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Sudden gait perturbations elicit sex-specific neuromuscular trunk responses in persons with low back pain

Juliane Mueller[a,e], Eduardo Martinez-Valdes[b,c], Steffen Mueller[a], Kornelia Kulig[d], Frank Mayer[e],

[a] Professorship for Physiotherapy: Exercise Science and Applied Biomechanics, Department of Computer Science – Therapy Sciences, Trier University of Applied Sciences, Germany

[b] School of Sport, Exercise and Rehabilitation Sciences, Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), College of Life and Environmental Sciences, University of Birmingham, Birmingham, United Kingdom

[c] Centro de Investigacion en Fisiologia del Ejercicio (CIFE), Universidad Mayor, Santiago, Chile

[d] Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA, USA.

[e] University Outpatient Clinic, Sports Medicine & Sports Orthopaedics, University of Potsdam

Address for correspondence:

Dr. Juliane Mueller

Ju.Mueller@hochschule-trier.de

Fon: +49 651 8103-752

Fax: +49 651 8103-454

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ABSTRACT

Persons with low back pain (LBP) exhibit delayed trunk muscle onset and increased co-contractions as a response to quasi-static and dynamic sudden trunk loading in comparison to back-healthy controls. Although LBP is more prevalent in females, sex-specific responses have not been well documented. Therefore, the purpose was to explore sex-specific neuromuscular differences, to gait perturbation, in LBP patients.

Twenty-nine LBP patients (12m/17f;31±10yrs;174±12cm;71±16kg) walked on a split-belt treadmill at 1m/s, while 15 right-sided random perturbations (treadmill-belt decelerating, 40m/s^2, 50ms duration; 200ms after heel contact) were applied. Muscle activity was assessed using a 12-lead surface EMG (6 back/6 abdominal muscles;4000Hz). EMG-RMS [%] (0-200ms after perturbation) was calculated and normalized to RMS of unperturbed gait for each muscle. Furthermore, muscle onsets (ms) were determined. Two-way ANOVA (factors: sex/muscle) was applied to account for sex differences in main outcomes.

EMG-RMS (amplitudes; mean) ranged from 356% to 901% in males and 349% to 694% in females representing a significant interaction effect (sex*muscle: p=0.017). Post-hoc analysis revealed significant differences for EMG-RMS analysis of rectus abdominis left (p=0.043; f>m) as well as obliques externus right/left (p=0.018/p=0.005; f<m). In the time domain, females showed overall, shorter (mean: 90±16ms) response times compared to males (mean: 98±22ms, sex effect: p<0.0001).

In this LBP population, abdominal muscle activation discriminated females from males. Specifically, females had higher activity of the rectus abdominis muscles and lower activation of the externus oblique muscles. These different activation strategies might be relevant to the development of sex-specific intervention strategies.

KEYWORDS: core, gait perturbation, EMG, MISPEX*

INTRODUCTION

Non-specific low back pain (LBP) is a major societal burden, with a lifetime prevalence of about 85% and frequently leading to disability in 10% to 15% of all patients concerned (Balagué et al., 2012; Falla and Hodges, 2017; Hartvigsen et al., 2018). Women are more likely to report LBP than men in all age groups. In detail, differences are reported between sexes of ~7% in the younger (18-29 years of age) and ~12% (65-74years of age) in the older population (Hoy et al., 2012; Meucci et al., 2015; Robert-Koch-Institut, 2015). In general, every fourth woman (25%) and about one in six men (17%) suffers from chronic non-specific LBP in a period of twelve months (Hoy et al., 2012; Meucci et al., 2015; Robert-Koch-Institut, 2015).

