

Motor Training of the Lumbar Paraspinal Muscles Induces Immediate Changes in Motor Coordination in Patients With Recurrent Low Back Pain

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Abstract: Recurrent low back pain (LBP) is associated with altered motor coordination of the lumbar paraspinal muscles. Whether these changes can be modified with motor training remains unclear. Twenty volunteers with unilateral LBP were randomly assigned to cognitively activate the lumbar multifidus independently from other back muscles (skilled training) or to activate all paraspinal muscles with no attention to any specific muscles (extension training). Electromyographic (EMG) activity of deep (DM) and superficial multifidus (SM) muscles were recorded bilaterally using intramuscular fine-wire electrodes and that of superficial abdominal and back muscles using surface electrodes. Motor coordination was assessed before and immediately after training as onsets of trunk muscle EMG during rapid arm movements, and as EMG amplitude at the mid-point of slow trunk flexion-extension movements. Despite different intentions of the training tasks, the pattern of activity was similar for both. After both training tasks, activation of the DM and SM muscles was earlier during rapid arm movements. However, during slow trunk movements, DM and SM activity was increased, and EMG activity of the superficial trunk muscles was reduced only after skilled training. These findings show the potential to alter motor coordination with motor training of the lumbar paraspinal muscles in recurrent LBP.

Perspectives: *Changes in motor coordination differed between skilled and extension training during slow trunk movements. As identical patterns of muscle activity were observed between training protocols, the results suggest that training-induced changes in motor coordination are not simply related to the muscle activation, but appear to be related to the task.*

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Key words: Low back pain, motor control, skilled motor training, lumbar multifidus, electromyography.

Coordination of the deep and superficial trunk muscles is changed in recurrent low back pain (LBP). Activity of the lumbar multifidus muscles is delayed¹⁹ and reduced^{5,30} during postural and functional tasks. In contrast, activity of the more superficial trunk muscles is often increased,^{2,10,26,38} although this varies between individual subjects and between tasks.^{10,36} The lumbar multifidus muscles contribute to the control of

intervertebral motion.^{16,20,37} Delayed and reduced activity of this muscle and concurrent increased activity of the large superficial muscles are argued to change spinal loading and movement, which may contribute to the recurrence of low back symptoms.¹⁰ Motor training interventions that aim to achieve appropriate coordination between the deep and superficial trunk muscles have been shown to be effective in the management of LBP.⁷ Although a previous study showed that motor training in people with LBP did not restore pain-related reduction in cross-sectional area of the lumbar multifidus,⁶ it remains unclear whether motor training can change coordination of these muscles.

One approach to rehabilitation of patients with recurrent LBP involves skilled cognitive activation of trunk muscles to elicit precise patterns of activity.²⁸ Skilled training can improve coordination of the abdominal muscles during untrained functional tasks. For instance, immediate³³ and persistent³⁴ improvements in postural

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Table 1. Subject Demographics (Mean \pm SD)

	SKILLED TRAINING	EXTENSION TRAINING
Age (years)	31 \pm 11	33 \pm 13
Sex	5 males, 5 females	4 males, 6 females
Height (cm)	170 \pm 9	172 \pm 10
Weight (kg)	68 \pm 11	70 \pm 15
Pain VAS (/10)	5.1 \pm 1.4	4.9 \pm 1.0
Pain duration (months)	Range, 4 - 260	Range, 12 - 216

Abbreviation: VAS, Visual analogue scale.

NOTE: No differences in subject demographics between the 2 training groups were observed ($P > .36$).

activation of the deep abdominal muscles are produced by skilled cognitive activation of these muscles in individuals with recurrent LBP. Changes were not replicated by motor training that involved activation of all abdominal muscles in simple movements or bracing tasks without attention to the muscles activated.^{8,33} It is unclear whether skilled motor training can induce changes in the deep and superficial paraspinal muscles, or whether changes in these muscles depend on the type of motor training (eg, independent isolated contractions of deep trunk muscles versus general activation of all trunk muscles).

This study investigated the immediate effects of motor training of the paraspinal muscles on motor coordination during untrained tasks. If changes in motor coordination were induced, we also aimed to examine whether this was dependent on how the training was performed.

Methods

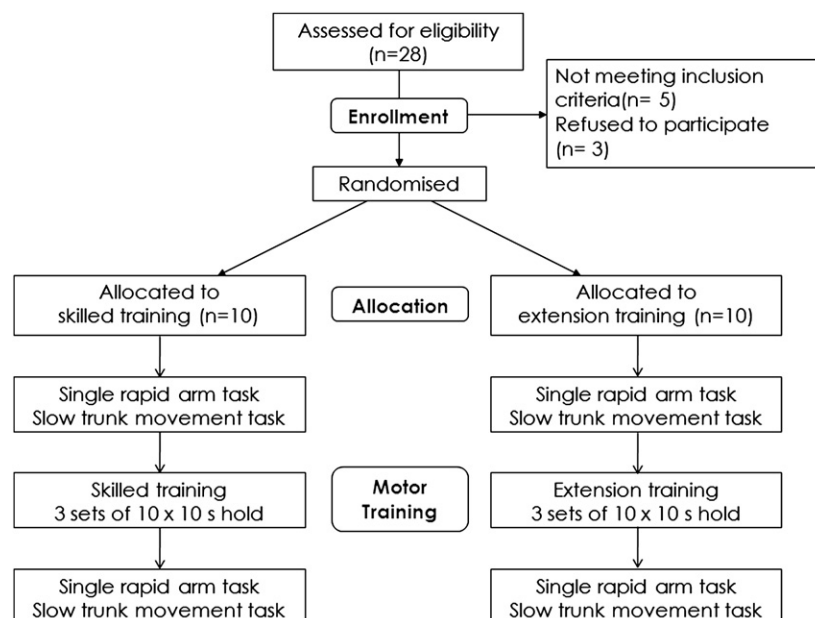
Participants

Twenty volunteers (11 females, 9 males) with unilateral, non-specific LBP lasting longer than 3 months

