Lumbar muscle adaptations to external perturbations are modulated by trunk posture

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Statements and Declarations: There is no conflict of interest.

Funding: This research received funding from Natural Sciences and Engineering Research Council of Canada (NSERC).

Category: Original article

Abstract

Purpose: To investigate if the recruitment of different regions within the lumbar extensor muscles in response to unexpected perturbations depends on trunk posture.

Methods: In a semi-seated posture, healthy adult participants experienced unexpected posterior-anterior trunk perturbations in three different postures: neutral, trunk flexion and left trunk rotation. High-density surface electromyography was used to identify the regional distribution of activation within the lumbar erector spinae muscles. The effect of posture and side (left vs right) on muscle activity and centroid coordinates was investigated at baseline and in response to perturbation.

Results: Higher muscle activity was observed in trunk flexion compared to neutral and rotation postures at baseline (multiple $p<0.001$) and in response to the perturbation (multiple $p<0.01$). At baseline, the centroid of the electromyographic amplitude distribution was localized more medially in trunk flexion compared to trunk neutral posture ($p=0.003$), while activation was localized more laterally in response to the perturbation (multiple $p<0.05$). When the trunk was rotated, the electromyographic amplitude distribution was localized more cranially on the left than the right side, both at baseline ($p=0.001$) and in response to the perturbation ($p=0.001$). Finally, a more lateral location of the centroid on the left side in rotation in compared to neutral posture was observed in response to the perturbation (multiple $p<0.001$).

Conclusions: Regional differences in the distribution of electromyography amplitude indicate that different muscle regions were recruited in different trunk postures and in response to perturbations, possibly based on regional mechanical advantage of the erector spinae muscle fibers.

Keywords: Erector spinae, Trunk, Postural perturbation, High-density EMG

Abbreviations:

ANOVA	Analysis of variance
EMG	Electromyography
HDsEMG	High-density surface electromyography
MVIC	Maximal voluntary isometric contractions
RMS	Root mean square
SD	Standard deviation

Introduction

Over the past two decades, there has been a growing interest in understanding how different lumbar muscles contribute to trunk postural control and its movement. Recently, a clear distinction in motor unit territories has been discovered between the upper (L1 to L3 vertebrae) and lower (L3 to L4 vertebrae) regions of the erector spinae muscles (Abboud et al. 2020), which allows a regional activation of these muscles during voluntary movements, such as trunk rotation. These localized motor unit territories are a neuroanatomical prerequisite for regional activation of the erector spinae, which has been observed in different functional tasks (Serafino et al. 2021) and when assessing neuromuscular strategies in individuals with low back pain (Falla et al. 2014). However, it is currently unclear whether the regional activation can be observed in response to perturbations applied with the trunk in different postures.

According to the neuromechanical principle (Hudson et al. 2019), motor units are recruited according to a mechanical advantage during complex tasks where joint angle and fibre orientation varies. For instance, recruitment of inspiratory motor unit is optimized with muscle length changes, i.e. motor unit are activated earlier or within specific muscle regions where the mechanical advantage is largest (Butler and Gandevia 2008). Anatomical variations in the erector spinae fiber orientation (Bogduk 2005) may confer a mechanical advantage for motor unit recruitment localized in different regions within this muscle. Since fiber orientation changes with trunk posture (Harriss and Brown 2015; McGill et al. 2000), this mechanical advantage may depend on the trunk position. In an erect posture, the muscle fibers of the lumbar erector spinae have a posterior and caudal orientation (Harriss and Brown 2015), which generates posterior shear forces to support any anterior reaction shear forces. When the trunk is flexed, however, they lose such ability because their line of action becomes parallel to the compression axis (McGill et al. 2000). Moreover, in a flexed posture, the gravitational moment increases, which increase the demand of the lumbar muscles to stabilise the trunk. When the trunk is rotated to the right, ipsilateral lumbar muscles showed higher activation while performing trunk extension in comparison with contralateral lumbar muscles (Ng et al. 2001), which may lead to asymmetrical responses in response to external perturbations. Therefore, changing the trunk posture would require adaptations of motor unit

recruitment according to the mechanical advantage of the muscles (Hudson et al. 2019). For instance, it has been shown that regional activity of the deep trunk muscles (quadratus lumborum) and the psoas major depends on their mechanical advantage during anticipatory postural adjustment tasks (Park et al. 2014). This observation can be explained by the anatomical variation of these muscles, such as orientation of the muscle fascicles, based on spine curvature. Based on these findings, it could be hypothesized that the regional activity of the erector spinae muscles depends on the mechanical advantage of this specific region.

