Journal of Electromyography and Kinesiology 50 (2020) 102378

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

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

Trunk and hip muscle activity during the Balance-Dexterity task in persons with and without recurrent low back pain

K. Michael Rowley[a,*], Tilman Engel[b], Kornelia Kulig[a]

[a] Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA, USA
[b] University of Potsdam, Department of Sports and Health Sciences, University Outpatient Clinic, Potsdam, Germany

ARTICLE INFO

Keywords:
Balance
Low back pain
Trunk and hip coordination
Lumbopelvic

ABSTRACT

Coordination of the trunk and hips is crucial for successful dynamic balance in many activities of daily living. Persons with recurrent low back pain (rLBP), both while symptomatic and during periods of symptom remission, exhibit dysfunctional muscle activation patterns and coordination of these joints. In a novel dynamic balance task where persons in remission from rLBP exhibit dissociated trunk motion, it is unknown how trunk and hip musculature are coordinated. Activation of hip and trunk muscles were acquired from nineteen persons with and without rLBP during the Balance-Dexterity Task, which involves balancing on one limb while compressing an unstable spring with the other. There were no between-group differences in activation amplitude for any muscle groups tested. In back-healthy control participants, hip and trunk muscle activation amplitudes increased proportionally in response to the added instability of the spring ($R = 0.837$, $p < 0.001$). Increases in muscle activation amplitudes in the group in remission from rLBP were not proportional ($R = 0.113$, $p = 0.655$). Instead, hip muscle activation in this group was associated with task performance, i.e. dexterous control of the spring ($R = 0.676$, $p = 0.002$). These findings highlight atypical coordination of hip and trunk musculature potentially related to task demands in persons with rLBP even during remission from pain.

1. Introduction

Motor control is fundamental to the human body, serving as the foundation for functional movement as well as for protecting it from overload/injuries (Winter et al., 1990; Hodges et al., 2013). Recurrent low back pain (rLBP) has been found to be associated with a variety of motor control impairments (Hodges and Richardson 1996; Radebold et al., 2000; Radebold et al., 2001; Reeves et al., 2005; Jones et al., 2012). In particular, altered motor control was revealed in this population during experimental situations requiring reactive responses to external loads (Radebold et al., 2000; Radebold et al., 2001; Reeves et al., 2005; Cholewicki et al., 2005; Henry et al., 2006). Persons with rLBP exhibited delayed muscular responses of trunk muscles following rapid shoulder movements or sudden load releases in standing position (Magnusson et al., 1996; Hodges and Richardson 1996). Furthermore, quick load releases in seated/semi-seated position demonstrated delayed reflex responses of agonistic muscles and changes in the pattern of co-contraction strategies in this group (Radebold et al., 2000). When investigating activation amplitude instead of timing, studies revealed contradictory results in regards to changes in trunk muscle activation levels both prior to and in response to sudden load perturbations (Stokes et al., 2006; MacDonald et al., 2010; Larivière et al., 2010).

Whereas most of the studies researching muscular activities in rLBP focused exclusively on muscles surrounding the abdomen and spine, others investigated muscles adjacent to the trunk such as the hip muscles (Borghuis et al., 2008; Nelson-Wong et al., 2008). Those are known to be important contributors to core function and stability, especially in tasks involving force transfer from the lower extremities, which often occurs in daily life activities (Kankaanpää et al., 1998; Nadler et al., 2001; Nelson-Wong et al., 2008). Increased activation of gluteus medius and gluteus maximus were found in those with back pain during static unipedal and bipedal stance situations (Penney et al., 2014; Ciesielska et al., 2015). A decrease in maximum activation amplitudes was found, however, subsequent to lateral perturbations in standing position (Nötzel et al., 2011). Also during prolonged standing, increased bilateral gluteus medius co-activation was found to be predictive of developing transient low back pain during the prolonged (70–120 min) standing task (Nelson-Wong et al., 2008; Bussey et al., 2016), whereas no difference was found for assessed trunk muscle activities (Nelson-Wong et al., 2008). While these investigations have provided useful information about hip motor control, they relied primarily on static, unperturbed postural tasks whereas most ecological

* Corresponding author.
E-mail address: kmichaelrowley@pt.usc.edu (K.M. Rowley).

https://doi.org/10.1016/j.jelekin.2019.102378
Received 16 July 2019; Received in revised form 15 November 2019; Accepted 18 November 2019

balance challenges are dynamic. In dynamic balance, postural control is not limited to the trunk or hip but rather embedded in a coordinated strategy across multiple axial and appendicular joints (Winter 1995). It is further suspected that in LBP these strategies are altered in a complex and task dependent manner, with complementary, additive, or competitive changes at different locations and levels of the motor system, both in the presence of real or perceived risks of pain or injury (Hodges and Tucker 2011).

Continuing to investigate motor control in a population of persons in remission from rLBP is worthwhile as dysfunctional trunk control has been linked to the recurrence of pain experimentally (Cholewicki et al., 2005) and conceptually (Hodges and Tucker 2011). The personal and societal impacts of these recurrent episodes of pain have long been recognized. LBP is ranked as one of the greatest contributors to global disability (Hoy et al., 2014), and LBP and neck pain accounted for $87.6 billion in US healthcare spending in 2013 (Dieleman et al., 2016). Of persons who had sought medical care and recovered from at least one episode of low back pain, rates of seeking care for another episode ranged between 22.1% at three months and 77.1% at three years follow-up with increasing disability and work-time loss for each recurrence (da Silva et al., 2017). Studying motor control in persons with rLBP during periods of symptom remission allows us to remove the effects of current pain and identify residual aspects of motor control dysfunction.

