The Effect of Inspiratory Muscles Fatigue on Postural Control in People With and Without Recurrent Low Back Pain

Lotte Janssens, PT,* Simon Brumagne, PhD, PT,* Kathelijne Polspoel, PT,*
Thierry Troosters, PhD, PT,† and Alison McConnell, PhD‡

Study Design. A 2-group experimental design.

Objective. To determine postural stability and proprioceptive postural control strategies of healthy subjects and subjects with recurrent low back pain (LBP) during acute inspiratory muscles fatigue (IMF).

Summary of Background Data. People with LBP use a more rigid proprioceptive postural control strategy than control subjects during postural perturbations. Recent evidence suggests that respiratory movements create postural instability in people with LBP. The role of the respiratory muscles in postural control strategies is unknown, but can be studied by inducing acute IMF.

Methods. Postural control was evaluated in 16 people with LBP and 12 healthy controls, both before and after IMF. Center of pressure displacement was determined on a force plate to evaluate postural stability. Proprioceptive postural control strategies were examined during vibration of the triceps surae muscles or lumbar paraspinal muscles, while standing on both a stable and unstable support surface and without vision. Proprioceptive postural control strategies were determined by examining the ratio of mean center of pressure displacement measured during triceps surae muscles vibration to that measured during lumbar paraspinal muscles vibration.

Results. After IMF, control subjects showed a significantly larger sway compared to the unfatigued condition while standing on an unstable support surface ($P < 0.05$). IMF induced an increased reliance on proprioceptive signals from the ankles, which resembled the postural control strategy used by people with LBP ($P < 0.05$). Subjects with LBP showed that same ankle steered postural control strategy in the unfatigued and IMF states ($P > 0.05$).

Conclusion. After IMF, control subjects use a rigid proprioceptive postural control strategy, rather than the

normal “multisegmental” control, which is similar to people with LBP. This results in decreased postural stability. These results suggest that IMF might be a factor in the high recurrence rate of LBP.

Key words: proprioceptive postural control strategy, postural stability, low back pain, inspiratory muscles fatigue, muscle vibration, sensory reweighting. **Spine 2010; 35:1088–1094**

The upright posture requires a continuous dynamic stabilization, which is essential in daily activities. This control of posture involves inputs from 3 sensory systems (visual, vestibular, and proprioceptive), which interact centrally.¹ Proprioception is a primary sense for postural control, which comprises the sensations of joint position and movement, force, heaviness associated with muscular contractions, and perceived timing of muscular contractions.² Postural control has been shown to be impaired in people with low back pain (LBP).^{3,4} When balance is disturbed temporarily, a strategy must provide recovery of the upright posture. The proprioceptive postural control strategies employed to achieve this, appear to differ in people with LBP and may lead to a reduction in overall postural stability. Healthy subjects normally maintain postural stability using “multisegmental” control that is not based on a fixed set of equilibrium strategies, but on flexible centrally organized responses.^{5,6} In contrast, people with LBP lack the ability to use multisegmental control.^{7,8} Instead, they control postural balance using a more rigid strategy involving the ankle (*i.e.*, ankle-strategy).⁹ The mechanisms that explain this impairment in subjects with LBP are not yet clear. Putative mechanisms include pain,¹⁰ change in coordination,¹¹ muscle fatigue,¹² and an impaired ability of the proprioceptive system.¹³

When visual and vestibular feedback are compromised, the central nervous system (CNS) is obliged to reweight within proprioception itself, instead of between proprioception and the other 2 senses.¹⁴ Under these conditions, it appears that the CNS of people with LBP tends to rely less on proprioceptive signals from the hips or trunk, and more on input from other locations such as the ankles.⁸ This sensory reweighting can vary depending on external (*e.g.*, the environmental context) and internal (*e.g.*, muscle fatigue) factors.

