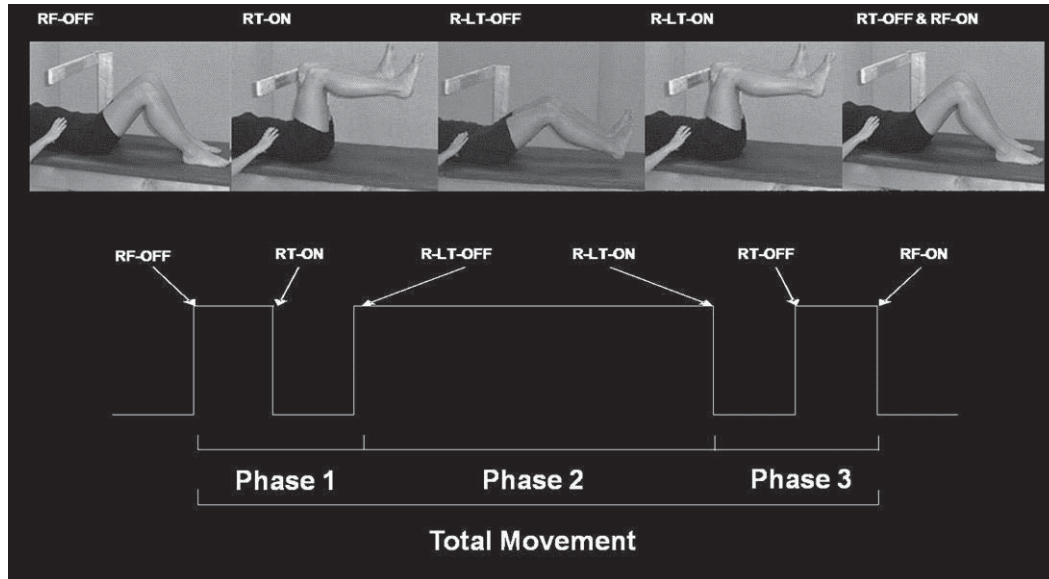


Figure 1. A description of the exercise protocol. Briefly, subjects (A) lay supine and (B) were asked to abdominal hollow “by trying to tuck their navel under their ribcage.” C) Then they lifted their right then left knee so that the hip and knees were at 90 degrees of flexion. D) they extended their knee and hip of both legs to full knee extension, (E) they touched their heels lightly on the exercise table at full extension, (F) flexed back to 90-degree knee and hip angles, and (G) lowered their left then right leg. Level 4 included a bilateral leg extension with a slide of the heels lightly touching the exercise table, and level 5 included a bilateral leg extension without a slide. The total exercise was completed to a count of 8 seconds. The event markers are depicted here. RF = right foot; RT = right thigh; R-LT = right and left thighs.

Standard skin preparation was performed over 5 muscle sites on the right side of the body: (a) lower rectus abdominus: centered on the muscle belly midway between the umbilicus and the pubis (4,6); (b) upper rectus abdominus: centered on the muscle belly midway between the sternum and the umbilicus (4,6); (c) anterior fibers of the external oblique: over the eighth rib adjacent to the costal cartilage (4,17); (d) lateral fibers of the external oblique: approximately 15 cm lateral to umbilicus (2,4); and (e) posterior fibers of the external oblique: midpoint between the superior iliac crest and lowest part of rib cage (4,15). Meditrace silver/silver chloride pellet electrodes (Kendall-LTP, Chicopee, MA, USA; 10 mm in diameter) were placed along the muscle fiber orientation in a bipolar configuration with an interelectrode distance of 25 mm. The skin/ amplifier impedance ratio of  $<0.1\%$  was well below the recommended  $1\%$  ratio (13). A reference electrode was placed over the right anterior superior iliac spine. The electrode placements were validated using contractions aimed at isolating the individual components of the abdominal muscle sites (11).

The raw EMG signals were preamplified ( $200\times$ ) and further amplified using an AMT-8 EMG bioamplifier system (Bortec, Calgary, Alberta, Canada; 10-1,000 Hz, CMRR = 115 dB, input impedance  $\sim 10$  G[ $\Omega$ ]). The gains were calibrated by using a 166-Hz sine wave with 0.6-mV peak-to-peak amplitude. Baseline activity was recorded for 0.25 seconds while subjects completely relaxed in a supine position. The root mean square amplitude of the noise and baseline activity on all channels was less than  $6 \mu\text{V}$ . The EMG channels and 1 event marker

channel were analog to digitally converted at 1,000 Hz using a National Instruments digital interface card (12-bit resolution) and Labview software (Version 5) (National Instruments Corporation, Austin, TX, USA).

