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Motion analysis of 3D multi-segmental spine during gait in symptom remission people with low back pain: a pilot study

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Abstract

Background Low back pain (LBP) is a long-lasting condition with a variable course rather than pain episodes of unrelated occurrences. Thus, the remission stage between the symptom recurrence is critical. This study aimed to investigate the trunk control of the symptom remission people with low back pain (LBP-R) during gait based on a multi-segmental spine model, including the musculoskeletal factors of lumbar muscle activity and regional thoracic and lumbar kinematics.

Methods Twenty-one males (10 LBP-R, age 23–37, height 165–185 cm, weight 60–74 kg; 11 controls, age 23–38, height 164–183 cm, weight 55–80 kg) were evaluated using 3D motion analysis and surface electromyography (sEMG). The thoracic (T) and lumbar (L) spine were divided into upper and lower portions separately (T3-T7; T7-T12; T12-L3; L3-L5). This pilot study investigated the segmental redundancy with the cross-correlation analyses of spine kinematic time series (R_{xy}) and correlation analyses of the range of motion between adjacent segments (R_{ROM}) during gait. Meanwhile, the bilateral lumbar erector spinae (ES) and multifidus (MF) muscle activation during the stance and swing phases were calculated respectively.

Results The Upper Thoracic/Lower Thoracic pairing in the sagittal plane significantly showed a very strong correlation (R_{xy}:0.93) in the LBP-R group, while the controls displayed a weak correlation (R_{xy}:0.22). In addition, the Lower Thoracic/Upper Lumbar and Lower Lumbar/Pelvis pairings in the sagittal plane for the LBP-R group significantly showed very weak to weak correlations (R_{xy}range: 0.17–0.24), while the healthy controls displayed moderate correlations (R_{xy}range: 0.49–0.52). Most R_{ROM} values demonstrated very weak to moderate correlations (Number of pairings: 21/24). Compared with healthy controls, left-side ES muscle activation in the LBP-R group was significantly greater during the ipsilateral swing phase and smaller during the ipsilateral stance phase ($P < 0.05$).

Conclusions Compared with healthy controls, the LBP-R group exhibited higher lumbar ES activation during the swing phase and altered movement redundancy between adjacent spinal segments in the sagittal plane. As effectively mechanical biomarkers, such findings may help establish a new approach to rehabilitation and self-management for LBP experiencers. A larger sample size is required to generalize these findings to the broader population.

Keywords Low back pain, Spine kinematics, Multi-segment, Cross-correlation, Muscle activation

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Introduction

Low back pain (LBP) is frequently referred to in coming decades along with the quickly developing society and increasing life stress [1]. Several recent studies have attached the importance to the remission gap between back pain recurrence episodes. They reported that the pain remission stage might also disturb the trunk control except for in-pain episodes, including modified back muscle recruitment pattern, decreased spinal movement, altered thorax-pelvis coordination and maladaptive behaviours [2–4]. Therefore, current findings collectively suggested that LBP was a long-lasting condition with a variable course rather than pain episodes of unrelated occurrences [5]. Spine kinematics was considered a good choice to better describe the function disorder of trunk control during the remission stage [6, 7]. However, the research scope on spine kinematics among the symptom remission people with LBP (LBP-R) currently lacks sufficient evidence.

Regarding spine kinematics, the most common reflective marker setting in gait analysis is the Plug-in-Gait model, whose landmark number of the spinous portion is only two (C7 and T10) [8]. This model is too simplistic to accurately capture the biomechanical characteristics of a multi-segmental spine, which provides a more precise representation of the trunk in terms of fit [9]. A growing body of empirical evidence supported that we should break up the rigid spine into smaller portions, detecting the inter- or intra-segmental rhythm of the spine by increasing the degrees of freedom (DOF) [10–15]. Various types of multi-segmental spine models have been employed among the several studies of LBP, ranging from 2 to 8 subsections [16]. The essential markers to accurately describe the motions of the regional spine were mainly located at the T1/T3, T6/T7, T12/L1, L3 and L5 of vertebrae. One of the most fitting protocols was dividing the thoracic and lumbar spine into upper and lower portions separately [17, 18]. The prior studies related to this type of multi-segmental spine model have proved the difference in altered spine segmental redundancy, decreased motions of lower lumbar in the frontal plane and more asymmetrical lower thoracic motion in the transverse plane when compared the LBP people with healthy controls [12, 19]. However, these problems among the LBP-R group remain unclear, which might provide more evidence to support the maladaptive theory on regional spine kinematics.