The Balance-Dexterity Task (Rowley et al., 2018) a combination of single-limb balance and aspects of the lower-extremity dexterity test, (Lyle et al., 2013) serves as a functional and useful task to observe aspects of submaximal, unstable trunk-in-space control (Rowley et al., 2019). Participants must balance on one limb while compressing an unstable spring with the other limb. Adding the challenge of dexterous force control to single-limb balance provides increased postural demands and evokes greater trunk motion, making observing trunk control strategies in the frontal plane more feasible than traditional single-limb stance (Lawrence et al., 2015; Rowley et al., 2018). Dysfunctional frontal plane trunk control has already been identified in persons in remission from rLBP where these participants exhibited more dissociated thorax and pelvis motion during perturbed balance than their matched back-healthy controls (Rowley et al., 2019). It is yet unknown how hip musculature responds to the added challenge of dexterous force control in coordination with trunk musculature during this task.

The purpose of this investigation was to examine the association between hip and trunk muscle activity during dynamically perturbed single-limb balance using the Balance-Dexterity Task in persons with and without rLBP. We expected back-healthy control participants to modulate hip and trunk muscle activity together in the Balance-Dexterity Task, i.e. if an individual increased trunk muscle activity in response to the unstable forces perturbing balance, they would also increase hip muscle activity. Given previous work showing persons in remission from rLBP exhibited more dissociated thorax and pelvis motion during the Balance-Dexterity Task, we hypothesized that hip and trunk muscle activity would be associated to a lesser degree among the participants in remission from rLBP compared to back-healthy control participants. Furthermore, we expected that persons in remission from rLBP would adapt to unstable forces preferentially using hip muscles, as an attempt to protect the trunk from perceived or actual pain and injury.

2. Methods

This study was approved by the local institutional review board and complies with international ethical guidelines including acquiring informed consent from all participants. Persons in symptom remission from rLBP (pain $< 1.5/10$ on a VAS at the time of testing and for the preceding seven days) were recruited for the study from student extracurricular groups, flyers, and physical therapy clinics. Participants must have recalled at least two episodes of pain in the low back per year for at least one year, but felt pain less than half of the preceding six months. Painful episodes must have been severe enough to limit function based on functional limitations participants recalled during a recent painful episode and reported in the Oswestry Disability Index (ODI) (Fairbank and Pynsent 2000). Exclusion criteria included age > 45 years; low back surgery; a radiological or clinical diagnosis of spinal stenosis, scoliosis, malignancy, infection, or radiculopathy; current or previous musculoskeletal injury or surgery affecting locomotion or balance; a history of diabetes mellitus, rheumatic joint disease, any blood-clotting disorder or current anti-coagulant therapy, or polyneuropathy; or current pregnancy. Back-healthy participants with no history of LBP in the past year were matched for sex, leg dominance, age within five years, body mass index category, and Baecke Activity Scale (Baecke et al., 1982) within two points. Participants completed the pain catastrophizing scale (Sullivan et al., 1995) and the Tampa scale for kinesiophobia (Vlaeyen et al., 1995) to characterize the groups and be able to assess the potential role of psycho-social differences between the groups on outcome measures. VAS measures of pain were acquired by asking participants to mark a 10 cm line with anchors at 0: “No pain” and 10: “Worst pain possible”.

Participants were instrumented with surface electromyography (EMG) of the external oblique (EO), rectus abdominis (RA), gluteus maximus (GMax), and gluteus medius (GMed) and fine-wire EMG of the internal oblique (IO), lumbar multifidus (MF), and erector spinae (ES) at the level of L4 (Noraxon Wireless EMG; Scottsdale, AZ; 3000 Hz). Surface EMG data were collected with bipolar silver/silver chloride electrodes with an interelectrode distance of 22 mm placed per guidelines from SENIAM, and fine-wire EMG data were collected with a pair of 50 μm nickel-chromium alloy wires insulated with nylon with distal 2 mm exposed and loaded into a 25-gauge hypodermic needle and sterilized. Insertions were done under ultrasound guidance and confirmed with electrical stimulation. Muscles were instrumented on the side contralateral to the participant’s preferred kicking limb. Hereafter, the instrumented side is referred to as the stance side. Force data were captured with two Advanced Medical Technology Inc. force plates (Watertown, MA; 3000 Hz).

Participants completed the Balance-Dexterity Task protocol (Rowley et al., 2018) (Fig. 1). After a familiarization trial, participants completed five practice trials lasting 30 s each where they balanced on their stance limb while compressing an unstable spring with the contralateral limb and viewing real-time feedback of the vertical force they produced under the spring. Participants were instructed to raise this force as high as they could while maintaining balance. Using the last three practice trials, the mean vertical force from the middle half of the 30 s trials was used to calculate an individualized goal compression force. Participants then completed five test trials where they were instructed to keep the vertical force as stable as possible at their individualized goal compression force for 30 s. Interspersed were three trials where the spring was replaced with a stable block with the same compression goal. Previous work has shown the Balance-Dexterity Task can be accomplished safely while participants compress the unstable spring with between 100 and 159 N of force, representing 13.8–23.0% of body weight, with no differences between persons with and without a history of rLBP (Rowley et al., 2019). This task has been shown to elicit different trunk coupling patterns between persons with and without rLBP while these groups exhibit similar task performance when quantified by variability of the dexterous force produced under the spring (Rowley et al., 2019).