The test exercises were videotaped to obtain a permanent record of the exercise trials. The videotape was assessed to determine pelvic motion and whether the lumbar lordosis changed during the exercise, indicative that the neutral spine was not maintained. A subset of trials was assessed independently by 2 orthopedic physiotherapists using the criteria for correct performance (18), and good intertester agreement was previously reported (4). In all cases subjects either had minimal motion that could not be detected visually or excessive anterior pelvic tilt and or lordosis easily observed, making classification into the stable or unstable group clear. We did not attempt to measure spinal segment motion-just gross motion as indicated.

EMG data were full-wave rectified and low-pass filtered at 6 Hz using a second-order Butterworth filter to yield a linear enveloped profile (21). The data for the total exercise were then time normalized to 100% using a linear interpolation algorithm; then the amplitude was normalized to the average amplitude over the entire exercise (21). This amplitude normalization was used to allow for comparison of the temporal patterns only by removing differences associated with differences in volume-conducting properties and muscle strength between groups. The waveform data were used as input to the pattern-recognition algorithm. Sample ensemble-average profiles (21) for each muscle for each level were calculated for the stable and unstable groups separately for qualitative comparisons.

A pattern recognition technique was applied to the EMG profiles from all muscle sites for both groups together, as described in detail elsewhere (9). This technique attempts to determine the characteristics (magnitude and shape) that best capture the variance in the waveforms (i.e., principal patterns). Then a weighting coefficient or score is calculated that determines how much that principal pattern contributes to each measured waveform. Figure 2 provides a schematic of the process. The number of principal patterns (k) needed to accurately reconstruct the original waveforms was determined using 2 criteria from the percent trace (5): (a) those that added to a percent trace greater than 90% and (b) only those patterns contributing more than 1% to the overall variance. All matrix manipulations were performed using Matlab (version 5.2.0 MathWorks Inc., Natwick, MA, USA). The scores for each of the patterns were the dependent measures in the statistical analysis.

