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Reorganised motor control strategies of trunk muscles due to acute low back pain

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1   REORGANISED MOTOR CONTROL STRATEGIES OF TRUNK MUSCLES

2   DUE TO ACUTE LOW BACK PAIN

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1 **ABSTRACT**

2 This study assessed how the low back motor control strategies were affected by experimental pain.

3 In twelve volunteers the right m. longissimus was injected by hypertonic and isotonic (control)

4 saline. The pain intensity was assessed on a visual analogue scale (VAS). Subjects were seated on a

5 custom-designed chair including a 3-dimensional force sensor adjusted to the segmental height of

6 T1. Electromyography (EMG) was recorded bilaterally from longissimus, multifidus, rectus

7 abdominis, and external oblique muscles. Isometric trunk extensions were performed before,

8 during, and after the saline injections at 5%, 10%, and 20% of maximum voluntary contraction

9 force. Visual feedback of the extension force was provided whereas the tangential force components

10 were recorded. Compared with isotonic saline, VAS scores were higher following hypertonic saline

11 injections ($P<0.01$). Experimental low back pain reduced the EMG activity bilaterally of the rectus

12 abdominis muscles during contractions at 10 and 20% MVC ($P<0.01$) although force accuracy and

13 tangential force variability was not affected. Increased variability in the tangential force

14 composition was found during pain compared with the non-painful condition ($P<0.05$). The

15 immediate adaptation to pain was sufficient to maintain the quality of the task performance;

16 however the long-term consequence of such adaptation is unknown and may overload other

17 structures.

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19 **Key words**: experimental muscle pain, EMG, isometric force, three-dimensional force variability

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1. Introduction

Most people have had an episode of low back pain (LBP) (Hoy, Brooks, Blyth, & Buchbinder, 2010). The prevalence of LBP have been reported from 6 to 19% (Biering-Sorensen, 1982; Cassidy, Cote, Carroll, & Kristman, 2005; Hestbaek, Leboeuf-Yde, Engberg, et al., 2003) for a first episode and recurrence reach up to 50% over a 5 years period (Hestbaek, Leboeuf-Yde, & Manniche, 2003). Besides the individual suffering this constitutes an enormous socio-economic burden (Andersson, 1999; Filho, Simmonds, Protas, & Jones, 2002; Hoy et al., 2010; Steenstra, Verbeek, Heymans, & Bongers, 2005). Patients suffering from LBP often present a multi-factorial pathogeneses (McCowin, Borenstein, & Wiesel, 1991), with symptoms including referred limb pain (Mellin & Hurri, 1990), often associated with numbness and radiation to the leg (Wolff et al., 2006), as well as muscle weakness (Helewa, Goldsmith, & Smythe, 1993) and biomechanical changes, such as increased spinal stiffness (P. Hodges, van den Hoorn, Dawson, & Cholewicki, 2009), and spinal deformations (Schroeder, Schaar, & Mattes, 2013). Insufficient spine stabilization has been associated with LBP (P. W. Hodges & Richardson, 1996; MacDonald, Moseley, & Hodges, 2009) and may be important for understanding mechanisms involved in LBP.

Experimental pain models, have been widely used to study motor adaptations caused by deep-tissue pain per se, excluding the multiple confounding factors observed in chronic pain patients (Bank, Peper, Marinus, Beek, & van Hilten, 2013). In particular, injection of hypertonic saline in the erector spinae muscle has been shown to mimic the pain sensation perceived in LPB patients and produce motor adaptations comparable to what has been observed in patients (Arendt-Nielsen, Graven-Nielsen, Svarrer, & Svensson, 1996; P. W. Hodges, Moseley, Gabrielsson, & Gandevia, 2003; Smith, Coppieters, & Hodges, 2005; Tsao, Tucker, Coppieters, & Hodges, 2010). In another example, experimental low back pain in healthy subjects delayed the onset of EMG activity of deep abdominal muscles in postural adjustments to fast arm movements (P. W. Hodges

1   et al., 2003), similar to results found in LBP patients (P. W. Hodges, 2001; P. W. Hodges &

2   Richardson, 1998; Tsao, Galea, & Hodges, 2008; Tsao & Hodges, 2008). Although these

3   adaptations are believed to compromise spinal stability during rapid movements (P. W. Hodges et

4   al., 2003) it is still an open question if they contribute to deficits in trunk stability during sustained

5   submaximal tasks. It is important to note that due to the complex biomechanics of the lumbar spine

6   (Pope, 1989), the anatomical configuration of abdominal and trunk muscles (Harrison, Harrison, &

7   Troyanovich, 1997; van Dieen, 1997), and the high level of muscular redundancy controlling the

8   trunk (Cholewicki & VanVliet, 2002), trunk stability is achieve by a multidirectional control of the

9   lumbar spine. This allows reorganization of the activity from different muscular groups to avoid or

10   reduce the pain sensation while maintaining the task performance, which also causes increase in

11   movement/force variability compared with pain free conditions (Hirata, Arendt-Nielsen, Shiozawa,

12   & Graven-Nielsen, 2012; Salomoni, Ejaz, Laursen, & Graven-Nielsen, 2013; Tucker & Hodges,

13   2010). When specifically investigating the effects of pain in multidirectional force fluctuations

14   during submaximal tasks, Salomoni *et al.* (2013; 2012a) found increased variability in tangential

15   force components during painful compared with non-painful tasks. This findings support the theory

16   that adaptations to pain might include redistribution of activity within and between muscles (P. W.

17   Hodges & Tucker, 2011) which controls movement in different directions. Therefore, evaluating the

18   effects of pain on multidirectional force fluctuations controlling the trunk can provide deeper

19   understanding on the relationship between insufficient muscular stabilization of the trunk and low

20   back pain (P. W. Hodges & Richardson, 1996; MacDonald et al., 2009).

21   The aim of the present study was to investigate the effects of pain during different levels of

22   isometric trunk extensions on multidirectional force variability and muscle activation. It was

23   hypothesized that (i) unilateral low back muscle pain will cause a reorganization of muscle

1   activation during trunk extension, and (ii) the reorganized muscle activity will cause an increase in

2   force variability and <mark>alter the tangential forces intensity</mark>.

