Full Title: Regional Flexion Relaxation Phenomenon in Lumbar Extensor Muscles Under Delayed-Onset Muscle Soreness: High-Density Surface Electromyography Insights

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Disclosure

Competing interest statement

The authors have no competing interest to declare.

Conflict of interest

The authors have no actual or potential conflicts of interest, including any financial, personal, or other relationships with other people or organisations within 3 years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

Abbreviations

Delayed-onset muscle soreness (DOMS)

Flexion Relaxation Phenomenon (FRP)

Flexion relaxation ratio (FRR)

High-density surface electromyography (HDsEMG)

Low back pain (LBP)

Maximal voluntary isometric contractions (MVIC)

Pressure pain threshold (PPT)

Root mean square (RMS)

Range of motion (ROM)

ABSTRACT

Purpose This study aimed to investigate whether lumbar delayed-onset muscle soreness (DOMS), impact the magnitude of the flexion relaxation phenomenon regionally. **Methods** Eighteen adult participants (9 men and 9 women) performed flexion extension movement under two conditions (without DOMS, with DOMS). Lumbar muscle activation strategies were recorded using high-density surface electromyography (HDsEMG) on both sides. To determine the spatial distribution of flexion relaxation phenomenon, flexion relaxation ratio of muscle activity was computed for all electrodes of the HDsEMG grid and the coordinates of the centroid (average position of flexion relaxation ratio across the HDsEMG grid) in the mediolateral and craniocaudal axis were calculated. **Results** The results revealed a cranial shift (~ 6 mm) of flexion relaxation phenomenon within the lumbar extensor muscles when DOMS was present (both sides: $p < 0.05$), possibly attributed to the increased recruitment of lumbar stabilizing muscles located caudally as a guarding mechanism to pain. **Conclusion** These results highlight the importance of evaluating the entire lumbar region when assessing the flexion relaxation phenomenon.

Acknowledgments

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Keywords

High Density Surface Electromyography; Flexion Relaxation Phenomenon; Lumbar Extensor Muscles; Delayed-Onset Muscle Soreness; Low back pain

INTRODUCTION

The Flexion Relaxation Phenomenon (FRP) is characterized by a sudden reduction or cessation of muscle activity in the lumbar extensor muscles when the trunk is near, approaching full flexion. This suggests a shift in load distribution from active muscle engagement to passive support, primarily from ligaments and the viscoelastic passive components of the lumbar extensor muscles (Floyd and Silver, 1955, Kippers and Parker, 1984, McGill and Kippers, 1994). Numerous individuals with chronic low back pain (LBP) have an altered FRP (decreased or absent), suggesting its potential as a biomarker for discriminating chronic LBP patients from pain-free controls based on musculoskeletal alterations (Sihvonen et al., 1991, Ahern et al., 1988, Gouteron et al., 2022, Moissenet et al., 2021, Colloca and Hinrichs, 2005). However, a significant limitation in using the FRP as a biomarker is the heterogeneity in its alteration, with an altered FRP prevalence estimated at around 55% among chronic LBP patients (Gouteron et al., 2022).

This heterogeneity may be attributed to confounding factors related to chronic LBP, such as the level of disability (Gouteron et al., 2022). Experimental pain models can replicate both pain presentation and dysfunctions observed in chronic pain conditions while controlling for confounding factors, as each participant serves as their own control (Cheung et al., 2003, Mouraux et al., 2021). Movement-evoked pain, often observed in chronic LBP (Knox et al., 2022), is thought to contribute to various psychological and neuromuscular dysfunctions. These include increased pain-related fear, avoidance of movement, and decreased range of motion (ROM) (Corbett et al., 2019, Leemans et al., 2022), which have all been associated with FPR alterations in chronic LBP patients (Alschuler et al., 2009, Geisser et al., 2004, Neblett et al., 2003). Delayed-onset muscle soreness (DOMS) can induce similar movement-evoked pain resulting from muscle damage and inflammation caused by eccentric contractions, both of which are also present in chronic LBP (Cheung et al., 2003, Farias-Junior et al., 2019, Morris et al., 2020, Noonan and Brown, 2021). Moreover, DOMS can replicate movement-related psychological and neuromuscular dysfunctions seen in chronic LBP patients (Bishop et al., 2011, Trost et al., 2012, Trost et al., 2011). Thus, the shared characteristics between DOMS and chronic LBP make DOMS a relevant pain model to replicate FRP alterations observed in chronic LBP within a controlled experimental setting.

The heterogeneity in reported result may also be attributed to the current FRP assessment methods, such as using bipolar electromyography, which measure a specific and localized region of the lumbar extensor

muscles and might not represent the whole muscle behavior (Gouteron et al., 2022, Colloca and Hinrichs, 2005). Given that lumbar extensor muscles can redistribute their activation across different muscles and regions in response to both clinical and acute LBP, more comprehensive evaluation is needed (Hodges and Tucker, 2011, Ducas et al., 2024c, Ducas et al., 2024a, Sanderson et al., 2019b, Sanderson et al., 2019a). For instance, muscle activity tends to be located more cranially in clinical LBP compared to pain-free controls during tasks such as endurance and functional lifting tasks (Sanderson et al., 2019b, Sanderson et al., 2019a). By contrast, in acute experimental LBP, redistribution of muscle activity within the lumbar extensors tend to be individualized, with each participant exhibiting a unique redistribution pattern during isometric back extension tasks at different trunk angles (Ducas et al., 2024a, Ducas et al., 2024c). To assess these nuanced redistributions accurately, high-density surface electromyography (HDsEMG) is particularly valuable, as its large array of electrodes can record muscle activity across the entire lumbar region, which can provide information about the temporal and spatial features of muscle activation (Gallina et al., 2022). This technique enables spatial mapping for a more comprehensive understanding of the FRP within the lumbar extensor muscles (Murillo et al., 2019). Using HDsEMG, a study showed a delayed onset of the FRP in the cranial region of lumbar extensor muscles in individuals with LBP compared to pain-free controls (Murillo et al., 2019). This suggests that the cranial region of lumbar extensor muscles remains activated longer during trunk flexion (Murillo et al., 2019). However, despite the observed regional delay in FRP, the impact of pain on the magnitude of FRP within different lumbar regions remains unknown and could explain the heterogenous results found in the chronic LBP literature.

Therefore, the aim of this study was to investigate whether LBP, characterized by neuromuscular alterations induce by DOMS (including pain, inflammation, and muscle damage), impact the magnitude of the FRP regionally. It was hypothesized that inducing LBP will result in regional changes in FRP magnitude within the lumbar extensor muscles.

