Gait & Posture 70 (2019) 53–58

Contents lists available at ScienceDirect

Gait & Posture

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

Full length article

# Multi-segment spine range of motion in dancers with and without recent low back pain

Christopher T.V. Swain[a,*], Elizabeth J. Bradshaw[b,c], Christina L. Ekegren[d], Karl F. Orishimo[e], Ian J. Kremenic[e], Marijeanne Liederbach[f], Marshall Hagins[f]

[a] School of Exercise Science, Australian Catholic University, Daniel Mannix Building, 17 Young St, Fitzroy, VIC 3065, Australia
[b] Centre for Sport Research, School of Exercise and Nutrition Sciences, Deakin University, 221 Burwood Highway, Burwood, VIC 3125, Australia
[c] Sport Performance Research Institute New Zealand, Auckland University of Technology, 17 Antares Place, Rosedale, Auckland 0632, New Zealand
[d] Department of Epidemiology and Preventive Medicine, Monash University, 553 St Kilda Road, Melbourne VIC 3004, Australia
[e] Nicholas Institute of Sports Medicine and Athletic Trauma, Lenox Hill Hospital, 210 East 64th St, 5th Floor, New York, NY 10065, USA
[f] Harkness Center for Dance Injuries, NYU Langone Health, 614 2ndAv, Suite G, 2nd Floor, New York, NY 10016, USA

ARTICLE INFO

*Keywords:*
Biomechanics
Injury prevention
Gait
Dance

ABSTRACT

*Background:* Altered spine kinematics are a common in people with LBP. This may be especially true for populations such as dancers, who are required to perform repetitive movements of the spine, although this remains unclear.

*Research question:* Do dancers with recent LBP display altered spine kinematics compared to their asymptomatic counterparts?

*Methods:* A cross-sectional study of multi-segment spine kinematics was performed. Forty-seven pre-professional and professional female dancers either with LBP in the past two months ($n = 26$) or no LBP in the past 12 months ($n = 21$) participated. Range of motion (ROM) during standing side bending, seated rotation, and walking gait were compared.

*Results:* Female dancers with LBP displayed reduced upper lumbar transverse plane ROM in seated rotation (Effect Size (ES) = −0.61, 95% Confidence Interval (CI): −1.20, 0.02, $p = 0.04$), as well as reduced lower lumbar transverse plane ROM (ES = −0.65, 95% CI: −1.24, −0.06, $p = 0.03$) in gait. However, there was increased lower thoracic transverse plane ROM (ES = 0.62, 95% CI: 0.04, 1.21, $p = 0.04$) during gait. No differences in the frontal plane were observed.

*Significance:* Altered transverse plane spine kinematics were evident in dancers with recent LBP for select segments and tasks. This may reflect a protective movement strategy. However, as the effect sizes of observed differences were moderate, and the total number of differences between groups was small, collectively, it seems only subtle differences in spine kinematics differentiate dancers with LBP to dancers without.

## 1. Introduction

Dancers are vulnerable to the experience of low back pain (LBP) [1]. The point prevalence of LBP is estimated to range between 8–25% in pre-professional and professional dancers, and in this population, LBP is associated with activity limitation, care-seeking, and medication use [2]. Although it is acknowledged that multiple factors contribute to LBP, recent evidence suggests that physical factors, such as posture and spinal range of movement (ROM), contribute to the experience of LBP [3,4]. Therefore, an understanding of how these factors relate to LBP in a population exposed to repetitive, end-range spine movements is needed.

Research on non-dancer populations has shown that people with LBP move differently than those without LBP. For example, reduced spine mobility has been identified as a risk factor for serious first time LBP [5], and people with less spine mobility sustain greater spine stresses during lifting tasks [6]. Movement inhibition may also represent a protective strategy in people with LBP [7]. Studies that have induced LBP via a nociceptive stimulus in healthy volunteers support this [8]. A protective response is not necessarily positive and, if it persists, may have long term consequences [7].

Mechanical factors, such as spine mobility, may be of increased

* Corresponding author.
*E-mail addresses:* chris.swain@acu.edu.au (C.T.V. Swain), liz.bradshaw@deakin.edu.au (E.J. Bradshaw), christina.ekegren@monash.edu (C.L. Ekegren), karl@nismat.org (K.F. Orishimo), ian@nismat.org (I.J. Kremenic), marijeanne.liederbach@nyumc.org (M. Liederbach), m.hagins@nyumc.org (M. Hagins).

https://doi.org/10.1016/j.gaitpost.2019.02.012
Received 20 August 2018; Received in revised form 8 February 2019; Accepted 19 February 2019

importance within a population such as dancers because the end range, multiplanar spine movements typical of dance increase the potential number and magnitude of physical stresses the spine may experience. In support of this, dancers with a history of LBP display impaired trunk damping, which suggests an impaired ability to control spine movement is related to LBP in this population [9]. However, other mechanical properties of the spine system, such as trunk stiffness, did not differ between dancers with and without LBP [9] and, unlike non-dancers, sagittal plane spine mobility was not associated with LBP in dance students [10]. Given these contrasting findings, there is scope for more detailed investigations of spinal mobility in dancers with LBP.