Normal walking is described as an important functional dynamic task of almost everyone´s daily-life that is influenced by chronic non-specific LBP (Ghamkhar and Kahlaee, 2015; Lamoth et al., 2002; Vogt et al., 2003). Regardless of sex, chronic non-specific LBP patients show changes in gait, e.g. decreased self-selected walking speed, step length, timing of gait phases and altered trunk coordination (Lamoth et al., 2002; 2004; Vogt et al., 2003). Moreover, a systematic review by Ghamkar et al. (Ghamkhar and Kahlaee, 2015) generalized that persons with chronic non-specific LBP demonstrate higher global trunk muscle activity during walking compared to back-healthy controls. In detail, the erector spinae (ES) as well as the rectus abdominis (RA) muscles showed higher activity in LBP patients (Anders et al., 2005; Ghamkhar and Kahlaee, 2015). Moreover, Vogt et al. (Vogt et al., 2003) reported significant earlier onset and prolonged activity of the lumbar ES muscle in the stance and swing phase. These alterations are discussed as adaptation strategies in chronic non-specific LBP patients to ensure stability of the lumbar spine (Ghamkhar and Kahlaee, 2015).

Although chronic non-specific LBP is more prevalent in females, sex-specific neuromuscular responses of the trunk, especially in functional daily-life activities as walking, have not been well documented. In a previous study, Anders et al. (Anders et al., 2008) reported sex-specific differences in the activation pattern of the trunk muscles during treadmill walking in asymptomatic participants. Females showed higher activity of the M. oblique externus (EO)

during walking while men showed higher activity of the M. oblique internus (IO) at 2, 3 and 6 km/h. The authors suggested that this finding was because of the more rotational walking (trunk vs. hip) pattern in females and compared to the upright walking pattern commonly seen in males (Anders et al., 2008; Cho et al., 2004). Following this, Anders et al. (Anders et al., 2008) suggested that the human gait requires a sex-specific analysis. This might be necessary even in the context and influence of (musculoskeletal) pathologies like chronic non-specific LBP. Besides normal gait, there has been wide interest in investigating trunk muscle responses to external perturbations, as such assessments first, allow engaging the trunk musculature in a greater extent compared to normal walking and second, allow investigating trunk-muscle reflex activity (Maaswinkel et al., 2016; Radebold et al., 2001). Previous studies examining trunk-muscle responses to quasi-static quick-release external perturbations have reported that individuals with LBP exhibit delayed trunk muscle onset and increased co-contraction in comparison to back-healthy controls (Cholewicki et al., 2000; Radebold et al., 2001). Despite these interesting findings, it is important to mention that quasi static external perturbations are not closely representative of the activities of the daily living and therefore recent studies (Gombatto et al., 2015; Hodges et al., 2001; Mueller et al., 2017; R. Müller et al., 2015) have focused their efforts in studying perturbations during more functional activities such as walking. Indeed very recent research from our group has shown that individuals with LBP demonstrate different neuromuscular compensation strategies for sudden gait perturbation while walking, presenting increased latencies in muscle response time compared to back healthy controls (Mueller et al., 2017). However, up to this date, there are no studies focusing in studying the effect of LBP and sex on trunk-muscle activity in response to sudden gait perturbations. Such information is relevant to understand the distinct neural activation strategies employed by men and women in response to these perturbations. This knowledge might be of primary interest in order to develop individualized intervention regimes in LBP patients. Hence, the purpose of

this study was to explore sex-specific neuromuscular activation patterns of the trunk in response to gait perturbations in individuals with LBP.

MATERIAL AND METHODS

The present study is a retrospective analysis of an already published study (Mueller et al., 2017), focusing on the neuromuscular trunk response to sudden gait perturbations in comparison of asymptomatic controls and LBP patients regardless of gender.

