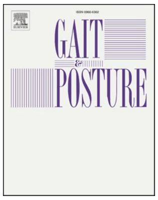
Gait & Posture 107 (2024) 96–103

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost



Relationships between trunk muscle activation and thoraco-lumbar kinematics in non-specific chronic low back pain subgroups during a forward bending task

Rebecca Hemming [a,*], Alister du Rose [b], Liba Sheeran [a], Robert van Deursen [a], Valerie Sparkes [a]

[a] Biomechanics and Bioengineering Research Centre Versus Arthritis, School of Healthcare Sciences, Cardiff University, Cardiff CF24 0AB, Wales, UK
[b] AECC University College, Bournemouth BH5 2DF, England, UK

ARTICLE INFO

Keywords:
Kinematics
Trunk muscle
Non-specific chronic low back pain
Muscle activity
Bending

ABSTRACT

Background: Trunk muscle activity and thoraco-lumbar kinematics can discriminate between non-specific chronic low back pain (NSCLBP) subgroups and healthy controls. However, research commonly focuses on lumbar kinematics, with limited understanding of relationships between kinematics and muscle activity across clinical subgroups. Similarly, the thoracic spine, whilst intuitively associated with NSCLBP, has received less attention and potential relationships between spinal regions and muscle activity requires exploration.

Research question: Is there a relationship between trunk muscle activation and regional thoracic and lumbar kinematics in NSCLBP subgroups during a forward bending task?

Methods: Observational, case-control study. Fifty subgrouped NSCLBP motor control impairment participants (27 Flexion Pattern (FP-MCI), 23 Active Extension Pattern (AEP-MCI)) and 28 pain-free controls were evaluated using 3D motion analysis (Vicon™) and surface electromyography during a forward bending and return to upright task. Mean sagittal angles for the upper-thoracic (UTx), lower-thoracic (LTx), upper-lumbar (ULx) and lower-lumbar (LLx) regions were compared with normalised (% sub-maximal voluntary contraction) mean amplitude electromyography of bilateral transversus abdominis/internal oblique, external oblique, superficial lumbar multifidus and erector spinae (longissimus thoracis) muscles between groups. Pearson correlations were computed to assess relationships (significance $p < 0.01$).

Results: AEP-MCI individuals demonstrated statistically significant relationships between superficial lumbar multifidus and ULx and LLx kinematics (−.812 to.659). FP-MCI individuals exhibited statistically significant relationships between erector spinae and superficial lumbar multifidus and LLx and LTx kinematics (−.686 to.664) in both task phases, and between external oblique and LTx during forward bending) (−.459 to.572). Correlations were moderate to strong for all significant relationships (−.812 to .664).

Significance: Relationships between muscle activity and regional spinal kinematics varied between NSCLBP subgroups, suggesting that those with flexion- or extension-related LBP adopt different motor control strategies when performing a bending task. As effectively mechanical biomarkers, these findings may inform treatment by improving understanding of varied motor strategies in subgroups.

Abbreviations: **AEP**, Active Extension Pattern; **BMI**, Body Mass Index; **EMG**, Electromyography; **EO**, External Oblique; **ES**, Erector Spinae (Longissimus Thoracis); **FP-MCI,**, Flexion Pattern; **LBP**, Low Back Pain; **LLx**, Lower Lumbar; **LTx**, Lower Thoracic; **NISCHR**, National Institute for Social Care and Health Research; **NSCLBP**, Non-Specific Chronic Low Back Pain; **ROM**, Range of Movement; **TrA/IO**, Transversus Abdominis / Internal Oblique; **SD**, Standard Deviation; **sEMG**, Surface Electromyography; **SLM**, Superficial Lumbar Multifidus; **SMVC**, Sub-Maximal Voluntary Contraction; **ULx**, Upper Lumbar; **UTx**, Upper Thoracic; **VAS**, Visual Analogue Scale.

[*] Corresponding author.

E-mail addresses: hemmingrl@cardiff.ac.uk (R. Hemming), adurose@aecc.ac.uk (A. du Rose), sheeranl@cardiff.ac.uk (L. Sheeran), vandeursenr@cardiff.ac.uk (R. van Deursen), sparkesv@cardiff.ac.uk (V. Sparkes).

https://doi.org/10.1016/j.gaitpost.2023.09.018
Received 11 October 2022; Received in revised form 6 September 2023; Accepted 28 September 2023
Available online 29 September 2023

Fig. 1. Forward Bending to pick up a pen (and return to upright).

Table 1
Participant baseline characteristics across groups.

Variable		AEP-MCI (n = 23)	FP-MCI (n = 27)	Healthy (n = 28)	Significance
Gender	Male	4 (17.4 %)	21 (77.8 %)	12 (42.9 %)	$p < 0.01$*
	Female	19 (82.6 %)	6 (22.2 %)	16 (57.1 %)	
Age (years)		43.7 (11.2)	41.0 (10.0)	38.5 (11.2)	$p = 0.238$
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	8 (34.8 %)	5 (18.5 %)	-	-
	Left	2 (8.7 %)	3 (11.1 %)		
	Central	13 (56.4 %)	19 (70.4 %)		
Pain score (VAS)		4.6 (1.4)	4.5 (1.4)	-	$p = 0.986$

Key: FP = Flexion pattern motor control impairment, AEP-MCI = Active extension pattern motor control impairment, H = Healthy, BMI = Body Mass Index (mass (kg)/height (m)^2), *significant difference ($p < 0.01$), VAS = Visual Analogue Scale
(Note: Values are mean (Standard Deviation) unless otherwise stated)

1. Background

Evaluation of trunk muscle activity and thoraco-lumbar kinematics have been shown to discriminate between non-specific chronic low back pain (NSCLBP) subgroups, as well as between NSCLBP and healthy controls [1,2]. Clinically, these NSCLBP motor control impairment (MCI) subgroups have been commonly observed with opposing directional preference patterns of motion in the sagittal plane (e.g. flexion pattern MCI (FP-MCI), active extension MCI (AEP-MCI) subgroups) [3]. O'Sullivan [4] has proposed that FP-MCI is associated with poor control and activity of the spinal stabilising musculature, whereas AEP-MCI is associated with increased spinal muscle activity and subsequently, increased spinal loading. This clinical classification system utilises a multidimensional approach [3], has established reliability and validity [5–7] and has repeatedly been shown to highlight biomechanical differences between subgroups [1, 8–11].