3

2. Methods

2.1. Subjects

Twelve young volunteers (7 males; age 25 ± 4 yrs.; height 172 ± 11 cm; weight 70 ± 13 kg; mean ± SD) with no known musculoskeletal disorder participated in this study. All participants received detailed written and verbal information and signed an informed consent before inclusion. Four subjects did not complete the entire protocol and were therefore excluded from the data analysis. The study was conducted in accordance with the Declaration of Helsinki and approved by the local Ethics Committee (N-20090036).

2.2. Experimental low-back pain

Acute low-back pain was induced by an intramuscular injection of sterile hypertonic saline (1.0 ml, 5.8%) into the right m. longissimus and injection of isotonic saline (1.0 ml, 0.9%) was used as control. The needle (25G × 38mm) was inserted perpendicular to the surface about 40 mm lateral to spinal process L2 with a depth of 15 to 20 mm. The pain intensity was assessed on a 10-cm electronic visual analogue scale (VAS), where 0 cm indicated "no pain" and 10 cm was anchored to "maximal pain". Immediately after the injection, the VAS signal was recorded continuously for 10 minutes (sampling frequency of 0.5 Hz) and subjects were asked to update the VAS scores between trials by adjusting an external handheld slider. Additionally, subjects were asked to indicate the pain distribution by filling out a body chart. Five subjects had the hypertonic saline as the first injection and 7 had the isotonic saline as first injection.

2.3. Protocol

A randomized, single-blinded, controlled, crossover design was used to assess the effects of experimental low-back pain on the variability of force. Subjects performed three trunk extension

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1 and three trunk flexion isometric maximal voluntary contractions (MVCs, 5 s) where each was

2 followed by at least 1.5 minutes of rest. The EMG results for the trunk flexion MVC are not shown,

3 and were only used to normalize the subsequent muscle activity recordings. The MVC force in the

4 task-related (anterior-posterior) direction was extracted for calculation of all the following

5 submaximal target force levels. Subjects then performed a total of six series of submaximal

6 isometric trunk extensions with at least 1.5 minutes of rest between series: Before, during, and after

7 the effects of a painful or non-painful injection (baseline, during and post conditions). The sequence

8 of injection type was randomized and balanced across subjects, and the post-injection condition was

9 initiated one minute after the subject reported the last pain sensation. Immediately after the last

10 resting period, one additional MVC trial for trunk extension was performed. The series of

11 contractions included 5%, 10%, and 20% MVC force contractions (45 sec) performed in random

12 order and each followed by at least 40 seconds of rest. During each contraction level, a ramp-and-

13 hold force feedback was provided on a computer screen (41 seconds of hold phase) using a variable

14 visual gain, resulting in a constant visual scale across all target forces. Before starting the

15 recordings, subjects were familiarized with the setup and the protocol by performing 1 maximal and

16 1 submaximal for each contraction level (5,10 and 20% MVC) as practice trials.

17

18 *2.4. Force recordings*

19 Trunk extension forces were recorded using a high-sensitivity 3 dimensional force sensor (MC3A,

20 AMTI, USA). During the recordings, the subjects were seated on a custom-designed chair which

21 could be adjusted according to the subject's size. The pelvis was stabilized to avoid movements,

22 while the weight of the subjects was supported mainly by the seat. The subjects did not touch the

23 floor with their feet, and both hips and knees were partially flexed, allowing the shanks to be

24 supported by an extra seat, securing that the feet were always above the floor. The force sensor was

1   attached to the setup and adjusted in height for each subject at the T1 (2012b). The arms were

2   crossed in front of the chest. The analogue output of the force sensor was low-pass filtered at 500

3   Hz, amplified (MSA-6, AMTI, USA), sampled at 1 kHz, and stored after 12 bits A/D conversion.

4

5   *2.5. Surface electromyography (EMG)*

6   EMG signals were recorded bilaterally from *m. longissimus* (LO), *m. multifidus* (MUL), *m. rectus*

7   *abdominis* (RA), and *m. external oblique* (EO) using pairs of disposable Ag/AgCl surface

8   electrodes (Ambu Neuroline 720, Denmark) in bipolar configuration, placed 2 cm apart and

9   positioned according to the standard recommendations: (i) LO muscles, the electrodes were

10 orientated vertically and placed at 2 finger width lateral from the spinous process of L1. (ii) MUL

11 muscles, the electrodes were placed on and aligned with a line from caudal tip posterior spina iliaca

12 superior to the interspace between L1 and L2 interspace at the level of L5 spinous process. (iii) RA

13 muscles, the electrodes were placed aligned with the umbilicus and oriented parallel with the

14 muscle fibers, and over the muscle belly (identified via palpation). (iv) EO muscles, above the

15 anterior superior iliac spine, halfway between the iliac crest and the ribs at approximately 5 degrees

16 oblique angle in the umbilicus direction. Signals were amplified (Counterpoint MK2, Dantec,

17 Denmark), filtered (10-500 Hz), sampled at 1 kHz, and stored after 12 bits A/D conversion.

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19   *2.6. Data analysis*

20 All analyses were performed over the epoch of 20 s (15 s from beginning end of ramp), avoiding

21 excessive fluctuations due to slow force development and anticipation of trial termination

22 (Salomoni & Graven-Nielsen, 2012b).

The average VAS score between all trials was calculated for each injection paradigm. The drawings indicating the pain areas were scanned and each scan was loaded in Matlab [Mathwroks, Version: 8.1.0.604 (R2013a), USA] to extract the pain area in arbitrary units (a.u.).

The EMG signals were digitally band-pass filtered at 20 Hz - 400 Hz using a Butterworth filter of 2nd order. The force signals were filtered with a low-pass 20 Hz, 6th order Butterworth filter (Kamavuako, Farina, Yoshida, & Jensen, 2009). The maximum root-mean-square (RMS) EMG peak activation between the 3 MVCs for both trunk flexion and extension was extracted. The muscle activity for both RA and EO muscles during the submaximal tasks, were normalized by the RMS EMG peak activation for each respective muscle obtained during trunk flexion MVC. For normalizing the MUL and LO muscle activity, the RMS EMG peak activation obtained for the respective muscle during trunk extension MVC was used. After normalization by MVC, the integral (bin length equal to 1 ms) of the filtered EMG signal (iEMG) was calculated.

