HHS Public Access

Author manuscript

*Neuroscience*. Author manuscript; available in PMC 2017 December 17.

Published in final edited form as:

*Neuroscience*. 2016 December 17; 339: 511–524. doi:10.1016/j.neuroscience.2016.10.032.

# Neural mechanisms and functional correlates of altered postural responses to perturbed standing balance with chronic low back pain

**Jesse V. Jacobs**[a,b], **Carrie L. Roy**[a], **Juvena R. Hitt**[a], **Roman E. Popov**[a], and **Sharon M. Henry**[a,c]

Jesse V. Jacobs: jesse.jacobs@libertymutual.com; Carrie L. Roy: carrieinvt@gmail.com; Juvena R. Hitt: Juvena.Hitt@med.uvm.edu; Roman E. Popov: roman.popov@uvm.edu; Sharon M. Henry: Sharon.Henry@uvmhealth.org

[a]Department of Rehabilitation and Movement Science, University of Vermont, 305 Rowell Building, 106 Carrigan Dr., Burlington, Vermont, 05405, USA

[b]Center for Physical Ergonomics, Liberty Mutual Research Institute for Safety, 71 Frankland Rd., Hopkinton, MA, 01748, USA

[c]Department of Rehabilitation Therapy, University of Vermont Medical Center, 111 Colchester Ave., Burlington, VT 05401

## Abstract

This study sought to determine the effects of chronic low back pain (LBP) on the cortical evoked potentials, muscle activation, and kinematics of postural responses to perturbations of standing balance. Thirteen subjects with chronic, recurrent, non-specific LBP and 13 subjects without LBP participated. The subjects responded to unpredictably timed postural perturbations while standing on a platform that randomly rotated either “toes up” or “toes down”.

Electroencephalography (EEG) was used to calculate the negative peak (N1) and subsequent positive peak (P2) amplitudes of the perturbation evoked cortical potentials. Passive-marker motion capture was used to calculate joint and center-of-mass (CoM) displacements. Surface electromyography was used to record muscle onset latencies. Questionnaires assessed pain, interference with activity, fear of activity, and pain catastrophizing. Results demonstrated that subjects with LBP exhibited significantly larger P2 potentials, delayed erector spinae, rectus abdominae, and external oblique onset latencies, as well as smaller trunk extension yet larger trunk flexion, knee flexion, and ankle dorsiflexion displacements compared to subjects without LBP. For the subjects with LBP, CoM displacements significantly and positively correlated with knee displacements as well as activity interference and fear scores. The P2 potentials significantly and negatively correlated with CoM displacements as well as activity interference, catastrophizing, and fear scores. These results demonstrate that people with LBP exhibit altered late-phase cortical processing of postural perturbations concomitant with altered kinematic and muscle responses,

Corresponding Author Information: Jesse V. Jacobs, Liberty Mutual Research Institute for Safety, 71 Frankland Rd., Hopkinton, MA, 01748, Jesse.Jacobs@LibertyMutual.com, Phone: 508-497-0296, Fax: 508-435-3456.

and these cortical and postural response characteristics correlate with each other as well as with clinical reports of pain-related fears and activity interference.

**Keywords**

posture; balance; low back pain; cortex; EEG

## Introduction

Chronic low back pain (LBP) represents the highest ranking health condition of global disease burden for years lived with disability, has a point prevalence of 9.4%, and its disability burden appears to be increasing over recent decades (Hoy et al., 2014). Thus, it is important to understand mechanisms of impairment associated with LBP in order to inform intervention strategies and improve global health.

Although the causes of chronic LBP likely include psychological, motor, mechanical, and sensory factors (Langevin and Sherman, 2007), altered postural coordination – muscle activation and associated movement to maintain orientation and equilibrium – is often reported as coincident with LBP. Changes in postural coordination are evident during voluntary movements (e.g., (Hodges and Richardson, 1996; Kuriyama and Ito, 2005; Shum et al., 2005a, b; Jacobs et al., 2009; Scholtes et al., 2009)), quiet stance (e.g., (Mazaheri et al., 2013)), and when responding to externally induced postural perturbations (referenced literature specified below). This study focuses on altered postural responses to extrinsically induced perturbations in people with LBP.

Studies on externally induced postural responses often evaluate the kinematic and muscle responses of people with LBP to sudden weight loading, load release, or displacements of the support surface (translations or rotations of the floor under the subjects' feet). From these studies, people with LBP exhibit higher-amplitude or prolonged body sway induced by the perturbation (Radebold et al., 2001; Henry et al., 2006; Mok et al., 2011; Ayhan et al., 2015), diminished proximal joint torques and increased trunk stiffness (Hodges et al., 2009; Jones et al., 2012), as well as altered patterns of trunk muscle activation such as delayed responses (Radebold et al., 2000; Radebold et al., 2001; Cholewicki et al., 2005; Reeves et al., 2005), diminished activation amplitude (MacDonald et al., 2010; Jacobs et al., 2016), decreased incidence of muscle activation (Newcomer et al., 2002; Jacobs et al., 2011) and antagonistic muscle co-contraction (Radebold et al., 2000; Jones et al., 2012). Although delayed muscle responses may represent a prospective predictive factor for experiencing LBP (Cholewicki et al., 2005), the practical relevance of altered postural responses with LBP remains largely unclear.

The practical relevance of assessing postural responses could be further realized if mechanisms of impairment and clinical correlates were better defined, because such an understanding could aid in directing intervention. The neurophysiologic mechanisms of these impairments, however, remain uncertain. It has been suggested that early phases of the postural response more likely reflect generation by sub-cortical neural circuits (although also potentially influenced by cortical mechanisms of central set), whereas later phases of the

response exhibit greater potential for cortical influence (Jacobs and Horak, 2007; Bolton, 2015). LBP-associated alterations in postural responses span early and late phases of the postural response, suggesting both sub-cortical and cortical impairments, but the preponderant impairment appears with the late-phase trunk-muscle responses (Jacobs et al., 2011; Jacobs et al., 2016). Thus, muscle activation patterns during postural responses suggest potential changes in cortical processing of the response with LBP (Jacobs et al., 2011).

Despite behavioral data that suggest cortical involvement in impaired postural responses of people with LBP, cortical responses to extrinsically induced postural perturbations have yet to be reported for people with LBP. The perturbation evoked potential, as recorded by electroencephalography (EEG), has been described for healthy young adults. The potential is characterized by a large negative peak between 100–200 ms after perturbation onset (the N1 potential), followed by a positive peak (the P2 potential). As reviewed by Bolton (Bolton, 2015), the N1 potential appears to signal that an individual's postural position has been unexpectedly perturbed, but the N1 potential does not purely reflect the sensory processing of the amplitude of the physical perturbation to the body. Instead, the N1 potential appears to be an event detector for unexpected postural error such that the amplitude of the N1 potential (a) increases when the timing of the perturbation is unpredictable, (b) decreases with attention distraction that is elicited by dual tasking, and (c) increases with enhanced fear of postural perturbation that is elicited, for example, by manipulating the height of the ledge on which a subject stands (Bolton, 2015). The N1 potential has also been found unchanged by direction of perturbation, delayed but unchanged in amplitude by peroneal nerve damage that slows peripheral conduction velocity, unchanged in timing or amplitude by ischemic nerve block or vestibular loss, and estimated to arise from the supplementary motor area, thus further supporting the interpretation of a higher-order function such as detection of postural error rather than pure sensory processing (Dietz et al., 1985; Marlin et al., 2014; Mierau et al., 2015). Although the neural generators of the P2 potential are not yet known, the P2 potential appears to reflect ongoing monitoring of postural challenge. This interpretation has been suggested based on observations that the P2 potential's amplitude is larger when the postural displacement is allowed to progress without attempted recovery (Quant et al., 2004b) or when there is an ongoing requirement for postural recovery (i.e., when comparing standing versus seated responses (Mochizuki et al., 2009a)). Unlike the N1 potential, however, the P2 potential is not modulated by cognitive distraction or by fear induced by performing postural responses at heights (Quant et al., 2004a; Sibley et al., 2010), thereby differentiating the influence of cognitive factors on the N1 potential's proposed function for detecting postural error versus the P2 potential's proposed function in monitoring of ongoing postural challenge. Thus, together, the N1-P2 complex of the perturbation evoked potential appears functionally relevant to the detection of postural perturbations and monitoring of postural challenge during postural responses to extrinsically induced perturbations.

These mechanisms of cortical response could be altered in people with LBP. Specifically, people with LBP exhibit (1) impaired proprioception and kinesthetic control that relates to altered use of the trunk during standing balance (Gill and Callaghan, 1998; Brumagne et al., 2000; Brumagne et al., 2008; Lee et al., 2010; Claeys et al., 2011; Johanson et al., 2011),

and (2) delayed muscle responses to postural perturbations (Radebold et al., 2000; Radebold et al., 2001; Cholewicki et al., 2005; Reeves et al., 2005) that suggest impaired proprioceptive signaling (Inglis et al., 1994; Stapley et al., 2002). In addition, people with LBP often exhibit pain-related fear of movement (Vlaeyen and Crombez, 1999), and could accordingly detect a greater perceived error to posture. Thus, it is possible that people with LBP would exhibit impaired detection of a postural perturbation due to altered proprioceptive signaling or enhanced detection due to fear of movement, and their delayed and altered late-phase postural responses may coincide with greater late-phase cortical monitoring of the response. Therefore, the N1 and P2 potentials could be insightful for understanding differences in cortical processing relevant to LBP-related postural impairment.

The objectives of this study were to determine the effects of chronic LBP on cortical perturbation evoked potentials during postural responses to rotations of the support surface and to evaluate the functional associations of perturbation evoked potentials to (a) postural response characteristics, (b) the extent pain interferes with daily activities, (c) pain severity, and (d) pain-related fears. We hypothesized people with LBP would exhibit altered postural responses, impaired detection of the postural perturbation, and enhanced late-phase monitoring of postural challenge. We thus predicted people with LBP would exhibit delayed trunk muscle activation, increased center-of-mass (CoM) displacements, decreased N1 amplitudes, and increased P2 amplitudes. We further hypothesized that pain-related fear and interference associates with induced postural displacement, altered detection of the perturbation, and enhanced perception of postural challenge, as predicted by significant correlations among questionnaire measures of pain interference in daily activity and pain-related fears with CoM displacements and perturbation- evoked-potential amplitudes.