Furthermore, the relationship between spinal biomechanics and muscle activity indicates that decreased spinal mobility is often associated with increased back muscle activation and enhanced trunk stiffness in individuals with LBP [20]. Although increased stiffness of back muscle may protect the spinal structures, it also has long-term consequences for spinal health and LBP recurrence due to compromised trunk dynamics [21]. Hence, in this study, research on paraspinal muscles is necessary. The analysis of the lumbar muscle activation during gait might broaden the understanding of multi-segmental spine kinematics. The paraspinal lumbar muscles are usually divided into the erector spinae (ES, also called lumbar longissimus) and the transversospinales (MF, multifidus as a major component). In the previous study, the LBP-R group displayed decreased bilateral longissimus co-activation and redistribution of activity across the back ES muscle during gait [3, 4]. Regarding the MF, LBP-R patients would have delayed recruitment onset and morphology changes like increased muscle thickness to respond to insufficient preparation for spinal loading [22, 23]. However, simultaneous combined muscle activation along with regional spine kinematics has not been previously studied. This study integrated both aspects, offering a comprehensive perspective on musculoskeletal characteristics and improved insights into altered motor control strategies, with implications for clinical rehabilitation.

Therefore, the purpose of this study was to investigate the trunk control of the LBP-R group during gait based on a multi-segmental spine model, including the musculoskeletal factors of lumbar muscle activity and regional thoracic and lumbar kinematics. Considering the predominant current literature, this study hypothesized that the LBP-R group would show a stiffness trunk control, consisting of increased back muscle activation, reduced motions of the spine and altered regional spine couplings between adjacent segments, which might be parts of evidence that the altered motor control was related to adaptive changes rather than the presence of pain.

Methods

Participants

In the current pilot study, 21 males were recruited due to the consideration of gender differences among LBP subjects. The occupational and ergonomic factors, such as standing posture leaning forward were more associated with women LBP experiencers, which may affect the spine kinematics during gait [24]. The control group ($n=11$) was matched with the LBP-R group ($n=10$) by age, height, weight, and body mass index (BMI). This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Institutional Review Board of Tohoku University Graduate School of Medicine (2021–1–049). All participants gave written informed consent approved by the Ethics Institutional Review Board.

Participants in the LBP-R group were included if they met the following criteria: 1) males; 2) 20–40 years old;

3) experienced localized back pain between the lower posterior margin of the 12th rib cage and the horizontal gluteal fold; 4) experienced LBP no less than twice within the past two years; 5) self-reportedly LBP has affected their daily life or work; and 6) were in the remission stage at the time of data collection (i.e., before and after walking trials, self-evaluated back pain intensity by visual analog scale (VAS, 0–100 mm) twice, required < =5/100 mm score) [20]. The participants were excluded when they: 1) had a history of low back surgery, spinal stenosis, scoliosis, malignancy, spinal infection, or lumbar radiculopathy; 2) had a severe history of musculoskeletal or neurological injury; or 3) were unable to independently walk.

Experimental procedures

Participants' demographics, LBP history, and Fear-Avoidance Beliefs Questionnaire (FABQ-Japanese version) answers were investigated before the trials [25]. Five trials for the 7-m pathway were conducted at the preferred speed of level walking. A 30–60 s rest was provided between each trial. Participants were instructed to do several active monoplanar movement after trials, consisting of forward flexion and backward extension, bilateral lateral flexion when both in standing pose, and axial rotation to each side when sitting on a solid chair with arms crossed. Lastly, experienced physical therapists did a straight leg raising test to screen for radiculopathy symptoms, which are common in lumbar disc herniation patients.

Laboratory testing

The walking process was recorded with an 8-camera motion analysis system (MAC 3D; Motion Analysis Corporation, Santa Rosa, CA, USA). Thirty-two retroreflective markers were placed on the following anatomical landmarks for all subjects (Fig. 1) referring to previous studies on patients with LBP [17, 18]: bilateral acromion; the spinous processes of T3, T12, L3, and L5; 6 cm to the right and left of the T7 spinous process; 4 cm to the right and left of the L1 and L4 spinous processes; bilateral anterior and posterior superior iliac spine (ASIS, PSIS); bilateral greater trochanter, lateral and medial epicondyle, lateral and medial malleolus, 1st and 5th metacarpophalangeal joints, and calcaneus. Spine palpation has proven excellent intra-rater reliability [26, 27].