The middle half of each 30 s trial was analyzed. Force plate data were low-pass filtered with a cutoff frequency of 50 Hz. Surface and fine-wire EMG data were band-pass filtered between 20 and 500 Hz and 20 and 1000 Hz, respectively, all using a dual-pass 4th order Butterworth filter. EMG data were then rectified and smoothed with a moving weighted average window of 500 ms. Signals were normalized to averaged signal amplitude during the stable block trials. This allowed EMG amplitude to be interpreted as a response to the added challenge

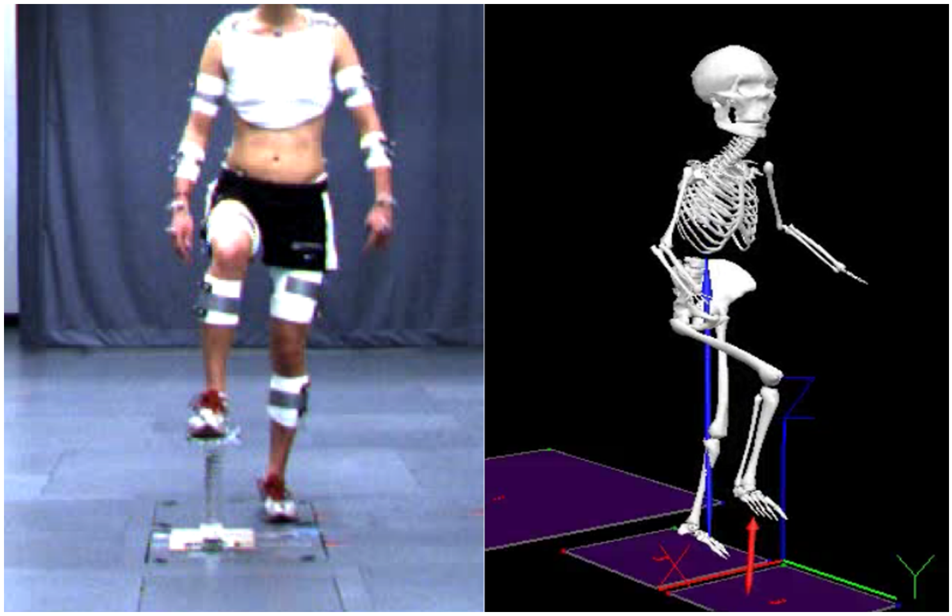


Fig. 1. The Balance-Dexterity Task. Participants stand on their non-dominant limb while trying to compress an unstable spring with their dominant limb. The stance foot and the spring are on separate force plates, and participants watch real-time feedback of the vertical force they produce under the spring (Rowley et al., 2018).

of controlling the unstable spring, not to the body position or vertical force production alone. This also avoided limitations of trying to elicit maximal contractions in a population with LBP, which are less reliable than submaximal reference contractions (Dankaerts et al., 2004).

Dexterous force control was measured using the vertical force produced under the spring and quantified as root-mean-squared error (RMSE) from the goal line. Mean muscle activation data were captured for each trial. Hip and trunk muscle group amplitudes were calculated by averaging GMax and GMed for the hip group and EO, IO, MF, and ES for the trunk group. This dynamic balance task induced multi-planar continuous perturbations to standing balance. For the hip, this included demands to maintain extension and abduction on the stance limb. Thus, activations of GMax and GMed were combined to represent overall utilization of the hip to maintain balance, and activations of abdominals and paraspinals were combined to represent trunk activation. Trials were screened for aberrant or large out-of-plane trunk motions during collection and post-hoc, and one such trial for one subject was removed. Results were reported as mean ± standard deviation for normally distributed data and as median [inter-quartile range] for data not normally distributed. Group differences were tested using paired t-tests. Associations between outcome measures were tested with bivariate Pearson correlations, or Spearman correlations in cases where normality or homoscedasticity were violated, with $\alpha = 0.05$ for all tests (PASW Statistics, IBM Corp., Armonk, NY).

3. Results

3.1. Participants

Nineteen back-healthy control participants and nineteen participants with rLBP participated in the study (Table 1). The participants suffering from rLBP were young (age 23.5 ± 2.8yrs), recalled being minimally disabled during their last painful episode (ODI 12.0% [6% – 16% inter-quartile range]), and in pain remission at the time of testing (0.4 ± 0.4 out of 10 on VAS). On average, participants reported 3.4 ± 1.2 episodes of pain per year and recalled their pain during these episodes as 4.9 ± 2.2 out of 10 on VAS. This population in remission from pain did not exhibit different demographic characteristics or levels of pain catastrophizing (Control: 6 [1–9]; rLBP: 5 [3–11]) or kinesiophobia (Control: 30.5 ± 6.0; rLBP: 31.3 ± 6.5) compared to the control group.

Table 1
Participant demographics (mean ± standard deviation for parametric data and median [IQR] for non-parametric data). rLBP = recurrent low back pain; CNTRL = back-healthy controls; BMI = body mass index; VAS = visual analog scale; ODI = Oswestry Disability Index; PCS = pain catastrophizing scale; TSK = Tampa scale for kinesiophobia.