Assessment of maximum spine range of motion (ROM) and walking gait have been used to identify spine kinematic impairment associated with LBP in athletic and non-athletic populations [3,11–13]. However, methods previously used to examine spine kinematics relative to LBP have been sub optimal. First, many prior studies have used only a single segment model to assess spine kinematics [11,12]. As regional spine segments display distinct patterns of movement across different tasks [14], these measures are limited in their ability to accurately describe lumbar spine kinematics. In contrast to a single segment model, a multi-segment model of the lumbar spine was able to detect kinematic differences between males and females during a sit to stand task [15]. In addition, during gait, studies that have used a multi-segment spine model have detected ROM differences between persons with and without LBP [13] that were not detected in studies that modelled the trunk as a single segment [12,16]. Second, many previous investigations of spine kinematics have been limited to the lumbar spine. More recently, differences in lumbar-thoracic kinematics has differentiated between LBP patients and healthy controls [17,18], which implies that modelling the thoracic as well as lumbar segments may provide unique information about spine movement changes associated with LBP. Third, the few studies that examined kinematic variables in clinical and functional tasks have predominantly focused on the sagittal plane [14,18]. As spine movements involving lateral bending or axial rotation have been associated with increased stresses distributed across different structures of the spine [19], as well as LBP outcomes [20], knowledge of the frontal and transverse planes is required, particularly in individuals with high multi-planar mobility demands, such as dancers.

The aim of this study was to use a multi-segment spine model to examine differences in spine ROM in the frontal and transverse planes in both clinical movement tasks and walking gait in dancers with and without LBP. It was hypothesised that dancers with recent LBP would have reduced spine segment ROM in the transverse and frontal planes during both clinical movement tasks and gait.

## 2. Methods

We aimed to recruit male and female pre-professional (students enrolled in a tertiary dance programme) and professional (including full time, part time, and independent professionals) dancers aged 18–40 years with and without LBP from the New York Metropolitan area via a series of posters, social media posts, and information sessions. Low back pain was defined as pain experienced in the posterior aspect of the body from the bottom of the 12th rib to the lower gluteal folds [21]. Dancers with LBP had experienced at least one episode of LBP that had an impact on their dance practice (i.e., more than a transient episode) during the last two months. Dancers without LBP had not experienced any form of LBP in the last 12 months. Exclusion criteria were the presence of a separate injury that prevented participation in dance activity or impacted kinematics, known spinal deformities, a spinal curvature greater than 7° (measured with a scoliometer by a physical therapist), a history of spinal or abdominal surgery or current pregnancy. All volunteers provided written informed consent and ethics approval was obtained from the NYU School of Medicine's Institutional Review Board (study number 17-00490).

Participants attended a single data collection session at the Harkness Center for Dance Injuris, NYU Langone Medical Center. Participants completed a questionnaire that contained items relating to demographics (e.g. age, sex), dance participation (e.g. style, dance level, training background), LBP (e.g. duration, impact), and, to obtain a more complete description of the LBP experience, psychosocial factors (emotional distress [22], Harkness Discomfort Scale (HDS) [23], and the Tampa Scale for Kinesiophobia (TSK) [24]). Emotional distress was determined using two valid and reliable 11-point scales relating to the experience of anxiety and depression in the past week that were taken from the Orebro Musculoskeletal Pain Questionnaire [22]. The HDS is a validated outcome measure which provides a score reflecting the frequency and severity of six painful body regions [23].

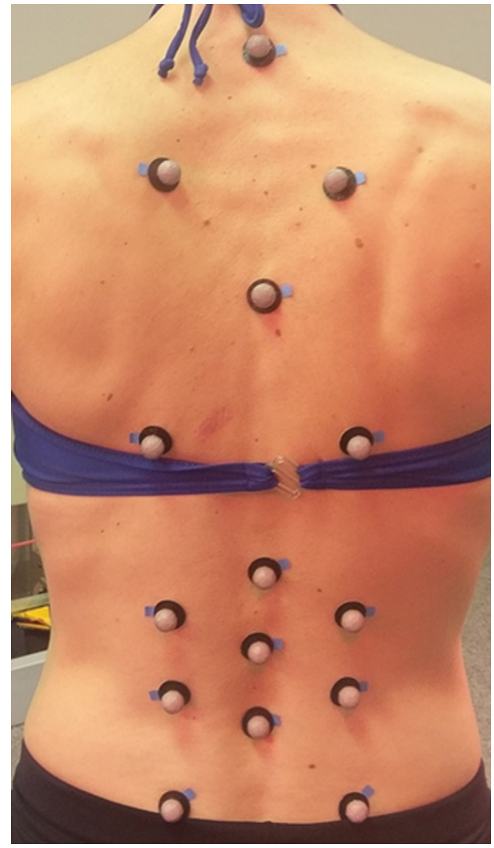

Fig. 1. Regional spine marker set.