## Methods

### Subjects

Thirteen subjects with chronic, recurrent LBP and 13 subjects without LBP participated in the study (Table 1). This sample size represents a convenience sample achieved within the duration of the funded study. Subjects with LBP were included if their LBP required them to seek treatment or limited them on at least 3 activities (as determined by the Patient Specific Functional Scale; (Maughan and Lewis, 2010)), and if they experienced chronic or recurrent episodes for at least one year. Subjects were excluded if they reported neurological, psychiatric, cardiovascular, or musculoskeletal disorders other than back pain as well as uncorrected vision problems, vertebral fracture, tumor or infection, spinal stenosis, previous spinal surgery, systemic infection, current pregnancy, history of any surgery in the three months prior to testing, scoliosis or kyphosis, injury to the lower extremity, or radiating pain below the knee. Subjects were also excluded if they were receiving disability compensation for their LBP, or if they were in litigation because of the LBP. Subjects without LBP were excluded if they had any of the above-listed criteria as well as if they had a history of back pain that required them to seek treatment or resulted in limited activity. All subjects were currently employed or active as a full-time student or homemaker. Subjects participated only

after providing written informed consent, and the protocol was approved by the local institutional review board.

## Data Collection and Processing

**Questionnaires—**Subjects first completed a set of questionnaires that included a health history form, the Brief Pain Inventory Short Form (BPI; (Keller et al., 2004)), the Fear Avoidance Beliefs Questionnaire (FABQ; (Waddell et al., 1993)), and the Coping Strategies Questionnaire (CSQ; (Rosenstiel and Keefe, 1983)). These questionnaires were selected in order to provide insight regarding associations of perturbation-evoked cortical potentials and induced postural displacement with pain severity, interference with daily life, pain-related fear of activity, and pain-related coping.

The BPI generates a pain severity score and a pain interference score. The pain severity score represents the average of four 0–10 point rating scales that inquire about current pain as well as average, least, and worst pain over the previous 24 hours. The pain interference score represents the average of seven 0–10 point rating scales relating to the extent that a person's pain interferes with their general activity, mood, walking, work/housework, relations with other people, sleep, and life enjoyment. Higher scores represent greater pain severity and interference; maximum average scores are 10 points for both the pain severity and pain interference scores.

The FABQ generates a physical activity score and a work score. The physical activity score represents the sum of four 0–6 point rating scales regarding the subjects' agreement that physical activity worsens pain, harms their back, should not be engaged in activities that worsen their pain, and that they cannot perform activities that worsen their pain. The work score represents the sum of seven 0–6 point rating scales regarding the subjects' agreement that work caused their pain, aggravated their pain, and that their work is too heavy, worsens their pain, harms their back, should not be done given current pain, and that they will not return to normal work within 3 months. Higher scores represent greater fear that physical activity or work will enhance their pain state; maximum scores are 24 for the physical activity score and 42 for the work score.

The CSQ is a multi-dimensional questionnaire of many cognitive and behavioral domains. The CSQ was utilized in this study for its catastrophizing sub-scale regarding the extent people experience cognitions of helplessness and exaggeration related to their pain status. The CSQ catastrophizing score represents a sum of six 0–6 point rating scales regarding whether the person can stand their pain, go on with the pain, worries about whether their pain will end, feels their life is worth living, feels their pain is awful and overwhelming, and feels their pain is terrible and never going to improve. Higher scores represent greater catastrophizing, with a maximum score of 36.

**Postural Response Task—**The experimental task was to maintain standing balance in response to rotations of the support surface. The subjects first looked approximately 6 meters straight ahead at an X-shaped fixation point on the wall with their arms relaxed at their sides while standing on a moveable platform. Their feet were positioned so the medial edges were parallel and the heel-to-heel stance width was 11% body height (McIlroy and

Maki, 1997) and placed so that the lateral malleoli aligned with the axis of platform rotation. The subjects were instructed to try to minimize eye blinking. At unpredictable inter-stimulus intervals of 15–30 seconds, the platform rotated 5 degrees under their feet with peak velocity of 23 degrees per second and duration of 490 ms. The subjects completed 30 trials of toes-up rotations and 30 trials of toes-down rotations. The direction of perturbation was pseudo-randomized between toes-up and toes-down perturbations. The unpredictable timing and direction were utilized in order to enhance the likelihood of eliciting perturbation evoked potentials (Adkin et al., 2006). In addition, two directions of perturbation were analyzed because the effects of low back pain may be directionally specific (Jacobs et al., 2011). The small perturbation displacement and slow velocity were selected to minimize the potential for eye-blink, EMG, and motion artifact in the EEG signal.

**Electromyography (EMG)—**For recording of muscle activity during the postural-response task, subjects were prepared for recording by shaving the skin overlying the recorded muscles and then cleaning the skin with a conductive gel to obtain impedances below 10 kΩ. Bipolar surface EMG electrodes (1-cm silver/silver-chloride disk electrodes with fixed 2-cm inter-electrode distance; Myotronics, Kent, WA) were applied as previously reported (Jacobs et al., 2011) to the left and right lumbar erector spinae (ES), rectus abdominus (RA), and external oblique (EO) muscles. These locations were chosen due to past research demonstrating delayed or diminished trunk-muscle responses to extrinsic perturbations in people with LBP (Radebold et al., 2000; Newcomer et al., 2002; Cholewicki et al., 2005; Reeves et al., 2005; MacDonald et al., 2010; Jacobs et al., 2011; Jacobs et al., 2016).

The EMG signals were sampled at 1000 Hz, pre-amplified by 1000 at the skin's surface and then amplified further for a total amplification of 2000–10000. EMG data were synchronously recorded with the motion capture data through VICON Nexus software (VICON, Denver, CO). For offline processing using Matlab software (Matlab, Natick, MA, USA), the EMG signals were band-pass filtered at 30–400 Hz with a Butterworth filter, baseline corrected by subtracting the mean of the signal, and full-wave rectified. The high-pass limit was set to minimize cardiac artifact in the EMG signals of our evaluated trunk muscles (Drake and Callaghan, 2006). The integrated protocol method was used to identify EMG activation onset, in which the maximum difference between the integrated signal and an amplitude-normalized integral of the linear envelope is identified. The integrated protocol method is less susceptible to changes in baseline amplitude or to false onset detection compared with traditional threshold techniques (Allison, 2003). Onsets of muscle activation were bounded to after the onset of platform rotation. If no onset was detected, then the trial was coded as such and not included for statistical analysis. No significant differences were evident between the groups with and without LBP in the percentage of trials with detected activation onsets for any muscle within either condition (range of $T = 0.04–0.98$; range of $P = 0.34–0.97$). For each trial, EMG onset latencies were derived by subtracting the onset of platform rotation from the onset of EMG activation. These latencies were then averaged by subject and condition (toes-up and toes-down platform rotations) for analysis.

**Kinematics—**Subjects were also prepared for passive-marker motion capture (7-camera system; VICON, Denver, CO) by placing reflective markers at 29 locations over the subjects' joints, bony landmarks, and along limb segments. The motion capture data were used to estimate joint and CoM displacements in order to characterize movement strategies and induced postural displacement.

The motion capture data were sampled at 100 Hz. Using Matlab software, marker position data were low-pass filtered at 10 Hz. Limb segments of the foot, shank, thigh and trunk were derived from adjacent pairs of the markers located at the 5$^{th}$ metatarsal, lateral malleolus, lateral femoral condyle, greater trochanter, and acromion. Sagittal ankle, knee, and trunk angles were then calculated from the adjacent segments of the foot, shank, thigh, and trunk. We note that our marker set did not permit transformation to a standardized joint coordinate system (Wu et al., 2002), but all methods of marker placement, foot alignment and position, and processing of marker data were standardized across subjects within this study. These joint angles were then baseline corrected by subtracting the average angle of the 100-ms epoch just prior to perturbation onset. The peak joint flexion and extension displacements were calculated by automated detection of the minimum and maximum values within one second following perturbation onset.

The marker kinematics used in defining the joint angles were also combined with published body segment parameters (Dempster, 1955) in order to estimate the CoM. First, the anterior-posterior position of segmental CoM was defined for the head-arms-and-trunk segment, as well as the thigh, shank and foot segments using the published ratios for the distance of the segmental CoM relative to the length of each segment. Segmental positions and lengths were defined from the positions of the kinematic markers. These segmental CoM positions were then weighted as a percentage of the total-body CoM per the published parameters, and these weighted segmental CoM positions were then summed to derive the anterior-posterior total-body CoM position. Peak anterior-posterior total-body CoM displacements were then derived in similar fashion to the peak displacements of the joint angles. CoM displacements were chosen as an outcome of interest because they represent a direct measure of postural displacement, whereas measures derived from the center of pressure represent ground reaction forces related to both induced displacement and corrective responses to control that displacement. The peak joint-angle and CoM displacements of each trial were averaged by subject and condition for analysis.

**EEG—**The subjects wore a Waveguard 128-channel EEG head cap (sintered silver/silver-chloride electrodes; standard 10/5 system placement (Oostenveld and Praamstra, 2001); Advanced Neuro Technology, Enschede, the Netherlands). A conductive electrode gel (Electro-gel; Electro-Cap International; Eaton, OH, USA) was used to obtain impedances below 10 kΩ. The EEG was recorded to derive the perturbation evoked potentials in order to gain insight into the neural detection of the perturbation and monitoring of perceived postural challenge during the response.