However, focus has typically been placed on lumbar kinematics, with only limited research exploring relationships between kinematics and muscle activity in these clinical subgroups [1,2,10,12]. For example, imbalances in muscle activation during prolonged aggravating postures, such as sustained flexion during cycling, may be a causal mechanism for maladaptive spinal kinematics and increased spinal loading leading to Low back pain (LBP) [13]. Further, the literature provides many examples of co-dependence between the movements of different anatomical regions, for example the differences shown in lumbo-pelvic hip kinematics between those with and without LBP [14–17].

Individuals with LBP have been shown to exhibit less well coordinated lumbar spinal motion and reduced flexion-relaxation responses in multifidus during bending activities [18], however, few studies investigate regional spinal kinematics (including the thoracic spine) and multiple trunk muscles (including the abdominals) concurrently. Such investigations would enable identification of aberrant postures/muscle activities as an underpinning mechanism for persistent LBP to inform more effective preventative and responsive management strategies.

Changes in kinematics in one region of the spine can directly affect the kinematics of those nearby [19]. Thoracic biomechanics, whilst intuitively associated with NSCLBP, have however received less attention in the literature, and the possibility of relationships between regional spinal kinematics (upper and lower thoracic and lumbar spine) and trunk muscle activity remains an area for exploration [20].

The separation of the spine into regions is advocated, as without evaluation of regions, important kinematic data can be missed [1,2,21]. A recent investigation demonstrated that the lower lumbar region contributes significantly more to range of motion (ROM) than the upper lumbar region during forward flexion and lifting exercises [22], suggestive of a compensatory function between regions [23]. This phenomenon has been demonstrated in lumbo-pelvic kinematics with lumbar dominant and pelvic dominant patterns shown in healthy participants [24], however there is an apparent lack of investigation into relationships between regional lumbar and thoracic kinematics. Thoracic movement is expected to occur prior to lumbar movement onset [25] and hence is likely to play a pivotal role in the development of maladaptive spinal behaviours.

Previous studies investigating trunk muscle electromyography (EMG) activity and spinal kinematics concurrently have focused on the lumbar spine in isolation [20], or the lumbar-pelvic complex with a focus on the erector spinae muscles [26]. du Rose and Breen [20] provided an inter-vertebral insight into spinal interactions and demonstrated clear relationships between the sagittal ROMs of upper (L2-L3 and L3-L4) and lower (L4-L5) lumbar regions. Their work demonstrated that when lumbar erector spinae muscle activity increases relative to that of thoracic erector spinae there is a reduction in the maximal intervertebral motion at L4–5 which is suggestive of regional compensation strategies.

The purpose of this study was to explore the relationships between trunk muscle activation and regional thoracic and lumbar kinematics in two clinical NSCLBP subgroups - AEP-MCI and FP-MCI (as proposed by O'Sullivan [4]) - and healthy controls during a forward bending task.

2. Methods

This study is a secondary analysis of previously published papers exploring the kinematics and muscle activity of NSCLBP and healthy controls during functional tasks [1,2].

Ethical approval was obtained from The Research Ethics Committee 3 Wales (10/MRE09/28) within the Biomechanics and Bioengineering Centre Versus Arthritis, Cardiff University, UK. Data collection was conducted at the Research Centre for Clinical Kinesiology, School of Healthcare Sciences, Cardiff University.

50 NSCLBP patients (27 FP-MCI, 23 AEP-MCI aged 18–65) were recruited from routine physiotherapy waiting lists within the Cardiff and Vale University Health Board, Cardiff, UK. 28 healthy participants aged 18–65 were also recruited from students and staff at Cardiff University and members of the local community. Written informed consent was obtained from all participants. Sample size calculation is reported elsewhere [1]. Full details of inclusion and exclusion criteria are included in the supplementary data file.

Only participants classified as FP-MCI or AEP-MCI were included. Classification was achieved via agreement between RH and LS, musculoskeletal physiotherapists trained in the subclassification approach. To

Table 2
Pearson's correlations between regional spinal kinematics and normalised (%SMVC) EMG of the trunk muscles across in the AEP-MCI group during forward bending to pick up a pen and return to upright.

