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Increased spinal kinematic variability in people with chronic low back pain revealed by alterations in helical axis parameters

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ABSTRACT

Changes in spine kinematics are common in people with chronic low back pain (CLBP) and this includes changes in trunk angular displacement and angular velocity. The helical axis (HA) of motion is an approach to investigate three-dimensional variability of joint kinematics. In this study we investigate whether the variability of trunk movement is modified in people with CLBP by measuring the dispersion of HA parameters during repeated trunk movements performed at different movement speed. Nineteen people with CLBP and twenty asymptomatic volunteers performed repetitive continuous trunk movements at three different speeds. Two parameters of the HA were extracted to characterise movement variability at the lumbo-sacral and thoraco-lumbar regions: mean angle (MA) and mean distance (MD). Two-Way mixed ANOVA showed significantly higher MA and MD ($p < 0.001$) especially at the thoraco-lumbar region for those with CLBP. Interestingly, this was not consistent across all directions or speed of movement; higher HA parameters for those with CLBP at the lumbo-sacral region was mainly observed during flexion/extension cycles. In addition, there was a speed and group interaction effect during rotational cycles ($p = 0.010$) which showed higher thoraco-lumbar MA values for those with CLBP during the faster speed ($p = 0.029$, mean dif.(95 % CI) = 2.28, (0.247;4.328)) and slower speed condition ($p = 0.003$, mean dif.(95 % CI) = 2.78, (1.009;4.565)). This study shows that people with CLBP move their spine in a more variable way, a characteristic that could be influenced by speed and direction of trunk movement. This could reflect an adaptive behaviour to long-lasting pain.

1. Introduction

It is widely acknowledged that individuals experiencing chronic low back pain (CLBP) move differently compared to pain free individuals (Hodges and Tucker, 2011; Solomonow, 2012; van Dieen et al., 2019). As an attempt to understand how movement is controlled in the presence of CLBP, trunk motor control has been studied extensively by evaluating both trunk muscle activity and trunk movement patterns (van Dieen et al., 2019). Alterations of spine kinematics is a common motor adaptation to pain and includes changes in trunk angular displacement, angular velocity, and variability in kinematic features (Gizzi et al., 2019; Hodges and Smeets, 2015; Vaisy et al., 2015; van Dieen et al., 2017). A recent systematic review on movement variability in individuals with CLBP identified that while changes in movement variability are commonly found in studies, the direction of the change is not consistent (Alsubaie et al., 2023). For example, previous research demonstrated that individuals with CLBP often exhibit inconsistent intra-individual movement variability between repetitions when performing repetitive trunk bending. This is evident as either heightened kinematic variability (Bauer et al., 2017) or increased trunk movement stability compared to pain-free individuals (Asgari et al., 2015). Further, a recent scoping review identified large variability in the tasks and techniques considered for movement variability studies, as well as the low methodological quality of the studies driven by large potential for biases (Saito et al., 2021). It should be noted, for example, that factors such as movement speed or direction was not consistently taken into

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account when evaluating movement variability in people with CLBP. This lack of consideration could significantly impact movement variability, along with the clinical characteristics of the participants or the assessment position.

The helical axis (HA) of motion is one approach to investigate three-dimensional joint kinematic variability (Barbero et al., 2017). The HA method allows estimation of the unique orientation and position for each axis of motion that is created with each cycle of motion (Dugailly et al., 2015). The mean angle (MA) and mean distance (MD) are two parameters which have been described to evaluate the behaviour of the HA in order to describe joint kinematics during different movements (Barbero et al., 2017; Cescon et al., 2019; Cescon et al., 2014). Lower values of MD and MA indicate reduced variability when performing repetitive movements (Alsultan et al., 2019). HA parameters have also been used in research as an index of joint stability, which means a higher stability index is indicative of lower variable movement (Cescon et al., 2019).

The behaviour of HA has now been studied in vivo on several joints such as the knee joint (Grip and Hager, 2013; Grip et al., 2015; Grip et al., 2019; Konda et al., 2019; Markstrom et al., 2020; Temporiti et al., 2020), shoulder joint (Cescon et al., 2019; Temporiti et al., 2019), temporomandibular joint (Gallo et al., 1997; Gallo et al., 2006), metacarpophalangeal joint (Fioretti et al., 1990) and in the cervical spine (Barbero et al., 2017). Investigating the cervical spine using parameters of HA in those with chronic neck pain compared to asymptomatic participants, revealed less variable movement i.e., decreased MA and MD with different movements speeds for those with chronic neck pain (Alsultan et al., 2019). In addition, HA parameters also detected reduced movement variability as a result of acute neck muscle soreness (Alsultan et al., 2020). In contrast, the lumbar spine has mainly been investigated using HA methods either in vitro or in simulation studies (Ellingson and Nuckley, 2015; Metzger et al., 2010; Rockenfeller et al., 2021; Schmidt et al., 2008; Wachowski et al., 2009). Some previous work has used the HA technique to examine the lumbar spine in vivo (Aiyangar et al., 2017), identifying differences in a healthy population across vertebral levels during a lifting task. However, this work directly imaged the spine using x-ray fluoroscopy, precluding future clinical application due to the complexity of the techniques. Measurements of the HA in the lumber region, using optoelectronic systems may provide a comprehensive assessment of how movement variability is affected in people with CLBP, offering insights into spinal dynamics that are not fully captured by other assessments.

Therefore, this study aimed to explore kinematic variability of trunk movement in people with and without CLBP, assessed via parameters of the HA during seated repetitive trunk movements performed at different movement speeds. As this study is exploratory in nature, a two-tailed hypothesis was developed which was that that people with CLBP would present with altered kinematic variability during repetitive trunk movements when compared with asymptomatic individuals considering the conclusions of recent reviews on the effect of LBP on kinematic variability (Alsubaie et al., 2023; Saito et al., 2021). Furthermore, it was expected that the speed of movement might influence the extent of this effect on HA parameters (Alsultan et al., 2019).

2. Methods

2.1. Design and Setting

This cross-sectional study was approved by the Ethics Committee of the University of Birmingham, United Kingdom (approval number: ERN_19-1862) and was conducted according to the Declaration of Helsinki. All participants attended one laboratory session and provided written informed consent.

