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Article

Relationships Between Muscle Activation and Thoraco-Lumbar Kinematics in Direction-Specific Low Back Pain Subgroups During Everyday Tasks

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Abstract: Background/Objectives: The assessment of relationships between trunk muscle activity and thoraco-lumbar movements during sagittal bending has demonstrated that low back pain (LBP) subgroups (flexion pattern and active extension pattern motor control impairment) reveal distinct relationships that differentiate these subgroups from control groups. The study objective was to establish whether such relationships exist during various daily activities. Methods: Fifty participants with non-specific chronic low back pain (NSCLBP) (27 flexion pattern (FP), 23 active extension pattern (AEP)) and 28 healthy controls were recruited. Spinal kinematics were analysed using 3D motion analysis (Vicon™, Oxford, UK) and the muscle activity recorded via surface electromyography during a range of activities (box lift, box replace, reach up, step up, step down, stand-to-sit, and sit-to-stand). The mean sagittal angles for upper and lower thoracic and lumbar regions were correlated with normalised mean amplitude electromyography of bilateral transversus abdominis/internal oblique (IO), external oblique (EO), superficial lumbar multifidus (LM), and erector spinae (ES). Relationships were assessed via Pearson correlations (significance $p < 0.01$). Results: In the AEP group, increased spinal extension was associated with altered LM activity during box-replace, reach-up, step-up, and step-down tasks. In the FP group, increased lower lumbar spinal flexion was associated with reduced muscle activation, while increased lower thoracic flexion was associated with increased muscle activation. The control group elicited no significant associations. Correlations ranged between −0.812 and 0.754. Conclusions: Differential relationships between muscle activity and spinal kinematics exist in AEP, FP, and pain-free control groups, reinforcing previous observations that flexion or extension-related LBP involves distinct motor control strategies during different activities. These insights could inform targeted intervention approaches, such as movement-based interventions and wearable technologies, for these groups.

Keywords: functional movement; kinematics; trunk muscle; thoracic; lumbar; non-specific chronic low back pain; NSCLBP; muscle activity; functional activities

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1. Introduction

Chronic low back pain (LBP) is a significant global issue, affecting approximately 10% of the world's population. This has substantial global economic implications, including financial and societal costs and increased pressures on healthcare systems [1,2]. Despite this there have been few advances in understanding the biomechanical underpinning of LBP disorders. This may be attributable in part to the heterogeneity of LBP and the complex interactions between the biopsychosocial domains of the disorder. Additionally, the specificity of the measurement tools used to understand LBP mechanisms (especially biomechanically) has limitations.

There have, however, been some interesting recent observations regarding the biomechanics of LBP. A promising area for further work is the incorporation of multiple co-dependent spinal regions in a biomechanically focused investigation. While people with LBP exhibit a reduced lumbar spine range of motion [3], altered thoracic spine kinematics have been identified in several studies as a potential compensatory mechanism in this population [4–6]. Further, the identification of direction-specific subgroups of LBP patients has opened new avenues to explore the interactions between biomechanical variables in subgroups of the wider LBP population, for whom biomechanical factors may be a primary contributory factor to pain persistence.

Differential spinal kinematics have been consistently observed in non-specific chronic low back pain (NSCLBP) movement-based subgroups [7–10]. Hemming et al. [5] showed that there were significant differences in the regional spinal kinematics between NSCLBP subgroups (flexion pattern (FP) and active extension pattern (AEP) [7]) and healthy control groups during everyday functional tasks. Similarly, reduced movement of the upper lumbar region in FP individuals has been demonstrated during sagittal and coronal tasks [11]. There have also been numerous studies suggesting that muscle activation differs in these subgrouped populations [12,13], suggesting that potential differences in both kinematic and muscular behaviours in symptomatic populations and pain-free individuals warrant further exploration.

Despite this emerging evidence, there remains a critical gap in understanding how spinal kinematics and muscle activation interact during dynamic functional tasks in NSCLBP subgroups. While some studies have evaluated these domains independently, few have simultaneously examined their interplay, and existing work has focused on isolated or simplistic movements, such as forward bending [11]. The integration of muscle activity and kinematic analysis across a broader range of functional activities—particularly in regions such as the thoracic spine, which has been comparatively under-explored—is necessary to enhance our understanding of the biomechanical adaptations underlying chronic LBP.

Interactions between spine kinematics and muscle activity during dynamic spinal movements are crucial to inform specific rehabilitation strategies for people with LBP and may also inform preventative strategies, and physical conditioning approaches, to avoid LBP chronicity. Indeed, it has been suggested that rehabilitation in such populations would be enhanced with the use of more targeted movement-based interventions for subgroups [4,14], the effectiveness of which has been demonstrated by aspects of cognitive functional therapy approaches [15,16]. There is also potential value in further exploring biomechanical adaptations and interactions in the thoracic region, as regional insights may provide an understanding of the development and subsequent management of chronic LBP [3,5,11]. An initial investigation into the relationships between muscle activity and regional spinal kinematics demonstrated distinct variations between NSCLBP subgroups during a simple bending task in the sagittal plane [11]. As potential mechanical biomarkers, there is a clear need to establish if these associations are evident during additional tasks of daily living.

Therefore, the present study aimed to explore the relationship between trunk muscle activation and regional thoracic and lumbar kinematics across two clinically defined NSCLBP subgroups—AEP and FP—and healthy controls during a series of functionally relevant tasks. By addressing the current gap in the literature regarding the dynamic interaction of spinal motion and neuromuscular control, this study seeks to inform more nuanced and effective therapeutic strategies for individuals with NSCLBP.

2. Materials and Methods

The study received ethical approval from The Research Ethics Committee 3 Wales (10/MRE09/28). Data were collected at the Research Centre for Clinical Kinesiology, School of Healthcare Sciences, Cardiff University. Fifty patients (aged 18–65 years) with NSCLBP (27 FP, 23 AEP) were recruited via Cardiff and Vale University Health Board (Cardiff, UK) routine physiotherapy waiting lists. Twenty-eight healthy participants (aged 18–65 years) from the local community, who responded to the study adverts, were recruited as a control group. This group included Cardiff University staff and students. Calculation of sample size is reported elsewhere [5].

2.1. Inclusion and Exclusion Criteria

Exclusion criteria for all participants were: vestibular, visual or neurological dysfunction affecting balance, pregnancy or breastfeeding, or history of spinal surgery, fracture or malignancy. NSCLBP participants were additionally excluded if they had current radiating symptoms, and/or neurological deficit, below the level of the buttock crease [7] or displayed any red flags [17–19]. Healthy participants were additionally excluded if they had a history of LBP in the previous 2 years or had had any previous LBP with radiating symptoms below the level of the buttock crease. For NSCLBP participants the inclusion criteria was: current LBP (>12 weeks) and pain in the lumbar region which did not radiate below the level of the buttock crease, a clear mechanical basis of the disorder aligned with specific aggravating and easing postures and movements as described by O'Sullivan [7] and a clinical diagnosis of specific motor control impairment—either AEP or FP [20]. Classification assessment procedures, as confirmed by two clinicians, is detailed elsewhere [5].

2.2. Data Collection

Gender, age, weight, and height were recorded for all participants. The patient-reported visual analogue scale (VAS) for pain [21] was recorded for the NSCLBP subgroups. Full details of the motion analysis and electromyography protocol are reported elsewhere [5].

2.3. Motion Analysis

The sagittal angles of the 4 sub-divided spinal regions (i.e., upper thoracic (UTx), lower thoracic (LTx), upper lumbar (ULx) and lower lumbar (LLx) were measured using an 8-camera Vicon 3D motion analysis system, using a sampling frequency of 100 Hz. Retro-reflective spinal markers were attached at the levels of C7, T2, T4, T6, T8, T10, T12, L2, and L4, and over the anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS) and iliac crest bilaterally. In addition, markers were also placed at the manubrium sterni (superior border); acromioclavicular joints; ulna styloid processes; a point 10 cm lateral of T12 (bilaterally), the lateral knee joint lines; and on the lateral malleoli. Within-subject consistency and variability, using this novel spinal marker set in healthy subjects, has shown substantial to excellent reliability (ICC 0.746 to 0.977), with errors not exceeding 5.8° [22].