EEG data were collected at 1024 Hz using a DC amplifier and pre-processed using ASA software version 4.7.3 (Advanced Neuro Technology, Enschede, Netherlands). Following collection, blinking artifacts were removed using the artifact correction tool of the ASA

software, selecting the two components that most represented the artifacts' characteristics. The EEG recordings were band-pass filtered from 1 to 30 Hz. The signal from an accelerometer on the moveable platform was used to synchronize the EEG recordings with the EMG and kinematics. The onset of platform acceleration was used to splice the continuously recorded EEG data into epochs of two seconds, defined from one second before to one second after perturbation onset. Using Matlab software, data were visually evaluated for trials with artifact for removal prior to analysis. Artifacts were determined based on topology, form, and amplitude. Specifically, EMG artifacts (such as from the neck) were presumed to arise as a widespread waveform of high frequency and amplitude relative to the EEG signal, and to propagate from the edges of the electrode cap toward the vertex. Likewise, although eye-blink artifacts were removed by the software's correction tool, we searched for evidence of remaining artifact with a fronto-polar origin. Artifacts of unstable electrode interaction with the scalp surface were detected as linear vertical displacements of several microvolts that spanned one sample unit (< 1 ms). Separate from these focused artifact searches, any displacement greater than 75 microvolts, regardless of form, was rejected from analysis. The number of trials retained for analysis is reported in the results. The FCz (midline frontal-central), Cz, (midline central) and CPz (midline central-parietal) electrodes were chosen for analysis based on previous studies that described the topography of maximal potential amplitudes and estimated sources of the perturbation evoked potential (Quant et al., 2004b; Mochizuki et al., 2009a; Marlin et al., 2014; Mierau et al., 2015).

The EEG signals were baseline corrected by subtracting the average value of the 100-ms epoch prior to perturbation onset. Trial data were averaged by condition and subject. From the average waveforms, the peak amplitude of the N1 potential was determined as the minimum value 100–250 ms after perturbation onset, and the peak amplitude of the P2 potential was determined as the maximum value from 150–300 ms after perturbation onset. We interpret more negative values of N1 potentials as representing a greater perceived error in postural status or position (Bolton, 2015), and we interpret less negative or more positive values of P2 potentials as representing a greater amount of continued monitoring of postural challenge (Mochizuki et al., 2009a).

## Statistical Analysis

Differences between groups in anthropometric and questionnaire measures were determined by two-tailed independent-samples t tests. Equal variances were assumed unless a Levene's test required correction. For the measures recorded during the postural response task, mixed-model ANOVA were utilized to determine differences between groups (2 levels; with and without LBP) and conditions (2 levels; toes-up and toes-down perturbations) with *a priori* interest in group main effects and group-by-condition interaction effects. Greenhouse-Geisser corrections were applied to correct for any violations on the assumption of sphericity. Because people with LBP can exhibit increased baseline EMG prior to perturbation onset (Jacobs et al., 2011), and baseline EMG can affect the detection of EMG activation onset time, EMG onset latencies were evaluated with baseline integrated EMG amplitude as a covariate, which was derived from the integral of the rectified EMG signal over the 200ms epoch just prior to perturbation onset.

Within the group with LBP, Pearson's correlation coefficients were used to examine associations of CoM displacements with EMG onset latencies, joint-angle displacements, and questionnaire measures in order to provide insight about potential mechanisms contributing to induced postural displacement. Pearson's coefficients were also used to examine associations of perturbation-evoked-potential amplitudes with CoM displacements and questionnaire measures in order to provide insight about the relevance of perturbation-evoked cortical processes to induced postural displacement and clinically relevant measures of the subjects' LBP condition.

Measures were tested for the assumption of normality with Shapiro-Wilks tests. If data did not meet this assumption, non-parametric tests for group differences were evaluated by Mann-Whitney U tests, and Spearman's correlation coefficients were evaluated in place of the Pearson's coefficients. Statistical significance was set at a level of 0.05. Effect size is reported with partial eta-squared ($\eta_p^2$). When the results of the parametric and non-parametric statistics were consistent with regard to comparisons or correlations that did or did not reach the level of significance, we only report the parametric statistics, but when inconsistencies arose, we report both and interpret based on the non-parametric analysis. All analyses were performed in SPSS version-21 software (IBM, Armonk, NY, USA).

## Results

### Qualitative Observations of Postural and Cortical Responses

Due to the low amplitude and velocity of the perturbations, the postural responses were not as stereotyped as responses that larger perturbations typically elicit. Although no statistically significant differences in the incidence of trunk muscle activations were evident between subjects with and without LBP, the incidence of trunk muscle activation was not consistent across trials, and the timing of peak joint displacements also varied among individual trials. For this reason, the grand mean traces of kinematic and EMG signals may not demonstrate displacements and onsets that were evident in individual trials. Likewise, due to variability in postural response patterns, presenting a single representative trial would not exactly illustrate all mean findings either. Nevertheless, despite this variability, robust patterns did emerge.

The toes-up perturbations induced backward sway of the center of mass and a sustained ankle dorsiflexion due to the platform rotation, whereas the toes-down perturbations induced a forward sway with a sustained ankle plantarflexion. For the subjects without LBP, toes-up perturbations elicited a small sustained trunk flexion and a brief knee extension, whereas toes-down perturbations elicited a small trunk extension and knee flexion. The subjects with LBP, however, showed signs of an enhanced knee and trunk flexion in response to both directions of perturbation, with a less sustained ankle plantarflexion in response to toes-down perturbations. These patterns are suggestive of an enhanced knee flexion strategy for the subjects with LBP rather than utilizing a mixed ankle and hip strategy. For subjects without LBP, trunk muscle responses included early activation of the EO muscles in response to both directions of perturbation that were accompanied by early ES activation and later RA activation in the toes-up condition versus an early RA activation with an ES inhibition-excitation pattern in the toes-down condition. Qualitatively, the subjects with LBP

exhibited delayed trunk muscle activation for all muscles and conditions, although statistical significance was evident in the left ES as well as right RA and EO muscles, as indicated below. Interestingly, despite the variability in trial-by-trial responses and differences in patterns between perturbation conditions, the perturbation-evoked cortical potentials remained remarkably consistent, with peak values at or near the vertex and the subjects with LBP exhibiting larger P2 amplitudes than the subjects without LBP. Statistical results are detailed below.

## Group Comparisons Between Subjects With and Without LBP

The subject groups' anthropometric measures were not statistically different, but the subjects with and without LBP significantly differed for BPI pain severity, BPI interference, CSQ catastrophizing and FABQ physical activity and work scores (Table 1).

The subjects with and without LBP significantly differed in regards to their perturbation evoked potentials. At the FCz and CPz electrodes, the subjects with LBP exhibited significantly larger (less negative or more positive values; the value did not always breach zero) P2 potential amplitudes across both conditions [group effects, respectively, for the FCz, Cz, and CPz electrodes: $F = 7.99, 2.34, 5.67$; $P = 0.01, 0.14, 0.026$; $\eta_p^2 = 0.258, 0.092, 0.198$], whereas the groups' N1 potential amplitudes did not significantly differ between groups [group effects, respectively, for the FCz, Cz, and CPz electrodes: $F = 0.61, 0.96, 1.85$; $P = 0.44, 0.34, 0.19$; $\eta_p^2 = 0.026, 0.04, 0.074$] (Fig. 1).

The subjects with LBP also exhibited delayed EMG latencies across both conditions at the right RA and EO muscles as well as the left ES muscle [group effects, respectively: $F = 4.73, 7.62, 5.99$; $P = 0.042, 0.012, 0.022$; $\eta_p^2 = 0.199, 0.276, 0.207$] (Fig. 2). We note, however, that non-parametric statistics were warranted for the left ES muscle, and Mann-Whitney U tests demonstrate significant delays in only the toes-down condition [$Z = 1.46$, $P = 0.15$ for the toes-up condition; $Z = 2.13$, $P = 0.034$ for the toes-down condition]. Noting the observed initial inhibition of the ES muscles in response to toes-down perturbations, mean onset latencies of these inhibitory responses were not significantly different between subjects with and without LBP [mean (95% CI) latencies: left ES = 141 (103–179) ms with LBP and 131 (73–190) ms without LBP, $Z = 0.67$, $P = 0.50$; right ES = 180 (134–227) ms with LBP and 146 (72–221) ms without LBP, $Z = 1.64$, $P = 0.10$].

Center-of-mass displacements did not significantly differ between groups [group effects: $F = 0.47$; $P = 0.50$; $\eta_p^2 = 0.02$] (Fig. 3). However, the subjects with LBP exhibited larger trunk flexion, knee flexion, and ankle dorsiflexion across conditions [group effects, respectively: $F = 9.15, 7.39, 7.53$; $P = 0.006, 0.012, 0.011$; $\eta_p^2 = 0.285, 0.243, 0.239$] as well as smaller trunk extension in the toes-down condition [group-by-condition interaction: $F = 4.85$; $P = 0.038$; $\eta_p^2 = 0.174$] (Fig. 3). We note, however, that non-parametric statistics were warranted for ankle dorsiflexion, and Mann-Whitney U tests demonstrate significant differences in only the toes-down condition [$Z = 1.87$, $P = 0.064$ for the toes-up condition; $Z = 2.31$, $P = 0.019$ for the toes-down condition].

The latencies of the peak EEG potentials and the peak kinematic displacements were not significantly different between groups with the exception of trunk flexion, for which the

subjects with LBP exhibited significantly delayed trunk flexion in the toes-down condition (Table 2).