Table 1	Demographics of Participants		
	rLBP	CNTRL	p
N	N = 19	N = 19	
Age (yrs)	23.5 ± 2.8	23.9 ± 3.3	0.679
Sex	7 M, 12F	7 M, 12F	
Leg Dominance	18 R, 1 L	18 R, 1 L	
Height (cm)	170.4 ± 8.4	169.1 ± 10.4	0.692
Weight (kg)	68.7 ± 10.3	67.1 ± 10.8	0.661
BMI	23.6 ± 2.4	23.3 ± 1.8	0.714
Baecke Physical Activity Scale (vector sum)	4.8 ± 1.0	4.9 ± 0.6	0.537
Episodes per year	3.4 ± 1.2		
Pain during episodes (recall, VAS 0–10)	4.9 ± 2.2		
Pain at time of testing (VAS 0–10)	0.4 ± 0.4		
ODI (recall, %)	12 [6–16]		
PCS (0–52)	5 [3–11]	6 [1–9]	0.770
TSK (17–68)	31.3 ± 6.5	30.5 ± 6.0	0.706

3.2. Trunk and hip muscle activity

There were no differences in average amplitude of trunk ($p = 0.616$) or hip ($p = 0.311$) muscle activation between groups (Fig. 2). Muscle activations were reported as a percent of activation during the stable block condition and thus represent additional muscle activation utilized in response to instability of the spring. In the back-healthy control group, mean trunk muscle amplitude was 163 ± 60%, and mean hip muscle amplitude was 168 ± 66%. In those with rLBP, mean trunk muscle amplitude was 174 ± 59%, and mean hip muscle amplitude was 151 ± 55%. Comparisons between groups in isolated hip muscle activation also revealed no differences between groups (GMax: $p = 0.242$; GMed: $p = 0.741$). Note that one participant with rLBP is missing trunk EMG data due to failed fine-wire EMG insertion of

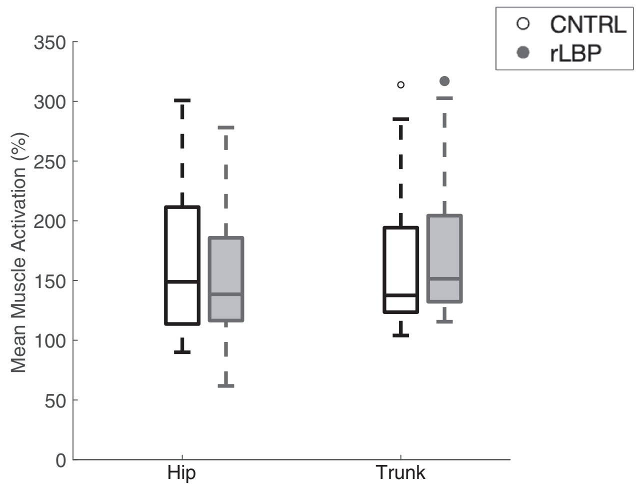


Fig. 2. Activation amplitudes of trunk and hip musculature during the Balance-Dexterity Task in persons with (filled) and without (open) recurrent low back pain (rLBP).

the MF and IO.

Trunk and hip muscle activation amplitudes were correlated in the back-healthy control group (mean hip activation: $R = 0.837$, $p < 0.001$; GMax: $R = 0.705$, $p = 0.001$; GMed: $R = 0.590$, $p = 0.008$) but were modulated independently of each other in the group in remission from rLBP (mean hip activation: $R = 0.113$, $p = 0.655$; GMax: $R = 0.294$, $p = 0.236$; GMed: $R = -0.067$, $p = 0.793$) (Fig. 3). This means back-healthy participants responded to the added instability from the spring by increasing hip and trunk muscle activation proportionally. Some persons in remission from rLBP responded by increasing both hip and trunk muscle activation, but others primarily increased activation of only one of these muscle groups. Interestingly, mean hip muscle activation amplitude and GMax activation amplitude were associated with dexterous force control in the group with rLBP using the RMSE outcome measure (mean hip activation: $R = 0.676$, $p = 0.002$; GMax: $R = 0.696$, $p = 0.001$), and GMed amplitude was marginally associated (GMed: $R = 0.418$, $p = 0.084$) (Fig. 4). Hip muscle activation was not associated with dexterous force control in the back-healthy control group (mean hip activation: $R = 0.362$, $p = 0.128$; GMax: $R = 0.255$, $p = 0.293$; GMed: $R = 0.296$, $p = 0.218$), and trunk muscle activation was not associated with dexterous force control in either group (Control: $R = 0.457$, $p = 0.050$; rLBP: $R = 0.252$, $p = 0.314$). These between-group differences were observed despite similar spring compression forces (Control: 121.2 ± 12.3 N; rLBP: 123.5 ± 15.4 N; $p = 0.593$) and variability of those compression forces (RMSE) (Control: 6.5 ± 2.5 N; rLBP: 7.0 ± 2.7 N; $p = 0.640$) (Rowley et al., 2019).

4. Discussion

Trunk and hip muscles responded to the added demand of dexterous force control in a coordinated way in the back-healthy control group, but not in those in remission from rLBP, supporting the hypothesis. It was also predicted that the rLBP group would preferentially utilize hip musculature to accomplish the task. While there were no differences in hip muscle activation amplitude between groups, hip muscle activation was associated with task performance in the rLBP, but not in the back-healthy control group.

The association between task performance – dexterous control of the unstable spring – and hip muscle activation amplitudes in the rLBP group supports the idea that this group preferentially uses hip activation to manage balance demands. During static balance tasks such as unipedal or bipedal standing, persons with LBP exhibit greater GMed activity compared to back-healthy persons (Penney et al., 2014; Ciesielska et al., 2015). Other studies found that greater bilateral GMed co-activation during prolonged standing was predictive of LBP (Nelson-Wong et al., 2008; Bussey et al., 2016). In response to a chair tilt perturbation, persons with rLBP had increased hip range of motion and reduced trunk range of motion compared to the control group, again suggesting a preference for using the hip to respond to the perturbation (Freddolini et al., 2014). These findings, however, were from samples of a population with current, symptomatic LBP. In the present study on individuals in remission from rLBP, there were no differences in gluteal muscle activation amplitudes, but the mean hip activation and GMax activation amplitudes were associated with task performance. It is possible this represents a meaningful extrapolation of previous findings to a minimally disabled population in remission from pain performing a dynamic balance task. The rLBP group is still preferentially modulating hip activation and task performance together, but for those in pain remission this may not result in overall greater muscle activity during a dynamic balance task.