2.2. Participants

Thirty-nine volunteers including 20 asymptomatic individuals and 19 with CLBP were recruited, matched for age and sex. Both CLBP and asymptomatic participants were recruited from the staff, students and community of the University of Birmingham via poster recruitment. Potential participants were required to contact the primary investigator directly, were screened for eligibility and invited to participate if eligible. The required sample size was estimated based on a previous study evaluating parameters of the HA for the cervical spine in people with and without chronic neck pain (Alsultan et al., 2019). The sample size was calculated using G*Power 3.1.9.4 based on an α of 0.05, a power of 0.80 and a small to moderate effect size of (f) 0.23 (Faul et al., 2009). For each group being measured across nine observations during different test conditions, at least 17 participants were needed per group to detect a significant effect. We aimed to recruit 20 participants in each group to account for the potential loss of participants.

2.3. Inclusion and exclusion criteria

We recruited both men and women aged between 18 and 55 years. Individuals with chronic non-specific LBP were considered for the study if their CLBP had persisted for at least 3 months and resulted in pain on at least half the days in the past 6 months (Dionne et al., 2008). Pain-free participants were required to have no relevant history over the last three years of back or lower limb pain or injury that limited their function and/or required treatment from a health care professional.

The exclusion criteria for both groups were as follows: confirmed LBP diagnosis with clinical symptoms (e.g., spinal stenosis), LBP with neurological signs or referred leg pain, spinal deformity or surgery, concurrent systemic issues including rheumatic and neuromuscular disorders which may confound testing, history of chronic respiratory or neurological problems, cardiovascular conditions or pregnancy.

2.4. Questionnaires

Anthropometric data including height and weight were collected at the beginning of the session. In addition, recent physical activity levels were assessed using the International Physical Activity Questionnaire (IPAQ) (Booth, 2000; Craig et al., 2003). Participants with CLBP were required to complete additional baseline questionnaires including the Oswestry Disability Index (ODI) to assess perceived disability (Fairbank and Pynsent, 2000; Vianin, 2008). An 11-point (0–10) Pain Numeric Rating Scale (PNRS) to assess current back pain intensity at the time of testing, pain over the prior week and month as well as on completion of the session (Breivik et al., 2008).

Participants were asked to complete the Fear Avoidance Beliefs Questionnaire (FABQ) to assess potential fear of movement and this patient-reported outcome measures has excellent reliability for people with CLBP (George et al., 2010). In addition, a self-rating scale of depression, anxiety and stress was used (DASS-21) (Crawford and Henry, 2003; Lovibond and Lovibond, 1995).

2.5. 3D kinematics of the trunk

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 (Preuss and Popovic, 2010) was used. Marker placement defined three spinal segments using fourteen reflective markers (14 mm) placed with double-sided tape directly over the skin of the anatomical landmarks illustrated in Fig. 1. A laser pointer was also fixed using a chest strap over the participant's sternum to help direct the trunk movement (5 cm below sternal notch).

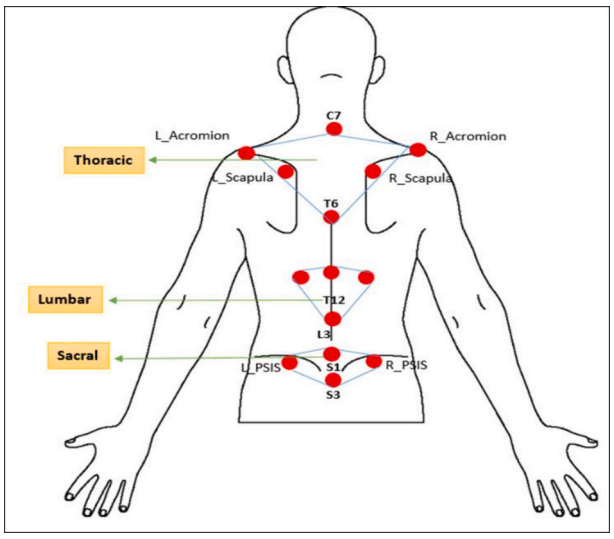

Fig. 1. Marker placement and spine segmentation for the kinematic model of the spine. Thoracic segment: spinous processes of 7th cervical vertebra (C7), right & left acromion (R & L Ac), right & left scapular spine (R & L Sc), 6th thoracic vertebra (T6). Lumbar segment: 12th thoracic vertebra (T12), at least 50 mm lateral to the spinous process of T12 (R & L T12), 3rd lumbar vertebra (L3). Sacral segment: 1st sacral vertebra (S1), 3rd sacral vertebra (S3), and posterior superior iliac spine (R & L PSIS).

2.6. Experimental procedure

The participants were asked to sit comfortably on a stool with their feet resting on a wooden step, hips and knees at 90° flexion and with their arms crossed over chest. This position was selected to minimise the influence of pelvic motion on task completion. From the seated position, the participants were asked to perform 30-cycles of repeated trunk flexion/extension, right/left rotation, and right/left side bending at three different speeds (fast, slow, self-selected speed) in a random order (Fig. 2).

In order to standardize trunk range of motion (ROM) between participants, they were instructed to use the beam of the laser as a guide to limit their trunk movements by moving between targets: flexion (35°) and extension (15°) movements, and right/left rotational movements (30° each), and right/left side bending (15° each).

The speed of the movement during the fast and slow speed repetition was controlled using a metronome, which was set at 30 and 50 beats-per-minute for the slow and fast speed, respectively based on pilot testing. During the self-selected speed trials, the metronome was not used in order to allow the participant control over their own pace without external input. To ensure a smooth completion of movement cycles, the participant was asked to point at a target with each beat (60 beats total) and start every trial from a neutral sitting position to perform 30-cycles of continuous trunk movements without stopping in the midline. Each task was demonstrated to the participant, and they were given an opportunity to practice one repetition of the movement prior to starting the task.

