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ORIGINAL ARTICLE

Effects of volitional spine stabilization on lifting task in recurrent low back pain population

Ram Haddas[1] · James Yang[2] · Isador Lieberman[3]

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Abstract
Purpose To examine the influence of volitional preemptive abdominal contraction (VPAC) and recurrent low back pain (rLBP) on trunk mechanics and neuromuscular control during a symmetric lifting task.
Methods A 2 × 2 crossover mixed design was used to examine the effects of VPAC and group. Thirty-seven healthy individuals and 32 rLBP individuals performed symmetric box lifting trials with and without VPAC to a 1-m height table 3D trunk, pelvis, and hip joint angle and electromyographic magnitude variables were obtained. Selected variables were analyzed using ANOVA.
Results The VPAC induced differences in joint kinematics and muscle activity in rLBP and healthy subjects during symmetric lifting. A significant two-way interaction effect was observed for the semitendinosus activity. The VPAC increased external oblique muscle activity, reduced erector spinae and multifidus muscles activity, and induced greater trunk flexion angle, greater trunk side flexion angle, and greater hip flexion angle, and decreased pelvis obliquity angle in both groups. In addition, the rLBP subjects presented with a reduced external oblique and gluteus maximus muscle activity, greater erector spinae and multifidus muscles activity, and greater pelvis posterior tilt angle.
Conclusions Our results provide evidence that a VPAC strategy performed during symmetric lifting may potentially reduce exposure to biomechanical factors that can contribute to lumbar spine injury. The hamstring muscles may play an important role in achieving pelvic balance during the lifting maneuver. Incorporating the VPAC during dynamic stressful activities appears to help improve sensorimotor control and facilitate positioning of the lower extremities and the pelvis, while protecting the lumbar spine.

Keywords Spine stability · Low back pain · Lifting · Spine biomechanics · Injury prevention

IRB approval: The study was approved by the Institutional Review Board for the Protection of Human Subjects at Texas Tech University (IRB#: 504051).

✉ Ram Haddas
rhaddas@texasback.com

[1] Texas Back Institute Research Foundation, 6020 West Parker Road, Plano, TX 75093, USA

[2] Mechanical Engineering, Texas Tech University, Lubbock, TX, USA

[3] Texas Back Institute, Plano, TX, USA

Introduction

Low back pain (LBP) is reported in 75–80 % of the population and can significantly influence an individual's quality of life [1]. LBP is the second leading cause for missed days at work, potentially leading to disability and major socioeconomic consequences [2]. LBP can result from mechanical irritations of selected anatomical structures, such as the intervertebral disc [3–5], the facet joints [6, 7], and the associated lumbar spine nerve roots [8]. While LBP can be gradually developed in response to various pathological conditions, such as degenerative arthritis [9, 10] or intervertebral disc disease [11, 12], it does commonly occur after abrupt or repetitive mechanical stressors, such as heavy lifting, a fall, or prolonged periods of sitting or standing [13]. The majority of individuals with LBP experience the condition on a recurrent basis, suggesting that once individuals experience an acute LBP episode, it is more likely that they will experience further episodes [14]. As a result of limitations in flexibility and range of motion, recurrent LBP (rLBP) can alter an individual's overall functional capacity and ultimately heighten the risk for additional lower extremity injury [15–18].

Lifting is a ubiquitous activity, where individuals are required to manually manage materials and loads throughout occupational tasks and activities of daily living. Such lifting behaviors are used in a repeated fashion during various occupational engagements, such as healthcare [21, 22], farm animal management [23], labor employment [24], and performing arts [25]. Individuals typically sustain a slouched posture during a lift sequence that is accentuated when returning to upright position with the load [26]. Such a lifting pattern appears to increase the compressive forces between the lumbar vertebrae [27]. Moreover, the shear forces on the lumbar intervertebral discs are increased when lifting from that slouched position. However, repeated lifting in a slouched posture appears to increase those shear forces during manually demanding activities, especially when the individual has a history of LBP [18, 23]. Such repeated loading places the individual at a higher risk for injuries to the lumbar spine and lower extremity.

Spine stabilization can be defined as a synergy between spine stiffness and spine sensorimotor control [28]. Spine instability results from buckling of the spine during any trunk compressive force [28, 29]. A volitional preemptive abdominal contraction (VPAC) is commonly used to improve lumbar spine stabilization and reduce pelvic motion in individuals with spine dysfunction [30]. A commonly used VPAC strategy is the abdominal bracing maneuver, which produces a global trunk muscle contraction [31]. The VPAC has been investigated during landing and lifting maneuvers, with conflicting results regarding lower extremity control and the ability to reduce injury risk [15, 17, 30] Abdominal muscle activation influences lower extremity motion control and potentially reduces the risk of injury [32]. Recruitment of the trunk muscles is necessary to control trunk momentum and increase intra-abdominal pressure, which can improve spine stabilization [33, 34].

The effect of spine stabilization on people with recurrent LBP is well documented [30, 33]. Recurrent LBP has been established in the literature as a significant predictor for lower extremity injury [17, 35]. However, there is the limited literature on whether spine stabilization strategies can increase spine stability, trunk control and decrease the risk of injury during lifting in subjects with rLBP. The purpose of this study was to examine the influence of VPAC and rLBP trunk mechanics, as well as neuromuscular control, during a 1-m box-lift task. Such findings will help elucidate the underlying mechanisms that contribute to the connection between spine stability, lifting response, and the risk for developing and sustaining rLBP.