Muscle fatigue has a negative influence on proprioceptive feedback. This has been investigated by studying postural control in fatigued and nonfatigued limb and

From the *Musculoskeletal Research Unit, Department of Rehabilitation Sciences, University of Leuven (K.U. Leuven), Leuven, Belgium; †Respiratory Rehabilitation and Respiratory Division, University Hospitals, Leuven, Belgium; and ‡The Centre for Sports Medicine and Human Performance, Brunel University, Uxbridge, United Kingdom. Acknowledgment date: February 12, 2009. First revision date: June 19, 2009. Second revision date: July 20, 2009. Acceptance date: July 21, 2009.

The manuscript submitted does not contain information about medical device(s)/drug(s).

Foundations funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

Supported by the Research Foundation–Flanders grants (1.5.104.03 and G.0674.09). Lotte Janssens received a PhD fellowship of the Research Foundation–Flanders (FWO).

Address correspondence and reprint requests to Lotte Janssens, PT, Musculoskeletal Research Unit, Department of Rehabilitation Sciences, University of Leuven (K.U. Leuven), Tervuursevest 101, B-3001 Leuven, Belgium; E-mail: lotte.janssens@faber.kuleuven.be

low back muscles.^{15–17} There is evidence that the diaphragm is activated during tasks that challenge the stability of the spine,¹⁸ and that it is also activated in the preparatory phase of movements that induce postural instability.¹⁹ Further, it has been suggested that the diaphragm plays a role in contributing to spinal stiffness *via* its influence on intra-abdominal pressure, as well as *via* direct mechanical effect *via* the attachments of the diaphragm crurae.²⁰ It is reasonable to suppose that some proprioceptive signals may be derived from the diaphragm during such activities, and that this may be altered by specific fatigue.

A recent study suggested that disorders of respiration are related strongly to recurrent LBP.²¹ In addition, it has been suggested that respiratory movement serves as a postural disturbance that necessitates the need for corrective postural control.^{22,23} Collectively, these findings suggest that respiration imposes a significant disturbing effect on balance in people with LBP.²³ Furthermore, compensation for this disturbance may be less effective in this population.²⁴ This being the case, it is reasonable to postulate that diaphragm fatigue may exacerbate postural instability. However, the influence of inspiratory muscles fatigue (IMF) on postural control has not been studied in either healthy people or those with LBP.

The main objective of this study was to investigate the influence of acute IMF on postural stability and proprioceptive postural control strategies. In addition, our aim was to investigate whether this influence is different in persons with LBP in comparison to healthy subjects. To achieve these aims, postural control characteristics were determined on a stable and unstable support surface²⁵ and muscle vibration was used to specifically evaluate the role of proprioceptive signals in postural control.^{26,27}

■ Materials and Methods

Subjects

A total of 28 university students, 16 individuals (11 women, 5 men) with a history of nonspecific LBP and 12 healthy control subjects (7 women, 5 men), volunteered for this study. All subjects gave their written informed consent. The study conformed to the principles of the Declaration of Helsinki (1964) and was approved by the local Ethics Committee of Biomedical Sciences, Katholieke Universiteit Leuven.

The characteristics of all subjects are summarized in Table 1. Ages ranged from 18 to 33 years. A physical activity questionnaire²⁸ and LBP questionnaire were completed. Subjects were included in the LBP group if they had at least 3 episodes of nonspecific LBP in the last 6 months and reported at the moment of testing a score of at least 6 of 100 on the Oswestry Disability Index, version 2 (adapted Dutch version).²⁹ An episode of LBP was identified by patient-reported recurrent symptoms (*i.e.*, the most liberal definition of LBP recurrence). This was found to be the most sensitive evaluation of LBP recurrence.³⁰ The persons in the LBP group did not have a more specific medical diagnosis than nonspecific mechanical LBP. The participants were tested when they were not in a recurrence of their LBP and they rated the pain lower than 2 of 10 on the moment of testing.³¹ Subjects were included in the control