AEP-MCI	Spinal Region	Midpoint Sagittal Spinal Angle (degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations		Significant Relationships ($p < 0.01$)
					r	p	
Pick up pen (forward bend)	Upper Thoracic	17.2 (10.5)	EO	52.9 (26.5)	-.077	.777	
			IO	73.3 (61.5)	-.026	.919	
			ES	25.5 (24.3)	-.216	.524	
			SLM	45.6 (82.2)	.123	.662	
	Lower Thoracic	20.4 (9.9)	EO	52.9 (26.5)	-.032	.905	
			IO	73.3 (61.5)	.225	.369	
			ES	25.5 (24.3)	-.309	.355	
			SLM	45.6 (82.2)	-.119	.673	
	Upper Lumbar	-1.6 (7.0)	EO	52.9 (26.5)	-.151	.576	
			IO	73.3 (61.5)	.098	.698	
			ES	25.5 (24.3)	-.344	.300	
			SLM	45.6 (82.2)	**-.807***	**.000**	↑ext = ↑SLM activity
	Lower Lumbar	-5.2 (16.3)	EO	52.9 (26.5)	-.119	.661	
			IO	73.3 (61.5)	-.062	.806	
			ES	25.5 (24.3)	.394	.231	
			SLM	45.6 (82.2)	**.643***	**.010**	↑ext = ↓SLM activity
Pick up pen (return to upright)	Upper Thoracic	14.3 (11.5)	EO	53.1 (28.0)	.026	.923	
			IO	74.5 (59.7)	.006	.980	
			ES	25.8 (23.7)	-.273	.416	
			SLM	47.5 (88.1)	.15	.594	
	Lower Thoracic	19.0 (8.7)	EO	53.1 (28.0)	.048	.860	
			IO	74.5 (59.7)	.259	.299	
			ES	25.8 (23.7)	-.303	.365	
			SLM	47.5 (88.1)	-.086	.760	
	Upper Lumbar	-1.9 (7.3)	EO	53.1 (28.0)	-.211	.433	
			IO	74.5 (59.7)	-.038	.882	
			ES	25.8 (23.7)	-.213	.529	
			SLM	47.5 (88.1)	**-.812***	**.000**	↑ext = ↑SLM activity
	Lower Lumbar	-5.3 (15.2)	EO	53.1 (28.0)	-.12	.659	
			IO	74.5 (59.7)	-.112	.657	
			ES	25.8 (23.7)	.347	.296	
			SLM	47.5 (88.1)	**.659***	**.007**	↑ext = ↓SLM activity

Key: EO = external obliques, IO = internal obliques, ES = erector spinae (longissimus thoracis), SLM = superficial lumbar multifidus, AEP-MCI = active extension pattern, FP-MCI = flexion pattern, p = p-value, %SMVC = % sub-maximal voluntary contraction, r = r-value (correlation coefficient), SD = standard deviation, ext = extension, flex = flexion, ↑ = increased, ↓ = decreased
Note: Negative correlations indicate an inverse relationship between muscle activity and spinal movement.

establish NSCLBP classification a comprehensive subjective and objective assessment was conducted, which included a series of video-recorded functional movements of the spine which were used for analysis between clinicians' post-data collection. Location of pain was recorded on a body chart. Full assessment procedures are published elsewhere [4,27]. The key clinical features of these subgroups are outlined in the supplementary data file. Gender, age, BMI and a patient reported measure for pain (Visual Analogue Scale (VAS)) [28] were collected at baseline.

3. Data collection

3.1. Motion analysis

An 8-camera Vicon 3D motion -analysis system evaluated sagittal angles in 4 sub-divided spinal regions (upper thoracic (UTx), lower thoracic (LTx), upper lumbar (ULx) and lower lumbar (LLx)). Data was captured at a sampling frequency of 100 Hz. Spherical retro-reflective markers (10 mm) were attached over the: spinous processes of C7, T2, T4, T6, T8, T10, T12, L2, and L4, and bilaterally over the anterior superior iliac spine, posterior superior iliac spine and iliac crest. Additional markers were placed on the manubrium sterni (superior border); acromioclavicular joint (bilaterally); ulna styloid process (bilaterally); a point 10 cm lateral of T12 (bilaterally), lateral knee joint line (between the tibial plateau and femoral condyle) (bilaterally); and lateral malleolus (bilaterally).

3.2. Electromyography

Surface Electromyography (sEMG) data was collected through an 8 Channel Bortec EMG system, synced with Vicon® Nexus. Electrodes were placed parallel to the muscle fibres of the Erector Spinae (Longissimus Thoracis) (ES), superficial Lumbar Multifidus (SLM), External Oblique (EO) and Transversus Abdominis / Internal Oblique (TrA/IO) bilaterally as described elsewhere [2]. Differential pre-amplifiers with fixed gain of 500, input impedance of 1OGOhm, common rejection ratio set at 115 dB and a sampling frequency of 1000 Hz were used [29,30]. sEMG data was normalised to sub-maximal voluntary contractions (SMVC) as SMVC may be more valuable and reliable in chronic LBP populations compared to the use of maximal voluntary contractions [29,31]. A crook-lying double leg raise was used to achieve SMVC of the abdominal muscles (knees 90°, hips 45°, feet lifted approximately 1 cm off the bed, held for 3 s). For the ES and SLM muscles, SMVC values were obtained from a prone lying double knee lift, with the participant lying prone on the plinth (knees 90°, knees lifted approximately 5 cm off the bed, held for 3 s) [29]. Three SMVCs were recorded over 3 s with a 30 s rest between trials.

3.3. Task protocol

A functional bending task was evaluated in two phases (forward bending to pick up a pen from the floor and return to upright from picking up a pen) (Fig. 1).

Table 3
Pearson’s correlations between regional spinal kinematics and normalised (%SMVC) EMG of the trunk muscles across in the FP-MCI group during forward bending to pick up a pen and return to upright.

