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Center of pressure trajectories, trunk kinematics and trunk muscle activation during unstable sitting in low back pain patients

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ABSTRACT

Trunk motor behavior has been reported to be altered in low-back pain. This may be associated with impaired lumbar proprioception, which could be compensated by trunk stiffening. We assessed trunk control by measuring center-of-pressure, lumbar kinematics and trunk muscle electromyography in 20 low-back pain patients and 11 healthy individuals during a seated balancing task, in conditions with and without disturbance of lumbar proprioception and occlusion of vision. We hypothesized that low-back pain patients show larger postural sway, but smaller thoraco-lumbar movements than healthy individuals. Repeated measures analyses of variance indicated that the effects of proprioception disturbance and vision occlusion were similar between groups. Interestingly, low-back pain patients grabbed the safety rail more often, while differences between groups in sway measures were rather subtle. This suggests that low-back pain patients were more cautious. Furthermore, low-back pain patients had an about 20 degrees less flexed lumbar posture than healthy individuals, and, in contrast to our hypothesis, made larger thoraco-lumbar movements in the sagittal plane, as indicated by higher SDs of thoraco-lumbar flexion and lower (more negative) correlations between pelvis and thorax movements. Activation of the intersegmental longissimus relative to the iliocostalis muscle, which spans all lumbar segments, was lower in low-back pain patients compared to healthy individuals. This difference in muscle activation may be causal for larger thoraco-lumbar movements, and may be causative of reduced control over segmental lumbar movement, but may also reflect the need for larger corrective movements to compensate balance impairments.

1. Introduction

Differences in trunk motor behavior between low-back pain (LBP) patients and healthy control (HC) subjects have been reported in upright standing [1,2], walking [3,4] and sitting [5,6]. Findings from studies with lumbar muscle vibration, which is known to perturb proprioceptive feedback from muscle spindles [7], suggest that these differences in motor control could in part be explained by impaired proprioception in LBP-patients [8]. Consequently, to compensate for proprioceptive deficits, LBP-patients may use trunk muscle activation strategies aimed at trunk stiffening, in order to protect the painful area [9].

Seated balancing, i.e. balancing on a chair with the lower extremities supported and a hemisphere under the seat, allows studying trunk control in an implicit, challenging and natural way, while avoiding compensation by knee and ankle motion. Previous studies compared LBP-patients and HC-subjects during this task in terms of either center-of-pressure (CoP) trajectories [10,11] or trunk kinematics [12]. Radebold et al. found that balance performance in LBP-patients was lower than in HC-subjects, especially in more challenging conditions [10], while Van Dieën et al. found larger CoP-amplitudes in subjects with a recent history of LBP, but not in subjects with current LBP [11]. The latter group demonstrated lower CoP-frequencies which was in line with earlier suggestions that LBP-patients stiffen their lumbar spine [9,13,14]. However, while such a trunk stiffening strategy would result in smaller movements of the spine, Van Daele et al. reported larger pelvis and trunk movements in LBP-patients [12]. Regrettably the authors did not report lumbar spine (i.e. trunk relative to pelvis) motion. So, although seated balancing seems a convenient task for studying trunk control [15], and published data point at impaired seated balance in patients, the exact nature of differences between patients and controls, and more specifically the question whether or not patients employ a stiffening strategy, remain to be elucidated.

Therefore, our goal was to evaluate CoP-trajectories, trunk kinematics and trunk muscle activation during seated balancing in LBP-patients. In addition, we evaluated the effects of eliminating

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visual information and disturbing proprioception on postural balance. We hypothesized that LBP-patients show larger CoP-movements, coinciding with larger trunk movements, but smaller movements of the lumbar spine. In line with this, LBP-patients were hypothesized to show larger ratios of longissimus over iliocostalis, and lumbar over thoracic longissimus muscle electromyography (EMG) amplitudes, since larger ratios would reflect lumbar spine stiffening strategies. This assumption is based on differences in anatomical characteristics between muscles, i.e. the number of spinal segments crossed is larger for the iliocostalis than for the longissimus muscle and larger for the thoracic compared to the lumbar part of the longissimus muscle [16]. Model calculations indicate that preferential recruitment of muscles with multiple intersegmental insertions, over their synergist that cross more spinal segments, leads to a higher stiffness of the lumbar area [14,17,18]. Based on indications of impaired proprioception in LBP-patients, we further hypothesized that LBP-patients show larger deterioration of balance when vision is occluded and that disturbance of proprioception, through lumbar muscle vibration, degrades balance performance more in HC-subjects.