METHODS

Participants

Eighteen adult participants (9 men and 9 women) age at 26.22 ± 5.33 years; height at 1.72 ± 0.07 m weight at 72.19 ± 17.48 kg and body mass index at 24.24 ± 4.85 kg/m^2 participated in this study. A post-hoc

power calculation was conducted for a two-tailed paired t-test on the craniocaudal centroid coordinates of the FRP (left side), using an alpha level of 0.05 and a total sample size of 18 (G*Power 3.1 (Faul et al., 2007)). This resulted in a power of 0.82, aligning with current standards. Participants were recruited from the local university community as well as from various regions across Quebec through advertisements on social media. Participants were excluded if they had experienced LBP within the past year, undergone previous spinal surgery, had inflammatory arthritis affecting the axial skeleton, suffered from advanced osteoporosis, or experienced severe pain that would limit their ability to complete the assessment protocol in the laboratory. Approval for the project was obtained from the Research Ethics Board for human research at "Université du Québec à Trois-Rivières" (CER-22-290-07.11), and all participants provided written informed consent. The study was conducted in accordance with the principles outlined in the Declaration of Helsinki (Association, 2013).

Experimental Protocol

The experimental procedure consisted of two sessions, during which participants provided sociodemographic information such as age, sex, weight, and height in the first session. During these sessions, participants performed 5 trunk flexion extension movements. The 1st session occurred prior having DOMS, while the 2nd session took place 24-36 hours after a DOMS-inducing protocol implemented at the end of the first session (Figure 1). This time frame was chosen because lumbar DOMS typically peaks in pain and soreness during this period (Cheung et al., 2003, Coudreuse et al., 2007, Abboud et al., 2019). To assess the induction of DOMS, evaluations were conducted for pain levels, soreness, and pressure pain threshold in the lumbar extensor muscles. Additionally, to assess trunk kinematics, the ROM of the lumbar spine, hip and trunk was calculated using fourteen three-dimensional markers. During the flexion extension movement, the muscle activation patterns of both the left and right lumbar extensor muscles were recorded using two HDsEMG grids of 8x8 electrodes, resulting in a total of 64 channels per grid. These recordings were used to assess the FRP magnitude, calculated through the flexion relaxation ratio (FRR) of muscle activity.

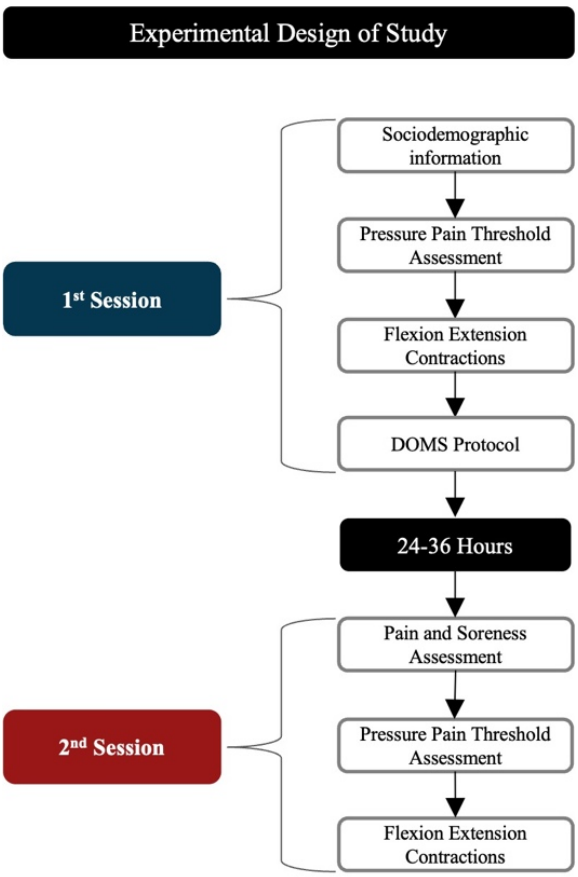

Fig. 1 Flow chart illustrating the experimental design of the study

Flexion Extension Movement

Participants performed five flexion extension movements by initiating from a neutral spine position. To ensure a standardized baseline position, participants were instructed to stand upright with their feet shoulder width apart and focus on a fixed point on the wall located three meters away. For the contractions, participants were instructed to flex their spine gradually to achieve maximum trunk flexion within a span of five seconds, maintaining this fully flexed position for three seconds, before gradually returning to the neutral spine position over a five-second duration. They were instructed not to bend their knees and to cross their arms at their chest during the flexion extension movement. Additionally, participants were instructed to synchronize their trunk flexion movement with a metronome set to a rate of 60 beats per minute. Before the measurements, participants were given the opportunity to practice and familiarize themselves with the flexion

extension movement task. This flexion extension movement protocol is similar to previous studies that investigated the lumbar FRP (Descarreaux et al., 2008, Nougarou et al., 2012, Murillo et al., 2019).

Delayed-Onset Muscle Soreness Protocol

Prior to the DOMS protocol, maximal voluntary isometric contractions (MVICs) of trunk extension were assessed. Participants were positioned on a 45° inclined Roman chair, aligning their trunk parallel to the ground. Participants exerted their maximal force against a shoulder-attached belt for five seconds, which completely restricted movement along the y-axis. The MVICs were measured using a force gauge (Model LSB350; Futek Advanced Sensor Technology Inc, Irvine, CA, USA). Three MVICs trials were conducted, with a one-minute rest between each trial, followed by a five-minute rest period before the DOMS protocol.

During the DOMS protocol, participants were instructed to hold their arms crossed at their chest while carrying an external load equivalent to 10% of their highest MVICs value obtained (Abboud et al., 2019). This protocol involved five sets, each consisting of 20 repetitions of trunk flexion and extension contractions. A one-minute break separated each set, resulting in a total of 100 repetitions. Each repetition included a three-second 60° eccentric trunk flexion contraction, followed by a three-second isometric contraction, and a one-second 60° concentric trunk extension contraction to return to the starting position (as indicated by the person highlighted in gray in Figure 2). To minimize pelvic tilt movement and restrict lower limbs muscle involvement, hip and ankle straps were used. Throughout the protocol, participants received continuous verbal encouragement, and adjustments were made to set size and rest intervals as necessary to ensure completion of the targeted 100 contractions (Abboud et al., 2019). All participants successfully accomplished the intended 100 contractions.