## Correlations Among Cortical Responses, Induced Postural Displacements and Clinical Measures for the Subjects with LBP

For the subjects with LBP, larger (less negative or more positive) P2 potentials at the CPz electrode significantly correlated with smaller CoM displacements [toes-up: Pearson $R^2$ = 0.61, $P$ = 0.0027; toes-down: $R^2$ = 0.42, $P$ = 0.023] as well as lower BPI interference scores [toes-up: Pearson $R^2$ = 0.59, $P$ = 0.002; toes-down: $R^2$ = 0.52, $P$ = 0.0053], FABQ physical activity scores [toes-up: Pearson $R^2$ = 0.63, $P$ = 0.0013; toes-down: $R^2$ = 0.74, $P$ = 0.00017], FABQ work scores [toes-up: Pearson $R^2$ = 0.43, $P$ = 0.015; toes-down: $R^2$ = 0.30, $P$ = 0.051], and CSQ catastrophizing scores [toes-up: Pearson $R^2$ = 0.48, $P$ = 0.0089; toes-down: $R^2$ = 0.57, $P$ = 0.0029], (Fig. 4). Significant correlations were also evident at the Cz electrode for BPI interference scores [toes-up: Pearson $R^2$ = 0.37, $P$ = 0.028; toes-down: $R^2$ = 0.31, $P$ = 0.046] and FABQ physical activity scores [toes-up: Pearson $R^2$ = 0.48, $P$ = 0.008; toes-down: $R^2$ = 0.54, $P$ = 0.004], as well as for peak CoM displacement in the toes-up condition [toes-up: Pearson $R^2$ = 0.35, $P$ = 0.044; toes-down: Pearson $R^2$ = 0.08, $P$ = 0.38], but not for FABQ work scores [toes-up: Pearson $R^2$ = 0.16, $P$ = 0.18; toes-down: $R^2$ = 0.02, $P$ = 0.67] or CSQ catastrophizing scores [toes-up: Pearson $R^2$ = 0.09, $P$ = 0.32; toes-down: $R^2$ = 0.08, $P$ = 0.37]. Despite P2 amplitudes being maximum at FCz, no significant correlations were evident for P2 amplitudes at the FCz electrode with CoM displacement or with the BPI, CSQ, or FABQ scores [range of Pearson $R^2$ = 0.001–0.20, range of $P$ = 0.13–0.91]. Peak N1 amplitudes did not significantly correlate with CoM displacements or questionnaire scores within the group with LBP [range of Pearson $R^2$ = 0.00002–0.19, range of $P$ = 0.14–0.99]. The N1and P2 potential amplitudes did not significantly correlate with BPI pain severity scores [range of Pearson $R^2$ = 0.000025–0.25, range of $P$ = 0.081–0.99].

For the subjects with LBP, larger CoM displacements significantly correlated with higher BPI interference scores [Pearson $R^2$ = 0.51, $P$ = 0.00095 in the toes-up condition] and FABQ work scores [Pearson $R^2$ = 0.54, 0.66; $P$ = 0.0064, 0.0012 for the toes-up and toes-down conditions, respectively], as well as with larger knee-angle displacements [Pearson $R^2$ = 0.42, $P$ = 0.029 and Pearson $R^2$ = 0.70, $P$ = 0.00073 for knee extension in the toes-up and toes-down conditions, respectively; Pearson $R^2$ = 0.46, $P$ = 0.015 for knee flexion in the toes-down condition]. In the toes-down condition, larger CoM displacements correlated with more delayed left ES latencies [Pearson $R^2$ = 0.56, $P$ = 0.0049] and larger ankle dorsiflexion [Pearson $R^2$ = 0.38, $P$ = 0.034; although Spearman $R$ = 0.519, $P$ = 0.084], whereas smaller CoM displacements associated with larger ankle plantarflexion [Pearson $R^2$ = 0.66, $P$ = 0.0013]. Peak CoM displacements did not significantly correlate with BPI pain severity scores [Pearson $R$ = 0.13, 0.22; $P$ = 0.25, 0.12 for toes-up and toes-down conditions, respectively].

## Post-Hoc Analysis of N1 and P2 Stability Based on the Number of Averaged Trials

Following artifact rejection, the mean (95% CI) number of trials retained for analysis was 27 to 28 (± 2) trials for each group and condition, with no significant differences between

groups or conditions [group: $F = 0.28$, $P = 0.60$, $\eta_p^2 = 0.011$; condition: $F = 0.77$, $P = 0.39$, $\eta_p^2 = 0.031$; group-by-condition: $F = 0.14$, $P = 0.71$, $\eta_p^2 = 0.006$].

A secondary post-hoc analysis was performed to ascertain whether our study, and potentially past studies of perturbation evoked potentials, generated N1 and P2 potentials from a sufficient number of trials to elicit stable N1 and P2 amplitudes. Because group effects and significant correlations were most consistently evident at the CPz electrode, the analysis focused on the CPz electrode. We utilized paired t-tests and Pearson correlation coefficients to analyze whether N1 or P2 amplitudes differed and whether the N1 or P2 amplitudes correlated when generated from waveforms representing the average of 5, 10, 15, 20, or 25 trials within each condition and across all subjects. Although significant differences were evident for both N1 and P2 amplitudes when they were generated from waveforms representing the average of 5 or 10 trials compared to when they were generated from waveforms representing the average of 15, 20 or 25 trials [range of $T = 0.07–5.20$, range of $P = 0.00003–0.95$], no significant differences were evident when comparing amplitudes derived from averages of 15, 20, and 25 trials [range of $T = 0.05–1.75$, range of $P = 0.093–0.96$]. Amplitudes of both the N1 and P2 potentials derived from averages of 15, 20, and 25 trials were highly correlated [range of Pearson $R = 0.84–0.99$, $P < 0.0001$]. Thus, N1 and P2 amplitudes did not significantly differ and were highly correlated when generated from a waveform representing an average of 15, 20, or 25 trials. When reviewing 19 past studies of perturbation evoked potentials (Dietz et al., 1984; Dietz et al., 1985; Quintern et al., 1985; Ackermann et al., 1986; Berger et al., 1990; Duckrow et al., 1999; Quant et al., 2004a; Quant et al., 2004b; Quant et al., 2005; Adkin et al., 2006; Adkin et al., 2008; Mochizuki et al., 2008; Mochizuki et al., 2009a; Mochizuki et al., 2009b; Mochizuki et al., 2010; Sibley et al., 2010; Marlin et al., 2014; Little and Woollacott, 2015; Mierau et al., 2015), the number of subjects included per group was: mean = 11, median = 10, mode = 10, range = 4–37; the number of trials performed per condition was: mean = 33, median = 30, mode = 30, range = 10–64. Some studies, however, only reported the number of trials performed and not the number retained for analysis following artifact rejection.

In order to confirm this study's main effect of group on P2 amplitudes remained evident when the P2 potential was derived from a waveform representing the average of more trials, we evaluated the amplitude of the P2 potential after generating waveforms that represented the average of all artifact-free trials from both conditions (mean (95% CI) of 54 and 55 (±4) trials for the group with and without LBP, respectively [$T = 0.53$, $P = 0.60$]). Consistent with the original 2-factor ANOVA analysis, the group with LBP exhibited significantly less negative or more positive P2 amplitudes than the group without LBP at the FCz (mean = 1.44 vs. −2.08 μV; [$T = 3.36$, $P = 0.0027$]) and CPz (mean = −0.58 vs. −3.90 μV; [$T = 2.36$, $P = 0.027$]) electrodes, but not at the Cz electrode (mean = −1.18 vs. −3.98 μV; [$T = 1.67$, $P = 0.11$]).

## Discussion

The results partially support our hypothesis that people with LBP would exhibit altered postural responses, impaired detection of the postural perturbation, and enhanced late-phase monitoring of postural challenge. The subjects with LBP exhibited evidence of enhanced

late-phase cortical monitoring of postural challenge (as determined by P2 amplitudes) and altered postural responses that were characterized by enhanced knee motion, ankle dorsiflexion, and trunk flexion, diminished trunk extension, as well as delayed trunk muscle responses and trunk flexion. Correlation analyses also supported our hypothesis that altered cortical and postural response characteristics would associate with clinical measures of activity interference and pain-related fear. Specifically, the subjects with LBP who reported greater pain-related fears and interference in daily life exhibited larger induced postural displacement and more enhanced use of the knee, perhaps as an avoidance strategy to limit use of the back. In contrast, the subjects with LBP who exhibited less pain-related fear and interference in daily life exhibited less postural displacement and greater cortical monitoring of postural challenge. Contrary to our hypothesis, the results demonstrated that the subjects with LBP did not exhibit significantly different levels of neural processing related to the detection of postural error (as determined by N1 amplitudes) or significantly different amplitudes and timing of induced postural (CoM) displacement.

Although this study's demonstration of delayed trunk-muscle responses is consistent with past reports (Radebold et al., 2000; Radebold et al., 2001; Cholewicki et al., 2005; Reeves et al., 2005), we did not replicate previous reports of increased postural displacement with LBP (Henry et al., 2006; Mok et al., 2011; Ayhan et al., 2015). Inconsistencies could reflect differences among studies in subject characteristics: this study demonstrated that CoM displacement associates with subject-reported levels of pain-related fears and interference in daily life; thus any inter-study differences in these subject characteristics could translate to inter-study differences in CoM displacements. The inconsistencies could also reflect differences in the perturbation characteristics among studies; our study utilized a small low-velocity perturbation of platform rotation in order to limit artifact in EEG recording. Thus, our perturbation may not have been as large of a postural challenge as provided in other studies to elicit group differences in CoM displacement due to LBP.

The lack of difference between the groups with and without LBP in CoM displacements coincides with a lack of difference in N1 amplitudes and latencies. We had predicted diminished N1 amplitudes, because people with LBP exhibit (1) impaired proprioception and kinesthetic control that relates to altered use of the trunk during standing balance (Gill and Callaghan, 1998; Brumagne et al., 2000; Brumagne et al., 2008; Lee et al., 2010; Claeys et al., 2011; Johanson et al., 2011), and (2) delayed muscle responses to postural perturbations (Radebold et al., 2000; Radebold et al., 2001; Cholewicki et al., 2005; Reeves et al., 2005) that suggest impaired proprioceptive signaling (Inglis et al., 1994; Stapley et al., 2002). As such, we anticipated a diminished capacity of the nervous system to detect error in postural status. The evidence from this study suggests, however, that the detection of postural error is intact with LBP, likely because the proprioceptive impairment is isolated to the trunk and people with LBP redistribute their control strategy to distal body segments (Brumagne et al., 2008; Claeys et al., 2011; Jacobs et al., 2011). This study supports such a redistribution of control strategy to distal body segments as demonstrated by the enhanced use of the knee with diminished trunk extension and delayed trunk flexion.