2. Methods

2.1. Participants

Twenty LBP-patients (9 female) and 11 HC-subjects (4 female) participated in the experiment. Subjects in the LBP-group had experienced LBP during the last 6 weeks or longer, and any specific diagnosis had been excluded by a general practitioner or physical therapist. Subjects were excluded when they had had previous surgery on the spine or scored >105 on a questionnaire identifying psychosocial risk factors [19,20]. Subjects participating in the HC-group did not experience LBP during the previous year. No differences between groups were found in age (HC: 32.6 ± 10.4, LBP: 33.4 ± 15.5 years, $p = 0.893$) and BMI (HC: 22.5 ± 2.5, LBP: 23.6 ± 3.0 kg/m^2, $p = 0.312$). LBP-patients scored 2.7 ± 1.7 on a 10 cm visual analog pain scale at the start of the measurements. The experimental protocol was approved by the local medical ethical committee and all subjects provided informed consent.

2.2. Experimental setup

An aluminum hemisphere (radius: 25 cm) was attached underneath a seat, creating instability in all directions (height of the seat relative to the lowest point of the hemisphere: 17 cm). An adjustable footplate was attached to the seat, in order to limit the influence of the lower extremities to balance control by keeping knee and angle angles fixed at 90° (Fig. 1). Three force transducers (KAP-E, AST, Germany) recorded vertical forces with 200 samples/s. A safety rail surrounded the seat, to provide security in case of balance loss. A pulse-signal was generated when subjects touched the rail.

Trunk kinematics were measured by opto-electronic markers (Optotrak 3020, Northern Digital Inc., Canada) on the spinous processes of the T1, T7, L4 and L5 vertebrae at a rate of 100 samples/s. Trunk muscle surface EMG was used to record activation of four back muscles bilaterally (Porti 17, TMS-Enschede, The Netherlands, 22-bits AD-conversion after 20× amplification, input impedance > 10^{12} Ω, CMRR > 90 dB). The skin was shaved and cleaned with alcohol. Based on a detailed anatomical study [16], we placed bipolar electrodes (Ag/AgCl) 4 cm lateral to T9, 6 cm lateral to T11 and L2, and 3 cm lateral to the midpoint between the spinous processes of L3 and L4, reflecting activation of the thoracic longissimus and iliocostalis muscles, and the lumbar iliocostalis and longissimus muscles, respectively. EMG-signals were recorded at a rate of 1000 samples/s and a pulse-signal synchronized the EMG-recordings to the opto-electronic and force-plate data.

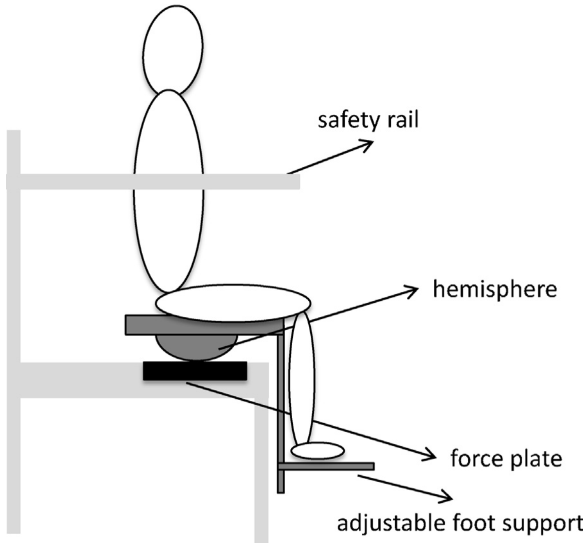

Fig. 1. Schematic representation of the experimental setup.

To apply lumbar muscle vibration, we used a motor (Maxon Graphite Brushes S2326.946 driven by a 4-Q-DC Servo Control LSC30/2 in a velocity loop) rotating an eccentric mass. Vibration frequency was 90 Hz, and the vibration device was attached at the level of L3/4 by neoprene bands (Fig. 2).