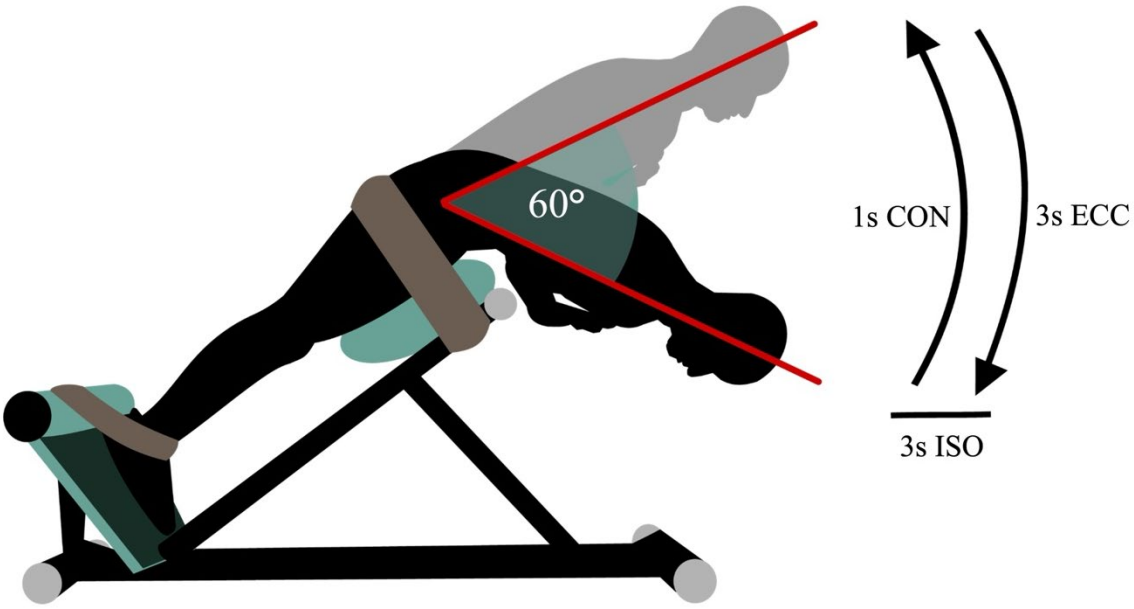

Fig. 2 Illustration of the initial position of participants (shown in gray) and the final position (shown in black) on the 45-degree Roman chair during the DOMS protocol. ECC: eccentric contraction, CON: concentric contraction, ISO: isometric contraction

Pain and Soreness Rating

At the beginning of the 2nd session, participants were asked to assess their overall level of perceived pain and soreness in the lower back using a numeric rating scale (NRS). The NRS is widely recognized as a valid and reliable instrument for assessing pain (Hawker et al., 2011, Breivik et al., 2008). Auto evaluation scales have been effectively used to measure various clinical indicators, including muscle soreness (Andersen et al., 2013, Abboud et al., 2019, Arvanitidis et al., 2024). Participants were asked to rate their pain and soreness on a scale from 0, indicating no pain or soreness, to 10, representing the maximum level of pain or soreness.

Pressure Pain Threshold Assessment

Pressure pain threshold (PPT) measurements provide a valuable method for assessing DOMS. PPT effectively evaluates peripheral sensitization, which reflects increased nervous system sensitivity triggered

by the inflammation and tissue damage associated with DOMS (Latremoliere and Woolf, 2009). By measuring this sensitivity, PPT provides an objective measure of the extent of DOMS (Abboud et al., 2019, Bishop et al., 2011). To assess PPT of the lumbar extensor muscles, the erector spinae muscles at the L2 and L4 levels on both sides were evaluated using an algometer equipped with a 12 mm circular tip (Model 01163; Lafayette Instrument Company, Lafayette, IN, USA). Moreover, the right vastus lateralis was assessed as a control measure, as it was expected to remain unaffected by eccentric back extension exercises. To ensure consistency across sessions, the muscle locations were identified by palpation and marked with a small dot. Participants were instructed to lie prone on a chiropractic table for the assessment. The algometer's tip was positioned at the center of each muscle belly, aligned with either the L2 or L4 level. The algometer was consistently applied perpendicular to the area with a steady force of approximately 1 kg/s by the same experimenter across both sessions, following methodologies from prior studies (Chesterton et al., 2007, Ducas et al., 2024b). Participants were instructed to notify the experimenter immediately upon experiencing a change from a pressure sensation to a pain sensation (Bishop et al., 2011). PPT assessments were conducted three times for each location. To minimize bias, the sequence of assessment was randomized among participants. Previous research has demonstrated excellent between-session reliability when measuring PPT using an algometer (Mailloux et al., 2021, Potter et al., 2006).

Kinematic

Previous study found associations between trunk kinematic and the FRP (Neblett et al., 2003). Therefore, incorporating kinematic analysis into the assessment of the FRP can help explain the neuromuscular adaptations of the lumbar spine to DOMS. During the flexion extension movement, kinematic was recorded using a three-dimensional motion analysis system (12 cameras, OptiTrack; NaturalPoint, Corvallis, OR, USA) sampled at 200 Hz. This OptiTrack system is a validated and reliable tool for 3D motion analysis, enabling precise assessments of trunk movements (Carse et al., 2013, Hansen et al., 2014). Fourteen markers were used to assess both the lumbar spine and hip kinematic. Two three-dimensional kinematic markers were positioned on the lumbar spine at the spinous processes of L1 and L5. Four markers were placed on the hips: two on the anterior spine of the iliac crest (left and right) and two on the midpoint of the iliac crest (left and right). Additionally, four markers were placed on the thighs: two on the greater trochanter

(left and right) and two on the medial epicondyle of the femur (left and right; Figure 3, subplot A). Marker placements were consistently performed by the same experimenter and identified through palpation.

High-Density Surface Electromyography

During each flexion extension movement, the myoelectric activity of both the right and left lumbar extensor muscles were recorded using two HDsEMG grids. These HDsEMG grid consisted of 64 electrodes arranged in an 8x8 matrix with 10 mm spacing between electrodes (semi-disposable adhesive matrix; model GR10MM0808, 3mm electrode diameter, OTBioelettronica, Torino, Italy; Figure 3, subplot B). To prepare the skin overlying the lumbar extensor muscles, shaving was performed followed by cleaning using fine-grade sandpaper (Red DotTrace Prep; 3M, St. Paul, MN) and rubbing alcohol (ethyl alcohol 70%). The center of each grid was placed at the L3 level, with the medial edge approximately 1 cm away from the L3 spinous process. The grid spanned approximately from the L1 to the L4-L5 region. The grid was positioned with its columns aligned to approximate the orientation of the muscle fibers. To ensure consistency, the same investigator placed the grids for all participants. To prevent grid movement during the task, hypoallergenic flexible tape was used (Hypafix, BSN Medical, Charlotte, NC, USA). This tape was secured to the trunk while the trunk was in mid-flexion, allowing proper adhesion of the grids without limiting the range of flexion movement. The signal amplification was either at X5000 or X2000 depending on signal saturation. Signals were digitized at a sampling rate of 2048 Hz using a 12-bit A/D converter (256-channel EMG-USB2; OTBioelettronica) with a bandwidth of 10-500 Hz (-3 dB; 1st order). The reference electrode, connected to the main amplifier, was placed over the right iliac crest. Simultaneously with the HDsEMG recordings, a trigger signal was recorded to indicate the beginning and end of the kinematic data recording. This trigger signal was used for the synchronization between the kinematic and the HDsEMG recordings. Grid's boundaries were marked on the skin to ensure consistent electrode placements across sessions. HDsEMG has demonstrated good test-retest reliability for measuring trunk muscle activity (Abboud et al., 2015, Van Helden et al., 2022).