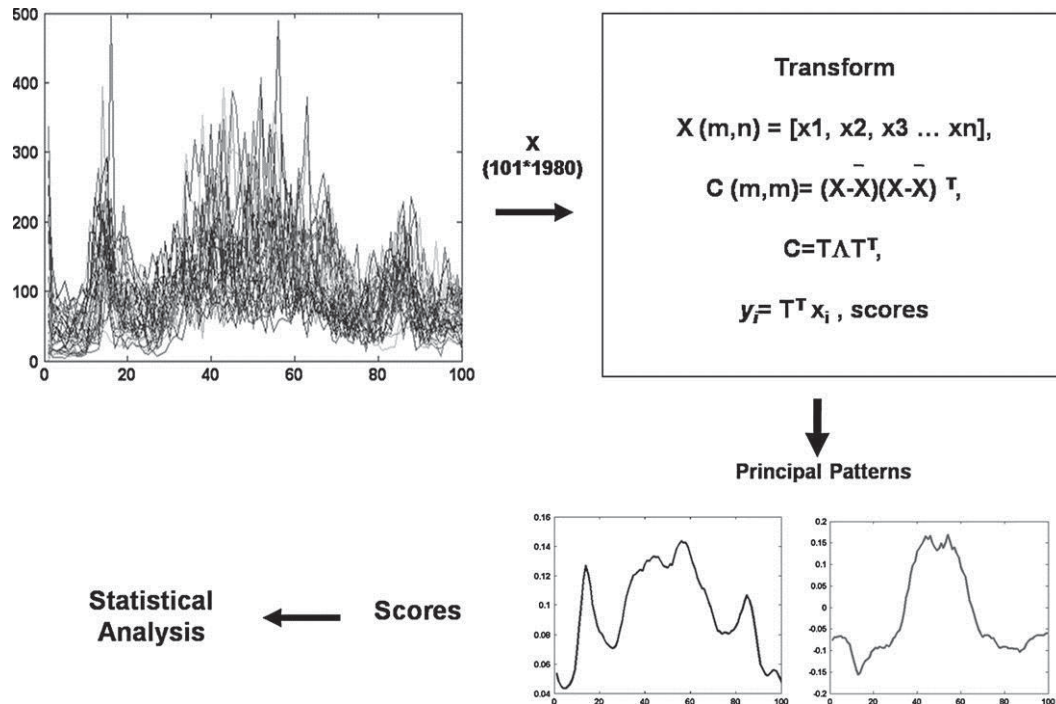


Figure 2. The application of the pattern recognition procedure. A) The time and amplitude normalized measured electromyography (EMG) waveforms for all 5 muscle sites for each participant (e.g., in the top left) form the Matrix X (101 × 1980). B) Application of the transform with the equations in the lower transform box in which a covariance matrix C of X (101,101) is formed and the transform matrix T (101,101) is calculated from an eigenvector decomposition of matrix C. T is a matrix of patterns (orthonormal eigenvectors) and [LAMBDA] is a diagonal matrix of the associated variances (eigenvalues). C) Principal patterns are depicted in the top right. D) A score for each principal pattern derived from the eigenvector analysis, for each participant, for each EMG muscle profile was calculated representing the weighting of that principal pattern to the overall measured waveform as indicated in the transform box. E) These scores are used in the statistical analysis.

### Statistical Analyses

Means and standard deviations (SD) were calculated for all descriptive variables, and t-tests evaluated differences between groups ( $[\alpha] = 0.05$ ). Homogeneity of variance and normality were tested for all scores. Four-factor analysis of variance (ANOVA) models (group, muscle, level, and trial) were used to test main effects and interactions for the scores for the k principal patterns ( $[\alpha] = 0.05$ ). The statistical analyses were performed by Minitab statistical software package, release 14 (Minitab Inc., State College, PA, USA). Bonferonni post hoc analyses were performed on all significant main effects and interactions using the appropriate mean square error term from the original model (7).

### Results

The ensemble average waveforms for the 5 muscle sites and for the 2 levels are in [Figure 3](#) for both groups. There was a distinctive burst of muscle activation when the second leg was lifted (approximately 15% time) and a slightly lower burst during the first leg lowering (approximately 85% time) with a gradual increase and decrease during leg extension (between

25% and 75% of the time). A qualitative assessment indicates that the stable group waveforms appeared to be less variable than the unstable group.