were randomized via cards concealed in consecutive opaque envelopes into 1 of 2 motor training groups (Table 1); 1) training that involve cognitive attention to activate the multifidus muscles independently from the other back muscles (skilled training) or 2) gentle back extension to activate all paraspinal muscles together without attention to any muscle (extension training). Fig 1 illustrates subject screening and testing procedures. Subjects were included if they had a history of recurrent pain that was sufficient to limit activities of daily living. No subject experienced aggravation of their back pain during the experimental tasks. Participants were excluded if they had any neurological, respiratory, orthopedic or circulatory disorders, previous spinal or abdominal surgery, pregnancy in the last 2 years, or had undertaken any form of abdominal or back muscle training during the past 12 months. The Institutional Medical Ethics Committee approved the study. Informed consent was obtained for each subject and all procedures conformed to the Declaration of Helsinki.

Electromyography

Electromyographic (EMG) activity of the deep and superficial fibers of the lumbar multifidus (also known as the deep [DM] and superficial multifidus [SM]) was recorded using bipolar fine-wire electrodes (Teflon-coated stainless steel wire 75 μ m diameter with 1 mm of insulation removed from the ends and bent back by 1 mm and 4 mm). Fine-wire electrodes were inserted via a hypodermic needle with ultrasound guidance into the DM and SM muscles adjacent to the L5 spinous process on both sides.^{19,23} For DM, the needle was inserted \sim 3 cm lateral to the L5 spinous process until the needle reached the most medial aspect of the L5 lamina. For SM, the needle was inserted \sim 4 cm lateral to the spinous process until the electrodes were positioned in the more superficial fibers of multifidus.

**Figure 1.** Flow diagram of subject screening and experimental protocol.

Our observations from anatomical specimens suggest that these locations allow optimal recording from DM and SM of the lumbar multifidus at this level.

In addition, pairs of surface electrodes (Ag/AgCl disc electrode, 10 mm diameter, 20 mm electrode spacing; Grass Telefactor, West Warwick, RI) were placed over the lumbar erector spinae (LES) 5 cm lateral to the L2 spinous process, thoracic erector spinae (TES) 3 cm lateral to the T9 spinous process, latissimus dorsi (LD) lateral to T9 over the muscle belly,²¹ obliquus externus (OE; inferior to rib angle aligned inferomedially toward the pubis²⁴) and internus abdominis (OI; medial to anterior superior iliac spine aligned inferomedially toward the pubis²⁴) and rectus abdominis (RA; adjacent to umbilicus²⁴). As it is not possible to exclude the contribution of transversus abdominis (TrA) to OI recordings,²⁴ we will refer to OI as OI/TrA. Surface electrodes were also placed over the anterior (AD) and posterior deltoid (PD) muscles of the left arm. A reference electrode was positioned over the left iliac crest.

EMG data were amplified 2000 times, band-pass filtered between 20 Hz and 1 kHz, and sampled at 2 kHz using a Power 1401 Data Acquisition System with Signal2 software (Cambridge Electronic Design, Cambridge, UK). Data were exported for analysis with Matlab 7 (MathWorks, Inc., Natick, MA).

Procedures

Coordination of the trunk muscles was assessed during single rapid arm movements and slow trunk movements. Single arm movements were used to evaluate pre-programmed activity of the trunk muscles as a component of feed-forward postural adjustments.^{3,12} Subjects stood with feet shoulder-width apart and were instructed to remain relaxed before flexing or extending their left arm as fast as possible in response to auditory tones triggered by the experimenter.¹³ Distinct tones indicated the direction of arm movement. Ten repetitions of arm flexion and extension were completed in random order to yield sufficient repeatability of the data (Moseley and Hodges, unpublished data). EMG activity was recorded during arm movement before and immediately after a single session of training. Due to the limitations in the number of channels available and the need to record from the AD and PD muscles, RA EMG was not recorded during arm movements. As onsets of trunk muscle EMG change with speed of arm movement,¹³ angular acceleration of the arm was recorded using an accelerometer attached at the left wrist.

Subjects also performed slow trunk flexion and extension movements to evaluate muscle activity associated with maintenance of trunk stability in the mid upright position of the spine.⁴ Around the neutral or mid-position, minimal trunk muscle activity is required to maintain equilibrium against gravity and the activity in this position is argued to be the minimum activity required to maintain stability.⁴ The trunk muscles are critical in this neutral position as this is where the spine exhibits the least passive stiffness.²⁵ A rigid frame was used to fix the pelvis and lower extremity such that

movements were restricted to the trunk.²⁶ An electronic inclinometer (Spectron, Ventura, CA) was attached to a shoulder harness worn by the subject to monitor trunk movement. EMG activity was recorded during 4 trials that involved flexion and extension of the trunk. With arms crossed over the chest, the first trial started from $\sim 20^\circ$ lumbar flexion and subjects moved slowly to $\sim 20^\circ$ extension over a period of ~ 7 seconds. Verbal instructions were provided to ensure accuracy of the task. Subjects held their trunk at $\sim 20^\circ$ extension for ~ 3 seconds and then moved slowly in the opposite direction to return to the flexed starting position, which was held for ~ 3 seconds. The procedure was repeated. Two practice trials were allowed for task familiarization. Slow trunk movement tasks were conducted before and immediately after the motor training intervention.