2.4. Electromyography

An 8 Channel Bortec EMG system was synchronised with the Vicon® Nexus, to collect surface electromyography (sEMG) data. Electrode placements, as detailed elsewhere [13], were placed bilaterally over longissimus thoracis (ES), superficial lumbar multifidus (LM), external oblique (EO), and transversus abdominis/internal oblique (IO). System parameters were set as follows, Input impedance of 10GOhm, differential pre-amplifiers with fixed gain of 500, and common rejection ratio was 115 dB. A sampling frequency of 10 Hz to 1000 Hz was used. sEMG data was normalised to sub-maximal voluntary contractions (SMVC) as described previously [13]. Three SMVCs were recorded over 3 s with a 30 s rest between trials.

2.5. Task Protocols

Full details of the task procedures are available in Appendix A. The following functional tasks were evaluated:

- Sit-to-stand-to-sit: This was performed from a usual unsupported sitting position on a plinth with feet on the floor.
- Box lift and replace: The subject was instructed to move a box from left to right, on a plinth set at waist height in front of them, with the box starting and finishing facing the same direction.
- Reaching: The subject stood directly in front of the custom-made shelf (height of the ulna styloid process when the shoulder was fully elevated). The subject placed a jar onto the shelf using their right hand.
- Stepping up and down: Subjects stepped onto a 6-inch Reebok® step (Adidas International Trading, Amsterdam, The Netherlands), then stepped down (self-selected leading leg).

Tasks were repeated until three good quality trials were obtained (where all markers and sEMG traces were clearly recorded and viewed within the Vicon System). Tasks were selected to reflect a cross-section of usual activities of daily living whilst also being representative of activities commonly reported as pain provocative. Protocols were carefully considered to allow for natural functional movement, reflective of habitual behaviour (Appendix A).

2.6. Data Processing and Analysis

Full processing and analysis details have been published previously [5,11,13]. Vicon Nexus (Nexus 1.8.2 Vicon Motion Systems, Oxford, UK) was used to perform all data processing.

Kinematics: Midpoint sagittal spinal angles (UTx, LTx, ULx, LLx spinal regions) [5] were calculated as the sum of the angular changes between all markers within each region (e.g., UTx: C7–T6, LTx: T6–T12, ULx: T12–L3, LLx: L3–S2).

$$Midpoint\ sagittal\ spinal\ angle = (Maximum\ flexion\ sagittal\ spinal\ angle + Maximum\ extension\ sagittal\ spinal\ angle)/2$$

Positive angles are indicative of relative flexion; negative angles are indicative of relative extension.

Surface Electromyography (sEMG): Mean amplitude (%SMVC) of LM, ES, IO and EO muscles from the duration of each task. Raw signals were band pass filtered using zero phase lag and 20 Hz cut-off with full wave rectification. The signal was amplified by a gain of 2000. A 20 Hz high pass filter was applied to suppress movement artefacts.

$$Normalised\ amplitude\ sEMG\ (\%) = (processed\ sEMG/SMVC) \times 100$$

SPSS (IBM SPSS Statistics 26) was used to conduct statistical analysis according to the normal distribution and homogeneity of variance of the data. Baseline descriptive statistics were calculated [23–25]. Pearson correlations established relationships between kinematics (mean regional sagittal angle: UTx, LTx, ULx, LLx) and sEMG (normalised, mean amplitude, % sub-maximal voluntary contraction) of trunk muscles (LM, ES, IO, EO) between groups. Alpha level was 0.01. Correlation coefficients were interpreted as: negligible (0.0–0.1), weak (0.10–0.39), moderate (0.40–0.69), strong (0.70–0.89), very strong (0.9–1.0) [25]. Positive r-values indicate associations between increased flexion and increased muscle activity. Negative r-values indicate inverse associations between muscle activity and spinal kinematics.

3. Results

3.1. Participant Characteristics

Data were collected from 23 AEP, 27 FP and 28 healthy individuals. Participant characteristics are outlined in Table 1. Weight was significantly greater in the FP group compared to the AEP group, and height was significantly greater in the FP group (and compared to both AEP and the control group). Significant differences in gender between groups (males: AEP 17.1%, FP 77.8%) were noted, although these reflect observed clinical subgroup presentations [9,10]. Both FP and AEP groups reported similar locations of LBP (primarily in the lumbar region). No significant between-group differences in VAS scores for pain were noted.

Table 1. Participant baseline characteristics across groups. (*Note: Values are mean (SD) unless otherwise stated*).

Variable		AEP (n = 23)	FP (n = 27)	Healthy (n = 28)	Significance
Gender	Male Female	4 (17.4%) 19 (82.6%)	21 (77.8%) 6 (22.2%)	12 (42.9%) 16 (57.1%)	***p* < 0.001 ***
Age (years)		43.7 (11.2)	41.0 (10.0)	38.5 (11.2)	*p* = 0.238
Mass (kg)		68.9 (18.0)	82.5 (14.6)	72.9 (15.2)	***p* = 0.005 *** (AEP vs. FP)
Height (cm)		164.9 (10.2)	175.9 (8.7)	169.4 (7.3)	***p* < 0.001 *** (AEP vs. FP/FP vs. H)
BMI (kg/m^2)		20.8 (4.9)	23.4 (3.5)	21.5 (4.1)	*p* = 0.127
Site of back pain N (%)	Right Left Central	8 (34.8%) 2 (8.7%) 13 (56.4%)	5 (18.5%) 3 (11.1%) 19 (70.4%)	-	-
Time since pain onset N (%)	3–6 months 6–12 months >1 year	2 (8.7%) 7 (30.4%) 14 (60.9%)	8 (29.6%) 2 (7.4%) 17 (63.0%)	- -	- -
Pain score (VAS)		4.6 (1.4)	4.5 (1.4)	-	*p* = 0.986

Key: FP = flexion pattern motor control impairment, AEP = active extension pattern motor control impairment, H = healthy, BMI = body mass index (mass (kg)/height (m)^2), kg = kilogrammes, cm = centimetres, * significant difference ($p < 0.05$), VAS = visual analogue scale, SD = standard deviation, N = number of participants.

3.2. Relationships Between Spinal Kinematics and Muscle Activity Across Functional Tasks

Example raw data are detailed in Figure 1 to demonstrate marker positioning in the global co-ordinate system, regional spinal kinematics and raw EMG traces for each muscle (bilaterally) for one participant in each group (FP, AEP, control) during a step up and step down task. Full results tables are detailed in Appendix B (Tables A2–A4). Correlations were moderate to strong, with the strongest negative correlation being r = −0.812 and the strongest positive correlation being r = 0.754. A summary of the correlations between spinal kinematic data with muscle activity are detailed in Table 2.