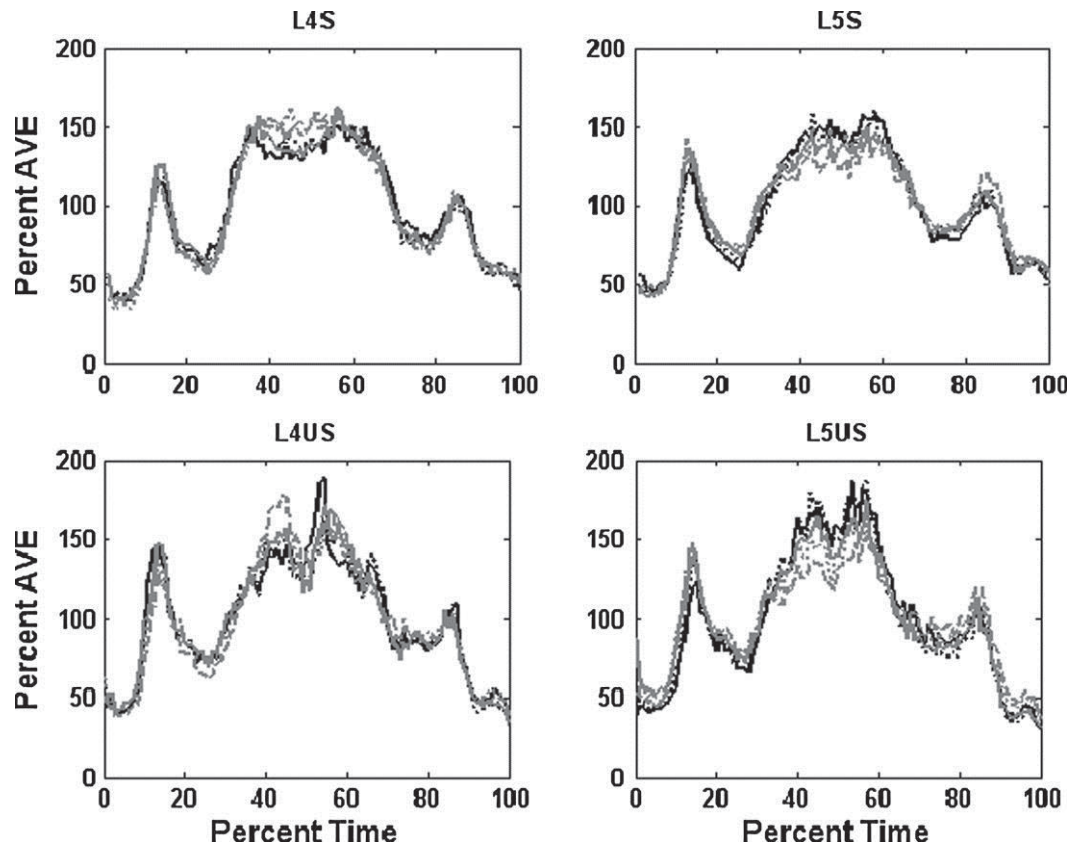


Figure 3. The sample ensemble average waveforms for the 5 muscle sites for the stable (S) group ( $n = 19$ ) level 4 (L4) top left and level 5 (L5) top right and for the unstable (US) group ( $n = 14$ ) level 4 (L4) lower left and level 5 (L5) lower right. The y-axis is the normalized electromyography (EMG) amplitude in percent of average activity (%AVE), and the x-axis is percent exercise cycle. For each panel, the lower rectus abdominus (LRA) is solid black, the upper rectus abdominis (URA) is dotted black, the anterior external oblique (EO1) is solid grey, the lateral external oblique (EO2) is dotted grey, and the posterior external oblique (EO3) is dashed grey.

Comparing the principal pattern scores quantified these qualitative differences in patterns found in [Figure 3](#). Ninety percent of the variance in the normalized waveforms was explained by 4 principal patterns. These patterns are illustrated in [Figure 4C, D, G, and H](#). There were no trial main effects ( $p = 0.64$ ) or interactions with the trial ( $p = 0.60$ ) for any of the principal pattern (PP) scores indicative of the consistency in patterns among trials. Therefore, only the results from the 3-factor (muscle, group, and level) ANOVAs are presented. Principal pattern 1 ([Figure 4C](#)) explained 85% of the variance in the waveform data and captured the predominant shape and overall relative magnitude of the waveforms. This is the mean pattern. It captured the initial burst of activity as the second foot was lifted from the table (15% time) and the hips and knees were flexed to 90 degrees and the smaller burst during leg lowering (85%) as the first foot was



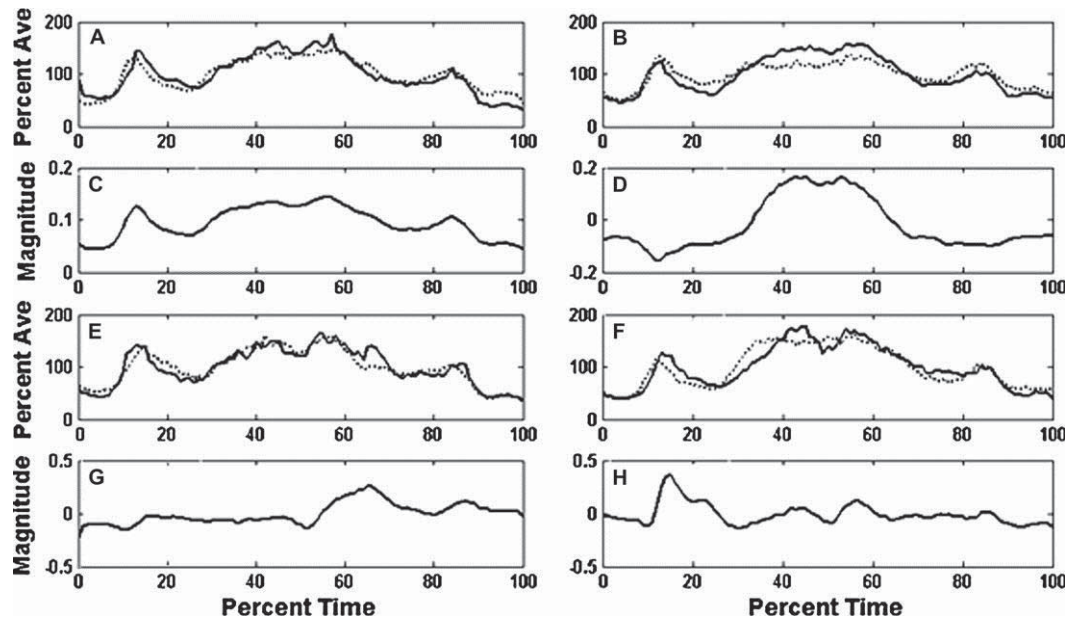


Figure 4. The top and third rows depict the ensemble average waveforms for curves that had statistically different PP scores for the principal patterns depicted directly below in the second and fourth rows. The solid lines depict the higher score, and the dotted line depict the lower score. Principal pattern 1 (PP1) is found in C; the corresponding high score was for the anterior external oblique for the unstable group, and the low score was for the anterior external oblique (level 4) for the stable group. PP2 is found in D; the corresponding high score was for lower rectus abdominus (level 4) for the stable group compared to upper rectus abdominus (level 4) for the stable group. PP3 is found in E; the corresponding high score is upper rectus abdominus for level 4 compared to upper rectus abdominus (level 3). PP4 is found in F; the corresponding high score is for posterior external oblique for the unstable group for level 4 compared to posterior external oblique (level 4) for the stable group.

