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Postural sway and integration of proprioceptive signals in subjects with LBP

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ABSTRACT

Patients with non-specific low back pain (LBP) may use postural control strategies that differ from healthy subjects. To study these possible differences, we measured the amount and structure of postural sway, and the response to muscle vibration in a working cohort of 215 subjects. Subjects were standing on a force plate in bipedal stance. In the first trial the eyes were open, no perturbation applied. In the following 6 trials, vision was occluded and subjects stood under various conditions of vibration/no vibration of the lumbar spine or m. Triceps Surae (TSM) on firm surface and on foam surface. We performed a factor analysis to reduce the large amount of variables that are available to quantify all effects. Subjects with LBP showed the same amount of sway as subjects without LBP, but the structure of their sway pattern was less regular with higher frequency content. Subjects with LBP also showed a smaller response to TSM vibration, and a slower balance recovery after cessation of vibration when standing on a solid surface. There was a weak but significant association between smaller responses to TSM vibration and an irregular, high frequency sway pattern, independent from LBP. A model for control of postural sway is proposed. This model suggests that subjects with LBP use more co-contraction and less cognitive control, to maintain a standing balance when compared to subjects without LBP. In addition, a

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reduced weighting of proprioceptive signals in subjects with LBP is suggested as an explanation for the findings in this study.

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1. Introduction

A greater understanding of possible causes and mechanisms underlying the development and the persistence of low back pain (LBP) is needed for the development of new and better treatment strategies (Costa et al., 2013). Changes in motor control have been established in subjects with LBP, and could be one of the mechanisms that could cause LBP or could result from LBP and then play a role in persistence or recurrence (Hodges & Tucker, 2011).

Postural control, the part of motor control involved in maintaining an upright position (Massion, 1992), is often studied by analyzing postural sway. Postural sway is usually quantified as the movement of the center of pressure (CoP), the point at which the resultant of the exerted forces is applied to the support surface. Recently, two reviews investigating standing postural sway in subjects with LBP were published. The majority of the included studies reported an increased postural sway in LBP, or no effect of LBP on postural sway. In a minority of studies, a decreased sway was found in patients with LBP (Mazaheri, Coenen, Parnianpour, Kiers, & van Dieen, 2013; Ruhe, Fejer, & Walker, 2011a). No systematic differences that could explain these differences were identified (Mazaheri et al., 2013). Only studies that used sway amplitude or velocity related variables were included. Non-linear variables, that give insight into the dynamic structure of the sway pattern, have been used much less frequently in LBP research. This is surprising since CoP regularity has helped understanding the complexity of changes in postural control in many other pathologies. For example, increased regularity of postural sway has been interpreted as evidence of increased cognitive control over posture (Donker, Roerdink, Greven, & Beek, 2007), to compensate for impairments due to e.g., contusion (Cavanaugh et al., 2005), cerebral palsy (Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008), Ehlers–Danlos syndrome (Rigoldi et al., 2013) and stroke (Roerdink et al., 2006).

Postural control depends, among other sources of information, on proprioception, which may be impaired in subjects with LBP (Brumagne, Lysens, & Spaepen, 1999; Gill & Callaghan, 1998; O'Sullivan et al., 2003; Willigenburg, Kingma, Hoozemans, & van Dieen, 2013; Yilmaz et al., 2010). The relative weight assigned to proprioceptive signals from a specific body part can be quantified by means of muscle vibration. Muscle vibration is a potent stimulus for muscle spindles (Burke, Hagbarth, Lofstedt, & Wallin, 1976; Roll, Vedel, & Ribot, 1989) and muscle spindles play the major role in the detection of movement (Proske & Gandevia, 2012). Under vibration, the muscle is usually perceived to be longer than it actually is (Cordo, Gurfinkel, Brumagne, & Flores-Vieira, 2005; Goodwin, McCloskey, & Matthews, 1972; Roll & Vedel, 1982), and consequently a corrective movement is made. For example, when Triceps Surae muscles (TSM) are vibrated, a backward shift in CoP occurs. The magnitude of the shift depends on the weight that the central nervous system assigns to these artificially induced signals compared to other sources of information (Brumagne, Cordo, & Verschueren, 2004). This weighting is influenced by the surface a person is standing on (Ivanenko, Talis, & Kazennikov, 1999; Kiers, Brumagne, van Dieën, van, & Vanhees, 2011), but is also changed in subjects with LBP (Brumagne et al., 2004; Brumagne, Janssens, Knapen, Claeys, & Suuden-Johanson, 2008; Claeys, Brumagne, Dankaerts, Kiers, & Janssens, 2011).

