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DOI:
10.1016/j.jelekin.2023.102832

Journal of Electromyography and Kinesiology 73 (2023) 102832

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

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

Spinal kinematic variability is increased in people with chronic low back pain during a repetitive lifting task

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ARTICLE INFO

Keywords:
Spine
Lumbar
LBP
Kinematic
Variability
Lifting

ABSTRACT

Changes in spinal kinematic variability have been observed in people with chronic non-specific LBP (CNSLBP) during the performance of various repetitive functional tasks. However, the direction of these changes (i.e., less or more kinematic variability) is not consistent. This study aimed to assess differences in kinematic variability of the 3D angular displacement of thoracic and lumbar spinal segments in people with CNSLBP compared to asymptomatic individuals during a repetitive lifting task. Eleven people with CNSLBP and 11 asymptomatic volunteers performed 10 cycles of multi-planar lifting movements while spinal kinematics were recorded. For the three planes of motion, point-by-point standard deviations (SDs) were computed across all cycles of lifting and the average was calculated as a measure of kinematic variability for both segments. People with CNSLBP displayed higher thoracic ($F = 8.00$, $p = 0.010$, $\eta p^2 = 0.286$) and lumbar kinematic variability ($F = 5.48$, $p = 0.030$, $\eta p^2 = 0.215$) in the sagittal plane. Moreover, group differences were observed in the transversal plane for thoracic ($F = 7.62$, $p = 0.012$, $\eta p^2 = 0.276$) and lumbar kinematic variability ($F = 5.402$, $p = 0.031$, $\eta p^2 = 0.213$), as well as in the frontal plane for thoracic ($F = 7.27$, $p = 0.014$, $\eta p^2 = 0.267$) and lumbar kinematic variability ($F = 6.11$, $p = 0.022$, $\eta p^2 = 0.234$), all showing higher variability in those with CNSLBP. A significant main effect of group was not detected ($p > 0.05$) for spinal range of motion (ROM). Thus, people with CNSLBP completed the lifting task with the same ROM in all three planes of motion as observed for asymptomatic individuals, yet they performed the lifting task with higher spinal kinematic cycle-to-cycle variation.

1. Introduction

Low back pain (LBP) is one of the major leading causes of disability globally [Abrams et al, 2020, Hartvigsen et al, 2018]; chronic non-specific LBP (CNSLBP) accounts for the vast majority of cases [van Tulder et al, 2006]. Alterations in trunk movement patterns have been observed in people with LBP, however, the underlying mechanisms behind these motor control changes remains poorly understood [Hodges and Tucker, 2011, van Dieën et al, 2019]. Numerous studies have studied trunk movement patterns and trunk muscle activity in an attempt to understand strategies of trunk motor control in association with LBP [van Dieën et al, 2019]. One of the well-established strategies of motor adaptation to LBP are changes in spine kinematics, such as changes in trunk angular displacement, velocity, acceleration, as well as changes in the variability of these kinematic variables [Gizzi et al, 2019, Hodges and Smeets, 2015, Vaisy et al, 2015, van Dieën et al, 2017].

Kinematic variability is crucial when performing activities of daily living with high repeatability as well as in occupational settings [Abboud et al, 2014]. Repetitive lifting is one of the common functional tasks that has a reported causative role in LBP development and has frequently been investigated to better understand potential injury risks and strategies to improve lifting performance [Abdoli-Eramaki et al, 2019]. Yet, the majority of these studies explored lift-to-lift variability to understand the physical demands of the task in healthy individuals in

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https://doi.org/10.1016/j.jelekin.2023.102832
Received 28 July 2023; Received in revised form 26 September 2023; Accepted 13 October 2023
Available online 14 October 2023

order to optimise ergonomics [Oomen et al. (2023a); Oomen et al. (2023b), Tetteh and Mirka, 2018, Tetteh and Mirka, 2021]. The quantitative analysis of such inherent motor control variability during trunk repetitive movements was frequently driven from linear measures of spine kinematics such as range of motion, velocity or acceleration. Alterations in kinematic variability among people with LBP has also been observed as aberrant movement patterns when patients are asked to perform active trunk movements in different planes of motion during the physical examination [Biely et al, 2014, Gombatto et al, 2007, Marich et al, 2020]. These quantitative and qualitative analyses of kinematic features suggest inconsistent intra-individual movement variability when people with CNSLBP execute repetitive trunk movements [Dijk et al, 2021, Wattananon et al. (2023)].

A limited number of studies have explored kinematic variability during repetitive lifting in people with CNSLBP [Asgari et al, 2017, Bauer et al, 2015, Dideriksen et al, 2014, Fujii et al, 2022, Moreno Catalá et al, 2018, Pranata et al, 2018]. One study identified that the variability of lumbar movement patterns, in terms of angular displacement, was altered in those with greater LBP intensity as they performed a repetitive lifting task [Bauer et al, 2015]. However, most studies have explored coordination variability during repetitive lifting tasks in one plane of motion (trunk flexion and extension) and they have failed to identify different kinematic variability patterns in people with CNSLBP compared to asymptomatic individuals [Asgari et al, 2017, Fujii et al, 2022, Pranata et al, 2018].

The purpose of this study was to assess differences in kinematic variability of 3D angular displacement of two spine segments (thoracic and lumbar) in people with CNSLBP compared to asymptomatic individuals as they performed a cyclic lifting task performed in a multi-planar pattern. We hypothesised that people with CNSLBP would present with differences in motor control strategies revealed as a change in spinal kinematic variability given the more complex, multi-planar nature of the lifting task.

2. Methods

This was an observational study, conducted at the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine) at the University of Birmingham. Ethical approval for the study was granted by the University Ethics Committee (Approval number: ERN_16-1389B), and the study was conducted according to the Declaration of Helsinki. All participants provided written informed consent. The study is reported in line with the STROBE guidelines [von Elm et al, 2008].

2.1. Participants

Twenty-two volunteers (men and women) aged 18–65 years were recruited from the student and staff community of the University of Birmingham, UK via poster and social media advertisements. Participants with CNSLBP were eligible if they had experienced LBP symptoms for more than three of the previous six month [Dionne et al. (2008)]. LBP participants were excluded if their pain was related to trauma, spinal stenosis, fractures, or if they experienced radiating leg pain. Age and BMI matched control participants were recruited and had to have no history of low back or lower limb pain which warranted attention from a healthcare practitioner. Participants from both groups were excluded if they were on high doses of anti-inflammatories (>30 mg morphine equivalent dose), pregnant, or were experiencing any concurrent systemic, rheumatic or neuro-musculoskeletal disorders which could confound testing.

2.2. Questionnaires

Baseline characteristics of participants were assessed by questionnaires prior to data collection. Anthropometric data were recorded at the beginning of the session. For the LBP participants, a bespoke back pain questionnaire was used to collect information on their LBP history and intensity which was assessed using a Pain Numeric Rating Scale (PNRS) [Breivik et al, 2008]. In addition, participants from both groups were required to complete several questionnaires including back disability assessed using the Oswestry Disability Index (ODI) [Fairbank and Pynsent (2000)], and their beliefs and fears about movement related to pain assessed by the Fear Avoidance Beliefs Questionnaire (FABQ) [Waddell et al, 1993]. Moreover, recent activity levels were assessed by the International Physical Activity Questionnaire (IPAQ) [Craig et al, 2003] and recent mental health by the Depression, Anxiety and Stress Scale (DASS-21) [Henry and Crawford, 2005, Lovibond and Lovibond, 1995]. General health at the time of data collection was assessed using the SF-36 (V2) [Walsh et al. (2003)]. Finally, the Borg Rating of Perceived Exertion (RPE) scale was used to measure the exertion rate after the performance of the lifting task [Borg, 1998].