FP-MCI	Spinal Region	Midpoint Sagittal Spinal Angle (degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations		
					r	p	Significant Relationships ($p < 0.01$)
Pick up pen (forward bend)	Upper Thoracic	19.2 (9.0)	EO	51.8 (27.5)	.508	.019	
			IO	68.9 (40.9)	.315	.189	
			ES	22.2 (16.8)	.215	.337	
			SLM	19.8 (19.1)	.231	.302	
	Lower Thoracic	26.4 (6.6)	EO	51.8 (27.5)	**.572***	**.007**	↑flex = ↑EO activity
			IO	68.9 (40.9)	.43	.066	
			ES	22.2 (16.8)	**.561***	**.007**	↑flex = ↑ES activity
			SLM	19.8 (19.1)	**.664***	**.001**	↑flex = ↑SLM activity
	Upper Lumbar	4.3 (6.3)	EO	51.8 (27.5)	.329	.170	
			IO	68.9 (40.9)	.448	.071	
			ES	22.2 (16.8)	.146	.528	
			SLM	19.8 (19.1)	.155	.514	
	Lower Lumbar	-5.4 (11.9)	EO	51.8 (27.5)	-.459	.042	
			IO	68.9 (40.9)	-.468	.050	
			ES	22.2 (16.8)	**-.686***	**.000**	↑flex = ↓ES activity
			SLM	19.8 (19.1)	-.462	.035	
Pick up pen (return to upright)	Upper Thoracic	15.1 (8.5)	EO	50.8 (27.0)	.541	.011	
			IO	68.9 (42.2)	.3	.212	
			ES	22.5 (17.2)	.195	.385	
			SLM	19.7 (18.5)	.245	.272	
	Lower Thoracic	25.0 (6.1)	EO	50.8 (27.0)	.529	.014	
			IO	68.9 (42.2)	.285	.237	
			ES	22.5 (17.2)	.501	.018	
			LM	19.7 (18.5)	**.652***	**.001**	↑flex = ↑LM activity
	Upper Lumbar	3.9 (6.2)	EO	50.8 (27.0)	.27	.264	
			IO	68.9 (42.2)	.419	.094	
			ES	22.5 (17.2)	.044	.851	
			LM	19.7 (18.5)	.068	.776	
	Lower Lumbar	-4.8 (13.1)	EO	50.8 (27.0)	-.444	.050	
			IO	68.9 (42.2)	-.429	.076	
			ES	22.5 (17.2)	**-.657***	**.001**	↑flex = ↓ES activity
			LM	19.7 (18.5)	-.486	.025	

Key: EO = external obliques, IO = internal obliques, ES = erector spinae (longissimus thoracis), LM = superficial lumbar multifidus, AEP-MCI = active extension pattern, FP-MCI = flexion pattern, p = p-value, %SMVC = % sub-maximal voluntary contraction, r = r-value (correlation coefficient), SD = standard deviation, ext = extension, flex = flexion, ↑ = increased, ↓ = decreased
Note: Negative correlations indicate an inverse relationship between muscle activity and spinal movement

3.4. Data processing and analysis

Data processing was conducted in Vicon Nexus (Nexus 1.8.2 Vicon Motion Systems, Oxford, UK). Results were calculated for both phases of the forward bending task (i.e., forward bend and return to upright). The kinematic outcomes of interest in this study were the midpoint sagittal spinal angles for the UTx (C7-T6), LTx (T6-T12), ULx (T12-L3) and the LLx (L3-S2) spinal regions. For the sEMG data, outcomes of interest were the mean amplitude (%SMVC) of the SLM, LT, TrA/IO and EO muscles during the forward bending and return to upright tasks. Full data processing and analysis procedures are detailed in the Supplementary Data File.

Statistical analyses were performed in SPSS (IBM SPSS Statistics 26). Pearson’s chi-square test [32–34] was used to evaluate differences in gender between groups. sEMG data analyses were performed on the average values of the left and right sides combined [35] due to the symmetrical nature of the task. Pearson correlations were computed to assess relationships between mean sagittal angle for the UTx, LTx, ULx and LLx regions and normalised (% sub-maximal voluntary contraction) mean amplitude sEMG of trunk musculature (SLM, LT, TrA/IO and EO) between groups. The alpha level was set at 0.01 due to multiple correlation analyses being used and the potential risk of type 1 errors. Correlation coefficients were interpreted as follows: 0.0–0.1 negligible, 0.10–0.39 weak, 0.40–0.69 moderate, 0.70–0.89 strong, 0.9–1.0 very strong [36]. A positive r-value indicates that operating in relatively greater flexion in that region is associated with an increase in muscle activity. Negative r-values indicate that muscle activity and movement are inversely related.

4. Results

4.1. Participant demographics

23 AEP-MCI, 27 FP-MCI and 28 healthy individuals completed data collection. Participant baseline characteristics are presented in Table 1. No significant between group differences were noted for age or body mass index (BMI). The location of the LBP was similarly reported between LBP groups. No significant differences between AEP-MCI and FP-MCI groups in VAS scores were observed (Table 1).

4.2. Relationships between spinal kinematics and muscle activity

Correlations were moderate to strong, with the strongest negative correlation being $r = -.812$ and the strongest positive correlation being $r = 0.664$.

The correlation of spinal kinematic data with muscle activity are shown in Tables 2–5.

AEP-MCI: Significant relationships between SLM and ULx and LLx kinematics were identified in the AEP-MCI group (Table 2 and Table 5), where operating in relatively greater extension in the ULx was associated with increase in SLM activity and operating in relatively greater extension in the LLx was associated with reduction in SLM activity, both during the forward bend and returning to upright ($p < 0.01$).

FP-MCI: Multiple significant relationships were demonstrated in the

Table 4
Pearson's correlations between regional spinal kinematics and normalised (%SMVC)EMG of the trunk muscles across in the control group during forward bending to pick up a pen and return to upright.