placed back on the table. [Figure 4A](#) provides an example to illustrate the differences detected in the waveforms associated with high and low PP1 scores. This higher score waveform depicts a pattern that more closely fits the principal pattern 1 in [Figure 4A](#) with the lower score showing slight variations with a less distinctive second peak. Principal pattern 2 ([Figure 4D](#)) explained 4% of the variance. This pattern captured the relative increase in amplitude as the hips and knees were extended with maximum amplitude at full extension and the gradual decrease as the hips and knees were flexed back to 90 degrees (25-75% of the time). [Figure 4B](#) illustrates differences in the EMG waveforms with high and low scores for this pattern. This example shows the higher relative increase in activation required during the leg extension phase associated with the higher demand double leg (high score) versus the slide condition (low score). Principal pattern 3 explained 1% of the variance capturing the burst of activity at 60-70% time corresponding to the beginning of the hip and knee flexion phase at the end of the leg extension ([Figure 4G](#)). An example of differences in PP3 scores is depicted in [Figure 4E](#), showing a burst of activity at approximately 60% time at the end of the slide when the heels were lifted back off the table (high score), whereas no burst was present for the low score. Principal pattern 4 explained 1% of the variance in the waveforms, capturing an exaggerated burst of activity during the second leg lift (15% time) compared to the burst during the leg lowering (85% time) and the distinctive dip inactivity at 50% of the exercise time

corresponding to when the hip and knee were fully extended and the heel touched down lightly. [Figure 4F](#) illustrates the higher initial bursts and a noticeable dip in activity at 50% for the high score compared to the low score.

There were statistically significant group:level muscle interactions for PP1 ( $p = 0.005$ ) and PP2 ( $p = 0.011$ ) scores. The interaction plots for PP1 and PP2 scores are found in [Figures 5A and 5B](#), respectively. There were significant muscle ( $p = 0.000$ ) and level ( $p = 0.003$ ) main effects for PP3 scores and a significant group:muscle interaction ( $p = 0.012$ ) for PP4 scores. The main effects and interaction plots are found in [Figures 5C and 5D](#) for PP3 and PP4 scores, respectively. The significant post hoc differences are depicted in [Table 2](#) for PP1 and PP2 scores and in [Figure 5](#) for all 4 principal pattern scores.

Muscle	Level	PP1		PP2	
		S	US	S	US
LRA	4	1053.05 (5.78)†	1065.64 (8.55)†	8.03 (27.70)†	33.01 (40.91)†
URA	4	1039.70 (5.64)†	1069.52 (7.74)†	-33.39 (24.39)†	52.84 (36.70)†
EO1	4	999.40 (5.29)¶	1026.40 (8.29)	-140.76 (19.30)	-93.30 (30.64)
EO2	4	1018.35 (5.22)	1026.64 (7.45)	-113.95 (24.79)	-97.95 (27.86)
EO3	4	1010.35 (4.36)	1015.62 (7.93)	-136.71 (19.55)	-108.38 (32.22)
LRA	5	1124.56 (4.31)†	1129.05 (7.43)†	358.14 (18.58)†	362.63 (31.82)†
URA	5	1102.98 (5.59)†	1130.48 (6.69)†	271.57 (22.23)†	378.17 (26.28)†
EO1	5	1042.05 (5.70)‡	1076.60 (7.51)	50.97 (18.74)¶	143.90 (24.13)
EO2	5	1071.75 (4.97)	1068.52 (5.68)	140.17 (21.03)	113.03 (22.70)
EO3	5	1064.63 (4.85)	1042.52 (6.20)§	111.74 (15.64)	32.70 (21.08)§

\*Lower (LRA) and upper (URA) rectus abdominus, anterior (EO1), lateral (EO2) and posterior (EO3) external oblique.

†Significant differences between RAs and all EO sites ( $p < 0.005$ ).

‡Significant differences between EO1 and EO2 & EO3 ( $p < 0.005$ ).