2.3. Lifting task

The task consisted of a repetitive loaded lifting task between six shelves positioned in front and to the sides of the participant. In order to reduce the load on the low back during task performance, ergonomic interventions were applied individually for each participant by adjusting the location and height of each shelf based on their anthropometry [Faber et al, 2007]. Using adjustable shelves and palatable anatomical landmarks, the height and positions of shelves were determined (Fig. 1).

To reflect a task of lifting that may be encountered in daily living, the participants were asked to repetitively lift a standardised weight (5 kg) (35.5cm x 29cm x 13.5cm) in a multi-planar pattern of movement between the six shelves. The weight was standardized to ensure consistency and comparability among participants, while the choice of a 5 kg weight was based on it being considered manageable yet challenging enough to elicit physical exertion. To complete the task, participants were required to stand in a quiet standing position, with their heels 17 cm apart and feet at a 14° angle to each other [McIlroy and Maki, 1997]. From the standing position, participants performed 10 cycles of lifting. Specifically, the lifting task required the participant to move the box from the lower shelf-1 (S1) to a sequential shelf (e.g., S2), and then return to the starting position on S1, before moving to the next sequential shelf (i.e., S3, S4, S5, and S6), with rest between movements. Thus, S1 was identified as the start and the end of each lifting movement. For example, moving from S1 to S5 then back to S1 was defined as one complete lifting movement. In total, each participant completed 10 cycles of 5 lifting movements (i.e., S1-S2-S1,…, S1-S6-S1). In order to control the speed, the rhythm of the task was controlled by a metronome (30 beats per minute) with 2s allocated to each lifting movement followed by a rest of 2s. Participants were asked to not move their feet during lifting and to try to limit knee movement, but no further instructions were given regarding the lifting technique.

Before starting, the task was explained by researchers using standardised instructions, and a demonstration of one complete cycle was given. Participants were then allowed to practise one complete timed cycle with an unweighted box to ensure that the pattern and lifting technique at the knees and feet were performed as instructed. The task was completed in one continuous acquisition lasting approximately 7 min in total. Following task completion, participants were asked to rate their perceived effort using the RPE scale.

2.4. Motion capture

Three-dimensional movements of the trunk were captured using eight infrared cameras (BTS Bioengineering, Milan, Italy). The kinematic data was acquired at a frequency of 250 Hz following system calibration. A modified version of a previously described kinematic trunk model was used [Müller et al, 2016]. Ten reflective markers (14 mm) were placed with double-sided tape over the anatomical landmarks as illustrated in Fig. 2 in order to define two spinal segments. The

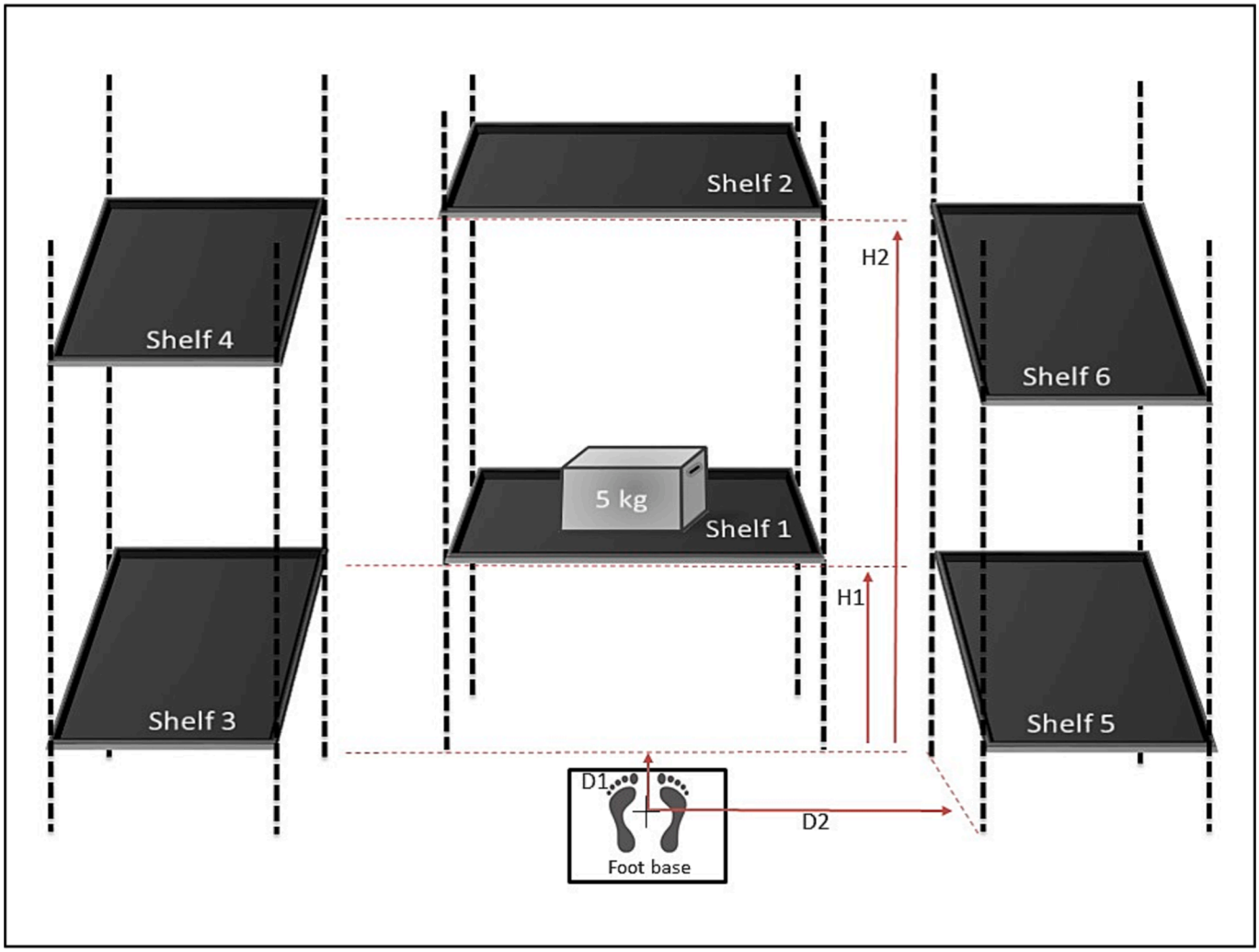

Fig. 1. Illustration of the experimental set-up showing the six adjustable shelves and the distance of the shelves from the foot-base which is located half-way between the two olecranon processes when the arms are abducted 90°. **D1**: the distance from acromion process to the ulnar styloid process when the arms are flexed 90°; **D2:** from the foot-base to the olecranon processes when the arms are abducted 90°. **H1:** the height of the lower shelves to the lateral femoral epicondyle height; **H2** the height of the upper shelves to manubriosternal angle height.

markers were placed in triangular patterns overlying the spine to facilitate division of the spinal regions into segments (Fig. 2). Reflective markers were also placed on the box, and the distal edge of each shelf (S1-S6).