Table 1. Descriptive Characteristics of Control Group and LBP Group

	Control Group (n = 12)	LBP Group (n = 16)	P
Age (yr)	22.8 ± 0.6	21.4 ± 1.0	NS
Height (cm)	174.3 ± 2.7	171.3 ± 2.4	NS
Weight (kg)	66.3 ± 3.4	64.6 ± 2.3	NS
PAI	9.5 ± 1.5	9.4 ± 1.2	NS
ODI-2	0	14.4 ± 6.3	
NRS pain	0	1.6 ± 1.8	
LBP (yr)	0	3.7 ± 2.2	
FEV ₁ % pred	106.8 ± 9.1	107.8 ± 8.9	NS
FVC % pred	106.0 ± 8.3	109.3 ± 7.4	NS
P _{I_{max}} % pred	117.9 ± 23.5	106.9 ± 36.5	NS
P _{E_{max}} % pred	116.9 ± 28.4	122.8 ± 8.7	NS

Data are presented as mean ± SD.

PAI indicates Physical Activity Index questionnaire (max. score = 15); ODI-2, Oswestry Disability Index version 2 (max. disability = 100); NRS pain, Numerical Rating Scale for pain (0–10); LBP, amount of years suffering from low back pain; FEV₁, forced expiratory volume in 1 second; FVC, forced vital capacity; P_{I_{max}}, maximal inspiratory pressure; P_{E_{max}}, maximal expiratory pressure; % pred, percentage predicted; NS, not significant (*P* > 0.05).

group if they had no history of LBP and reported a score equal to zero on this questionnaire. Subjects were excluded if they presented any history of vestibular disorder, respiratory disease, previous spinal surgery, hip/knee/ankle/foot problems, or the use of pain relieving medication or physical treatment. All subjects had normal spirometry. In the week before the experimental protocol, maximal inspiratory pressure (P_{I_{max}}) and maximal expiratory pressure (P_{E_{max}}) of each subject were assessed using an electronic pressure transducer (MicroRPM, MicroMedical Ltd., Kent, UK). P_{I_{max}} was measured at residual volume and P_{E_{max}} at total lung capacity according to the method of Black and Hyatt.³² A minimum of 5 repetitions were made and tests were repeated until there was less than 5% difference between the best and second best test. The highest pressure sustained over 1 second was defined as P_{I_{max}} or P_{E_{max}}, respectively.

Kinematic Analysis

Postural sway characteristics were measured using a 6-channel force plate (Bertec, OH). Force plate signals were sampled at 500 Hz using a Micro1401 data acquisition system using Spike2 software (Cambridge Electronic Design, UK) and were filtered using a low pass filter with a cut-off frequency of 5 Hz. Relative position of the trunk in space was recorded by 2 piezoresistive accelerometers (IC Sensors, London, UK) placed over the spinous process of T1 and S2 vertebra, which were connected to the data acquisition system.

Muscle Vibration

Mechanical muscle vibration was used to investigate the role of proprioception in postural control. During vibration, the proprioceptive sense is changed due to an illusion of muscle-lengthening.²⁶ During standing in normal subject, vibration of the triceps surae (TS) muscles induces an involuntary body sway in backwards direction, whereas lumbar paraspinal (LP) muscles vibration results in a forward body sway.^{8,9} Displacement of the center of pressure (CoP) indicates the manner in which the individual makes use of signals from the vibrated muscle to control posture. The muscle vibrator was strapped onto the muscle tendon of the TS muscles or LP muscles, respectively. Activation and deactivation of the muscle vibrator

Figure 1. Inspiratory muscles fatiguing protocol. Patient consent obtained.

were controlled manually. The proprioceptive stimulation was delivered by vibration at a high frequency and low amplitude (60 Hz, 0.5 mm).³³

Inspiratory Muscles Fatigue

During the fatiguing protocol, all participants underwent inspiratory threshold loading to induce IMF (Figure 1). Before the test, a short warm-up routine familiarized the subjects with the resistive threshold load. While standing, subjects breathed through a mouthpiece (POWERbreathe Medic, HaB