Data Analysis

Pressure Pain Threshold

For each location and side, the mean of the three PPT measurements was calculated. Session-to-session changes in PPT values were analyzed to assess the presence of DOMS. Side differences were evaluated by comparing the session-to-session differences between the left and right sides at each location for each PPT except for the vastus lateralis as it was measured only on one side. Location differences in the lumbar region were assessed by comparing session-to-session changes between L2 and L4 for both sides.

Kinematics

Kinematic marker signals underwent filtering using a 2nd-order low-pass Butterworth filter set at 3 Hz (Howarth and Mastragostino, 2013, Zwambag et al., 2016). Three segmental vectors were then calculated based on marker positions coordinates, which were averaged on both sides. The lumbar vector was derived from the position of markers at the L1 and L5 spinous processes. The hip vector was derived from the positions of markers on the anterior spine of the iliac crest and the positions of markers on the midpoint of the iliac crest. Similarly, the thigh vector was calculated from the positions of markers on the greater trochanter and the positions of markers at the medial epicondyle of the femur.

The lumbar ROM was determined as the angles between the lumbar and hip vectors, while hip ROM was calculated as the angle between the hip and thigh vectors (Esola et al., 1996). Trunk ROM was determined as the angle between the lumbar and thigh vectors. The angle corresponding to Trunk ROM was visually inspected and marked to differentiate the different phases of flexion, full flexion, and extension, which were used to segment the HDsEMG recording signal for the calculation of the FRR. All angles were computed on the sagittal plane (Figure 3, subplot E). To enhance robustness, the lumbar ROM, hip ROM, and trunk ROM value were averaged across the five flexion-extension contractions.

High-Density Surface Electromyography

HDsEMG signals were processed using Matlab (version 2024a; The MathWorks, Natick, MA). The data were collected and analyzed separately for the left and right sides. Differential signals were computed from HDsEMG by subtracting consecutive monopolar signals along the craniocaudal direction, resulting in a final grid configuration of 7 × 8 channels. Both grids' signals underwent digital band-pass filtering using a 4th-order Butterworth filter with a frequency range of 30–400 Hz. Additionally, second-order Butterworth

notch filters were used to eliminate interference from the 60 Hz power line and its harmonics. Raw HDsEMG signals underwent a thorough visual inspection to detect electrodes with contact issues, artifacts or noise. These electrodes, once identified, underwent replacement using an interpolation technique that relied on data from adjacent electrodes. Specifically, the interpolation was performed based on the mean data value from the electrodes above and below the detected electrode, along the craniocaudal axis (fiber orientation). In cases where there were no electrodes above or below, such as in the first and last rows of the grid, the electrode was removed from analysis to ensure data integrity. Recordings with more than 10% of electrodes showing poor or unstable signals were excluded from the analysis (Gallina et al., 2022).

Flexion-Relaxation Ratio

The magnitude of FRP was assessed using the FRR (Figure 3, subplot C and D). FRR was computed for each channel of the grid based on 1-second epoch of maximal root mean square (RMS) muscle activity during the flexion and full-flexion phases using this formula (Rose-Dulcina et al., 2020, Kim et al., 2013):

$$FRR = \frac{1s\ epoch\ of\ maximal\ RMS\ value\ during\ flexion}{1s\ epoch\ of\ maximal\ RMS\ value\ during\ full\ flexion}$$

The RMS was calculated over 1-second windows with 50ms overlap during each contraction phase. Then the highest value was considered for analysis. A higher FRR indicates a higher level of muscle relaxation Non-normalized EMG signals were used in this calculation, as the ratio inherently normalizes the data. FRR has demonstrated high sensitivity and specificity for discriminating altered from non-altered FRP in patients with chronic LBP (De Carvalho et al., 2024, Gouteron et al., 2023). Additionally, there is evidence of moderate to excellent test-retest reliability for FRR (Gouteron et al., 2022).

Dependent variables were calculated for each session (1st session without DOMS and 2nd session with DOMS) and for both the left and right side of the lumbar extensor muscles. To determine the spatial distribution of FRP magnitude, the coordinates of the centroid in the mediolateral (x) and craniocaudal (y) axis were calculated. The centroid represents the average position of the channels that had FRR values higher than 70% of the maximum FRR value across all channels of the grid. Specifically, channels with values exceeding the 70% threshold were selected, and their estimates were averaged to generate a single estimate for each side. This approach was used as it aligns with the consensus recommendation for experimental design in electromyography for the analysis of muscle activity amplitude localization on HDsEMG (Vieira

et al., 2010, Gallina et al., 2022). The selection of electrodes with the highest FFR values, rather than the lowest, aligns with our objective to accurately localize the presence of FRP. To aid in the interpretation of the spatial coordinates, the right array was flipped along the x-axis, so higher x-coordinates indicate a more medial location of the centroid on both sides. Moreover, the average FRR of the lumbar region was computed by averaging the FRR value of all electrodes of the grid. This approach provides an overall assessment of the gross changes in FRP across the whole lumbar extensor muscles regions. To enhance robustness, dependent variables of FRR were averaged across the five flexion-extension contractions.