2.5. Processing of 3D kinematic data

Using BTS SMART software suite (SMART Tracker& Analyzer; BTS Bioengineering, Italy), data from the reflective markers were tracked and labelled using a custom kinematic model for the trunk. Data were then processed using Matlab (R2022a, MathWorks, Natick, MA, USA). First, the 3D kinematic data obtained during the repetitive lifting task were interpolated and smoothed using a 2nd order Butterworth low-pass filter with a cut-off frequency of 5 Hz [Sanderson et al, 2019]. Then, the fifty continuous cycles (5 cycles × 10 times each) were divided into 50 separate trials using the markers positioned on the six shelves and the displacement of the marker placed on the box. Subsequently, each cycle was time-normalized to obtain 101 samples per cycle (0–100 % of cycle time) [Asgari et al, 2015].

The markers along the subject's spine were divided into a group of four markers in triangular patterns to define the two trunk segments (Fig. 2). The thoracic segment (TS) was defined by the markers on T12, T6 and 10 cm lateral to T6; the lumbar segment (LS) was defined by the markers on the S1, T12 and 10 cm lateral to T12. A Cartesian axis system was created for each trunk segment. In addition to the global coordinate system of the laboratory, a local coordinate system was defined at the pelvis level using three markers on the S1 and right and left iliac crest. Spinal angular displacement was expressed as the relative Euler angle of the movement of each spine segment with respect to the adjacent segment below, with the thoracic segment being relative to the lumbar segment and the lumbar segment relative to the pelvis. The three-dimensional rotation angles were calculated using an X-Z-Y (Frontal - Sagittal - Transverse) Cartesian sequence (Fig. 3) [Cotter et al, 2014, Needham et al, 2016, Preuss and Popovic, 2010].

To analyse the range of motion (ROM) during lifting movements, the angular displacement of each spinal segment has been measured as participants moved from the starting position (S1) to each subsequent shelf in three planes of motion in order to quantify the ROM achieved by each participant, even within the defined constraints of shelf positions and levels.

To quantify the kinematic variability of the spine angular displacement (thoracic, lumbar), point-by-point standard deviations (SDs) were computed across all 10 cycles for the five lifting movements in three planes of motions then averaged to measure the MeanSDs (Fig. 3) [Asgari et al, 2015].

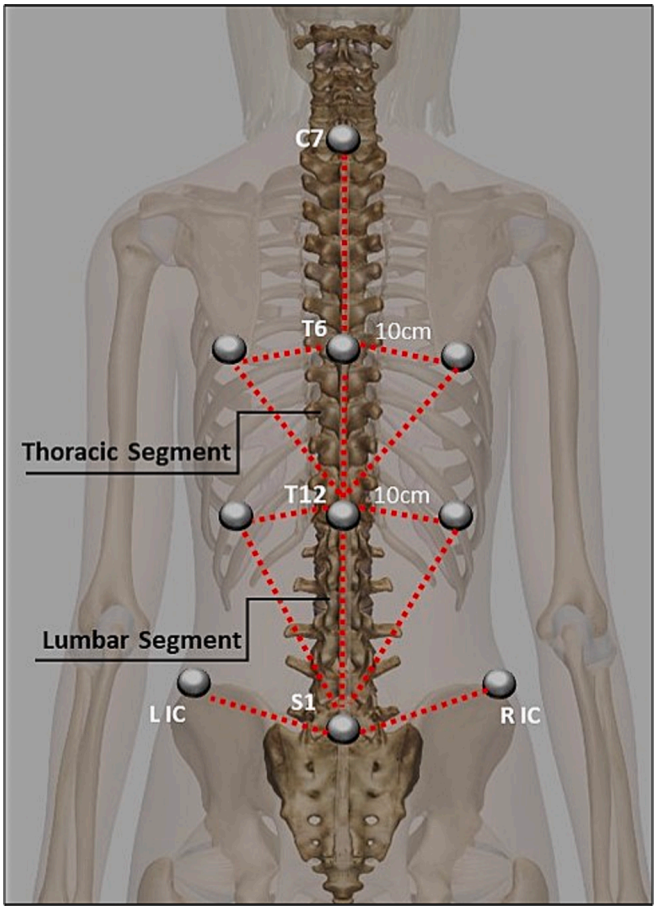

Fig. 2. Marker placement and segmentation for the spine kinematic model; the markers were adhered to the skin overlying 7th cervical vertebra **(C7),** 6th thoracic vertebra **(T6),** 12th thoracic vertebra (**T12**) and 1st sacral vertebra (**S1**), right iliac crest **(R IC)** and left iliac crest **(L IC)**.

2.6. Statistical analysis

Normal distribution of the data was confirmed using a Shapiro–Wilk test and thus parametric tests were applied. Independent t-tests were used to compare differences in anthropometric data and clinical characteristics between groups. Separately for each plane of motion, two-way mixed Analysis of Variance (ANOVA) were conducted to compare main and interaction effects of group (control vs. CNSLBP; between subject factor), and shelves (S1-S2-S1,…, S1-S6-S1; within-subject factor) on thoracic and lumbar kinematic variability (MeanSDs). Whenever main effects were identified by ANOVA, Bonferroni post-hoc test was used for pairwise comparisons. The same analysis was also performed to assess spinal ROM (i.e., thoracic and lumbar angular displacement). Effect sizes were reported where appropriate with ANOVA results, in the form of ηp^2 values [Lakens, 2013]. Statistical analysis was performed using SPSS 29 (IBM, USA) with an alpha level set at $\alpha = 0.05$. All results are expressed as mean and standard deviation (Mean ± SD).

3. Results

Participants' characteristics are presented in Table 1. No significant anthropometric differences were found between groups for age or BMI ($P > 0.05$). The CNSLBP group reported mild current LBP intensity of 2.82/10 (±2.04), minimal disability level based on the ODI (15.59 ± 7.82 %) and reported moderate exertion during the task on the Borg scale (12.55 ± 1.80). As expected, those with CNSLBP presented with significantly higher degrees of back disability, fear of movement, and greater perceived exertion compared with asymptomatic individuals.

There was no significant main effect of group for the range of thoracic angular displacement in the sagittal plane while performing the lifting movement ($F = 1.34$, $p = 0.260$, $\eta p^2 = 0.063$). However, there was a main effect of shelf ($F = 13.83$, $p < 0.001$, $\eta p^2 = 0.40$), but no interaction effect between group and shelf ($F = 2.03$, $p = 0.140$, $\eta p^2 = 0.092$). In addition, there was also no significant main effect for group on the range of lumbar angular displacement in the sagittal plane ($F = 0.98$, $p = 0.332$, $\eta p^2 = 0.047$). Moreover, there was a main effect of shelf ($F = 18.84$, $p < 0.001$, $\eta p^2 = 0.40$), however, no interaction effect between group and shelf ($F = 0.19$, $p = 0.843$, $\eta p^2 = 0.009$).

In the transversal plane, there was no significant main effect of group on the range of thoracic angular displacement during the lifting movement ($F = 2.88$, $p = 0.105$, $\eta p^2 = 0.126$). However, there was again a main effect of shelf ($F = 8.14$, $p = 0.005$, $\eta p^2 = 0.28$), but no interaction effect between group and shelf ($F = 0.37$, $p = 0.594$, $\eta p^2 = 0.019$). In addition, there was no significant main effect of group on the range of lumbar angular displacement in the transversal plane during the lifting movement ($F = 0.74$, $p = 0.397$, $\eta p^2 = 0.036$). Moreover, there was no main effect of shelf ($F = 2.94$, $p = 0.064$, $\eta p^2 = 0.128$), nor interaction effect between group and shelf ($F = 2.13$, $p = 0.131$, $\eta p^2 = 0.097$).