A bivariate histogram (1000 squares defined by a 100-by-100 equally spaced grid) was fitted to the plot of the two tangential force components (medial-lateral and cephalo-caudal directions) for each contraction (Mista, Christensen, & Graven-Nielsen, 2015) and the centroid of the histogram was calculated. The centroid position represents the preferable (most used) tangential force intensity while performing the task. During and post injection conditions, the centroid position was normalized by subtracting the values obtained during baseline conditions for each contraction level. This normalized variable is then referred to as centroid's position difference (CPD) and the origin in the CPD graphic indicates the forces levels used during baseline. Any deviation from baseline condition values will shift the centroid position away from the origin, indicating that new combinations of tangential forces were used to accomplish the task. Positive values in the x-axis (medial-lateral) indicate forces located to the left when compared with baseline values, while positive values in the y-axis (cephalo-caudal) indicated forces located above (cephalo direction)

baseline values. The absolute value (modulus) of the CPD was also extracted (ACPD) to quantify the absolute deviation from baseline condition. Contraction task accuracy for the task-related force (anterior-posterior direction) during the force matching tasks (provided as biofeedback) was estimated by the mean absolute error between the task force level and the corresponding requested target force

2.7. Statistical analysis

Baseline Conditions

Baseline EMG parameters were analyzed for each muscle by a three-way repeated measures analysis of variance (RM-ANOVA) with *injection* (prior isotonic, prior hypertonic), *side* (left and right), and *force* (5%, 10%, 20% MVC force) as within-subject factors. Baseline force variability, range, accuracy and centroid's position were analyzed by a two-way RM-ANOVA with *injection* (prior isotonic, prior hypertonic) and *force* (5%, 10%, 20% MVC) as within-subject factors.

During and Post-Injection Conditions

The EMG, force variability, range, accuracy, CPD and ACDP values during and post-injection conditions were normalized to the baseline values. The EMG parameters *during* injections and post-injection conditions, were analyzed for each muscle by a four-way RM-ANOVA with *side* (left and right), *injection* (isotonic, hypertonic), *condition* (during, post), and *force* (5%, 10%, 20% MVC force) as within-subject factors. For the force variability, range, accuracy, CPD and ACDP values during and post-injection conditions, a three-way RM-ANOVA was used with, *injection* (isotonic, hypertonic), *condition* (during, post), and *force* (5%, 10%, 20% MVC) as within-subject factors.

1   For the MVC force after the submaximal contractions, a 2-way RM-ANOVA with *injection*

2   (isotonic, hypertonic), and *condition* (during, post) as main factors was used. In case of significant

3   factors or interactions, the Newman-Keuls (NK) post-hoc test was applied incorporating correction

4   for multiple comparisons. The VAS scores and pain areas elicited by each injection type were

5   analyzed with the non-parametric Wilcoxon test. Statistical significance was considered for P-

6   values lower than 0.05. All results are reported as mean ± standard error of the mean (SEM).

3. Results

3.1. Experimental low back pain

VAS scores elicited by the hypertonic injection was higher than control (isotonic saline) injection (hypertonic: 2.6 ± 0.4 cm, isotonic 0.5 ± 0.2 cm; Wilcoxon, $P < 0.01$). Both saline injections provoked pain unilaterally (right side) around the injection site, however, hypertonic saline injection induced pain in all subjects, while isotonic injection (control) provoked pain in 4 out 12 subjects (Fig. 1). Additionally, 2 subjects (16%) also indicated referral pain (pain occurring outside the injection-pain area) in the gluteous and lower leg area during the hypertonic injection. Subjects drew significantly larger areas during hypertonic saline injection compared with isotonic saline injection (hypertonic: 3180 ± 1911 a.u., isotonic: 460 ± 254 a.u.; Wilcoxon, $P < 0,01$).

3.2. Force variables

Analysis of force variables during baseline conditions did not reveal any significant main factors (injection and force) or interactions (Table 1).

The analysis of tangential forces is embedded in the centroid's position difference (CPD) parameter illustrated for all subjects immediately after hypertonic and isotonic saline injections at the three contraction levels in Figure 2. Although the CPD for the medial-lateral direction was not significantly affected by pain (Figure 3A), the respective absolute centroid's position difference (ACPD) was higher during hypertonic injection condition than isotonic injection and post injection conditions, regardless the contraction level (Figure 3B; RM-ANOVA: $F (1, 11) = 13.1$, $P < 0.01$, NK: $P < 0.05$).

The MVC force (Newton) after the submaximal contractions (anterior-posterior direction) was not significantly different between conditions [mean (± SEM, N = 12); Baseline 1: 275 ± 24;

1   Isotonic Injection: 262 ± 32; Post Isotonic Injection: 259 ± 29; Baseline 2: 272 ± 28; Hypertonic

2   Injection 263 ± 27 and Post Hypertonic Injection: 259 ± 30; F (2, 22) = 0.16, P = 0.84].

3

4   *3.3. Muscle activity during submaximal trunk extension*

5   The analysis of baseline conditions indicated that only the factor *force* (5, 10 and 20% MVC)

6   significantly affected muscle activation (iEMG, Table 1). The bilateral *rectus abdominis* muscle

7   showed increased iEMG during both the 20% MVC task compared with the other force levels and

8   10% MVC compared with 5% MVC (RM-ANOVA: F(2,22) = 34.6, P < 0.01; NK: P < 0.01). The

9   bilateral *external oblique* muscles showed increased iEMG during the 20% MVC force task

10   compared with the 5% of MVC task (RM-ANOVA; F(2,22) = 13.8, P < 0.01; NK: P < 0.02).

11   A significant interaction between *injection*, *condition* and *force* factors showed that pain in

12   the right *m. longissimus* decreased bilaterally the iEMG in the left *m. rectus abdominis* during the

13   trunk extensions at 20% MVC force compared with control (isotonic saline) injection condition

14   (Figure 4; RM-ANOVA: F(2,22) = 4.5, P = 0.02; NK: P = 0.03).