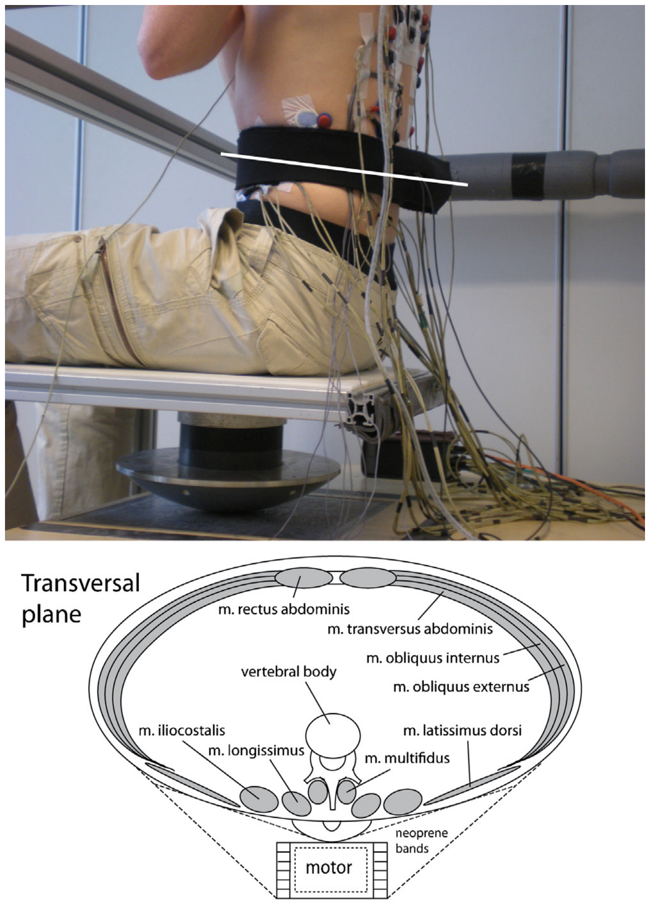

Fig. 2. Lumbar muscle vibration was applied at the level of L3/L4. A custom-made holder (shown in lower panel) ensured bilateral vibration of the paraspinal muscles, while leaving the spinous processes free.

2.3. Experimental protocol

To prevent influence of the upper extremities, subjects were instructed to place their hands on the contra-lateral shoulders. Subjects started each trial with the hands on the rail and after a 5 s count-down, moved the arms toward the instructed position. Data collection started 5 s later, to provide a fixed amount of time to obtain a steady-state. For each trial, 50 s of data were collected and between trials, subjects held the rail in order to prevent fatigue and learning effects. One practice trial was performed, in which subjects practiced to sit as quietly as possible, but also explored their 'stable' range of motion. During the experimental trials, subjects were instructed to sit as quietly as possible. In case of balance loss, subjects grabbed the safety rail, but continued the balancing task as quickly as possible.

In the reference condition (REF), subjects performed the task with their eyes open and without lumbar muscle vibration. In the condition with lumbar muscle vibration (VIB), vibration was applied continuously throughout the trial. In the condition with eyes closed (ECL), subjects were instructed to keep their eyes closed during the measurement. The order of the REF and VIB-conditions was counterbalanced between subjects and the ECL-condition was always performed afterwards. All conditions were performed twice.

3. Data analysis

Data were analyzed in Matlab 7.10.0 (R2010a) and the two repetitions of each condition were averaged. Details on data analysis are described below.

3.1. CoP trajectories

A running average over 2 data points down-sampled the vertical forces to 100 samples/s and forces were 8 Hz low-pass filtered (2nd order bi-directional Butterworth) before CoP-trajectories were calculated. Root-mean-square differences of the CoP with respect to its mean in the frontal (RMSx) and sagittal (RMSy) planes quantified sway amplitude. In addition, mean velocity of the resultant of the CoP-excursions in x- and y-direction (meanV) was calculated, since it is a highly reliable and sensitive parameter in this task [21]. Spectral content (Welch's periodogram method, windowsize 10s with 9s overlap) of the CoP-trajectories was quantified via mean power frequencies in the frontal (MPFx) and sagittal (MPFy) planes. Finally, short-term diffusion coefficients (DSx and DSy) were calculated to evaluate the level of stochastic control of trunk posture [21,22].