The surface electromyography (sEMG) data of bilateral ES and MF was recorded by four surface electrodes (sEMG: WEB-1000, Nihon Kohden Corporation, Tokyo, Japan; surface electrodes: ZB-150H, Nihon Kohden Corporation, Tokyo, Japan) according to SENIAM on recommendations for sensor locations in back muscles. The setting method of surface electrodes: 1) ES: vertical

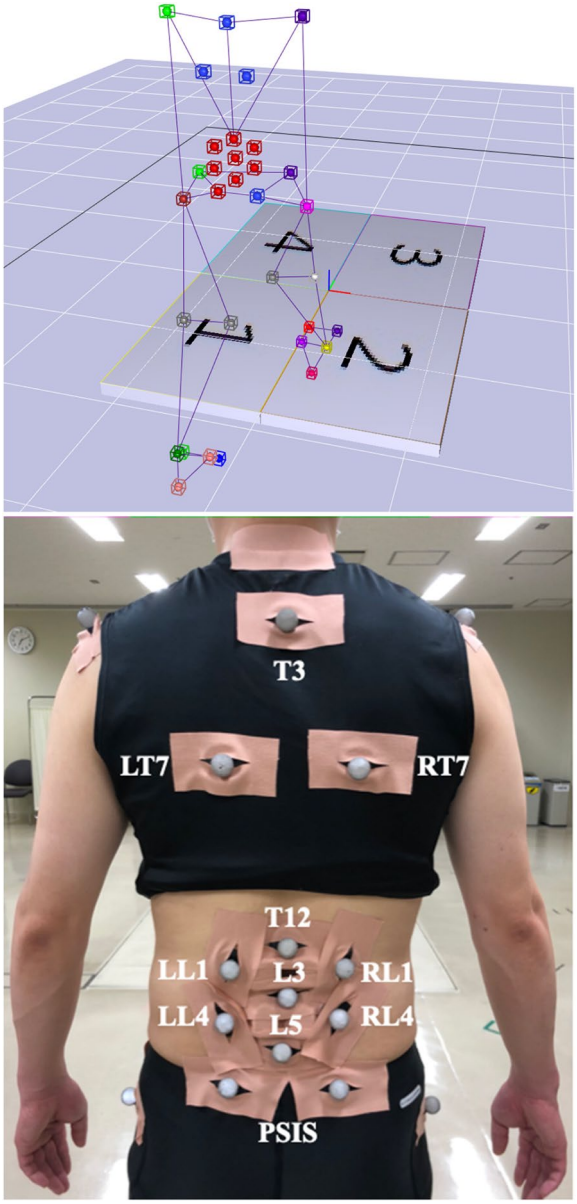

Fig. 1 Thirty-two retroreflective markers' location and the multi-segmental spine model description of a typical participant with markers from a back view

orientation and over the palpable bulge of muscle, where two finger widths (approx. 3 cm) lateral from the L1 spinous process, 2) MF: on and aligned with a line from the caudal tip of the PSIS to the interspace between the L1 and the L2 spinous processes and kept at the level of the L4 spinous process [28, 29].

Data analysis

All kinematic data analysis used Visual3D (Version 6, C-Motion, Inc., Germantown, MD, USA) and was

primarily low-pass filtered at 6 Hz [30]. Time series gait data from the right heel strike (RHS) to the subsequent RHS was normalized to 101 data points. This study determined the gait event of the RHS and right toe off (RTO) using foot speed relative to the pelvis [31, 32].

A kinematic model of the multi-segmental spine was used to derive the joint angles in three anatomical planes. This model has been evaluated to be valid ($R^2 > 0.84$) and reliable (greater intraclass correlation coefficient than 0.97) [17]. Each spine segment was defined with the x-axis oriented from left to right using two lateral spine markers (+x: from left to right), the z-axis oriented from the marker on the spinous process cephalad to the mid-distance between the lateral spine markers (+z: from below to up), the y-axis oriented orthogonal to the x–z plane (+y: from posterior to anterior). This coordinate system building method was employed in the upper thoracic (UT), lower thoracic (LT), upper lumbar (UL), and lower lumbar (LL). The CODA pelvis in Visual3D was used to define the pelvic segment by bilateral ASISs and PSISs, as shown in Fig. 2.

Relative joint angles between adjacent spine segments were then calculated. The pelvis was defined based on the position of the pelvic segment relative to the laboratory coordinate system. The range of motion (ROM) in all three planes for each spine segment was calculated as the difference between the maximum and minimum angles. The mean of ROM was determined across the five trials and in each segment and used to calculate correlation coefficients between adjacent segments (R_{ROM}).