§Significant differences between EO3 and EO1 & EO2 ( $p < 0.005$ ).

||Significant differences between LRA and URA ( $p < 0.005$ ).

¶Significant differences between EO1 and EO2 ( $p < 0.005$ ).

Table 2. Significant differences ( $p < 0.005$ ) among muscles\* within stability exercise levels for stable (S) and unstable (US) groups for PP1 and PP2 scores. Data presented as mean (SEM).

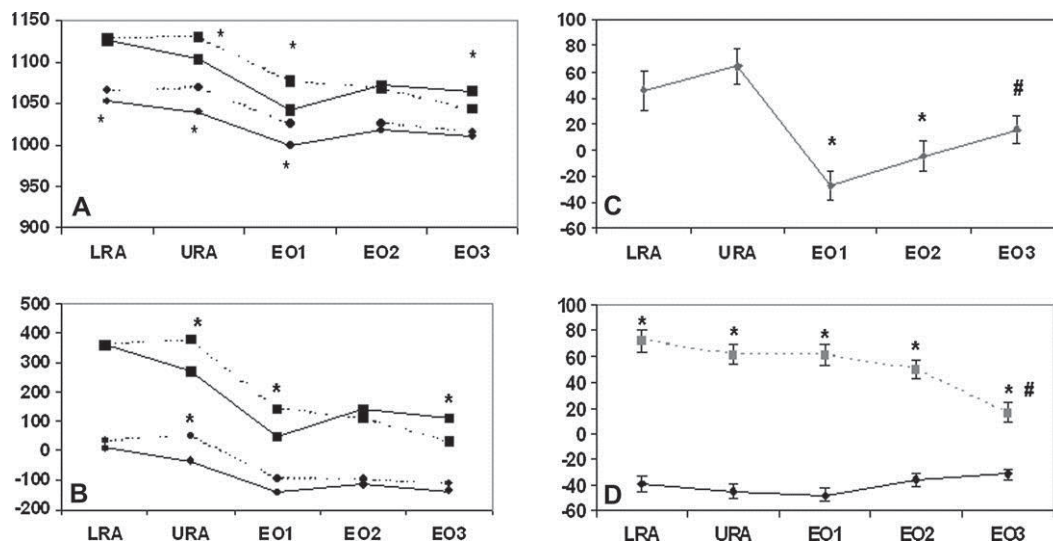


Figure 5. The interaction plots for the statistically significant results ( $p < 0.05$ ). a) PP1 scores, \*indicates significant between group differences ( $p < 0.005$ ), b) PP2 scores, \*indicates significant between group differences ( $p < 0.005$ ), c) PP3 scores, \*indicates lower (LRA) and upper (URA) rectus abdominus differ from anterior (EO1) and lateral (EO2) external oblique ( $p < 0.005$ ) and #indicates upper rectus abdominus (URA) differs from posterior external oblique (EO3), and d) PP4 scores, \*indicates significant between group differences ( $p < 0.005$ ) and #indicates that the posterior external obliques (EO3) for the unstable group was different from all other muscle sites. For a and b the squares are level 5 and circles level four, the solid line is for stable and dotted line for unstable. For d) the solid line is for the stable group and the dotted line for the unstable group. Error bars are standard errors.

With respect to the first objective, there was a high degree of similarity in temporal patterns among muscles, but the statistical results showed that not all muscles had identical temporal patterns to perform these tasks. The differences among muscles were dependent on group and muscle for PP1 and PP2 scores as shown in [Table 2](#). The differences in the general shape of the waveform from mean pattern were more evident in the external oblique sites with rectus abdominus sites having higher overall scores for PP1. The rectus abdominus sites had higher relative increases in amplitude during the leg extension phase than the external oblique sites for both groups and both exercise levels. The differences among the external oblique sites for the stable group showed that the anterior fibers of external oblique had the lowest score whereas the posterior fibers of external oblique were lowest for the unstable group. The difference among muscles for PP3 also showed higher scores for the rectus abdominus compared to the external oblique sites. The only muscle difference for PP4 was for the unstable group with the posterior fibers of external oblique lower than all other sites. This suggests that the posterior fibers of external oblique did not respond in a similar manner to the anterior or lateral fibers for the unstable group.

With respect to objective 2, the PP1 and PP2 scores were all higher for level 5 compared to level 4. In contrast, for PP3 level 5 was lower than level 4 scores. For objective 3, there were significant differences between groups for specific muscle sites for PP1 and PP2 ([Figure 5A and B](#)), and these reflect subtle differences in relative amplitudes. The key difference between the groups was for the PP4 scores ([Figure 5D](#)). Essentially the unstable group had significantly higher values for this pattern and a high score captured the distinctive increase burst at 15% time and the large dip at 50% time.