In the frontal plane, there was no significant main effect of group on the range of thoracic angular displacement while performing the lifting movements ($F = 1.91$, $p = 0.182$, $\eta p^2 = 0.087$). There was also no main effect of shelf ($F = 1.85$, $p = 0.163$, $\eta p^2 = 0.085$) or an interaction effect between group and shelf ($F = 1.22$, $p = 0.307$, $\eta p^2 = 0.058$). Furthermore, there was no significant main effect of group on the range of lumbar angular displacement in the frontal plane during the lifting movement ($F = 3.27$, $p = 0.085$, $\eta p^2 = 0.141$). However, there was a main effect of shelf ($F = 13.4$, $p < 0.001$, $\eta p^2 = 0.401$); but no interaction effect between group and shelf ($F = 2.38$, $p = 0.093$, $\eta p^2 = 0.124$).

The range of angular displacement for each segment are presented in Table 2 in degrees of motion (°) and are expressed as Mean ± SD.

3.1. Differences in kinematic variability

3.1.1. Sagittal plane

For the thoracic segment, there was a significant main effect of group showing that people with CNSLBP displayed higher thoracic kinematic variability ($F = 8.00$, $p = 0.010$, $\eta p^2 = 0.286$) compared with healthy controls, independent of the five lifting movements. Thoracic kinematic variability for the CNSLBP group was 6.29°±0.70(SE), whereas for the healthy controls it was 3.48°±0.70(SE) with a mean difference of 2.81° and 95 % confidence interval (95 %CI) = 0.645, 2.23. In addition, there was a significant main effect for shelf ($F = 13.25$, $p < 0.001$, $\eta p^2 = 0.39$); thoracic kinematic variability was found to be higher for movements to the lower shelves (S3, S5) compared with the upper shelves (S4, 5, 6) (Bonferroni post-hoc results are shown in Table 3). Nevertheless, no interaction effect was observed between group and shelf ($F = 2.66$, $p = 0.095$, $\eta p^2 = 0.118$) (Fig. 4).

For the lumbar segment, there was a significant main effect for group and people with CNSLBP had greater lumbar kinematic variability ($F = 5.48$, $p = 0.030$, $\eta p^2 = 0.215$) compared with healthy controls, independent of the five lifting movements. Lumbar kinematic variability for the CNSLBP group was 5.69°±0.68(SE), whereas for the healthy controls it was 3.43°±0.68(SE) with a mean difference of 2.25° and 95 %CI = 0.246, 4.267. There was a significant main effect of shelf ($F = 14.51$, $p < 0.001$, $\eta p^2 = 0.42$); lumbar kinematic variability was found to be higher for movements to the lower shelves (S3, S5) compared with the upper shelves (S4, 5, 6) (Bonferroni post-hoc results are shown in Table 3). However, no group by shelf interaction effect was observed for lumbar kinematic variability ($F = 1.10$, $p = 0.346$, $\eta p^2 = 0.052$) (Fig. 4).

3.1.2. Transverse plane

For thoracic segment, there was a significant main effect of group revealing that people with CNSLBP showed higher thoracic kinematic

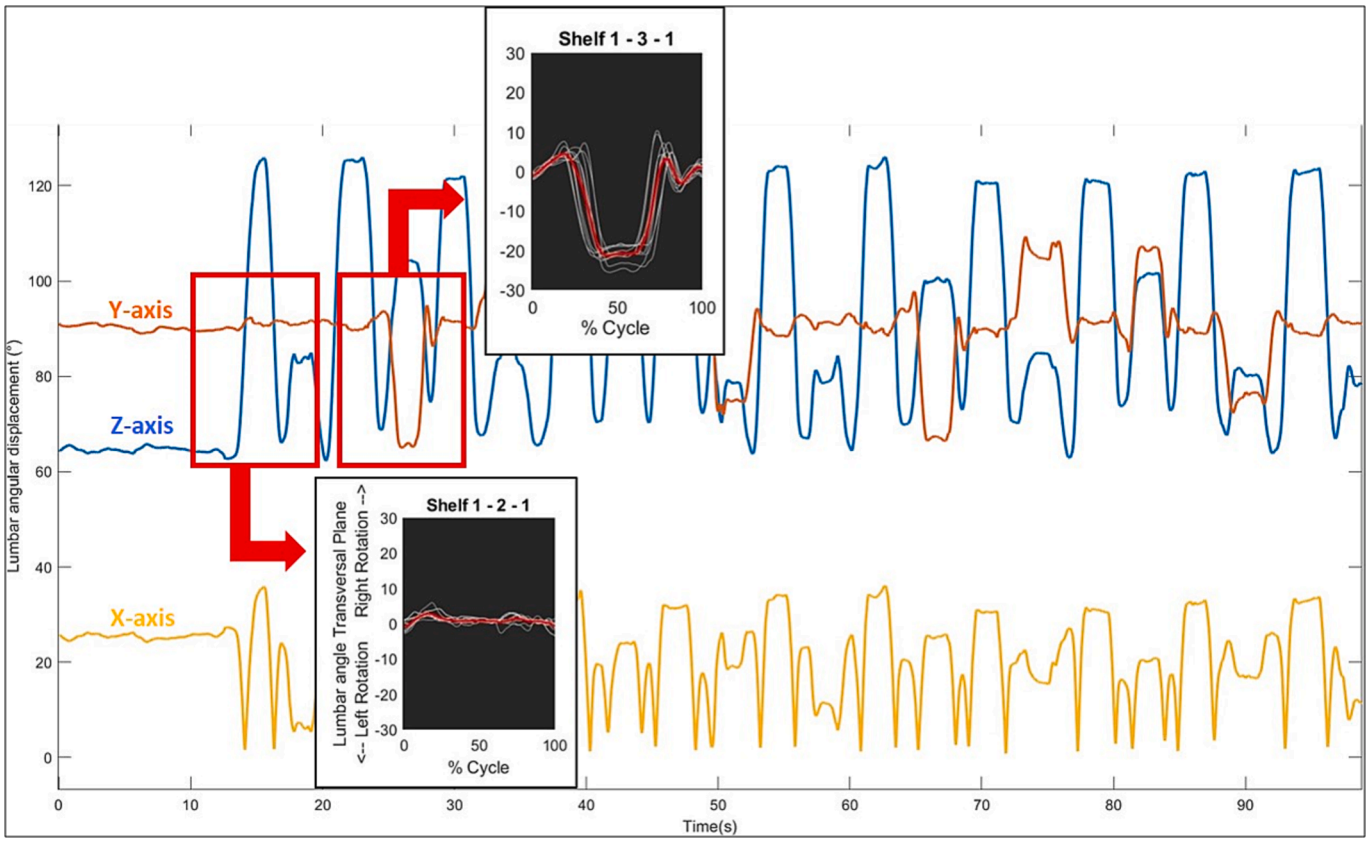

Fig. 3. An example outcome of lumbar angular displacements measured in three planes of motion (XYZ); (x-axis). Frontal, (z-axis): Sagittal, (y-axis): Transversal. Additionally, an example is presented of an extracted measure of kinematic variability as MeanSDs from the first and second lifting movement from transversal plane.

Table 1
Participant anthropometrics and questionnaires, data presented as Mean ± SD. **BMI:** body mass index, **IPAQ:** International Physical Activity Questionnaire, **ODI**: Oswestry Disability Index, **PNRS:** Pain Numeric Rating Scale, **FABQ:** Fear Avoidance Beliefs Questionnaire, **DASS-21:** Depression, Anxiety and Stress Scale, **RPE:** Borg Rating of Perceived Exertion, **CNSLBP:** chronic non-specific low back pain.