Cross-correlation analyses were conducted on the time series of 3D angle data between pairings of adjacent spine segments to assess segmental redundancy [12]. A total of 4 analyses were performed (UT vs LT, LT vs UL, UL vs LL, LL vs Pelvis). Cross-correlation analysis determines the spatial and temporal similarity between two signals, which could assess the extent of the association between the kinematic time series of two adjacent segments. When the time series are aligned, cross-correlation coefficients (R_{xy}) at time lag zero were extrapolated to quantify the strength of relationship. Raw cross-correlation coefficients (R_{xy}) were transformed with a Fisher Z-transformation, used to calculate the mean R_{xy} over five gait trials for each participant, and then averaged across both groups to enable a comparison between segmental redundancy. Calculations were performed with MATLAB (The MathWorks, Inc., Natick, USA).

EMG data were bandpass filtered between 30 and 470 Hz, then the signal was smoothed using a 100 ms moving window, and the full wave was rectified finally. Bilateral ES and MF muscle activity was divided into each gait cycle's stance phase (defined from RHS to RTO) and swing phase (defined from RTO to RHS). For the detailed normalization method, the averaged values of EMG in the stance phase and swing phase separately relative to the whole gait cycle were used as the results of each walking trial. Later, the final data was averaged within five gait cycles.

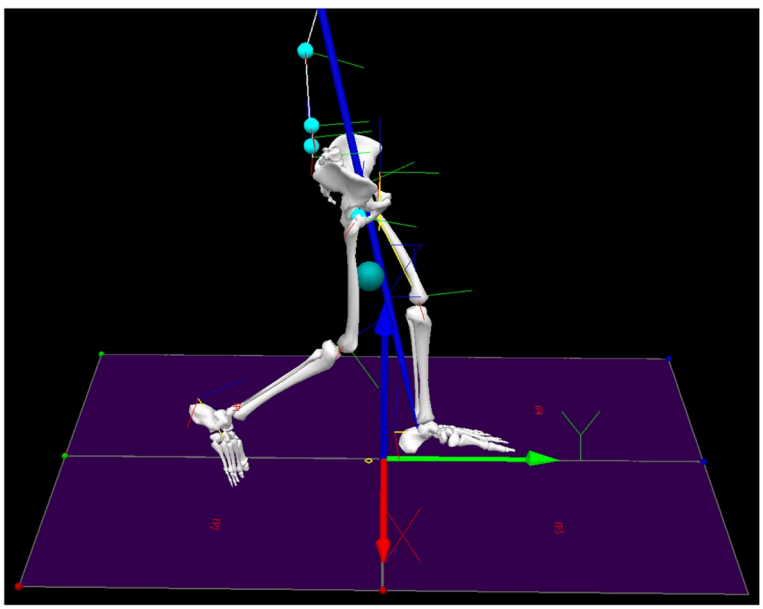

Fig. 2 The coordinate system building method used in Visual3D

Statistical analysis

Independent t-tests were performed between groups to test for differences in demographics, gait parameters, sEMG of ES and MF, mean ROMs and R_{xy} values. Spearman's rank correlation and Pearson product moment correlation coefficients (R_{ROM}) were calculated for non- and normally distributed data respectively, showing the correlation of ROMs between adjacent spinal segments in the three anatomical planes. The normality of the data was assessed using Q-Q plots and the Shapiro–Wilk test. Correlation coefficients (R_{xy}, R_{ROM}) were interpreted as follows [19]: very weak (0.00–0.19), weak (0.20–0.39), moderate (0.40–0.59), strong (0.60–0.79) and very strong (0.80 –1.00). All statistical analysis used SPSS version 26 (IBM SPSS Inc., Armonk, NY), and the level of significance was set at $P < 0.05$.

Results

According to the investigation of past back pain duration, all the LBP-R participants could be identified as acute LBP experiencers (< 6 weeks) in this study. Table 1 showed no significant differences between groups in gait parameters of speed and cadence, but the LBP-R group showed a faster speed and cadence than the controls. The level of the fear-avoidance beliefs on physical activity (PA) in the LBP-R group was approximately equal to the cut-off value (= 14), while the part of work (W) was lower than the cut-off score (< 29). One participant reported mild back pain after the trials, but the VAS score was no more than 5/100 mm.

