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Reduced variability of erector spinae activity in people with chronic low back pain when performing a functional 3D lifting task

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ABSTRACT

Background: Chronic low back pain (LBP) is a leading cause of disability, which is exacerbated in some by repeated lifting. Electromyography (EMG) assessments of isolated erector spinae (ES) regions during lifting identified conflicting results. Here, high-density EMG comprehensively assesses the lumbar and thoracolumbar ES activity in people with and without LBP performing a multiplanar lifting task.
Methods: Four high-density EMG grids (two bilaterally) and reflective markers were affixed over the ES and trunk to record muscle activity and trunk kinematics respectively. The task involved cyclical lifting of a 5 kg box for ~7 min from a central shelf to five peripheral shelves, returning to the first between movements, while monitoring perceived exertion.
Results: Fourteen LBP (26.9 ± 11.1 years) and 15 control participants (32.1 ± 14.6 years) completed the study. LBP participants used a strategy characterised by less diffuse and more cranially-focussed ES activity ($P < 0.05$). LBP participants also exhibited less variation in ES activity distribution between sides during movements distal to the central shelf ($P < 0.05$). There were few consistent differences in kinematics, but LBP participants reported greater exertion ($P < 0.05$).
Conclusion: In the presence of mild LBP, participants used a less variable motor strategy, with less diffuse and more cranially-focussed ES activity; this motor strategy occurred concomitantly with increased exertion while completing this dynamic task.

1. Introduction

Chronic low back pain (LBP) is consistently identified as a leading cause of years lived with disability globally (James et al., 2018). Between 70–84 % of people experience LBP during their lifetime, with a point-prevalence of activity-limiting LBP in 540 million people (Hartvigsen et al., 2018, Hong et al., 2013). Recent indications also suggest that this burden is increasing, an increase of 17.5 % in years lived with disability caused by LBP between 2007 and 2017 (James et al., 2018).

Repetitive lifting is commonly thought to underlie the development of LBP, although systematic reviews and meta-reviews have found no clear causal link (Kwon et al., 2011). Instead, studies which have considered manual occupational tasks, including repeated and routine heavy lifting, have continued to present conflicting evidence for contributing to the persistence of LBP symptoms (Kwon et al., 2011), Silvetti et al., 2019). Moreover, the presence of LBP has repeatedly been demonstrated to affect participants' movement patterns (Shojaei et al., 2017), perception of pain (Kuithan et al., 2019), and spinal stability during lifting tasks (Hemming et al., 2018). In a recent systematic review on the influence of LBP on lifting kinematics, a majority of studies included described a difference in lifting strategy between those with and without LBP (Nolan et al., 2020). However the nature of these differences was varied, for example of the four studies which considered spinal range of motion as an outcome; two studies described reduced range, however the other two studies described no differences (Nolan et al., 2020).

Surface electromyography (EMG) has been used to investigate the

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activity of the lumbar erector spinae (ES) across a variety of tasks in LBP participants (Abboud et al., 2014, Martinez-Valdes et al., 2019, Murillo et al., 2019, Sanderson et al., 2019b). Several investigations have focussed on the activity of the paraspinal muscles during lifting movements (Fabian et al., 2005, Falla et al., 2014, Lariviere et al., 2002). Lariviere et al. (2002) identified activity in more cranial ES regions in individuals with LBP during lifting tasks, however this analysis was based on proportional activity between two points on the ES. Similarly, another study described a trend for individuals with LBP to exhibit lower lumbar ES activity than pain-free controls during a lifting task (Fabian et al., 2005). However, both of these studies used bipolar electrodes, focussing measurement on single points rather than across regions. In their review on lifting and LBP, Nolan, O'Sullivan (2020) highlighted the inconsistencies in the evidence around muscle activity during lifting, with studies identifying results of both greater and less muscle activity during different phases of lifting. Using high-density EMG (HDEMG), which involves placing electrode arrays over muscle regions, Falla et al. (2014) identified that individuals with LBP were unable to redistribute activity within a painful muscle during a repeated sagittal lifting task. However, this use of HDEMG remained limited to the specific region of interest, e.g. unilateral measurement (Falla et al., 2014).