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4. Discussion

The present study is the first to assess how experimental low back pain affects 3-dimensional force steadiness and trunk muscle activation in different high precision isometric force tasks. During submaximal force tasks, pain in the right m. longissimus decreased the activity of left m. rectus abdominis and increased the centroid position difference in the medial-lateral direction suggesting that acute back pain causes an adaptation in the motor control strategies ensuring that the task is still completed without compromising its quality

4.1. Effect of force level on force variability and muscle activation

Motor-output variability is inherent to every muscle contraction, probably due to variability in basic mechanisms involved in force generation such as motor-unit firing rate and recruitment order (Jones, Hamilton, & Wolpert, 2002; Stein, Gossen, & Jones, 2005). Observations of monotonic increases in force variability (less accuracy) with higher force levels during isometric contractions is often described as signal-dependent noise (SDN) in motor control studies (Enoka, Burnett, Graves, Kornatz, & Laidlaw, 1999; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). However, accuracy, standard deviation (SD) or range of the task-related force component was not significantly different across force levels in this study. Reeves *et al.* (2008) and McCook *et al.* (2009) found an increase in the task-related force variability at higher *vs* lower force levels by using higher target forces (10, 20, 40, 60 and 80% of MVC) or fixing the increment in force (50N) between difference force levels. In the present study all three target forces corresponded to contractions of relatively low intensity (20% MVC is on average 53N) and small force increment between levels (average increase of approximately 13.25N for every 5% of MVC), compared with both Reeves *et al* (2008) and McCook *et al* (2009), which may explain the differences in the results.

1   In the present study higher force levels (20% MVC) increased bilateral muscle activity in both

2   external oblique and rectus abdominis muscles compared with 5% MVC task. Additionally,

3   bilateral increase in the rectus abdominis muscle was observed during 10% MVC compared with

4   5% MVC. Given that higher contraction levels of the abdominal muscles during trunk extension

5   would counteract the action of the agonistic muscles (trunk extensors), there is not a straightforward

6   explanation of why the central nervous system adopts such strategy when controlling the trunk.

7   Nevertheless, such phenomenon has been extensively observed in previous studies, and the most

8   recent findings indicates a co-contraction strategy aiming to increase trunk stiffness (Lee, Rogers, &

9   Granata, 2006) and enhance stability during trunk extension (Cholewicki & McGill, 1996;

10   Cholewicki & VanVliet, 2002; McCook et al., 2009; Reeves et al., 2008; van Dieen, Kingma, &

11   van der Bug, 2003). Since the tasks demanded high levels of accuracy, increasing trunk stability

12   would diminish trunk oscillations and improve performance in the task. Interestingly, the trunk

13   extensor muscles (agonistic) evaluated in this study did not show increased muscular activity in

14   higher force levels, contrary to results reported previously (McCook et al., 2009). However,

15   Willigenburg *et al.* (2013) showed recently in both control subjects and LBP patients that during

16   dynamic trunk movements (spiral-tracking task requiring precise trunk movements), there was no

17   correlation between tracking errors and agonistic muscle activation. The absence of increased

18   activity of trunk extensor muscles during progressively increasing the trunk extension force may be

19   explained by several factors: (i) Despite using a similar experimental setup, McCook *et al.* (2009)

20   applied the load through a shoulder harness, while in the present study, the subjects pulled a fixed

21   force transducer attached to the frame; and (ii) Cholewicki *et al.* (2002) showed large redundancy in

22   the motor system (ten major muscle groups were evaluated) while controlling isometric trunk

23   exertions, where none of the muscle groups could be identified as the most important for controlling

24   the trunk stability. Therefore, the small difference in the experimental setup between McCook *et al.*

1 (2009) and the present study and the high number of degrees of freedom involved in the task might

2 suggest that the extensor trunk muscles that actually had their muscle activity increased were not

3 analyzed in this study, for example deep muscles or muscles located higher at the trunk segment

4 (Cholewicki & McGill, 1996). In addition, the present setup (different spine posture and trunk

5 extension force) allowed a different motor strategy compared with the previous studies, where the

6 extensor torque at the trunk segment might have been achieved via shared muscular contraction

7 among different trunk extensor muscle groups (Cholewicki & VanVliet, 2002). This flexibility in

8 the motor strategy could also have affected the normalization process in this study, where the motor

9 strategy (i.e. muscle activation patterns) used during the MVC does not relate to the one used when

10 the task requires trunk accuracy during low contraction levels. Nevertheless, the present results

11 reinforce the previous findings indicating increased activation in the antagonistic muscles as

12 common strategy when controlling the trunk segment in pain free conditions (van Dieen et al.,

13 2003).

14

15 *4.2. Effect of pain on force variability and muscle activation*

16 This study used an experimental pain model to test the hypotheses that pain would provoke a

17 reorganized muscle activation pattern and increase in force variability during isometric force-

18 matching tasks in an otherwise healthy system. Similar to observations using experimental knee-

19 related pain (Salomoni et al., 2013), experimental muscle pain per se did not affect the force

20 variability in the tangential directions for which biofeedback was not shown to the subjects.

21 Moreover, in this study, the force range in both tangential directions was not affect by pain,

22 showing that healthy subjects are able to maintain the trunk stability in the frontal plane in presence

23 of pain. Likewise, the variability, range, and accuracy of the task-related force were not altered by

24 pain. Furthermore the MVC force (Newton) after the submaximal contractions (in the anterior-

posterior direction) was not affected by unilateral pain at right m. longissimus, probably indicating

that the maximal capacity for producing trunk extension forces was maintained during the

experiment. However, pain reduced bilaterally the activation of the rectus abdominis muscle,

although the pain drawings indicated that subjects perceived pain only in the ipsilateral side to the

painful injection. Such bilateral decrease in muscular activation might have been beneficial for

trunk stability by avoiding asymmetrical muscle contraction and therefore, minimizing

displacements of the trunk. Indications that such bilateral decreased muscle activity have indeed

occurred without affecting the trunk stability is also indicated by the similar accuracy scores before

and during pain (Table 1). Decreasing the antagonist muscle activity during painful trunk extension

may however be interpreted as contrary to the observed strategy in pain free conditions of this

experiment (Table 1), which in turn could impair the trunk stability (Cholewicki & McGill, 1996;

Cholewicki & VanVliet, 2002; McCook et al., 2009; Reeves et al., 2008; van Dieen et al., 2003)

and decrease the trunk stiffness (Lee et al., 2006), the last not estimated in this study. Overall, the

decreased activity of the bilateral rectus abdominis muscles may indicate the robustness (ability to

couple with disturbances while performing a movement) of the central nervous system in healthy

individuals when utilizing visual feedback to control and correct the trunk force during low

isometric trunk extension in presence of pain (Cholewicki & VanVliet, 2002).