International Ltd., Warwickshire, UK) with their nose occluded. With each inspiration, resistance was added to the inspiratory valve so that the subjects had to generate a negative threshold pressure of 80% of their P_{Imax} .³⁴ The participants were instructed to inspire maximally and as rapidly as possible. Verbal encouragement was given to ensure that subjects worked maximally and to maintain a constant respiratory rhythm. The end of the task was signaled by failure of the subject to sustain the breathing task despite encouragement of the investigator. The time to this point of task failure was recorded as the endurance time.³⁵ For pragmatic reasons, the maximum length of the protocol was set at 600 seconds. An adapted Borg scale (from 0 to 10) was chosen to evaluate the respiratory effort during inspiratory loading.³⁶

Experiment Protocol

The experimental set up is shown in Figure 2. All participants had to stand barefoot on the force plate with their hands relaxed and at their sides. The feet positions were marked on a plastic sheet in order to ensure standardization throughout the experiment. The vision of the subjects was occluded by non-transparent glasses and subjects were asked to keep their gaze in a straight-ahead direction. We did not focus on occluding the vestibular sense since no large accelerations/decelerations of the head are expected during quiet standing. Therefore, the vestibular organ plays a negligible role in these postural conditions. Subjects were instructed to try to maintain their balance at all times during the experiment and an investigator stood next to the subject during the trial to prevent actual falls.

Each subject was tested in following 2 conditions: (1) control condition and (2) IMF condition. Each condition involved 4 trials that are summarized in Table 2. All trials were performed on stable (Figure 2A) and unstable support surface (Figure 2B). Trial 1 (no vision) served as a baseline. In trial 2, the effect of a ballistic bilateral arm antelexion (after 15 sec-

Figure 2. **A**, Stable support surface (lumbar paraspinal muscles vibration). **B**, Unstable support surface (triceps surae muscles vibration). Patient consent obtained.

Table 2. Experimental Protocol

Trial	Description
1	Upright stance, without vision (30 sec)
2	Upright stance, ballistic bilateral arm anteflexion, without vision (at 30 sec)
3	Upright stance, bilateral triceps surae muscles vibration, without vision (60 sec)
4	Upright stance, bilateral lumbar paraspinal muscles vibration, without vision (60 sec)

onds) on postural stability was evaluated. In trials 3 and 4, mechanical muscle vibration (of TS muscles and LP muscles, respectively) started at 15 seconds, lasted for 15 seconds, and data collection continued for 30 seconds. For the unstable support condition, a foam (Airex balance pad; 49.5 cm length $\times$ 40.5 cm width $\times$ 6.5 cm thick) was used to decrease the reliability of ankle proprioception. The CNS decreases the reliance on proprioceptive input when this source of signals is confounded by support surface stability (ankle proprioception). In this way, the CNS was forced to use other proprioceptive signals to provide postural control.²⁵ In the second condition, all postural balance measurements were repeated following acute IMF. Thus, the IMF protocol described above was used before the stable support surface trials and was repeated before the unstable support surface trials. All trials were completed on the same day.

Data Reduction and Data Analysis

Postural balance measurements were calculated using Spike 2 software and Microsoft Excel. Displacements of the CoP in anterior-posterior direction were estimated from the raw force plate data using the equation: $\text{CoP} = \text{Mx/Fz}$. Root mean square values of the CoP displacements were used for the analysis of postural stability measures and mean values were calculated for both vibration trials to analyze the expected directional effect. The ratios of the CoP displacements of the TS muscles vibration trial regard to the LP muscles vibration trial were calculated to determine the proprioceptive postural control strategy, using the following equation: $\text{RW TS/LP} = \text{absolute TS}/(\text{absolute TS} + \text{absolute LP})$. In this equation, RW refers to the relative proprioceptive weighting ratio. A RW outcome of 1 indicates use of a 100% ankle muscles steered proprioceptive control strategy. An outcome of 0 indicates the use of a 100% LP muscles steered proprioceptive control strategy.