To determine targets for motor training, 3 maximal voluntary isometric lumbar extension contractions (MVC) were performed. In a semi-seated position, subjects were stabilized around the pelvis and a harness was placed over their shoulders. The instruction was to pull backwards as hard as possible and verbal encouragement was provided. The highest root-mean-square (RMS) EMG for each paraspinal muscle (DM, SM, TES, and LES) across the 3 MVCs was identified. The target level of muscle contraction for the training intervention was set at 5% of the highest RMS EMG for the DM on the most painful side of the back. This level of activation is approximately consistent with activity of the lumbar multifidus muscles during functional tasks such as walking.²⁹ MVCs for other trunk muscles were also performed at the end of the experiment. This involved 3 repetitions of resisted sit-up (RA), left and right trunk rotation (OE and OI), forced expiratory manoeuvre (TrA) and shoulder adduction (LD⁴).

Motor Training Interventions

Subjects were positioned in prone with arms by the side and a pillow underneath the legs for comfort. An experienced musculoskeletal physiotherapist instructed the subjects to perform 2 training tasks: skilled activation of multifidus and a simple extension motor training task.

Skilled Motor Training

This intervention involved cognitive attention to activation of the lumbar multifidus muscles (particularly the deep fibers) with minimal or no activity of the more superficial paraspinal muscles. To help train the desired contraction, techniques that included detailed anatomical description, motor imagery, palpation and co-activation with deep abdominal muscles and/or pelvic floor muscles were implemented as required to obtain the best performance that could be achieved by the participant. The intensity of voluntary contractions was set at 5% of DM MVC on the symptomatic side and is consistent with clinical recommendations.²⁸ Substitution or co-contraction with more superficial spinal extensors was discouraged and was monitored through palpation and EMG feedback. Once performance was optimal (independent contraction of lumbar multifidus with

minimal superficial paraspinal muscle activity), subjects held the contraction for 10 seconds and continued breathing.

Extension Training

This intervention involved no attention to specific muscles, but rather simple performance of a trunk extension manoeuvre with DM EMG amplitude matched to that performed in skilled motor training task (~5% DM MVC). The aim of this training approach was for subjects to activate all paraspinal muscles with a gentle lift of their head and upper body. The contraction was held for 10 seconds while breathing.

All subjects from both training groups completed 3 sets of 10 repetitions with 2-minute rests between each set. Feedback was provided to the subject with respect to the intensity and quality of each contraction.

Data Analysis

For rapid arm movements, onsets of trunk and deltoid muscle EMG were visually identified. Data were coded by a research assistant such that analysis was performed without reference to the identity of the subject, muscle, direction of arm movement, or whether the data was before or after training. Data were high-pass filtered at 30 Hz to remove movement artifact, and onset of EMG was selected as the point at which EMG increased above baseline level. Visual identification of onsets is valid and is less affected by factors such as increased background activity.⁹ Onsets of all trunk muscle EMG relative to that of the prime mover deltoid were calculated.

For slow trunk movements, the electrocardiogram was removed from EMG data with a modified turning point filter.^{1,4} Data were rectified, low-pass filtered at 1 Hz (4th order Butterworth), and down-sampled to 100 Hz. The total RMS amplitude of 12 surface EMG recordings (LES, TES, LD, RA, OI/TrA, and OE) was calculated from the raw EMG data with respect to trunk angle. As the study investigated changes before and immediately after a single session of motor training, and for each muscle the pre-training data acted as the control, it was not necessary to normalize the data for calculation of aggregate RMS amplitude. Furthermore, a previous study by Cholewicki et al⁴ recorded from the multifidus adjacent to L4/5 spinous process using surface EMG whereas we recorded from the LD. As the lumbar multifidus is situated close to the spine and thus argued to function predominantly as a stabilizer of the spine,^{16,20,37} we elected to record from the LD bilaterally. The minimum value of this aggregate RMS vector (RMS_{min}) is argued to occur at the mid position of the spine and represents the minimum intensity of trunk muscle co-activation required for mechanical stability of the spine.⁴ The RMS_{min} was averaged over the 2 trials and a ratio of the post- to pre-training RMS_{min} values was calculated. In addition, the trunk angle corresponding to the RMS_{min} value was identified as the subject's neutral or mid position. At this position, the raw EMG amplitude for each individual muscle was calculated from surface and intramuscular recordings, averaged across the 2 trials for each movement direction, and

normalized to peak RMS EMG (identified over a 1-second period) during MVC contractions.

The amplitude of EMG activity of the trunk muscles during performance of skilled and extension training was also evaluated. EMG data were high-pass filtered at 30 Hz. RMS EMG for each muscle over a 3-second period was calculated around the time of peak activity in the initial 5 contractions of the first set, and the final 5 contractions of the third set of motor training. This was normalized to the peak RMS EMG recorded during MVCs.

Statistical Analysis

Onsets of all trunk muscles relative to prime mover deltoid during rapid arm movements were compared between trials before and immediately after motor training using a repeated-measures analysis of variance (AN-OVA) with 2 repeated measures (time: pre- vs post-training; arm-direction: flexion vs extension) and 3 independent factors (arm-side [ipsilateral vs contralateral to moving arm], pain-side [pain vs non-pain side], and training [skilled vs extension]). Significant main effects and interactions were further analysed with post hoc testing using Duncan multiple range test. To evaluate changes in RMS_{min} during slow trunk movement, the ratio of values were compared between interventions with a *t* test for independent samples. Each intervention was also compared with no change (ratio = 1) with a *t* test for single samples. To investigate changes in the activity of individual trunk muscles at the RMS_{min} trunk angle, normalized RMS EMG were compared using a repeated-measures ANOVA, with time and trunk-direction (flexion to extension or extension to flexion) as repeated measures, and muscle and training as independent measures. In addition, normalized EMG amplitudes collected during both training tasks were also compared between initial and final contractions, between training groups and between muscles using repeated measures ANOVA. As the study was largely exploratory in nature, we considered any adjustment for multiple comparisons too conservative. Thus, the significance level was set at .05.