	Control group (N = 11; ♂: 4, ♀ 7)	CNSLBP group (N = 11; ♂: 5, ♀ 6)	P-value Two-sided
Age (years)	24.27 ± 4.62	25.82 ± 8.32	$P = 0.597$
BMI (kg/m^2)	23.34 ± 4.71	25.17 ± 3.28	$P = 0.304$
IPAQ	83.33 % High	83.33 % High	–
SF-36 General Health	58.89 ± 2.04	49.38 ± 4.54	$P < 0.001^{***}$
ODI (%)	0.36 ± 1.20 %	15.59 ± 7.82	$P < 0.001^{***}$
Current PNRS	0	2.82 ± 2.04	$P < 0.001^{***}$
Last 24hrs PNRS	0	3.82 ± 2.18	$P < 0.001^{***}$
Average PNRS	0	5.32 ± 2.05	$P < 0.001^{***}$
FABQ- total	1.91 ± 4.11	26.73 ± 11.55	$P < 0.001^{***}$
DASS-21	9.82 ± 9.22	23.09 ± 28.83	$P = 0.161$
BORG (RPE) Scale	10.82 ± 1.83	12.55 ± 1.80	$P = 0.038^{*}$

* $p < 0.05$; $^{**}p < 0.005$
*** $p < 0.001$.

variability (F = 7.62, $p = 0.012$, $\eta p^2 = 0.276$) compared with healthy controls. Thoracic kinematic variability for the CNSLBP group was 5.96° ±0.73(SE), whereas for the healthy controls it was 3.08°±0.73(SE) with a mean difference of 2.87° and 95 %CI = 0.702, 5.043. Moreover, there was a significant main effect of shelf (F = 22.41, $p < 0.001$, $\eta p2 = 0.52$); thoracic kinematic variability was found to be higher for movements to the lower shelves (S3, S5) (Bonferroni post-hoc results are shown in Table 3). In addition, there was also an interaction effect observed between group and shelf, with only the CNSLBP group showing a significant change of thoracic kinematic variability with the lifting movements (F = 5.60, $p = 0.011$, $\eta p^2 = 0.219$) (Fig. 5).

For the lumbar segment, there was a significant main effect of group; people with CNSLBP displayed greater lumbar kinematic variability (F = 5.402, $p = 0.031$, $\eta p2 = 0.213$) compared with healthy controls, independent of the five lifting movements. Lumbar kinematic variability for the CNSLBP group was 5.28°±0.75(SE), whereas for the healthy controls it was 2.80°±0.75(SE) with a mean difference of 2.47° and 95 % CI = 0.254, 4.692. In addition, there was a significant main effect of shelf (F = 14.67, $p < 0.001$, $\eta p^2 = 0.42$); lumbar kinematic variability was found to be higher for movements to the lower shelves (S3, S5) (Bonferroni post-hoc results are shown in Table 3). However, no group by shelf interaction effect was observed for lumbar kinematic variability (F = 2.12, $p = 0.122$, $\eta p^2 = 0.096$) (Fig. 5).

3.1.3. Frontal plane

For the thoracic segment, there was a significant main effect for group revealing that people with CNSLBP showed higher thoracic kinematic variability (F = 7.27, $p = 0.014$, $\eta p^2 = 0.267$) compared with healthy controls. Thoracic kinematic variability for the CNSLBP group was 7.06°±0.79(SE), whereas for the healthy controls it was 4.03°±0.79 (SE) with a mean difference of 3.02° and 95 %CI = 0.686, 5.364. Moreover, there was a significant main effect of shelf (F = 24.43, $p < 0.001$, $\eta p^2 = 0.55$); thoracic kinematic variability was found to be higher for movements to the lower shelves (S3, S5) compared with the upper shelves (S4, 5, 6) (Bonferroni post-hoc results are shown in Table 3). In addition, there was also a group by shelf interaction effect (F = 3.61, $p = 0.049$, $\eta p^2 = 0.153$) (Fig. 6).

For the lumbar segment, there was a significant main effect of group; people with CNSLBP presented with greater lumbar kinematic

Table 2
Range of motion (ROM°) of thoracic and lumbar segments in three planes of motion while performing the lifting task.

Spinal segment: lifting movement	Group	ROM (°) Mean	SD
SAGITTAL PLANE			
TS: S1-2	Control	25.7076	23.79404
	CNSLBP	40.4448	30.34752
TS: S1-3	Control	35.2604	26.19830
	LBP	36.1412	22.00213
TS: S1-4	Control	24.6175	22.16953
	LBP	37.2505	28.97142
TS: S1-5	Control	9.6917	9.94578
	LBP	24.0107	22.65711
TS: S1-6	Control	27.6501	23.37993
	LBP	41.9509	30.28087
LS: S1-2	Control	24.1168	21.49180
	CNSLBP	34.1504	24.19698
LS: S1-3	Control	16.1412	12.86101
	LBP	23.8328	17.01420
LS: S1-4	Control	19.0390	17.03051
	LBP	26.8556	22.07910
LS: S1-5	Control	15.4389	14.54993
	LBP	22.7258	17.49828
LS: S1-6	Control	30.2190	23.26092
	LBP	36.9345	22.67231
TRANSVERSAL PLANE			
TS: S1-2	Control	0.9683	0.98345
	CNSLBP	2.0167	2.70154
TS: S1-3	Control	8.4676	7.15455
	LBP	17.5623	20.45796
TS: S1-4	Control	1.8536	1.73907
	LBP	3.3260	3.54669
TS: S1-5	Control	17.6183	20.53886
	LBP	20.1340	23.32670
TS: S1-6	Control	2.5131	1.51985
	LBP	4.9295	2.79128
LS: S1-2	Control	1.2955	1.17631
	CNSLBP	1.6796	1.75091
LS: S1-3	Control	2.8687	2.16165
	LBP	7.8367	8.59439
LS: S1-4	Control	8.7878	9.53290
	LBP	5.9735	9.55615
LS: S1-5	Control	8.5365	10.50324
	LBP	6.4309	4.31799
LS: S1-6	Control	2.7626	1.98506
	LBP	9.1921	9.77465
FRONTAL PLANE			
TS: S1-2	Control	1.4515	0.89976
	CNSLBP	0.3187	0.40559
TS: S1-3	Control	1.5263	1.00950
	LBP	1.6917	1.72632
TS: S1-4	Control	1.8074	1.36744
	LBP	1.5620	1.11343
TS: S1-5	Control	1.5833	1.31127
	LBP	1.4447	1.56585
TS: S1-6	Control	1.6872	1.45466
	LBP	0.9116	0.77797
LS: S1-2	Control	2.8065	1.74536
	CNSLBP	3.6037	2.85834
LS: S1-3	Control	1.9131	2.58310
	LBP	2.3729	2.77053
LS: S1-4	Control	4.5378	2.90925
	LBP	11.3994	9.29414
LS: S1-5	Control	1.1377	0.94547
	LBP	1.1069	1.46266
LS: S1-6	Control	5.3744	5.64915
	LBP	10.3013	8.82721

SD: Standard Deviation**: TS**: thoracic segment, **LS:** lumbar segment, **S1-2:** shelf1 to shelf2, **CNSLBP:** chronic non-specific low back pain.

variability (F = 6.11, $p = 0.022$, $\eta p^2 = 0.234$) compared with healthy controls and again this was independent of the five lifting movements. The lumbar kinematic variability for the CNSLBP group was 4.94°±0.43 (SE), whereas for the healthy controls it was 3.44°±0.43(SE) with a mean difference of 1.50° and 95 %CI = 0.236, 2.776. Further, there was a significant main effect of shelf (F = 8.15, $p < 0.001$, $\eta p^2 = 0.290$); lumbar kinematic variability was again found to be higher for movements to the lower shelves (S3, S5) (Bonferroni post-hoc results are shown in Table 3). However, no group by shelf interaction effect was observed for the measure of lumbar kinematic variability (F = 2.24, $p = 0.106$, $\eta p^2 = 0.101$) (Fig. 6).