This study's finding that people with LBP exhibit increased P2 potential amplitudes suggests that LBP associates with an enhanced monitoring of postural challenge and is consistent

with an enhanced influence of the cerebral cortex on postural control with LBP. Previous studies on postural coordination during voluntary arm-raising tasks have demonstrated that the area of cortical activation, or the responsive area to cortical stimulation, is larger in subjects with LBP, and that the cortical activation or change in responsiveness correlates with measures of postural coordination for subjects with LBP (Tsao et al., 2008; Jacobs et al., 2010). It was unexpected, however, that the value of the P2 potential often did not reach positive magnitudes and, instead, exhibited negative values of the voltage signal. Although previous research demonstrates positive values of the P2 potential (Quant et al., 2004b; Quant et al., 2005; Mochizuki et al., 2009a), the magnitude of the P2 is known to depend on the extent of ongoing postural challenge (Mochizuki et al., 2009a), and the previous studies utilized transient perturbations that allowed reacquisition of the original postural orientation. Our study utilized a small perturbation that may not have required a large enough P2 potential to recover from the negativity of the N1 potential; that is, the postural challenge was not as high because the perturbation was not as large. Alternatively, the lack of rebound from the N1 potential to positive values of the P2 potential could reflect this study's use of a surface rotation that generated a sustained toes-up or toes-down postural orientation, which could have elicited a sustained negativity of postural error. A combination of these factors may explain the results of our study, such that the control subjects identified the postural perturbation through an N1 potential, and then the negativity was sustained because their final postural orientation was not at a level surface and they did not perceive an ongoing postural challenge to elicit a large positive P2 potential. The subjects with LBP likewise may have detected the postural perturbation through an N1 potential, and then some negativity may have been sustained due to the continued error in postural orientation on a rotated surface, but they may have perceived a greater level of postural challenge, which elicited a less negative or more positive P2 potential.

In addition to identifying differences between groups with and without LBP in postural and cortical responses to perturbed standing balance, this study also demonstrated that, within the group of subjects with LBP, the cortical monitoring of postural challenge and the induced postural displacement of the response were correlated with each other and with clinically relevant measures of pain-related interference and fears. Consistent with previous research that demonstrated altered postural responses independent of current pain state in people with a history of LBP (MacDonald et al., 2010), the perturbation evoked potentials and induced postural displacement were not significantly correlated with pain severity. Although expected that pain-related fears and interference in daily life would associate with cortical processing and postural displacement, the direction of the association was unexpected. Because increasing P2 amplitudes correlated with decreasing levels of pain-related fears and interference – and both were associated with decreasing induced postural displacement – the results suggest that enhanced cortical monitoring of postural challenge is part of an adaptive compensation. Although correlative, the results suggest interactions among very automatic processes of postural control and pain-related cognitions or disability that are potentially modifiable with intervention. These correlations may help explain the value of combination therapies that include both cognitive-behavioral therapy and physical exercises (Khan et al., 2014).

Lastly, we provide a novel quantitative analysis on the number of trials needed to achieve stable N1 and P2 potential amplitudes. Dietz et al., 1985, qualitatively reported that waveforms appeared stable when they represented averages of 30, 100 or 300 trials. In our analysis, significant differences in N1 or P2 potential amplitudes were not evident when generated from waveforms derived from an average of 15, 20 or 25 trials, and the amplitudes were also highly correlated among these derivations. The stability of the N1 and P2 potentials became tenuous, however, when averaging only 5 or 10 trials. Given our study's use of 27 to 28 trials per condition for each group, as well as the robustness of our group effects on P2 amplitudes when derived from these trial numbers versus when derived from an average of over 50 trials across both conditions, we are confident that our reported N1 and P2 potential amplitudes are stable representations of the response. Further, given the number of trials utilized in past studies of perturbation evoked potentials is often about 30 trials per condition, assuming generalizability of our findings to other studies, it is likely we can have confidence in the stability of the waveform across the literature on this topic.

In summary, subjects with LBP exhibit delayed trunk-muscle responses and altered kinematic strategies that suggest an attempt to minimize trunk extension through enhanced distal limb responses. The use of a knee strategy with LBP, however, appears maladaptive because it associates with larger induced postural displacement (although still within the range of postural displacement exhibited by subjects without LBP), and those who exhibit larger induced postural displacement also exhibit higher levels of pain-related fears and interference on daily life. In contrast, subjects with LBP who appear well-adapted to their condition exhibit smaller induced postural displacement and higher levels of cortical monitoring of postural challenge. People with LBP retain the capacity for cortical detection of a postural perturbation, and their response characteristics and perturbation evoked potentials are unrelated to pain severity. These correlative results suggest need for further longitudinal or intervention studies on the interaction of pain-related cognitions, automatic processes of postural coordination, and clinical outcomes of disability.

## Acknowledgments

The authors wish to thank Bryana Park, Kim Copley, and Karen Lomond for their participation in data collection and processing. We also thank Dee Physical Therapy, Evolution Physical Therapy and Yoga, University of Vermont Medical Center (previously Fletcher Allen Health Care), Timberlane Physical Therapy, and Physical Therapy of Copley Hospital for help with subject recruitment. The study was supported by the National Institutes of Health, National Center for Research Resources, award number P20 RR016435.

## Abbreviations

| | |
|---|---|
| **ANOVA** | Analysis of Variance |
| **BPI** | Brief Pain Inventory Short Form |
| **CoM** | center of mass |
| **CPz** | electroencephalographic electrode located mid-sagittal at the central-parietal region |
| **CSQ** | Coping Strategies Questionnaire |

| | |
|---|---|
| **Cz** | electroencephalographic electrode located mid-sagittal at the central region |
| **EEG** | electroencephalography |
| **EMG** | electromyography |
| **EO** | external oblique |
| **ES** | erector spinae |
| **FABQ** | Fear Avoidance Beliefs Questionnaire |
| **FCz** | electroencephalographic electrode located mid-sagittal at the frontal-central region |
| **LBP** | low back pain |
| **N1** | negative peak electroencephalographic potential in response to postural perturbation |
| **P2** | positive peak electroencephalographic potential in response to postural perturbation |
| **RA** | rectus abdominus |

## References


Ackermann H, Diener HC, Dichgans J. Mechanically evoked cerebral potentials and long-latency muscle responses in the evaluation of afferent and efferent long-loop pathways in humans. Neurosci Lett. 1986; 66:233–238. [PubMed: 3725188]

Adkin AL, Campbell AD, Chua R, Carpenter MG. The influence of postural threat on the cortical response to unpredictable and predictable postural perturbations. Neurosci Lett. 2008; 435:120–125. [PubMed: 18337005]

Adkin AL, Quant S, Maki BE, McIlroy WE. Cortical responses associated with predictable and unpredictable compensatory balance reactions. Exp Brain Res. 2006; 172:85–93. [PubMed: 16418848]

Allison GT. Trunk muscle onset detection technique for EMG signals with ECG artefact. J Electromyogr Kinesiol. 2003; 13:209–216. [PubMed: 12706601]

Ayhan C, Bilgin S, Aksoy S, Yakut Y. Functional contributors to poor movement and balance control in patients with low back pain: A descriptive analysis. J Back Musculoskelet Rehabil. 2015

Berger W, Horstmann GA, Dietz V. Interlimb coordination of stance in children: divergent modulation of spinal reflex responses and cerebral evoked potentials in terms of age. Neurosci Lett. 1990; 116:118–122. [PubMed: 2259442]

Bolton DA. The role of the cerebral cortex in postural responses to externally induced perturbations. Neurosci Biobehav Rev. 2015; 57:142–155. [PubMed: 26321589]

Brumagne S, Cordo P, Lysens R, Verschueren S, Swinnen S. The role of paraspinal muscle spindles in lumbosacral position sense in individuals with and without low back pain. Spine (Phila Pa 1976). 2000; 25:989–994. [PubMed: 10767813]

Brumagne S, Janssens L, Knapen S, Claeys K, Suuden-Johanson E. Persons with recurrent low back pain exhibit a rigid postural control strategy. Eur Spine J. 2008; 17:1177–1184. [PubMed: 18594876]

Cholewicki J, Silfies SP, Shah RA, Greene HS, Reeves NP, Alvi K, Goldberg B. Delayed trunk muscle reflex responses increase the risk of low back injuries. Spine (Phila Pa 1976). 2005; 30:2614–2620. [PubMed: 16319747]

Claeys K, Brumagne S, Dankaerts W, Kiers H, Janssens L. Decreased variability in postural control strategies in young people with non-specific low back pain is associated with altered proprioceptive reweighting. Eur J Appl Physiol. 2011; 111:115–123. [PubMed: 20824281]

Dempster WT. Space requirements of the seated operator: geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs. WADC Technical Report. 1955; 1:55–159.

Dietz V, Quintern J, Berger W. Cerebral evoked potentials associated with the compensatory reactions following stance and gait perturbation. Neurosci Lett. 1984; 50:181–186. [PubMed: 6493623]

Dietz V, Quintern J, Berger W, Schenck E. Cerebral potentials and leg muscle e.m.g. responses associated with stance perturbation. Exp Brain Res. 1985; 57:348–354. [PubMed: 3972035]

Drake JD, Callaghan JP. Elimination of electrocardiogram contamination from electromyogram signals: An evaluation of currently used removal techniques. J Electromyogr Kinesiol. 2006; 16:175–187. [PubMed: 16139521]

Duckrow RB, Abu-Hasaballah K, Whipple R, Wolfson L. Stance perturbation-evoked potentials in old people with poor gait and balance. Clin Neurophysiol. 1999; 110:2026–2032. [PubMed: 10616107]

Gill KP, Callaghan MJ. The measurement of lumbar proprioception in individuals with and without low back pain. Spine (Phila Pa 1976). 1998; 23:371–377. [PubMed: 9507628]

Henry SM, Hitt JR, Jones SL, Bunn JY. Decreased limits of stability in response to postural perturbations in subjects with low back pain. Clin Biomech (Bristol, Avon). 2006; 21:881–892.