Results

Rapid Arm Movements

Figs 2 and 3 show EMG onsets during rapid arm movement tasks before and immediately after motor training interventions. Activation of all trunk muscles except the LD was earlier during arm flexion compared with extension tasks (interaction for arm-direction \times muscle: $F(1,6) = 6.94$, $P < .001$, post hoc for all muscles $P < .007$ except LD $P = .09$). No difference in EMG onsets was found between pain and non-pain side (main effect for pain-side: $F(1,1) = .50$, $P = .48$), or between muscles contralateral and ipsilateral to the arm moved (main effect for arm-side: $F(1,1) = 1.27$, $P = .26$).

After a single session of exercise (either skilled or extension), EMG activity in the SM and DM muscles was earlier (interaction for time and muscle: $F(1,6) = 3.48$,

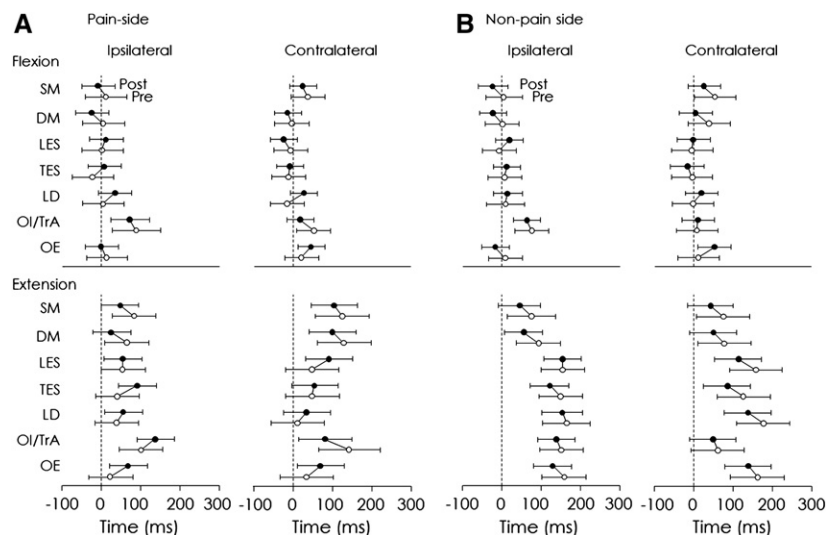


Figure 2. Skilled training: Onset of trunk muscle EMG relative to onset of prime mover deltoid (vertical dotted line) during arm flexion (top panel) and extension (bottom panel) for muscles contralateral (left panel) and ipsilateral (right panel) to the arm that was moved. Mean and 95% confidence intervals for muscles on the pain (**A**) and non-pain side (**B**) are shown. Note earlier EMG onset of most muscles after training. OE, obliquus externus abdominis; OI/TRA, obliquus internus abdominis/transversus abdominis; LD, latissimus dorsi; TES, thoracic erector spinae; LES, lumbar erector spinae.

$P = .003$; post hoc $P < .036$). The onset of OI/TrA EMG was also earlier following both motor training tasks ($P = .026$). However, this was not observed when pain-side or arm-side was added to the interaction (interaction for time, muscle, and pain-side: $F(1,6) = .22$, $P = .97$; interaction for time, muscle and arm-side: $F(1,6) = .58$, $P = .75$). Changes were not different between skilled and extension training groups (main effects for training: $F(1,1) = .08$, $P = .77$).

No difference in peak arm acceleration was found between training groups (main effect for training: $F(1,1) = 1.10$, $P = .31$), or between pre- and post-training trials for arm flexion (interaction for time and arm-direction:

$F(1,1) = .34$, $P = .669$; pre-training [averaged across training groups]: $2329 \pm 582^\circ/\text{s}$; post-training: $2157 \pm 743^\circ/\text{s}$) and extension tasks (pre-training: $1811 \pm 463^\circ/\text{s}$; post-training: $1725 \pm 497^\circ/\text{s}$). This suggests that the arm was moved in a similar manner between training groups, and before and after motor training.

Slow Trunk Movements

In most subjects, muscle activity switched between flexors and extensors in the upright position during slow trunk movements (Fig 4). However, in 2 subjects (1 from each intervention group), no reduction in flexor

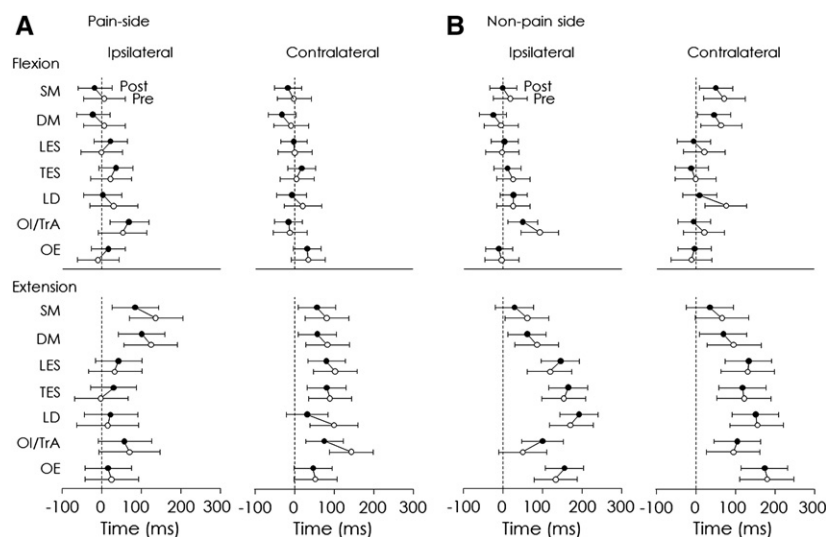


Figure 3. Unskilled extension training: Onset of trunk muscle EMG relative to onset of prime mover deltoid (vertical dotted line) during arm flexion (top panel) and extension (bottom panel) for muscles contralateral (left panel) and ipsilateral (right panel) to the arm that was moved. Mean and 95% confidence intervals for muscles on the pain (**A**) and non-pain side (**B**) are shown. After extension training, earlier EMG onsets of the most muscles were observed. OE, obliquus externus abdominis; OI/TRA, obliquus internus abdominis/transversus abdominis; LD, latissimus dorsi; TES, thoracic erector spinae; LES, lumbar erector spinae.