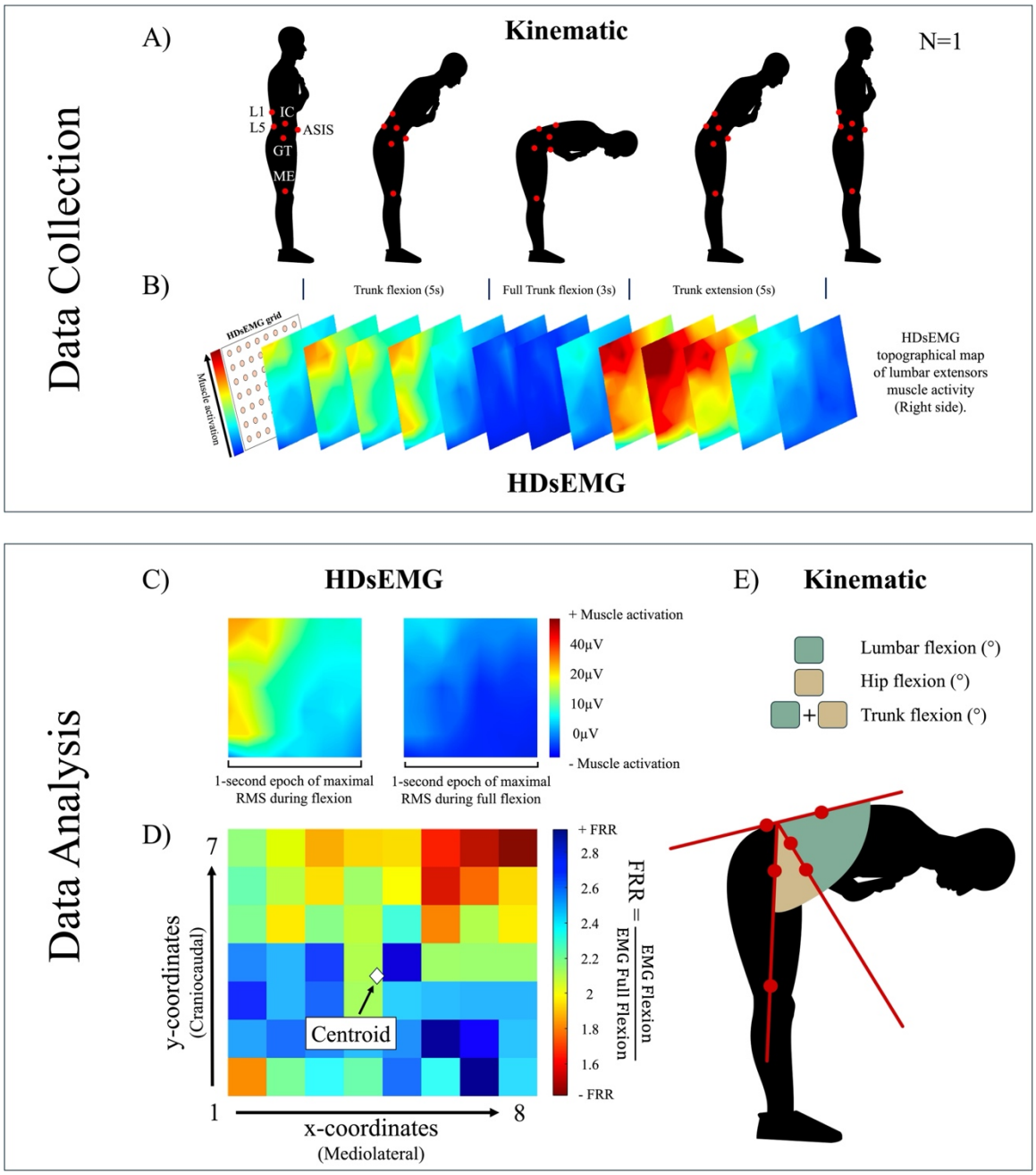

Fig. 3 Describes the data collection and analysis of HDsEMG and kinematics data from a single participant. Data collection includes two subplots: Subplot A illustrates trunk flexion extension with marker placement, while Subplot B shows multiple topographical maps over time of HDsEMG on lumbar extensor muscles activation on the right side of the trunk. Topographical maps were computed from RMS values (1s epochs) on each channel of the grid, using color coding for enhanced visualization. Data analysis section included

three subplots: Subplot C presents the topographical map of muscle activity computed from 1s epoch of maximal RMS value during trunk flexion and full-trunk flexion. Subplot D illustrates topographical maps of the flexion relaxation ratio, calculated as the division of EMG flexion by EMG full flexion on each channel. Red indicates lower flexion relaxation ratio values, representing a reduced flexion relaxation phenomenon, while blue represents higher values, indicating an increased flexion relaxation phenomenon. Subplot E illustrates kinematic analysis, where vectors are created using the markers' coordinates, and angles are calculated based on vector orientation. L1: first lumbar vertebrae; L5: fifth lumbar vertebrae; IC: midpoint of the iliac crest; ASIS: anterior superior iliac spine; GT: great trochanter; ME: medial epicondyle of the femur; RMS: root mean square; HDsEMG: High-density surface electromyography; FRR: Flexion relaxation ratio

Statistical Analysis

The statistical analyses were conducted using SPSS Statistics for Mac, version 28 (SPSS Inc., IBM Corp., Armonk, NY, USA). Parametric tests were chosen based on the data's normal distribution, which was assessed using the Kolmogorov-Smirnov test and visual inspection. For normally distributed dependent variables, a paired-sample T-test was used to evaluate the effects of sessions (1st session without DOMS and 2nd session with DOMS) on each dependent variable. Alternatively, non-normally distributed variables were analyzed using the Wilcoxon test. A significance threshold of $p < 0.05$ was used for all statistical tests. Effect sizes were quantified using Cohen's d for normally distributed variables and $r = \frac{|Z|}{\sqrt{n_x+n_y}}$ for non-normally distributed variables (Pallant, 2020). Both value can be interpreted using Cohen D, with values of 0.2, 0.5, and 0.8 indicating small, medium, and large effect sizes, respectively (Cohen, 2013). The findings were reported using mean values ± standard deviations (SD) for normally distributed variables and median and quartiles (Q1, Q3) for non-normally distributed variables (Weissgerber et al., 2015).

RESULTS

Pain, Soreness and Pressure Pain Threshold

Participants reported a pain rating of 1.56 ± 1.95 and a soreness rating of 4.42 ± 2.02 with lumbar DOMS. PPT results were significantly lower in the 2nd session (i.e. under DOMS condition) than in the 1st

session (without DOMS) for all lumbar extensor muscles sites. Details on the PPT scores between sessions are reported table 1. Additionally, no significant side differences were observed at the L2 and L4 sites (L2: Z = -1.568, p = 0.117, r = 0.261; L4: t(17) = -1.392, p = 0.182, d = 0.328). However, a significant difference in pressure pain threshold (PPT) was observed between the L2 and L4 locations on the left side, while no significant difference was found on the right side (Left: t(17) = 3.156, p = 0.006, d = 0.744; Right: t(17) = 1.592, p = 0.130, d = 0.375). Specifically, on the left side, the mean PPT score reduction between sessions at L2 was 3.78 ± 3.30 kg, compared to a reduction of 2.22 ± 2.55 kg at L4, indicating a difference of 1.56 kg. For the right side, the mean PPT score reduction between sessions at L2 was 3.13 ± 2.70 kg, while the reduction at L4 was 2.63 ± 2.22 kg.

Table 1 Comparison of pressure pain threshold (PPT) between the 1st and the 2nd session (Kg).