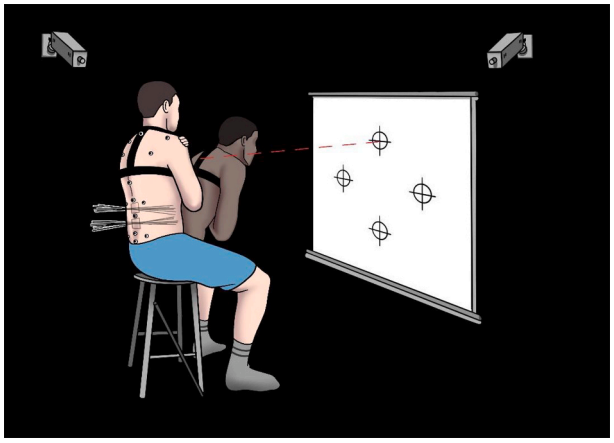

Fig. 2. Experimental set-up.

Previously HA parameters showed almost perfect intra- and inter-session reliability based on ten consecutive cycles of cervical movements (Barbero et al., 2017). Therefore, only the middle 15 cycles were analysed in this study and to ensure a steady-state movement behaviour (Granata and England, 2006). Every test condition was repeated three times with 90 s of rest between trials to minimise fatigue (Agostinete et al., 2016).

2.7. Data Processing

The 3D kinematic data were time-normalized using a linear interpolation procedure to obtain 100 samples per cycle (0–100 %).

2.7.1. 3D kinematic data

Using BTS-SMART software suite (SMART Tracker& Analyzer; BTS Bioengineering, Italy), data from the markers were tracked and labelled using a custom trunk model. A mathematical model was used to evaluate two parameters proposed to describe the HA behaviour during joint kinematics: MA and MD. These two variables were measured at two spinal levels: between the thoracic and lumbar segments (thoraco-lumbar), and between the lumbar and sacral segments (lumbo-sacral). The neutral position of each segment and the end positions (i.e., flexion, extension, rotation, side bending) were identified to create multiple HAs between the two segments (Figs. 2 and 3). For each set of HAs, the MA was extracted between each axis and their average calculated (Barbero et al., 2017). For each movement cycle, the MD of the sets of HAs was also calculated, as previously described in detail by Cescon et al. (2019) and Alsultan et al. (2019). In brief, we chose a reference plane, perpendicular to the axis of average angle, and calculated its intersection points with all HAs of the set. From the obtained set of points we determined the barycentre as well as the mean distance of all points relative to it. MD was defined as the minimum mean distance found across all possible perpendicular planes – the corresponding plane being the reference plane mentioned above. The measure MD is thought to represent the spatial variability of the HAs during a certain movement.

2.8. Statistical analysis

Statistical analysis was performed using SPSS 29 (IBM, USA) with an alpha level set at $\alpha = 0.05$. Normal distribution of the data was confirmed using a Shapiro–Wilk test and thus parametric tests were applied. Separately for each spinal segments and plane of motion, two-way mixed Analysis of Variance (ANOVA) were conducted to compare main and interaction effects of group (control vs. CLBP), and speed of motion (within-subject factors). Whenever significant effects were identified by ANOVA, Bonferroni post-hoc test was used for pairwise comparisons. Additionally, differences in demographics, velocity and ROM were evaluated with the same analysis based on main effect. Effect size has been reported where appropriate with ANOVA results, in the format of $\eta^2 p$ values (Lakens, 2013).

3. Results

No significant differences were found between groups ($p > 0.05$) for age, weight nor height (Table 1). The CLBP group reported mild current pain intensity and presented with minimal pain-related disability.

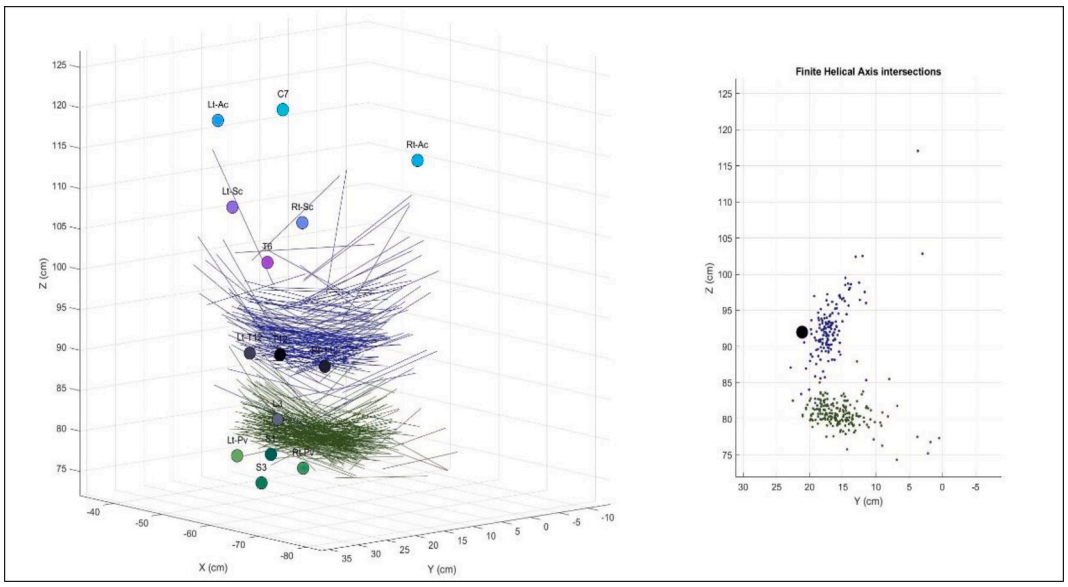

Fig. 3. Example of the helical axis distribution. On the left: 3D representation of the HA during 15 flexion/extension cycles. On the right: intersection points with the sagittal plane. The different colours represent the two corresponding spinal segments (Blue: thoraco-lumbar, and Green: lumbo-sacral), and the black dot marks the location of the T12 marker within 3D space. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Participant demographics and results of patient-reported outcome measures as Mean ± SD; ODI: Oswestry Disability Index, PNRS: Pain Numeric Rating Scale, FABQ: Fear Avoidance Beliefs Questionnaire. Chronic low back pain (CLBP).