A *t* test was used to examine differences in baseline characteristics between the 2 groups (Table 1). A repeated measures

analysis of variance was used to examine between-subjects and within-subjects differences. When a significant main or interaction effect was found, a *post hoc* test was performed to further analyze these results in detail. Statistical analysis was performed with Statistica 8.0 (Statsoft, OK). The level of significance was set at $P < 0.05$.

Results

Inspiratory Muscles Endurance

There was no significant difference in inspiratory muscle endurance time between the LBP group (322.8 ± 213.4 seconds) and the control group (399.1 ± 209.1 second), although there was a trend for endurance to be lower in the LBP group ($F(1, 26) = 2.44$, $P = 0.087$). About 12 subjects (58% of the controls, 31% of the LBP subjects) reached the maximal endurance time of 600 seconds. During the IMF breathing task, no difference in breathing effort was found between the control group (7.7 ± 1.9) and LBP group (7.6 ± 1.0), neither between the subjects who reached 600 seconds (7.3 ± 1.4) and the subjects who did not (7.9 ± 0.7), for the reason that all Borg scores denote “very strong” breathing effort sensation.

Postural Stability Measures

Compared with the unfatigued condition, control subjects show an increased postural sway when the inspiratory muscles were fatigued, although this was only observed when standing on an unstable support surface ($P = 0.0002$) (Table 2: trial 1–2). Table 3 presents in more detail the mean root mean square values for both conditions (unfatigued and IMF) in both experimental groups.

Proprioceptive Postural Control Strategies

Figure 3 compares the proprioceptive postural control strategies for all conditions (Table 2: trial 3–4). In the unfatigued condition, control subjects used an ankle steered proprioceptive control strategy on a stable support surface (RW TS/LP: 0.73 ± 0.11), but switched to a multisegmental control strategy on an unstable support surface (RW TS/LP: 0.52 ± 0.16). In contrast, after IMF the control group demonstrated an even greater reliance on ankle steered proprioceptive control, both on the sta-

Table 3. Mean Root Mean Square (RMS) Values With Standard Deviations (SD) for the Postural Stability Trials During Standing on Stable and Unstable Support Surface

Group	Support Surface	Trial	Unfatigued		IMF		<i>F</i>	<i>P</i>
			RMS (m)	SD	RMS (m)	SD		
Control	Stable	1	0.071	0.040	0.089	0.040	4.090	0.082
		2	0.070	0.038	0.081	0.038	0.210	0.648
	Unstable	1	0.081	0.025	0.140	0.027	26.350	0.0002
		2	0.079	0.028	0.126	0.027	15.100	0.0002
LBP	Stable	1	0.079	0.039	0.078	0.045	4.090	0.998
		2	0.074	0.036	0.080	0.044	0.210	0.648
	Unstable	1	0.123	0.033	0.132	0.035	26.350	0.545
		2	0.131	0.280	0.136	0.023	15.100	0.870

IMF indicates inspiratory muscles fatigue; LBP, low back pain.

Figure 3. Relative weighting ratios from ankle over low back vibration (RW TS/LP) in unfatigued and inspiratory muscles fatigued (IMF) condition (Mean $\pm$ SD; ** $P < 0.01$, *** $P < 0.001$).

ble (RW TS/LP: 0.80 ± 0.10) and unstable support surface (RW TS/LP: 0.70 ± 0.12). In other words, after IMF, control subjects decreased their reliance on proprioceptive signals from the low back in both the stable ($P = 0.007$) and unstable ($P = 0.0007$) conditions. In contrast, in the LBP group, there was no difference in RW following IMF on either the stable ($P = 0.1$) or unstable surface ($P = 0.6$). Indeed, the LBP group were already very reliant on ankle steered postural control in unfatigued condition on both the stable (RW TS/LP: 0.85 ± 0.07) and unstable support surface (RW TS/LP: 0.86 ± 0.07), and maintained this proprioceptive control strategy after IMF (RW TS/LP: 0.89 ± 0.06 , RW TS/LP: 0.90 ± 0.05 , respectively).