Participants

The investigation was conducted at the University Outpatient Clinic. Participants involved students and/or academic staff undergoing physical examination and recreational athletes receiving annual health check-ups. Ninety-seven participants were initially recruited for the study. After receiving a written explanation of the protocols and additional oral information from the study coordinator, 94 (37m / 57f) participants agreed to participate by signing the consent form, approved by the University´s Ethical Commission (Ethic approval No: 36/2011). All participants read and signed a written informed consent form before voluntary participation. To determine the presence of chronic non-specific low back pain, all participants answered the German version of "The Graded Chronic Pain" questionnaire (von Korff) (Klasen et al., 2004; Korff et al., 1992; Niederer et al., 2016) (online-based (ProWebDB, Germany). A categorization based on the sub score "characteristic pain intensity score (CPIS)" of this questionnaire exclusively was favored in the present analysis. The CPIS represents the three items referring to mean intensity ratings reported for (1) current, (2) worst and (3) average pain over the period of the last three months. All three items consisted of a numeric rating scale ranging from 0 (no pain/disability) to 10 (highest pain/disability). The CPIS score was calculated as mean of the 3 items*10. Therefore, LBP patients were defined by a CPIS of $\geqslant$30 points. This threshold was chosen in agreement with previous classifications of LBP describing

this threshold as a transition from mild to moderate pain intensities (Cedraschi et al., 1999; Korff and Miglioretti, 2005).

Based on the results of this classification, twenty-nine chronic non-specific LBP patients (31±10yrs;174±12cm;71±16kg) were included into final analysis. Demographic and anthropometric data for the 12 males and 17 females are detailed in Tab. 1. Significant differences in anthropometric data were shown between groups ($p<0.001$).

Tab. 1 Anthropometrics for males and females

Experimental setup

Anthropometric assessment was followed by a clinical examination conducted by an experienced physician to ensure eligibility for the upcoming stumbling protocol and to exclude specific low back pain patients. Afterwards, all participants were prepared for EMG data acquisition of the trunk. EMG electrodes were placed over twelve trunk muscles (Fig. 1B)(Mueller et al., 2017; 2016). Subject preparation was followed by a standardized walking perturbations protocol beginning with a warm-up and familiarization procedure where the participants walked 5 minutes at 1m/s on a split belt treadmill (Woodway, Weil am Rhein, Germany) without perturbation (Engel et al., 2017; J. Müller et al., 2016). Next, each subject walked for about 10 minutes at a baseline velocity of 1m/s; while walking, 15 right- and left-sided perturbations were randomly applied 200ms after initial heel contact triggered by a plantar pressure insole (Pedar X, Novel, Munich, D). This ensures that participants are perturbed in the early phase of the gait cycle (weight acceptance) and single support phase bearing full load of body weight on the foot. During perturbation, one of the treadmill belts decelerated to a velocity of -1m/s (amplitude: 2 m/s) resulting in a deceleration of $-40 m/s^2$ for 50ms, returning to baseline velocity after an additional 50ms. Additional information (validity, reliability) of the perturbation characteristics are presented elsewhere (Engel et al., 2017; J. Müller et al., 2016). For the data analysis, only right-sided perturbations were examined due to direct triggering of

the perturbations by the plantar pressure insole used only in the right shoe. Left-sided perturbations were also applied to ensure that participants did not adapt their normal walking pattern to only right-sided perturbations.

Overall, participants were instructed to walk as natural as possible on the treadmill while random perturbations are applied. As a consequence, participants walked on the treadmill while knowing that perturbations will be applied but not knowing when (time) and where (leg) they would be perturbed. For safety reasons, all participants worn a waist belt connected to an emergency stop release.

Figure 1: 12-lead EMG set-up of the trunk

EMG analysis

Trunk muscle activity was assessed with a 12-lead surface EMG (Radebold et al., 2001). The setup included six ventral (Mm rec. abd. (RA), obl. ext. abd. (EO), obl. int. abd (IO) of left and right side) and six dorsal (Mm erec. spinae thoracic (T9; UES)/lumbar (L3; LES), latis. dorsi (LD) of left and right side) muscles. Muscular activity was analyzed using bilateral and bipolar surface EMG (bandpass filter: 5 – 500 Hz; sampling frequency: 4000 Hz, amplification: overall gain: 1000; myon, Switzerland). Before electrodes (AMBU Medicotest, Denmark, Type N-00-S, inter- electrode distance: 2 cm) were applied, the skin was shaved, slightly exfoliated to remove surface epithelial layers, and finally disinfected. In addition, skin resistance was controlled by measuring skin impedance (<5 kΩ). The longitudinal axes of the electrodes were in line with the presumed direction of the underlying muscle fibers. The signal was rectified before calculation of the amplitudes. No additional filter was applied post processing as this provided clearer and more reliable analysis for muscle activation onsets of the trunk muscles as reported by Engel et al. (Engel et al., 2017). The root mean square analysis as well as the calculation of the onset of muscular activity served as primary outcomes for EMG analysis.