	Control group (N = 20; ♂: 10, ♀ 10)	CLBP group (N = 19; ♂: 9, ♀ 10)	P-value
Age (years)	28.23 ± 4.36	29.93 ± 5.24	p = 0.278
Weight (kg)	71.31 ± 15.95	71.23 ± 17.16	p = 0.976
Height (m)	1.71 ± 0.09	1.66 ± 0.11	p = 0.122
IPAQ	65.00 % High	36.84 % High	–
ODI (%)	–	16.05 ± 8.56	–
Current PNRS	–	3.26 ± 1.69	–
After session PNRS	–	3.53 ± 2.50	–
Week prior PNRS	–	4.21 ± 2.07	–
Month prior PNRS	–	4.15 ± 1.74	–
FABQ- work scale	–	9.52 ± 7.22	–
FABQ- physical scale	–	10.47 ± 4.53	–
FABQ- total	–	25.00 ± 11.19	–
DASS-21 Depression score	–	2.94 ± 2.75	–
DASS-21 Stress score	–	4.21 ± 3.50	–
DASS-21 Anxiety score	–	2.36 ± 2.36	–

3.1. Angular displacement and velocity

ROM of each movement cycle for both groups are presented in Table 2. People with CLBP presented with significantly (p = 0.049) reduced ROM compared to asymptomatic individuals specifically in trunk extension, right side bending and right rotation, however effect sizes were generally small ($\eta^2 p \approx 0.1$). There was no significant (p = 0.116) difference between groups in the velocity of their movement.

3.2. Kinematic variability of movement

All HA parameters measured for both groups during all test conditions are presented as mean and standard deviation in Table 3.

3.2.1. Flexion/Extension task cycles

People with CLBP displayed a higher MA for the thoracolumbar segment during flexion/extension cycles (p = 0.005). However, there was no effect of speed (p = 0.371) nor an interaction effect between group and speed (p = 0.174). For the lumbosacral segment, there was greater MA for those with CLBP compared to the asymptomatic individuals (p = 0.007). Both groups demonstrated an effect of speed (p = 0.022), with post-hoc comparisons showing higher MA during fast speed compared to the self-selected speed (p = 0.058, mean dif. (95 % CI) = 0.938, (−0.024;1.901)); however, there was no interaction between group and speed (p = 0.180) (Fig. 4).

There was no difference in MD at the thoracolumbar segment related to CLBP (p = 0.483), speed of task (p = 0.362), or an interaction effect between group and speed (p = 0.223). However, individuals with CLBP demonstrated larger MD at the lumbosacral segment compared to asymptomatic individuals (p = 0.012), however, there was no effect of speed (p = 0.521) nor an interaction between group and speed (p = 0.650) (Fig. 4).

3.2.2. Rotation task cycles

During rotation tasks, people with CLBP presented with higher MA for the thoracolumbar segment compared to the asymptomatic group (p = 0.039). Both groups demonstrated altered MA between the speed conditions (p < 0.001). Post-hoc tests revealed a lower MA at the self-selected speed compared to both the slow speed (p < 0.001, mean dif. (95 % CI) = 1.55°, (0.760;2.35)) and the fast speed (p = 0.007, mean dif.(95 % CI) = 1.019°, (0.233;1.80)). Furthermore, the analysis revealed an interaction between speed and group (p = 0.010), with post-hoc tests showing higher MA values for the CLBP group compared with asymptomatic individuals during movements at the fast speed (p = 0.029, mean dif.(95 % CI) = 2.28°, (0.247;4.328)) and slow speed (p = 0.003, mean dif. (95 % CI) = 2.78°, (1.009;4.565)). The lumbosacral MA did not differ between groups (p = 0.089). However, the speed of the task had an impact on lumbosacral MA for both groups (p < 0.001) with higher values of the MA observed during both slow movements (p < 0.001, mean dif. (95 % CI) = 1.95°, (0.978;2.93)), and fast movements when compared to the self-selected speed (p < 0.001, mean dif. (95 % CI) = 1.43°, (0.645;2.23)). There was no interaction between speed and group (p = 0.370) (Fig. 5).

Table 2
Mean ± SD of the total thoracic and lumbar segments ROM as well as velocity in all movement planes to reflect the speed of movement between the targets. η^2p: Eta-squared. *$p < 0.05$; **$p < 0.005$; *** $p < 0.001$;.

			Fast	Self-selected speed	Slow	P value Main effect	*F*	η^2p
Flexion/ Extension	**Flexion ROM (°)**	**Control**	38.76 ± 0.96	38.15 ± 0.77	37.69 ± 0.79	$P = 0.052$	4.0	0.098
		CLBP	35.63 ± 1.23	36.49 ± 1.05	35.21 ± 0.98			
	Extension ROM (°)	**Control**	17.11 ± 1.00	16.49 ± 0.82	15.76 ± 0.73	$P = 0.049$*	4.1	0.101
		CLBP	14.06 ± 1.22	14.77 ± 1.03	14.94 ± 0.90			
	Velocity (mm/s)	**Control**	569.40 ± 118.2	502.98 ± 105.2	396.92 ± 88.4	$P = 0.116$	2.5	0.065
		CLBP	566.08 ± 112.6	550.99 ± 107.8	409.56 ± 67.4			
Rotation	**Rt. ROM (°)**	**Control**	28.22 ± 1.05	28.02 ± 1.07	28.11 ± 0.95	$P = 0.049$*	4.1	0.101
		CLBP	27.13 ± 1.25	26.96 ± 1.36	26.71 ± 1.15			
	Lt. ROM (°)	**Control**	28.37 ± 1.03	28.31 ± 1.02	28.23 ± 0.98	$P = 0.052$	4.0	0.098
		CLBP	27.50 ± 1.44	27.14 ± 1.28	26.95 ± 1.11			
	Velocity (mm/s)	**Control**	369.69 ± 79.1	378.04 ± 78.09	244.85 ± 54.7	$P = 0.116$	2.5	0.065
		CLBP	385.30 ± 82.4	428.54 ± 102.4	298.40 ± 81.3			
Side bending	**Rt. ROM (°)**	**Control**	22.27 ± 1.67	22.27 ± 1.55	24.73 ± 1.57	$P = 0.049$*	4.1	0.101
		CLBP	18.95 ± 1.63	18.75 ± 1.74	19.98 ± 1.96			
	Lt. ROM (°)	**Control**	22.30 ± 1.58	22.27 ± 1.51	24.75 ± 1.52	$P = 0.052$	4.0	0.098
		CLBP	18.95 ± 1.62	19.23 ± 1.57	20.27 ± 1.55			
	Velocity (mm/s)	**Control**	414.18 ± 108.5	420.61 ± 110.6	295.03 ± 77.42	$P = 0.116$	2.5	0.065
		CLBP	428.63 ± 106.8	447.36 ± 84.6	311.17 ± 94.14			