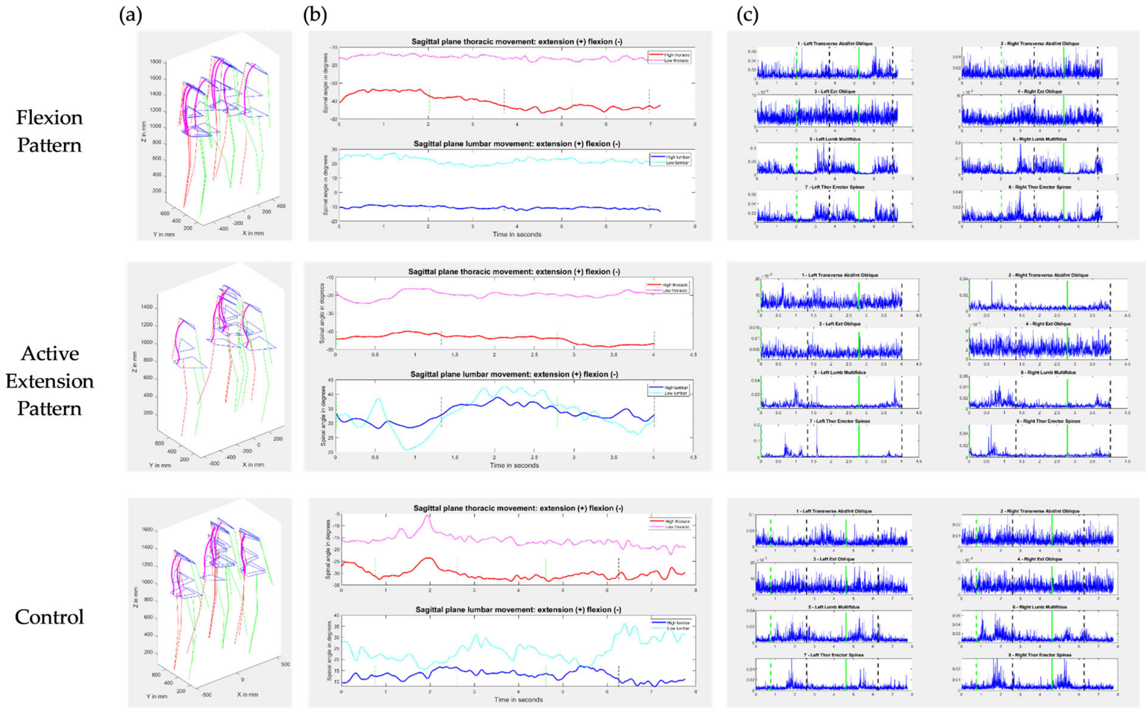

Figure 1. Example raw data during a step up and down task showing (**a**) kinematic marker position in global co-ordinate system, (**b**) regional spinal kinematics throughout the task and (**c**) raw EMG traces for each muscle (bilaterally) for one participant in each group (FP, AEP, control). Key: high thoracic = upper thoracic (UTx), low thoracic = lower thoracic (LTx), high lumbar = upper lumbar (ULx), low lumbar = lower lumbar (LLx), mm = millimetres, Transverse Abd/Int Oblique = transversus abdominis/internal oblique (IO), Ext Oblique = external oblique (EO), Lumb Multifidus = lumbar multifidus (LM), Thor Erector Spinae = thoracic erector spinae (ES). *NB: dashed vertical lines indicate the defined start and end points of each task phase, as outlined in Appendix A (Table A1). A green line indicates the start of the task phase. A black line indicates the end of the task phase.*

Table 2. Summary of all significant relationships ($p < 0.01$) observed across the three groups (AEP, FP and healthy control) during a series of functional tasks.

	Spinal Region	Muscle	AEP	FP	Control
Box Lift	LTx	ES		**↑flex = ↑ES activity**	
		LM		**↑flex = ↑LM activity**	
	LLx	ES		**↑flex = ↓ES activity**	
Box Replace	LTx	ES		**↑flex = ↑ES activity**	
		LM		**↑flex = ↑LM activity**	
	LLx	EO		**↑flex = ↓EO activity**	
		ES		**↑flex = ↓ES activity**	
		LM	**↑ext = ↓LM activity**		
Reach Up	UTx	ES		**↑flex = ↑ES activity**	
	LTx	EO		**↑flex = ↑EO activity**	
		ES		**↑flex = ↑ES activity**	
		LM		**↑flex = ↑LM activity**	
	ULx	LM	**↑ext = ↑LM activity**		
	LLx	ES		**↑flex = ↓ES activity**	

Table 2. *Cont.*

	Spinal Region	Muscle	AEP	FP	Control
Step Up	UTx	EO		**↑flex = ↑EO activity**	
	LTx	EO		**↑flex = ↑EO activity**	
		ES		**↑flex = ↑ES activity**	
		LM		**↑flex = ↑LM activity**	
	ULx	LM	**↑ext = ↑LM activity**		
	LLx	EO		**↑flex = ↓EO activity**	
		IO		**↑flex = ↓IO activity**	
		ES		**↑flex = ↓ES activity**	
		LM		**↑flex = ↓LM activity**	
Step Down	LTx	ES		**↑flex = ↑ES activity**	
		LM		**↑flex = ↑LM activity**	
	ULx	LM	**↑ext = ↑LM activity**		
	LLx	EO		**↑flex = ↓EO activity**	
		IO		**↑flex = ↓IO activity**	
		ES		**↑flex = ↓ES activity**	
Sit-to-Stand	LLx	ES		**↑flex = ↓ES activity**	

Key: EO = external obliques, IO = transversus abdominis/internal obliques, ES = erector spinae (longissimus thoracis), LM = superficial lumbar multifidus, AEP = active extension pattern, FP = flexion pattern, ext = extension, flex = flexion, ↑ = increased, ↓ = decreased, UTx = upper thoracic spine, LTx = lower thoracic spine, ULx = upper lumbar spine, LLx = lower lumbar spine. *NB: No significant differences were observed during stand-to-sit in any group.*

3.2.1. AEP

In the AEP group, associations between increased extension and altered LM activity were evident in the lumbar (upper or lower regions) during the box-replace, reach-up, step-up and step-down tasks. No associations between spinal kinematics and muscle activity were noted in the box-lift, stand-to-sit or sit-to-stand tasks. No significant associations were observed between spinal kinematics and IO, EO or ES muscle activity.

3.2.2. FP

In the FP group, many associations between spinal kinematics and muscle activity were observed. Overall increased flexion in the LLx region was associated with a reduction in muscle activity across the abdominal (EO, IO) and extensor musculature (ES, LM) across the tasks. Conversely increased flexion in the LTx region was associated with greater muscle activity of the EO, ES and LM musculature across the box-lift, box-replace, step-up, step-down and reach-up tasks. During the sit-to-stand-to-sit task, the only significant interaction observed was an association between increased LLx flexion and a reduction in ES activity.

3.2.3. Control

In the control group, no associations between spinal kinematics and muscle activity were observed in any task.

Table 2 summarises where significant relationships were observed and the direction of these relationships for each group, spinal region and muscle. The FP group demonstrated the greatest number of relationships between kinematics and muscle activity, followed by the AEP group, with no significant relationships observed in the healthy control group. The scatter plots detailed in Figures 2 and 3 provide an example of the opposing directions of the significant relationships observed between different spinal regions (LLx and LTx) and ES during the box-replace task.

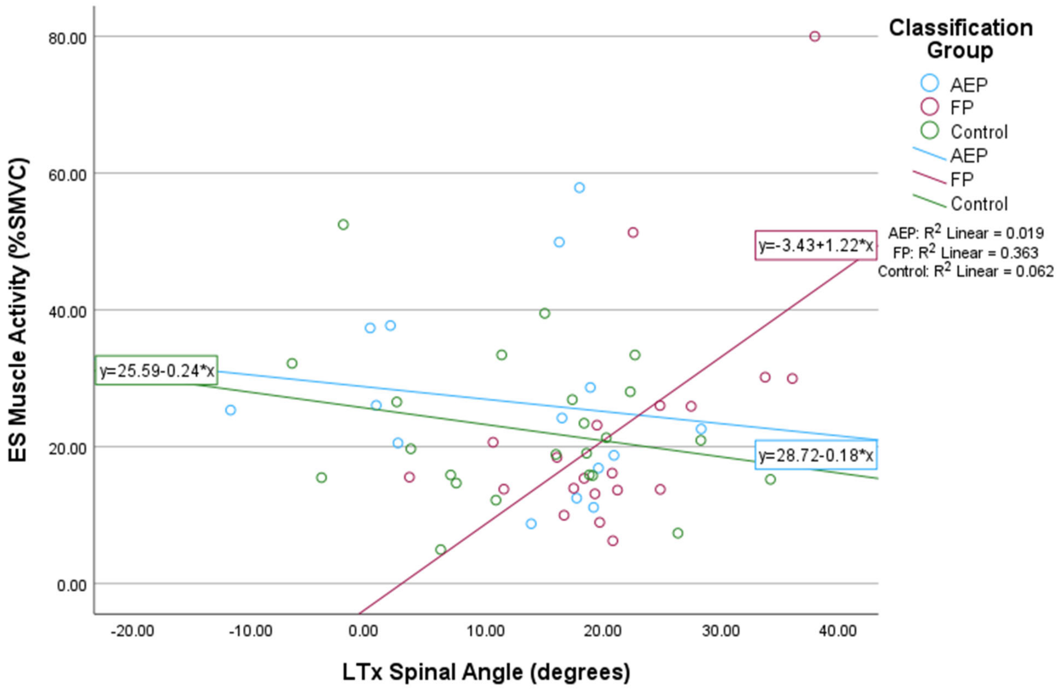

Figure 2. A scatterplot, with regression lines, to show relationships between mean amplitude EMG (%SMVC) for erector spinae and lower thoracic spinal angles during the box-replace task between groups (*NB: significant positive correlation observed in the FP group only*). *Key: ES = erector spine, %SMVC = Percentage of sub-maximal voluntary contraction, LTx = lower thoracic spine, AEP = active extension Pattern, FP = flexion pattern.*