Based on the above, we were interested in the relationship of LBP with the structure of the postural sway pattern in standing and the effects of muscle vibration. However, the pattern of CoP movement in quiet standing and in response to muscle vibration can be characterized by a large number of parameters. It is unknown which parameters represent unique properties of the sway pattern and which parameters covary. This makes an a priori choice of parameters not possible, while measuring all possible parameters results in an unacceptable increase in the probability of type I errors. A well-known method to reduce dimensionality in multi-dimensional data sets is factor analysis. Therefore, we tested our hypotheses on factor analysis scores.

Our primary research questions were: (1) is there a difference in the amount and/or structure of postural sway between people with LBP and healthy individuals? (2) Is proprioceptive weighting in subjects with LBP different from non-LBP subjects? (3) Is there an association between postural sway and effects of muscle vibration? We hypothesized that, compared to subjects without LBP, subjects with LBP would show a more regular sway pattern, a decrease in response to lumbar paraspinal musculature (LPM) vibration and an increase to TSM vibration, that these differences would increase when standing on foam, and that recovery after cessation of vibration would take more time in subjects with LBP.

2. Methods

We examined a cohort of 215 subjects (162 males, 53 females, age 39 years ± 11, weight 80 kg ± 13, height 179 cm ± 9) from The Utrecht Police Lifestyle Intervention Fitness and Training (UPLIFT) study. The UPLIFT study is a voluntary fitness and lifestyle test for police employees in Utrecht, The Netherlands. Data for the present study were collected between December 2007 and June 2008. All subjects provided written informed consent and the protocol had been approved by the Ethical Committee of University Medical Center Utrecht. Subjects presenting with neurological disorders, vestibular impairment or pathologies of the lower extremities were excluded. The subjects were asked for any LBP, which was defined as “pain in the lumbar and sacral region”. For the purpose of this study, we collected pain intensity in the hour preceding the test, with a Numeric Rating Scale (NRS-11), activities and participation level by means of the Oswestry Disability Index (ODI), and Fear Avoidance with the Fear Avoidance Beliefs Questionnaire (FABQ). The duration of the current LBP was also registered. We interpreted a NRS score for LBP of 1 or 2 as discomfort, rather than pain, and classified subjects in two groups: no LBP ($NRS \leqslant 2$), and LBP ($NRS \geqslant 3$). Physical activity was assessed with the Short Questionnaire to Assess Health – Enhancing Physical Activity (SQUASH). The level of Physical Activity was expressed as metabolic equivalent values (PA-MET), in hours per week spent on walking, cycling and sports activities (Ainsworth et al., 2000). The characteristics of the subjects can be found in Table 1. Differences between pain intensity groups were tested for significance with an unpaired *t*-test for normally distributed data, with a Mann–Whitney *U* test for data that were not normally distributed, and with Chi-Square for percentages.

2.1. Experimental procedure

Participants were asked to stand relaxed, immobile and barefoot on a force plate (Kistler 9286 AA), with the feet at shoulder width and the arms hanging loosely by the side. Foot position was marked on a transparent sheet, to ensure an equal position across trials. Seven test conditions were used (Table 1). In all trials, with exception of the first one, vision was occluded by means of taped safety glasses. The first three trials were trials without vibration; (1) upright standing with transparent safety glasses and

Table 1
Description of experimental trials.

Trial	Vision	Surface	Vibration
Stability			
1	Transparent glasses	Solid	No
2	Occluded vision	Solid	No
3	Occluded vision	Foam	No
Vibration	Occluded vision		
1		Solid	Lumbar paraspinal musculature (LPM)
2		Solid	Triceps Surae muscles (TSM)
3		Foam	Lumbar paraspinal musculature (LPM)
4		Foam	Triceps Surae muscles (TSM)