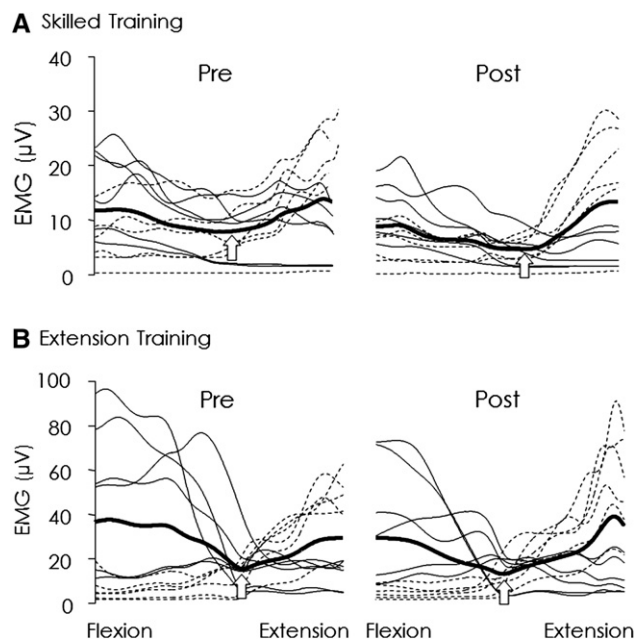


Figure 4. Representative data a single subject from each training group during slow trunk movements before (left panel) and immediately after (right panel) skilled (A) and extension training (B). Bold lines represent the aggregate RMS superficial muscle activity. Thin solid lines represent activity of superficial back muscles (thoracic erector spinae [TES], lumbar erector spinae [LES], latissimus dorsi [LD]). Arrows indicate time of minimum RMS EMG amplitude. Thin dashed lines represent abdominal muscles (rectus abdominis [RA], obliquus externus [OE], and obliquus internus abdominis/transversus abdominis [OI/TRA]). Note reduced minimum aggregate RMS muscle activity after skilled training.

and extensor activity was observed as the trunk moved through the neutral position. As the minimum point could not be identified, the data for these subjects were excluded from group analysis.

After a single session of skilled training, the minimum aggregate superficial muscle activity (RMS_{min}) recorded during slow trunk movements was reduced (Fig 5). That is, the ratio of post- to pre-training RMS_{min} was less than 1 ($P = .04$). In contrast, no change in RMS_{min} was observed after extension training. The RMS_{min} ratio was lower in the skilled training group compared with the extension training group ($P = .05$).

When EMG amplitude at the RMS_{min} position was evaluated for each muscle (Fig 6), no changes were observed in the activity of any individual superficial trunk muscles (recorded with surface electrodes) at the RMS_{min} position (significant interaction between direction, time, muscle, and training: $F(1,15) = 2.02$, $P = .023$; post hoc: $P > .06$). Thus, although net activity of the superficial trunk muscles decreased, there was no systematic decrease for any individual muscle. After skilled training, SM and DM amplitude on the pain side was greater (post hoc: $P < .001$). However, after extension training, activity of the SM and DM muscles on the pain side was reduced (post hoc: $P < .034$). These changes were only evident during extension to flexion trials (Fig 6A) and were not observed on the non-pain side (post hoc for DM and SM on non-pain side: $P > .10$; Fig 6B).

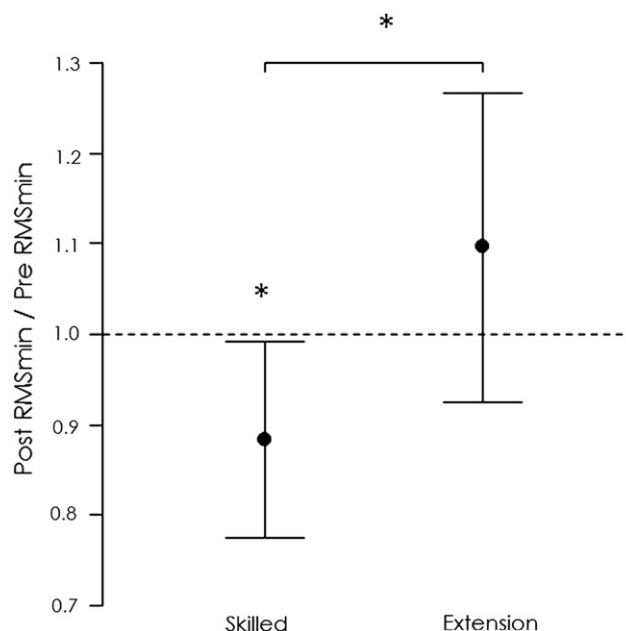


Figure 5. Aggregate superficial trunk muscle EMG activity expressed as the ratio of post-training to pre-training RMS_{min} for each training group. Mean and 95% confidence interval are shown. Values less than 1 denote a reduction in aggregate EMG activity with training. Note reduced activity in skilled training group post-intervention and compared with the extension training group. $*P < .05$.

Motor Training Intervention

Fig 7 shows the amplitude of RMS EMG for the paraspinal muscles during skilled and extension training. Despite different instructions and intentions of the tasks, there were no differences in amplitude of paraspinal muscle activation between muscles (main effect for muscle: $F(1,7) = 2.80$, $P = .14$), training groups (main effect for training: $F(1,7) < .97$, $P > .36$) or between the first 5 and last 5 contractions (main effect for initial vs final contractions: $F(1,1) = .16$, $P = .69$; Fig 7).