Spinal kinematics were captured using a previously described multi-segment spine kinematics model [13,17]. Five reflective markers (12.7 mm, B & L Engineering, USA) were placed on the spinous processes of T1, T6, L1, L3 and L5, which were identified via palpation, eight lateral markers were placed 5 cm from the midpoint between each pair of spinous process markers, and four markers were placed on the right and left anterior superior-iliac spines and posterior superior iliac spines (Fig. 1). Marker positions were collected at 250 Hz using eight Eagle cameras (EGL500RT, Cortex, Motion Analysis Corp, CA, USA). After marker placement, trials of normal standing posture, frontal plane ROM in standing, transverse plane ROM in sitting, and walking gait were completed. For each task, a demonstration was provided along with standardised instructions and verbal cues (Supplement 1). Verbal instructions were consistent with those used in previous studies [13,25,26]. Each task was completed at a self-selected pace in the same order. Multiple practice attempts were provided, and two successful captures of each task were completed. Nine participants returned for a second testing session for reliability assessment purposes.

Data processing was conducted in Visual 3-D (6.01.09, C-Motion, Inc. MD, USA). Marker data were filtered at 6 Hz with a low-pass Butterworth filter to eliminate motion artefact. The trunk was divided

**Table 1**
Participant Characteristics. Results are reported as mean (standard deviation) for continuous variables and frequencies (percentage) for categorical variables.

| | | All (n = 47) | LBP (n = 26) | No LBP (n = 21) | P |
|---|---|---|---|---|---|
| Age | Age (Yrs) | 24.8 (6.2) | 24.7 (5.9) | 25.1 (6.7) | 0.83 |
| Anthropometric | Height (CM) | 164.2 (7.0) | 162.8 (6.8) | 168.0 (7.0) | 0.12 |
| | Body Mass (KG) | 58.8 (6.4) | 58.2 (6.5) | 59.6 (6.3) | 0.44 |
| | BMI | 21.8 (2.2) | 22.0 (2.5) | 21.6 (1.9) | 0.60 |
| | Curvature 3-7$^0$ (Y/N) | 6 (13) | 4 (15) | 2 (10) | 0.55 |
| Dance Level | Full time Professional | 8 (17) | 5 (19) | 3 (14) | 0.53 |
| | Independent/ Part time Professional | 22 (47) | 14 (54) | 8 (38) | |
| | Pre-Professional Student | 17 (36) | 7 (27) | 10 (48) | |
| Primary Dance Style | Ballet | 4 (9) | 2 (8) | 2 (10) | 0.60 |
| | Modern/Contemporary | 36 (77) | 19 (73) | 17 (81) | |
| | Musical Theatre/Other | 17 (15) | 5 (19) | 2 (10) | |
| Emotional Distress | Tension/Anxiety (/10) | 5.4 (2.2) | 6.1 (2.1) | 4.5 (2.5) | **0.01** |
| | Depression (/10) | 3.2 (2.3) | 4.0 (1.5) | 2.2 (1.6) | < **0.01** |
| | Emotional Distress Total (/20) | 8.6 (4.0) | 10.1 (4.1) | 6.7 (3.0) | < **0.01** |
| Harkness Discomfort Scale | Total Score (not incl. LB region) (/80) | 12.9 (7.7) | 14.6 (7.3) | 10.7 (7.8) | 0.08 |

The significant of bold value is $P < 0.05$.

into a series of five segments, including the pelvis, lower lumbar, upper lumbar, lower thoracic and upper thoracic spine segments. For each task, lower lumbar angles (LLa) were defined as the angles between the lower lumbar and pelvis segments, the upper lumbar angles (ULa) as the angles between the upper lumbar and lower lumbar segments, the lower thoracic angles (LTa) as the angles between the lower thoracic and upper lumbar segments and the upper thoracic angles (UTa) as the angles between the upper thoracic and lower thoracic segments [13]. To calculate ROM in the movement tasks, the start position was subtracted from the end position for both right and left sides, and the higher value of the two trials to the right was added to the higher value of the two trials to the left. For gait, the first and second right heel strikes were defined as the start and end of the gait cycle respectively. Using a customised Matlab script (R2016b, MathWorks, Inc, MA, USA), joint angles captured with the standing reference posture were subtracted from the time series data, with the gait cycle time normalised to 100 points for each trial. Minimum and maximum peaks for each segment were extracted and used to calculate ROM [13].