The mean amplitude for each muscle was calculated out of the first 5 unperturbed strides and the 15 perturbed strides of the walking perturbations protocol. The root mean square (RMS; [%]) within the first 200ms following start of the perturbation was normalized to the whole stride cycle of the unperturbed stride and analyzed afterwards (Mueller et al., 2017; 2018). Additionally, co-contraction was analyzed between the ventral (V) and dorsal (D) muscles (formula: mean all ventral muscles / mean all dorsal muscles; V:D) as well as the side right : side left ratio (formula: mean of all right-sided muscles / mean of all left-sided muscles; S_{right}:S_{left})(Baritello et al., 2019). As a measure of asymmetry, the IO:EO ratio was calculated (Anders et al., 2008).

In the time domain, we measured the onset of muscular activity (T; ms), representing a response to the perturbation. A semi-automated detection method (IMAGO process master, LabView®-based, pfitec, biomedical systems, Endingen, Germany) was used to define muscle activity onset (Hodges and Bui, 1996; Mueller et al., 2018). After performing signal rectification and filtering, one average stride cycle was calculated out of the 15 consecutive stride cycles in which a perturbation occurred. Therefore, an ensemble average from all the fifteen right-sided perturbations was applied (Mueller et al., 2018). Within this detection method, an increase in the averaged EMG signal (ensemble average; filter: 4th order moving average) of more than 2 standard deviations from baseline level was defined for automatic onset detection. Every automatic detection was controlled through visual inspection. If automatic detection failed (e.g. due to movement artefact), the investigator applied manual correction (<2% of all cases analysed).

Data analysis and statistics

All non-digital data were documented in a paper and pencil-based case report form (CRF) and transferred to the statistical database (JMP Statistical Software Package 14, SAS Institute®). After a plausibility check (range check + extreme value analysis for all outcomes), the data

were presented descriptively (means, SD) for all given outcomes. All outcomes were checked for normal distribution with Shapiro-Wilk-Test. Since the majority of the main outcomes (EMG-RMS (%); muscle onset (T)) were normally distributed, a two-way repeated measures ANOVA was applied to test for differences between factors sex (between subjects: male/female) and muscle (within-subjects: 12 muscles). Tukey-Kramer test was applied for post hoc analysis. Furthermore, for secondary outcomes (ratios: V:D; S_{right}:S_{left}) student´s t-test was applied to test for differences between sexes based on the knowledge of robustness of the t-test to non-normal distributed data. The level of significance was set at α=0.05.

RESULTS

Amplitude (RMS)

EMG-RMS (amplitudes; mean) ranged from 356% to 901% in males and 349% to 694% in females (Fig. 2). The statistical analysis revealed a significant interaction effect (sex*muscle: p=0.017). Post-hoc analysis presented significant differences for EMG-RMS analysis of rectus abdominis left (RA le; p=0.043; f>m) as well as obliques externus right/left (OE ri/le; p=0.018/p=0.005; f<m). Additionally, results of co-contraction analysis (V:D; S_{right}:S_{left}) revealed no significant sex differences, even though the p value is close to significance (p=0.07) for S_{right}:S_{left}. Additional asymmetry analysis (IO:EO ratio) revealed no statistical significant differences between sexes, although the p value is close to significance (p=0.08) for IO:EO_r. The results are detailed in Tab. 2.