4. Discussion

This study investigated the kinematic variability of spinal movement during repetitive lifting to test whether people with CNSLBP present with changes in trunk angular displacement variability as a potential motor adaptation to chronic pain. The results of this study showed no differences in thoracic nor lumbar ROM between asymptomatic individuals and people with CNSLBP when executing the repetitive loaded lifting task between six shelves arranged in a multi-planar manner. However, people with CNSLBP performed the task with significantly higher thoracic and lumbar kinematic variability between the ten cycles of lifting movements. This effect was observed for all five lifting movements in the sagittal, transverse and frontal planes of motion.

Recently, cross-sectional evidence demonstrated that people with LBP tend to lift with a slower and deeper squat with less spinal ROM compared to asymptomatic people [Nolan et al, 2020, Saraceni et al, 2021]. In the current study a similar ROM was observed for both groups, and this was expected given the standardization of the lifting task. The heights of the shelves which determined the ROM were individualized for each participant, therefore, no differences were expected or observed while executing the lifting movements [Matheve et al, 2019].

Interestingly, those with CNSLBP, despite performing the task with the same ROM as asymptomatic individuals, showed an altered strategy to execute the lifting task with higher cycle-to-cycle variation. Previous studies which have examined spinal kinematics during a repetitive lifting task have revealed that people with chronic LBP present with different movement control strategies when compared with asymptomatic individuals [Asgari et al, 2017, Bauer et al, 2015, Dideriksen et al, 2014, Fujii et al, 2022, Moreno Catalá et al, 2018, Pranata et al, 2018]. A more common observation in kinematic variability is an increase in kinematic variation in the sagittal plane of motion when picking up a box from the floor [Bauer et al, 2015]. The same finding was observed in the current study albeit while performing a more complex multi-planar lifting task.

There are several possible explanations for the increased spinal kinematic variability observed for those with CNSLBP, for example, it may reflect an attempt to avoid aggravating pain or an attempt to minimise back muscle fatigue. The relationship between motor variability and fatigue has been explored previously based on the variability in muscle activation [Falla et al, 2014, Farina et al, 2008], which revealed that higher variability can lead to longer endurance and reduced development of fatigue in healthy volunteers [Farina et al, 2008]. In contrast, people with LBP have reduced variability of back muscle activity during repetitive lifting tasks and this is thought to contribute to pain provocation during task performance [Falla et al, 2014]. In the current study however, people with CNSLBP presented with greater perceived exertion despite higher kinematic variability.

While pain and fatigue are considered potential explanations for the higher kinematic variability in CNSLBP people, other research proposes that changes in spinal kinematics may be influenced by psychological pain-related factors, such as fear of movement [Fujii et al, 2022, Fujii et al, 2021]. Although those with CNSLBP that were recruited in the current study presented with higher levels of fear of movement compared with asymptomatic individuals, the limited number of participants in our study prevented us from examining any potential associations between clinical and kinematic variables.

Table 3
Results of Bonferroni post hoc multiple comparisons for shelf effect on the thoracic and lumbar kinematic variability in all planes of motions.

SAGITTAL PLANE							
Thoracic Kinematic variability							
Shelf- Shelf:Mean (°)			**Mean Difference**	**Std. Error**	**Sig.**	**95 % Confidence Interval for Difference**	
						Lower Bound	**Upper Bound**
S2 (4.005)	S3	6.053	−2.049*	0.614	0.033	−3.984	-0.113
	S4	3.864	0.141	0.224	1.000	-0.565	0.846
	S5	6.905	−2.900*	0.812	0.019	−5.459	-0.340
	S6	3.639	0.365	0.299	1.000	-0.577	1.308
S3 (6.053)	S2	4.005	2.049*	0.614	0.033	0.113	3.984
	S4	3.864	2.189**	0.563	0.009	0.413	3.966
	S5	6.905	-0.851	0.381	0.371	−2.053	0.350
	S6	3.639	2.414**	0.619	0.009	0.461	4.368
S4 (3.864)	S2	4.005	-0.141	0.224	1.000	-0.846	0.565
	S3	6.053	−2.189**	0.563	0.009	−3.966	-0.413
	S5	6.905	−3.041**	0.751	0.006	−5.408	-0.674
	S6	3.639	0.225	0.412	1.000	−1.075	1.525
S5 (6.905)	S2	4.005	2.900*	0.812	0.019	0.340	5.459
	S3	6.053	0.851	0.381	0.371	-0.350	2.053
	S4	3.864	3.041**	0.751	0.006	0.674	5.408
	S6	3.639	3.265**	0.755	0.003	0.884	5.647
S6 (3.639)	S2	4.005	-0.365	0.299	1.000	−1.308	0.577
	S3	6.053	−2.414**	0.619	0.009	−4.368	-0.461
	S4	3.864	-0.225	0.412	1.000	−1.525	1.075
	S5	6.905	−3.265**	0.755	0.003	−5.647	-0.884
Lumbar Kinematic variability							
S2 (3.941)	S3	4.798	-0.857*	0.245	0.022	−1.629	-0.085
	S4	4.103	-0.162	0.165	1.000	-0.682	0.357
	S5	5.890	−1.950**	0.428	0.002	−3.298	-0.601
	S6	4.077	-0.137	0.211	1.000	-0.803	0.529
S3 (4.798)	S2	3.941	0.857*	0.245	0.022	0.085	1.629
	S4	4.103	0.695**	0.204	0.028	0.051	1.338
	S5	5.890	−1.092	0.373	0.082	−2.267	0.082
	S6	4.077	0.720	0.332	0.424	-0.327	1.768
S4 (4.103)	S2	3.941	0.162	0.165	1.000	-0.357	0.682
	S3	4.798	-0.695*	0.204	0.028	−1.338	-0.051
	S5	5.890	−1.787***	0.333	<0.001	−2.837	-0.738
	S6	4.077	0.025	0.215	1.000	-0.651	0.702
S5 (5.890)	S2	3.941	1.950**	0.428	0.002	0.601	3.298
	S3	4.798	1.092	0.373	0.082	-0.082	2.267
	S4	4.103	1.787***	0.333	<0.001	0.738	2.837
	S6	4.077	1.813*	0.389	0.002	0.586	3.039
S6 (4.077)	S2	3.941	0.137	0.211	1.000	-0.529	0.803
	S3	4.798	-0.720	0.332	0.424	−1.768	0.327
	S4	4.103	-0.025	0.215	1.000	-0.702	0.651
	S5	5.890	−1.813**	0.389	0.002	−3.039	-0.586
TRANSVERSAL PLANE							
Thoracic Kinematic variability							
S2 (2.775)	S3	7.202	−4.427***	0.785	<0.001	−6.903	−1.951
	S4	3.780	−1.005**	0.300	0.032	−1.951	-0.059
	S5	6.236	−3.461***	0.642	<0.001	−5.486	−1.437
	S6	2.627	0.148	0.395	1.000	−1.098	1.393
S3 (7.202)	S2	2.775	4.427***	0.785	<0.001	1.951	6.903
	S4	3.780	3.422***	0.662	<0.001	1.334	5.510
	S5	6.236	0.965	0.429	0.358	-0.387	2.318
	S6	2.627	4.575***	0.925	<0.001	1.657	7.492
S4 (3.780)	S2	2.775	1.005**	0.300	0.032	0.059	1.951
	S3	7.202	−3.422***	0.662	<0.001	−5.510	−1.334
	S5	6.236	−2.456**	0.602	0.006	−4.353	-0.559
	S6	2.627	1.153	0.400	0.092	-0.108	2.413
S5 (6.236)	S2	2.775	3.461***	0.642	<0.001	1.437	5.486
	S3	7.202	-0.965	0.429	0.358	−2.318	0.387
	S4	3.780	2.456**	0.602	0.006	0.559	4.353
	S6	2.627	3.609**	0.767	0.001	1.190	6.028
S6 (2.627)	S2	2.775	-0.148	0.395	1.000	−1.393	1.098
	S3	7.202	−4.575***	0.925	<0.001	−7.492	−1.657
	S4	3.780	−1.153	0.400	0.092	−2.413	0.108
	S5	6.236	−3.609**	0.767	0.001	−6.028	−1.190
Lumbar Kinematic variability							
S2 (2.495)	S3	5.586	−3.091***	0.592	<0.001	−4.957	−1.225
	S4	4.054	−1.559***	0.314	<0.001	−2.550	-0.568
	S5	4.542	−2.046**	0.495	0.005	−3.608	-0.485
	S6	3.538	−1.043	0.366	0.099	−2.198	0.112
S3 (5.586)	S2	2.495	3.091***	0.592	<0.001	1.225	4.957
	S4	4.054	1.532	0.517	0.077	-0.097	3.161
	S5	4.542	1.045	0.378	0.119	-0.147	2.236