3.2. Thoraco-lumbar kinematics

Since the vibration device covered some opto-electronic markers, thoraco-lumbar kinematics were only calculated for the REF and ECL-conditions. Opto-electronic data were 2.5 Hz low-pass filtered (2nd order bi-directional Butterworth). Lines through the T1–T7 and through the L4–L5 spinous processes reflected the high-thoracic and low-lumbar angle, respectively. Means and SDs of their difference, reflecting thoraco-lumbar flexion, as well as the correlation between high-thoracic and low-lumbar angles over time series, were calculated in the frontal and sagittal planes.

3.3. Trunk muscle activation

We applied eight repetitive band-stop filters to remove 50 Hz interference and its harmonics up to 400 Hz (4th order bi-directional Butterworth; target frequency $\pm$ 0.5 Hz). Subsequently, EMG-signals were 30 Hz high-pass filtered (2nd order bi-directional Butterworth), to reduce contamination by the electrocardiogram, and absolute Hilbert amplitudes were calculated. VIB-conditions were discarded from this analysis since vibration affected the EMG-signals. In four LBP-patients, left lumbar iliocostalis signals were discarded from analysis due to technical malfunctioning. After averaging over left and right muscles, ratios of longissimus over iliocostalis (long/ilioc) and of lumbar over thoracic (lumb/thor) longissimus muscle EMG-amplitudes were calculated, with larger ratios reflecting activation aimed at spinal stiffening [14,17,18].

3.4. Statistics

Statistics were performed in SPSS 16.0, using repeated measures ANOVAs with group (HC vs. LBP) as between-subjects factor, condition as within-subjects factor and $\alpha = 0.05$. For CoP-measures, three conditions (REF, VIB and ECL) were included and post hoc pairwise comparisons (with Bonferroni adjustments) were made to test the effects of VIB and ECL with respect to the REF-condition. For thoraco-lumbar kinematics and EMG-ratios the within-subjects factor only included the REF and ECL-condition. Since many outcome measures deviated from a normal distribution, we applied a Fisher-transformation to the correlations and log-transformed the other data before running the statistical tests.

4. Results

4.1. CoP-trajectories

Strikingly, six LBP-patients grabbed the safety rail 2.2 ± 1.6 (range 1–5) times, all during the ECL-condition, while only one HC-subject grabbed the safety rail once, during the REF-condition. Because subjects continued the task immediately after any balance loss, and to prevent introducing a bias between groups by excluding trials with large CoP-excursions, both trials with and without balance loss were included in the analysis.

RMS, MPF and DS are shown in Fig. 3. No effect of group was found on RMS and MPF (all $p \geq 0.312$). Larger diffusion coefficients, indicating more 'random' control, were found in LBP-patients, with this difference between groups reaching significance in the frontal ($p = 0.044$), but not in the sagittal plane ($p = 0.068$). MeanV tended to be about 20% larger in LBP-patients (1.15 ± 0.34 cm/s vs. 0.94 ± 0.17 cm/s in HC-subjects), but this effect did not reach significance ($p = 0.069$).

Significant main effects of condition were found on meanV and on RMS and DS in both directions, but not on MPF. Pairwise comparisons revealed a 12% increase in meanV due to lumbar muscle vibration (REF: 0.78 ± 0.24 cm/s vs. VIB: 0.87 ± 0.27 cm/s, $p = 0.003$). Significant effects of vibration were also found on DS (both $p \leq 0.026$), but not on RMS (both $p \geq 0.376$). In the ECL-condition, meanV approximately doubled to 1.57 ± 0.50 cm/s and RMS and DS were significantly larger in both directions (all $p < 0.001$). No significant interactions between group and condition were found on any COP-measure (all $p \geq 0.086$).

4.2. Thoraco-lumbar kinematics

Kinematics data from two LBP-patients were not available, so these results are based on 18 LBP-patients. Since no significant differences between groups were found in the frontal plane (all $p \geq 0.351$), Fig. 4 shows thoraco-lumbar kinematics in the sagittal plane only. Trunk posture was about 20° more upright in LBP-patients than in HC-subjects ($p = 0.007$). In addition, and in contrast with our hypotheses, LBP-patients demonstrated larger SDs of thoraco-lumbar flexion ($p = 0.005$), coinciding with a lower (more negative) correlation between high-thoracic and low-lumbar segment angles ($p = 0.018$) compared to HC-subjects, implying that thoraco-lumbar movements were larger in LBP-patients.