The Shapiro-Wilk test was used to determine whether data were normally distributed. Variables identified as non-parametric were log-transformed prior to any further analysis [27]. Independent T-tests were used to examine differences between groups and effect size (ES) was calculated using Cohen's d [28]. Effect Size results were interpreted as < 0.1: trivial, 0.1–0.6: small, 0.6–1.2: moderate, and > 1.2: large [29]. Intraclass correlation coefficients (ICC) (2-way mixed effects) and typical error of measurement expressed as a coefficient of variation (CV) were used to assess the test-retest reliability of kinematic variables collected on the day of testing as well as for measures collected on two separate days [30]. All statistical analyses were performed using SPSS software for Windows (version 22.0, SPSS Inc., IL, USA). Statistical significance was set at $P < 0.05$ for all tests.

## 3. Results

Forty-seven female volunteers, including 26 with LBP in the past two months and 21 with no LBP in the past 12 months, met the inclusion criteria for this study. The female sample size allowed a 0.99 power to detect a large (ES = 1.2) difference between groups and a 0.64 power to detect a moderate (ES = 0.6) difference between groups, using an alpha of 0.05. A total of 12 male dancers (No LBP = 3) were recruited, which allowed for a power of only 0.51 to detect a large effect size and 0.21 to detect a moderate effect size. As the number of males was not deemed appropriate for statistical analysis, they were not included in the final study.

There were no differences between the LBP and No LBP groups for age, height, body mass, BMI, or sagittal standing posture. Dancers with LBP had significantly higher tension and anxiety, depression, and total emotional distress than dancers without LBP (Table 1). Of the dancers with LBP, 13 (50%) reported current LBP, 22 (83%) reported chronic LBP, 11 (42%) experienced leg pain referral, 19 (73%) consulted a medical professional, and 15 (58%) consumed medication for their LBP. Only one dancer with LBP was classified as having moderate kinesiophobia (score = 33–42). The remaining dancers were classified as having sub-clinical (13–22) or mild (23–32) kinesiophobia [24].

Good to excellent same day test-retest reliability for all ROM measures was demonstrated with ICC scores of 0.75–0.98 and CV scores between 4%–24% [30]. Test-retest reliability on two different days was moderate to good with ICC's ranging from 0.63 to 0.88 and CV scores between 8–25%.

**Table 2**
Differences between groups: standing frontal plane ROM and seated transverse plane ROM.

| | | No LBP | LBP | ES (95% CI) | p |
|---|---|---|---|---|---|
| Frontal Plane (degrees) | UTa | 30.54 (7.76) | 29.93 (3.74) | −0.11 (−0.68, 0.47) | 0.72 |
| | LTa | 42.29 (8.71) | 41.67 (8.86) | −0.07 (−0.65, 0.51) | 0.81 |
| | ULa | 27.71 (8.07) | 23.89 (8.71) | −0.50 (−1.09, 0.08) | 0.10 |
| | LLa | 16.52 (6.75) | 15.63 (5.90) | −0.14 (−0.72, 0.44) | 0.63 |
| Transverse Plane (degrees) | UTa | 34.07 (10.65) | 31.29 (8.36) | −0.30 (−0.87, 0.28) | 0.32 |
| | LTa | 42.74 (11.16) | 42.53 (9.15) | −0.02 (−0.60, 0.56) | 0.96 |
| | ULa | 17.80 (3.45) | 15.35 (4.42) | −0.61(−1.20, 0.02) | **0.04** |
| | LLa | 6.79 (3.09) | 6.30 (2.93) | −0.16 (−0.74, 0.41) | 0.58 |