Regional activation could be a strategy to minimize the functional cost while maintaining the task goal. When executing a voluntary motor task such as bending forward, the central nervous system may optimize certain cost functions to determine how motion of the spine will be performed (Todorov and Jordan 2002). This strategy could also be relevant for rapid motor responses, such as unexpected movements (Pruszynski and Scott 2012). Recent studies have shown that spatial variations of muscle activity between and within trunk muscles could occur to control the trunk movements (Hodges et al. 2013), even in response to unexpected trunk perturbations (Abboud et al. 2016). A better understanding of the neuromuscular strategies employed to oppose perturbations when the trunk is in different trunk postures may be more representative of real-life events, when the trunk can be subjected to external unexpected forces while the individual is not standing with their trunk in an erect position.

The aim of this study was to investigate if the recruitment of different regions within the lumbar extensor muscles is modulated by the mechanical advantage of its fibers, which we manipulated by changing trunk orientation during unexpected trunk perturbations. We also compared side differences since trunk rotation is associated to asymmetrical activation of the lumbar muscles. We hypothesized that the erector spinae would be activated regionally based on the trunk position, in line with the presumed mechanical advantage of the recruited muscle region.

Methods

Participants

Twenty healthy adult participants (10 men and 10 women) took part in this study. Exclusion criteria were as follows: presence of low back pain in the past year; spinal surgery; inflammatory arthritis of the axial skeleton; advanced osteoporosis; severe and incapacitating pain limiting the ability to perform the evaluation protocol in the laboratory; pregnancy. Participants mean for age, weight, height, and BMI were respectively: 24.3±3.9 years, 67.49±12.45 kg, 169.3±9.2 cm and 23.44±3.24 kg/m^2. Participants were recruited among the university community. The project received approval from the Research Ethics Board for human research of the "Université du Québec à Trois-Rivières" (CER-21-276-07.06). All participants gave written informed consent, acknowledging their right to withdraw from the experiment without consequences.

Study design

To answer the aim of this study, the experimental protocol was conducted over one session during which the lumbar extensor regional activation was assessed across 3 series of 10 perturbations, each in a different trunk posture. The order of the posture was randomized between participants, and a rest-period of 10 min was added between each series of trunk perturbations. Electromyography (EMG) data of the right side of one participant was excluded from the analysis due to excessive movement artefacts in the signals.

Trunk perturbation protocol

Before the trunk perturbation protocol, participants were asked to perform three trunk extension maximal voluntary isometric contractions (MVICs) using the same apparatus as the perturbation protocol. A belt was positioned on the upper thoracic and in a neutral posture, participants were asked to pull posteriorly against this belt. A 1-min rest period was provided between each MVIC to limit muscle fatigue. The highest MVIC in trunk extension was used for EMG normalization.

Participants then experienced sudden external posterior-anterior trunk perturbations (Figure 1). To induce these perturbations, participants were in a semi-seated positioned on a custom-made

apparatus as described previously (Dupeyron et al. 2010; Larivière et al. 2010; Radebold et al. 2000). This position was chosen to minimize the contribution of the lower limb to better assess the contribution of the trunk muscles to oppose the perturbation. On this apparatus, participants were asked to adopt three different postures. The 'Neutral' posture corresponded to a neutral semi-seated position with participants' knees flexed at ~75°. The 'Trunk flexion' posture corresponded to a 40° of trunk flexion in a semi-seated position. Finally, the 'Trunk Rotation' posture corresponded to 30° of left trunk rotation in a semi-seated position. The target trunk flexion posture was monitored in real-time using a digital inclinometer (± 0.1° of precision, model 40–6067, Johnson Level & Tool Mfg. Co., Inc. Mequon, WI) placed on the L3 vertebrae. Trunk rotation posture was standardized with the help of a laser pointer mounted on the right acromion of the scapula and a target on the wall in front of the participant. The laser and a target in front of the participants were also used to ensure consistent trunk rotation posture within and between trials. In all posture, the perturbations were delivered via a cable attached to a custom-made harness installed over the upper body, approximately at the T9 vertebra level. This cable was connected to a load cell (Model LSB350; Futek Advanced Sensor Technology Inc, Irvine, CA, USA) which was connected to a small motor (Figure 1). When the motor released the cable, a posterior to anterior perturbation was applied since participants were performing an isometric trunk flexion. The magnitude of the trunk perturbation was computed based on participants' MVIC in trunk flexion in a neutral semi-seated position. Three MVIC in trunk flexion were performed with one minute of rest between them and the highest value was considered for the perturbation protocol. Then, participants were asked to maintain 20% of their MVIC. They were provided visual feedback of their force using a computer screen positioned in front of them. Once the targeted force was achieved and maintained, a sudden perturbation was induced with a random delay between 1, 3 and 5s to avoid any anticipation of the trunk perturbation onset. Participants wore headphones to mute the sound of the perturbation trigger. Participants were asked to return to their initial position after each perturbation.