Materials and methods

Experimental approach to the problem

A mixed two factor design was used to determine the effects of rLBP (rLBP versus healthy) and abdominal contraction condition (VPAC versus no VPAC) on biomechanical and neuromuscular control variables in symmetric lifting. The within-subjects factors were abdominal contraction condition, and the independent factor was subject group. The sample size needed in this study to approach 80 % statistical power was estimated from the data of the previously examined lifting literature [20, 30]. A large effect size index of $f = 0.40$ was estimated. With a desired power of 80 % ($1 - \beta = 0.80$) and desired $\alpha = 0.05$, this effect size index would require a minimum sample size of 26 per group [36].

Subjects

Thirty-seven healthy individuals (20 males and 17 females) and thirty-two rLBP individuals (16 males and 16 females) participated in the study (Table 1). All subjects were between the ages of 18 and 35 years. Volunteers were excluded if they had a history of knee pain, surgery to the knee or lumbar spine, active abdominal or gastrointestinal conditions, BMI above 30 or pregnancy, all documented by self-report. An additional inclusion criterion for the rLBP group was a history of rLBP that was intermittent, unilateral or bilateral symptoms, between T12 and the mid-thigh, including the following: (1) a severity sufficient to require medical or allied health intervention; and or (2) a severity sufficient to impair the subject's ability to perform their normal activities of daily living. Subjects who experienced these symptoms for one or more episode over the previous 18 months were recruited. At the time of testing, subjects were in a period of remission from their LBP symptoms [37]. All participants read and signed an informed consent form approved by Texas Tech University review board.

Data collection procedures

Subjects reported their scores based on a visual analog pain scale to indicate if they were experiencing any pain, along with a map defining the pain location (Table 1). The subjects were trained how to perform the VPAC, when they were instructed to place their first webspace of each hand over the respective iliac crest. Once placed, each subject was then requested to 'make their lower trunk wider' while

Table 1 Anthropometrics data

	Healthy		rLBP	
	Males ($N = 20$)	Females ($N = 17$)	Males ($N = 16$)	Females ($N = 15$)
Age (years)	19.6 ± 4.22	21.29 ± 4.22	22.31 ± 1.80	20.87 ± 2.53
Mass (kg)	77.25 ± 12.20	58.81 ± 7.21	84.27 ± 10.77	65.63 ± 9.75
Height (m)	1.77 ± 0.09	1.65 ± 0.05	1.81 ± 0.09	1.70 ± 0.05
Box mass (kg)	17.12 ± 3.89	9.20 ± 2.51	16.30 ± 4.54	9.82 ± 2.97
Same day pain[a]	0.13 ± 0.57	0.00 ± 0.00	0.83 ± 0.75	1.12 ± 1.03
Last week average pain[a]	0.12 ± 0.36	0.03 ± 0.11	2.62 ± 1.51	3.15 ± 1.52
Last week worst pain[a]	0.62 ± 1.61	0.01 ± 0.02	4.21 ± 1.71	5.42 ± 2.04

[a] Visual analog scale from least to worst (1–10)

continuing with diaphragmatic respiration [29]. The subjects were then instructed how to perform the protocol of symmetric lifting. Lifting technique was based on the discretion of the individual, and the subject's box weight was determined by their maximum psychophysically acceptable weight (Table 1) [18]. Participants performed nine box (0.65 m long, 0.35 m wide, and 0.15 m high) lifting trials with VPAC and nine trials without VPAC to a 1-m height table in forward directions (Fig. 1). The VPAC condition was presented in random order.

Fig. 1 Marker set

Electromyography (EMG) data from the right external oblique (EO), erector spinae (ES), and multifidus (Mf) at the fifth lumbar (L5) spinal level, semitendinosus (ST), and gluteus maximus (GM) [38] were recorded using preamplified surface electrodes (DelsysInc, Boston, MA) at 2000 Hz. The skin was cleaned with alcohol, shaved as necessary, and then lightly abraded to reduce impedance. Subjects then performed maximum voluntary contraction (MVC) tests for all muscles listed above. The MVC outcomes were used later to normalize subjects' muscle activity during the lifting maneuver. EMG data, kinematic data, and ground reaction force (GRF) data were recorded with each lifting trial.

Forty-seven reflective markers (0.9 cm diameter) were used to collect three-dimensional kinematics (VICON Nexus 1.7.1, Denver, CO) of the lower extremity and trunk at a sampling rate of 100 Hz (Fig. 1). Raw 3D coordinates were smoothed using a fourth-order no-phase-shift Butterworth low-pass digital filter with cutoff set to 6-Hz prior to exporting for further analysis. A static trial was then collected to note marker placement. GRFs were recorded at 2000 Hz using two parallel force plates positioned side-by-side (AMTI, Watertown, MA).