Discussion

Our main finding was that after IMF control subjects decreased their reliance on proprioceptive signals from the low back when standing on an unstable support surface. This proprioceptive postural control strategy resembled that used by people with LBP. As in people with LBP, adopting this postural control strategy induced a reduction in postural stability. People with LBP show the same ankle steered postural control strategy and reduced postural stability in the unfatigued and IMF states.

Postural Control During Acute IMF

Regarding postural stability measures, no significant differences in CoP displacement were observed between the unfatigued and IMF condition while standing on a stable support surface. In contrast, on an unstable support surface, IMF increased postural sway significantly, although only in the control group. These results are in agreement with a previous finding where differences in postural control could only be found when the task involved increased complexity.³⁷

The increased CoP displacement following IMF may be the result of a change in the proprioceptive postural control strategy, which was manifest in the relative proprioceptive weighting ratio. In control subjects, the ratio (RW TS/LP: mean CoP displacement during ankle vibration over low back vibration) significantly increased following IMF. This calculated ratio implies that ankle proprioception plays a dominant role in postural control following IMF, likely because input from the low back becomes less reliable. Due to centrally organized reweighting, the control subjects displayed a tendency to use a rigid postural control strategy (*i.e.*, ankle-strategy), which was similar to that employed by people with LBP in an unfatigued state.⁸ In other words, a way to compensate for proprioceptive deficits is to shift the focus of reliance from a less reliable proprioceptive input to other regions with more reliable inputs.²⁵ Following IMF, increased use of ankle signals suggests that the ability to switch from “single segment” control to a more complex multisegmental control is challenged.

Recent studies suggest that, under changing postural conditions, people with LBP exhibit an ankle steered postural control strategy.^{7,9} Interestingly, in our group of subjects with LBP, IMF failed to induce any greater reliance on ankle steered postural control. A possible explanation is that these subjects were already exploiting this strategy to its maximum effect. This finding does not rule out that inspiratory muscle training can improve postural control in people with LBP, and thus adjust the treatment of LBP. However, this hypothesis requires further investigation.

The physiological changes associated with muscle fatigue provided possible underlying mechanisms to explain the impaired multisegmental control following IMF. Localized muscle fatigue can impair postural control directly through the inability to produce or sustain a required muscle output.¹² Indirectly, it influ-

ences postural control through changes in proprioception. The properties of the muscle spindles change,³⁸ which can affect proprioception through supraspinal projections and, in order to control posture, the central motor commands change to compensate (*e.g.*, spatial sensory reweighting).^{12,14}

Previous studies suggest that the diaphragm plays an important role in maintaining an upright posture, and in stabilizing the spine under conditions of postural challenge and loading.^{19,39} The present data support the importance of this postural role for the diaphragm, and suggest that specific fatigue of the inspiratory muscles may impair this function. Since postural control is impaired in persons with LBP and IMF impairs postural control, the present study allows speculation on a potential mechanism for the proprioceptive deficit in persons with LBP. The mechanisms underlying this deficit following IMF require further investigation.

Limitations

The principal limitation of our study was the failure to verify the presence of IMF following the loaded breathing task. However, the task in question was extremely challenging, and we believe that it is very unlikely that participants were not in a state of IMF after breathing against a substantial inspiratory load for 600 seconds, or to task failure. In addition, our evaluation of IMF (constant-load resistive breathing test to task failure) seems to be the only noninvasive test to securely assess IMF.³⁵ Nevertheless, to provide definitive evidence of diaphragmatic fatigue, we suggest future studies to record transdiaphragmatic pressures and evoked potential responses to bilateral phrenic nerve magnetic stimulation.⁴⁰ Second, we acknowledge that the results of this study cannot be generalized to a more typical population with LBP. However, the findings of this study might support clarifying the underlying mechanisms of the high recurrence rate of LBP. Therefore, future research (with a larger sample size) studying older persons with higher disability would further test the proposed clinical implementation.