Muscle site	Session	Mean Score ± SD	Median Score (Q1, Q3)	Statistic Test (Z or t)	p-value	Effect size
Left lumbar extensor muscles (L2)	1st	10.30 ± 5.78		t = 4.852	**<0.001**	d=1.144
	2nd	6.52 ± 3.33				
Right lumbar extensor muscles (L2)	1st		7.60 (5.81, 14.68)	Z = -3.593	**<0.001**	r=0.599
	2nd		5.08 (4.00, 11.58			
Left lumbar extensor muscles (L4)	1st		7.13 (5.38, 13.33)	Z = -2.896	**0.004**	r=0.483
	2nd		6.45 (4.53, 9.73)			
Right lumbar extensor muscles (L4)	1st		7.03 (5.73, 12.24)	Z = -3.680	**<0.001**	r=0.613
	2nd		5.30 (3.74, 9.38)			
Right vastus medialis (control site)	1st		8.10 (6.93, 15.89)	Z = -1.416	0.157	r=0.236

	2^{nd}	8.47 (6.49, 13.42)	

*Statistically significant results are highlighted in bold

Kinematics

There were no differences between sessions on lumbar ROM ($t(17) = 1.957$, $p = 0.067$, $d = 0.461$), hip ROM ($t(17) = -1.132$, $p = 0.273$, $d = 0.267$), or trunk ROM ($t(17) = 0.357$, $p = 0.726$, $d = 0.084$). Specifically, lumbar ROM was 34.80° ± 9.78 in the 1st session and 31.61° ± 8.38 in the 2nd session. Hip ROM was 60.07° ± 16.87 in the 1st session and 62.34° ± 17.57 in the 2nd session. Trunk ROM was 94.88° ± 17.49 in the 1st session and 93.95° ± 18.97 in the 2nd session. These findings confirmed similar task performance.

Craniocaudal (y) Centroid Coordinates of FRP

The Wilcoxon signed-rank test and pairwise T-test revealed an effect of session on the craniocaudal coordinates of FRP on both sides (Left: $Z = -3.245$, $p < 0.001$, $r = 0.541$; Right: $t(17) = -2.478$, $p = 0.012$, $d = 0.584$). Specifically, on the left side, the craniocaudal coordinates for the 1st session were 3.79 (2.96, 4.32) and 4.46 (3.92, 4.90) for the 2nd session, indicating a 6.7 mm cranial shift of the FRP with DOMS. On the right side, the craniocaudal coordinates for the 1st session were 4.02 ± 1.00 and 4.49 ± 0.79 for the 2nd session, indicating a 4.7 mm cranial shift of the FRP with DOMS. Individual data points are presented in Figure 4 and Figure 5.

Mediolateral (x) Centroid Coordinates of FRP

The pairwise T-test did not reveal any effect of sessions on the mediolateral coordinates of FRP on both sides (Left: $t(17) = 0.003$, $p = 0.499$, $d = 0.001$; Right: $t(17) = 0.265$, $p = 0.397$, $d = 0.062$). On the left side, the mediolateral coordinates were 6.18 ± 0.95 for the 1st session and 6.17 ± 1.07 for the 2nd session. On the right side, the mediolateral coordinates were 6.20 ± 0.67 for the 1st session and 6.27 ± 0.96 for the 2nd session. Individual data points are presented in Figure 4.

Total FRP Magnitude

The pairwise T-test and the Wilcoxon signed-rank test did not reveal an effect of session on the total FRP magnitude across all channels of HDsEMG on both sides (left: $t(17) = -0.037$, $p = 0.485$, $d = 0.009$; right: $Z = -1.546$, $p = 0.122$, $r = 0.258$). On the left side, the total FRP magnitude was 4.94 ± 3.36 for the 1st session and 4.95 ± 3.33 for the 2nd session. On the right side, the total FRP magnitude was 3.66 (2.70, 8.90) for the 1st session and 4.14 (2.37, 7.72) for the 2nd session. Individual data points are presented in Figure 4.

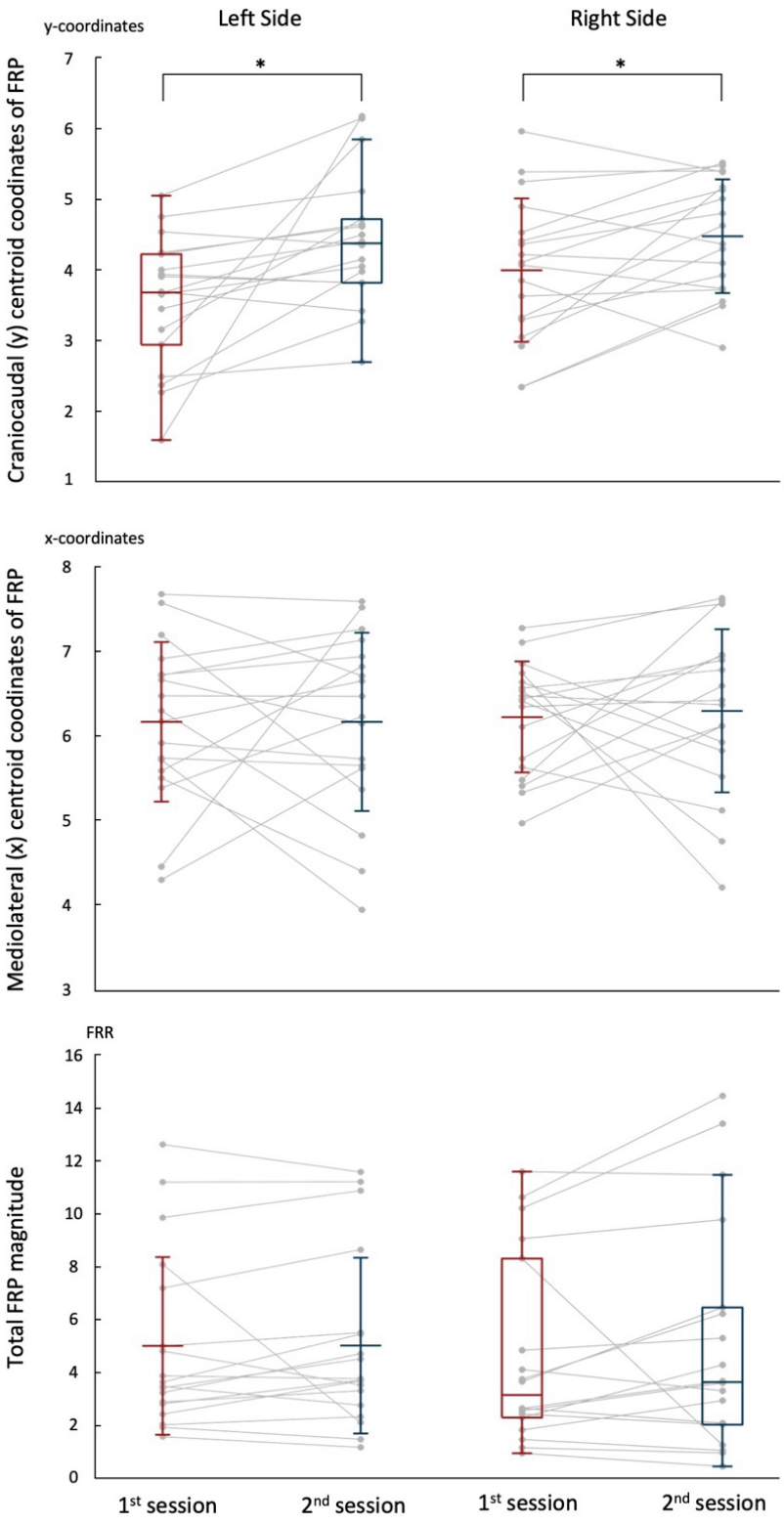

Fig. 4 Comparisons between the two sessions for the centroid coordinates location of FRP in both x- and y-axis, as well as the total FRR magnitude. Individual data points are connected by lines for both sessions. The