Data reduction

Dependent variables included 3D trunk, pelvic, and hip joint angle and EMG linear envelop magnitude for lower extremity and trunk muscles. Kinematics and linear envelop variables were analyzed at two time instances, i.e., at the initial position −0.05 s after lifting was initiated (Fig. 2) and again at the final position −0.05 s before the subject placed the box on the table (Figs. 1, 2). Those time instances were chosen, since the body is at a mechanical disadvantage for lifting at the initial position; the load is far from the body center of mass, which creates a substantial moment across the trunk at the final

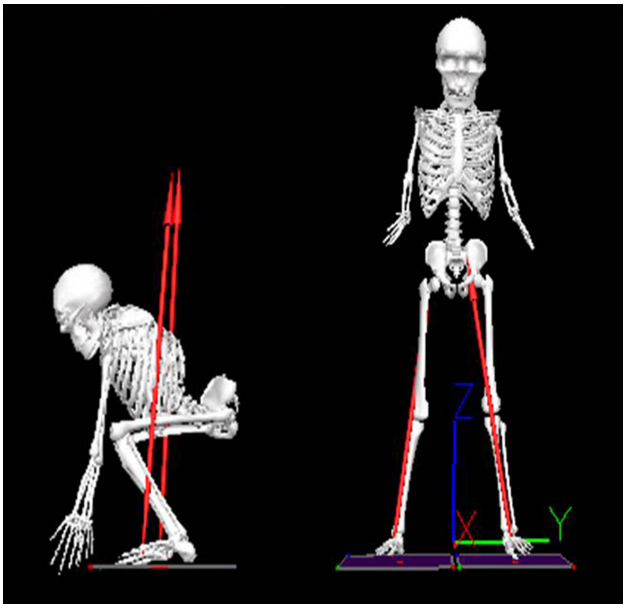

Fig. 2 Initial and final positions of a symmetric lifting. Initial position is 0.05 s after lifting was initiated; final position is 0.05 s before the subject placed the box on the table

position. All raw data were exported from the Vicon Nexus system and imported into a custom Matlab program (Mathworks Inc., v7.10.0, Natick, MA) and Visual3D for processing.

Statistical analyses

All dependent variables were assessed for distribution normality using the Shapiro–Wilk test. A 2 (group) × 2 (abdominal contraction) crossover mixed ANOVA design was used to determine differences abdominal contraction and group independent variables for each dependent variable. This study included two statistical families of dependent variables. The first group included muscle magnitude of EO, ES, Mf, GM, and ST at the initial and final positions. The second group included trunk, pelvic, and hip angle in the sagittal and frontal planes at the initial and final positions. A conservative alpha correction was made within each statistical family using Holm–Sidak correction for the multiple-dependent variables [39] to avoid type I error, resulting in an initial alpha level of 0.010 for the EMG variables and 0.008 for the kinematic variables, based on the number of dependent variables within each family. Follow-up tests were conducted as necessary, with alpha correction at each step. Effect size (η_p^2) and power were recorded as well for each dependent variable. In addition, one-way ANOVA was used to compare between group anthropometric and pain data. Statistical analyses were conducted using SPSS, Version 21.0 (IBM, Inc., Chicago, IL).

Results

In all subjects, the performance of the VPAC altered joint kinematic and muscle activity during symmetric lifting. All dependent variables were assessed for distribution normality using the Shapiro–Wilk test (p value range: 0.05–0.78 and W statistic range 0.71–0.98 for healthy subjects, and p value range 0.02–0.86 and W statistic range 0.78–0.98 for LBP subjects). Mean comparison for the anthropometric data was not significant between the groups ($p > 0.05$). Mean comparison for the pain data was significant between the groups ($p < 0.05$, Table 1).

Semitendinosus activity in the final position exhibited a significant two-way interaction effect in a symmetric lifting ($p = 0.010$ $\eta_p^2 = 0.124$, power $= 0.857$). Both rLBP and healthy subjects exhibited decrease in ST activity with the VPAC compare with the no-VPAC condition in the final position when rLBP subjects exhibited more substantial declines (Fig. 3). This finding verifies the importance of the hamstring muscle in stabilizing the pelvis during a lifting task. No other dependent variables exhibited a significant two-way interaction effect.

Several significant main effects for group and gender were observed during the 1-m lifting maneuver (Figs. 4, 5; Tables 2, 3).

The rLBP subjects presented reduced EO ($p = 0.003$ $\eta_p^2 = 0.115$, power $= 0.894$), GM ($p = 0.009$ $\eta_p^2 = 0.089$, power $= 0.812$), and greater Mf ($p = 0.004$ $\eta_p^2 = 0.119$, power $= 0.832$) muscle activity at initial position, reduced EO ($p = 0.005$ $\eta_p^2 = 0.102$, power $= 0.937$), greater ES ($p = 0.006$ $\eta_p^2 = 0.119$, power $= 0.848$) muscle activity and greater anterior posterior tilt angle ($p = 0.006$ $\eta_p^2 = 0.031$, power $= 0.832$) at the final position.