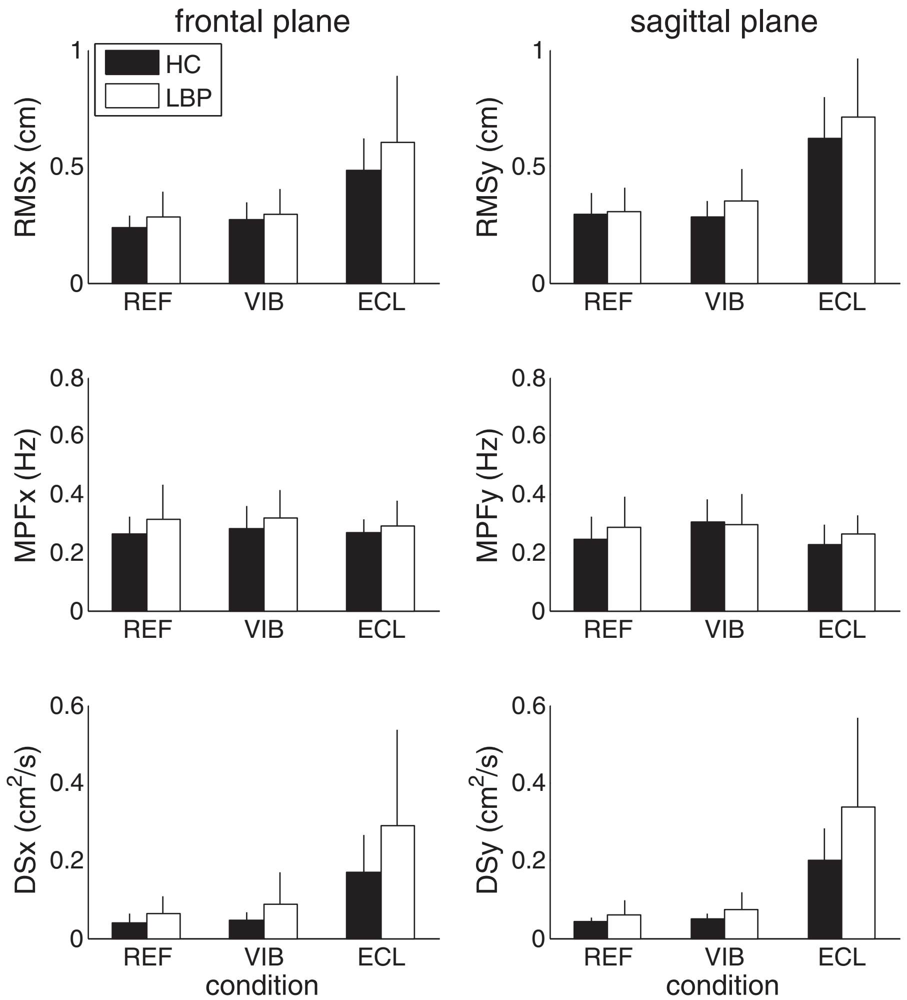

Fig. 3. Seated balancing CoP-amplitude (upper panel), frequency (middle panel) and level of stochastic control (lower panel) in both planes of motion in the reference (REF), vibration (VIB) and eyes closed (ECL) conditions for healthy control (HC) and low back pain (LPB) groups. Error bars represent SDs over subjects within groups.

Vision occlusion resulted in an increase of thoraco-lumbar movements ($p < 0.001$), while the average thoraco-lumbar flexion and the correlation between low-lumbar and high-thoracic angles were unaffected (all $p \geq 0.215$). No significant interactions between group and vision condition were found on thoraco-lumbar kinematics (all $p \geq 0.093$).

4.3. EMG ratios

In contrast with our hypothesis, the long/ilioc ratio (Fig. 5, left panel) was significantly lower in LBP-patients compared to HC-subjects ($p = 0.004$). The lumb/thor ratio (Fig. 5, right panel) appeared somewhat higher in LBP-patients, but this difference did not reach significance ($p = 0.177$). No significant main effects of vision occlusion and no significant interactions between group and vision occlusion were found on EMG-ratios (all $p \geq 0.101$).