**ES = Effect size, 95% CI = 95% Confidence interval.**
The significant of bold value is $P < 0.05$.

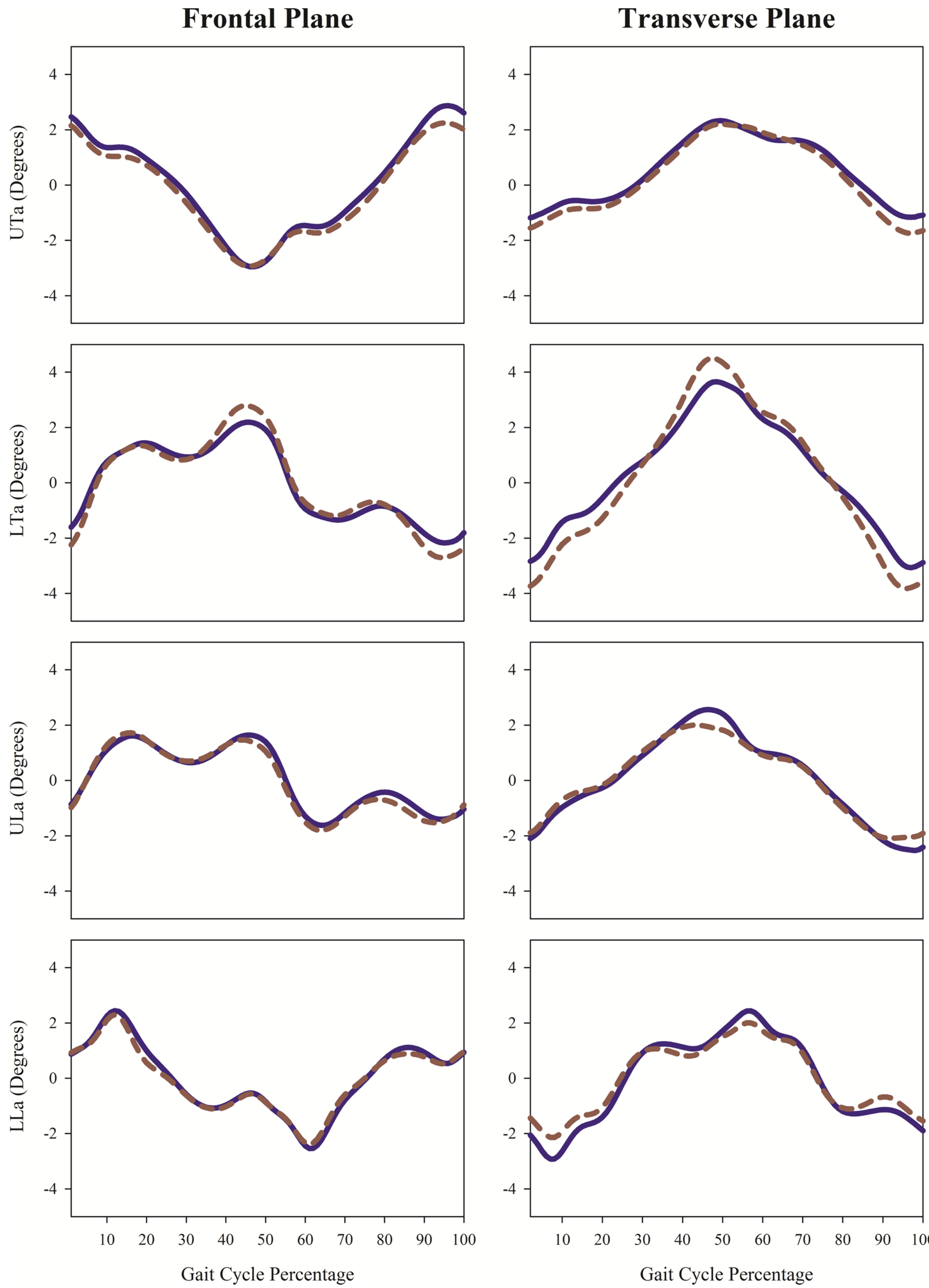


**Fig. 2.** Mean time normalised spine mobility during gait for female dancers. The No LBP group is represented by the blue (complete) line, the LBP group by the red (dash) line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Dancers with LBP displayed reduced ULa in seated rotation (ES = −0.61, 95% Confidence Interval (CI): −1.2, 0.02 p = 0.04). No other differences in maximum ROM were observed for the frontal or transverse plane (Table 2). During walking gait, no frontal plane differences were observed between groups. In the transverse plane, significantly reduced LLa (ES = −0.65, 95% CI: −1.24, −0.06, p = 0.03) and increased LTa (ES = 0.62, 95% CI: 0.04, 1.21, p = 0.05) were observed (Fig. 2, Table 3).

## 4. Discussion

This study examined differences in spine mobility in female dancers

**Table 3**
Differences between groups: ROM in walking gait.

| | | No LBP | LBP | ES | 95% CI | p |
|---|---|---|---|---|---|---|
| Frontal Plane (degrees) | UTa | 6.13 (2.27) | 5.91 (1.85) | −0.11 | (−0.68, 0.47) | 0.72 |
| | LTa[a] | 5.01 (1.53) | 5.75 (1.60) | 0.3 | (−0.28, 0.88) | 0.30 |
| | Ula[a] | 3.92 (1.51) | 4.18 (1.45) | 0.17 | (−0.41, 0.74) | 0.57 |
| | LLa | 5.44 (1.25) | 5.13 (1.71) | −0.2 | (−0.78, 0.37) | 0.49 |
| Transverse Plane (degrees) | UTa[a] | 4.16 (1.49) | 4.27 (1.51) | 0.06 | (−0.05, 0.64) | 0.83 |
| | LTa[a] | 6.86 (1.46) | 8.61 (1.42) | 0.62 | (0.04, 1.21) | **0.04** |
| | Ula[a] | 4.93 (1.68) | 4.48 (1.48) | −0.21 | (−0.79, 0.36) | 0.47 |
| | LLa | 5.82 (1.05) | 4.90 (1.66) | −0.65 | (−1.24, −0.06) | **0.03** |