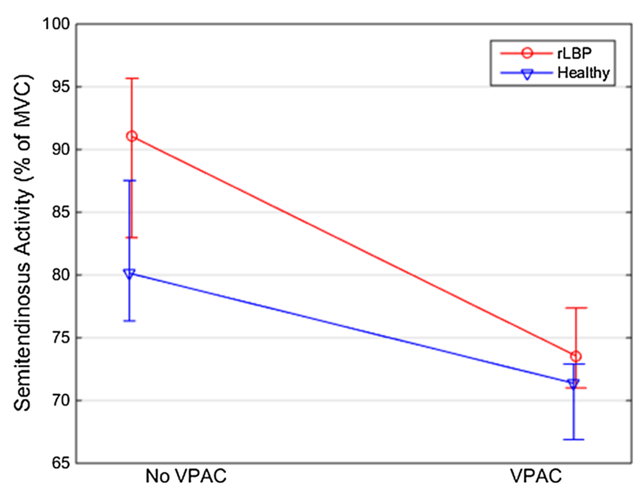

Fig. 3 Significant two-way interaction effect between VPAC and group for Semitendinosus muscle activity at final position in symmetric lifting. *MVC* maximum voluntary contraction

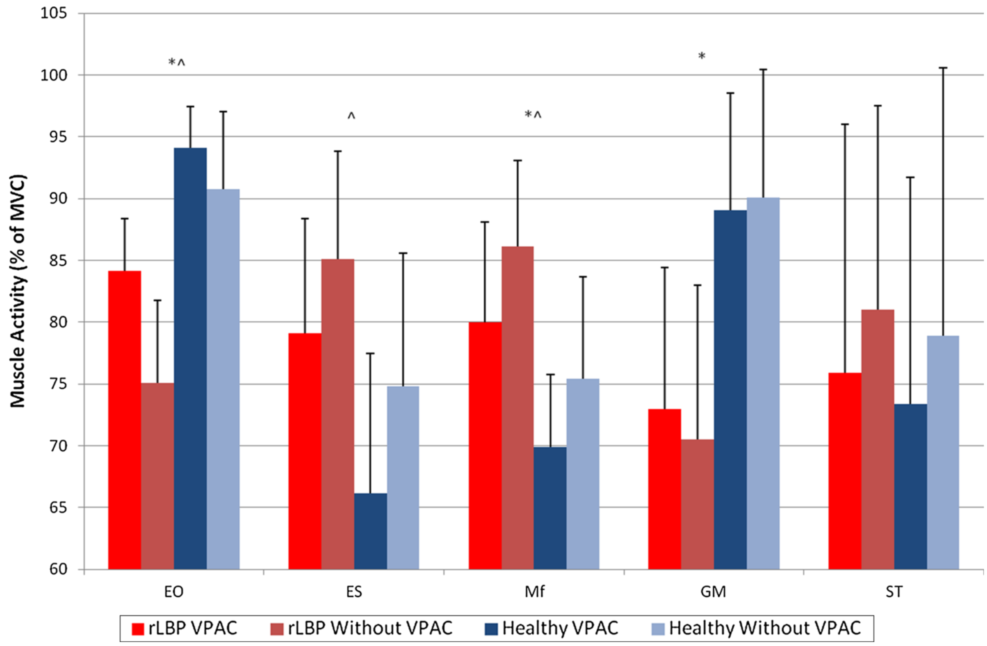

Fig. 4 EMG variables during initial position in symmetric 1-m lifting. *MVC* maximum voluntary contraction. *Plus* two-way interaction. *Cap symbol* VPAC main effect. *Asterisk* Group main effect

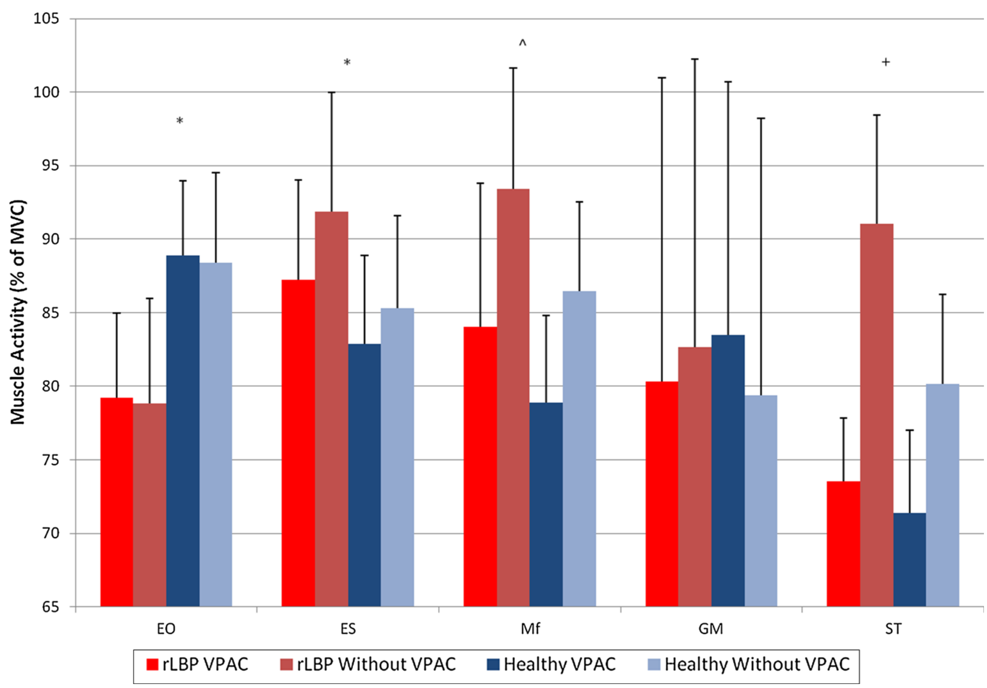

Fig. 5 EMG variables during final position in symmetric 1-m lifting. *MVC* maximum voluntary contraction. *Plus* Two-way interaction. *Cap symbol* VPAC main effect. *Asterisk* Group main effect