Hodges P, van den Hoorn W, Dawson A, Cholewicki J. Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. J Biomech. 2009; 42:61–66. [PubMed: 19062020]

Hodges PW, Richardson CA. Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. Spine (Phila Pa 1976). 1996; 21:2640–2650. [PubMed: 8961451]

Hoy D, March L, Brooks P, Blyth F, Woolf A, Bain C, Williams G, Smith E, Vos T, Barendregt J, Murray C, Burstein R, Buchbinder R. The global burden of low back pain: estimates from the Global Burden of Disease 2010 study. Ann Rheum Dis. 2014; 73:968–974. [PubMed: 24665116]

Inglis JT, Horak FB, Shupert CL, Jones-Rycewicz C. The importance of somatosensory information in triggering and scaling automatic postural responses in humans. Exp Brain Res. 1994; 101:159–164. [PubMed: 7843295]

Jacobs JV, Henry SM, Jones SL, Hitt JR, Bunn JY. A history of low back pain associates with altered electromyographic activation patterns in response to perturbations of standing balance. J Neurophysiol. 2011; 106:2506–2514. [PubMed: 21795622]

Jacobs JV, Henry SM, Nagle KJ. People with chronic low back pain exhibit decreased variability in the timing of their anticipatory postural adjustments. Behav Neurosci. 2009; 123:455–458. [PubMed: 19331469]

Jacobs JV, Henry SM, Nagle KJ. Low back pain associates with altered activity of the cerebral cortex prior to arm movements that require postural adjustment. Clin Neurophysiol. 2010; 121:431–440. [PubMed: 20071225]

Jacobs JV, Horak FB. Cortical control of postural responses. J Neural Transm (Vienna). 2007; 114:1339–1348. [PubMed: 17393068]

Jacobs JV, Lomond KV, Hitt JR, DeSarno MJ, Bunn JY, Henry SM. Effects of low back pain and of stabilization or movement-system-impairment treatments on induced postural responses: A planned secondary analysis of a randomised controlled trial. Man Ther. 2016; 21:210–219. [PubMed: 26324322]

Johanson E, Brumagne S, Janssens L, Pijnenburg M, Claeys K, Paasuke M. The effect of acute back muscle fatigue on postural control strategy in people with and without recurrent low back pain. Eur Spine J. 2011; 20:2152–2159. [PubMed: 21533851]

Jones SL, Henry SM, Raasch CC, Hitt JR, Bunn JY. Individuals with non-specific low back pain use a trunk stiffening strategy to maintain upright posture. J Electromyogr Kinesiol. 2012; 22:13–20. [PubMed: 22100719]

Keller S, Bann CM, Dodd SL, Schein J, Mendoza TR, Cleeland CS. Validity of the brief pain inventory for use in documenting the outcomes of patients with noncancer pain. Clin J Pain. 2004; 20:309–318. [PubMed: 15322437]

Khan M, Akhter S, Soomro RR, Ali SS. The effectiveness of Cognitive Behavioral Therapy (CBT) with general exercises versus general exercises alone in the management of chronic low back pain. Pak J Pharm Sci. 2014; 27:1113–1116. [PubMed: 25016276]

Kuriyama N, Ito H. Electromyographic functional analysis of the lumbar spinal muscles with low back pain. J Nippon Med Sch. 2005; 72:165–173. [PubMed: 16046833]

Langevin HM, Sherman KJ. Pathophysiological model for chronic low back pain integrating connective tissue and nervous system mechanisms. Med Hypotheses. 2007; 68:74–80. [PubMed: 16919887]

Lee AS, Cholewicki J, Reeves NP, Zazulak BT, Mysliwiec LW. Comparison of trunk proprioception between patients with low back pain and healthy controls. Arch Phys Med Rehabil. 2010; 91:1327–1331. [PubMed: 20801248]

Little CE, Woollacott M. EEG measures reveal dual-task interference in postural performance in young adults. Exp Brain Res. 2015; 233:27–37. [PubMed: 25273924]

MacDonald D, Moseley GL, Hodges PW. People with recurrent low back pain respond differently to trunk loading despite remission from symptoms. Spine (Phila Pa 1976). 2010; 35:818–824. [PubMed: 20228708]

Marlin A, Mochizuki G, Staines WR, McIlroy WE. Localizing evoked cortical activity associated with balance reactions: does the anterior cingulate play a role? J Neurophysiol. 2014; 111:2634–2643. [PubMed: 24647435]

Maughan EF, Lewis JS. Outcome measures in chronic low back pain. Eur Spine J. 2010; 19:1484–1494. [PubMed: 20397032]

Mazaheri M, Coenen P, Parnianpour M, Kiers H, van Dieen JH. Low back pain and postural sway during quiet standing with and without sensory manipulation: a systematic review. Gait Posture. 2013; 37:12–22. [PubMed: 22796243]

McIlroy WE, Maki BE. Preferred placement of the feet during quiet stance: development of a standardized foot placement for balance testing. Clin Biomech (Bristol, Avon). 1997; 12:66–70.

Mierau A, Hulsdunker T, Struder HK. Changes in cortical activity associated with adaptive behavior during repeated balance perturbation of unpredictable timing. Front Behav Neurosci. 2015; 9:272. [PubMed: 26528154]

Mochizuki G, Boe S, Marlin A, McIlRoy WE. Perturbation-evoked cortical activity reflects both the context and consequence of postural instability. Neuroscience. 2010; 170:599–609. [PubMed: 20633605]

Mochizuki G, Sibley KM, Cheung HJ, Camilleri JM, McIlroy WE. Generalizability of perturbation-evoked cortical potentials: Independence from sensory, motor and overall postural state. Neurosci Lett. 2009a; 451:40–44. [PubMed: 19110034]

Mochizuki G, Sibley KM, Cheung HJ, McIlroy WE. Cortical activity prior to predictable postural instability: is there a difference between self-initiated and externally-initiated perturbations? Brain Res. 2009b; 1279:29–36. [PubMed: 19422812]

Mochizuki G, Sibley KM, Esposito JG, Camilleri JM, McIlroy WE. Cortical responses associated with the preparation and reaction to full-body perturbations to upright stability. Clin Neurophysiol. 2008; 119:1626–1637. [PubMed: 18479966]

Mok NW, Brauer SG, Hodges PW. Changes in lumbar movement in people with low back pain are related to compromised balance. Spine (Phila Pa 1976). 2011; 36:E45–52. [PubMed: 21192214]

Newcomer KL, Jacobson TD, Gabriel DA, Larson DR, Brey RH, An KN. Muscle activation patterns in subjects with and without low back pain. Arch Phys Med Rehabil. 2002; 83:816–821. [PubMed: 12048661]

Oostenveld R, Praamstra P. The five percent electrode system for high-resolution EEG and ERP measurements. Clin Neurophysiol. 2001; 112:713–719. [PubMed: 11275545]

Quant S, Adkin AL, Staines WR, Maki BE, McIlroy WE. The effect of a concurrent cognitive task on cortical potentials evoked by unpredictable balance perturbations. BMC Neurosci. 2004a; 5:18. [PubMed: 15147586]

Quant S, Adkin AL, Staines WR, McIlroy WE. Cortical activation following a balance disturbance. Exp Brain Res. 2004b; 155:393–400. [PubMed: 14968271]

Quant S, Maki BE, McIlroy WE. The association between later cortical potentials and later phases of postural reactions evoked by perturbations to upright stance. Neurosci Lett. 2005; 381:269–274. [PubMed: 15896482]

Quintern J, Berger W, Dietz V. Compensatory reactions to gait perturbations in man: short- and long-term effects of neuronal adaptation. Neurosci Lett. 1985; 62:371–376. [PubMed: 4094724]

Radebold A, Cholewicki J, Panjabi MM, Patel TC. Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. Spine (Phila Pa 1976). 2000; 25:947–954. [PubMed: 10767807]

Radebold A, Cholewicki J, Polzhofer GK, Greene HS. 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). 2001; 26:724–730. [PubMed: 11295888]

Reeves NP, Cholewicki J, Milner TE. Muscle reflex classification of low-back pain. J Electromyogr Kinesiol. 2005; 15:53–60. [PubMed: 15642653]

Rosenstiel AK, Keefe FJ. The use of coping strategies in chronic low back pain patients: relationship to patient characteristics and current adjustment. Pain. 1983; 17:33–44. [PubMed: 6226916]

Scholtes SA, Gombatto SP, Van Dillen LR. Differences in lumbopelvic motion between people with and people without low back pain during two lower limb movement tests. Clin Biomech (Bristol, Avon). 2009; 24:7–12.

Shum GL, Crosbie J, Lee RY. 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). 2005a; 30:1998–2004. [PubMed: 16135992]

Shum GL, Crosbie J, Lee RY. Symptomatic and asymptomatic movement coordination of the lumbar spine and hip during an everyday activity. Spine (Phila Pa 1976). 2005b; 30:E697–702. [PubMed: 16319739]

Sibley KM, Mochizuki G, Frank JS, McIlroy WE. The relationship between physiological arousal and cortical and autonomic responses to postural instability. Exp Brain Res. 2010; 203:533–540. [PubMed: 20424830]

Stapley PJ, Ting LH, Hulliger M, Macpherson JM. Automatic postural responses are delayed by pyridoxine-induced somatosensory loss. J Neurosci. 2002; 22:5803–5807. [PubMed: 12122040]

Tsao H, Galea MP, Hodges PW. Reorganization of the motor cortex is associated with postural control deficits in recurrent low back pain. Brain. 2008; 131:2161–2171. [PubMed: 18669505]

Vlaeyen JW, Crombez G. Fear of movement/(re)injury, avoidance and pain disability in chronic low back pain patients. Man Ther. 1999; 4:187–195. [PubMed: 10593107]

Waddell G, Newton M, Henderson I, Somerville D, Main CJ. A Fear-Avoidance Beliefs Questionnaire (FABQ) and the role of fear-avoidance beliefs in chronic low back pain and disability. Pain. 1993; 52:157–168. [PubMed: 8455963]

Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D'Lima DD, Cristofolini L, Witte H, Schmid O, Stokes I. Standardization Terminology Committee of the International Society of B. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine. International Society of Biomechanics. J Biomech. 2002; 35:543–548. [PubMed: 11934426]

## Highlights

- Neural mechanisms of impaired postural responses with low back pain (LBP) assessed.
- Responses to platform rotations recorded by electroencephalography (EEG), electromyography (EMG), and kinematics.
- Subjects with LBP had larger perturbation-evoked EEG responses, delayed EMG onsets, and altered joint-angle displacements.
- EEG responses and center-of-mass displacements correlated with questionnaire measures of pain-related fears and disability.