with eyes open, (2) upright standing, and (3) upright standing on a foam support surface (Airex balance pad, 6 cm thick). In the first trial with vibration (1), a muscle vibrator (Maxon motors, Switzerland) was attached with Velcro straps over the lower LPM. In vibration trial 2, muscle vibrators were attached bilaterally to the TSM, also with Velcro straps. Muscle vibration, with a frequency of 70 Hz and amplitude of approximately 0.5 mm, was initiated 15 s after the start of the trial for the duration of 15 s. Each trial lasted for 60 s, with subjects standing on the force plate for 5 s before the trial started. All 60 s were used in the analysis of the CoP data. The same procedure was repeated in vibration trials 3 and 4, but in these trials the subjects were standing on the foam surface. A research assistant was always standing directly behind the participant to prevent falls. Trials in which the research assistant touched the participant to prevent him or her from falling were discarded and repeated after a break of at least five minutes. Two habituation trials with 5 s vibration on LPM in the first, and 5 s vibration on TSM in the 2nd trial, were performed before the test protocol started.

2.2. Data analysis

Force plate data were sampled at 200 Hz using Bioware 3.24 software. Synchronization of the force plate measurements with activation of the vibrators was controlled by custom-made software. All data analysis was done off-line using custom-made Matlab 7.0.1 software (Mathworks, Natick MA, USA). CoP data were filtered with a second order low pass Butterworth filter with a cut-off frequency of 3 Hz.

A broad range of 15 parameters was computed for each stability trial. These parameters were taken from three different categories that are used to describe the CoP pattern: range and velocity, frequency content and nonlinear variables. For a detailed description see Table 3.

For the vibration trials, proprioceptive parameters were included based on the findings in a previous study, and with at least a fair reliability in intra- and inter-day reliability ($ICC > 0.4$) (Kiers, Brumagne, van Dieën, & Vanhees, 2014). The response to muscle vibration was quantified as the difference in mean CoP position before and during vibration (dP), and the difference in mean CoP velocity before and during vibration (dV). dP and dV were calculated as respectively CoP position 15–30th s (during muscle vibration) minus CoP position 0–15th s (preceding muscle vibration); CoP velocity 15–30th s /CoP velocity 0–15th s. Proprioceptive weighting between calf and paravertebral musculature (PW) was characterized by:

$$\mathrm{PWd} = \mathrm{abs}\ dP_{\mathrm{TSM}}/(\mathrm{abs}\ dP_{\mathrm{TSM}} + \mathrm{abs}\ dP_{\mathrm{LPM}}), \quad \text{and}$$

$$\mathrm{PWv} = dV_{\mathrm{TSM}}/(dV_{\mathrm{TSM}} + dV_{\mathrm{LPM}}),$$

where PW stands for proprioceptive weighting, abs for absolute value, TSM for m. Triceps Surae, and LPM for lumbar paraspinal musculature.

Variables describing recovery of the CoP after vibration were analyzed relative to the last five seconds of the vibration period (25–30th s).

2.3. Statistics

A factor analysis with Oblimin rotation with Kaiser normalization was applied separately to sway variables and proprioceptive variables. Factors had to present with an eigenvalue of at least 1 to be considered in further analysis. Items are presented within the factor with their highest loading (Tables 2 and 3). Differences between groups in sway, vibration and recovery factors, were tested with ANCOVA. In all procedures a correction for possible confounders (i.e., gender, age, height, weight and physical activity level) was performed.

Vibration factors that significantly differed between subjects with and subjects without LBP, were tested on their correlation with significant postural sway factors by means of regression. In every model the aforementioned confounders were incorporated, added to these was pain category, to search for an association independent of pain. Alpha was set at 0.05 for all tests. Statistical analysis was performed with SPSS 18.0 (SPSS Inc., Chicago, USA).

Table 2
Characteristics of subjects (means and standard deviations).

	LBP NRS $\leqslant 2$	LBP NRS $\geqslant 3$
n	182	33
Gender (% female)	23%	36%
Age	39 (11)	41.3 (11)
Height	179 (9)	176 (8)
Body mass	80 (13)	80 (13)
Pain (NRS)	0.18 (0.5)	4.5 (1.4)*
ODI	4.5 (9.5)	21.6 (20)*
FABQ work	2.3 (4.6)	7.3 (6.9)*
FABQ physical	3.9 (5.7)	7.4 (6.3)*
Duration of current complaint (days)	322 (1295)	1101 (2170)*
Physical activity (METhour)	52.3 (45.7)	65.1 (51.3)

Pain intensity according to NRS in the preceding hour. ODI = Oswestry Disability Index. FABQ = Fear Avoidance Beliefs Questionnaire. ODI = Oswestry Disability Index. METhour = Metabolic equivalents hours (intensity * duration).