5. Discussion

We compared CoP-trajectories, thoraco-lumbar kinematics and EMG-ratios between LBP-patients and HC-subjects during a seated balancing task. The differences between groups were most

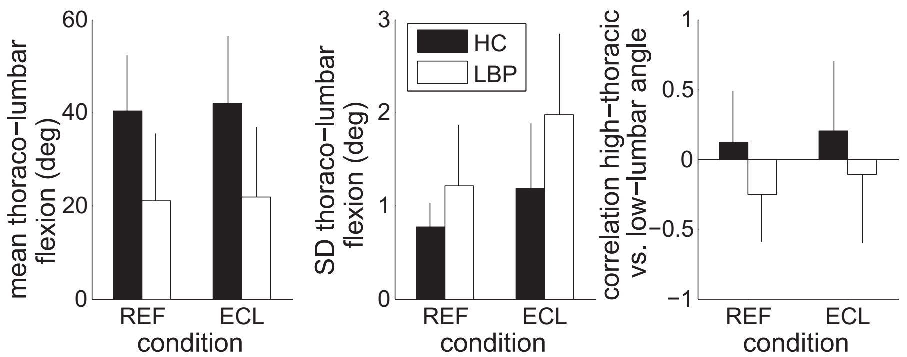

Fig. 4. Thoraco-lumbar kinematics in the sagittal plane for both groups in the reference and eyes closed conditions. Error bars represent SDs between subjects within groups.

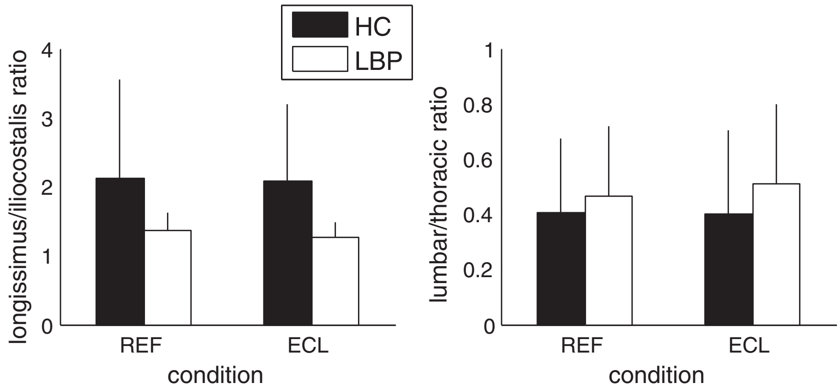

Fig. 5. EMG-ratios for both groups in the reference and eyes closed conditions. Error bars represent SDs between subjects within groups.

prominent in thoraco-lumbar kinematics, with, in contrast to our hypothesis, larger thoraco-lumbar movements in LBP-patients. Moreover, LBP-patients demonstrated more upright trunk postures than HC-subjects. Surprisingly, the ratio of longissimus over iliocostalis muscle activation was lower in the LBP-group. Since the effects of lumbar muscle vibration and vision occlusion were similar in both groups, differences in task performance could not be attributed to differences in weighting of these information sources. Instead, differences in trunk muscle recruitment may explain the current findings.

The long/ilioc and lumb/thor EMG-ratios were hypothesized to be higher in LBP-patients under the assumption that these ratios would reflect trunk stiffening strategies. The finding that neither long/ilioc, nor lumb/thor EMG-ratios were higher with LBP, together with the findings that sway frequency was not lower and thoraco-lumbar movements were not smaller in LBP-patients compared to HC-subjects, suggests that LBP-patients did not stiffen their spine during unstable sitting. Surprisingly, the long/ilioc ratio was in fact smaller and thoraco-lumbar movements were larger in LBP-subjects. Preferential recruitment of the longissimus muscle, which has multiple segmental insertions, may allow for subtle adjustments of lumbar curvature, while increased activation of the iliocostalis muscle, which spans more lumbar segments and has a larger moment arm, would cause larger thoraco-lumbar movements. While this interpretation, implying more subtle control in HC-subjects than in LBP-subjects, could explain the current findings, future studies will be needed to elucidate the causality of these differences in trunk muscle recruitment and LBP. Specifically, we do not know whether this activation pattern caused larger movements, or was a response to the necessity to make larger movements as a consequence of other deficits, e.g. delayed responses [10].