Data collection

The right and left lumbar extensor muscle activity was recorded with two high-density surface EMG (HDsEMG) of 64 electrodes arranged in 8 columns and 8 rows spaced by 10 mm (semidisposable adhesive matrix; model ELSCH064, OTBioelettronica, Torino, Italy). The skin over the lumbar extensor muscles was cleaned with fine-grade sandpaper (Red DotTrace Prep; 3 M, St. Paul, MN), and shaved. The electrode grids were placed orienting the columns along the approximate fiber orientation of the erector spinae muscles. The center of each grid was located at L3 level, and the medial edge of the grid was at ~1 cm from the L3 spinous process. The grid spanned approximately L1 to L4-L5. The reference electrode was placed over T12 spinous process. Signals from the bipolar HDsEMG were amplified (x2000 or x5000) and digitized at 2048 Hz using a 12-bit A/D converter (128-channel EMG-USB; OTBioelettronica; –3 dB, bandwidths 10–500 Hz). The same assessor was responsible for the placement of the grids to minimize variability between participants. Moderate to good between-day reliability (ICC ranging from 0.604 to 0.978) has been established for amplitude distribution parameters measured with HDsEMG on low back muscles (Afsharipour et al. 2016).

Data analysis

HDsEMG data were extracted during the trunk perturbation protocol and the left and right sides were analyzed separately. Differential signals were calculated from HDsEMG by subtracting consecutive monopolar signals along the cranio-caudal direction (Figure 2). Consequently, the final grid consisted of a 7x8 channels. Each HDsEMG signal obtained from both grids were digitally band-pass filtered in the frequency bandwidth 20-400 Hz (4^{th} order Butterworth filter). Notch filters were also applied to eliminate the 60 Hz power line interference (2^{nd} order Butterworth filter) and its harmonics. Electrodes with contact problems were identified through visual inspection of the raw HDsEMG signals and were reconstructed by interpolation of the neighbouring electrodes. If these electrode artifacts were excessive (>10%), the recording was discarded from the analysis (Gallina et al. 2022). Dependent variables were computed for all trials (x10) of each posture (x3). Baseline muscle activation corresponded to the mean root mean square (RMS) across channel, calculated in a 500 ms window before the perturbation onset. Response latency corresponded to the time (in

milliseconds) between perturbation onset and EMG response onset. This variable was only used to identify perturbation onset and then to compute EMG response amplitude. To compute the onset of the EMG response, rectified differential HDsEMG signals were low-pass filtered (Butterworth 6th order, dual-pass zero-lag, 50 Hz cutoff frequency) and assessed using a sliding window of 25-ms (Larivière et al. 2010). EMG response onset occurred when the myoelectric signals exceeded three SDs above the baseline muscle activity (Hodges and Bui 1996). Responses were considered voluntary and removed from the analysis when response latency exceeded 200 ms. Response amplitude was defined as the mean RMS values computed in a 100-ms window centered on the response peak. Response peak corresponded to the highest RMS value present in a 200-ms window following the perturbation onset. The medio-lateral and cranio-caudal coordinates of the centroid were computed to identify the spatial distribution of the lumbar extensor muscle activity at baseline and in response to the perturbation (Figure 3). To facilitate interpretation of the spatial coordinates, the right array was flipped along the x-axis, so higher x coordinates mean a more medial location of the centroid on both sides. The centroid corresponded to the average weighted position of the channels exhibiting RMS response values higher than 70% of the maximum of all channels (Vieira et al. 2010). For baseline activation and response amplitude, estimates across channels higher than 70% of the maximum of all channels were averaged, resulting in a single estimate for each side. For all dependent variables, the mean of the perturbation trials of each posture was considered for the statistical analysis. All data analyses were performed in Matlab (2020a version, Mathworks, Natick, MA, USA).