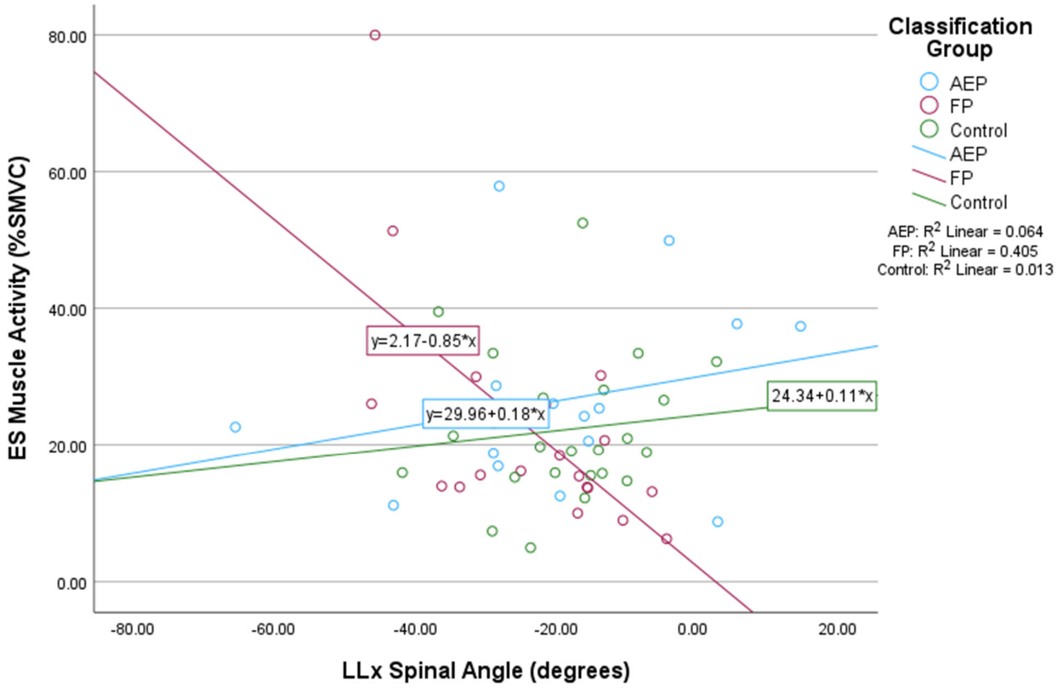

Figure 3. A scatterplot, with regression lines, to show relationships between mean amplitude EMG (%SMVC) for erector spinae and lower thoracic spinal angles during the box-replace task between groups. (*NB: significant negative correlation observed in the FP group only*). *Key: ES = erector spine, %SMVC = Percentage of sub-maximal voluntary contraction, LTx = lower lumbar spine, AEP = active extension pattern, FP = flexion pattern.*

4. Discussion

The novel contribution of this study is the identification of distinct patterns of coordination between regional spinal kinematics and muscle activity to perform specific tasks in NSCLBP subgroups which is not observed in pain-free controls.

Participants in the AEP subgroup exhibited a relative increase in upper lumbar (ULx) extension during tasks such as reach up, step up, and step down. This postural strategy in the ULx was consistently associated with heightened activity of the lumbar multifidus (LM) muscle. These kinematic and muscular patterns align with previously reported behaviours observed during sagittal plane-bending tasks (e.g., pen pick up and return) [11]. Similarly, previous work evaluating kinematic data alone within such subgroups established significant differences between AEP and FP groups with AEP demonstrating significantly more extension in the ULx during reach-up, step-up-and-step-down (and pen-pick-up, and pen-replace) tasks [5]. While causality cannot be inferred, the relationships observed may reflect either a compensatory response to maintain spinal stability or an adaptation to limit excessive movement in the lower lumbar spine.

In contrast, participants in the FP subgroup demonstrated a relative increase in flexion of the lower thoracic (LTx) region during tasks including box lift, box replace, step up, and step down. This increased flexion was also associated with elevated LM activity, suggesting a subgroup-specific neuromechanical strategy. These behaviours may represent adaptations to reduce loading or motion in the lower lumbar region, potentially as a protective mechanism against pain provocation. These findings show the presence of subgroup-specific kinematic-muscular interactions in NSCLBP, supporting the need for targeted rehabilitation strategies based on individual movement profiles.

These strategies have been consistently observed previously [5,9,11–13]; however, the current study further corroborates these findings in activities beyond the sagittal plane, highlighting the need for more targeted active physical interventions. As mechanical biomarkers, these results could be valuable in guiding treatment for these subgroups.

Interestingly, no associations between regional kinematics and trunk muscle activity were noted in the pain-free controls suggesting that the presence of pain, or fear of pain provocation, is an influencing factor in the findings observed. CLBP individuals have been observed to exhibit differences in kinematic movement variability during the performance of repetitive functional tasks; therefore, it may be hypothesised that the absence of pain-driven motor adaptations may have led to greater movement variability in the control group [26]. Further research is required to test such hypotheses.

No statistically significant differences between symptomatic and asymptomatic groups in the LLx region in terms of either flexion or extension were observed. It could be hypothesised that, in the presence of pain, the lower lumbar region is stabilised to avoid pain provocation, potentially utilizing other spinal regions to compensate. It is pertinent to consider whether current generic rehabilitation strategies continue to re-enforce mal-adaptive patterns. The recent successes of strategies such as cognitive functional therapy [15], are perhaps demonstrating increased efficacy due to encouraging movement in the lower lumbar regions which may be a focus for future research. Focusing on the areas of restriction, or in this case maladaptive movement, may therefore be of importance for optimizing patient outcomes [4].

Further, during the sit-to-stand task, the only significant association observed was between increased flexion and reduced ES activity in the LLx in the FP group. The lack of significant associations during this activity may be attributable to the lower postural demands of this task with, potentially, end-range spinal flexion or extension activities being avoided.

Limitations and Future Work

It could be argued that due to the number of analyses and *p*-values reported in this study, there is the potential for type 1 errors. However, the repeatability of the findings throughout the different tasks suggests that the findings are less likely to be because of a type I error. No associations were observed between kinematics and muscle activity within the control group, suggesting that it is the LBP itself, and potential associated maladaptive behaviours, that led to the observed findings. *p*-values have been set at 0.01 to tighten the associations. However, the authors acknowledge that no corrections for multiple comparisons were conducted which may weaken confidence in the reported associations.

The unequal gender distribution (FP: 77.8% male, AEP: 82.6% female) between the subgroups may be considered a confounding variable; however, proportionally, gender is reflective of typical clinical presentation patterns reported in previous research [9,10]. Since the analysis focused on correlational patterns within each subgroup, and not on mean differences across groups, together with the modest sample size, any additional covariate or sensitivity analyses were not considered appropriate or statistically meaningful.