Fig. 2 Neuromuscular reflex activity (EMG-RMS; %; mean±SD) of all 12 trunk muscles for females and males

Tab. 2 Results of neuromuscular trunk co-contraction analysis illustrated by a ratio of ventral:dorsal muscles (A; V:D), $side_{right}$:$side_{left}$ muscles (B; S_{right}:S_{left}) and asymmetry

ratio oblique internus:oblique externus (C; IO:$EO_{r/l}$) as response to gait perturbations in male and female LBP patients

Muscle onset (T)

T (mean) ranged from 83ms to 127ms in males and from 79ms to 113ms in females (Fig. 3; Tab. 3). In the time domain, females presented, overall, shorter (mean: 90±16ms) response times (T) compared to males (mean: 98±22ms; sex effect: $p<0.0001$) for all 12 muscles without significant interaction effect (sex*muscle: $p=0.9$).

Fig. 3 Polarplot of neuromuscular response (ms) of all 12 trunk muscles to perturbation for females and males

Tab 3. Neuromuscular response (ms) of all 12 trunk muscles to perturbation for females and males (mean±SD)

DISCUSSION

The main purpose of this study was to analyse whether males and females with LBP would show sex-specific trunk neuromuscular responses to sudden perturbations while walking. The presented study demonstrated a significant interaction effect (sex*muscle) for neuromuscular trunk activity, with females showing higher activity of the rectus abdominis (RA_{left}) and males higher activity of the externus oblique ($EO_{left/right}$) trunk muscles. Moreover, females presented overall shorter trunk-muscle response times compared to males.

Gait perturbations elicit sex-specific neuromuscular trunk responses in individuals with LBP. The higher rectus abdominis muscle activity in women might be discussed in the background of a sagittal plane-based muscle activation strategy in response to the asymmetric and unilateral stimulus applied, where higher rotational muscle activity is required to compensate for the perturbation (J. Müller et al., 2016). In this context, Rogers & Mille (Rogers and Mille, 2003)

stated that an impaired ability to control postural balance in the frontal plane seems to be predominantly relevant to a possible risk of stumbling. In addition to this, previous results of our applied walking perturbation could show an increased lateral flexion as well as a slightly increased axial rotation to compensate these gait disturbances in healthy participants (J. Müller et al., 2016). Therefore, externus oblique muscle activity of the male patients in our study, seems to be suitable with respect to the right unilateral gait perturbation applied to keep the balance and the trunk in a central position (Rogers and Mille, 2003). Moreover, the back muscles, especially of men, showed an asymmetric response pattern, with the right muscles showing higher EMG-RMS compared to the left-sided back muscles although the difference with females did not reach significance. This result suggests that men are able to counterbalance our applied gait perturbation, that provokes a sudden trunk bending to the left (J. Müller et al., 2016), by increasing the activation of the right back muscles as well as the external oblique muscle, which is in line with the results of previously published results (Thomas et al., 1998). However, our results contrast with those of Thomas et al. (Thomas et al., 1998) also as he did not report gender-specific neuromuscular response patterns to an asymmetric perturbation applied directly to the torso. Nevertheless, comparisons between the findings from this study and those from Thomas et al. (Thomas et al., 1998) require caution as the protocol applied to induce perturbations is not comparable to the one used in our study.

Another interesting finding were the sex-related differences in onsets of muscle activity. Female LBP individuals present 3 to 12% shorter muscle response times compared to males with LBP. Even though there was no significant interaction effect, this sex-effect has to be discussed as clinically relevant (Mueller et al., 2017; Radebold et al., 2000). Faster response times in LBP women might be a neural compensation strategy for the above-mentioned inconvenient muscle activation strategy. Furthermore, regardless of gender, the order of activation of trunk muscles following the perturbation, highlight the importance of earlier lateral-muscle activation in response to the asymmetrical perturbation applied in this study. Such strategy is likely required

to keep balance and avoid a fall (Hodges and Richardson, 1998; 1997). Besides, it cannot be ruled out, that the faster response times in women might also be related to sex-specific anthropometric differences in the analysed cohort (body height/mass) as larger segments in men would require more time to stabilize the trunk after perturbation. Nevertheless, Miller et al (Miller et al., 2010) reported shorter reflex latencies for healthy females than males after a quasi-static trunk flexion perturbation during standing, even after correction for maximum trunk flexion velocity. Therefore, the higher prevalence of LBP among females does not appear to result from slower muscle response times in sudden loading situations (Miller et al., 2010).