ES = Effect size, 95% CI = 95% Confidence interval.
The significant of bold value is $P < 0.05$.
[a] Effect size calculated based on log transformed data. Mean and SD has been back transformed.

with and without LBP. Assessment of maximum ROM and walking gait was undertaken as these tasks have previously been used to identify kinematic impairment associated with LBP [3,11–13]. For the movement tasks, differences were only observed for one segment in the transverse plane, with the LBP group displaying reduced upper lumbar angles compared with the no LBP group. For walking gait, dancers with recent LBP did display altered transverse plane spine kinematics compared to their asymptomatic counterparts (e.g., reduced LL segments but increased LT segments), but no differences in the frontal plane were observed. Overall, while a small number of significant differences do provide evidence of altered kinematics in dancers with recent LBP, the effect sizes were low to moderate and, collectively, the total number of differences was small.

An absence of clear differences in the maximum ROM assessments between groups was unexpected and contrasts with prior research conducted in non-dancers. Previously, a meta-analysis of 26 studies identified significantly reduced lumbar spine mobility all three planes of motion for people with LBP compared to those without [11], as did a study that used a multi-segment spine model in athletes [3]. Although we did observe reduced upper lumbar angles in the transverse plane in dancers with LBP, the key finding is that these measures had limited ability to discriminate between dancers with and without recent LBP, who were significantly different in other measures, such as emotional distress. This finding does suggest dancers are unlike other studied populations, which is not an unprecedented observation. Two recent studies conducted within a professional ballet company found that, unlike non-athletic and other athletic populations, trunk stiffness was not significantly higher in dancers with a history of LBP compared to dancers without [9], and that dancers with LBP did not have a reduced ability to reduce the abdominal cross-sectional area during a 'draw-in' manoeuvre [31]. Possible explanations for this may include that dance practice, which places large emphasis on how movements are performed, protects against kinematic changes associated with LBP, that spine mobility is required for progression within dance and that some natural selection has occurred, or that there is such variability within the population that differences may be hidden.

For walking gait, female dancers with recent LBP displayed reduced lower lumbar and increased lower thoracic angles in the transverse plane during walking gait. Previous studies have found altered spine kinematics during gait in people with LBP, although the specific differences vary between studies. For example, a series of studies on walking gait in persons with LBP identified a more rigid and less variable coordination pattern for people with LBP in the transverse plane, but not the frontal plane [16,32]. However, unlike the current study, these studies did not detect differences in ROM during gait. Importantly, as the trunk was modelled as a single segment between the pelvis and shoulders, comparison with the current study is difficult. Using the same model as the current study, Christe, Kade [13] identified reduced lower lumbar angles in the frontal plane in chronic LBP participants, confirming the presence of altered kinematics in the LBP patients, but unlike in the current study did not observe differences in absolute range of motion for any segment in the transverse plane. The population studied may provide explanation for some of these differences. On average, dancers have flatter standing postures than non-dancers [10], unique abdominal muscle morphology [31], and bone morphology that may allow greater ROM at the hip [33].

Differences in spine segment ROM observed in walking gait may indicate an altered movement strategy, whereby female dancers with recent LBP compensate for reduced mobility in painful regions by increasing mobility in less painful regions. If so, these changes may offer short term protective benefit. However, as the effect sizes for these differences were only moderate, altered movement strategy should be considered subtle. In addition, caution should be exercised when considering the utility of adaptation. If the differences represent a sub-optimal response, or persist for longer than required, they may result in abnormal tissue loading and contribute to the recurrence of symptoms [7]. The subtle differences observed during gait implies that movement rehabilitation should consider how movement is performed at different spine segments, rather than simply focussing on whole spine movement and task completion.

The findings present several implications. First, for clinical practice, collectively, the simple assessments of maximum range of motion did not provide clear information about the experience of LBP in dancers. Future research should consider whether more challenging or dance specific movement assessments, subgrouping (e.g. based on sagittal posture profiles) or novel analysis techniques (e.g. statistical parametric mapping) are better able to identify movement impairment in dancers with LBP. Second, the current study does not support that movement changes related to pain are more pronounced in a population with high mechanical demands such as dancers. Whether dance practice protects against these changes, or dancers possess pain thresholds that allow them to resist movement change warrants further attention. Third, although pain can change movement, that dancers with recent and impactful LBP displayed only a limited number of moderate sized differences in spine movement reminds that LBP is not exclusively a movement condition.