Investigating trunk and hip coordination during the Balance-Dexterity Task – a submaximal, unstable "trunk-in-space" control task – also helps explain trunk control in persons with rLBP. Persons in remission from rLBP exhibit more dissociated trunk motion (lower trunk coupling) while performing the Balance-Dexterity Task without, however, any differences between groups in any muscle activation amplitude (Rowley et al., 2019). Back-healthy control participants here modulated trunk and hip musculature together in response to the unstable spring. Persons with rLBP modulated hip muscle activation in

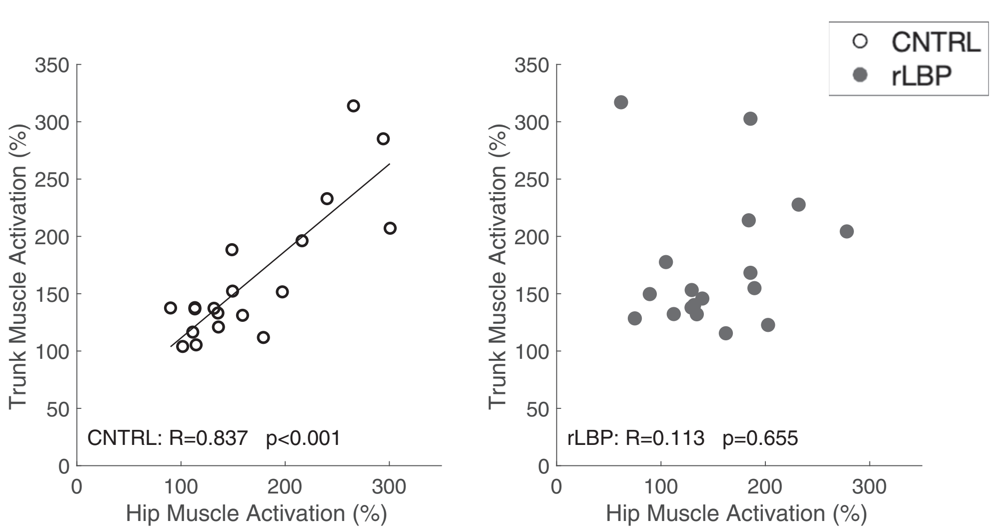


Fig. 3. Association between hip and trunk muscle activation during the Balance-Dexterity Task in persons with (right) and without (left) recurrent low back pain (rLBP). Activation amplitudes are expressed as a percent of activation amplitude during the stable block condition, allowing activation here to be interpreted as a response to the added instability of the spring. Lines of best fit are shown when Pearson Correlation $p < 0.05$.

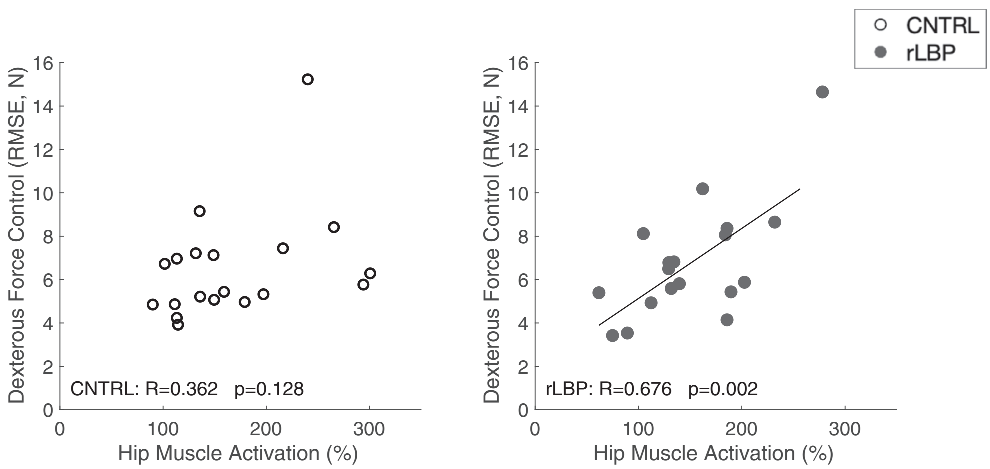


Fig. 4. Association between task performance and hip muscle activation during the Balance-Dexterity Task in persons with (right) and without (left) recurrent low back pain (rLBP). Task performance was quantified as the root-mean-squared-error (RMSE) of the vertical force produced under the spring. Activation amplitudes are expressed as a percent of activation amplitude during the stable block condition, allowing activation here to be interpreted as a response to the added instability of the spring. Lines of best fit are shown when Pearson Correlation $p < 0.05$.

association with dexterous control of the spring but independent of trunk muscle activation. Potentially, this group avoided increasing trunk muscle activation in a coordinated way. This could be to avoid increased spine loading that occurs when trunk muscle co-contraction and trunk stiffness is high in this population (Marras et al., 2001; 2004). This population also exhibits specific dysfunction at the trunk such as reduced trunk proprioception (Lee et al., 2010; Osthoff et al., 2015), paraspinal atrophy (Beneck and Kulig 2012), and increased trunk extensor fatiguability (Beneck et al., 2013), potentially limiting the ability of this group to optimally utilize the trunk to accomplish the dynamic balance challenge. The consequence may be the more dissociated trunk motion observed. In contrast, the back-healthy control group may have the ability to use a control strategy which included contributions from more than just the hip, indicated by the fact that hip activation alone did not correlate with task performance.