Statistical analysis

Statistical analyses were performed with Statistica statistical package version 13 (TIBCO Software Inc, Palo Alto, CA, USA). Parametric tests were chosen based on the normality of data distribution (Kolmogorov-Smirnov test and visual inspection). A within-subject two-way repeated-measures ANOVA was conducted to assess the effect of Posture (neutral, trunk flexion and left trunk rotation), Side (left and right) and interaction (Posture x Side) on each dependent variable. When significant, main effects were decomposed using pairwise comparisons with p value corrected for the number

of comparisons using the Bonferroni test. For all statistical analyses, $p < 0.05$ was considered to be significant.

Results

EMG data of the right side of one participant was excluded due to many electrodes with contact problems (>10%). Latencies results for all postures ranged from 74 to 102 milliseconds.

MUSCLE ACTIVATION

All main (Side and Posture) and interaction effect (Side x Posture) results for baseline activity and response amplitude from the repeated-measure ANOVAs are presented in Table 1 and in Figure 4.

Posture had a significant effect on baseline activity ($F(2,36)=110.99$ $p<0.001$). Post-hoc comparisons revealed a higher baseline activity in Flexion compared to the other two postures (Bonferroni-corrected $p<0.001$), but no difference between Neutral and Rotation (Bonferroni-corrected $p=0.352$). No interaction ($F(2,36)=2.20$ $p=0.126$) was observed.

A significant Side x Posture interaction was observed for muscle activation in response to perturbation ($F(2,36)=4.30$, $p=0.021$). Post-hoc comparisons revealed a higher EMG response for the right and left side during Flexion compared to the right side during Rotation (Bonferroni-corrected for right Flexion $p<0.001$; for left Flexion $p=0.006$), as well as a higher EMG response in right Flexion compared to left Neutral posture (Bonferroni-corrected $p=0.005$). No significant effect of side (multiple $p>0.127$) was observed for these two variables.

MEDIO-LATERAL DISTRIBUTION

Centroid results are illustrated in Table 1 and Figures 5 and 6. Posture influenced the medio-lateral distribution of activation, both at baseline and in response to perturbations.

At baseline, posture had an effect on the medio-lateral centroid coordinates ($F(2,36)=17.36$, $p<0.001$). Post-hoc comparisons revealed a more medial location of the centroid in Flexion compared to both Neutral (Bonferroni-corrected $p=0.003$) and Rotation (Bonferroni-corrected

p<0.001) at baseline. An effect of side (F(2,36)=5.09, p=0.037) was also observed, with more lateral centroid locations on the left compared to the right. No interactions were significant (F(2,36)=2.57, p=0.090).

In response to the perturbation, an interaction Side x Posture (F(2,36)=8.55, p<0.001) was identified. The distribution of activation was more lateral on the left compared to the right side during Rotation (Bonferroni-corrected p<0.001). Post-hoc comparisons revealed a more medial location of the centroid on the right side in Neutral compared to the Flexion on both sides (Bonferroni-corrected ps<0.05) and a more medial location of the centroid on both sides in Neutral compared to the left side in Rotation (Bonferroni-corrected ps<0.001).

CRANIO-CAUDAL DISTRIBUTION

Posture influenced the cranio-caudal distribution of activation, both at baseline and in response to perturbations.

At baseline, a significant interaction side x posture (F(2,36)=14.30, p<0.001) was observed. The EMG distribution was located more cranially on the left side than the right side in Rotation (Bonferroni-corrected p<0.001). Moreover, on the right side, a more caudal location of the centroid was observed in Rotation compared to Neutral on the right side (Bonferroni-corrected p=0.009) and on the left side (Bonferroni-corrected p=0.036). The EMG distribution was located more caudally on the left and right sides in Flexion than the left side in Rotation (Bonferroni-corrected p=0.014 and p=0.007, respectively). No other post-hoc comparisons were significant (p>0.05).

After perturbation, a significant interaction side x posture (F(2,36)=7.18, p=0.002) was observed. Post-hoc comparisons revealed a more cranial location of the centroid on the left side in comparison to the right side in trunk rotation (Bonferroni-corrected p=0.002), whereas other post-hoc comparisons did not reach significance (p>0.063).