People with CLBP displayed larger thoracolumbar MD compared with asymptomatic individuals ($p = 0.007$). The speed of the task also had an impact on the thoracolumbar MD ($p = 0.009$) with a higher MD during the slow speed condition compared to the self-selected speed ($p = 0.003$, mean dif.(95 % CI) = 0.288 cm, (0.086;0.490)). There was no interaction effect between speed and group ($p = 0.431$). There was no impact of CLBP found on lumbosacral MD ($p = 0.329$). However, the lumbosacral MD was affected by the speed of the task ($p = 0.011$), with larger MD during faster movements compared to those performed at the slow speed ($p = 0.018$, mean dif. (95 % CI) = 0.339 cm, (0.046;0.631)). In addition, there was a speed by group interaction ($p = 0.035$) which showed higher MD values for the CLBP group compared with asymptomatic individuals during the fast speed movement ($p = 0.044$, mean dif. (95 % CI) = 0.47 cm, (0.014;0.927)) (Fig. 5).

3.2.3. Side bending task cycles

During side-bending tasks, people with CLBP displayed higher thoracolumbar MA during side bending cycles compared with asymptomatic individuals ($p < 0.001$). The speed of the task also affected the thoracolumbar MA ($p < 0.001$), with a higher MA during the slow speed condition compared to both the faster speed condition ($p < 0.001$, mean dif. (95 % CI) = 2.43°, (0.844;4.02)) and compared to self-selected speed ($p < 0.001$, mean dif.(95 % CI) = 2.57°, (1.12;4.02)). However, there was no interaction effect between speed and group ($p = 0.837$). For lumbosacral MA, there was no group impact of the presence of CLBP ($p = 0.346$), task speed ($p = 0.107$), nor an interaction effect between group and speed ($p = 0.882$) (Fig. 6).

People with CLBP displayed a larger thoracolumbar MD compared with asymptomatic individuals ($p = 0.012$). The speed of the task did not impact the performance ($p = 0.648$) nor was there an interaction effect between group and speed ($p = 0.748$). In contrast, there was no difference in lumbosacral MD in people with CLBP compared to controls ($p = 0.507$). However, the task speed did affect lumbosacral MD ($p = 0.008$) with larger MD values observed for the self-selected speed condition compared to movements at the faster speed ($p = 0.049$, mean dif. (95 % CI) = 0.397 cm, (0.001;0.792)) and compared to the slower speed ($p = 0.027$, mean dif.(95 % CI) = 0.563 cm, (0.051;1.07)). Nevertheless, there was no interaction between speed and group ($p = 0.302$) (Fig. 6).

4. Discussion

This study is the first to quantify the parameters of HA during active trunk movements in people with and without CLBP. The HA parameters were estimated using 15 continuous cycles of trunk movements in three planes of motion. In this study, people with CLBP presented with higher values of HA parameters, especially at the thoracolumbar segment, indicating higher kinematic variability while performing repetitive seated trunk movements.

It is well established that people with CLBP commonly present with altered movement characteristics such as reduced multi-segment spinal range of motion, slower movement, and changed trunk muscle activation (Alsubaie et al., 2021; Laird et al., 2019; Shum et al., 2005; Swain et al., 2019). This finding of variable changes in kinematic parameters explored in our prior review (Alsubaie et al., 2023) is also replicated within this study to some extent, with extension movements, and movements to the right demonstrating reduced ROM in the CLBP group. However, this result was not consistent, with flexion and movements to the left showing no differences in ROM between groups.

Uniquely to this study, we applied measures of the HA within CLBP which appeared to identify that people with CLBP also move with altered kinematic variability of spinal motion. Kinematic variability was quantified for the thoracolumbar and lumbosacral spinal segments during repetitive trunk motion using the two proposed parameters of HA, the MD and MA (Cescon et al., 2014). Kinematic variability appeared to be higher for those with CLBP as revealed by differences in both MA and MD parameters during movement in all planes of motion, especially at the thoracolumbar region. In contrast, kinematic variability at the lumbosacral region only seemed to differ during flexion/extension cycles. In addition, slower speed cycles were found to increase kinematic variability regardless of the direction of movement. This relationship between movement variability and movement speed has been observed previously in people with CLBP during repetitive flexion–extension movements (Asgari et al., 2015). This observation could be explained by the kinematic theory proposed by Hancock and Newell (1985) and later refined by Plamondon and Alimi (1997) in motor control of human movements which suggests a trade-off between speed and accuracy. In addition, and to a lesser extent, kinematic variability at the lumbosacral region, was found to be higher at the faster speed, which could be an attempt to find a suitable path of movement to alleviate pain during fast motion. An interesting interaction effect was observed during trunk rotational cycles, where individuals with CLBP exhibited higher movement variability compared to asymptomatic individuals in slow and fast speeds, but not in self-selected speed. The need for quick responses or to increase trunk stability during fast and slow movements in CLBP individuals may lead to compensatory strategies that may not be needed while moving at a self-preferred pace. This consideration of the speed of the task should be explored in further research, as this could lead to the development of novel interventions for CLBP, addressing speed-specific

Table 3
Results of the mixed ANOVA to evaluate differences between people with chronic low back pain (CLBP) and healthy controls during the three speed conditions using the two helical axis HA parameters: MA (Mean Angle) and MD (Mean Distance) measured at the Thoraco-lumbar (TL) and Lumbo-sacral (LS) regions; ηp^2: Eta-squared, 95 % CI: 95 % confidence interval *$p < 0.05$; **$p < 0.005$; *** $p < 0.001$.