Nevertheless, these previous studies investigating lifting primarily investigated muscle activity during monoplanar lifting movements, which do not reflect the multiplanar nature of daily functional movement. Where contractions to produce movements in three planes has previously been assessed, these contractions were isometric and strictly limited to each cardinal plane (Ng et al., 2002). Recent studies have begun to consider muscle activity bilaterally in the lumbar and thoracolumbar region in individuals with LBP, however the tasks considered remain largely monoplanar in nature (Sanderson et al., 2019a, Serafino et al., 2021). Our previous work investigating this region was focussed on a singular monoplanar lift, which does not reflect repetitive, multiplanar functional lifting (Sanderson et al., 2019a). The work by Serafino et al. (2021) investigated muscle activity during a series of 'low-effort' functional tasks, however these tasks were considered in isolation, so therefore occur largely within a single plane.

Thus, in the current study we aimed to use a more complex multiplanar lifting task to simulate a functional task of daily life in individuals with and without LBP. During this task we investigated the influence of the presence of LBP on (1) lumbar and thoracolumbar ES muscle activity bilaterally using HDEMG, and (2) lumbar and thoracolumbar 3D motion. It was hypothesised that people with LBP would display a different distribution of ES activity during the lifting task in line with our previous work, characterised by a more cranial distribution of activity, centred towards the thoracolumbar region. Additionally, that this difference in muscle behaviour would be reflected in a different movement strategy characterised by less lumbar spinal motion in those with LBP.

2. Methodology

This study was an observational, case control study, conducted at the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine) at the University of Birmingham. Ethical approval was granted by the university ethics committee (ERN_16-1389B), and the procedures followed the Declaration of Helsinki. The EMG procedures are reported in line with the checklist for reporting and critically appraising studies using EMG (CEDE-Check) (Besomi et al., 2024).

2.1. Participants

Participants aged 18–65 were recruited via poster and social media advertisements from the students, staff and community of the University of Birmingham, UK. Participants with LBP were eligible if they had experienced LBP symptoms for more than three of the previous six months (Dionne et al., 2008). LBP participants were excluded from this study if their pain was related to trauma, spinal stenosis, fractures, or if they experienced radiating pain in the leg. Age- and gender-matched control participants were recruited with no history of low back or lower limb pain. Participants from both groups were excluded if they were on high doses of anti-inflammatories (>30 mg morphine equivalent dose), were pregnant, or were experiencing any concurrent systemic, rheumatic or neuro-musculoskeletal disorders which could confound testing. To support a normal distribution for statistical analysis, in line with previous comparable studies, a planned sample size of 30 participants was selected, with 15 in each group (Falla et al., 2014, Ghasemi and Zahediasl, 2012).

2.2. Questionnaires

Baseline characteristics of participants were assessed by questionnaires prior to data collection. Participant height, weight and age characteristics were recorded. A bespoke back pain questionnaire was used to collect information regarding severity, using the pain Numeric Rating Scale (NRS) and duration of a participant's LBP (Breivik et al., 2008). Disability was assessed using the Oswestry Disability Index (ODI) (Fairbank and Pynsent, 2000); and beliefs and fears about movement related to pain were assessed by the Fear Avoidance Beliefs Questionnaire (FABQ) (Waddell et al., 1993) and the Pain Catastrophising Scale (PCS) (Osman et al., 1997). 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). Finally, general health at the time of data collection was assessed using the SF-36 (V2) (Walsh et al., 2003).