Control	Spinal Region	Midpoint Sagittal Spinal Angle (degrees) Mean (SD)	Muscle	Muscle Activity (%SMVC) Mean (SD)	Correlations		
					r	p	Significant Relationships ($p < 0.01$)
Pick up pen (forward bend)	Upper Thoracic	18.8 (8.2)	EO	40.5 (17.5)	-.071	.772	
			IO	74.4 (67.3)	.079	.713	
			ES	21.4 (11.1)	-.362	.082	
			SLM	13.8 (6.8)	-.308	.163	
	Lower Thoracic	20.4 (7.4)	EO	40.5 (17.5)	.397	.093	
			IO	74.4 (67.3)	.255	.23	
			ES	21.4 (11.1)	-.226	.289	
			SLM	13.8 (6.8)	.528	.012	
	Upper Lumbar	0.1 (5.3)	EO	40.5 (17.5)	-.357	.133	
			IO	74.4 (67.3)	.175	.414	
			ES	21.4 (11.1)	-.255	.229	
			SLM	13.8 (6.8)	.193	.39	
	Lower Lumbar	-2.2 (10.3)	EO	40.5 (17.5)	-.278	.25	
			IO	74.4 (67.3)	.174	.415	
			ES	21.4 (11.1)	.144	.501	
			SLM	13.8 (6.8)	.363	.097	
Pick up pen (return to upright)	Upper Thoracic	15.6 (9.1)	EO	41.6 (17.5)	-.12	.624	
			IO	66.7 (64.2)	.081	.728	
			ES	21.0 (10.5)	-.392	.058	
			SLM	13.9 (6.8)	-.308	.164	
	Lower Thoracic	19.3 (7.6)	EO	41.6 (17.5)	.355	.136	
			IO	66.7 (64.2)	.439	.046	
			ES	21.0 (10.5)	-.24	.258	
			SLM	13.9 (6.8)	.39	.073	
	Upper Lumbar	1.1 (5.4)	EO	41.6 (17.5)	-.112	.649	
			IO	66.7 (64.2)	.338	.134	
			ES	21.0 (10.5)	-.256	.228	
			SLM	13.9 (6.8)	.288	.193	
	Lower Lumbar	-2.5 (10.0)	EO	41.6 (17.5)	-.285	.237	
			IO	66.7 (64.2)	-.028	.902	
			ES	21.0 (10.5)	.221	.299	
			SLM	13.9 (6.8)	.292	.188	

Key: EO = external obliques, IO = internal obliques, ES = erector spinae (longissimus thoracis), SLM = superficial lumbar multifidus, AEP-MCI = active extension pattern, FP-MCI = flexion pattern, p = p-value, %SMVC = % sub-maximal voluntary contraction, r = r-value (correlation coefficient), SD = standard deviation
Note: Negative correlations indicate an inverse relationship between muscle activity and spinal movement

FP-MCI group (Table 3 and Table 5). Significant relationships between ES and LLx kinematics were identified, where operating in relatively greater flexion in the LLx was associated with a reduction in ES activity. In the LTx region significant relationships were observed with SLM where operating in relatively greater flexion in the LTx was associated with an increase in SLM activity both during the forward bend and returning to upright ($p < 0.01$). Additionally increased flexion in the LTx during the forward bend was associated with an increase in both EO and ES activity ($p < 0.01$).

Healthy: No significant relationships were observed in healthy controls (Table 4 and Table 5).

Summary of results: Table 5 summarises the significant relationships observed and direction of each relationship for each group, muscle and spinal region. The greatest number of relationships between kinematics and muscle activity were observed in the FP-MCI group, followed by the AEP-MCI group, with none observed in the healthy group.

5. Discussion

5.1. Flexion pattern

The contrasting relationships between muscle activity and kinematics in the LLx and LTx regions in the FP-MCI group is potentially illustrative of unique adaptive strategies in this subgroup. These relationships may be either a protective mechanism preventing pain aggravation[37] or a mal-adaptive strategy driving the pain disorder[3]. Whilst the causative effect and nature of those movement adaptations is not possible to detect from this study design, the results indicate granularity within both movement strategies and its likely nature (adaptive or mal-adaptive) warranting further study. Knowing the exact mechanism underlying the movement strategies adopted by individuals with NSCLBP would be beneficial to tailor LBP exercise protocols. Further, the observed relationships between muscle activity and kinematics in the LTx region in the FP-MCI group highlights the possible importance of regional thoracic measurements in LBP patients.

5.2. Active extension pattern

The results from the AEP-MCI group implies that those who extend from the ULx are likely to activate SLM to maintain this position during the forward bend and return to upright task phases, whilst those with greater relative extension in the LLx likely employ other strategies to maintain LLx extension. Also of interest was that the SLM muscle activity in the AEP-MCI group was associated with movement in the LLx. The muscle and kinematic relationships shown differed to that of the FP-MCI group, in that operating in greater extension in the LLx was associated with increased SLM muscle activity in the AEP-MCI group, whilst operating in greater flexion in the LLx in the FP-MCI group was associated with a reduction in ES activity.

5.3. Potential mechanisms underlying the differential relationships between kinematics and muscle activity in subgroups of LBP

The feedback control mechanisms, and subsequent stabilisation of the lumbar spine during movement is dependent on numerous individual parameters [38], and as a result it is likely that inter-individual

Table 5
Summary of the significant relationships ($p < 0.01$) observed across the three groups (AEP-MCI, FP-MCI and healthy control) during forward bending to pick up a pen and return to upright.