symbols '*' indicate statistical significance with p-values < 0.05. The labels '1st session (red)' and '2nd session (blue)' correspond to the sessions without and with DOMS, respectively. Mean and standard deviation are presented for normally distributed variables. Median and quartiles are presented using a box plot for non-normally distributed variables. FRP: Flexion relaxation phenomenon, FRR: flexion relaxation ratio

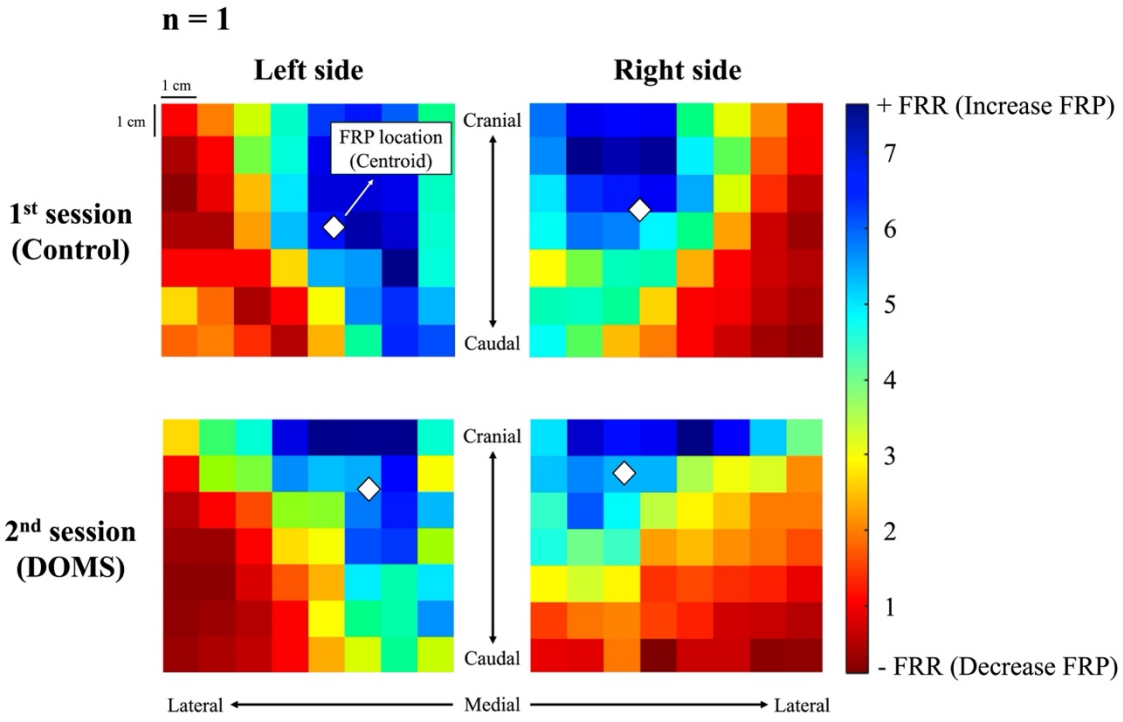

Fig. 5 Distribution of the flexion relaxation ratio (FRR), illustrating the flexion relaxation phenomenon (FRP) across the lumbar extensor muscles during the first and second sessions. Data shown are representative of a single participant. DOMS; delayed-onset muscle soreness

DISCUSSION

The main aim of this study was to investigate whether LBP, characterized by neuromuscular alterations induce by DOMS, impact the magnitude of the FRP regionally. Initially, we hypothesized that DOMS would lead to regional changes in FRP magnitude within lumbar extensor muscles. Our hypothesis was supported by the study findings, which revealed a cranial localization of the FRP within the lumbar extensor muscles in the presence of lumbar DOMS.

Impact of Delayed-Onset Muscle Soreness

The results showed that the lumbar DOMS protocol induced mild pain and moderate soreness, which is consistent with previous studies (Houle et al., 2020, Bishop et al., 2011, Ducas et al., 2024b). Additionally, the PPT results revealed an increase in pressure pain sensitivity with DOMS in both the upper and lower lumbar regions, consistent with prior studies (Abboud et al., 2019, Hanada et al., 2022). These findings are consistent with studies on chronic LBP, where increased sensitivity in the lumbar extensors is commonly observed (Farasyn and Meeusen, 2005, Farasyn and Lassat, 2016). This increase sensitivity suggests potential inflammatory processes or tissue damage (sarcomeres) over the whole lumbar region (Latremoliere and Woolf, 2009, Friden et al., 1983). Furthermore, a more pronounced decrease in PPT values was observed at L2 on the left side, indicating an increased sensitivity in the cranial L2 region on that side.

Regional Flexion Relaxation Phenomenon in the Lumbar Extensor Muscles

This study found regional FRP alteration within the lumbar extensor muscles. Specifically, the FRP was localized cranially within the lumbar extensor muscles with lumbar DOMS compared to a more caudal localization without DOMS. This shift in FRP location is likely due to alterations in the recruitment of the lumbar extensor muscles in response to pain induced by DOMS, serving as a protective mechanism. Previous research has shown that lumbar pain can affect lumbar muscle recruitment strategies (Ducas et al., 2024a). These FRP changes suggest that the cranial region of these muscles was less active during full-trunk flexion in the DOMS condition. The HDsEMG grid covered two primary lumbar extensor muscles: the superficial multifidus, and the erector spinae muscles (Gallina et al., 2024). In the erector spinae muscle, motor unit territories are organized into two main regions: one cranially from L1 to L3 and another caudally at L3 to L4, with some motor units spanning both areas, allowing for region-specific activation (Abboud et al., 2020). The cranial region of the grid predominantly record muscle activity from the upper motor unit territories of the erector spinae muscle (Gallina et al., 2024, Abboud et al., 2020). These motor unit territories likely innervate fibers that insert on the thoracic vertebrae and have little stabilizing function of the lower back (Macintosh and Bogduk, 1987, Bogduk, 2005). In contrast, the caudal region of the grid predominantly record muscle activity from both the lower motor unit territories of the erector spinae muscle and the superficial multifidus muscle (Gallina et al., 2024, Abboud et al., 2020). These muscles' fibers directly insert into the

lumbar vertebrae, thus contributing to spinal stabilization (Macintosh and Bogduk, 1987, Bogduk, 2005). Therefore, the cranial shift of FRP when acute lumbar pain is induced implies that when the trunk is fully flexed, the muscles contributing to spinal stabilization in the caudal region may be more activated as a guarding strategy to protect the spine from further injuries (Hodges and Tucker, 2011, Kaigle et al., 1998, Kaigle et al., 1997, Solomonow et al., 2003). Conversely, in the cranial region, where sensitivity is heightened compared to the caudal region, muscle activation may be reduced to alleviate tension in the painful area, allowing the caudal muscles to fully take on the protective role for the spine (Hodges and Tucker, 2011). Furthermore, the increased sensitivity on the left side only in the cranial region may explain the greater shift in the FRP observed on this side, as a greater response is anticipated in response to a bigger threat.