Another indication of the motor reorganization while performing the task can be observed in

the centroid position difference (CPD). The CPD in figure 2 graphically shows the mean force

values in the tangential directions (medial-lateral and cephalo-caudal directions) generated while

controlling the task-related force via visual feedback for every subject analyzed. During pain the

high level of accuracy in the task-related force was probably preserved by reorganizing the activity

of the different muscles in the trunk (including relevant deep trunk muscles not evaluated in this

study (P. W. Hodges et al., 2003)), which affected the tangential forces. Similar motor

reorganization during pain has already been suggested in postural control tasks, where experimental pain induced dissimilar muscle contraction strategies among healthy subjects, although balance was maintained while recovering from external perturbations (Hirata et al., 2012). Inline, such phenomenon seems to be observed in Figure 2 by the larger variability and distance of each point (centroid's position) from the histogram origin during the painful condition, whereas during isotonic saline condition (control) the points were more centered on the origin of the histogram. However, the CPD (the difference between the centroid's position between baseline and during injections condition) was not significantly different between injections (painful vs control, Figure 3A and C), indicating that there was not a consistent change among all subjects when controlling the tangential forces during pain. Interestingly, the absolute difference in the CPD (ACPD) was significantly higher during pain compared to control (isotonic saline injection) conditions in the medial-lateral direction (Figure 3B). This indicates that during pain, the mean force generated in the tangential medial-lateral was different from baseline values without altering the force variability (force SD). Interestingly the significant difference was only found in the absolute centroid position difference (ACPD, Figure 3) and not in the difference per se (CPD), reflecting an individualized attempt of the CNS to find the most comfortable or efficient trunk extension movement pattern potentially also reducing the pain. The search pattern for the most optimal strategy is still to be clarified. Although this immediate adaptive strategy to acute pain in healthy subjects seems to be beneficial in maintaining accuracy in the task, using such strategies regularly could result in overloading different structures, which in a long term could lead to other painful states (P. W. Hodges & Tucker, 2011).

5. Conclusions

1   The present study demonstrated a reorganization of trunk muscle activity during painful trunk

2   extensions. This adaptive strategy was distinct for each subject, although the final motor output did

3   not affected the task-related force variability. Such achievement may be due to the robustness and

4   high redundancy of the trunk motor system in healthy subjects, and in addition, low intensity

5   isometric trunk extensions forces do not provide enough challenge to the sensory-motor system.

6   These findings stress the importance to target and focus on individual treatment procedures in LBP

7   patients to their individual pain adaptation pattern.

8

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1 **Figures Legend**

2 **Figure 1.** Superimposed body chart pain drawings (n = 12) after saline injections into the into the

3 right longissimus muscle. The pain distribution after isotonic saline (left) and hypertonic saline

4 (right) injections are illustrated.

5

6 **Figure 2.** Three-dimensional shaded surface based on the mean value for the centroid's position

7 difference (CPD), in bins, for both medial-lateral (ML) and cephalo-caudal (CC) direction during

8 injections of hypertonic and isotonic saline in the right m. longissimus muscle. Positive values in

9 the ML direction indicate that CPD is positioned more to the left compared with the baseline

10 condition. Positive values in the CC direction indicate that CPD is located higher than baseline

11 condition. The centre of the figure (0 x 0) indicates the relative CPD position during baseline for all

12 subjects. Warm colors indicate larger number of subjects showing similar CPD than cool colors.

13 During isotonic injection, the distribution of the CPD is more centered on the origin than during

14 hypertonic injection condition.

15

16 **Figure 3.** Mean (+ SD, N = 12) of centroid's position difference (CPD) and the absolute centroid's

17 position difference (ACPD) in the medial-lateral and cephalo-caudal directions during and post

18 saline injections (hypertonic and isotonic). **(A)** CPD in medial lateral direction. **(B)** ACPD in medial

19 lateral direction. **(C)** CPD in cephalo-caudal direction. **(D)** ACPD in cephalo-caudal direction.

20 During hypertonic saline injections, the ACPD was significantly increased compared with the

21 isotonic saline injection and its respective post injection condition (*, NK: P < 0.05)

22

23 **Figure 4.** Mean (+ SD, N = 12) of iEMG (% MVC) values for left (A) and right (B) rectus

24 abdominis muscles for baseline, during (injection) and post-injection conditions during 3
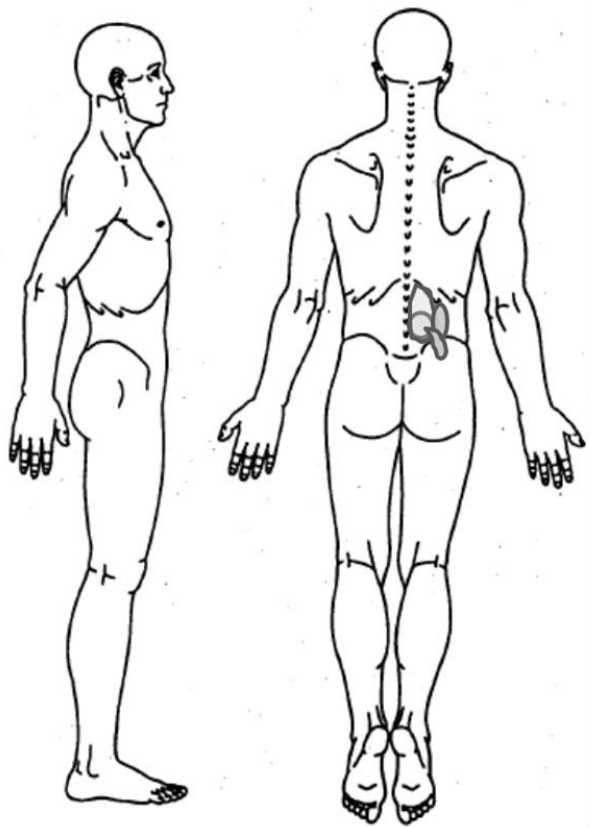
1   submaximal (5, 10 and 20% MVC) isometric trunk extension. The symbol "*" indicates significant

2   3-way interaction between the factors *injection*, *condition* and *force* for the iEMG data after

3   normalization by baseline values (NK: $P = 0.03$).