Plane of Motion	Spinal Segment	HA	Speed	Group Effect	Speed Effect	Group*Speed Interaction Effect	Groups	Mean ± SD	Group Effect Mean Difference (95 % CI)
Flexion/ Extension	**TL**	**MA (°)**	Fast	$p = 0.005^*F = 8.7\eta 2p = 0.191$	$p = 0.371F = 0.99\eta 2p = 0.026$	$p = 0.174F = 1.8\eta 2p = 0.047$	Controls	8.62° ±2.7°	2.50 (0.79, 4.22)
							CLBP	12.03° ±4.3°	
			Self-selected				Controls	9.01° ±2.9°	
							CLBP	11.40° ±3.1°	
			Slow				Controls	8.87° ±2.8°	
							CLBP	10.59° ±2.1°	
		MD (cm)	Fast	$p = 0.483F = 0.503\eta 2p = 0.013$	$p = 0.362F = 1.008, \eta 2p = 0.027$	$p = 0.223F = 1.542\eta 2p = 0.040$	Controls	3.52 ± 1.5	0.21 (−0.39, 0.81)
							CLBP	3.35 ± 1.0	
			Self-selected				Controls	2.93 ± 0.6	
							CLBP	3.40 ± 0.9	
			Slow				Controls	3.19 ± 1.2	
							CLBP	3.52 ± 1.3	
	LS	**MA (°)**	Fast	$p = 0.007^*F = 8.0\eta 2p = 0.178$	$p = 0.022^*F = 4.6\eta 2p = 0.111$	$p = 0.180F = 1.8\eta 2p = 0.047$	Controls	7.95° ±2.8°	1.88 (0.53, 3.23)
							CLBP	10.5° ±3.1°	
			Self-selected				Controls	7.49° ±1.8°	
							CLBP	9.09° ±1.5°	
			Slow				Controls	8.06° ±2.2°	
							CLBP	9.5° ±2.1°	
		MD (cm)	Fast	$p = 0.012^*F = 6.92\eta 2p = 0.158$	$p = 0.521F = 0.658\eta 2p = 0.017$	$p = 0.650F = 0.433\eta 2p = 0.012$	Controls	2.53 ± 0.6	0.62 (0.14, 1.11)
							CLBP	3.32 ± 0.9	
			Self-selected				Controls	2.67 ± 1.0	
							CLBP	3.27 ± 1.2	
			Slow				Controls	2.54 ± 0.7	
							CLBP	3.03 ± 0.8	
Rotation	**TL**	**MA (°)**	Fast	$p = 0.039^*F = 4.58\eta 2p = 0.110$	$p < 0.001^{***}F = 13.87\eta 2p = 0.273$	$p = 0.010^*F = 5.03\eta 2p = 0.120$	Controls	10.96° ±3.1°	2.00 (0.10, 3.90)
							CLBP	13.24° ±3.1°	
			Self-selected				Controls	10.61° ±4.1°	
							CLBP	11.55° ±2.4°	
			Slow				Controls	11.24° ±2.8°	
							CLBP	14.03° ±2.5°	
		MD (cm)	Fast	$p = 0.007^*F = 8.15\eta 2p = 0.181$	$p = 0.009^*F = 5.22\eta 2p = 0.124$	$p = 0.431F = 0.838\eta 2p = 0.022$	Controls	2.55 ± 0.6	0.41 (0.12, 0.69)
							CLBP	2.99 ± 0.3	
			Self-selected				Controls	2.45 ± 0.5	
							CLBP	2.73 ± 0.5	

(*continued on next page*)

Table 3 (*continued*)

Plane of Motion	Spinal Segment	HA	Speed	Group Effect	Speed Effect	Group*Speed Interaction Effect	Groups	Mean ± SD	Group Effect Mean Difference (95 % CI)
			Slow				Controls	2.62 ± 0.5	
							CLBP	3.13 ± 0.6	
	LS	**MA (°)**	Fast	$p = 0.089 F = 3.04 \eta 2p = 0.076$	$p < 0.001^{***} F = 17.63 \eta 2p = 0.323$	$p = 0.370 F = 0.99 \eta 2p = 0.026$	Controls	9.31° ±2.4°	1.26 (−0.20, 2.74)
							CLBP	10.70° ±2.7°	
			Self-selected				Controls	8.20° ±1.5°	
							CLBP	8.94° ±2.2°	
			Slow				Controls	9.69° ±2.8°	
							CLBP	11.37° ±3.3°	
		MD (cm)	Fast	$p = 0.329 F = 0.977 \eta 2p = 0.026$	$p = 0.011^{*} F = 5.08 \eta 2p = 0.121$	$p = 0.035^{*} F = 3.6 \eta 2p = 0.090$	Controls	2.52 ± 0.5	0.14 (−0.14, 0.43)
							CLBP	2.99 ± 0.9	
			Self-selected				Controls	2.57 ± 0.7	
							CLBP	2.49 ± 0.5	
			Slow				Controls	2.40 ± 0.4	
							CLBP	2.44 ± 0.4	
Side Bending	**TL**	**MA (°)**	Fast	$p < 0.001^{***} F = 16.30 \eta 2p = 0.306$	$p < 0.001^{***} F = 13.52 \eta 2p = 0.268$	$p = 0.837 F = 0.143 \eta 2p = 0.004$	Controls	14.22° ±3.1°	4.77 (2.38, 7.17)
							CLBP	18.74° ±3.6°	
			Self-selected				Controls	13.79° ±2.9°	
							CLBP	18.89° ±4.6°	
			Slow				Controls	19.56° ±4.8°	
							CLBP	21.26° ±5.4°	
		MD (cm)	Fast	$p = 0.012^{*} F = 6.93 \eta 2p = 0.158$	$p = 0.648 F = 0.365 \eta 2p = 0.010$	$p = 0.748 F = 0.226 \eta 2p = 0.006$	Controls	2.54 ± 0.7	0.62 (0.14, 1.09)
							CLBP	3.28 ± 0.8	
			Self-selected				Controls	2.07 ± 0.7	
							CLBP	3.24 ± 0.7	
			Slow				Controls	2.75 ± 1.3	
							CLBP	3.33 ± 1.0	
	LS	**MA (°)**	Fast	$p = 0.346 F = 0.912 \eta 2p = 0.024$	$p = 0.107 F = 2.39 \eta 2p = 0.061$	$p = 0.882 F = 0.097 \eta 2p = 0.003$	Controls	16.27° ±3.8°	1.06 (−1.19, 3.32)
							CLBP	16.99° ±3.8°	
			Self-selected				Controls	16.93° ±3.4°	
							CLBP	18.03° ±4.1°	
			Slow				Controls	17.59° ±4.9°	
							CLBP	18.97° ±5.7°	
		MD (cm)	Fast	$p = 0.507 F = 0.448 \eta 2p = 0.012$	$p = 0.008^{*} F = 5.52 \eta 2p = 0.130$	$p = 0.302 F = 1.20 \eta 2p = 0.032$	Controls	3.41 ± 1.6	0.25 (−1.02, 0.51)
							CLBP	2.84 ± 0.8	
			Self-selected				Controls	3.56 ± 1.4	