Discussion

In the present study, we investigated the effect of trunk posture on muscle recruitment strategies during unexpected posterior-anterior trunk perturbations. Regional differences in the distribution of

surface EMG amplitude indicate that different muscle regions were preferentially activated in isometric contractions and in response to perturbations applied when the trunk is in different postures. Our results demonstrate that, in response to unexpected postural perturbations, healthy individuals activate lumbar muscles regionally when forward perturbations are applied in different trunk postures. This regional activation may be based on the mechanical advantage of regions within the lumbar extensor muscles.

Using HDsEMG, this study was able to reveal an uneven distribution of muscle activity over the low back region when assessing responses to trunk perturbations. Together with a large body of literature that identified uneven activation over the lumbar extensor muscles in a variety of tasks (Falla et al. 2014; Readi et al. 2015; Ringheim et al. 2019; Serafino et al. 2021), our study further highlights how recordings from multiple regions of the lumbar extensors may be needed to accurately represent the activation of these muscles. For instance, since the distribution of electromyographic amplitude differs between postures, a single bipolar electrode with a small interelectrode distance may record smaller or larger differences in EMG amplitude between postures depending on where it is placed. Similarly, the large differences in the cranio-caudal coordinate of the centroid between left and right during trunk rotation suggest that global muscle activation estimates from a single bipolar electrode with a small interelectrode distance placed in the same location on the left and right lumbar extensor muscles may be misleading, since side differences in EMG amplitude may be related to regional activation as opposed to changes in global muscle activation. Overall, our findings support the recent consensus papers in electrode selection that identify HDsEMG as a relevant tool to assess the distribution of activity between regions of a muscle (Besomi et al. 2019; Gallina et al. 2022).

Trunk flexion postures may result in a mechanical disadvantage while facing unexpected perturbations. When the trunk is flexed, the moment arm due to gravity increases, which increase the activation of the erector spinae required to maintain this posture. In addition to this change, the

orientation of the erector spinae muscle fibers in a flexed posture reduces their ability to generate a great amount of force (Tveit et al. 1994), which increase the risk of spinal instability. Finally, an increase of the lumbar flexion angle will result in an increase of muscle fiber length, which will also reduce the production of force as demonstrated by the well-known force-length relation of muscle (Hill 1953; Malakoutian et al. 2022). Based on these biomechanical reasons, we expected differences in the neuromuscular strategies used to maintain a flexed trunk posture and resist perturbations. During the baseline period, which corresponded to 500 milliseconds before the unexpected perturbation onset, muscle activity was higher in the trunk flexion posture compared to the neutral posture and trunk rotation. In the trunk flexion posture, participants were asked to bend forward at 40°. Consequently, a pre-activation of the erector spinae muscle is necessary to maintain the trunk posture against the gravity and to stabilise the trunk. A previous study has reported a similar EMG amplitude increase when participants were asked to bend at 20° in similar semi-seated position (Shahvarpour et al. 2014). In response to the perturbation, a higher response of the erector spinae was also observed in trunk flexion posture compared to the other postures where the trunk was upright. In this posture, the moment of the perturbation is added to the moment exerted by the gravity. Consequently, it could be suggested that the erector spinae muscles need to produce a higher moment in trunk flexion when facing a perturbation to stabilise the trunk. Regarding the spatial distribution of muscle activity at baseline, a more medial contribution of the lumbar extensor muscles was identified bilaterally in the trunk flexion posture. A possible influence of the activation of superficial multifidus could explain the medial distribution of muscle activity. The medial edge of the HDsEMG was at one centimetre from the lumbar spinous process and the grids spanned approximately the entire lumbar region. Based on the anatomy of the lumbar region, the grid would cover mostly the erector spinae muscles (longissimus) and the superficial multifidus closer to the spine (Macintosh and Bogduk 1987; Macintosh et al. 1986) which could explain the medial shift of the muscle activity. Therefore, our current results of more medial distribution of activation suggest a large contribution of the superficial multifidus during trunk flexion postures, possibly to help stabilise the trunk isometrically. Interestingly, in response to the perturbation, we observed a more lateral location of the muscle activity in the trunk flexion posture compared to neutral on both sides.

This finding suggests that, compared to when the trunk is in neutral posture, the erector spinae muscle is preferentially recruited to resist the trunk perturbation. Biomechanically these different activation strategies observed during trunk flexion (medial muscle regions when maintaining posture, lateral muscle regions in response to perturbations) may be associated with the different biomechanical function of muscles within the lumbar extensors, i.e., spinal stabilisation for multifidus, response to postural perturbations due to a larger moment arm for the erector spinae. However, since the trunk flexion posture induced a consistent increase in muscle activation at baseline, it is not possible to determine whether these different strategies are associated to the trunk posture, or to the large muscle activation at baseline.