Table 1

Table 1: Muscular activity, force variability, accuracy and MVC force during 5, 10 and 20% MVC submaximal tasks (n = 12)
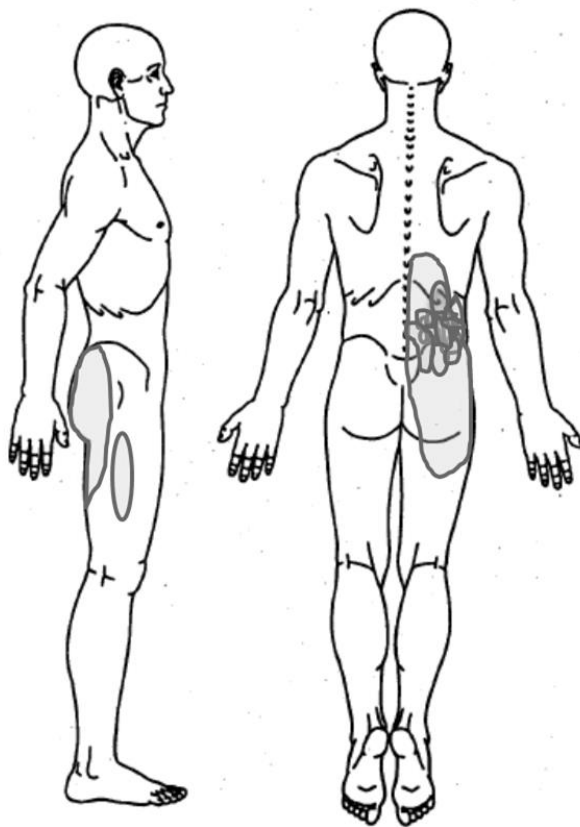
	Baseline 1 - Prior Isotonic Injection			Baseline 2 - Prior Hypertonic Injection		
	5 % MVC	**10 % MVC**	**20 % MVC**	**5 % MVC**	**10 % MVC**	**20 % MVC**
Force Variability, Range and Accuracy (N)						
Medial-lateral force SD	0.39 ± 0.12	0.52 ± 0.33	0.66 ± 0.33	0.52 ± 0.23	0.54 ± 0.25	0.65 ± 0.48
Cephalo-caudal force SD	1.83 ± 0.73	1.93 ± 0.56	2.23 ± 0.85	2.15 ± 1.26	2.56 ± 1.21	2.32 ± 1.20
Anterior-posterior force SD	0.82 ± 0.30	0.83 ± 0.21	0.94 ± 0.24	0.78 ± 0.27	0.83 ± 0.28	0.86 ± 0.36
Medial-lateral force Range	2.18 ± 0.64	2.7 0 ± 1.39	3.10 ± 1.35	2.43 ± 0.93	2.59 ± 0.83	3.23 ± 2.47
Cephalo-caudal force Range	7.48 ± 2.96	8.32 ± 2.76	9.25 ± 3.67	8.97 ± 5.53	10.26 ± 5.34	9.93 ± 5.84
Anterior-posterior force Range	4.99 ± 2.16	5.26 ± 1.33	5.7 ± 1.51	4.99 ± 2.48	4.87 ± 2.18	5.44 ± 2.37
Accuracy - Mean absolute Error	0.62 ± 0.20	0.64 ± 0.17	0.72 ± 0.18	0.59 ± 0.18	0.66 ± 0.22	0.68 ± 0.29
Centroid's Position (mm)						
Cephalo-caudal	53.1 ± 9.4	56.3 ± 9.9	57.7 ± 9.7	55.3 ± 8.7	54.2 ± 8.1	53.0 ± 6.5
Medial-lateral	49.5 ± 4.4	50.8 ± 7.6	49.6 ± 7.6	50.7 ± 8.8	50.8 ± 6.9	49.1 ± 7.5
Muscle Activity (EMG, pooled within left and right side, % MVC)						
Rectus abdominis	20.7 ± 19.4	*24.8 ± 19.4**	*33.9 ± 21.5***	17.1 ± 15.6	*24.7 ± 16.4**	*38.2 ± 25.1***
External oblique	16.9 ± 16.7	18.5 ± 11.4	*25.6 ± 15.9**	14.3 ± 9.0	16.0 ± 10.0	*25.3 ± 16.2**
Longissimus	5.1 ± 2.7	6.7 ± 4.1	6.1 ± 3.1	5.0 ± 2.7	5.7 ± 3.1	8.0 ± 6.6
Multifidus	3.1 ± 1.4	3.5 ± 1.4	3.4 ± 1.4	3.5 ± 2.1	3.3 ± 1.7	5.8 ± 8.0

1

2 Data presented as mean (± SD, N = 12) for both baselines conditions (prior hypertonic and isotonic injection). Muscle activity

3 (EMG, % of MVC) and standard deviation (SD) and accuracy (mean absolute error) for the 3 force directions [medial-lateral

4 (ML), cephalo-caudal (CC) and anterior-posterior (AP), in Newton (N)] and centroid's positions for CC and ML direction are

5 presented for each force level: 5%, 10% and 20% of maximal voluntary contraction (MVC). Significant differences in the EMG

6 level between force levels are indicated by: one asterisk "*" when higher than 5% MVC condition; and two asterisks "**" when

7 higher than all other conditions (P<0.05).