	Spinal region	Muscle	AEP-MCI	FP-MCI	Control
Pick up pen (forward bend)	Upper Thoracic	EO			
		IO			
		ES			
		SLM			
	Lower Thoracic	EO		↑flex = ↑EO activity	
		IO			
		ES		↑flex = ↑ES activity	
		SLM		↑flex = ↑SLM activity	
	Upper Lumbar	EO			
		IO			
		ES			
		SLM	↑ext = ↑SLM activity		
	Lower Lumbar	EO			
		IO			
		ES		↑flex = ↓ES activity	
		SLM	↑ext = ↓SLM activity		
Pick up pen (return to upright)	Upper Thoracic	EO			
		IO			
		ES			
		SLM			
	Lower Thoracic	EO			
		IO			
		ES			
		SLM		↑flex = ↑SLM activity	
	Upper Lumbar	EO			
		IO			
		ES			
		SLM	↑ext = ↑SLM activity		
	Lower Lumbar	EO			
		IO			
		ES		↑flex = ↓ES activity	
		SLM	↑ext = ↓SLM activity		

Key: EO = external obliques, IO = internal obliques, ES = erector spinae (longissimus thoracis), SLM = superficial lumbar multifidus, AEP-MCI = active extension pattern, FP-MCI = flexion pattern, ext = extension, flex = flexion, ↑ = increased, ↓ = decreased

differences alter mechanisms of motor control and modifed kinematics [39]. This study supports the previous kinematic investigations where FP and AEP related LBP were shown to adopt different motor control strategies during bending [1,2]. Previous work examining muscle activity in this cohort showed no clear patterns of activity in these NSCLBP subgroups [1,2], however this secondary analysis suggests that when the trunk musculature is considered in conjunction with the regional spinal kinematics there are notable, and different motor control strategies employed between NSCLBP subgroups.

The varied interactions between spinal kinematics and muscle activity in people with and without LBP are widely recognised. For example, electrical silence of ES is notably reduced or absent in the people with LBP suggesting a protective 'guarding' response through increased ES activity [18,26]. The findings of this study suggest that there may be other interactions such as decreased ES activity when flexion occurs in lower lumbar spine and increased SLM activity when flexion occurs in the lower thoracic region in people with FP-MCI who find flexion tasks largely pain provoking. Such kinematic and muscle activation patterns may therefore act as biomarkers, with kinematic and muscle activation relationships specific to individual subgroups. As effectively mechanical biomarkers, such findings may be useful to help inform treatment. If the same associations that are distinct to each subgroup can be demonstrated during further activities of daily living, such results would support the need for specificity in active physical interventions.

Whilst there are those that argue against pursuing subgroups, stating that there is little evidence to suggest that individualised treatments produce better outcomes [40], this study provides further evidence of biomechanical relationships that appear to differentially exist between NSCLBP subgroups. These strategies vary between MCI subgroups however there are some distinct similarities. For example, SLM activity appears to be influenced in both NSCLBP subgroups in response to increased lumbar extension in the AEP-MCI group and increased lower thoracic flexion in the FP-MCI group potentially highlighting the need for SLM training for NSCLBP MCI individuals irrespective of subgrouping.

Where the subgroups differ is in the level of the muscle function response. In FP-MCI the associations between the muscle function and spinal kinematics reached significance in ES and SLM, whilst in AEP-MCI significant associations between muscle activity and kinematics was only reached for SLM. Some of those movement strategies are therefore likely adaptive (i.e., helpful) and some mal-adaptive (i.e., pain drivers). The reason for this could be the forward spine bending task itself. Flexion related activities are pain provoking only in FP-MCI and act as a pain-relieving movement for AEP-MCI patients thus triggering different muscle and kinematic responses. FP-MCI patients may have therefore found the task more challenging, thus developing strategies moving further way from a 'pain free' movement pattern.

5.4. Limitations

The gender split is reflective of previous subgrouped cohorts (FP-MCI: 77.8 % male, AEP-MCI: 82.6 % female), however such between-group gender differences could have confounded the results. Given the exploratory nature of this study, forward bend, the most commonly assessed movement clinically, was used as a single functional task that was assessed. Whilst considered sufficiently challenging for all individuals with NSCLBP, forward bend predominantly triggers pain in people with FP–MCI and relieves pain in AEP-MCI. Participants in the current study were also encouraged to move using habitual movement strategies (e.g., knees flexed or extended) thus introducing variability which could partially explain the high standard deviation values observed in the kinematic results.

The use of surface EMG to evaluate trunk muscle activity is a limitation particularly for detecting deeper lumbar muscles (e.g. SLM) potentially introducing crosstalk [41]. To mitigate this, rigorous standardisation processes including accurate electrode placement and processing of the raw EMG signals were followed according to standardised and accepted recommendations [42].

5.5. Future research

Future investigations evaluating muscle activity and kinematics should consider NSCLBP subgrouping and the importance of regional kinematics beyond the lumbar spine, indeed, inter-vertebral measurements may provide more accurate insights into the importance of regional information [20]. Additional studies are also required to determine if the relationships observed are replicated during, and throughout, other everyday tasks.

6. Conclusions

FP-MCI and AEP-MCI subgroups demonstrated different associations between regional kinematics of the spine and muscle activity. The results are suggestive of varied compensatory behaviours between the spinal regions across NSCLBP subgroups indicating that regional insights are important for understanding biomechanical relationships in the spine. As effectively mechanical biomarkers, such findings may be useful to help personalise exercise rehabilitation approaches.