There are several methodological issues that require consideration when interpreting the findings of this study. As an insufficient number of males recruited prevented analysis on this group, the findings may not be generalisable to male dancers. Participants were eligible for the no pain group if they had not experienced any form of LBP in the past 12 months. While the authors believe that dancing at a high level without experiencing LBP for 12 months is enough to consider an individual back healthy, it is possible that some participants in the No LBP group had a history that may have influenced the kinematic measurements. Although individuals with a scoliosis were not eligible for participation, six participants presented with a curvature between 3-7°. As these participants did not meet the threshold for exclusion, and their total spine mobility was within the normal range of variance observed in the other participants, we did not exclude them from the analysis. Nonetheless, it is still possible that these spine characteristics influence spine mobility or LBP in ways not understood. The use of skin markers may influence kinematic data. However, the values obtained for segmental range of motion in clinical tasks agreed with data from x-ray analysis of normal spine movement [34], and the reliability of the methods was good, including testing on two separate days requiring reapplication of markers, indicating the measures used were appropriate. Analyses was limited to the frontal and transverse planes, and, due to the dancer's large mobility obstructing the identification of reflective markers during piloting, we did not collect data on maximum sagittal plane flexion or extension.

## 5. Conclusion

Subtle differences in spine movement during gait were associated with recent LBP in female dancers. While this may suggest a protective movement strategy, collectively, the ability of segmental spine ROM measures to discriminate between dancers with and without LBP was limited. The findings do not support that altered kinematic patterns associated with LBP are more pronounced in a movement orientated population such as dancers.

## Conflict of interest statement

The authors declare that they have no conflicts of interest relevant to the content of this study.

## Acknowledgements

The authors wish to acknowledge the Jacob and Valeria Langeloth Foundation for their support of this work. Additional thanks are delivered to each dancer that participated, and to Doug Whyte for comments on analysis and interpretation of the data. Christopher Swain was supported by an Endeavour Research Fellowship. Christina Ekegren is supported by a National Health and Medical Research Council (NHMRC) Early Career Fellowship (1106633).