In summary, although there was a general pattern of activation in response to the dynamic challenge to stability for this exercise protocol, the subtle differences in the waveforms between the groups, between exercise levels, and among muscles were confirmed by the statistical analysis of the principal pattern scores.

## Discussion

The 2 groups were similar with respect to demographic characteristics, with the main difference between the groups being the ability of the stable group to perform the exercise levels without excessive lumbar and pelvic motion, whereas the unstable group could not. Although the criteria used to determine group allocation was based on visually observed criteria, which may be considered a limitation, there was agreement between the 2 observers. Presumably, if an error was made in group allocation, then the differences in EMG patterns would be more evident than those reported. The 4 principal patterns captured the key characteristics including

the overall general shape and mean pattern (principal pattern 1), relative changes in amplitude during the leg-extension phase (principal pattern 2), and the subtle features such as bursts or dips in activity throughout the duration of the exercise (principal patterns 3 and 4). These results provide insight into the synchrony and coactivation of abdominal muscle responses to changes in demand and the differences between those able to minimize lumbar-pelvic motion and those who could not.

The overall mean pattern (principal pattern 1) was similar among the abdominal wall muscle sites, indicative of an underlying synergy. There were distinctive responses to the change in load (leg lift and lower), in particular when neither foot was in contact with the table to provide stability. The rectus abdominus muscles for both groups responded to the leg-lifting and -lowering task with patterns that more closely represented the mean pattern than the external oblique sites did based on the statistical results for PP1 scores. Given the low variability in PP1 scores, however, very small differences were statistically significant and this can be seen by the very subtle differences between the waveforms for the high and low scores in [Figure 4A](#). The relative changes in amplitude during the leg extension (principal pattern 2) also were higher for the rectus abdominus sites than for the external oblique sites for both groups. Thus, the rectus abdominus muscle sites were more responsive to the leg-loading perturbations, whereas the external oblique sites maintained a more consistent relative level of activity.

For both groups, all muscle sites had smaller increases in muscle responses (PP2 scores) during the leg extension phase for level 4 compared to level 5. This was expected and indicates a greater increase in relative activity with the greater challenge to stability when the feet were not supported vs. the slide condition. The only other difference in the temporal patterns between the 2 levels of the exercise was related to the burst of activity (principal pattern 3) after the heel touch down for level 4 only. This was consistent for both groups, was associated with the 2 rectus abdominus sites, and indicates that the rectus abdominus responded with a burst of activity to overcome inertia and lift the heels off the table after the slide during level 4. Overall these findings provide evidence of the role of the abdominal musculature in response to the dynamic leg perturbations and the increase in relative activity with the higher demand challenge. This is consistent with the finding of increased amplitudes normalized to maximum voluntary contractions for healthy subjects performing level 5 compared to level 4 of this task ([4](#)).

The differences between groups for PP1, PP2, and PP4 scores shed light on the role of the abdominal muscles for those able to perform the exercise protocol correctly (stable) vs. those who could not (unstable). This higher relative increase in lower rectus abdominus activity compared to the upper rectus abdominus site for the stable group suggests that the rectus abdominus fibers that attach directly to the pelvis (lower fibers) were more responsive to the change in demand than those that did not (upper fibers). This was not found for the unstable group in which there was no difference in response between the 2 rectus abdominus sites; they both had higher relative increases. The 3 external oblique sites responded differently between the 2 groups and between the 2 levels. For the stable group the lateral and posterior fibers of the external oblique responded with larger increases in relative activity during the extension phase than the anterior fibers. In contrast, the unstable group had a smaller increase in relative activity in the posterior fibers compared to anterior and lateral fibers. From a kinesiological perspective, the role of the anterior fibers to maintain lumbar-pelvic motion is unclear because it does not attach directly to the pelvis or the lumbar spine-the 2 anatomical structures perturbed by the leg

loading. Therefore, the pattern utilized by the unstable group in which the anterior external oblique sites are more responsive to the perturbation perhaps is 1 explanation for their lack of ability to minimize lumbar-pelvic motion.

The differences in relative increases in amplitude during the leg extension-flexion phase (PP2 scores) between groups illustrated that the unstable group had to increase their relative amplitudes of upper rectus abdominus and anterior external oblique to a higher degree to perform the exercise compared to the response of the stable group. However, their posterior fibers of external oblique had a smaller relative response. This suggests a differential response of the oblique muscles between the 2 groups and may reflect an ineffective bracing mechanism and may also partially explain the inability of the unstable group to minimize lumbar-pelvic motion. Focusing on recruiting the entire abdominal wall including these posterior fibers may be a training strategy for those unable to perform the exercise correctly.