Surface EMG as a tool to evaluate trunk musculature is limited in its ability to isolate deep musculature such as the multifidus and transversus abdominis. The use of sEMG also poses considerable limitations for interpreting the physiological meaning of EMG activity, especially due to the potential for cross-talk between muscles (e.g., influence of longissimus when recording LM activity). To mitigate against this, rigorous standardisation processes were adhered to, to standardise electrode placement and raw EMG signal processing. Future studies could consider the use of fine wire or high-density EMG to reduce such issues. Submaximal contractions were utilised to normalise EMG data due to potential kinesiophobia in NSCLBP. This is common practice when evaluating these subgroups [27,28]; however, alternative approaches to normalising EMG or comparing raw EMG signals could be considered in future work. Future clinical trials may explore the effect of focusing on functional rehabilitation interventions for each of the clinical subgroups outlined in this study. The potentially maladaptive strategies utilised by AEP and FP may be corrected with specific focus on the restoration of movement in the LLx region.

5. Conclusions

Distinct motor control patterns exist between these two NSCLBP subgroups (FP and AEP) when performing multiple functional tasks. However, it is difficult to establish whether these neuromuscular patterns contribute to pain persistence or arise as compensatory mechanisms in response to pain. The findings further re-enforce previous observations in these NSCLBP subgroups during bending tasks [11] (see Table 3), re-enforcing both the existence of clinical subgroups and previously observed movement patterns in these subgroups which may be of clinical interest. Subgroups may therefore be a target for future therapeutic interventions (such as movement-based interventions and wearable technologies) to improve the effectiveness of NSCLBP management and there is a need for targeted intervention that considers direction-specific pain provocation in NSCLBP.

Table 3. Highlights' summary: Common relationships observed in different NSCLBP subgroups.

Tasks	Subgroup	Region	Relationship
Reach up, step up, step down. Note: also *Pick up pen*, *and pick up pen* return from Hemming et al., (2024) [11]	AEP	ULx	**↑ext = ↑LM activity**
Box lift, box replace, reach up, step up, step down. Note: also *pick up pen*, *and pick up pen* return from Hemming et al., (2024) [11]	FP	LTx	**↑flex = ↑LM activity**
Box lift, box replace, reach up, step up, step down, sit to stand. Note: also *pick up pen*, *and pick up pen* return from Hemming et al., (2024) [11]	FP	LLx	**↑flex = ↓ES activity**

Key: ES = erector spinae (longissimus thoracis), LM = superficial lumbar multifidus, AEP = active extension pattern, FP = flexion pattern, ext = extension, flex = flexion, ↑ = increased, ↓ = decreased, LTx = lower thoracic spine, ULx = upper lumbar spine, LLx = lower lumbar spine.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee 3 Wales (10/MRE09/28) within the Arthritis Research UK Biomechanics and Bioengineering Centre, Cardiff University, UK.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement: The datasets generated and/or analysed during the current study are not publicly available due to ethics restrictions but are available from the corresponding author on reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

AEP	Active extension pattern
ASIS	Anterior superior iliac spine

BMI	Body mass index
EMG	Electromyography
EO	External oblique
ES	Erector spinae (longissimus thoracis)
FP	Flexion pattern
IO	Transversus abdominis/internal oblique
LBP	Low back pain
LM	Lumbar multifidus
LLx	Lower lumbar
LTx	Lower thoracic
MVC	Maximal voluntary contraction
NISCHR	National Institute for Social Care and Health Research
NSCLBP	Non-specific chronic low back pain
PSIS	Posterior superior iliac spine
ROM	Range of movement
SD	Standard deviation
sEMG	Surface electromyography
SMVC	Sub-maximal voluntary contraction
ULx	Upper lumbar
UTx	Upper thoracic
VAS	Visual analogue scale

Appendix A

Appendix A.1. Functional Task Protocols

Appendix A.1.1. Box

Task Objective: To lift and move a weighted box (2.5 kg) from left to right on a plinth.

Set-up/Standardisation: To achieve a standardised box position, tape was positioned at a set distance from the midline of the plinth (distance = 70% of the total upper limb length as measured (in cm) from the acromion process (apex) to the distal middle phalanx bilaterally). The plinth height was set to align with the participants' greater trochanter (in standing). A box (weighing 2.5 kg) was placed over the marked tape to the left side of the plinth.

Posture Standards: Each participant was instructed to adopt a comfortable standing position and ensure their feet remained stationary for the duration of the task. On completion of the task, the subject returned to their original, habitual standing position.

Movement Rhythm: Participants were instructed to stand facing the plinth and move the box from left to right (to a position over the marked tape to the right of the plinth). Participants were instructed to start and finish the motion with the box facing the same direction. No specific instructions on the lifting approach or technique were provided.

Number of Repetitions: 3

Appendix A.1.2. Reaching

Task Objective: Place a jar onto an elevated shelf.

Set-up/Standardisation: A custom-designed shelf was set to the height of the ulna styloid process (right upper limb) with the shoulder fully elevated (full flexion).

Posture Standards: Habitual standing. Feet remained stationary throughout the duration of the task with the participant instructed to always maintain heel contact with the floor. The participant kept hold of the jar throughout the task.

Movement Rhythm: Participants were instructed to stand directly facing the shelf, with the shelf base aligned with the midline of their trunk (frontal plane). Participants placed a jar onto the shelf using their right hand, allowed the jar to rest on the shelf for 2 s, and then returned the jar back to the original position.

Number of Repetitions: 3

Appendix A.1.3. Sit-to-Stand-to-Sit

Task Objective: Move from a sitting to a standing position and return to sitting from the edge of a plinth.

Set-up/Standardisation: The plinth was set to a height where the participants' hips and knees rested comfortably at 90 degrees. Knee and hip angles were determined using a goniometer (Lafayette Instrument Co. Ltd., Lafayette, IN, USA).

Posture standards: Habitual sitting starting position. Participants sat with their thighs well supported on the plinth.

Movement Rhythm: The participant was instructed to adopt their usual (unsupported) sitting position on the plinth, stand (waiting for 2 s), then return to their original sitting position.

Number of Repetitions: 3

Appendix A.1.4. Stepping Up and Down

Task Objective: Step up onto a step and then step down off the step.

Set-up/Standardisation: Participants stood facing a 6-inch Reebok® step (Adidas International Trading, Amsterdam, The Netherlands).

Posture Standards: Habitual standing starting position. The participant was required to ensure that their self-selected leading leg remained consistent throughout each trial.

Movement Rhythm: They were instructed to step up onto the step (self-selecting their preferred leading leg), wait in a double-stance position on the step (2 s), and then step down (self-selecting their preferred leading leg). To facilitate MATLAB data processing procedures, participants were required to wait in their usual standing position (following step down) for 2 s to assist with defining the end of the task.

Number of Repetitions: 3

Appendix A.2. Data Processing of Functional Tasks

Four tasks were collected during data collection (box lift rotate and replace, reaching, sit-to-stand-to-sit and step up and down). These were sub-divided into seven separate tasks within the MATLAB programme as detailed in Table A1.

Table A1. Table to show subdivision of the original data collection task into functional tasks used for analysis.

Original Task	Functional Task for Analysis
Box lift, rotate and replace *	Box lift
	Box replace
Reaching	Reach up
	Reach down **
Sit-to-stand-to-sit	Sit-to-stand
	Stand-to-sit
Step up and down	Step up
	Step down

* Box-lift, rotate and replace task—only the 'lifting' and 'replacing' components of the task were analysed.
** Reach-down task—data not included in analysis

Appendix B

Table A2. Overview of the Mean Regional Spinal Kinematics (Degrees), Muscle Activity (%SMVC) and Pearson Correlations (Including Significant Results) for the AEP Group.