(*continued on next page*)

Table 3 (*continued*)

SAGITTAL PLANE							
Thoracic Kinematic variability							
Shelf- Shelf:Mean (°)			**Mean Difference**	**Std. Error**	**Sig.**	**95 % Confidence Interval for Difference**	
						Lower Bound	**Upper Bound**
	S6	3.538	2.048**	0.490	0.005	0.503	3.593
S4 (4.054)	S2	2.495	1.559***	0.314	<0.001	0.568	2.550
	S3	5.586	−1.532	0.517	0.077	−3.161	0.097
	S5	4.542	-0.487	0.343	1.000	−1.568	0.594
	S6	3.538	0.516	0.349	1.000	-0.583	1.615
S5 (4.542)	S2	2.495	2.046**	0.495	0.005	0.485	3.608
	S3	5.586	−1.045	0.378	0.119	−2.236	0.147
	S4	4.054	0.487	0.343	1.000	-0.594	1.568
	S6	3.538	1.003*	0.288	0.023	0.097	1.910
S6 (3.538)	S2	2.495	1.043	0.366	0.099	-0.112	2.198
	S3	5.586	−2.048**	0.490	0.005	−3.593	-0.503
	S4	4.054	-0.516	0.349	1.000	−1.615	0.583
	S5	4.542	−1.003*	0.288	0.023	−1.910	-0.097
FRONTAL PLANE							
Thoracic Kinematic variability							
S2 (4.320)	S3	7.773	−3.453***	0.683	<0.001	−5.606	−1.301
	S4	4.353	-0.033	0.334	1.000	−1.086	1.019
	S5	7.820	−3.500**	0.771	0.002	−5.931	−1.069
	S6	3.474	0.846**	0.215	0.008	0.167	1.524
S3 (7.773)	S2	4.320	3.453***	0.683	<0.001	1.301	5.606
	S4	4.353	3.420***	0.559	<0.001	1.658	5.181
	S5	7.820	-0.047	0.362	1.000	−1.189	1.095
	S6	3.474	4.299***	0.731	<0.001	1.995	6.603
S4 (4.353)	S2	4.320	0.033	0.334	1.000	−1.019	1.086
	S3	7.773	−3.420***	0.559	<0.001	−5.181	−1.658
	S5	7.820	−3.467***	0.657	<0.001	−5.538	−1.396
	S6	3.474	0.879	0.445	0.621	-0.524	2.282
S5 (7.820)	S2	4.320	3.500**	0.771	0.002	1.069	5.931
	S3	7.773	0.047	0.362	1.000	−1.095	1.189
	S4	4.353	3.467***	0.657	<0.001	1.396	5.538
	S6	3.474	4.346***	0.852	<0.001	1.659	7.033
S6 (3.474)	S2	4.320	-0.846*	0.215	0.008	−1.524	-0.167
	S3	7.773	−4.299***	0.731	<0.001	−6.603	−1.995
	S4	4.353	-0.879	0.445	0.621	−2.282	0.524
	S5	7.820	−4.346***	0.852	<0.001	−7.033	−1.659
Lumbar Kinematic variability							
S2 (3.953)	S3	4.720	-0.767**	0.195	0.008	−1.380	-0.153
	S4	4.157	-0.204	0.319	1.000	−1.209	0.801
	S5	4.660	-0.707*	0.220	0.043	−1.399	-0.014
	S6	3.478	0.474	0.200	0.275	-0.155	1.104
S3 (4.720)	S2	3.953	0.767**	0.195	0.008	0.153	1.380
	S4	4.157	0.563	0.254	0.385	-0.238	1.364
	S5	4.660	0.060	0.130	1.000	-0.351	0.471
	S6	3.478	1.241***	0.249	<0.001	0.456	2.027
S4 (4.157)	S2	3.953	0.204	0.319	1.000	-0.801	1.209
	S3	4.720	-0.563	0.254	0.385	−1.364	0.238
	S5	4.660	-0.503	0.287	0.954	−1.409	0.403
	S6	3.478	0.678	0.371	0.822	-0.491	1.847
S5 (4.660)	S2	3.953	0.707*	0.220	0.043	0.014	1.399
	S3	4.720	-0.060	0.130	1.000	-0.471	0.351
	S4	4.157	0.503	0.287	0.954	-0.403	1.409
	S6	3.478	1.181**	0.248	0.001	0.399	1.963
S6 (3.478)	S2	3.953	-0.474	0.200	0.275	−1.104	0.155
	S3	4.720	−1.241***	0.249	<0.001	−2.027	-0.456
	S4	4.157	-0.678	0.371	0.822	−1.847	0.491
	S5	4.660	−1.181**	0.248	0.001	−1.963	-0.399

* $p < 0.05$.
** $p < 0.005$.
*** $p < 0.001$.

4.1. Methodological considerations

Certain limitations of this study need to be acknowledged. Firstly, we included a relatively a small sample size and this prevented us from investigating any potential correlations between kinematic variability and pain-related factors. Nevertheless, we were still able to determine significant differences in spinal kinematic variability between groups. Despite the modest mean differences in kinematic variability of around three degrees, the effect sizes ranged from moderate to large. Nevertheless, it remains unclear whether this is a clinically meaningful difference. However, this study provides new insights into motor adaptations to CNSLBP, which may lead to targeted interventions that can potentially improve the management of individuals with CNSLBP.

4.2. Conclusion

People with CNSLBP completed a standardised repetitive lifting task with the same spinal ROM as asymptomatic individuals, yet with a different motor strategy to execute the lifting task which was characterised by higher kinematic cycle-to-cycle variation.