* Significant difference with no LBP group.

3. Results

No significant differences were detected between groups in age, height, weight, gender and physical activity level. The group with moderate to severe pain differed from the group with mild pain in that they showed higher levels of disability (ODI) and pain, but did not differ in fear avoidance and duration of complaints (Table 2). Recovery data were missing for two subjects; one in the LBP group, one in the no LBP group.

Four factors were identified for CoP sway, with a combination of variables that mainly represented velocity and range, and frequency and regularity both on rigid surface and on foam (Table 3). These four factors together explained 66.5% of total variance.

Factor analysis on variables reflecting the reaction to vibration yielded three factors: TSM vibration, LPM vibration and proprioceptive weighting on foam, and LPM vibration and proprioceptive weighting on solid surface. These factors explained 68.2% of the total variance.

Factor analysis of recovery variables resulted in three factors, which explained a total variance of 93%. These factors described recovery on a solid surface, recovery on a foam surface and recovery on solid surface expressed relative to the peak position directly after cessation of vibration on solid surface (Table 4).

Subjects with LBP had significantly ($p = .02$) higher factor scores for factor 3, indicating a sway pattern, which contained higher frequencies and which was less regular. Subjects with LBP showed a smaller response to TSM vibration ($p = .03$). When standing on a solid surface, recovery was significantly slower in subjects with LBP (Table 5).

The response to TSM vibration was, independently from the presence of pain, weakly associated with the sway pattern on foam ($p = .001$), with smaller responses coinciding with high frequency, irregular sway.

4. Discussion

We studied postural sway and proprioceptive weighting in a cohort of 215 subjects. In contrast with our initial hypothesis, we found subjects with LBP not to show increased sway compared to subjects without or with minor LBP pain, but more irregular and higher frequency sway and only when standing on foam. Subjects with LBP also showed less impact of TSM vibration, which was correlated with higher frequency and irregularity of sway, independent from the presence of LBP (Table 6).

Based on the findings in our study and the literature, we propose a model for postural control below (Fig. 1).

Postural sway is in this model determined by three mechanisms, which attenuate internal and external perturbations and make postural sway controllable. Co-contraction increases stiffness and

Table 3
Factor analysis postural sway. Variables are presented with their highest factor loading.

	Factor				
	1	2	3	4	
Postural sway trials 1–3					
trial_1 recurrence 4	−0.893				Recurrence entropy
trial_1 recurrence 2	−0.869				Determinism
trial_1 sample_entropy	0.805				
trial_2 recurrence 2	−0.742				Determinism
trial_2 recurrence 4	−0.737				Recurrence entropy
trial_1 recurrence 1	−0.736				Recurrence rate
trial_1 recurrence 3	−0.731				Mean diagonal length
trial_1 lds1	0.707				Short term Lyapunov exonent (divergence rate from neighboring CoP states over short time interval)
trial_2 recurrence 3	−0.679				Mean diagonal length
trial_1 mpfy	0.654				Mean Power Frequency of anterior–posterior direction
trial_1 mpfx	0.59				Mean Power Frequency of medio-lateral direction
trial_2 sample_entropy	0.588				
trial_2 lds1	0.558				Short term Lyapunov exonent (divergence rate from neighboring CoP states over short time interval)
trial_2 recurrence 1	−0.551				Recurrence rate
trial_2 mpfx	0.513				Mean Power Frequency of medio-lateral direction
trial_2 mpfy	0.476				Mean Power Frequency of anterior–posterior direction
trial_1 rangey		0.865			Distance between max and min CoP position in a/p direction
trial_1 vxy		0.805			Total mean velocity
trial_1 sdy		0.798			Standard deviation of the CoP.in anterior–posterior direction
trial_1 vx		0.762			Mean Velocity in medio-lateral direction
trial_1 vy		0.724			Mean Velocity in anterior–posterior direction
trial_1 sdx		0.718			Standard deviation of the CoP.in medio-lateral direction
trial_1 rangex		0.716			Distance between maximum and minimum CoP position in medio-lateral direction
trial_2 vxy		0.708			Total mean velocity
trial_2 vx		0.696			Mean Velocity in medio-lateral direction
trial_2 rangey		0.677			Distance between max and min CoP position in a/p direction
trial_2 sdy		0.649			Standard deviation of the CoP.in anterior–posterior direction
trial_2 vy		0.631			Mean Velocity in anterior–posterior direction
trial_2 rangex		0.498			Distance between maximum and minimum CoP position in medio-lateral direction
trial_3 recurrence 4			−0.935		Recurrence entropy
trial_3 recurrence 3			−0.918		Mean diagonal length
trial_3 recurrence 2			−0.908		Determinism
trial_3 recurrence 1			−0.778		Recurrence rate
trial_3 sample_entropy			0.776		
trial_3 mpfy			0.711		Mean Power Frequency of anterior–posterior direction
trial_3 mpfx			0.683		Mean Power Frequency of medio-lateral direction
trial_3 lds1			0.603		Short term Lyapunov exponent (divergence rate from neighboring CoP states over short time interval)
trial_3 sdx				0.823	Standard deviation of the CoP.in medio-lateral direction