Table 1 Participant characteristics

	LBP-R ($n = 10$)	Control ($n = 11$)
Age (years)	28.5 ± 4.8	25.9 ± 4.7
Height (cm)	174.2 ± 7.8	175.0 ± 5.2
Weight (kg)	65.9 ± 5.3	67.6 ± 6.7
BMI (kg/m^2)	21.7 ± 1.6	22.1 ± 1.9
Time(mo.) since initial episode	49.0 ± 29.9 {1–104}	N/A
Time(mo.) since pain-free episode	9.7 ± 9.7 {0–24}	N/A
FABQ-PA (0–24)	14.6 ± 5.5 {5–24}	N/A
FABQ-W (0–42)	14.6 ± 6.8 {8–28}	N/A
Pain before walking VAS (mm) (0–100)	1.0 ± 2.1	0
Pain after walking VAS (mm) (0–100)	1.0 ± 2.1	0
speed (m/s)	1.39 ± 0.20	1.31 ± 0.10
cadence (steps/min)	113.50 ± 6.93	111.54 ± 3.55

Values given are Mean ± SD/{Range}

LBP-R low back pain remission group, *FABQ* Fear-Avoidance Beliefs Questionnaire, *PA* Physical Activity, *W* Work, *N/A* not applicable, *VAS* visual analog scale

sEMG of the ES and MF

Table 2 showed that compared with healthy controls, left-side ES muscle activation during the ipsilateral swing phase was significantly greater in the LBP-R group ($p = 0.016$). Meanwhile, the left-side ES muscle activation during the ipsilateral stance phase was significantly smaller in the LBP-R group ($p = 0.017$).

Rxy values between spine adjacent segments

Table 3 showed the R_{xy} values and the 95% confidence interval (CI) of the difference for three anatomical planes of motion in both groups during gait. In the sagittal plane, the UT/LT pairing significantly showed a very strong correlation (R_{xy}:0.93) in the LBP-R group, while the control group displayed a weak correlation (R_{xy}:0.22). On the contrary, the LT/UL and LL/Pelvis pairings in the LBP-R group significantly displayed very weak to weak correlations (R_{xy}range:0.17–0.24) while the control group showed moderate correlations (R_{xy}range:0.49–0.52). Although in the frontal and transverse planes, this study did not detect a significant difference between groups, the correlation values of adjacent segments in the LBP-R group (weak to moderate, R_{xy}range:0.25–0.54) were at a lower level than the control group (moderate to strong, R_{xy}range:0.37–0.74). In Fig. 4, the R_{xy} values were transformed into visualized color bars based on the five levels of correlation coefficients.

In addition, strong to very strong correlations were observed only in 2 cases out of 24 analyzed results, including the UT/LT pairing (R_{xy}:0.93) in the sagittal plane of the LBP-R group and the LL/Pelvis pairing (R_{xy}:0.74) in the frontal plane of the controls group, these are highlighted in Table 3 with bold font.

Table 2 sEMG of the lumbar ES and MF muscles

			LBP-R	Control
Erector Spinae	Right	Stance	0.78 ± 0.10	0.80 ± 0.09
		Swing	1.42 ± 0.19	1.33 ± 0.11
	Left	**Stance***	1.15 ± 0.07	1.07 ± 0.08
		Swing*	0.71 ± 0.13	0.88 ± 0.15
Multifidus	Right	Stance	0.86 ± 0.09	0.88 ± 0.14
		Swing	1.28 ± 0.17	1.23 ± 0.26
	Left	Stance	1.03 ± 0.06	1.02 ± 0.09
		Swing	0.96 ± 0.12	0.95 ± 0.17

Values given are Mean ± SD (%)

* Significant difference between groups ($P < .05$)

ES Erector spinae, *MF* Multifidus

Table 3 R_{xy} mean (SD) values between spine adjacent segments in both groups assessed in the three anatomical planes

		LBP-R	Control	95% CI of the Difference
Sagittal Plane	**UT/LT***	**0.93 ± 0.55**	0.22 ± 0.22	[−0.95, −0.77]
	LT/UL*	0.17 ± 0.26	0.52 ± 0.37	[0.11, 0.62]
	UL/LL	0.57 ± 0.23	0.48 ± 0.30	[−0.36, 0.13]
	LL/Pelvis*	0.24 ± 0.25	0.49 ± 0.25	[0.05, 0.49]
Frontal Plane	UT/LT	0.25 ± 0.29	0.51 ± 0.59	[−0.19, 0.66]
	LT/UL	0.46 ± 0.52	0.49 ± 0.52	[−0.45, 0.50]
	UL/LL	0.35 ± 0.45	0.56 ± 0.65	[−0.32, 0.70]
	LL/Pelvis	0.54 ± 0.21	**0.74 ± 0.73**	[−0.29, 0.74]
Transverse Plane	UT/LT	0.27 ± 0.30	0.37 ± 0.57	[−0.35, 0.53]
	LT/UL	0.48 ± 0.29	0.49 ± 0.62	[−0.45, 0.49]
	UL/LL	0.44 ± 0.27	0.47 ± 0.35	[−0.25, 0.33]
	LL/Pelvis	0.31 ± 0.24	0.50 ± 0.59	[−0.24, 0.60]

Values given are Mean ± SD

* Significant difference between groups ($P < .05$)

Bold values represent very strong correlations

CI Confidence Interval, *UT* Upper Thoracic, *LT* Lower Thoracic, *UL* Upper Lumbar, *LL* Lower Lumbar

ROM of regional spine segments in the three anatomical planes

3-dimensional ROM mean values of all analyzed segments were reported in Fig. 3 for both groups, which showed no significant difference between groups. The regional segment motions of the sagittal plane in the thoracic and lumbar spine were observed wider than the frontal or transverse plane during gait (ROM_{range_X}:2.78–19.23; ROM_{range_Y}:4.02–4.51; ROM_{range_Z}:1.66–8.78).