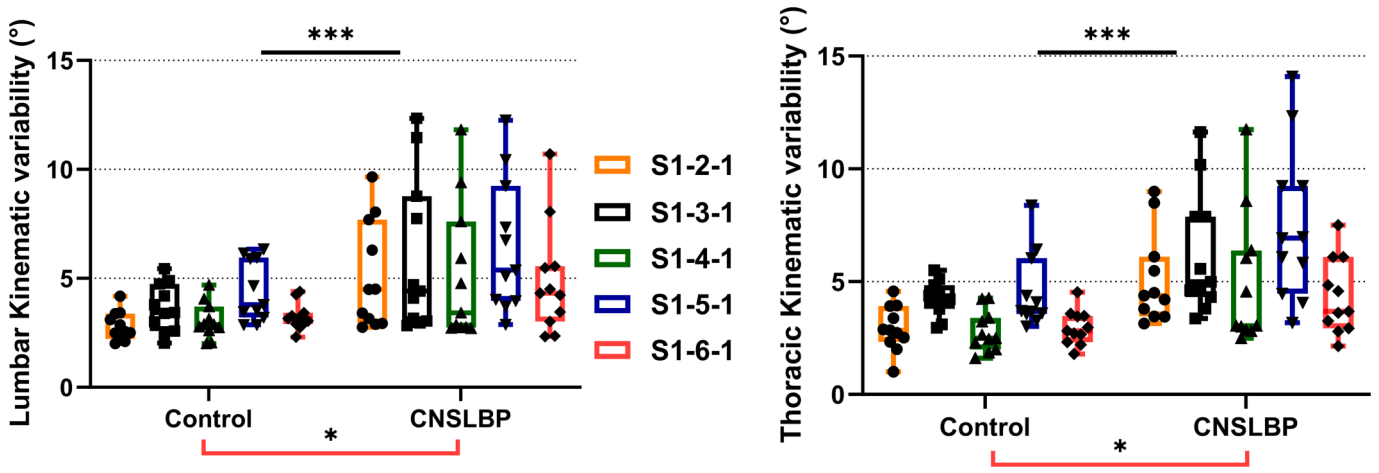

Fig. 4. Thoracic and lumbar kinematic variability differences between people with chronic non-specific low back pain (CNSLBP) and healthy controls in the **Sagittal** plane of motion, data presented as mean and standard deviation; **S1-2–1:** shelf1 to shelf2 to shelf1. The lower line represent the statistically significant main effect of group, the upper line represent the statistically significant main effect of shelf: *$p < 0.05$; **$p < 0.005$; *** $p < 0.001$.

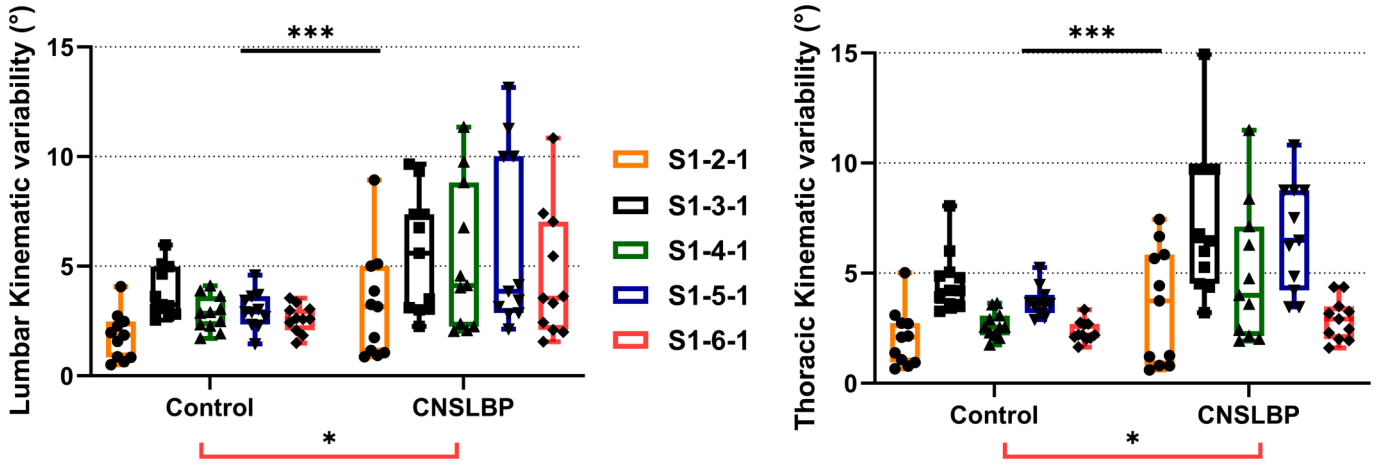

Fig. 5. Thoracic and lumbar kinematic variability differences between people with chronic non-specific low back pain (CNSLBP) and healthy controls in the **Transversal** plane of motion, data presented as mean and standard deviation; **S1-2–1:** shelf1 to shelf2 to shelf1. The lower line represent the statistically significant main effect of group, the upper line represent the statistically significant main effect of shelf: *p < 0.05; **p < 0.005; *** p < 0.001.

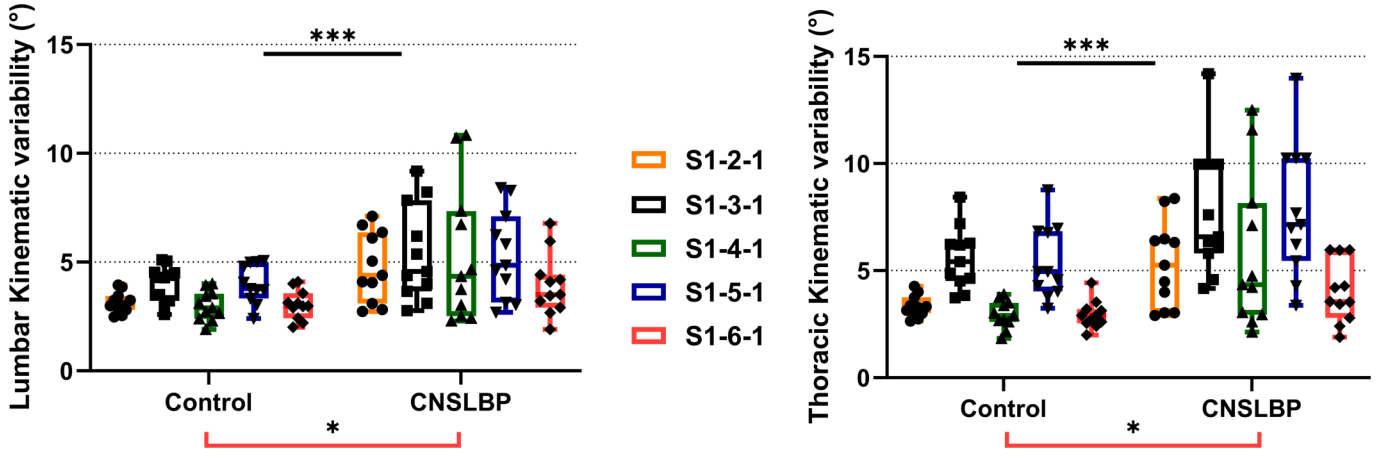

Fig. 6. Thoracic and lumbar kinematic variability differences between people with chronic non-specific low back pain (CNSLBP) and healthy controls in the **Frontal** plane of motion, data presented as mean and standard deviation; **S1-2–1:** shelf1 to shelf2 to shelf1. The lower line represent the statistically significant main effect of group, the upper line represent the statistically significant main effect of shelf: *p < 0.05; **p < 0.005; *** p < 0.001.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was funded by a Ph.D. scholarship awarded to the first author by King Abdulaziz University in Jeddah, Saudi Arabia.

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