Table 3 (*continued*)

	Factor				
	1	2	3	4	
trial_3 rangex				0.807	Distance between maximum and minimum CoP position in medio-lateral direction
trial_3 rangey				0.743	Distance between max and min CoP position in a/p direction
trial_3 sdy				0.711	Standard deviation of the CoP.in anterior–posterior direction
trial_3 vxy				0.684	Total mean velocity
trial_3 vx				0.659	Mean Velocity in medio-lateral direction
trial_3 vy				0.604	Mean Velocity in anterior–posterior direction
trial_2 sdx				0.486	Standard deviation of the CoP.in medio-lateral direction

Factors were attributed to 1. Frequency and irregularity on rigid surface, 2. Velocity and range on rigid, 3. Frequency and irregularity on foam, 4. Velocity and range on foam.

damping, which directly attenuates the effects of perturbations. Spinal feedback and supraspinal feedback loops likewise may attenuate perturbations in which the latter use weighted information from multiple sensory inputs. Supra-spinal control, most probably affected by attention, may in addition add feedforward deterministic variation of the CoP, i.e., the planned state need not be static (Zatsiorsky & Duarte, 2000), which could serve an exploratory role (Carpenter, Murnaghan, & Inglis, 2010). There is evidence that conscious control over a task increases postural sway (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Nafati & Vuillerme, 2011) and that withdrawing attention from the postural task leads to a decrease in postural sway (Andersson et al., 2002; Nafati & Vuillerme, 2011; Riley, Baker, & Schmit, 2003).

The contribution of the three controls mechanisms affects the character of the postural sway pattern. Supraspinal feedforward control likely induces a regular CoP sway pattern with low frequency content. Increasing co-contraction ('stiffening') and feedback gains would result in a sway pattern with a higher frequency content. Finally, a prominent use of spinal feedback will increase the sensitivity to muscle vibration.

In contrast with findings in other pathologies (Cavanaugh et al., 2006; Donker et al., 2008; Roerdink et al., 2006; Schmit et al., 2006), subjects with current LBP in the present study showed a more irregular sway pattern with a higher frequency content, when standing on foam. The subjects in these other studies had pathologies that contain larger threats to postural balance than LBP does, such as CVA and Parkinson disease. While standing on foam requires some effort to maintain balance, subjects with LBP may solve this not by increasing attention and supraspinal control of the postural task, but prefer lower level control due to pain distraction (i.e., increasing stiffness through co-contraction or by increasing feedback gains). To our knowledge two studies have been conducted before, in which subjects with LBP were compared to healthy controls with respect to the regularity of sway when standing on foam (Mazaheri, Salavati, Negahban, Sanjari, & Parnianpour, 2010; Sipko & Kuczyński, 2012). In the first study, no significant differences were found (Mazaheri et al., 2010). However, subjects had LBP on NRS <2, while we included subjects with back pain $\geqslant 3$. In our sample, we also included subjects with LBP <3 in the control group. In a separate analysis we did not find a difference in sway frequency and regularity between subjects with a VAS score of 1–2, and subjects without LBP (results not reported). In the second study (Sipko & Kuczyński, 2012), changing the stance condition from solid surface to foam increased sway regularity in subjects with low levels of LBP, while regularity was not affected in subjects with high levels of LBP. The authors conclude in line with our findings, that subjects with high levels of LBP have less cognitive investment in balance control, relying on lower levels of control when standing on foam (Sipko & Kuczyński, 2012).