Conclusion

The results of the present study show that during postural perturbation, IMF has a negative effect on postural stability in healthy subjects. Due to reweighting, they tend to use a rigid postural control strategy over a more effective “multisegmental control”-strategy. This resembles the behavior of people with LBP during an unfatigued condition. Our findings might shed some light on a potential underlying mechanism of nonspecific recurrent LBP.

Key Points

- The influence of inspiratory muscles fatigue on postural control was observed in people with and without recurrent low back pain under different support surface trials.

- Ratios of mean center of pressure displacement during triceps surae muscles vibration over lumbar paraspinal muscles vibration determined the spatial proprioceptive reweighting.
- Following inspiratory muscles fatigue, healthy individuals show a rigid proprioceptive postural control strategy (ankle steered), which resembles that used by people with low back pain.

References

1. Lackner JR, DiZio P. Vestibular, proprioceptive, and haptic contributions to spatial orientation. *Annu Rev Psychol* 2005;56:115–47.
2. Gandevia SC, McCloskey DI, Burke D. Kinaesthetic signals and muscle contraction. *Trends Neurosci* 1992;15:62–5.
3. Luoto S, Aalto H, Taimela S, et al. One-footed and externally disturbed two-footed postural control in patients with chronic low back pain and healthy control subjects. A controlled study with follow-up. *Spine* 1998;23:2081–9.
4. Radebold A, Cholewicki J, Polzhofer GK, et al. Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. *Spine* 2001;26:724–30.
5. Allum JH, Bloem BR, Carpenter MG, et al. Proprioceptive control of posture: a review of new concepts. *Gait Posture* 1998;8:214–42.
6. Schieppati M, Giordano A, Nardone A. Variability in a dynamic postural task attests ample flexibility in balance control mechanisms. *Exp Brain Res* 2002;144:200–10.
7. Mok NW, Brauer SG, Hodges PW. Hip strategy for balance control in quiet standing is reduced in people with low back pain. *Spine* 2004;29:E107–12.
8. Brumagne S, Cordo P, Verschuere S. Proprioceptive weighting changes in persons with low back pain and elderly persons during upright standing. *Neurosci Lett* 2004;366:63–6.
9. Brumagne S, Janssens L, Knapen S, et al. Persons with recurrent low back pain exhibit a rigid postural control strategy. *Eur Spine J* 2008;17:1177–84.
10. Moseley GL, Hodges PW. Are the changes in postural control associated with low back pain caused by pain interference? *Clin J Pain* 2005;21:323–29.
11. van Dieën JH, Selen LP, Cholewicki J. Trunk muscle activation in low-back pain patients, an analysis of the literature. *J Electromyogr Kinesiol* 2003;13:333–51.
12. Vuillerme N, Danion F, Forestier N, et al. Postural sway under muscle vibration and muscle fatigue in humans. *Neurosci Lett* 2002;333:131–5.
13. Brumagne S, Lysens R, Swinnen S, et al. Effect of paraspinal muscle vibration on position sense of the lumbosacral spine. *Spine* 1999;24:1328–31.
14. Carver S, Kiemel T, Jeka JJ. Modeling the dynamics of sensory reweighting. *Biol Cybern* 2006;95:123–34.
15. Yaggie JA, McGregor SJ. Effects of isokinetic ankle fatigue on the maintenance of balance and postural limits. *Arch Phys Med Rehabil* 2002;83:224–8.
16. Gribble PA, Hertel J. Effect of lower-extremity muscle fatigue on postural control. *Arch Phys Med Rehabil* 2004;85:589–92.
17. Wilson EL, Madigan ML, Davidson BS, et al. Postural strategy changes with fatigue of the lumbar extensor muscles. *Gait Posture* 2006;23:348–54.
18. Hodges PW, Gandevia SC. Activation of the human diaphragm during a repetitive postural task. *J Physiol* 2000;522:165–75.
19. Hodges PW, Butler JE, McKenzie DK, et al. Contraction of the human diaphragm during rapid postural adjustments. *J Physiol* 1997;505:539–48.
20. Hodges PW, Eriksson AE, Shirley D, et al. Intra-abdominal pressure increases stiffness of the lumbar spine. *J Biomech* 2005;38:1873–80.
21. Smith MD, Russell A, Hodges PW. Disorders of breathing and continence have a stronger association with back pain than obesity and physical activity. *Aust J Physiother* 2006;52:11–6.
22. Hodges PW, Gurfinkel VS, Brumagne S, et al. Coexistence of stability and mobility in postural control: evidence from postural compensation for respiration. *Exp Brain Res* 2002;144:293–302.
23. Hamaoui A, Do M, Poupard L, et al. Does respiration perturb body balance more in chronic low back pain subjects than in healthy subjects. *Clin Biomech* 2002;17:548–50.
24. Grimstone SK, Hodges PW. Impaired postural compensation for respiration in people with recurrent low back pain. *Exp Brain Res* 2003;151:218–24.
25. Ivanenko YP, Talis VL, Kazennikov OV. Support stability influences