The most consistent difference between the 2 groups was related to the exaggerated burst during the second leg lift off and the dip at 50% of time (PP4 scores). This dip in the unstable group at 50% would translate to a decrease in force and explains why this group was unable to minimize lumbar and pelvic motion at the end of the leg extension phase. The exaggerated burst associated with the second leg lifted off from the exercise table is consistent with an inappropriate feed-forward response that was previously reported for those with low back pain performing level 1 of this exercise protocol (9). The higher score for PP4 for all 5 muscle sites suggests that the unstable group members were less able to preprogram the correct activation amplitude required to perform the task, whereas the stable group could. The unstable group overestimated the activity required to lift the second leg off the table and underestimated the activity required at fully extension to prevent lumbar-pelvic motion. To put these changes in relative amplitude into perspective, the dip at 50% time shown for the high score in [Figure 4F](#) is about 40% average EMG amplitude. If we use the mean amplitudes normalized to maximal voluntary activations presented in the literature for healthy adults of 40% maximum voluntary activation (4), this dip equates to a decrease in activation of approximately 16% of a maximum voluntary contraction amplitude. This is a substantial decrease; thus, these results have implications with respect to training. A focus could be on providing feedback to ensure that the muscle response is consistent with the magnitude of the perturbation and to emphasize the need to maintain the activation throughout and not allow the muscles to relax at heel touch down.

In conclusion, there was a general pattern of temporal coactivation among the abdominal muscle sites; however, subtle differences were found that were specific to the level of the exercise performed, the group assignment (stable vs. unstable), and the specific muscle sites. The principal patterns quantified the mean pattern (principal pattern 1) and the relative increase in amplitude during the leg extension phase (principal pattern 2) for level 5 versus level 4. The more prominent role of the rectus abdominus, in particular the lower rectus abdominus for the stable group, and less variability in amplitude of the responses to the changes in the demands of the task for the stable vs. the unstable group (principal pattern 4) appear to be the key differences between the 2 groups. The temporal patterns were different between those who were able to minimize lumbar-pelvic motion and those who could not. The differences in the muscle responses were dependent on the magnitude of the challenge. Although much has been written in the literature on the importance of muscle synergy and coordination in dynamic stability exercises, this is the first study to quantify differences in synergistic coactivity and coordination

of activity between groups based on performance criteria during a dynamic stabilizing exercise protocol.

### **Practical Applications**

The leg-loading task and variations of this task are used as dynamic stability exercises for training the abdominal muscles. Previous work illustrated that the actual amplitude as a percent of maximum was not high enough to elicit a strengthening response, so the question remains as to what is the benefit of these exercises. Perhaps increasing the number of repetitions could elicit an improvement in endurance. However, this paper set out to examine a different aspect related to these exercises because dynamic stability exercises are supposed to also improve the coordination of muscle activation in response to the changes in dynamic loading during the task. Few studies have examined coordination among muscles and how this relates to performance of an exercise. The present study demonstrated that there was a general pattern of activation that corresponded to the demands of the task for all of the abdominal wall muscles. This included the coordinated burst in activity when the second foot was lifted off of the floor, the gradual increase in activation as the hip and knee were extended and the decrease as they were brought back to the flexed position, and finally the smaller burst when the first foot was placed back on the table. The results showed that a degree of synchrony or coordination among abdominal muscles, differential relative recruitment of different muscle sites, and consistent activation during the leg extension phase were the neuromuscular patterns associated with performing the task with minimal lumbar-pelvic motion (i.e., controlling lumbar-pelvic motion). Deviations from these patterns were present in those who were unable to perform the exercise correctly. In particular, the exaggerated burst of activity as the second foot is lifted off of the table and the inability to maintain the level of activation as the legs are fully extended implies an inappropriate neuromuscular response to the dynamically changing demands of the task. In addition, the increased variability for the unstable group has implications with respect to the need to focus on coordinated recruitment among abdominal wall muscles. These results suggest that simply focusing on increasing intensity of the abdominal wall muscle activation when performing stabilization training is clearly not the goal and there is a need to focus on control through appropriate muscle activation. Thus, the results provide potential areas of focus for dynamic stability training using this leg-loading exercise protocol and other protocols that provide dynamic stability challenges to the spine.

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