Lower level control of sway could involve proprioceptive feedback. The gain of the proprioceptive feedback can be assessed with the help of muscle vibration. In earlier studies, a larger response to TSM vibration, and a smaller response to LPM vibration, were found in subjects with LBP than in healthy subjects, both on foam (Brumagne et al., 2008; Johanson et al., 2011) and on a solid surface

Table 4
Results of factor analysis. Variables are presented with their highest factor loading.

	TSM	PW d & LPM foam	PW d & LPM solid	
Variables reflecting the effect of vibration				
dP TSM foam	0.839			Change in CoP mean position during TSM vibration on foam
dP TSM solid	0.801			Change in CoP mean position during TSM vibration on solid surface
dV TSM solid	−0.285			Change in CoP velocity during TSM vibration on solid surface
dP LPM foam		0.885		Change in CoP mean position under vibration of LS
Pw d foam		−0.832		Absolute dp TSM vibration/ (Absolute dp TSM vibration + Absolute dp vibration LS) on foam
dP LPM solid			−0.886	Change in CoP mean position under vibration of LS
Pw d solid			0.739	Absolute dp TSM vibration/(Absolute dp TSM vibration + Absolute dp vibration LS) on solid surface
	Recovery solid	Recovery foam	Recovery peak	
Recovery after vibration. $\mathrm{CoP}_{\mathrm{during}}$ = Mean CoP 25–30th s				
r3035abs solid	1.066			Mean CoP a/p position (xth–yth s) – $\mathrm{CoP}_{\mathrm{during}}$
r3040 abs solid	0.978			Mean CoP a/p position (xth–yth s) – $\mathrm{CoP}_{\mathrm{during}}$
r3540 abs solid	0.835			Mean CoP a/p position (xth–yth s) – $\mathrm{CoP}_{\mathrm{during}}$
avg_pos solid	0.808			Integral of position relative to CoP during
r4045abs solid	0.764			Mean CoP a/p position (xth–yth s) – $\mathrm{CoP}_{\mathrm{during}}$
r4550 abs solid	0.719			Mean CoP a/p position (xth–yth s) – $\mathrm{CoP}_{\mathrm{during}}$
Finalerror solid	0.676			Mean CoP a/p position 55–60 s – $\mathrm{CoP}_{\mathrm{during}}$
r3540 abs foam		0.927		Mean CoP a/p position (xth–yth s) – $\mathrm{CoP}_{\mathrm{during}}$
r3040 abs foam		0.902		Mean CoP a/p position (xth–yth s) – $\mathrm{CoP}_{\mathrm{during}}$
r3540 peak foam		−0.894		(Maximum CoP anterior position after vibration–mean CoP a/p position x–y s)/(Maximum CoP a/p position after vibration – $\mathrm{CoP}_{\mathrm{during}}$) on foam
r4045 peak solid			0.956	(Maximum CoP anterior position after vibration–mean CoP a/p position x–y s)/(Maximum CoP a/p position after vibration – $\mathrm{CoP}_{\mathrm{during}}$) on solid surface
r4550 peak solid			0.944	(Maximum CoP anterior position after vibration–mean CoP a/p position x–y s)/(Maximum CoP a/p position after vibration – $\mathrm{CoP}_{\mathrm{during}}$) on solid surface
r3540 peak solid			0.890	(Maximum CoP anterior position after vibration–mean CoP a/p position x–y s)/(Maximum CoP a/p position after vibration – CoP during) on solid surface

TSM = m. Triceps Surae. LPM = Lumbar paravertebral musculature.

Table 5
Ancova with low back pain as independent variable.

	P value	Direction of effect	Partial Eta Square
Variables reflecting postural sway			
Frequency and irregularity on rigid surface	.893		.000
Velocity and range on rigid	.648		.001
Frequency and irregularity on foam	**.016**	LBP higher frequency and more irregularity	**.028**
Velocity and range on foam	.604		.001
Variables reflecting effects or recovery of vibration			
TSM	**.034**	LBP less displacement	**.021**
PWd & LPM solid	.28		.006
PW d & LPM foam	.172		.009
Recovery solid	.875		.000
Recovery foam	.49		.002
Recovery peak	**.013**	LBP less recovery	**.029**

Gender, age, height, weight and physical activity as covariates. Significant outcomes in bold. TSM = m. Triceps Surae. LPM = Lumbar paravertebral musculature.