## References

[1] C.T.V. Swain, E.J. Bradshaw, C.L. Ekegren, D.G. Whyte, The epidemiology of low back pain and injury in dance: a systematic review, J. Orthop. Sports Phys. Ther. (2019) 1–41.
[2] C.T.V. Swain, E.J. Bradshaw, D.G. Whyte, C.L. Ekegren, The prevalence and impact of low back pain in pre-professional and professional dancers: a prospective study, Phys. Ther. Sport 30 (2017) 8–13.
[3] A. Campbell, P. O'Sullivan, L. Straker, B. Elliott, M. Reid, Back pain in tennis players: a link with lumbar serve kinematics and range of motion, Med. Sci. Sports Exerc. 46 (2013) 351–357.
[4] M. Dolphens, S. Vansteelandt, B. Cagnie, A. Vleeming, J. Nijs, G. Vanderstraeten, et al., Multivariable modeling of factors associated with spinal pain in young adolescence, Eur. Spine J. 25 (9) (2016) 2809–2821.
[5] M.A. Adams, A.F. Mannion, P. Dolan, Personal risk factors for first-time low back pain, Spine (Phila Pa 1976) 24 (1999) 2497–2505.
[6] P. Dolan, M.A. Adams, Influence of lumbar and hip mobility on the bending stresses acting on the lumbar spine, Clin. Biomech. (Bristol, Avon) 8 (1993) 185–192.
[7] P.W. Hodges, R.J. Smeets, Interaction between pain, movement, and physical activity: short-term benefits, long-term consequences, and targets for treatment, Clin. J Pain 31 (2015) 97–107.
[8] G.B. Ross, P.J. Sheahan, B. Mahoney, B.J. Gurd, P.W. Hodges, R.B. Graham, Pain catastrophizing moderates changes in spinal control in response to noxiously induced low back pain, J. Biomech. 58 (2017) 64–70.
[9] J.E. Gildea, W. Van Den Hoorn, J.A. Hides, P.W. Hodges, Trunk dynamics are impaired in ballet dancers with back pain but improve with imagery, Med. Sci. Sports Exerc. 47 (2014) 1665–1671.
[10] J. McMeeken, E. Tully, C. Nattrass, B. Stillman, The effect of spinal and pelvic posture and mobility on back pain in young dancers and non-dancers, J. Dance Med. Sci. 6 (2002) 79–86.
[11] R.A. Laird, J. Gilbert, P. Kent, J.L. Keating, Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis, BMC Musculoskelet. Disord. 15 (2014) 229.
[12] C.J. Lamoth, O.G. Meijer, P.I. Wuisman, J.H. van Dieen, M.F. Levin, P.J. Beek, Pelvis-thorax coordination in the transverse plane during walking in persons with nonspecific low back pain, Spine (Phila Pa 1976) 27 (2002) E92–E99.
[13] G. Christe, F. Kade, B.M. Jolles, J. Favre, Chronic low back pain patients walk with locally altered spinal kinematics, J. Biomech. 60 (2017) 211–218.
[14] M. Wade, A. Campbell, A. Smith, J. Norcott, P. O'Sullivan, Investigation of spinal posture signatures and ground reaction forces during landing in elite female gymnasts, J. Appl. Biomech. 28 (2012) 677–686.
[15] S. Parkinson, A. Campbell, W. Dankaerts, A. Burnett, P. O'Sullivan, Upper and lower lumbar segments move differently during sit-to-stand, Man. Ther. 18 (2013) 390–394.
[16] C.J. Lamoth, O.G. Meijer, A. Daffertshofer, P.I. Wuisman, P.J. Beek, Effects of chronic low back pain on trunk coordination and back muscle activity during walking: changes in motor control, Eur. Spine J. 15 (2006) 23–40.
[17] G. Christe, L. Redhead, T. Legrand, B.M. Jolles, J. Favre, Multi-segment analysis of spinal kinematics during sit-to-stand in patients with chronic low back pain, J. Biomech. 49 (2016) 2060–2067.
[18] R. Hemming, L. Sheeran, R. van Deursen, V. Sparkes, Non-specific chronic low back pain: differences in spinal kinematics in subgroups during functional tasks, Eur. Spine J. 27 (2018) 163–170.
[19] H. Schmidt, A. Kettler, F. Heuer, U. Simon, L. Claes, H.J. Wilke, Intradiscal pressure, shear strain, and fiber strain in the intervertebral disc under combined loading, Spine (Phila Pa 1976) 32 (2007) 748–755.
[20] W.S. Marras, S.A. Lavender, S.A. Ferguson, R.E. Splittstoesser, G. Yang, Quantitative dynamic measures of physical exposure predict low back functional impairment, Spine (Phila Pa 1976) 35 (2010) 914–923.
[21] C.E. Dionne, K.M. Dunn, P.R. Croft, A.L. Nachemson, R. Buchbinder, B.F. Walker, et al., A consensus approach toward the standardization of back pain definitions for use in prevalence studies, Spine (Phila Pa 1976) 33 (2008) 95–103.
[22] S.J. Linton, K. Boersma, Early identification of patients at risk of developing a persistent back problem: the predictive validity of the Örebro musculoskeletal pain questionnaire, Clin. J. Pain 19 (2003) 80–86.
[23] M. Liederbach, J. Honrado, A. Deleget, Evidence based on relationships between musculoskeletal discomfort rating scores and time-loss injuries among professional dancers, Proceedings from the 26th Annual Conference of the International Association of Dance Medicine and Science (2014).
[24] R. Neblett, M.M. Hartzell, T.G. Mayer, E.M. Bradford, R.J. Gatchel, Establishing clinically meaningful severity levels for the tampa scale for kinesiophobia (TSK-13), Eur. J. Pain (London, England) 20 (2016) 701–710.
[25] W. Dankaerts, P. O'Sullivan, A. Burnett, L. Straker, P. Davey, R. Gupta, Discriminating healthy controls and two clinical subgroups of nonspecific chronic low back pain patients using trunk muscle activation and lumbosacral kinematics of postures and movements: a statistical classification model, Spine (Phila Pa 1976) 34 (2009) 1610–1618.
[26] S.A. Weyrauch, S.C. Bohall, C.J. Sorensen, L.R. Van Dillen, Association between rotation-related impairments and activity type in people with and without low back pain, Arch. Phys. Med. Rehabil. 96 (2015) 1506–1517.
[27] J.M. Bland, D.G. Altman, Statistics notes: transformations, means, and confidence intervals, BMJ (Clin. Res. Ed.) 312 (1996) 1079.
[28] S. Nakagawa, I.C. Cuthill, Effect size, confidence interval and statistical significance: a practical guide for biologists, Biol. Rev. Camb. Philos. Soc. 82 (2007) 591–605.
[29] W.G. Hopkins, S.W. Marshall, A.M. Batterham, J. Hanin, Progressive statistics for studies in sports medicine and exercise science, Med. Sci. Sports Exerc. 41 (2009) 3–13.
[30] T.K. Koo, M.Y. Li, A guideline of selecting and reporting intraclass correlation coefficients for reliability research, J. Chiropr. Med. 15 (2016) 155–163.
[31] J.E. Gildea, J.A. Hides, P.W. Hodges, Morphology of the abdominal muscles in ballet dancers with and without low back pain: a magnetic resonance imaging study, J. Sci. Med. Sport 17 (2014) 452–456.
[32] C.J. Lamoth, O.G. Meijer, P.I. Wuisman, J.H. van Dieen, M.F. Levin, P.J. Beek, Pelvis-thorax coordination in the transverse plane during walking in persons with nonspecific low back pain, Spine (Phila Pa 1976) 27 (2002) E92–9.
[33] S. Mayes, A.R. Ferris, P. Smith, A. Garnham, J. Cook, Bony morphology of the hip in professional ballet dancers compared to athletes, Eur Radiol. 27 (2017) 3042–3049.
[34] M.J. Pearcy, S.B. Tibrewal, Axial rotation and lateral bending in the normal lumbar spine measured by three-dimensional radiography, Spine (Phila Pa 1976) 9 (1984) 582–587.