It is important to argue whether the reported differences during gait perturbations are sex-specific adaptations to LBP or just sex-specific adjustments to the perturbations. In recent studies assessing trunk responses to gait perturbations in healthy participants, gender specific re-analysis revealed shorter muscle onset times for females compared to males but not for all of the 12 trunk muscles analysed and gender differences were below 10% (Mueller et al., 2017; 2016). In addition, amplitude re-analysis showed higher ventral-central (M. rectus abdominis right) as well as ventral-lateral muscle activity (M. obliquus externus right/left) in males compared to females (Mueller et al., 2017; 2016), which contrasts with the results presented in the current study with LBP patients. Therefore, we suggest that the results reported in the current study are LBP induced sex-specific differential trunk activation strategies in response to the walking perturbations and not just sex-specific adaptations.

The presented results lead to the speculation, that exercise therapy in prevention and rehabilitation of LBP in females should include exercises that focuses on the increase of the EO muscle activity, as the EO is described to be involved in the lateral and axial rotational stability of the trunk (Konrad et al., 2001; Marras et al., 1998). In addition, various asymmetrical perturbations with sudden, unexpected loading could be added to train these abdominal muscles (Pedersen et al., 2004). Sensorimotor training, as described in previous studies including additional one-sided external perturbations, seems to be a feasible option for enhancing

performance of the specific trunk muscles (Hwang et al., 2013; Searle et al., 2015). Further validation of this approach is required by randomized controlled trials.

Certain limitations have to be considered when interpreting these results. During the experiment, all subjects walked at the same baseline velocity, not taking into account a potentially reduced self-selected (comfortable) gait velocity in LBP patients as well as differences between genders. With respect to standardization, a consistent test situation for all subjects was favored. Finally, differences in adipose tissue thickness between groups could have potentially influenced the results to a certain extent, but we minimized this effect by normalizing signals to unperturbed gait. The results for the asymmetry analysis, especially S_{right}:$S_{left,,}$ were not significant between sexes. However, the relatively low sample size might be responsible for this. With respect to pain level, it has to be stated, that there were no statistical significant differences between males and females in our study at time point of the evaluation. However, it cannot be ruled out that individuals were stressed to different extents by their pain, which might have influenced our results.

In conclusion, in this LBP population, abdominal muscle activation discriminated females from males. Specifically, females had higher activity of the rectus abdominis and lower activation of the externus oblique muscles, which might be interpreted as less efficient response to unilateral, asymmetrical postural perturbation. These different activation strategies might be relevant to the development of sex-specific intervention strategies. Accordingly, exercise therapy might aim for the improvement of trunk-muscle response to sudden unexpected perturbations during dynamic tasks and during walking, specifically focusing on sex-specific activation strategies of the abdominal muscles. Nevertheless, future research is needed to validate this approach.

CONFLICTS OF INTEREST STATEMENT

There is no conflict of interest.