Table 6
Associations between proprioceptive variables and postural sway frequency and irregularity.

Variable	Not adjusted for pain			Adjusted for pain		
	B	R^2	*P* value	*B*	R^2	*P* value
TSM	.243	.139	.000	.224	.155	.001
Recovery peak	.079	.093	.239	.053	.115	.433

Gender, age, height, weight and physical activity as covariates. *B* (=standardized Beta).

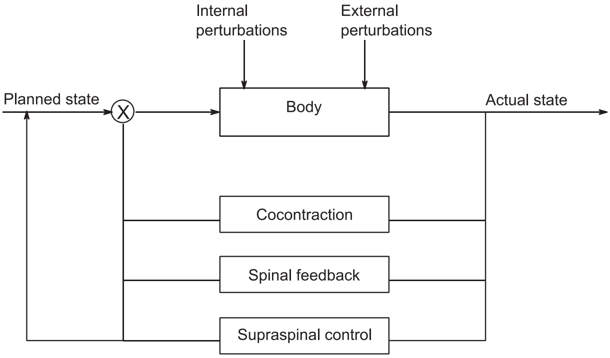

Fig. 1. Model for postural sway.

(Brumagne et al., 2004, 2008; Claeys et al., 2011). In contrast, we found a more generic decrease in sensitivity to muscle vibration, significant when applied to the TSM, non-significant when applied to the LPM. A striking difference between the latter studies and ours is the population enrolled. Our population consisted of a sample of working people between 18 and 65 years of age, while in the afore mentioned studies a case control design was used, with young (early twenties or younger) students, with low pain intensity or in a pain-free interval; VAS <3 (Brumagne et al., 2008), or NRS mean 2 (Claeys et al., 2011), and NRS 1.6 (Johanson et al., 2011). A possible explanation for the contradictory findings is that the ability to reweigh proprioceptive information depends on age and experience in balance activities (Gautier, Thouvarecq, & Larue, 2008; Vuillerme, Teasdale, & Nougier, 2001). The young students with LBP, tested in these previous studies, attenuated gains on proprioceptive signals from the lower back and enhance gains on proprioceptive signals from the ankle muscles (Brumagne et al., 2008; Claeys et al., 2011; Johanson et al., 2011). Like in the current study, no difference in proprioceptive weighting was found between older subject groups with and without LBP (Brumagne et al., 2004). It could be that older, perhaps less skilled, subjects with LBP rely on a generic stiffening strategy, reducing the contribution of proprioceptive feedback as well as feedforward supraspinal control to postural control.

The third method to control posture in our model is a stiffening strategy through co-contraction. Subjects with LBP have been suggested to use stiffening strategy to increase robustness of the trunk to mechanical perturbations (Hodges & Tucker, 2011; van Dieen, Selen, & Cholewicki, 2003). Stiffness through co-contraction has been suggested to be the main strategy to control posture in quiet standing (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998) and although this strategy cannot account for stability around the ankle joints, muscle stiffness has been shown to contribute substantially to stabilization of the ankle (Casadio, Morasso, & Sanguineti, 2005) and trunk (van Drunen, Maaswinkel, van, van Dieen, & Happee, 2013). Increasing stiffness through co-contraction reduces dependence on feedback and will cause higher sway frequencies (Winter et al., 1998). Subjects with LBP have shown a preference for such a stiffening strategy in maintaining standing posture (Mok, Brauer, & Hodges, 2004). Thus the present findings suggest that LBP patients preferably relied on a stiffening strategy with co-contraction around the ankles as well as the trunk in the more challenging condition on foam.

Following the cessation of vibration, time is needed to reintegrate proprioceptive signals and correct posture. In our study, subjects with LBP showed a larger ratio of recovery from peak COP position immediately after cessation of vibration, to the difference between this peak CoP position and the mean CoP position during vibration. This higher ratio was caused by a significantly larger peak in CoP anterior movement immediately after cessation of vibration in subjects with LBP (not reported). Factors that described recovery without using the peak CoP position directly after cessation of vibration, did not differ significantly between subjects with and subjects without LBP. This could indicate a less adequate reintegration of proprioceptive signals in subjects with LBP, the first seconds after cessation of vibration. Brumagne et al. also found indications that subjects with LBP have more problems reintegrating proprioceptive signals than healthy subjects, as the subjects with LBP in their study needed more time than healthy controls to return to a CoP position within 2 standard deviations from the original CoP position (Brumagne et al., 2004). When expressed in CoP velocity or variability of CoP velocity, recovery was also less after cessation of vibration in respectively non-gymnasts compared to gymnasts (Vuillerme et al., 2001), and in subjects with scoliosis compared to healthy controls (Simoneau, Mercier, Blouin, Allard, & Teasdale, 2006). We did not use velocity related recovery variables, because in a previous study (Kiers et al., 2014) they showed a less than fair reliability (<0.4).