During a left trunk rotation, a higher muscle activity amplitude on the left side has been reported in the upper lumbar spinal levels compared to the lower levels (Abboud et al. 2020). Moreover, it has been reported that the erector spinae (longissimus and iliocostalis) have a higher moment arm in the upper lumbar and thoracic regions because the distance between the middle of the muscle and the intervertebral disc increase when moving to upper spinal levels (McGill et al. 1993). Therefore, we could expect that the central nervous system prioritizes the activation of the lumbar region with the highest mechanical advantage to stabilise the trunk. While previous studies have reported a higher ipsilateral lumbar muscle activation compared to contralateral muscles during isometric voluntary trunk rotation against resistance (Kumar et al. 2001; Ng et al. 2001), in this study trunk rotation did not result in differences between sides at baseline or in response to the perturbation. The lack of significant differences in EMG amplitude at baseline in this study could be due to the fact that the participants did not perform a trunk rotation against resistance, but rather performed a 20% MVIC trunk flexion with their trunk in a rotated posture, and therefore it could be argued that the muscle demand to maintain the trunk rotation was minimal in comparison to the trunk flexion demand. Importantly, since the EMG amplitude at baseline was not different between side, differences in the baseline intensity of activation cannot explain the different neuromuscular strategies observed when perturbations were applied during trunk rotation. Regarding the distribution of activity between muscle regions, the present study revealed a more cranial

contribution of the lumbar extensor muscles on the left side during ipsilateral trunk rotation posture at baseline. Conversely, a more caudal location of the centroid was reported on the right side compared to the neutral posture. These cranio-caudal differences in the spatial distribution of activation, as well as a more lateral activation on the left compared to the right lumbar extensors, were also maintained in response to perturbations in the trunk rotation posture. Overall, these observations support the notion that the lumbar muscle region with the highest mechanical advantage is preferentially recruited when trunk postural control is challenged. Specifically, a 30-degree trunk rotation to the left may have placed the left erector spinae in a position where it is more aligned with the sagittal plane, and therefore mechanically more efficient to oppose a posterior-anterior perturbation. Since more cranial regions of the lumbar erector spinae have a better moment arm due to a larger distance from the intervertebral disc (McGill et al. 1993), a preferential activation of this region may be more effective to oppose forward-directed perturbations. Instead, left trunk rotation may have increased the angle between the right erector spinae line of action and the sagittal plane, making this muscle a less optimal choice to produce force to oppose posterior-anterior perturbations. Because of this, distal regions within the lumbar extensors may have been recruited to assist with spinal stabilisation. Further, our data suggest that the main neuromuscular strategies to oppose forward-directed perturbations when the trunk is rotated compared to neutral posture involve regional redistribution of activity without consistent changes in global muscle activation intensity.

In response to the perturbation, the EMG distribution was more lateral on the left compared to the right side in the trunk rotation posture, and on the left side it was more lateral in the trunk rotation posture compared to the neutral posture. This neuromuscular activation strategy, possibly representing a preferential contribution of the erector spinae, was similar to that observed in the trunk flexion posture. Since the erector spinae muscles are the main contributor to the trunk extension because of their larger size (McGill et al. 1993), these data suggest that that the central nervous system preferentially recruits the erector spinae over the superficial multifidus to oppose a trunk perturbation when the trunk is flexed or rotated, compared to when it is in neutral posture. It should be noted that, even if the centroid migration of muscle activity could be considered small,

it is likely to still be relevant from a physiological point of view since muscle fibers even just one centimeter apart could for instance insert on different vertebrae. The shift of muscle activity observed in this study is larger than that observed during trunk loading task (Tucker et al. 2009), and similar to the difference in average distribution observed when comparing individuals with and without low back pain (e.g., (Falla et al. 2014)). Overall, these observations suggest that the recruitment of motor units of the erector spinae muscles are dependent on posture, possibly because different postures modify the mechanical advantage of the erector spinae.