(*continued on next page*)

Table 3 (*continued*)

Plane of Motion	Spinal Segment	HA	Speed	Group Effect	Speed Effect	Group*Speed Interaction Effect	Groups	Mean ± SD	Group Effect Mean Difference (95 % CI)
							CLBP	3.48 ± 1.5	
			Slow				Controls	3.02 ± 1.1	
							CLBP	2.89 ± 1.2	

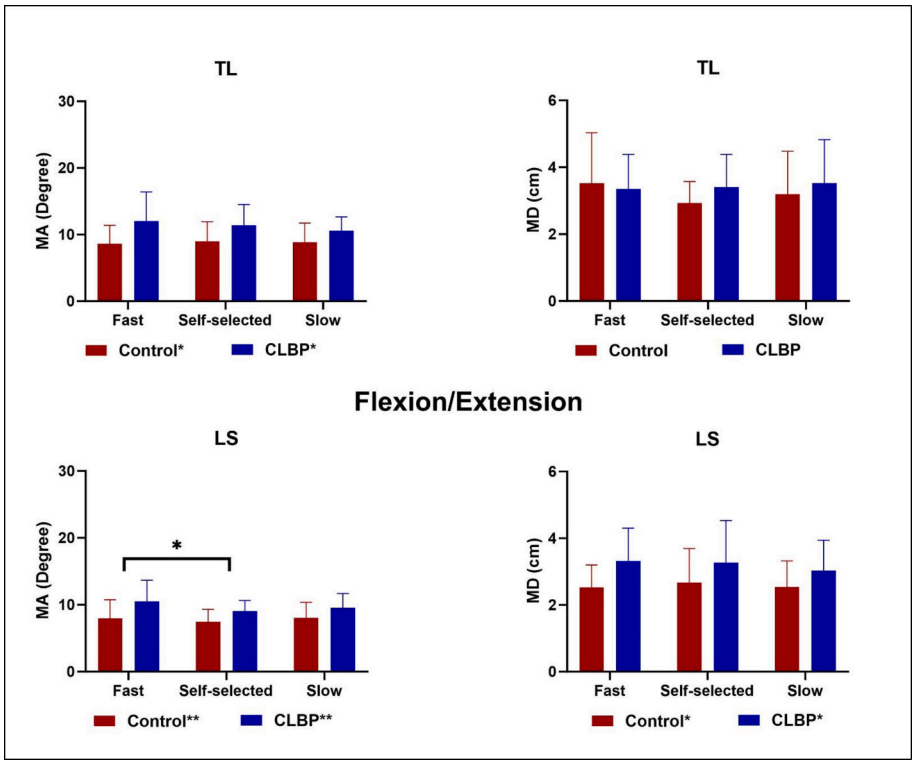

Fig. 4. Kinematic variability differences during trunk flexion and extension cycles between people with and without chronic low back pain (CLBP) based on mean and standard division (SD) of the helical axis parameters (HA); mean angle (MA) and mean distance (MD); between the thoracolumbar (TL) and lumbosacral (LS) segments. Statistically significant difference; $^{*}p < 0.05$; $^{**}p < 0.005$; *** $p < 0.001$; upper lines represent statistically significant differences between speed conditions.

challenges.

Altered spinal kinematic variability was previously observed in people with CLBP using other statistical tools including linear and non-linear metrics. For example, during repetitive functional tests, the variability of lumbar movement was found to be increased in people with CLBP with greater LBP intensity, as determined by decreased determinism or recurrence (Bauer et al., 2015). Similarly, during a sit-to-stand-to-sit task, people with CLBP showed less coordinated and a more variable lumbar movement pattern (Ippersiel et al., 2018). Furthermore, other studies have described the variability of lumbar movement as more irregular motions in people with CLBP compared to acute LBP using the irregularity quantification analysis (Williams et al., 2013).

HA dispersion during spinal movements has previously only been evaluated for the cervical spine, and this work revealed reduced MA and MD parameters in the presence of chronic neck pain (Alsultan et al., 2019). In contrast, our study appeared to reveal an increase in kinematic variability in the presence of CLBP. While the tasks within these studies were similar, and the populations presented similar levels of pain, it is not easy to directly compare these anatomical structures. This difference could be attributed to several factors which warrant further investigation, notably including the higher degrees of freedom available at the cervical spine compared to the thoracic and lumbar segments which have limited ROM due to anatomical differences in the bony congruency and the muscle attachments. Thus, it is speculated that people with chronic neck pain may have reduced their movement variability as a protective mechanism whereas people with CLBP could have adopted a control strategy in order to perform repetitive movements with more motor solutions to possibly reduce their pain or minimise fatigue.

We would suggest focusing on several specific areas to develop this exploratory study further. The population within this study had mild-moderate pain, so further studies could explore the effect of more severe pain and indeed a wider variety of pain ranges on the HA parameters. Additionally, while the results presented herein are novel in this field, it is suggested that further work could target greater effect sizes during recruitment to better support the statistical power.

4.1. *Methodological considerations*

The MA and MD parameters of the HA have been explored previously (Alsultan et al., 2019; Alsultan et al., 2020; Barbero et al., 2017; Cescon