We found a weak but significant association between the responses to TSM vibration, and sway frequency and irregularity. These associations are in agreement with the model suggested above. In summary, we suggest that attentional reserves are used less to control balance on foam in subjects with LBP, due to pain interference. When confronted with conditions in which balance is challenged LBP patients appear to display a preference for co-contraction and to reduce proprioceptive feedback gains and feedforward sway movement.

Inconsistent results have been reported regarding amplitude of postural sway in subjects with LBP (Mazaheri et al., 2013), with many studies showing increased sway in LBP, similar numbers showing no effect of LBP and a few studies showing a negative effect of LBP on sway. As an explanation for these conflicting results, Mazaheri et al. (2013) proposed a lack of power in some studies, and a competing influence of pain, and fear of pain on the amount of postural sway. Lack of power does not seem to be a probable explanation for the lack of findings in the present study, which involved 215 subjects. As to the competing effects of pain and fear of pain, our model may suggest a further refinement of this hypothesis. Nociception produces significant changes in the proprioceptive abilities of afferent neurons (Nijs et al., 2012). In subjects with LBP impairments in proprioception have been established (Brumagne et al., 1999; Gill & Callaghan, 1998; O'Sullivan et al., 2003; Yilmaz et al., 2010). These impairments have been suggested to cause an increase in sway amplitude (Ruhe, Fejer, & Walker, 2011b, 2012). We suggest that the competing effect of fear of pain on sway is achieved by means of increased use of co-contraction, specifically in the more challenging condition on foam. It should be noted that the model proposed suggests that factors which are difficult to control, such as anxiety of the subjects, can have important effects and cause random error as well as bias in outcomes of single studies and variance between studies.

Strengths of our study are the large number of subjects and the cohort design, which strengthen its external validity. Where all known studies that used LPM vibration found less response among subjects with LBP, we only found a trend towards less response. We believe this can be attributed to one of the weaknesses of our study, associated with the study size, which is the fact that several research assistants performed parts of the measurements. It is important to attach muscle vibrators over the same location and with the same pressure every time, and although research assistants were trained, variation in the way vibrators were attached is probably larger than when a single researcher applies the vibrators. We noticed that less experienced assistants tended to place the lumbar vibrator too low on the spine, thereby making the stimulus less effective.

There are more causes that could lead to a reduction of the effect sizes found in our study. It has been shown that other musculoskeletal pathologies can also cause changes in postural control. We did not exclude subjects with other musculoskeletal pathologies, which may affect postural sway (Negahban, Mazaheri, Kingma, & van Dieën, 2014; Ruhe, Fejer, & Walker, 2013). However, it has to be noted that we only vibrated lumbar and ankle musculature, which probably decreases the influence of pathologies from other body parts.

Another possible source of bias is the way in which subjects were questioned. Being part of a larger cohort, subjects filled out a self-administered questionnaire, with marginal control by research assistants. This could lead to misinterpretation of some of the questions, and a reduction in effect size. Also, for pragmatic reasons each sway and vibration trial was performed only once. It is known that the reliability of the measurement increases when 2–3 trials are averaged (Ruhe, Fejer, & Walker, 2010). This may have limited the power of our study, but given the sample size, this would not be a major limitation.

It could be argued that the large amount of variables in our study has led to an increase in type I error through multiple testing. However, we believe that this risk is acceptable, as we decreased the number of tests by means of factor analysis.

In conclusion, the present study showed that postural sway in subjects with LBP has a higher frequency content and is less regular than in subjects without or with only minor LBP when balance is challenged by standing on foam, which may indicate that subjects with LBP use more co-contraction and less cognitive control compared to healthy subjects. In addition, a reduced weighting of proprioceptive signals was found in subjects with LBP, which was associated with the changes in sway when standing on foam.

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