In Table 4, the correlation coefficient values (R_{ROM}) between segment pairings showed a different variability to R_{xy} across segment couplings and participant groups. The significant correlation results, which mainly in the healthy controls, were reported in the LT/UL ($p = 0.035$, $r_{ROM} = 0.636$) and UL/LL ($p = 0.026$, $r_{ROM} = 0.664$) pairings in the sagittal plane and the UL/LL pairing in the frontal plane ($p = 0.035$, $r_{ROM} = 0.636$). Most R_{ROM} values demonstrated very weak to moderate correlations (Number of pairings:21/24; R_{ROM_range}:0.002–0.562). Finally, the R_{ROM} values were visualized into corresponding color bars based on the five levels of correlation coefficients (Fig. 4).

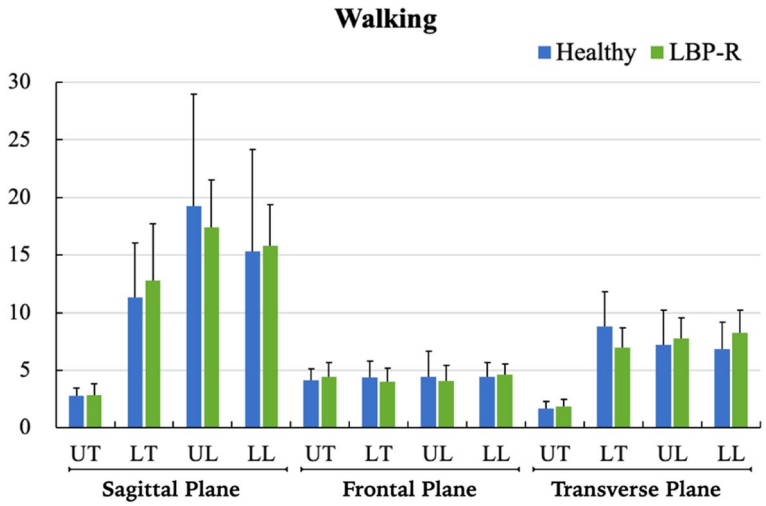

Fig. 3 ROM mean (± standard deviation) of thoracic and lumbar spine segments in the 3 anatomical planes when walking analyzed for healthy control (blue bars) and LBP-R (green bars) groups

Table 4 R_{ROM} values between spine adjacent segments in both groups assessed in the three anatomical planes

		LBP-R	Control
Sagittal Plane	UT/LT	−0.004	−0.062
	LT/UL	0.382	**0.636***
	UL/LL	0.141	**0.664***
	LL/Pelvis	−0.002	−0.045
Frontal Plane	UT/LT	0.379	0.487
	LT/UL	−0.194	0.200
	UL/LL	0.300	**0.636***
	LL/Pelvis	0.558	−0.140
Transverse Plane	UT/LT	0.504	0.501
	LT/UL	0.454	0.345
	UL/LL	0.562	0.164
	LL/Pelvis	0.170	0.483

Bold values represent strong to very strong correlations

Significant correlations are indicated with *(< .05)

UT Upper Thoracic, *LT* Lower Thoracic, *UL* Upper Lumbar, *LL* Lower Lumbar

Discussion

The study used a multi-segmental spine model to examine trunk control of the LBP-R population during gait, focusing on lumbar muscle activity and thoracic-lumbar kinematics. Results showed increased lumbar ES activation during the swing phase and reduced movement redundancy between adjacent spinal segments in the sagittal plane.

However, to generalize these findings to the entire population, a larger sample size is essential.

Regional spine kinematics

This study used the cross-correlation coefficient between adjacent segments to calculate the R_{xy} as a time-varying value of segmental redundancy. The R_{xy} results could help us understand how the spine coordinated within inter-segments and maintained a complicated interplay between stability and mobility during gait despite suffering local injuries. R_{xy} values of the UT/LT, LT/UL, and LL/Pelvis pairings in the sagittal plane of the LBP-R group were significantly different from the controls in this study. The previous restriction of the multi-segmental spine kinematics focused on the frontal and transverse planes, while the sagittal plane was seldom referred to before [6]. Thus, the results of segmental redundancy in the sagittal plane, as the primary characteristic of the LBP-R group in this study, could be interpreted as a maladaptive and prolonged strategy, responding to back pain or the fear of pain [33, 34].