Several significant VPAC main effects were observed in all subjects during the 1-m lift, and included a VPAC induced increase in EO ($p = 0.001$ $\eta_p^2 = 0.138$, power $= 0.912$) muscle activity, reduced ES ($p = 0.005$ $\eta_p^2 = 0.119$, power $= 0.832$), Mf ($p = 0.006$ $\eta_p^2 = 0.099$, power $= 0.889$) muscle activity at the initial position, and reduced Mf ($p = 0.003$ $\eta_p^2 = 0.107$, power $= 0.912$) muscle activity at the final position. Furthermore, the VPAC induced a greater trunk flexion angle ($p = 0.006$ $\eta_p^2 = 0.114$, power $= 0.902$), greater trunk side flexion angle ($p = 0.008$ $\eta_p^2 = 0.117$, power $= 0.825$), and a decrease pelvis obliquity angle ($p = 0.008$ $\eta_p^2 = 0.089$, power $= 0.883$), at the final position, along with a greater hip flexion angle at the initial position ($p = 0.003$ $\eta_p^2 = 0.128$, power $= 0.861$).

Table 2 Kinematic variables during initial position in symmetric 1-m lifting

Variable	rLBP				Healthy			
	VPAC		Without VPAC		VPAC		Without VPAC	
	Average ± SD	95 % CI	Average ± SD	95 % CI	Average ± SD	95 % CI	Average ± SD	95 % CI
Trunk flexion (°)	32.59 ± 11.20	28.41 to 36.77	31.29 ± 12.47	26.63 to 35.95	34.80 ± 13.65	30.25 to 39.35	35.01 ± 12.68	30.78 to 39.24
Trunk side flexion (°)	−1.00 ± 5.85	−3.18 to 1.18	−1.08 ± 5.97	−3.31 to 1.15	−1.42 ± 3.80	−2.69 to (−0.67)	−1.93 ± 4.18	−3.32 to (−0.53)
Pelvis anterior tilt (°)	−24.22 ± 11.50	−28.51 to (−19.92)	−25.15 ± 12.01	−29.63 to (−20.66)	−25.61 ± 11.41	−29.42 to (−21.80)	−26.60 ± 12.18	−30.66 to (−22.54)
Pelvis Obliquity (°)	1.39 ± 4.61	−0.32 to 3.12	1.34 ± 4.32	−0.26 to 2.96	1.21 ± 3.97	−0.10 to 2.54	1.91 ± 3.63	0.70 to 3.13
Hip flexion (°)[a]	56.06 ± 10.37	52.19 to 59.94	53.88 ± 9.78	50.23 to 57.53	56.82 ± 11.06	53.13 to 60.51	55.82 ± 9.95	52.50 to 59.14
Hip abduction (°)	35.25 ± 19.87	27.83 to 42.68	35.01 ± 23.59	26.20 to 43.83	35.49 ± 20.86	28.53 to 42.45	42.68 ± 17.11	36.98 to 48.39

Positive: flexion/anterior tilt, abduction/right tilt/right flexion

[a] Group main effect

Discussion

Individuals with rLBP exhibit differences in trunk neuromuscular control and spine kinematic during 1-m symmetric lifting. Recurrent LBP subjects have diminished trunk [40] and lower extremity strength, flexibility, and range of motion [18, 41], as well as altered lower extremity biomechanics and neuromuscular control [17, 18, 42]. Our results showed reduced activities in the EO and GM in people with rLBP in both the initial and final positions. Moreover, the rLBP subjects displayed increases in the ES and Mf muscles' activities in comparison with the healthy group in both the initial and final positions. These results are consistent with those of Laird and his group [40] which also revealed lack of lumbar spine range of motion and proprioception, and that rLBP individuals move more slowly compared with people without LBP as a result of increase lumbar muscles due to the high load demand. Pelvic posterior tilt was found to be higher at the final position in people with rLBP, which can explain the increase in ST activity in this group.

It was shown that the VPAC altered trunk neuromuscular control and kinematic during 1-m symmetric lifting. In addition, it was shown that abdominal muscle activation was correlated with the ST activity [17, 40]. Because pelvic stability is influenced by the activity of trunk muscles through their attachments to the pelvis, an inability to properly activate these muscles may create an unstable pelvic base and contribute to altered lower extremity neuromuscular control, especially inefficient ST activity. As reported by Haddas et al., trunk muscle function is altered in the LBP sufferers [17, 18, 43]. As a result, these individuals may not be able to produce sufficient pelvic stability to provide a stable base for lower extremity motion and control. LBP subjects have diminished lower extremity strength, flexibility, and range of motion [41], as well as altered lower extremity biomechanics and neuromuscular control [17, 42]. Based on our results, the VPAC showed a larger effect on the ST muscle activity in people with rLBP. Previous studies have shown that activation of the trunk musculature does affect lower extremity mechanics. For example, activation of the transversus abdominis significantly decreases activity of the lumbar erector spinae muscles, increases gluteus maximus and medial hamstring muscle activity, and decreases anterior pelvic tilt during prone active hip extension [17, 44]. People with rLBP are known to have weaker abdominal muscles and delay in their muscle recruitment. Our results show that subjects with rLBP and without the use of the VPAC present higher ST activity in the final position. The hamstring muscles may play an important role in achieving pelvic balance during the lifting maneuver. This confirms