These findings are further supported by research on chronic LBP patients, in which researchers assessed the erector spinae muscles at L1-L2 and superficial multifidus muscles at L5 using bipolar EMG (Ippersiel et al., 2021). The results revealed that both muscles showed an altered FRP (decreased FRR) in chronic LBP patients compared to pain-free controls. However, the difference was more pronounced in the multifidus muscles compared to the erector spinae muscles, with double the decrease. Specifically, the patient group showed approximately a 43% decrease in multifidus FRR, while the decrease for the erector spinae muscle was approximately 20% (Ippersiel et al., 2021).

The lack of change in the mediolateral axis aligns with studies showing muscle activity redistribution among chronic LBP patients, where most changes occur in the craniocaudal axis (Martinez-Valdes et al., 2019, Sanderson et al., 2019b, Falla et al., 2014, Falla and Gallina, 2020). This suggests that, in response to LBP, the central nervous system is more inclined to redistribute activation within different motor unit territories of the erector spinae muscle or superficial multifidus at different spine level (craniocaudal) to exert segmental control over the spine, rather than gross changes across different muscles (erector spinae or multifidus) or portions of the erector spinae muscle (longissimus or iliocostalis) (mediolateral).

Overall, these results suggest that pain, whether acute (as observed in this study) or chronic (as observed in other studies (Gouteron et al., 2023, Ippersiel et al., 2021)), disrupts neuromuscular balance and alters load sharing between muscles, increasing reliance on caudal lumbar extensor muscles. While this increased reliance may be advantageous in acute pain condition to protect the spine from further injuries,

prolonged reliance on caudal lumbar extensor muscles in chronic pain condition may lead to increased regional muscle fatigue.

Overall Magnitude of the Flexion Relaxation Phenomenon in the Lumbar Extensor Muscles

The overall magnitude of the FRP in the lumbar extensor muscles remained unchanged in the presence of DOMS. This finding, coupled with the observed redistribution of FRP magnitude across different regions of the lumbar extensor muscles, suggests subtle changes in the FRP within the lumbar extensor muscles in response to acute LBP. These results suggest that during acute LBP, the central nervous system can redistribute neural drive to muscles that can efficiently protect the spine with limited increase in functional cost. However, in chronic LBP patients, a study found that patients showed a regional delayed onset of the FRP compared to pain-free controls as well as an overall delayed onset across all regions of the lumbar extensor muscles (Murillo et al., 2019). These findings imply that while regional FRP alterations persist in chronic pain, the redistribution of neural drive alone is not sufficient. Consequently, this leads to significant changes in muscle activation patterns across the whole lumbar region resulting in a greater functional cost.

Future Recommendations

The observed regional changes in the FRP magnitude within the lumbar extensor muscles in acute pain (as demonstrated in this study) and in the FRP onset in chronic pain (Murillo et al., 2019) may explain the heterogeneous results observed in the chronic LBP literature on FRP alterations. These results highlight the impact of electrodes placement on the lumbar region as a likely contributor to the heterogeneity in reported FRP results in chronic LBP patients (Gouteron et al., 2022, Colloca and Hinrichs, 2005). Moreover, these findings highlight the importance of evaluating various muscles and muscle regions when evaluating the FRP in the lumbar extensor muscles to gain a comprehensive understanding of lumbar extensor muscles adaptations to pain. Additionally, these findings also imply that should only one bipolar electrode be available, it should be positioned in the caudal region of the erector spinae to effectively differentiate between LBP and pain-free conditions.

Limitation

This study is not without limitations. A limitation to consider is the small sample size, which may increase the risk of statistical errors and limit the generalizability of the findings. However, the effects observed in the study were highly significant with moderate effect sizes, highlighting the robustness of the observed outcomes.

Another limitation of our study is the age range of the participants, which was predominantly young. This restricts the applicability of our results primarily to this age group and limits the generalizability to older populations.

Additionally, the absence of a control group should be acknowledged as a limitation, as having one would have strengthened our ability to differentiate the effects of the DOMS protocol from potential confounding factors, such as repeated testing effects or natural variability in participants' responses.

Furthermore, another limitation is the lack of measurements for hip extensor muscles, which could have partially explained the observed results in the lumbar region, given their contribution to trunk extension. Future research should include assessments of all back extensor muscles for a more comprehensive evaluation.

While the NRS has demonstrated good validity and reliability in pain assessment (Hawker et al., 2011, Breivik et al., 2008), it should be noted the NRS used to measure muscle soreness in this study lack psychometric validation. Although self-report scales are commonly used for various clinical indicators, including muscle soreness (Andersen et al., 2013, Abboud et al., 2019, Arvanitidis et al., 2024), the absence of validated scales for soreness assessment may introduce accuracy errors in results.

Finally, these findings should be complemented with data from other experimental pain models. While we attribute our findings to pain adaptation due to research linking pain with FRP alterations (Dubois et al., 2011, McGorry and Lin, 2012), it is important to recognize that other factors, such as inflammation and muscle damage resulting from DOMS, may also contribute to the observed results. Additionally, this LBP model differs from chronic pain conditions, where other factors, such as pain types (nociceptive, neuropathic, or nociplastic) (IASP, 2017, Nijs et al., 2024), histomorphological muscle changes (including fat infiltration, muscle atrophy, and an increased proportion of type 2 fibers) (Matheve et al., 2023), and psychological factors (Alschuler et al., 2009), can also influence neuromuscular responses in chronic pain.

Conclusion

In conclusion, this study investigated whether LBP, characterized by neuromuscular alterations induce by DOMS, impacts the magnitude of the FRP regionally. The results revealed a cranial shift of FRP within the lumbar extensor muscles when DOMS was present, possibly attributed to the increased recruitment of lumbar stabilizing muscles located caudally as a guarding mechanism to pain. These results highlight the importance of assessing the entire lumbar region when assessing the FRP.

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