CRediT authorship contribution statement

RH designed the study, conducted all participant recruitment, data collection, analysis and interpretation and was the major contributor to writing the manuscript. **AdR** analysed and interpreted the data and was a substantial contributor to the writing of the manuscript. **LS**, **RvD** and **VS** all contributed to the research design, analysis, interpretation of the data and writing of the manuscript. **RvD** is the author of the MATLAB code to analyse the kinematic and electromyography data. All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare they have no competing interests. Dr Rebecca Hemming received funding from Arthritis Research UK as part of the Arthritis Research UK Biomechanics and Bioengineering Centre, Cardiff University. Dr Rebecca Hemming also received funding via a Presidents Scholarship Award, Cardiff University. For the remaining authors no funding was received. The funding bodies had no role in the design of the study, data collection, analysis, interpretation of the data or in writing the manuscript.

Acknowledgements

Dr Rebecca Hemming received funding from Versus Arthritis as part of the Biomechanics and Bioengineering Centre Versus Arthritis, Cardiff University. Dr Rebecca Hemming also received funding via a Presidents Scholarship Award, Cardiff University. Support for the study is acknowledged from Health and Care Research Wales (formerly National Institute of Social, Health and Care (NISCHR) Wales) who provided research officers to support data collection.

Consent for publication

The participant, whose images are included, provided full written consent for publication.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2023.09.018.

References

[1] R. Hemming, L. Sheeran, R. van Deursen, V. Sparkes, Non-specific chronic low back pain: differences in spinal kinematics in subgroups during functional tasks, Eur. Spine J. 27 (2017) 163–170.

[2] R. Hemming, L. Sheeran, R. van Deursen, V. Sparkes, Investigating differences in trunk muscle activity in non-specific chronic low back pain subgroups and no-low back pain controls during functional tasks: a case-control study, BMC Musculoskelet. Disord. 20 (1) (2019), 459.

[3] P. O'Sullivan, Diagnosis and classificiation of chronic low back pain disorders: Maladaptive movement and motor control impairments as underlying mechanism, Man Ther. 10 (2005).

[4] P. O'Sullivan, Diagnosis and classification of chronic low back pain disorders: maladaptive movement and motor control impairments as underlying mechanism, Man. Ther. 10 (2005) 242–255.

[5] W. Dankaerts, P. O'Sullivan, The validity of O'Sullivan's classification system (CS) for a sub-group of NS-CLBP with motor control impairment (MCI): overview of a series of studies and review of the literature, Man. Ther. 16 (1) (2011) 9–14.

[6] W. Dankaerts, P.B. O'Sullivan, L.M. Straker, A.F. Burnett, J.S. Skouen, The inter-examiner reliability of a classification method for non-specific chronic low back pain patients with motor control impairment, Man. Ther. 11 (2006) 28–39.

[7] K.V. Fersum, P.B. O'Sullivan, A. Kvale, J.S. Skouen, Inter-examiner reliability of a classification system for patients with non-specific low back pain, Man. Ther. 14 (5) (2009) 555–561.

[8] Moheb Seraj M. Shahbazi, J. Sarrafzadeh, N. Maroufi, I. Ebrahimi Takamjani, A. Ahmadi, H. Negahban, Comparison of postural balance between subgroups of nonspecific low-back pain patients based on O'Sullivan classification system and normal subjects during lifting, Arch. Bone Jt Surg. 7 (1) (2019) 52–60.

[9] M. O'Keeffe, W. Dankaerts, P. O'Sullivan, L. O'Sullivan, K. O'Sullivan, Specific flexion-related low back pain and sitting: comparison of seated discomfort on two different chairs, Ergonomics 56 (4) (2013) 650–658.

[10] W. Dankaerts, P. O'Sullivan, A. Burnett, L. Straker, Altered patterns of superficial trunk muscle activation during sitting in nonspecific chronic low back pain patients: importance of subclassification, Spine 31 (17) (2006) 2017–2023.

[11] W. Dankaerts, P. O'Sullivan, A. Burnett, L. Straker, Differences in sitting postures are associated with nonspecific chronic low back pain disorders when patients are subclassified, Spine 31 (2006) 698–704.

[12] W. Dankaerts, P. O'Sullivan, A. Burnett, L. Straker, P. Davey, R. Gupta, Discriminating healthy controls and two clinical subgroups of nonspecific chronic low back pain patients using trunk muscle activation and lumbosacral kinematics of postures and movements: a statistical classification model, Spine 34 (15) (2009) 1610–1618.

[13] G.M. Streisfeld, C. Bartoszek, E. Creran, B. Inge, M.D. McShane, T. Johnston, Relationship between body positioning, muscle activity, and spinal kinematics in cyclists with and without low back pain: a systematic review, Sports Health 9 (1) (2017) 75–79.

[14] S.M.H. Tsang, G.P.Y. Szeto, L.M.K. Li, D.C.M. Wong, M.M.P. Yip, R.Y.W. Lee, The effects of bending speed on the lumbo-pelvic kinematics and movement pattern during forward bending in people with and without low back pain, BMC Musculoskelet. Disord. 18 (2017), 157.

[15] A.F. Burnett, M.W. Cornelius, W. Dankaerts, P.B. O'Sullivan, Spinal kinematics and trunk muscle activity in cyclists: a comparison between healthy controls and non-specific chronic low back pain subjects-a pilot investigation, Man. Ther. 9 (4) (2004) 211–219.

[16] S.A. Scholtes, S.P. Gombatto, L.R. Van Dillen, Differences in lumbopelvic motion between people with and people without low back pain during two lower limb movement tests, Clin. Biomech. 24 (1) (2009) 7–12.

[17] R.A. Laird, J.L. Keating, K. Ussing, P. Li, P. Kent, Does movement matter in people with back pain? Investigating 'atypical' lumbo-pelvic kinematics in people with and without back pain using wireless movement sensors, BMC Musculoskelet. Disord. 20 (1) (2019), 28.