Typically, motor units are recruited according to Henneman's size principle, i.e. from the smallest motor units to the largest (Henneman 1981). Such recruitment strategy has important physiological benefits, such as minimizing the amount of muscle fatigue. More recently, the neuromechanical principle was superimposed to the size principle to explain motor unit recruitment (Butler and Gandevia 2008; Hudson et al. 2019). This new principle states that motor units are recruited according to a mechanical advantage during complex tasks where joint angle and fiber orientation varies, such as superficial lumbar muscles in trunk flexion (Harriss and Brown 2015), as well as intersegmental movements of the spine (McGill 2015). In the current study, we showed that the location of the erector spinae muscle activity varied according to the trunk orientation. Although mechanical advantage was not directly assessed in this study, changes in the mechanical effectiveness of regions within the lumbar muscles due to trunk posture are a plausible explanation for the observed differences in regional activation, both at baseline and in response to perturbations. The results of the current study have improved our understanding on how the lumbar muscles adapts to challenging trunk postures, demonstrating that the central nervous system can finely tune with region of the erector spinae is recruited in response to perturbations applied when the trunk is in different postures. These findings could provide some guidance for perturbation-based exercises used in prevention and rehabilitation.

The present study has some limitations that should be considered. The main limitation of this study was that we could not directly estimate the mechanical efficiency of the different muscle regions, therefore the interpretation of the results is based on the anatomical and biomechanical knowledge of the lumbar muscles. In the current experiment, a shift of the skin could have occurred, especially in the 45-degree trunk flexion posture as the lumbar muscle are lengthened. Based on the skin movement, a shift of the centroid on the cranio-caudal axis during this trunk posture could have been expected. However, results did not reveal a significant difference of the shift of the centroid in the cranio-caudal direction between the neutral and trunk flexion posture. The only difference identified between these two postures was in the medio-lateral coordinates of the centroid, which is unlikely to be explained by shift of the muscle relative to the skin. Therefore, even if the current study did not control for skin movement, it could be argued that it had negligible or no impact on centroid results. Also, the small sample size could increase the risk of statistical error. However, the main and interaction effects were highly significant which reduce this risk. The interpretation of the results should also be limited to control postural tasks which may not be as representative as real-life postural tasks. Finally, no direct measure of spinal stability was made in this study which limit the application of our results to general trunk postural control.

In conclusion, the present study shows that healthy individuals activate lumbar muscles regionally to maintain different trunk postures and to oppose unexpected trunk perturbation, possibly due to regional differences in the mechanical advantage of the erector spinae in different trunk postures. Moreover, the regional redistribution of activation observed in this study suggests that the central nervous system may take advantage of the complexity and flexibility of the trunk system to maintain stability of the spine even in challenging postures. The next step will be to identify the erector spinae recruitment strategies under more challenged posture, such as full trunk flexion, and to assess whether these strategies are conserved in patients with low back pain.

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Legends for illustrations and tables

Table 1. Effect of Side and Trunk Posture on lumbar muscle activation and centroid location. When significant, post-hoc are described bellow the main effects p value.

Figure 1. Illustration of the trunk perturbation protocols in three different postures: neutral (top figure), trunk flexion (bottom left figure) and trunk rotation (bottom right figure).

Figure 2. Organisation and position of the high-density surface EMG. Examples of EMG recordings for each Posture on the left and right side. The vertical grey line represents the perturbation onset. To calculate the centroid activation, the number of columns on the right grid has been mirrored so that for both grids higher values represent more medial activation. Each number corresponds to a differential signal. Data from a single participant.

Figure 3. Mapping of the distribution of muscle activity during the perturbation response. The white cross markers correspond to the location of the centroid. Data from a single participant.

Figure 4. Representation of the average normalized mean muscle activity amplitude at baseline and in response to the perturbation of channels higher than 70% of the maximum of all channels. Blue traces illustrate the Neutral Posture, red traces illustrate the Flexion Posture and black traces illustrate the Rotation Posture. The dashed vertical line represents the perturbation onset.

Figure 5. Medio-lateral and cranio-caudal coordinates of the centroid locations. The graphs depict means (filled circles), standard deviations and black circles identify responses from individual participants. N: Neutral posture F: Trunk Flexion posture; R: Trunk Rotation posture; l: left side; r: right side.

Figure 6. Spatial representation of the centroid locations at baseline (dashed lines) and in response to the perturbation (solid lines). Circles represent the mean locations and bars represent the standard deviations. Blue traces illustrate the Neutral Posture, red traces illustrate the Flexion Posture and black traces illustrate the Rotation Posture. C: channel.