Table 3 Kinematic variables during final position in symmetric 1-m lifting

Variable	rLBP				Healthy			
	VPAC		Without VPAC		VPAC		Without VPAC	
	Average ± SD	95 % CI	Average ± SD	95 % CI	Average ± SD	95 % CI	Average ± SD	95 % CI
Trunk flexion (°)[b]	1.87 ± 7.83	−2.79 to 3.05	0.32 ± 7.58	−2.50 to 3.16	2.24 ± 10.73	−1.33 to 5.82	−0.22 ± 10.44	−3.70 to 3.25
Trunk side flexion (°)[b]	−0.29 ± 2.93	−1.39 to 0.80	−0.60 ± 3.11	−1.76 to 0.56	0.30 ± 2.76	−0.61 to 1.22	−0.26 ± 3.02	−1.27 to 0.74
Pelvis anterior tilt (°)[a]	−9.41 ± 5.91	−11.62 to (−7.21)	−11.50 ± 5.23	−13.45 to (−9.54)	−7.78 ± 5.14	−9.50 to (−6.07)	−9.19 ± 5.35	−10.98 to (−7.41)
Pelvis Obliquity (°)[b]	0.19 ± 1.98	−0.34 to 1.13	0.43 ± 1.82	−0.24 to 1.11	−0.53 ± 2.16	−1.26 to 0.18	−0.29 ± 2.23	−1.13 to 0.35
Hip flexion (°)	10.43 ± 7.42	7.66 to 13.20	11.73 ± 6.98	9.12 to 14.33	8.28 ± 6.11	6.24 to 10.32	8.74 ± 6.30	6.64 to 10.84
Hip abduction (°)	4.39 ± 4.65	2.65 to 6.13	3.47 ± 4.67	1.72 to 5.21	5.03 ± 4.85	3.41 to 6.65	5.15 ± 4.65	3.60 to 6.71

Positive: flexion/anterior tilt, abduction/right tilt/right flexion

[a] Group main effect

[b] VPAC main effect

the presumption that rLBP individuals use a different kinematic lifting strategy.

As supported by ultrasound study, Nagar et al. [30] also found increases in abdominal muscle activity during lifting. Our results agree with Nagar's by virtue of the increased EO activity with the use of VPAC, which actively increase spine stability. A VPAC strategy using an abdominal bracing maneuver produces a global trunk muscle contraction, which includes the external and internal oblique muscles [31]. Oh et al. [44] found that activation of the abdominal muscles significantly decreases activity of the lumbar erector spinae muscles. Again, our results support this finding, VPAC reduced ES and Mf activity, which may potentially promote for a reduction in the trunk flexion moment. Although muscle co-contraction may lead to an inefficient movement pattern in the lower extremity [45, 46], spine co-contraction may increase spine stability [15, 28, 30]. Therefore, reduced lumbar spine extensor muscle activity could implement a more efficient lift. Increasing spine stability and alignment using VPAC may reduce trunk flexion load and reduce the need of the lumbar extensor muscles activity.

The VPAC causes a greater trunk flexion angle in the final position, which can be explained by the increased activity of the abdominal muscles. Furthermore, the VPAC results in a stable pelvis with less pelvic obliquity motion, which is supported by previous studies. Increase in pelvis stability is highly correlated with increased spine stability [17, 44].

Although subjects in this study were trained on lifting techniques, they were not assisted or guided in any way, and the subject's box weight was determined by their maximum psychophysically acceptable weight. We limited our subject to lifting to a 1 m height, with the aim to control for external validity. Our analysis focuses only on the subject's right side, thus assuming symmetry between sides. Disc pressure was not measure during this investigation. In addition, we acknowledge the limitations associated with the use of skin markers that may move during the lifting trials, as well as a potential system tracking error and data smoothing procedure error.

These results justify the recommendation to use a VPAC to increase spine stability during a bear loading task. Our results provide evidence that a VPAC strategy that is performed during symmetric lifting decreases exposure to biomechanical factors that can contribute to the lumbar spine injury. This apparent protective response is present in both healthy and LBP individuals when lifting to a 1 m height. Incorporating the VPAC during dynamic stressful activities appears to help improve sensorimotor control and facilitate positioning of the lower extremity, while protecting the lumbar spine. Neural pattern training has been used synonymously with motor learning, which is a form of procedural muscle memory that involves consolidating a specific motor task into memory through repetition. When a movement is repeated over time, a long-term muscle memory is created for that task, eventually allowing it to be performed without conscious effort. Therefore, strengthening the core muscle activation along with the use of abdominal bracing maneuver is recommended during dynamic stressful liftings. Clinicians can use this information when designing neuromuscular control training programs for people who have rLBP to improve lower extremity and spine control and spine stability, thus potentially decreasing injury risk.

Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict of interest

References

1. Martin BI, Turner JA, Mirza SK (2009) Trends in health care expenditures, utilization, and health status among US adults with spine problems. Spine 34(19):2077–2084
2. Hayden JA, Cartwright JL, Riley RD, Vantulder MW, Chronic Low Back Pain IPDM-AG (2012) Exercise therapy for chronic low back pain: protocol for an individual participant data meta-analysis. Syst Rev 1(64):64. doi:10.1186/2046-4053-1-64
3. Manchikanti L, Helm S, Singh V, Benyamin RM, Datta S, Hayek SM, Fellows B, Boswell MV, Asipp (2009) An algorithmic approach for clinical management of chronic spinal pain. Pain Phys 12(4):E225–E264
4. Manchikanti L, Glaser SE, Wolfer L, Derby R, Cohen SP (2009) Systematic review of lumbar discography as a diagnostic test for chronic low back pain. Pain Phys 12(3):541–559
5. Wolfer LR, Derby R, Lee JE, Lee SH (2008) Systematic review of lumbar provocation discography in asymptomatic subjects with a meta-analysis of false-positive rates. Pain Phys 11(4):513–538
6. Datta S, Lee M, Falco FJ, Bryce DA, Hayek SM (2009) Systematic assessment of diagnostic accuracy and therapeutic utility of lumbar facet joint interventions. Pain Phys 12(2):437–460
7. Manchukonda R, Manchikanti KN, Cash KA, Pampati V, Manchikanti L (2007) Facet joint pain in chronic spinal pain: an evaluation of prevalence and false-positive rate of diagnostic blocks. J Spinal Disord Tech 20(7):539–545. doi:10.1097/BSD.0b013e3180577812
8. Konnai Y, Honda T, Sekiguchi Y, Kikuchi S, Sugiura Y (2000) Sensory innervation of the lumbar dura mater passing through the sympathetic trunk in rats. Spine 25(7):776–782
9. Igarashi A, Kikuchi S, Konno S, Olmarker K (2004) Inflammatory cytokines released from the facet joint tissue in degenerative lumbar spinal disorders. Spine (Phila Pa 1976) 29(19): 2091–2095
10. Goode AP, Carey TS, Jordan JM (2013) Low back pain and lumbar spine osteoarthritis: how are they related?. Curr Rheumatol Rep 15(2):305. doi:10.1007/s11926-012-0305-z
11. Gawri R, Rosenzweig DH, Krock E, Ouellet JA, Stone LS, Quinn TM, Haglund L (2014) High mechanical strain of primary intervertebral disc cells promotes secretion of inflammatory factors associated with disc degeneration and pain. Arthritis Res Ther 16(1):R21. doi:10.1186/ar4449
12. Saleem S, Aslam HM, Rehmani MA, Raees A, Alvi AA, Ashraf J (2013) Lumbar disc degenerative disease: disc degeneration symptoms and magnetic resonance image findings. Asian Spine J 7(4):322–334. doi:10.4184/asj.2013.7.4.322
13. Gallagher S, Marras WS (2012) Tolerance of the lumbar spine to shear: a review and recommended exposure limits. Clin Biomech (Bristol, Avon) 27(10):973–978. doi:10.1016/j.clinbiomech.2012.08.009
14. Stanton TR, Latimer J, Maher CG, Hancock MJ (2010) How do we define the condition 'recurrent low back pain'? A systematic review. Euro Spine J 19(4):533–539. doi:10.1007/s00586-009-1214-3
15. Haddas R, Sawyer SF, Sizer PS Jr, Brooks T, Chyu MC, James CR (2016) Effects of volitional spine stabilization and lower extremity fatigue on trunk control during landing in individuals with recurrent low back pain. J Orthop Sports Phys Ther 46(2):71–78. doi:10.2519/jospt.2016.6048
16. Haddas R, Hooper LT, James CR, Sizer PS (2016) Effects of volitional preemptive abdominal contraction on trunk and lower extremity biomechanics and neuromuscular control during a drop vertical jump. J Athl Train **(in press)**
17. Haddas R, James CR, Hooper TL (2015) Lower extremity fatigue, sex, and landing performance in a population with recurrent low back pain. J Athl Train 50(4):378–384. doi:10.4085/1062-6050-49.3.61
18. Haddas R, Yang J (2015) Sizer P (2015) Effects of gender and recurrent low back pain on lifting style. Central Eur J Sport Sci Med 11(3):15–28
19. Ulrey BL, Fathallah FA (2013) Effect of a personal weight transfer device on muscle activities and joint flexions in the stooped posture. J Electromyogr Kinesiol 23(1):195–205. doi:10.1016/j.jelekin.2012.08.014
20. Gallagher S, Pollard J, Porter WL (2011) Electromyography of the thigh muscles during lifting tasks in kneeling and squatting postures. Ergonomics 54(1):91–102. doi:10.1080/00140139.2010.535025
21. Karahan A, Kav S, Abbasoglu A, Dogan N (2009) Low back pain: prevalence and associated risk factors among hospital staff. J Adv Nurs 65(3):516–524
22. Theilmeier A, Jordan C, Luttmann A, Jager M (2010) Measurement of action forces and posture to determine the lumbar load of healthcare workers during care activities with patient transfers. Ann Occup Hyg 54(8):923–933. doi:10.1093/annhyg/meq063
23. Pal P, Milosavljevic S, Gregory DE, Carman AB, Callaghan JP (2010) The influence of skill and low back pain on trunk postures and low back loads of shearers. Ergonomics 53(1):65–67
24. Ropponen A, Silventoinen K, Svedberg P (2012) Effects of work and lifestyle on risk for future disability pension due to low back diagnoses: a 30-year prospective study of Finnish twins. J Occup Environ Med 54(11):1330–1336
25. Alderson J, Hopper L, Elliott B, Ackland T (2009) Risk factors for lower back injury in male dancers performing ballet lifts. J Dance Med Sci 13(3):83–89
26. Maduri A, Pearson BL, Wilson SE (2008) Lumbar-pelvic range and coordination during lifting tasks. J Electromyogr Kinesiol 18(5):807–814. doi:10.1016/j.jelekin.2007.02.012
27. Arjmand N, Gagnon D, Plamondon A, Shirazi-Adl A, Lariviere C (2009) Comparison of trunk muscle forces and spinal loads estimated by two biomechanical models. Clin Biomech 24(7):533–541. doi:10.1016/j.clinbiomech.2009.05.008
28. Panjabi MM (2003) Clinical spinal instability and low back pain. J Electromyogr Kinesiol 13(4):371–379
29. Richardson C, Hodges P, Hides J (2004) Therapeutic exercise for lumbopelvic stabilization: a motor control approach for the treatment and prevention of low back pain. Churchill Livingstone, London
30. Nagar VR, Hooper TL, Dedrick GS, Brismee JM, Sizer PS Jr (2014) Effect of recurrent low back pain history on volitional pre-