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	p
Box Lift	UTx	23.3 (9.9)	EO	56.6 (26.1)	−0.176	0.471
			IO	64.0 (32.3)	−0.325	0.14
			ES	26.5 (12.5)	0.022	0.937
			LM	27.1 (15.0)	0.212	0.399
	LTx	14.1 (9.8)	EO	56.6 (26.1)	−0.257	0.289
			IO	64.0 (32.3)	0.129	0.568
			ES	26.5 (12.5)	−0.143	0.611
			LM	27.1 (15.0)	−0.124	0.623
	ULx	−11.6 (9.4)	EO	56.6 (26.1)	−0.563	0.012
			IO	64.0 (32.3)	−0.022	0.922
			ES	26.5 (12.5)	−0.218	0.436
			LM	27.1 (15.0)	−0.379	0.12
	LLx	−14.8 (16.7)	EO	56.6 (26.1)	−0.08	0.745
			IO	64.0 (32.3)	−0.217	0.333
			ES	26.5 (12.5)	0.17	0.544
			LM	27.1 (15.0)	0.415	0.086
Box Replace	UTx	26.8 (8.5)	EO	54.8 (25.9)	−0.193	0.427
			IO	63.1 (32.6)	−0.155	0.49
			ES	26.6 (14.0)	0.03	0.914
			LM	27.3 (15.5)	0.214	0.393
	LTx	13.0 (10.0)	EO	54.8 (25.9)	−0.261	0.28
			IO	63.1 (32.6)	0.193	0.39
			ES	26.6 (14.0)	−0.138	0.625
			LM	27.3 (15.5)	−0.125	0.622
	ULx	−13.8 (10.9)	EO	54.8 (25.9)	−0.502	0.029
			IO	63.1 (32.6)	0.085	0.707
			ES	26.6 (14.0)	−0.307	0.266
			LM	27.3 (15.5)	−0.524	0.026
	LLx	−20.5 (17.3)	EO	54.8 (25.9)	−0.095	0.698
			IO	63.1 (32.6)	−0.31	0.161
			ES	26.6 (14.0)	0.253	0.363
			LM	27.3 (15.5)	**0.599**	**0.009 ***
Reach Up	UTx	27.2 (8.2)	EO	49.9 (25.3)	−0.159	0.515
			IO	59.9 (37.0)	−0.202	0.366
			ES	25.7 (14.4)	0.076	0.779
			LM	22.3 (16.7)	0.345	0.148
	LTx	4.4 (13.1)	EO	49.9 (25.3)	−0.298	0.215
			IO	59.9 (37.0)	0.237	0.288
			ES	25.7 (14.4)	−0.002	0.994
			LM	22.3 (16.7)	0.032	0.897
	ULx	−19.2 (12.0)	EO	49.9 (25.3)	−0.205	0.4
			IO	59.9 (37.0)	0.15	0.505
			ES	25.7 (14.4)	−0.315	0.235
			LM	22.3 (16.7)	**−0.684**	**0.001 ***

Table A2. *Cont.*

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	*p*
Reach Up	LLx	−23.3 (19.8)	EO	49.9 (25.3)	−0.127	0.603
			IO	59.9 (37.0)	−0.31	0.16
			ES	25.7 (14.4)	0.307	0.248
			LM	22.3 (16.7)	0.474	0.04
Step Up	UTx	33.1 (7.5)	EO	56.7 (27.5)	−0.087	0.722
			IO	67.2 (39.5)	−0.2	0.385
			ES	22.6 (8.9)	−0.036	0.903
			LM	26.6 (23.3)	0.368	0.121
	LTx	10.0 (12.5)	EO	56.7 (27.5)	0.01	0.968
			IO	67.2 (39.5)	0.312	0.168
			ES	22.6 (8.9)	−0.472	0.089
			LM	26.6 (23.3)	0.147	0.548
	ULx	−17.0 (11.2)	EO	56.7 (27.5)	−0.038	0.879
			IO	67.2 (39.5)	0.198	0.389
			ES	22.6 (8.9)	−0.436	0.119
			LM	26.6 (23.3)	**−0.613**	**0.005** *
	LLx	−19.0 (19.6)	EO	56.7 (27.5)	−0.186	0.446
			IO	67.2 (39.5)	−0.378	0.091
			ES	22.6 (8.9)	0.421	0.134
			LM	26.6 (23.3)	0.232	0.34
Step Down	UTx	34.5 (8.2)	EO	56.9 (29.6)	−0.186	0.445
			IO	68.1 (37.9)	−0.317	0.161
			ES	21.9 (9.5)	−0.095	0.747
			LM	26.0 (21.6)	0.465	0.045
	LTx	9.5 (13.2)	EO	56.9 (29.6)	−0.099	0.688
			IO	68.1 (37.9)	0.292	0.199
			ES	21.9 (9.5)	−0.33	0.249
			LM	26.0 (21.6)	0.119	0.628
	ULx	−18.0 (11.8)	EO	56.9 (29.6)	−0.101	0.681
			IO	68.1 (37.9)	0.147	0.524
			ES	21.9 (9.5)	−0.446	0.11
			LM	26.0 (21.6)	**−0.695**	**0.001** *
	LLx	−21.1 (20.8)	EO	56.9 (29.6)	−0.01	0.968
			IO	68.1 (37.9)	−0.317	0.162
			ES	21.9 (9.5)	0.428	0.126
			LM	26.0 (21.6)	0.278	0.249
Stand-to-Sit	UTx	22.1 (8.8)	EO	54.3 (28.8)	0.192	0.46
			IO	56.8 (40.0)	−0.213	0.397
			ES	40.9 (24.4)	0.233	0.444
			LM	39.5 (37.3)	0.022	0.927
	LTx	8.8 (11.2)	EO	54.3 (28.8)	−0.121	0.643
			IO	56.8 (40.0)	0.399	0.101
			ES	40.9 (24.4)	−0.376	0.205
			LM	39.5 (37.3)	0.283	0.241
	ULx	−11.9 (9.7)	EO	54.3 (28.8)	−0.024	0.927
			IO	56.8 (40.0)	0.5	0.035
			ES	40.9 (24.4)	−0.21	0.491
			LM	39.5 (37.3)	−0.32	0.182

Table A2. *Cont.*

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	Correlations *p*
Stand-to-Sit	LLx	−11.6 (15.0)	EO	54.3 (28.8)	−0.013	0.959
			IO	56.8 (40.0)	−0.444	0.065
			ES	40.9 (24.4)	0.605	0.028
			LM	39.5 (37.3)	0.01	0.966
Sit-to-Stand	UTx	20.4 (8.7)	EO	50.5 (25.4)	−0.014	0.957
			IO	54.5 (36.4)	−0.499	0.03
			ES	26.2 (14.4)	−0.069	0.814
			LM	32.0 (43.2)	−0.144	0.581
	LTx	7.8 (11.0)	EO	50.5 (25.4)	−0.3	0.243
			IO	54.5 (36.4)	0.359	0.131
			ES	26.2 (14.4)	−0.227	0.434
			LM	32.0 (43.2)	0.338	0.184
	ULx	−10.6 (8.7)	EO	50.5 (25.4)	−0.268	0.299
			IO	54.5 (36.4)	0.264	0.275
			ES	26.2 (14.4)	−0.262	0.366
			LM	32.0 (43.2)	−0.328	0.198
	LLx	−11.0 (15.8)	EO	50.5 (25.4)	−0.121	0.644
			IO	54.5 (36.4)	−0.432	0.065
			ES	26.2 (14.4)	0.279	0.335
			LM	32.0 (43.2)	0.076	0.771

Key: EO = external obliques, IO = internal obliques, ES = erector spinae (longissimus thoracis), LM = superficial lumbar multifidus, AEP = active extension pattern, FP = flexion pattern, *p* = *p*-value, %SMVC = % sub-maximal voluntary contraction, r = r-value (correlation coefficient), SD = standard deviation, ext = extension, flex = flexion, * = significant ($p < 0.01$), UTx = upper thoracic spine, LTx = lower thoracic spine, ULx = upper lumbar spine, LLx = lower lumbar spine. Note: negative correlations indicate an inverse relationship between muscle activity and spinal movement.