The rather subtle differences between groups in terms of CoP-trajectories could not fully explain the finding that LBP-patients grabbed the safety rail more often that the HC-subjects. Since sway amplitude did not differ between groups, we think that LBP-patients were more cautious and grabbed the safety rail quicker to prevent expected balance loss, while the HC-subjects took more risk in maintaining balance without touching the safety rail.

We found a lower (more negative) correlation between thorax and pelvis movements in LBP-patients compared to HC-subjects, which appears to be in contrast with previous findings [12]. However, although Van Daele et al. interpreted their between-subjects correlation of trunk and pelvis angular deviations as support for the trunk stiffening hypothesis [12], the high correlation only indicates that subjects with large angular deviations of the pelvis also demonstrated large angular deviations of the thorax. We calculated correlations per subject in the time domain, which, in accordance with the larger SD of thoraco-lumbar angle, was lower in LBP-patients compared to HC-subjects, indicative of more countermovement of the thorax and pelvis segments in the patients.

In contrast to previous findings on trunk control in other experimental tasks [8,23], no reduced effect of lumbar muscle vibration was found in the LBP-group. Moreover, paraspinal muscle vibration did not affect sway amplitude or frequency. These findings, combined with the large effect of closing the eyes, suggest that certainly visual and possibly vestibular information were dominant in this seated balancing task. This supports a recent finding on standing on an unstable surface, that the relative importance of proprioception may be reduced when no direct relation exists between proprioceptive feedback and orientation of the body relative to the gravitational field [24].

We did not normalize EMG to percentages of (sub)maximal voluntary contractions, since this may introduce a bias between groups [9]. We are confident that the reported ratios of EMG-amplitudes provide robust measures of trunk muscle recruitment. Unfortunately, we cannot exclude that the difference in mean thoraco-lumbar flexion between the groups may partly explain the differences in the other outcome measures. A future study with specific instructions on trunk posture could elucidate the relation between thoraco-lumbar flexion and balancing behavior. Furthermore, no intramuscular EMG was recorded, so activation of deep muscle fibers was only partly detected [25,26]. Although we therefore cannot exclude that LBP-patients used a stiffening strategy based on recruitment of deep muscles, this would not fit with the group effects found on kinematics. Moreover, reported changes in activity of deep muscles in LBP-patients [27,28] indicate inhibition rather than increased activity of these muscles. One might speculate that such inhibition could underlie the larger amplitudes of trunk movements due to insufficient stabilization of the lumbar spine. Future studies could measure intramuscular EMG during seated balancing to evaluate the contribution of deep intersegmental muscle fibers.

In conclusion, LBP-patients demonstrated trunk control that differed from HC-subjects during a seated balancing task. While being more cautious can explain why LBP-patients grabbed the safety rail more often, LBP-patients also showed more upright trunk postures and larger thoraco-lumbar movements compared to HC-subjects. Furthermore, LBP-patients showed lower activation of the intersegmental longissimus muscle relative to the iliocostalis muscle, which spans all lumbar segments.

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Conflict of interest

There are no known conflicts of interest.