- postural responses to muscle vibration in humans. *Eur J Neurosci* 1999;11:647–54.
26. Goodwin GM, McCloskey DI, Matthews PB. The contribution of muscle afferents to kinaesthesia shown by vibration induced illusions of movement and by the effects of paralysing joint afferents. *Brain* 1972;95:705–48.
 27. Brumagne S, Cordo P, Lysens R, et al. The role of paraspinal muscle spindles in lumbosacral position sense in individuals with and without low back pain. *Spine* 2000;25:989–94.
 28. Baecke JA, Burema J, Frijters JE. A short questionnaire for the measurement of habitual physical activity in epidemiological studies. *Am J Clin Nutr* 1982;36:936–42.
 29. Fairbank JC, Pynsent PB. The oswestry disability index. *Spine* 2000;25:2940–53.
 30. Marras WS, Ferguson SA, Burr D, et al. Low back pain recurrence in occupational environments. *Spine* 2007;32:2387–97.
 31. McGorry RW, Webster BS, Snook SH, et al. The relation between pain intensity, disability, and the episodic nature of chronic and recurrent low back pain. *Spine* 2000;25:834–41.
 32. Black LF, Hyatt RE. Maximal respiratory pressures: normal values and relationship to age and sex. *Am Rev Respir Dis* 1969;99:696–702.
 33. Roll JP, Vedel JP. Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography. *Exp Brain Res* 1982;47:177–90.
 34. Johnson BD, Babcock MA, Suman OE, et al. Exercise-induced diaphragmatic fatigue in healthy humans. *J Physiol* 1993;460:385–405.
 35. Perret C, Pfeiffer R, Boutellier U, et al. Noninvasive measurement of respiratory muscle performance after exhaustive endurance exercise. *Eur Respir J* 1999;14:264–9.
 36. Borg G. *Borg's Perceived Exertion and Pain Scales*. Campaign, IL: Human Kinetics; 1998.
 37. Mientges MI, Frank JS. Balance in chronic low back pain patients compared to healthy people under various conditions in upright standing. *Clin Biomech* 1999;14:710–6.
 38. Pedersen J, Ljubisavljevic M, Bergenheim M, et al. Alterations in information transmission in ensembles of primary muscle spindle afferents after muscle fatigue in heteronymous muscle. *Neuroscience* 1998;84:953–9.
 39. Hemborg B, Moritz U, Löwing H. Intra-abdominal pressure and trunk muscle activity during lifting. IV. The causal factors of the intra-abdominal pressure rise. *Scand J Rehabil Med* 1985;17:25–38.
 40. Mador MJ, Khan S, Kufel TJ. Bilateral anterolateral magnetic stimulation of the phrenic nerves can detect diaphragmatic fatigue. *Chest* 2002;121:452–8.