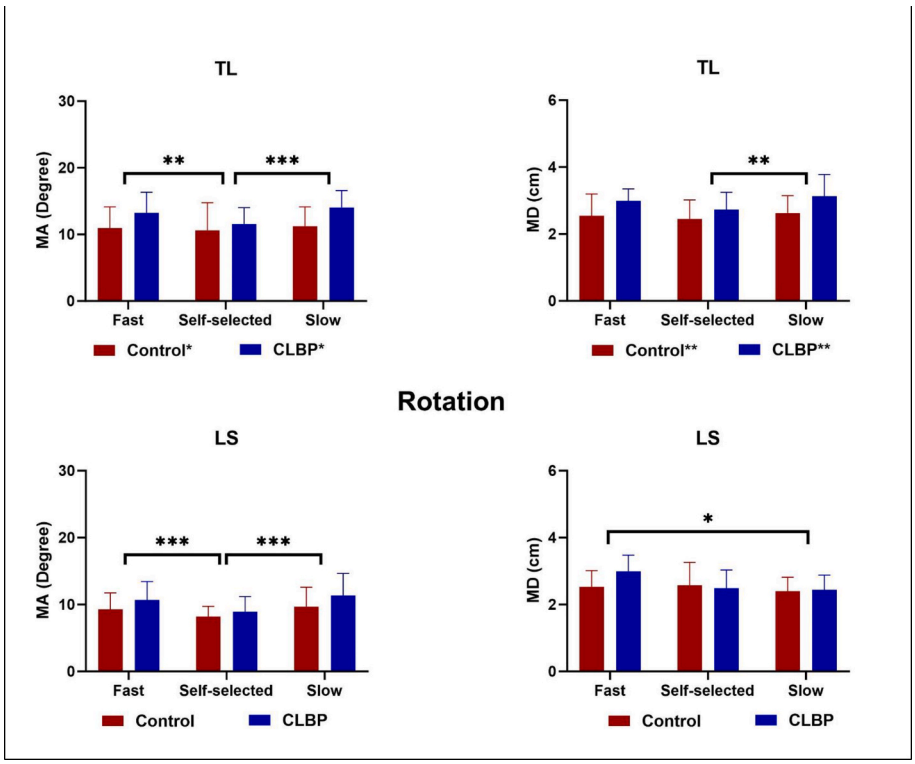

Fig. 5. Kinematic variability differences during trunk rotational cycles between people with and without chronic low back pain (CLBP) based on mean and standard division (SD) of the helical axis parameters (HA); mean angle (MA) and mean distance (MD); between the thoracolumbar (TL) and lumbosacral (LS) segments. Statistically significant difference; *$p < 0.05$; **$p < 0.005$; *** $p < 0.001$; upper lines represent statistically significant differences between speed conditions.

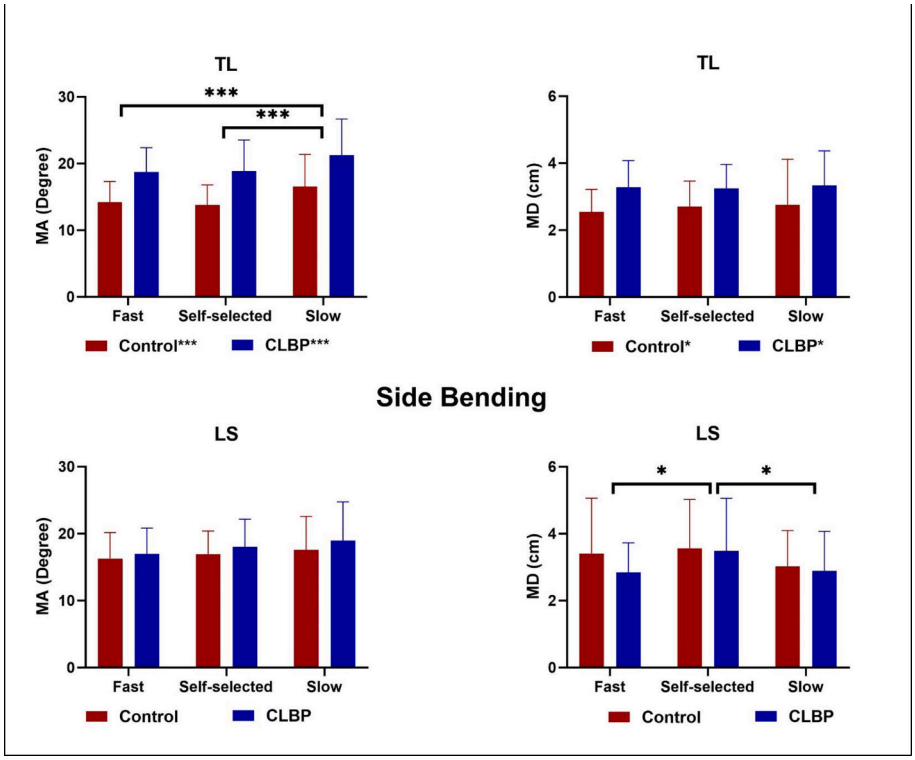

Fig. 6. Kinematic variability differences during trunk side bending cycles between people with and without chronic low back pain (CLBP) based on mean and standard division (SD) of the helical axis parameters (HA); mean angle (MA) and mean distance (MD); between the thoracolumbar (TL) and lumbosacral (LS) segments. Statistically significant difference; *$p < 0.05$; **$p < 0.005$; *** $p < 0.001$; upper lines represent statistically significant differences between speed conditions.

et al., 2019; Cescon et al., 2014). Further, MA and prior variation on the MD measure (convex hull area) have been shown to be reliable during active movements of the cervical spine (Barbero et al., 2017). However, the reliability of the measures have not been investigated for other spinal levels, and this may differ especially for people with spinal pain. Additionally, the reliability of the specific MD measure has not been assessed. Finally, pelvic movement was not constrained although any unnecessary pelvic movements was limited by asking the participants to perform the tasks while sitting, but this might have impacted the task performance.

It is worth considering the relatively low levels of pain symptoms reported by the CLBP group, of 3–5/10 on the PNRS. It is not known if these results would be altered in a group who were experiencing more severe pain symptoms. While these individuals were not excluded from the study, more individuals with lower pain levels chose to participate. This is potentially reflective of the relatively high proportion of the population who have consistent low levels of CLBP but continue to work and function with minimal impact on activities of daily life beyond experiencing pain symptoms (Carlesso et al., 2018).

5. Conclusion

In this exploratory study, people with CLBP appeared to demonstrate greater kinematic variability during active trunk movements, a characteristic that could be influenced by speed of trunk motion. This may reflect an adaptive behaviour to long-lasting pain, however further targeted research is required to fully ameliorate this relationship.

CRediT authorship contribution statement

A.M. Alsubaie: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Sanderson:** Writing – review & editing, Methodology, Investigation. **C. Cescon:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **E. Martinez-Valdes:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **M. Barbero:** Writing – review & editing, Methodology, Investigation, Conceptualization. **D. Falla:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Conceptualization.

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.

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