At the same time, this study first found the LBP-R group exhibited a very strong correlation in the UT/LT pairing of the sagittal plane, which implied the significance of the thoracic movement on LBP. The prior study has reported that the thoracic movement would occur before lumbar onset and might play a pivotal role in developing maladaptive spinal behaviours [35]. When considering the reverse result of the adjacent pairings between the UT/LT ($R_{xy\_LBP\text{-}R}$: 0.93; $R_{xy\_control}$: 0.22) and the LT/UL ($R_{xy\_LBP\text{-}R}$: 0.17; $R_{xy\_control}$: 0.52) in the sagittal plane, prior studies provided an inter-vertebral insight into spinal interactions within the anatomical plane and might explain the different behaviours of the segmental redundancy. The common analysis of regional spine kinematics is usually concentrated on a single plane

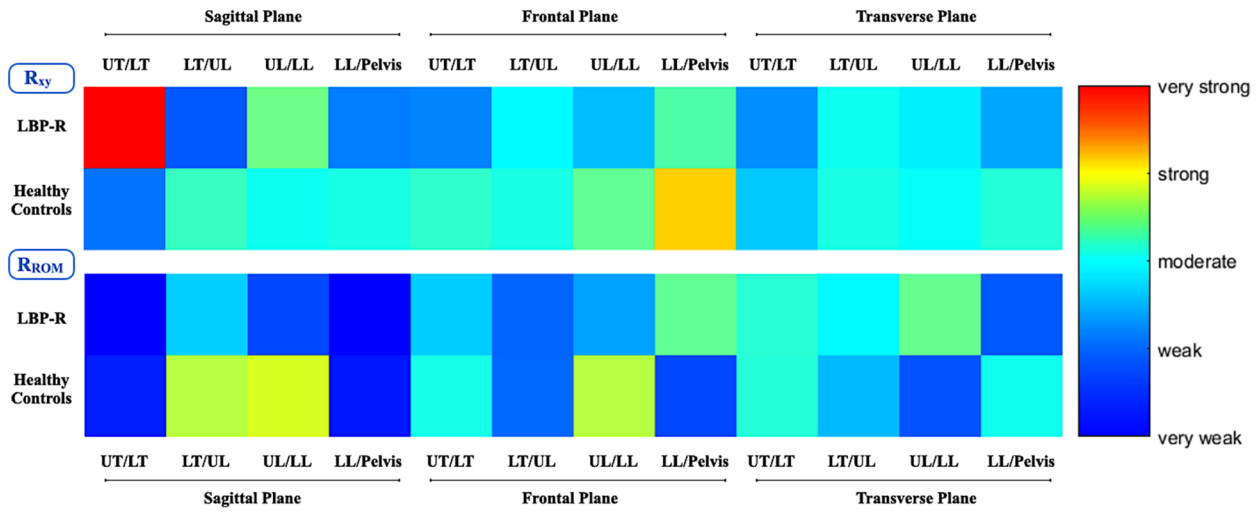

Fig. 4 Rxy and RROM values corresponding to the different color bars based on the five levels of the correlation coefficients, including: very weak (0.00–0.19), weak (0.20–0.39), moderate (0.40–0.59), strong (0.60–0.79) and very strong (0.80 –1.00)

rather than the coordination patterns of the monoplane or multiplanar. Due to the kinematic coupling system in the spine, the motor disorder in one of the planes tends to be compensated by the other two planes [36]. Thus, aside from planar motions, combined three-dimensional motions should also be included in further study, which is currently short of consolidated calculation methods of kinematic couplings between spinal segments.

Although this study divided the results of the R_{xy} and R_{ROM} into several levels, the increased correlation coefficient values were not always parallel to better spinal health. More criteria for the assessment of spinal kinematics should be established. For example, compared with the movement pattern of the spine between adjacent segments, the fluctuating variability of the total results in the LBP-R group might be the true reflection of spine kinematic alterations. In the future, the persuasive analysis of dynamic spinal alignment changes and compensation should be detected among the LBP-R group [37, 38].