Discussion

The findings suggest that training can induce changes in motor coordination but this is more dependent on the "intention" of motor training rather than the "actual" pattern of muscle activation. Skilled training induced earlier and greater activity of the lumbar multifidus muscles, and reduced aggregate activity of the superficial trunk muscles during slow movements. Although onset of EMG of lumbar multifidus was also earlier after extension training, there were no changes in activity during the slow trunk movement task. These findings further unravel the understanding of the possible mechanisms for efficacy of motor rehabilitation in patients with recurrent LBP.

Temporal Activation of the Trunk Muscles in Patients With Recurrent Low Back Pain Can Be Trained

Previous studies show that in healthy individuals, earlier activation of the DM is observed compared with

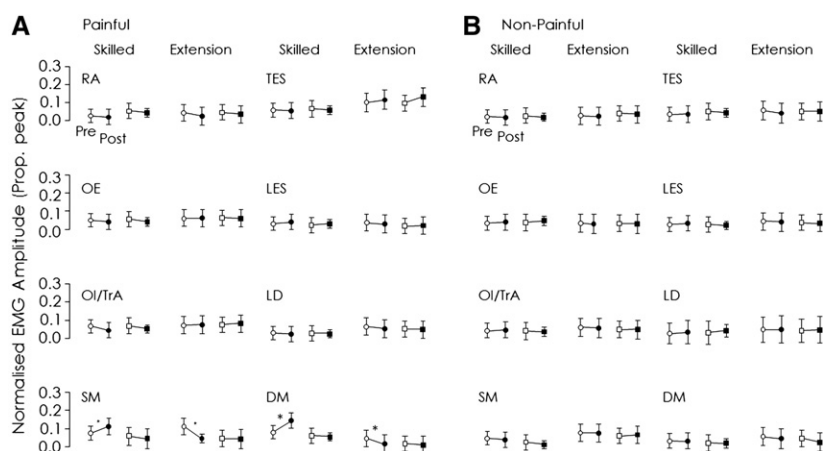


Figure 6. Normalized EMG amplitude recorded at the neutral trunk position from trunk muscles on the pain (A) and non-pain side (B). Group mean and 95% confidence interval of trunk extension to flexion trials (circles) and flexion to extension trials (squares) are shown pre-training (white) and post-training (black). Note increased activation of the deep (DM) and superficial multifidus (SM) on the pain side after skilled training but reduced activity after extension training. * $P < .05$. RA, rectus abdominis; OE, obliquus externus abdominis; OI/TRA, obliquus internus abdominis/transversus abdominis; SM, superficial multifidus; TES, thoracic erector spinae; LES, lumbar erector spinae; LD, latissimus dorsi.

that of the SM during rapid arm movement tasks.² In patients with unilateral LBP, we observed similar onsets for DM and SM on the pain side rather than before SM, which suggests a delay in activation of the DM muscles. This is consistent with previous findings for multifidus¹⁹ and other deep trunk muscles such as transversus abdominis.¹² The only difference from earlier data was that the onsets of DM and SM were similar on the non-pain side, which was not observed by MacDonald et al.¹⁹ As the methods and subject population in that study were similar to the current study, the findings may demonstrate variability of muscle responses in patients with recurrent LBP.

A single session of skilled motor training was sufficient to induce earlier postural activation of the lumbar multifidus muscles in patients with recurrent LBP. This mirrors previous findings in skilled training of the abdominal muscles.^{33,34} However, earlier onset of the lumbar multifidus EMG after a single session of unskilled extension training was also observed. This appears to contrast previous data for the other muscles, which showed that simple flexion training (which activated all abdominal muscles) did not lead to earlier onset of the deep abdominal muscles during some movements.³³ It is interesting to note that similar changes were observed between the SM and DM after motor training. It is likely that similar changes are due to similar amplitudes of activation between the SM and DM during motor training.

Skilled Training of DM Led to Differential Effects on Deep and Superficial Trunk Muscles in Slow Trunk Movements

The goal of skilled training is to reduce activity of the superficial trunk muscles, which may increase the contribution of the deep trunk muscles during functional tasks. After a single session of skilled training of the lumbar multifidus but not unskilled extension training, greater EMG activity of the SM and DM muscles and reduced aggregate EMG activity of the superficial trunk

muscles were observed around this mid-position during movements from trunk extension to flexion. The co-contraction of flexor and extensor muscles in the neutral position is argued to reflect a functional strategy to ensure spinal stability.⁴ Changes in coordination of the trunk muscles in the mid position may represent reorganization of the strategy used by the nervous system for spinal control. Conversely, it is possible that skilled

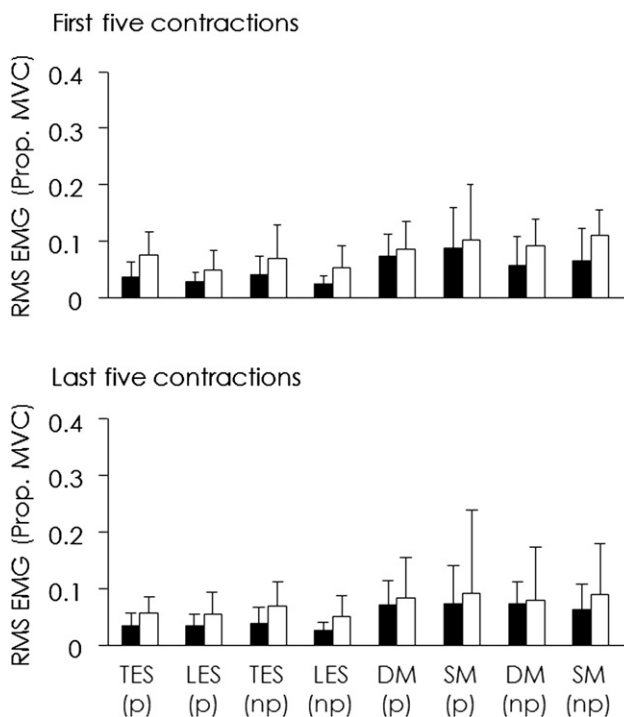


Figure 7. Amplitude of EMG activity (normalized to maximum voluntary contractions [MVC]) during the first and third set of skilled (black) and extension motor training (white). Mean and 95% confidence intervals are shown. No difference in EMG activity was found for all paraspinal muscles between training interventions. DM, Deep multifidus; SM, superficial multifidus; TES, thoracic erector spinae; LES, lumbar erector spinae; RMS, root-mean-square. * $P < .05$.