The patterns observed and discussed here could inform interventions aimed at preventing the recurrence of LBP. Lumbo-pelvic coordination exercises can be non-pain provoking (Selkowitz et al., 2006; Miller et al., 2017), and, as per this study, provide a physiologically meaningful stimulus for amplitude-based coordinated trunk-and-hip muscle activation. They are a recommended ingredient for managing persons with rLBP (Gatti et al., 2011; Paungmali et al., 2017; Hodges, 2019).

There are limitations to generalizing findings from this study. First, participants were a convenience sample of persons with and without rLBP recruited from student groups, classes, flyers, and university-affiliated physical therapy clinics. Our group of persons with rLBP were young, minimally disabled, and in pain remission. Applying these findings to persons with symptomatic rLBP or with acute or chronic LBP would be inappropriate, especially given what is known about how differently motor control is affected in these different groups (Hodges and Tucker 2011). Second, limitations of EMG methodology include the potential for cross-talk from surface EMG and potential errors in fine-wire placement. Data discussed in this study collapsed trunk muscles (MF, ES, IO, EO) and hip muscles (GMax, GMed) together. This has been done previously in research on the topic of LBP where muscles have been grouped by quadrant (McGill et al., 2013) and allows us to characterize muscle activation of a region or around a joint while individual muscle responses may vary between individuals. One limitation is that muscles were instrumented unilaterally due to a limit in the number of channels. Signal normalization to the stable block condition, however, cancels muscle activation from lifting the leg and pressing down on the block and allows us to isolate activation as a response to the added instability from the spring.

5. Conclusion

There were no between-group differences in activation amplitude for any muscle groups tested. Back-healthy control participants increased hip and trunk muscle activation amplitudes in response to the added instability of the spring in a coordinated way, while those in remission from rLBP did not. Instead, hip muscle activation and task performance were associated in those with rLBP. These findings suggest persons with rLBP preferentially, and potentially excessively, utilize hip musculature during challenging dynamic balance tasks. This represents an extrapolation of previous findings where persons with symptomatic LBP had greater hip muscle activity than controls, and this may help explain the dissociated trunk motion observed in those in remission from rLBP during the Balance-Dexterity Task.

Declaration of Competing Interests

The authors have no conflict of interests to disclose.

Acknowledgements

This study was funded by the International Society of Biomechanics and the American Society of Biomechanics. The study sponsors played a small role in study design by contributing feedback in response to the funding proposal. They did not play a role in data collection, analysis and interpretation of data, in the writing of the manuscript, or in the decision to submit the manuscript for publication.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2019.102378.

References

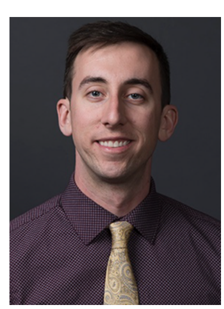
Baecke, J.A., Burema, J., Frijters, J.E., 1982. A short questionnaire for the measurement of habitual physical activity in epidemiological studies. Am. J. Clin. Nutr. 36, 936–942. https://doi.org/10.1093/ajcn/36.5.936.

Beneck, G.J., Baker, L.L., Kulig, K., 2013. Spectral analysis of EMG using intramuscular electrodes reveals non-linear fatigability characteristics in persons with chronic low back pain. J. Electromyogr. Kinesiol. 23, 70–77. https://doi.org/10.1016/j.jelekin.2012.07.001.

Beneck, G.J., Kulig, K., 2012. Multifidus atrophy is localized and bilateral in active persons with chronic unilateral low back pain. Arch. Phys. Med. Rehabil. 93, 300–306. https://doi.org/10.1016/j.apmr.2011.09.017.

Borghuis, J., Hof, A.L., Lemmink, K.A.P.M., 2008. The importance of sensory-motor control in providing core stability: implications for measurement and training. Sport