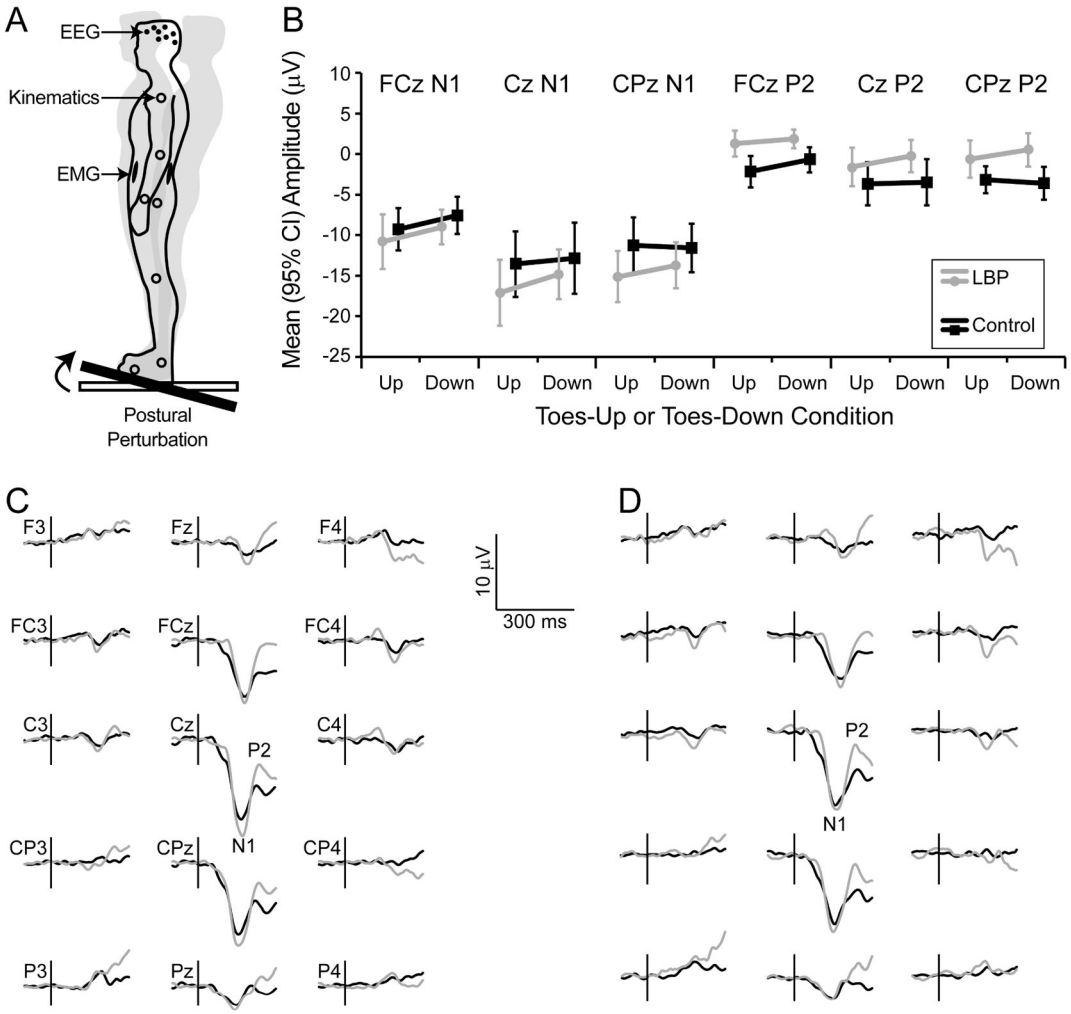


**Fig. 1.**

**(A)** Schematic of task, illustrating toes-up perturbations; toes-down perturbations also applied. **(B)** Group mean (95% confidence intervals) N1 and P2 potential amplitudes. N1 potentials are on the left and P2 potentials are on the right for each electrode location of FCz, Cz, and CPz. Statistically significant group differences evident for only the P2 potential amplitudes at FCz and CPz. Grand mean waveforms presented for the **(C)** toes-up and **(D)** toes-down conditions in order to demonstrate waveform topography and characteristics. Gray lines and symbols represent the group with LBP and the black lines and symbols represent the control group without LBP.

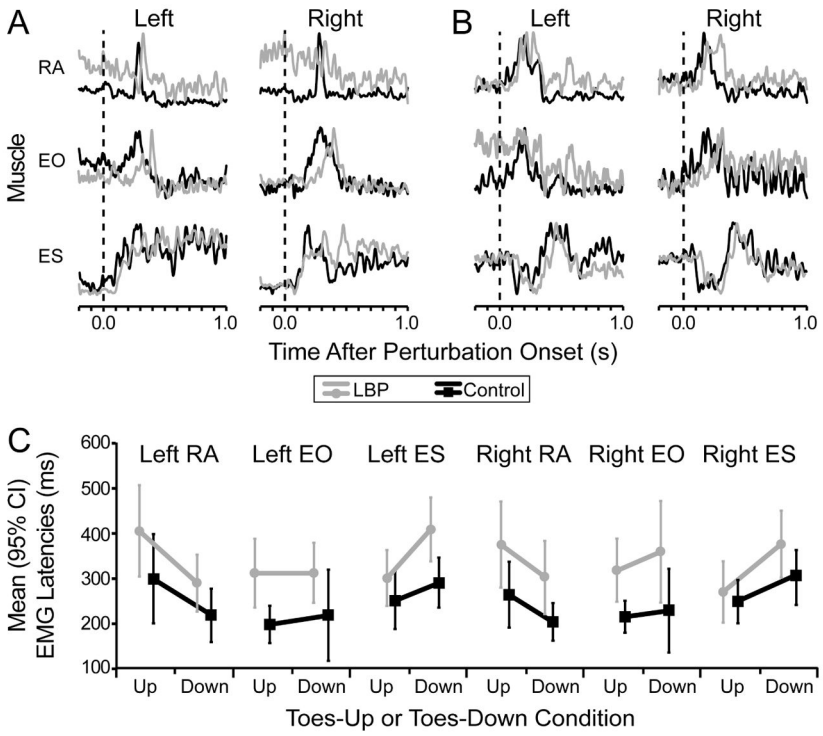


**Fig. 2.**

Grand mean EMG traces for each group in response to **(A)** toes-up and **(B)** toes-down perturbations. **(C)** Group mean (95% confidence intervals) EMG onset latencies. Gray lines and symbols represent the group with LBP and the black lines and symbols represent the control group without LBP. RA = rectus abdominus, EO = external oblique, and ES = erector spinae. Statistically significant group main effects were evident for the right RA and EO muscles, as well as a significant difference at the left ES muscle for the toes-down condition.