Table A3. Overview of the Mean Regional Spinal Kinematics (Degrees), Muscle Activity (%SMVC) and Pearson Correlations (Including Significant Results) for the FP Group

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	Correlations *p*
Box Lift	UTx	23.9 (7.1)	EO	50.6 (22.7)	0.184	0.438
			IO	73.2 (42.0)	0.013	0.955
			ES	22.5 (16.1)	0.127	0.595
			LM	22.6 (19.4)	0.131	0.55
	LTx	22.4 (7.9)	EO	50.6 (22.7)	0.521	0.018
			IO	73.2 (42.0)	0.371	0.108
			ES	22.5 (16.1)	**0.579**	**0.007** *
			LM	22.6 (19.4)	**0.706**	**0.000** *
	ULx	−2.4 (9.4)	EO	50.6 (22.7)	0.333	0.151
			IO	73.2 (42.0)	0.522	0.018
			ES	22.5 (16.1)	0.321	0.168
			LM	22.6 (19.4)	0.303	0.16
	LLx	−20.4 (13.7)	EO	50.6 (22.7)	−0.501	0.024
			IO	73.2 (42.0)	−0.37	0.108
			ES	22.5 (16.1)	**−0.585**	**0.007** *
			LM	22.6 (19.4)	−0.259	0.232

Table A3. *Cont.*

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	p
Box Replace	UTx	25.4 (7.2)	EO	50.4 (23.0)	0.239	0.31
			IO	72.9 (40.3)	0.216	0.36
			ES	22.3 (16.9)	0.22	0.351
			LM	21.9 (18.6)	0.227	0.298
	LTx	21.7 (8.2)	EO	50.4 (23.0)	0.512	0.021
			IO	72.9 (40.3)	0.447	0.048
			ES	22.3 (16.9)	**0.602**	**0.005** *
			LM	21.9 (18.6)	**0.66**	**<0.001** *
	ULx	−3.8 (8.6)	EO	50.4 (23.0)	0.317	0.174
			IO	72.9 (40.3)	0.444	0.05
			ES	22.3 (16.9)	0.266	0.257
			LM	21.9 (18.6)	0.293	0.175
	LLx	−24.7 (13.5)	EO	50.4 (23.0)	**−0.586**	**0.007** *
			IO	72.9 (40.3)	−0.418	0.066
			ES	22.3 (16.9)	**−0.636**	**0.003** *
			LM	21.9 (18.6)	−0.308	0.153
Reach Up	UTx	25.3 (7.8)	EO	50.2 (22.8)	0.406	0.068
			IO	69.0 (36.2)	0.366	0.123
			ES	21.0 (16.2)	0.485	0.035
			LM	19.7 (19.7)	0.262	0.251
	LTx	11.1 (9.2)	EO	50.2 (22.8)	**0.601**	**0.004** *
			IO	69.0 (36.2)	0.501	0.029
			ES	21.0 (16.2)	**0.754**	**0.000** *
			LM	19.7 (19.7)	**0.684**	**0.001** *
	ULx	−11.0 (10.0)	EO	50.2 (22.8)	0.304	0.18
			IO	69.0 (36.2)	0.384	0.104
			ES	21.0 (16.2)	0.277	0.25
			LM	19.7 (19.7)	0.223	0.331
	LLx	−29.9 (18.5)	EO	50.2 (22.8)	−0.511	0.018
			IO	69.0 (36.2)	−0.481	0.037
			ES	21.0 (16.2)	**−0.805**	**0.000** *
			LM	19.7 (19.7)	−0.376	0.093
Step Up	UTx	32.1 (7.4)	EO	52.5 (22.9)	**0.551**	**0.01** *
			IO	72.6 (38.3)	0.339	0.133
			ES	24.3 (17.3)	0.274	0.229
			LM	22.9 (20.4)	0.317	0.161
	LTx	18.0 (9.2)	EO	52.5 (22.9)	**0.563**	**0.008** *
			IO	72.6 (38.3)	0.472	0.031
			ES	24.3 (17.3)	**0.638**	**0.002** *
			LM	22.9 (20.4)	**0.65**	**0.001** *
	ULx	−7.3 (8.9)	EO	52.5 (22.9)	0.293	0.198
			IO	72.6 (38.3)	0.473	0.03
			ES	24.3 (17.3)	0.18	0.434
			LM	22.9 (20.4)	0.169	0.465
	LLx	−22.8 (15.7)	EO	52.5 (22.9)	**−0.644**	**0.002** *
			IO	72.6 (38.3)	**−0.554**	**0.009** *
			ES	24.3 (17.3)	**−0.762**	**0.000** *
			LM	22.9 (20.4)	**−0.562**	**0.008** *

Table A3. *Cont.*

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	Correlations *p*
Step Down	UTx	33.8 (7.9)	EO	51.9 (21.5)	0.435	0.049
			IO	69.4 (35.9)	0.312	0.168
			ES	24.5 (16.6)	0.325	0.15
			LM	22.8 (18.9)	0.299	0.189
	LTx	18.4 (9.1)	EO	51.9 (21.5)	0.528	0.014
			IO	69.4 (35.9)	0.504	0.02
			ES	24.5 (16.6)	**0.583**	**0.006** *
			LM	22.8 (18.9)	**0.635**	**0.002** *
	ULx	−8.1 (9.5)	EO	51.9 (21.5)	0.31	0.171
			IO	69.4 (35.9)	0.511	0.018
			ES	24.5 (16.6)	0.158	0.494
			LM	22.8 (18.9)	0.13	0.573
	LLx	−23.7 (16.1)	EO	51.9 (21.5)	**−0.604**	**0.004** *
			IO	69.4 (35.9)	**−0.587**	**0.005** *
			ES	24.5 (16.6)	**−0.739**	**0.000** *
			LM	22.8 (18.9)	−0.499	0.021
Stand-to-Sit	UTx	20.5 (6.7)	EO	50.7 (22.6)	0.248	0.307
			IO	70.7 (49.6)	0.304	0.22
			ES	32.9 (18.9)	−0.406	0.068
			LM	30.5 (17.8)	−0.007	0.975
	LTx	18.1 (8.5)	EO	50.7 (22.6)	0.43	0.066
			IO	70.7 (49.6)	0.374	0.126
			ES	32.9 (18.9)	0.266	0.244
			LM	30.5 (17.8)	0.45	0.046
	ULx	−0.8 (8.5)	EO	50.7 (22.6)	0.277	0.251
			IO	70.7 (49.6)	0.36	0.142
			ES	32.9 (18.9)	0.074	0.75
			LM	30.5 (17.8)	−0.088	0.711
	LLx	−12.0 (11.6)	EO	50.7 (22.6)	−0.489	0.033
			IO	70.7 (49.6)	−0.48	0.044
			ES	32.9 (18.9)	−0.239	0.297
			LM	30.5 (17.8)	−0.158	0.505
Sit-to-Stand	UTx	18.8 (6.2)	EO	49.2 (22.0)	0.093	0.705
			IO	57.7 (39.3)	0.05	0.845
			ES	23.0 (15.6)	−0.171	0.458
			LM	22.2 (20.6)	−0.075	0.753
	LTx	17.6 (8.1)	EO	49.2 (22.0)	0.372	0.117
			IO	57.7 (39.3)	0.509	0.031
			ES	23.0 (15.6)	0.342	0.129
			LM	22.2 (20.6)	0.31	0.184
	ULx	−0.6 (8.3)	EO	49.2 (22.0)	0.147	0.547
			IO	57.7 (39.3)	0.111	0.66
			ES	23.0 (15.6)	−0.232	0.312
			LM	22.2 (20.6)	−0.414	0.07

Table A3. *Cont.*

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	p
Sit-to-Stand	LLx	−11.3 (12.0)	EO	49.2 (22.0)	−0.551	0.014
			IO	57.7 (39.3)	−0.543	0.02
			ES	23.0 (15.6)	**−0.643**	**0.002** *
			LM	22.2 (20.6)	−0.226	0.339

Key: EO = external obliques, IO = internal obliques, ES = erector spinae (longissimus thoracis), LM = superficial lumbar multifidus, AEP = active extension pattern, FP = flexion pattern, p = p-value, %SMVC = % sub-maximal voluntary contraction, r = r-value (correlation coefficient), SD = standard deviation, ext = extension, flex = flexion, * = significant ($p < 0.01$), UTx = upper thoracic spine, LTx = lower thoracic spine, ULx = upper lumbar spine, LLx = lower lumbar spine. Note: negative correlations indicate an inverse relationship between muscle activity and spinal movement.

Table A4. Overview of the Mean Regional Spinal Kinematics (Degrees), Muscle Activity (%SMVC) and Pearson Correlations (Including Significant Results) for the Control Group.