Lumbar muscle activation

The result of higher left-side lumbar ES muscle activation during the ipsilateral swing phase in the LBP-R group corresponded to the evidence from the previous studies on chronic LBP [39, 40]. This finding supported the characteristics of muscle activation patterns in the type of stiffness trunk control. However, the possible explanation for this increase has not been determined, such as a protective strategy to compensate for spinal instability or excessive demand on the superficial muscles to generate high stress on the spine and exhibit guarded movement. Both muscularskeleton strategies could result from either an adaptation process to protect the low back or direct interference of back pain and related changes with trunk motor control [5]. However, persistent issues, such as increased loading and reduced movement, may compromise spine health. Therefore, later-stage clinical strategies should reduce excitability and co-contraction while promoting movement and its variability [41]. More studies on back and abdominal muscle activation patterns for the LBP-R group should be conducted.

All participants in this study were right-handed. Therefore, the significant result of left-side lumbar ES muscle activity implied the effect of hand dominance. Unbalanced muscle responses would prompt a decreased, uncoordinated, asymmetric bracing effect, thereby worsening the abnormal performance of non-dominant-side back muscles. Previous studies have referred to that in the early years but lack thorough evidence of biomechanics even today [42, 43]. This study did not detect a significant difference in MF muscle activation between groups. That might be explained as most participants were low-level experiencers of LBP, not severe enough to evoke the alteration of deep muscle fibres. On the other hand, the persisting pain might make the LBP patients learn to avoid painful motor solutions, thus modifying tissue loads and distributing stresses more evenly. However, these explanations required further detection through other functional tasks or more ultrasonic testing [2, 23]. Prior studies demonstrated that when lumbar ES muscle activity increased, there was a reduction in the maximal intervertebral motion at the lower lumbar, which suggested regional compensation strategies [44]. However, we did not apply the analysis of subphase to the regional spine motions in this study. It was difficult to clarify the detailed connections between lumbar kinematics and muscle activity, which could help strengthen the understanding of spinal stability and sub-system interactions in further study.

Trunk control strategy

In prior studies, the LBP group tends to choose a specific type of trunk control, like a "tighter" one or a "looser" one, equipped with obviously muscular or kinematic characteristics [4]. However, based on the findings in this study, people seem to adopt a more heterogeneous and interactive strategy of trunk control during the symptom remission stage. Several studies recently reported that LBP people persistently take an altered motor control strategy of muscle activity and spine kinematics adaptations even after pain compared with healthy controls [3, 21, 45]. These synthesized changes extend beyond the duration of a painful episode and could lead to potential long-term consequences, such as pain recurrence. Nevertheless, we did not know whether the degree of motor alterations would fluctuate along with the pain remission. In addition, researchers have proved that LBP people would adapt movement variability to compensate for the function between regions or muscles, but the direction of the changes could not be consistent across current studies [46]. The coexistence of significant symptoms may change gait because of the pain or adaptation of the musculoskeletal structures or both. A history of LBP without the overlay of a current symptomatic episode allows a better model to explore the impact on spinal coordination during walking. Although small, there were indicators that spinal movement and coordination alterations in subjects with recurrent LBP were due to adaptive changes rather than the presence of pain [13]. Furthermore, more than finding out a particular muscle or joint disorder, dealing with the coordination or harmony of the entire body might be better for clinical rehabilitation on non-specific LBP patients [47].

Limitations

There are limitations in this study that need to be considered. Firstly, more female participants and different pain severity of people with LBP history were required in the future [48]. Secondly, the current study did not set the markers at the sternum, which was essential to accurately describe the spine's motion [16]. Although the regional spinal kinematics and lumbar muscle activation were analyzed in this study, there is an apparent lack of synchronized investigation into relationships between them, which might provide an expansive view of trunk control [49]. Lastly, longitudinal studies covering different pain statuses for people with LBP are necessary to observe the changing process of pain and its effect on motor control.

Conclusion

The LBP-R group exhibited a varied trunk control strategy in gait, including higher left-side lumbar ES activation during the ipsilateral swing phase and altered segmental redundancy mainly focused in the sagittal plane. Insights of using a multi-segmental spine model in the symptom remission stage among the LBP group are significant to detecting the adaptive changes of regional spine kinematics. The findings above may improve normalized exercise rehabilitation approaches and provide new views of the long-lasting effects on back pain.

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Authors' contributions

Conceptualization and methodology, X.X., Y.S. and S.I.; data collection and analysis, X.X., Y.S. and K.H.; writing—review and editing, X.X., Y.S., K.H. and S.I. All authors have read and agreed to the published version of the manuscript.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

All participants provided written informed consent. The study was approved by the Ethics Institutional Review Board of Tohoku University Graduate School of Medicine (2021–1-049).

Consent for publication

All participants provided consent for publication of their data.

Competing interests

The authors declare no competing interests.

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