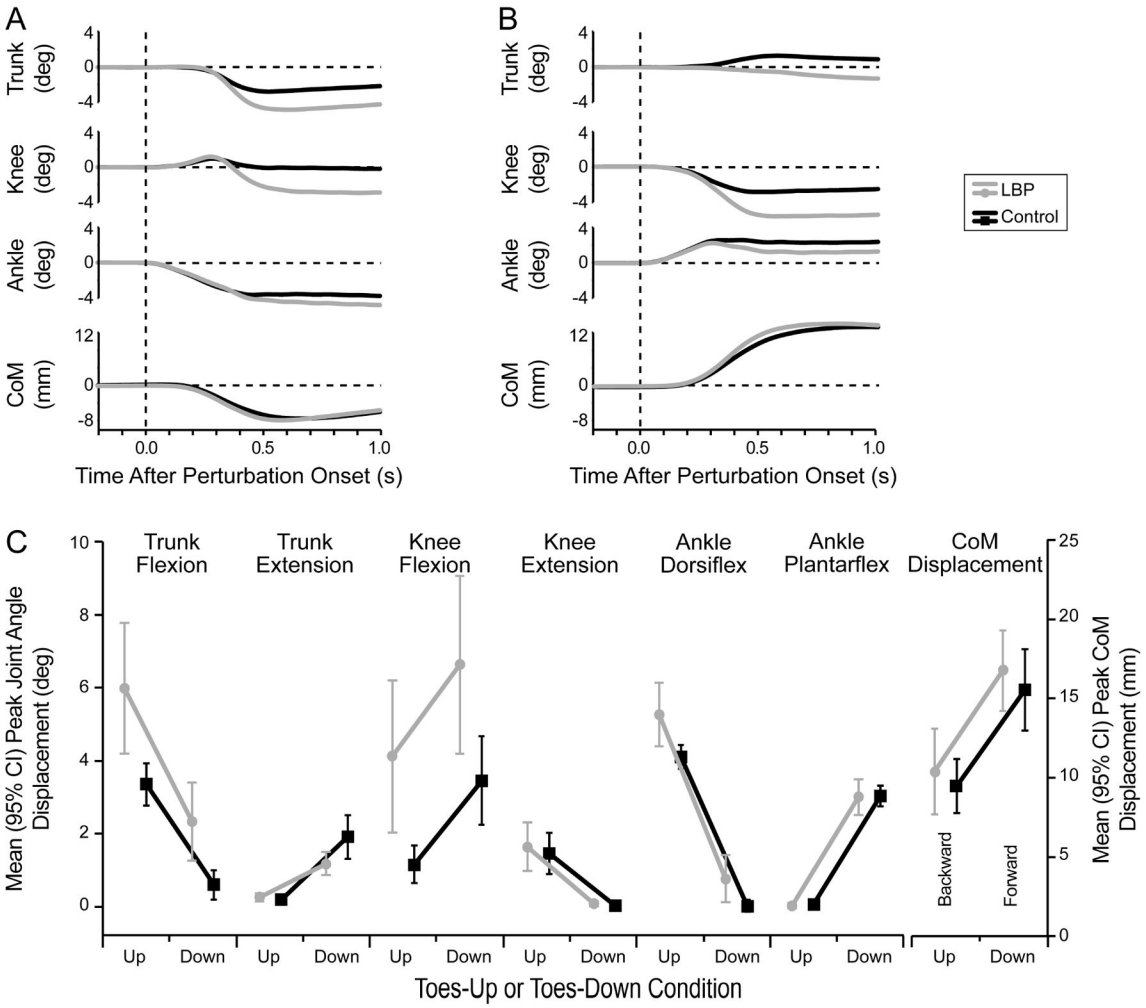


**Fig. 3.**

Grand mean joint-angle and center-of-mass (CoM) traces for each group in response to **(A)** toes-up and **(B)** toes-down rotations. Upward represents joint extension, ankle plantarflexion, or forward CoM displacement; downward, joint flexion, ankle dorsiflexion, or backward CoM displacement. **(C)** Group mean (95% confidence intervals) joint-angle and CoM displacements across both conditions. Gray lines and symbols represent the group with LBP and the black lines and symbols represent the control group without LBP. Statistically significant group main effects were evident for trunk flexion, knee flexion, and ankle dorsiflexion, with a significant group-by-condition interaction for trunk extension.

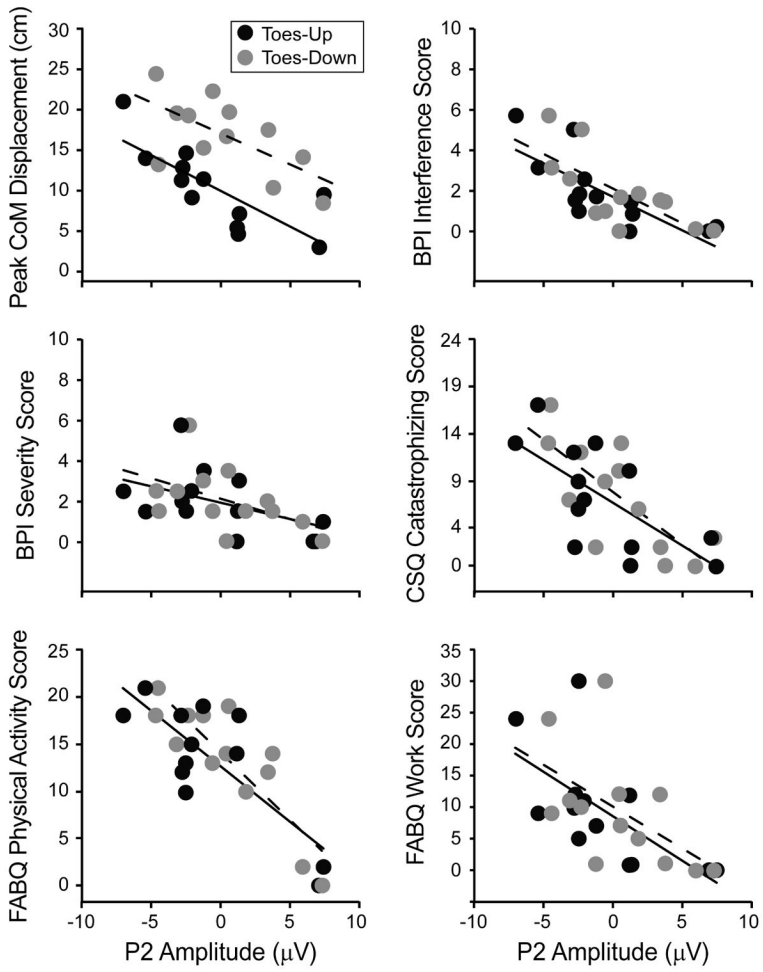


**Fig. 4.**

Scatter plots illustrating associations of P2 potential amplitudes from the CPz electrode with peak center-of-mass (CoM) displacements, Brief Pain Inventory (BPI) pain interference and severity scores, Coping Strategies Questionnaire (CSQ) catastrophizing scores, and the Fear Avoidance Beliefs Questionnaire (FABQ) physical activity and work scores. Circles represent individual subjects with LBP. Black-filled circles and the solid black fit line represent findings from the toes-up condition; gray-filled circles and the dashed black fit line represent findings from the toes-down condition. Statistically significant correlations with P2 potential amplitudes at the CPz electrode were evident for each variable except BPI severity.

## Table 1

Group Characteristics

| | Participant Group | | Statistic (P-Value) |
|---|---|---|---|
| | With LBP | Without LBP | |
| Number (Female, Male) | 13 (8, 5) | 13 (9, 4) | Fisher's $Chi^2$ = 0.70 (P = 1.0) |
| Mean (95% CI) Age, yr | 37 (31–43) | 35 (29–40) | T = 0.62 (P = 0.54) |
| Mean (95% CI) Height, m | 1.69 (1.63–1.75) | 1.66 (1.61–1.72) | T-Test = 0.68 (P = 0.51) |
| Mean (95% CI) Weight, kg | 65 (59–71) | 68 (60–77) | T-Test = 0.61 (P = 0.55) |
| Mean (95% CI) Heel-to-Heel Stance Width, cm | 18.6 (17.9–19.2) | 18.3 (17.7–18.9) | T-Test = 0.69 (P = 0.50) |
| Mean (95% CI) Brief Pain Inventory Pain Severity Score | 2.02 (1.10–2.94) | 0.04 (−0.05–0.12) | T-Test = 4.67 (P = 0.00052) |
| Mean (95% CI) Brief Pain Inventory Interference Score | 1.9 (0.8–3.0) | 0 (0–0) | T-Test = 3.86 (P = 0.0023) |
| Mean (95% CI) Fear Avoidance Beliefs Questionnaire Physical Activity Score | 13.4 (9.6–17.2) | 0 (0–0) | T-Test = 7.64 (P < 0.0001) |
| Mean (95% CI) Fear Avoidance Beliefs Questionnaire Work Score | 9.4 (3.9–14.9) | 0 (0–0) | T-Test = 3.71 (P = 0.0030) |
| Mean (95% CI) Coping Strategies Questionnaire Catastrophizing Score | 7.2 (3.9–10.6) | 0.5 (−0.4–1.3) | T-Test = 4.24 (P = 0.00089) |

## Table 2

Mean (95% CI) Latencies of Peak EEG Potentials and Peak Kinematic Displacements

| Measure | Condition | Participant Group | | Group and Interaction Effects: F-Value, P-Value, $\eta_p^2$ |
|---|---|---|---|---|
| | | With LBP | Without LBP | |
| N1 Latencies at FCz, Cz, and CPz, ms | Toes Up | 172 (158–185), 166 (152–180), 155 (140–171) | 162 (141–183), 169 (143–196), 156 (136–177) | Range of Group Effects: 0.12–0.59, 0.45–0.73, 0.005–0.025<br>Range of Interaction Effects: 0.19–0.39, 0.54–0.67, 0.008–0.017 |
| | Toes Down | 178 (168–188), 165 (150–181), 154 (137–170) | 174 (155–192), 173 (148–198), 160 (136–185) | |
| P2 Latencies at FCz, Cz, and CPz, ms | Toes Up | 251 (224–278), 238 (208–268), 244 (213–275) | 229 (182–277), 235 (193–277), 239 (198–280) | Range of Group Effects: 0.02–1.47, 0.24–0.90, 0.001–0.060<br>Range of Interaction Effects: 0.00–0.14, 0.71–0.99, 0.000–0.006 |
| | Toes Down | 263 (238–288), 240 (215–265), 239 (214–263) | 238 (208–268), 237 (204–271), 239 (207–271) | |
| CoM Latency, ms | Toes Up | 660 (586–733) | 680 (618–741) | Group: 0.20, 0.66, 0.008<br>Interaction: 0.019, 0.89, 0.001 |
| | Toes Down | 799 (732–866) | 811 (735–888) | |
| Trunk Extension Latency, ms | Toes Up | 200 (157–243) | 174 (123–225) | Group: 0.80, 0.38, 0.034<br>Interaction: 3.41, 0.078, 0.13 |
| | Toes Down | 477 (386–567) | 568 (470–666) | |
| Trunk Flexion Latency, ms | Toes Up | 606 (530–682) | 595 (544–647) | Group: 4.07, 0.055, 0.15<br>Interaction: 4.74, 0.040, 0.17 |
| | Toes Down | 513 (399–627) | 317 (173–460) | |
| Knee Extension Latency, ms | Toes Up | 346 (271–421) | 336 (269–403) | Group: 0.25, 0.62, 0.011<br>Interaction: 0.04, 0.85, 0.002 |
| | Toes Down | 109 (9–209) | 85 (19–151) | |
| Knee Flexion Latency, ms | Toes Up | 567 (427–707) | 478 (350–605) | Group: 1.61, 0.22, 0.065<br>Interaction: 0.25, 0.62, 0.011 |
| | Toes Down | 568 (503–633) | 527 (440–615) | |
| Ankle Plantarflexion Latency, ms | Toes Up | 25 (0–58) | 13 (1–24) | Group: 0.14, 0.71, 0.006<br>Interaction: 0.00, 0.99, 0.00 |
| | Toes Down | 575 (443–706) | 561 (472–650) | |
| Ankle Dorsiflexion Latency, ms | Toes Up | 752 (656–847) | 721 (634–808) | Group: 2.47, 0.13, 0.093<br>Interaction: 0.98, 0.33, 0.039 |
| | Toes Down | 191 (42–340) | 66 (0–143) | |