8

Figure 1

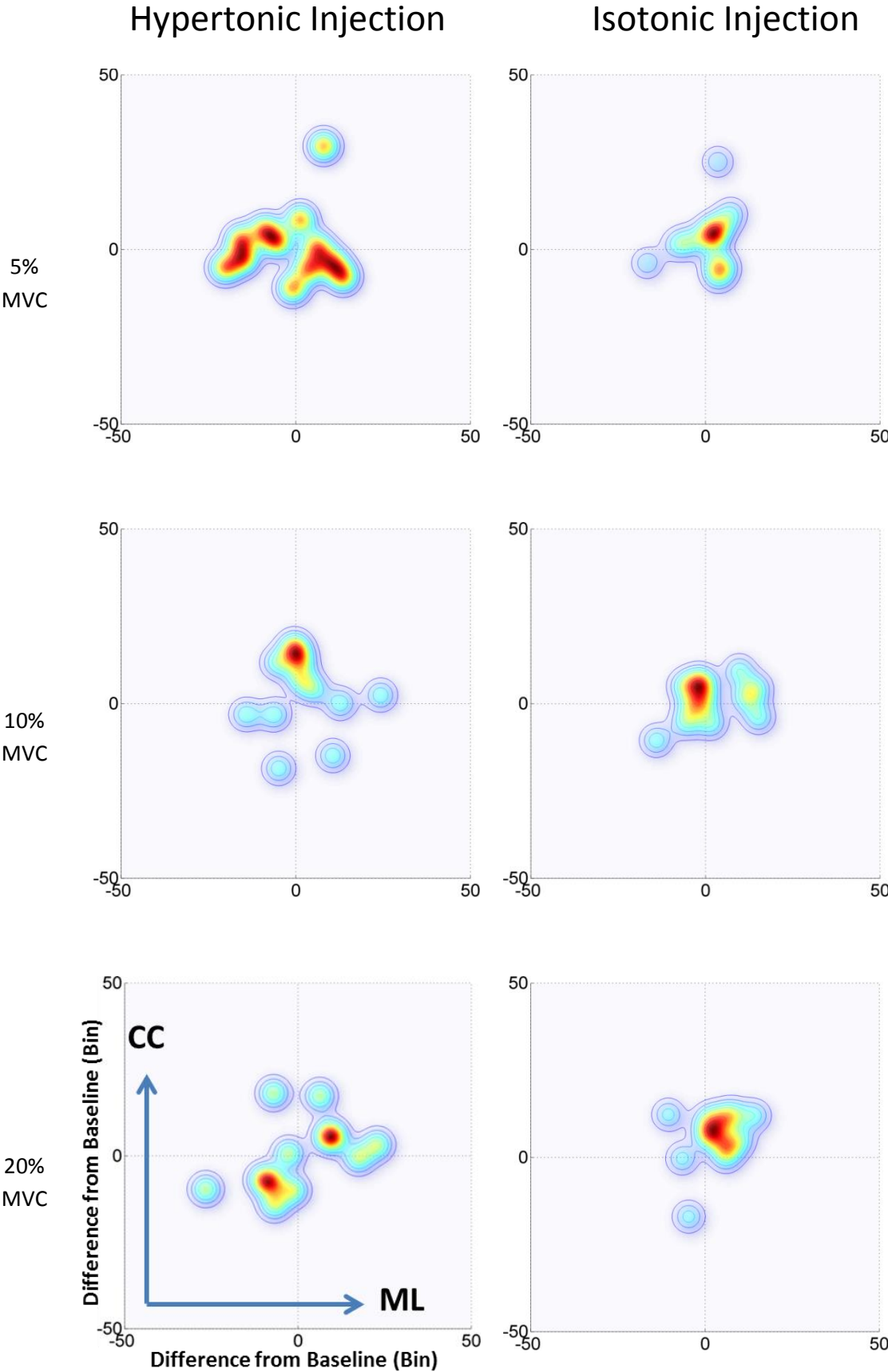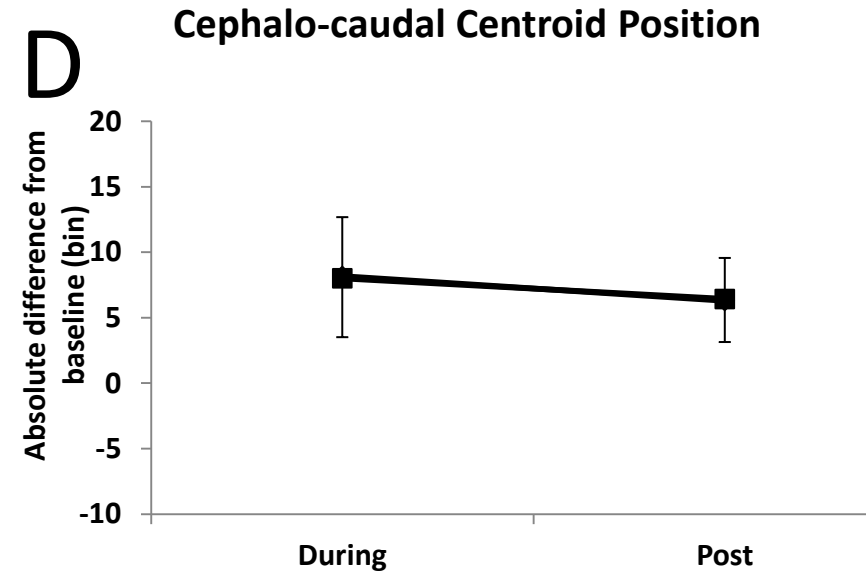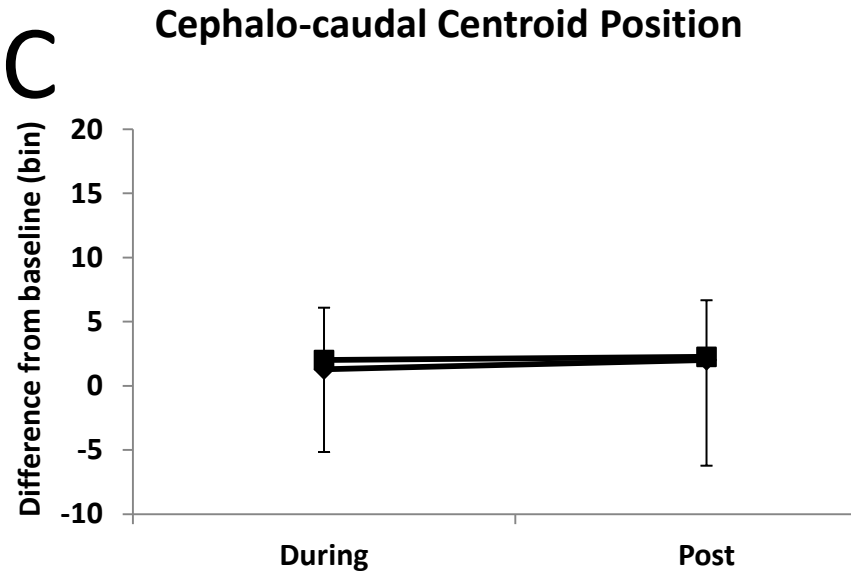