emptive abdominal activation during a loaded functional reach activity. SpineSpine (Phila Pa 1976) 39(2):E89–E96. doi:10.1097/BRS.0000000000000091
31. Mcgill S (2010) Core training: evidence translating to better performance and injury prevention. Strength Cond J 32:33–46
32. Haddas R, Sawyer S, Sizer P, Brooks T, Chyu M, James CR (2016) Effects of volitional spine stabilization and lower extremity fatigue on trunk control during landing in individuals with recurrent low back pain. J Orthop Sports Phys Ther 46(2):71–78
33. Iida Y, Kanehisa H, Inaba Y, Nakazawa K (2011) Activity modulations of trunk and lower limb muscles during impact-absorbing landing. J Electromyogr Kinesiol 21(4):602–609. doi:10.1016/j.jelekin.2011.04.001
34. Hall L, Tsao H, MacDonald D, Coppieters M, Hodges PW (2009) Immediate effects of co-contraction training on motor control of the trunk muscles in people with recurrent low back pain. J Electromyogr Kinesiol 19(5):763–773. doi:10.1016/j.jelekin.2007.09.008
35. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J (2007) Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. Am J Sports Med 35(7):1123–1130. doi:10.1177/0363546507301585
36. Portney LG, Watkins MP (2009) Foundation of clinical research: applications to practice. Julie Levin Alexander, New Jersy
37. MacDonald D, Moseley GL, Hodges PW (2010) People with recurrent low back pain respond differently to trunk loading despite remission from symptoms. Spine (Phila Pa 1976) 35(7):818–824. doi:10.1097/BRS.0b013e3181bc98f1
38. Barbero M, Merletti R, Rainoldi A (2012) Atlas of muscle innervation zones. Springer, Milan
39. Glantz SA (2011) Primer of biostatistics. McGraw-Hill, New York
40. Laird RA, Gilbert J, Kent P, Keating JL (2014) Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. BMC Musculoskelet Disord 15:229. doi:10.1186/1471-2474-15-229
41. Van-Dillen LR, Bloom NJ, Gombatto SP, Susco TM (2008) Hip rotation range of motion in people with and without low back pain who participate in rotation-related sports. Phys Ther Sport 9(2):72–81
42. Shum GL, Crosbie J, Lee RY (2005) Effect of low back pain on the kinematics and joint coordination of the lumbar spine and hip during sit-to-stand and stand-to-sit. Spine (Phila Pa 1976) 30(17):1998–2004
43. Hammill RR, Beazell JR, Hart JM (2008) Neuromuscular consequences of low back pain and core dysfunction. Clin Sports Med 27(3):449–462. doi:10.1016/j.csm.2008.02.005
44. Oh JS, Cynn HS, Won JH, Kwon OY, Yi CH (2007) Effects of performing an abdominal drawing-in maneuver during prone hip extension exercises on hip and back extensor muscle activity and amount of anterior pelvic tilt. J Orthop Sports Phys Ther 37(6):320–324
45. Wang R, Gutierrez-Farewik EM (2014) Compensatory strategies during walking in response to excessive muscle co-contraction at the ankle joint. Gait Posture 39(3):926–932. doi:10.1016/j.gaitpost.2013.12.002
46. Miura A, Kudo K, Ohtsuki T, Kanehisa H, Nakazawa K (2013) Relationship between muscle cocontraction and proficiency in whole-body sensorimotor synchronization: a comparison study of street dancers and nondancers. Mot Control 17(1):18–33