[18] P. Ippersiel, R. Preuss, A. Fillion, J. Jean-Louis, R. Woodrow, Q. Zhang, et al., Inter-joint coordination and the flexion-relaxation phenomenon among adults with low back pain during bending, Gait Posture 85 (2021) 164–170.

[19] P. Park, H.J. Garton, V.C. Gala, J.T. Hoff, J.E. McGillicuddy, Adjacent segment disease after lumbar or lumbosacral fusion: review of the literature, Spine (Phila Pa 1976) 29 (17) (2004) 1938–1944.

[20] A. du Rose, A. Breen, Relationships between paraspinal muscle activity and lumbar inter-vertebral range of motion, Healthcare 4 (1) (2016) 4.

[21] A.V. Pavlova, J.R. Meakin, K. Cooper, R.J. Barr, R.M. Aspden, The lumbar spine has an intrinsic shape specific to each individual that remains a characteristic throughout flexion and extension, Eur. Spine J. 23 (2014).

[22] R.S. Alqhtani, M.D. Jones, P.S. Theobald, J.M. Williams, Investigating the contribution of the upper and lower lumbar spine, relative to hip motion, in everyday tasks, Man. Ther. 21 (2016) 268–273.

[23] T. Mitchell, P. O'Sullivan, A. Burnett, L. Straker, A. Smith, Regional differences in lumbar spinal posture and the influence of low back pain, BMC Musculoskelet. Disord. 9 (1) (2008), 152.

[24] K. Hasebe, K. Sairyo, Y. Hada, A. Dezawa, Y. Okubo, K. Kaneoka, et al., Spino-pelvic-rhythm with forward trunk bending in normal subjects without low back pain, Eur. J. Orthop. Surg. Traumatol. 24 (1) (2014) 193–199.

[25] A. Du Rose, Have studies that measure lumbar kinematics and muscle activity concurrently during sagittal bending improved understanding of spinal stability and sub-system interactions? A systematic review, Healthcare 6 (3) (2018) 112.

[26] D. Sánchez-Zuriaga, J. López-Pascual, D. Garrido-Jaén, M.A. García-Mas, A comparison of lumbopelvic motion patterns and erector spinae behavior between asymptomatic subjects and patients with recurrent low back pain during pain-free periods, J. Manip. Physiol. Ther. 38 (2) (2015) 130–137.

[27] P. O'Sullivan, Lumbar segmental 'instability': Clinical presentation and specific stabilising exercise management, Man. Ther. 5 (2000) 2–12.

[28] M. Von Korff, R.A. Deyo, D. Cherkin, W. Barlow, Back pain in primary care: outcomes at 1 year, Spine 18 (7) (1993) 855–862.

[29] W. Dankaerts, P.B. O'Sullivan, A.F. Burnett, L.M. Straker, L.A. Danneels, Reliability of EMG measurements for trunk muscles during maximal and sub-maximal voluntary isometric contractions in healthy controls and CLBP patients, J. Electromyogr. Kinesiol. 14 (3) (2004) 333–342.

[30] L. Sheeran, V. Sparkes, B. Caterson, M. Busse-Morris, R. van Deursen, Spinal position sense and trunk muscle activity during sitting and standing in nonspecific chronic low back pain: classification analysis, Spine 37 (8) (2012). E486-E95.

[31] C. Larivière, A.B. Arsenault, D. Gravel, D. Gagnon, P. Loisel, Evaluation of measurement strategies to increase the reliability of EMG indices to assess back muscle fatigue and recovery, J. Electromyogr. Kinesiol. 12 (2) (2002) 91–102.

[32] A. Field, Discovering statistics using SPSS, Sage publications, 2009.

[33] R.A. Fisher, On the Interpretation of χ2 from Contingency ys, and the Calculation of P, J. R. Stat. Soc. 85 (1) (1922) 87–94.

[34] K. Pearson, X. On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling, Philos. Mag. Ser. 5 50 (302) (1900) 157–175.

[35] F.J. Vera-Garcia, J.M. Moreside, S.M. McGill, MVC techniques to normalize trunk muscle EMG in healthy women, J. Electromyogr. Kinesiol. 20 (1) (2010) 10–16.

[36] P. Schober, C. Boer, L.A. Schwarte, Correlation coefficients: appropriate use and interpretation, Anesth. Analg. 126 (5) (2018) 1763–1768.

[37] J.H. van Dieen, J. Cholewicki, A. Radebold, Trunk muscle recruitment patterns in patients with low back pain enhance the stability of the lumbar spine, Spine 28 (8) (2003) 834–841.

[38] N.P. Reeves, K.S. Narendra, J. Cholewicki, Spine stability: the six blind men and the elephant, Clin. Biomech. 22 (3) (2007) 266–274.

[39] M. Nematimoez, A. Breen, A. Breen, Spatio-temporal clustering of lumbar intervertebral flexion interactions in 127 asymptomatic individuals, J. Biomech. 154 (2023), 111634.

[40] B.M. Wand, N.E. O'Connell, Chronic non-specific low back pain – sub-groups or a single mechanism? BMC Musculoskelet. Disord. 9 (1) (2008), 11.

[41] A. Hofste, R. Soer, E. Salomons, J. Peuscher, A. Wolff, H. van der Hoeven, et al., Intramuscular EMG versus surface EMG of lumbar multifidus and erector spinae in healthy participants, Spine 45 (20) (2020).

[42] B. Freriks, H.J. Hermens, [SENIAM 9]: European Recommendations for Surface Electromyography: Results of the SENIAM project. Roessingh Research and Development b.v.1999.