training involved a greater intention to reduce activity of the superficial trunk muscles, which may result in increased demand for activity of the deeper trunk muscles. One interpretation is that the demand for co-activation of superficial trunk muscles is reduced when recruitment of the lumbar multifidus muscles is increased. Interestingly, when the 12 superficial muscles monitored with surface EMG were examined individually, none showed a systematic response to skilled training intervention across subjects, despite a reduction in aggregate activation. Such variation between subjects is not surprising given the heterogeneity of low back disorders and the redundancy in the motor system (ie, many options to control the trunk). This further illustrates that spinal control is dependent on the coordination of an array of trunk muscles.²² Notably, a variety of motor strategies exist for stabilization of the spine^{4,26} and individual subjects adopt a unique strategy in LBP.¹¹ As we investigated changes in aggregate RMS activity before and after motor training, it is unlikely that differences in motor strategy employed between each individual would influence the current findings.

In contrast, reduced activity of lumbar multifidus muscles was found after unskilled extension training, with no changes in aggregate activity of the superficial trunk muscles. These changes differed to that after skilled training, despite the fact that participants used similar patterns of trunk muscle activity for both training protocols. One interpretation is that differences in the response to training may be mediated by differences in the cognitive "intention" of the 2 training tasks. That is, skilled training involved greater attention to specific muscles (ie, lumbar multifidus) compared with extension training. Cognitive factors are argued to be critical to improve the execution of motor tasks and facilitate the transfer of skills to untrained tasks.¹⁸ Previous studies demonstrate skilled cognitive training induces greater improvements in motor performance than motor training that involves predominantly strengthening.²⁷ This is argued to be related to greater reorganization of the motor system after skilled compared with non-skilled training,^{15,17,31} which may contribute to the coordination of muscle activation during functional tasks.³² Regardless, if the lumbar multifidus provides an important contribution to spinal control,^{14,37} reduced activation of this muscle (as observed in the extension training group) may compromise lumbar intervertebral control.

Implications of Postural Control in LBP

People with LBP exhibit an abnormal strategy of spinal control with impaired recruitment of the lumbar multifidus and increased co-activation of the superficial trunk

muscles.^{10,35} Evidence of improved recruitment of the lumbar multifidus muscles with reduced co-activation of the superficial trunk muscles, which was most evident after skilled cognitive training, would be consistent with restoration of muscle activation towards that observed in pain free individuals. However, there is debate whether increased activation of superficial muscles in people with LBP is an adaptive mechanism required to stabilize and protect the spine³⁵ or a maladaptive change that may be appropriate in the short term but with long term negative consequences.¹⁰ If the goal of motor control changes with LBP is to maximize stability and protect the spine, then reduced net activity of superficial muscles induced by skilled motor training of lumbar multifidus would be interpreted to be problematic as stability would be reduced. However, given the efficacy of interventions that use this type of skilled motor training in the management of LBP,⁷ positive outcomes in pain, disability and symptom recurrence are likely to be the result of optimization of the balance between the deep and superficial muscles. In this interpretation of rehabilitation of people with LBP, the maintenance of spinal stability must be balanced against the negative consequences of excessive muscle co-activation such as increased spinal loading.²¹

The present findings detail the association between motor training and changes in postural motor coordination. This association may underlie the efficacy of interventions for the management of pain, disability and symptom recurrence. In particular, training that involves repeated cognitive activation of muscles can immediately influence the manner in which they are recruited during untrained functional movements. Motor rehabilitation that incorporates this approach to induce changes in motor strategy may lead to changes in spinal loading and improve symptoms. As the current study only involved a single session of motor training and a small group of subjects, changes in symptoms were not investigated. Nevertheless, further research is required to investigate whether the motor control changes described here can be further improved and retained with repeated sessions of training, whether these changes can be transferred to other functional tasks, and whether changes in postural control are linked to changes in symptoms.

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References

1. Aminian K, Ruffieux C, Robert C: Filtering by adaptive sampling (FAS). *Med Biol Eng Comput* 26:658-662, 1988
2. Arendt-Nielsen L, Graven-Nielsen T, Sværre H, Svensson P: The influence of low back pain on muscle activity and coordination during gait: A clinical and experimental study. *Pain* 64:231-240, 1996
3. Belen'kii VY, Gurfinkel VS, Pal'tsev YI: Control elements of voluntary movements. *Biofizika* 12:135-141, 1967
4. Cholewicki J, Panjabi MM, Khachatryan A: Stabilizing function of trunk flexor-extensor muscles around a neutral spine posture. *Spine* 22:2207-2212, 1997