Med. 38, 893–916. https://doi.org/10.2165/00007256-200838110-00002.
Bussey, M.D., Kennedy, J.E., Kennedy, G., 2016. Gluteus medius coactivation response in field hockey players with and without low back pain. Phys. Ther. Sport. 17, 24–29. https://doi.org/10.1016/j.ptsp.2015.03.002.
Cholewicki, J., Silfies, S.P., Shah, R.A., et al., 2005. Delayed trunk muscle reflex responses increase the risk of low back injuries. Spine (Phila Pa 1976) 30, 2614–2620. https://doi.org/10.1097/01.brs.0000188273.27463.bc.
Ciesielska, J., Lisiński, P., Bandosz, A., et al., 2015. Hip strategy alterations in patients with history of low disc herniation and non-specific low back pain measured by surface electromyography and balance platform. Acta Bioeng. Biomech. 17, 103–108. https://doi.org/10.5277/ABB-00178-2014-02.
da Silva, T., Mills, K., Brown, B.T., et al., 2017. Risk of recurrence of low back pain: a systematic review. J. Orthop. Sport Phys. Ther. 47, 305–313. https://doi.org/10.2519/jospt.2017.7415.
Dankaerts, W., O'sullivan, P.B., Burnett, A.F., et al., 2004. Reliability of EMG measurements for trunk muscles during maximal and sub-maximal voluntary isometric contractions in healthy controls and CLBP patients. J. Electromyogr. Kinesiol. 14, 333–342. https://doi.org/10.1016/j.jelekin.2003.07.001.
Dieleman, J.L., Baral, R., Birger, M., et al., 2016. US spending on personal health care and public health, 1996–2013. JAMA 316, 2627. https://doi.org/10.1001/jama.2016.16885.
Fairbank, J.C., Pynsent, P.B., 2000. The Oswestry Disability Index. Spine (Phila Pa 1976) 25, 2940–2952. https://doi.org/10.1097/00007632-200011150-00017.
Freddolini, M., Strike, S., Lee, R., 2014. Dynamic stability of the trunk during unstable sitting in people with low back pain. Spine (Phila Pa 1976) 39, 785–790. https://doi.org/10.1097/BRS.0000000000000296.
Gatti, R., Faccendini, S., Tettamanti, A., et al., 2011. Efficacy of trunk balance exercises for individuals with chronic low back pain: A randomized clinical trial. J. Orthop. Sports Phys. Ther. 41, 542–552. https://doi.org/10.2519/jospt.2011.3413.
Henry, S.M., Hitt, J.R., Jones, S.L., Bunn, J.Y., 2006. Decreased limits of stability in response to postural perturbations in subjects with low back pain. Clin. Biomech. 21, 881–892. https://doi.org/10.1016/j.clinbiomech.2006.04.016.
Hodges, P.W., 2019. Hybrid approach to treatment tailoring for low back pain: A proposed model of care. J. Orthop. Sports Phys. Ther. 49, 453–463. https://doi.org/10.2519/jospt.2019.8774.
Hodges, P.W., Richardson, C.A., 1996. Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. Spine (Phila Pa 1976) 21, 2640–2650. https://doi.org/10.1097/00007632-199611150-00014.
Hodges, P.W., Tucker, K., 2011. Moving differently in pain: A new theory to explain the adaptation to pain. Pain 152, S90–S98. https://doi.org/10.1016/j.pain.2010.10.020.
Hodges, P.W., van Dieën, J.H., Cholewicki, J., 2013. Introduction: convergence and divergence of opinions on spinal control. In: Hodges, P.W., Cholewicki, J., van Dieën, J.H. (Eds.), Spinal Control: The Rehabilitation of Back Pain State of the art and science, 1st ed. Churchill Livingstone - Elsevier, pp. 1–4.
Hoy, D., March, L., Brooks, P., et al., 2014. The global burden of low back pain: estimates from the global burden of disease 2010 study. Ann. Rheum. Dis. 73, 968–974. https://doi.org/10.1136/annrheumdis-2013-204428.
Jones, S.L., Henry, S.M., Raasch, C.C., et al., 2012. Individuals with non-specific low back pain use a trunk stiffening strategy to maintain upright posture. J. Electromyogr. Kinesiol. 22, 13–20. https://doi.org/10.1016/j.jelekin.2011.10.006.
Kankaanpää, M., Taimela, S., Laaksonen, D., et al., 1998. Back and hip extensor fatigability in chronic low back pain patients and controls. Arch. Phys. Med. Rehabil. 79, 412–417. https://doi.org/10.1016/s0003-9993(98)90142-3.
Larivière, C., Forget, R., Vadeboncoeur, R., et al., 2010. The effect of sex and chronic low back pain on back muscle reflex responses. Eur. J. Appl. Physiol. 109, 577–590. https://doi.org/10.1007/s00421-010-1389-7.
Lawrence, E.L., Cesar, G.M., Bromfield, M.R., et al., 2015. Strength, multijoint coordination, and sensorimotor processing are independent contributors to overall balance ability. Biomed. Res. Int. 2015. https://doi.org/10.1155/2015/561243.
Lee, A.S., Cholewicki, J., Reeves, N.P., et al., 2010. Comparison of trunk proprioception between patients with low back pain and healthy controls. Arch. Phys. Med. Rehabil. 91, 1327–1331. https://doi.org/10.1016/j.apmr.2010.06.004.
Lyle, M.A., Valero-Cuevas, F.J., Gregor, R.J., Powers, C.M., 2013. The lower extremity dexterity test as a measure of lower extremity dynamical capability. J. Biomech. 46, 998–1002. https://doi.org/10.1016/j.jbiomech.2012.11.058.
MacDonald, D., Moseley, G.L., Hodges, P.W., 2010. People with recurrent low back pain respond differently to trunk loading despite remission from symptoms. Spine (Phila Pa 1976) 35, 818–824. https://doi.org/10.1097/BRS.0b013e3181bc98f1.
Magnusson, M.L., Aleksiev, A., Wilder, D.G., et al., 1996. Unexpected load and asymmetric posture as etiologic factors in low back pain. Eur Spine J. 5, 23–35. https://doi.org/10.1007/BF00307824.
Marras, W.S., Davis, K.G., Ferguson, S.A., et al., 2001. Spine loading characteristics of patients with low back pain compared with asymptomatic individuals. Spine (Phila Pa 1976) 26, 2566–2574.