Isotonic Saline   Hypertonic Saline
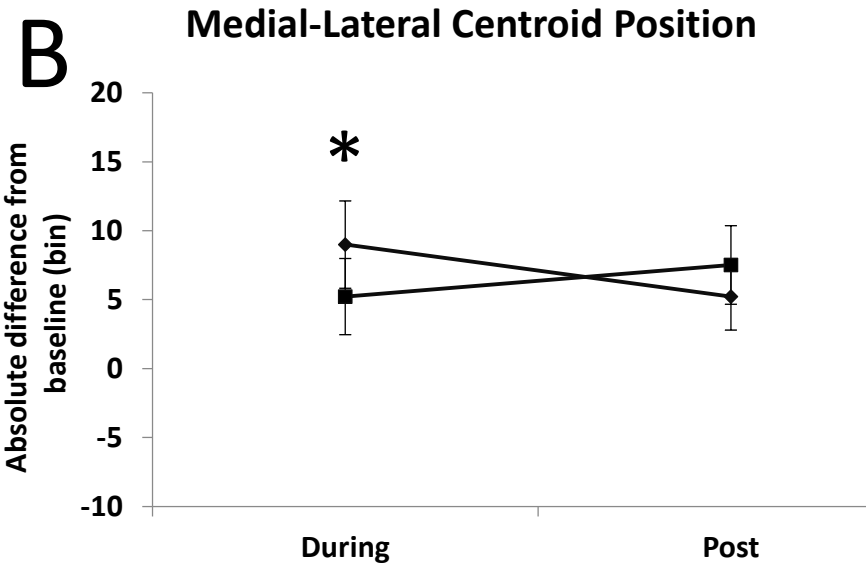
Figure 2

Hypertonic Injection | Isotonic Injection

5% MVC
10% MVC
20% MVC

CC
ML
Difference from Baseline (Bin)
Difference from Baseline (Bin)

Figure 3

A Medial-Lateral Centroid Position

B Medial-Lateral Centroid Position

C Cephalo-caudal Centroid Position

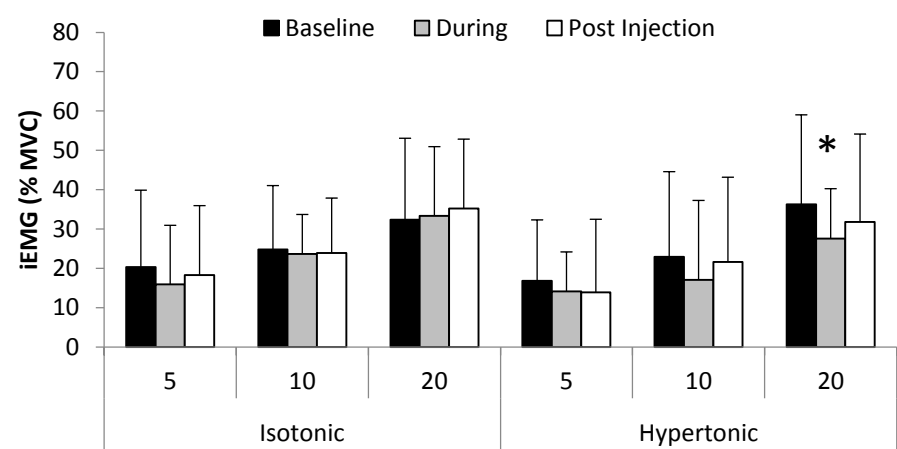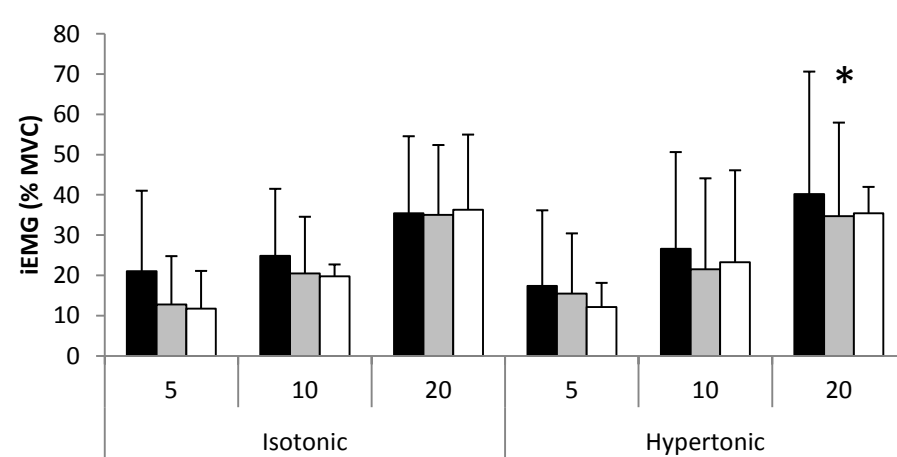**D** Cephalo-caudal Centroid Position
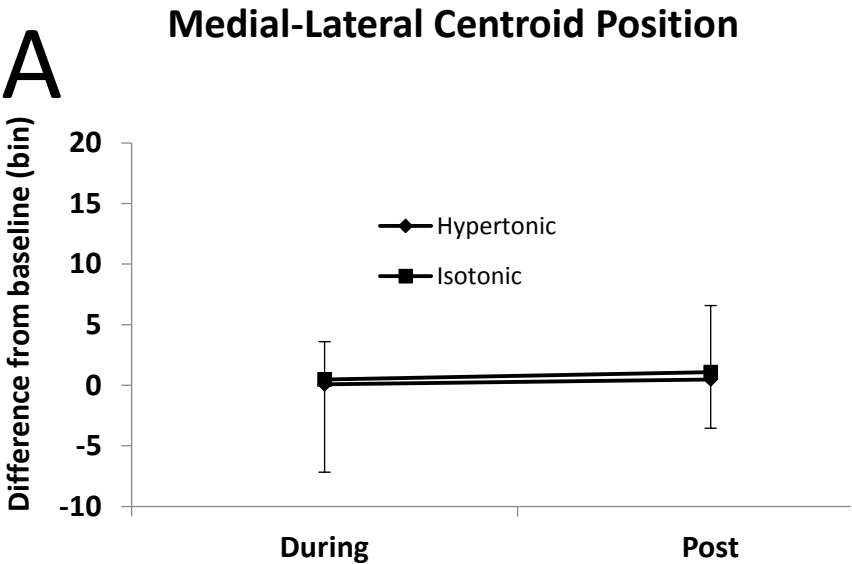
Figure 4

A **Left rectus abdominis muscle activity**

B **Right rectus abdominis muscle activity**

Highlights

- Experimental pain was applied in the longissimus muscle in healthy subjects while performing isometric trunk extensions.
- Pain decreased the EMG activity bilaterally of the rectus abdominis muscles.
- Performance of the task was not affected by pain.
- Tangential forces generated by the trunk segment were altered by pain.
- The motor adaptations to pain were unique for each individual.