5. Danneels LA, Coorevits PL, Cools AM, Vanderstraeten GG, Cambier DC, Witvrouw EE, De Cuyper HJ: Differences in electromyographic activity in the multifidus muscle and the iliocostalis lumborum between healthy subjects and patients with sub-acute and chronic low back pain. *Eur Spine J* 11: 13-19, 2002
6. Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, Bourgois J, Dankaerts W, De Cuyper HJ: Effects of three different training modalities on the cross sectional area of the lumbar multifidus muscle in patients with chronic low back pain. *Br J Sports Med* 35:186-191, 2001
7. Ferreira PH, Ferreira ML, Maher CG, Herbert RD, Refshauge K: Specific stabilisation exercise for spinal and pelvic pain: A systematic review. *Aust J Physiotherapy* 52:79-88, 2006
8. Hall L, Tsao H, MacDonald D, Coppieters MW, Hodges PW: Immediate effects of co-contraction training on motor control of the trunk muscles in people with recurrent low back pain. *J Electromyogr Kinesiol* 19:763-773, 2009
9. Hodges PW, Bui BH: A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. *Electroencephalogr Clin Neurophysiol* 101:511-519, 1996
10. Hodges PW, Moseley GL: Pain and motor control of the lumbopelvic region: Effect and possible mechanisms. *J Electromyogr Kinesiol* 13:361-370, 2003
11. Hodges PW, Moseley GL, Gabrielsson A, Gandevia SC: Experimental muscle pain changes feedforward postural responses of the trunk muscles. *Exp Brain Res* 151:262-271, 2003
12. Hodges PW, Richardson CA: Inefficient muscular stabilization of the lumbar spine associated with low back pain: A motor control evaluation of transversus abdominis. *Spine* 21:2640-2650, 1996
13. Hodges PW, Richardson CA: Relationship between limb movement speed and associated contraction of the trunk muscles. *Ergonomics* 40:1220-1230, 1997
14. Indahl A, Kaigle A, Reikerås O, Holm S: Electromyographic response of the porcine multifidus musculature after nerve stimulation. *Spine* 20:2652-2658, 1995
15. Jensen JL, Marstrand PCD, Nielsen JB: Motor skill training and strength training are associated with different plastic changes in the central nervous system. *J Appl Physiol* 99: 1558-1568, 2005
16. Kaigle AM, Holm SH, Hansson TH: Experimental instability in the lumbar spine. *Spine* 20:421-430, 1995
17. Karni A, Meyer G, Jezard P, Adams MM, Turner R, Ungerleider LG: Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature* 377: 155-158, 1995
18. Liu KP, Chan CC, Lee TM, Hui-Chan CW: Mental imagery for promoting relearning for people after stroke: A randomized controlled trial. *Arch Phys Med Rehabil* 85:1403-1408, 2004
19. MacDonald D, Moseley GL, Hodges PW: Why do some patients keep hurting their back? Evidence of ongoing back muscle dysfunction during remission from recurrent back pain. *Pain* 142:183-188, 2009
20. Macintosh JE, Bogduk N: The detailed biomechanics of the lumbar multifidus. *Clin Biomechanics* 1:205-231, 1986
21. Marras WS, Parnianpour M, Ferguson SA, Kim JY, Crowell RR, Bose S, Simon SR: The classification of anatomic and symptom-based low back disorders using motion measure models. *Spine* 20:2531-2546, 1995
22. McGill SM, Grenier S, Kavcic N, Cholewicki J: Coordination of muscle activity to assure stability of the lumbar spine. *J Electromyogr Kinesiol* 13:353-359, 2003
23. Moseley GL, Hodges PW, Gandevia SC: Deep and superficial fibers of the lumbar multifidus muscle are differentially active during voluntary arm movements. *Spine* 27: E29-E36, 2002
24. Ng JK-F, Kippers V, Richardson CA: Muscle fibre orientation of abdominal muscles and suggested surface EMG electrode position. *Electromyogr Clin Neurophysiol* 38:51-58, 1998
25. Panjabi MM: The stabilising system of the spine, II: Neutral zone and instability hypothesis. *J Spinal Disord* 5: 390-397, 1992
26. Radebold A, Cholewicki J, Polzhofer GK, Greene HS: Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. *Spine* 26:724-730, 2001
27. Remple MS, Bruneau RM, VandenBerg PM, Goertzen C, Kleim JA: Sensitivity of cortical movement representations to motor experience: Evidence that skill learning but not strength training induces cortical reorganization. *Behav Brain Res* 123:133-141, 2001
28. Richardson CA, Jull G, Hodges PW, Hodges J: *Therapeutic Exercise for Spinal Segmental Stabilization in Low Back Pain*. London, Churchill Livingstone, 1998
29. Saunders SW, Rath D, Hodges PW: Postural and respiratory activation of the trunk muscles varies with mode and speed of locomotion. *Gait Posture* 20:280-290, 2004
30. Sihvonen T, Lindgren KA, Airaksinen O, Manninen H: Movement disturbances of the lumbar spine and abnormal back muscle electromyographic findings in recurrent LBP. *Spine* 22:289-295, 1997
31. Tsao H, Galea MP, Hodges PW: Driving plasticity in the motor cortex in recurrent low back pain. *Eur J Pain* 2010 Feb 22 [Epub ahead of print]
32. Tsao H, Galea MP, Hodges PW: Reorganization of the motor cortex is associated with postural control deficits in recurrent low back pain. *Brain* 131:2161-2171, 2008
33. Tsao H, Hodges PW: Immediate changes in feedforward postural adjustments following voluntary motor training. *Exp Brain Res* 181:537-546, 2007
34. Tsao H, Hodges PW: Persistence of improvements in postural strategies following motor control training in people with recurrent low back pain. *J Electromyogr Kinesiol* 18: 559-567, 2008
35. van Dieen JH, Cholewicki J, Radebold A: Trunk muscle recruitment patterns in patients with low back pain enhance the stability of the lumbar spine. *Spine* 28:834-841, 2003
36. van Dieen JH, Selen LPJ, Cholewicki J: Trunk muscle activation in low-back pain patients, an analysis of the literature. *J Electromyogr Kinesiol* 13:333-351, 2003
37. Wilke HJ, Wolf SL, Claes LE, Arand M, Wiesend A: Stability increases of lumbar spine with different muscle groups: A biomechanical in vitro study. *Spine* 20:192-198, 1995
38. Zedka M, Prochazka A, Knight B, Gillard D, Gauthier M: Voluntary and reflex control of human back muscles during induced pain. *J Physiol (Lond)* 520:591-604, 1999