Marras, W.S., Ferguson, S.A., Burr, D., et al., 2004. Spine loading in patients with low back pain during asymmetric lifting exertions. Spine J. 4, 64–75. https://doi.org/10.1016/S1529-9430(03)00424-8.
McGill, S.M., Marshall, L., Andersen, J., 2013. Low back loads while walking and carrying: comparing the load carried in one hand or in both hands. Ergonomics 56, 293–302. https://doi.org/10.1080/00140139.2012.752528.
Miller, E., Sahrmann, S.A., Avers, D., 2017. A Movement system impairment approach to evaluation and treatment of a person with lumbar radiculopathy: A case report. Physiother. Theory Pract. 33, 245–253. https://doi.org/10.1080/09593985.2017.1282997.
Nadler, S.F., Malanga, G.A., Feinberg, J.H., et al., 2001. Relationship between hip muscle imbalance and occurrence of low back pain in collegiate athletes: a prospective study. Am. J. Phys. Med. Rehabil. 80, 572–577. https://doi.org/10.1097/00002060-200108000-00005.
Nelson-Wong, E., Gregory, D.E., Winter, D.A., Callaghan, J.P., 2008. Gluteus medius muscle activation patterns as a predictor of low back pain during standing. Clin. Biomech. (Bristol, Avon) 23, 545–553. https://doi.org/10.1016/j.clinbiomech.2008.01.002.
Nötzel, D., Puta, C., Wagner, H., et al., 2011. Altered hip muscle activation in patients with chronic non-specific low back pain. Der. Schmerz. 25, 199–206. https://doi.org/10.1007/s00482-010-1010-3.
Osthoff, A.-K.R., Ernst, M.J., Rast, F.M., et al., 2015. Measuring lumbar reposition accuracy in patients with unspecific low back pain: systematic review and meta-analysis. Spine (Phila Pa 1976) 40, E97–E111. https://doi.org/10.1097/BRS.0000000000000677.
Paungmali, A., Joseph, L.H., Sitilertpisan, P., et al., 2017. Lumbopelvic core stabilization exercise and pain modulation among individuals with chronic nonspecific low back pain. Pain Pract. 17, 1008–1014. https://doi.org/10.1111/papr.12552.
Penney, T., Ploughman, M., Austin, M.W., et al., 2014. Determining the activation of gluteus medius and the validity of the single leg stance test in chronic, nonspecific low back pain. Arch. Phys. Med. Rehabil. 95, 1969–1976. https://doi.org/10.1016/j.apmr.2014.06.009.
Radebold, A., Cholewicki, J., Panjabi, M.M., Patel, T.C., 2000. Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. Spine (Phila Pa 1976) 25, 947–954. https://doi.org/10.1097/00007632-200004150-00009.
Radebold, A., Cholewicki, J., Polzhofer, G.K., Greene, H.S., 2001. Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. Spine (Phila Pa 1976) 26, 724–730. https://doi.org/10.1097/00007632-200104010-00004.
Reeves, N.P., Cholewicki, J., Milner, T.E., 2005. Muscle reflex classification of low-back pain. J. Electromyogr. Kinesiol. 15, 53–60. https://doi.org/10.1016/j.jelekin.2004.07.001.
Rowley, K.M., Gordon, J., Kulig, K., 2018. Characterizing the balance-dexterity task as a concurrent bipedal task to investigate trunk control during dynamic balance. J. Biomech. 77, 211–217. https://doi.org/10.1016/j.jbiomech.2018.07.014.
Rowley, K.M., Smith, J.A., Kulig, K., 2019. Reduced trunk coupling in persons with recurrent low back pain is associated with greater deep-to-superficial trunk muscle activation ratios during the Balance-Dexterity task. J Orthop. Sport Phys. Ther. 1–41. https://doi.org/10.2519/jospt.2019.8756. (in press).
Selkowitz, D.M., Kulig, K., Poppert, E.M., et al., 2006. The immediate and long-term effects of exercise and patient education on physical, functional, and quality-of-life outcome measures after single-level lumbar microdiscectomy: a randomized controlled trial protocol. BMC Musculoskelet Disord 7, 70. https://doi.org/10.1186/1471-2474-7-70.
Stokes, I.A.F., Fox, J.R., Henry, S.M., 2006. Trunk muscular activation patterns and responses to transient force perturbation in persons with self-reported low back pain. Eur. Spine J. 15, 658–667. https://doi.org/10.1007/s00586-005-0893-7.
Sullivan, M., Bishop, S., Pivik, J., Plvik, J., 1995. The pain catastrophizing scale: development and validation. Psychol Assess 7, 432–524. https://doi.org/10.1037/1040-3590.7.4.524.
Vlaeyen, J.W., Kole-Snijders, A.M., Rotteveel, A.M., et al., 1995. The role of fear of movement/(re)injury in pain disability. J. Occup. Rehabil. 5, 235–252. https://doi.org/10.1007/BF02109988.
Winter, D.A., 1995. Human balance and posture control during standing and walking. Gait Post. 3, 193–214.
Winter, D.A., Patla, A.E., Frank, J.S., 1990. Assessment of balance control in humans. Med. Prog. Technol. 16, 31–51.



K. Michael Rowley attained his PhD in Biokinesiology from the University of Southern California. He currently researches neuromuscular control of movement in diverse athletic and clinical populations as well as preclinical animal models.

Tilman Engel attained his PhD in Clinical Exercise Science from the University of Potsdam. He currently researches functional diagnostics and biomechanics, neuromuscular compensation of interfering stimuli, and mobile motion analysis techniques.

Kornelia Kulig is a professor and co-director of the Jacquelin Perry Musculoskeletal Biomechanics Research Lab in the Division of Biokinesiology and Physical Therapy at the University of Southern California. She studies orthopedic conditions with recurrent symptoms, including low back pain and tendinopathies. In that context, she explores tissue morphology, physiology and movement strategies in a broad range of activities, pathology stages and populations.