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	p
Box Lift	UTx	24.0 (8.5)	EO	42.6 (17.8)	0.116	0.625
			IO	63.7 (46.1)	0.396	0.062
			ES	22.7 (10.1)	−0.3	0.154
			LM	16.4 (8.5)	−0.348	0.096
	LTx	16.7 (10.2)	EO	42.6 (17.8)	0.322	0.166
			IO	63.7 (46.1)	−0.171	0.436
			ES	22.7 (10.1)	−0.251	0.236
			LM	16.4 (8.5)	0.32	0.128
	ULx	−7.5 (7.5)	EO	42.6 (17.8)	−0.035	0.884
			IO	63.7 (46.1)	−0.107	0.629
			ES	22.7 (10.1)	−0.197	0.357
			LM	16.4 (8.5)	0.154	0.474
	LLx	−15.0 (9.7)	EO	42.6 (17.8)	−0.387	0.092
			IO	63.7 (46.1)	0.097	0.66
			ES	22.7 (10.1)	0.202	0.343
			LM	16.4 (8.5)	−0.156	0.466
Box Replace	UTx	26.6 (7.7)	EO	42.8 (17.6)	0.138	0.562
			IO	63.3 (46.9)	0.259	0.222
			ES	22.2 (10.6)	−0.23	0.279
			LM	15.7 (8.7)	−0.256	0.227
	LTx	15.5 (11.0)	EO	42.8 (17.6)	0.346	0.135
			IO	63.3 (46.9)	−0.136	0.526
			ES	22.2 (10.6)	−0.248	0.242
			LM	15.7 (8.7)	0.373	0.073
	ULx	−10.1 (7.4)	EO	42.8 (17.6)	0.039	0.871
			IO	63.3 (46.9)	−0.13	0.545
			ES	22.2 (10.6)	−0.283	0.18
			LM	15.7 (8.7)	0.04	0.851
	LLx	−18.9 (10.1)	EO	42.8 (17.6)	−0.319	0.171
			IO	63.3 (46.9)	0.07	0.747
			ES	22.2 (10.6)	0.115	0.593
			LM	15.7 (8.7)	−0.199	0.35

Table A4. *Cont.*

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	*p*
Reach Up	UTx	27.1 (7.6)	EO	42.2 (18.3)	0.052	0.828
			IO	55.5 (40.8)	0.482	0.023
			ES	20.9 (11.4)	−0.148	0.482
			LM	13.0 (7.6)	−0.209	0.317
	LTx	6.4 (11.4)	EO	42.2 (18.3)	0.363	0.115
			IO	55.5 (40.8)	0.004	0.987
			ES	20.9 (11.4)	−0.298	0.147
			LM	13.0 (7.6)	0.257	0.215
	ULx	−17.4 (8.0)	EO	42.2 (18.3)	0.121	0.611
			IO	55.5 (40.8)	−0.099	0.662
			ES	20.9 (11.4)	−0.257	0.215
			LM	13.0 (7.6)	−0.09	0.67
	LLx	−22.6 (13.9)	EO	42.2 (18.3)	−0.395	0.085
			IO	55.5 (40.8)	−0.122	0.588
			ES	20.9 (11.4)	0.015	0.943
			LM	13.0 (7.6)	0	1
Step Up	UTx	34.1 (6.9)	EO	42.7 (19.1)	0.007	0.975
			IO	63.8 (39.8)	0.154	0.473
			ES	21.7 (11.6)	−0.217	0.296
			LM	13.4 (7.6)	−0.215	0.314
	LTx	11.8 (10.3)	EO	42.7 (19.1)	0.429	0.059
			IO	63.8 (39.8)	−0.31	0.14
			ES	21.7 (11.6)	−0.146	0.486
			LM	13.4 (7.6)	0.43	0.036
	ULx	−14.1 (7.8)	EO	42.7 (19.1)	−0.038	0.872
			IO	63.8 (39.8)	−0.195	0.362
			ES	21.7 (11.6)	−0.233	0.263
			LM	13.4 (7.6)	0.04	0.851
	LLx	−17.4 (9.9)	EO	42.7 (19.1)	−0.288	0.217
			IO	63.8 (39.8)	0.189	0.377
			ES	21.7 (11.6)	0.103	0.624
			LM	13.4 (7.6)	−0.197	0.356
Step Down	UTx	35.2 (6.9)	EO	45.0 (20.3)	0.078	0.743
			IO	65.5 (37.7)	0.316	0.133
			ES	22.8 (10.9)	−0.168	0.422
			LM	14.7 (8.3)	−0.129	0.548
	LTx	12.6 (10.3)	EO	45.0 (20.3)	0.351	0.129
			IO	65.5 (37.7)	−0.346	0.098
			ES	22.8 (10.9)	−0.123	0.558
			LM	14.7 (8.3)	0.411	0.046
	ULx	−15.1 (8.4)	EO	45.0 (20.3)	−0.022	0.925
			IO	65.5 (37.7)	−0.288	0.172
			ES	22.8 (10.9)	−0.26	0.209
			LM	14.7 (8.3)	−0.133	0.536
	LLx	−20.2 (9.9)	EO	45.0 (20.3)	−0.373	0.105
			IO	65.5 (37.7)	0.276	0.192
			ES	22.8 (10.9)	−0.172	0.41
			LM	14.7 (8.3)	−0.254	0.231

Table A4. *Cont.*

	Spinal Region	Regional Spinal Angle (Degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations r	*p*
Stand-to-Sit	UTx	22.5 (7.8)	EO	41.8 (19.7)	−0.075	0.761
			IO	40.9 (23.1)	−0.298	0.178
			ES	35.2 (25.1)	−0.376	0.077
			LM	17.2 (14.4)	−0.282	0.204
	LTx	10.7 (10.9)	EO	41.8 (19.7)	0.442	0.058
			IO	40.9 (23.1)	0.21	0.349
			ES	35.2 (25.1)	−0.298	0.168
			LM	17.2 (14.4)	0.068	0.765
	ULx	−6.3 (7.3)	EO	41.8 (19.7)	−0.081	0.742
			IO	40.9 (23.1)	−0.049	0.828
			ES	35.2 (25.1)	−0.309	0.151
			LM	17.2 (14.4)	−0.047	0.837
	LLx	−9.7 (9.4)	EO	41.8 (19.7)	−0.502	0.029
			IO	40.9 (23.1)	−0.288	0.194
			ES	35.2 (25.1)	−0.365	0.087
			LM	17.2 (14.4)	−0.346	0.114
Sit-to-Stand	UTx	20.6 (7.4)	EO	40.8 (19.0)	−0.09	0.714
			IO	38.8 (23.0)	−0.156	0.488
			ES	26.1 (14.0)	−0.069	0.755
			LM	12.4 (6.9)	−0.214	0.339
	LTx	9.9 (11.2)	EO	40.8 (19.0)	0.426	0.069
			IO	38.8 (23.0)	0.247	0.268
			ES	26.1 (14.0)	−0.164	0.456
			LM	12.4 (6.9)	0.162	0.47
	ULx	−5.4 (7.6)	EO	40.8 (19.0)	0.04	0.87
			IO	38.8 (23.0)	−0.028	0.902
			ES	26.1 (14.0)	−0.1	0.649
			LM	12.4 (6.9)	0.15	0.505
	LLx	−9.0 (8.9)	EO	40.8 (19.0)	−0.503	0.028
			IO	38.8 (23.0)	−0.348	0.112
			ES	26.1 (14.0)	−0.203	0.353
			LM	12.4 (6.9)	−0.402	0.064

Key: EO = external obliques, IO = internal obliques, ES = erector spinae (longissimus thoracis), LM = superficial lumbar multifidus, AEP = active extension pattern, FP = flexion pattern, *p* = *p*-value, %SMVC = % sub-maximal voluntary contraction, r = r-value (correlation coefficient), SD = standard deviation, ext = extension, flex = flexion, UTx = upper thoracic spine, LTx = lower thoracic spine, ULx = upper lumbar spine, LLx = lower lumbar spine. Note: negative correlations indicate an inverse relationship between muscle activity and spinal movement.

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