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TABLES

Tab. 1 Anthropometrics and pain characteristics for males and females

Group	N	Age [yrs]	Body height* [cm]	Body weight* [Kg]	BMI	current LBP#	Worst LBP#	Average LBP#	CPIS¥
Females	17	29 ± 9	168 ± 10	64 ± 14	23 ± 1	2.1 ± 2.0	6.6 ± 1.4	3.8 ± 1.3	41.6 ± 12.5
Males	12	33 ± 10	183 ± 8	82 ± 11	25 ± 1	1.0 ± 1.2	6.1 ±1.8	4.3 ±1.7	38.1 ± 10.0

*significant differences between sexes ($p<0.0001$)

current, worst and average LBP in the last 3 month; all 3 items consisted of a numeric rating scale: 0 (no pain) -10 (worst pain)

¥characteristic pain intensity score (CPIS; 0-100; formula: mean of the 3 (current, worst, average LBP) items*10) of the graded chronic pain questionnaire from von Korff

Results

Tab. 2 Results of neuromuscular trunk co-contraction analysis illustrated by a ratio of ventral:dorsal muscles (A; V:D), $side_{right}$:$side_{left}$ muscles (B; S_{right}:S_{left}) and asymmetry ratio oblique internus:oblique externus (C; IO:$EO_{r/l}$) as response to gait perturbations in male and female LBP patients

A) V:D			
sex	**mean**	**SD**	**p-value**
male	1.30	0.53	
female	1.22	0.53	0.34

B) S_{right}:S_{left}			
sex	**mean**	**SD**	**p-value**
male	1.34	0.37	
female	1.15	0.26	0.07

C) IO:EO_r			
sex	**mean**	**SD**	**p-value**
male	0.74	0.34	0.08
female	1.25	0.90	

IO:EO_l			
sex	**mean**	**SD**	**p-value**
male	0.53	0.20	0.17
female	1.18	1.56	

Tab 3. Neuromuscular response (ms) of all 12 trunk muscles to perturbation for females and males (mean±SD)

sex		RA right	RA left	OE right	OE left	OI right	OI left	LD right	LD left	UES right	UES left	LES right	LES left
m	mean	123	127	98	92	100	108	89	92	90	88	88	83
	SD	25	32	14	16	18	32	8	10	9	11	11	10
f	mean	113	111	94	86	91	97	81	83	79	82	84	81
	SD	14	20	11	13	12	14	9	10	8	11	9	10

Legend: m=LBP males; f=LBP females; $RA_{right/left}$= M. rec. abd. right/left, $EO_{right/left}$= M. obl. ext. abd. right/left, $IO_{right/left}$= M. obl. int. abd. right/left; $LD_{right/left}$= M. latis. dorsi right/left, $UES_{right/left}$= M. erec. spinae thoracic (T9) right/left, $LES_{right/left}$= M. erec. spinae lumbar (L3) right/left

FIGURE LEGEND

Figure 1: 12-lead EMG set-up of the trunk

Legend: m=LBP males; f=LBP females; $RA_{r/l}$= M. rec. abd. right/left, $EO_{r/l}$= M. obl. ext. abd. right/left, $IO_{r/l}$= M. obl. int. abd. right/left; $LD_{r/l}$= M. latis. dorsi right/left, $UES_{r/l}$= M. erec. spinae thoracic (T9) right/left, $LES_{r/l}$= M. erec. spinae lumbar (L3) right/left

Fig. 2 2 Neuromuscular reflex activity (EMG-RMS; %; mean±SD) of all 12 trunk muscles for females and males

Legend: m=LBP males; f=LBP females; $RA_{r/l}$= M. rec. abd. right/left, $EO_{r/l}$= M. obl. ext. abd. right/left, $IO_{r/l}$= M. obl. int. abd. right/left; $LD_{r/l}$= M. latis. dorsi right/left, $UES_{r/l}$= M. erec. spinae thoracic (T9) right/left, $LES_{r/l}$= M. erec. spinae lumbar (L3) right/left

* significant interaction effect (sex*muscle); $p<0.05$

Fig. 3 Polarplot of neuromuscular response (ms) of all 12 trunk muscles to perturbation for females and males

Legend: m=LBP males; f=LBP females; RA= M. rec. abd. right/left, EO= M. obl. ext. abd. right/left, IO= M. obl. int. abd. right/left; LD= M. latis. dorsi right/left, UES= M. erec. spinae thoracic (T9) right/left, LES= M. erec. spinae lumbar (L3) right/left