References

[1] Lafond D, Champagne A, Descarreaux M, Dubois JD, Prado JM, Duarte M. Postural control during prolonged standing in persons with chronic low back pain. Gait and Posture 2009;29(3):421–7.
[2] Brumagne S, Janssens L, Janssens E, Goddyn L. Altered postural control in anticipation of postural instability in persons with recurrent low back pain. Gait and Posture 2008;28(4):657–62.
[3] Lamoth CJ, Meijer OG, Daffertshofer A, Wuisman PI, Beek PJ. Effects of chronic low back pain on trunk coordination and back muscle activity during walking: changes in motor control. European Spine Journal 2006;15(1):23–40.
[4] van den Hoorn W, Bruijn SM, Meijer OG, Hodges PW, van Dieën JH. Mechanical coupling between transverse plane pelvis and thorax rotations during gait is higher in people with low back pain. Journal of Biomechanics 2012;45(2): 342–7.
[5] Dunk NM, Callaghan JP. Lumbar spine movement patterns during prolonged sitting differentiate low back pain developers from matched asymptomatic controls. Work 2010;35(1):3–14.
[6] Dankaerts W, O'Sullivan P, Burnett A, Straker L. Differences in sitting postures are associated with nonspecific chronic low back pain disorders when patients are subclassified. Spine 2006;31(6):698–704.
[7] Roll JP, Vedel JP. Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography. Experimental Brain Research 1982;47(2):177–90.
[8] 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. European Journal of Applied Physiology 2011;111(1):115–23.
[9] van Dieën JH, Selen LP, Cholewicki J. Trunk muscle activation in low-back pain patients, an analysis of the literature. Journal of Electromyography and Kinesiology 2003;13(4):333–51.
[10] 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 2001;26(7):724–30.
[11] van Dieën JH, Koppes LL, Twisk JW. Low back pain history and postural sway in unstable sitting. Spine 2010;35(7):812–7.
[12] Van Daele U, Hagman F, Truijen S, Vorlat P, Van Gheluwe B, Vaes P. Differences in balance strategies between nonspecific chronic low back pain patients and healthy control subjects during unstable sitting. Spine 2009;34(11):1233–8.
[13] Mok NW, Brauer SG, Hodges PW. Failure to use movement in postural strategies leads to increased spinal displacement in low back pain. Spine 2007;32(19):E537–43.
[14] van Dieën JH, Cholewicki J, Radebold A. Trunk muscle recruitment patterns in patients with low back pain enhance the stability of the lumbar spine. Spine 2003;28(8):834–41.
[15] Cholewicki J, Polzhofer GK, Radebold A. Postural control of trunk during unstable sitting. Journal of Biomechanics 2000;33(12):1733–7.
[16] Macintosh JE, Bogduk N. The attachments of the lumbar erector spinae. Spine 1991;16(7):783–92.
[17] Bergmark A. Stability of the lumbar spine. A study in mechanical engineering. Acta Orthopaedica Scandinavica 1989;230:1–54.
[18] Crisco JJ, Panjabi MM. The intersegmental and multisegmental muscles of the lumbar spine—a biomechanical model comparing lateral stabilizing potential. Spine 1991;16(7):793–9.
[19] Kendall NAS, Linton SJ, Main CJ. Guide to assessing psycho-social yellow flags in acute low back pain: risk factors for long-term disability and work loss, 1997. Wellington, New Zealand: Accident Compensation Corporation and the New Zealand Guidelines Group; 2004, October.
[20] Linton SJ, Hallden K. Risk factors and the natural course of acute and recurrent musculoskeletal pain: developing a screening questionnaire. In: Proceedings of the 8th world congress on pain; 1996.
[21] van Dieën JH, Koppes LL, Twisk JW. Postural sway parameters in seated balancing: their reliability and relationship with balancing performance. Gait and Posture 2010;31(1):42–6.
[22] Collins JJ, De Luca CJ. Open-loop and closed-loop control of posture: a random-walk analysis of center-of-pressure trajectories. Experimental Brain Research 1993;95(2):308–18.
[23] Willigenburg NW, Kingma I, Hoozemans MJM, van Dieën JH. Precision control of trunk movement in low back pain patients. Human Movement Science, in press.
[24] Kiers H, Brumagne S, van Dieën J, van der Wees P, Vanhees L. Ankle proprioception is not targeted by exercises on an unstable surface. European Journal of Applied Physiology 2012;112(4):1577–85.
[25] Marshall P, Murphy B. The validity and reliability of surface EMG to assess the neuromuscular response of the abdominal muscles to rapid limb movement. Journal of Electromyography and Kinesiology 2003;13(5):477–89.
[26] Stokes IA, Henry SM, Single RM. Surface EMG electrodes do not accurately record from lumbar multifidus muscles. Clinical Biomechanics 2003;18(1): 9–13.
[27] Hodges PW, Moseley GL. Pain and motor control of the lumbopelvic region: effect and possible mechanisms. Journal of Electromyography and Kinesiology 2003;13(4):361–70.
[28] Hodges PW, Richardson CA. Delayed postural contraction of transversus abdominis in low back pain associated with movement of the lower limb. Journal of Spinal Disorders 1998;11(1):46–56.