2.3. Experimental task

The experimental task consisted of a cyclical lifting task of a 5 kg weighted box between six shelves situated anteriorly and laterally to the participant. Two shelf heights in each direction were selected for the task as this arrangement varied the demands on the spine and lumbar region during the lifting task. As ergonomic interventions have been demonstrated to influence lumbar loading, the location and height of each shelf was adjusted for each participant, based on palpated anthropomorphic characteristics (Faber et al., 2007, Motamedzade et al., 2013). The specific landmarks chosen to determine shelf height were adapted from previous work by Falla et al. (2014), and adjusted slightly based on feedback on task feasibility from pilot participants with LBP. The lower shelf was determined by the height of the lateral epicondyle of the femur and the upper by the height of the manubriosternal angle. Measured from the midpoint of the foot-base the lateral shelves were situated half of the distance between the right and left olecranon processes, with the arms abducted to shoulder height. The anterior shelves were placed the distance from the acromion process of the shoulder to the ulnar styloid process, anterior to the midpoint of the foot-base (Fig. 1).

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). During the task, participants performed 10 cycles of lifting a 5 kg box (35.5 cm × 29 cm × 13.5 cm) between 6 shelves. The speed of the task was controlled by a metronome with 2 s allocated to each movement between shelves followed by a rest of 2 s. Shelf 1 was situated anteriorly at knee height with shelves 3 and 5 lateral to the left and right respectively. Shelf 2 was situated anteriorly at sternal height with shelves 4 and 6 lateral to the left and right respectively (Fig. 1). The lifting movement for all participants began on shelf 1 and involved a basic pattern of lifting to a sequential shelf, return to the starting position on shelf 1, before moving to the next sequential shelf, with rests between movements. Therefore, an example of a sequence of movements would be from shelf 4-shelf 1, rest, shelf 1-shelf 5. A cycle was completed when the participant had visited each shelf and returned from shelf 6- shelf 1; the task was comprised of 10 cycles in total. This

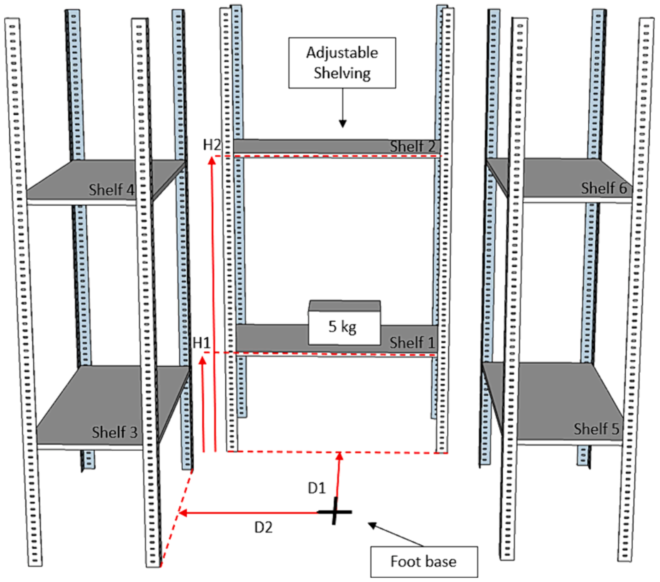

Fig. 1. Schematic of the task set-up depicting the adjustable shelving and the foot-base. The distance of the shelves from the foot-base are shown by D1 – acromion to ulnar styloid process and D2 – half of the inter olecranon distance. The height of the shelves is shown by H1 – lateral femoral epicondyle height and H2 – manubriosternal angle height. Not to scale.

movement pattern, involving the repeated lifting of a standardised weight (5 kg) in a three dimensional, multiplanar manner was designed to better reflect a task of daily life or functional lifting.

The task was explained by researchers using standardised instructions, and a demonstration of one complete cycle was given. Participants were asked to not move their feet and limit knee movement to standardise lower limb position and to focus the task by moving their lower back region, but were given no further instructions regarding lifting technique. Participants were then allowed to practise one complete timed cycle with an unweighted box to ensure that the pattern and lifting strategy at the knees and feet were correct. The task was completed in one continuous acquisition lasting approximately 7 min and following completion participants were asked to use the Borg Rating of Perceived Exertion (6–20, RPE) scale to rate how exerting they found the task to be (Borg, 1998) and to report the maximum level of pain they felt throughout the task using a NRS.

2.4. *Experimental set-up*

2.4.1. *Electromyography*

Surface EMG signals were recorded by four 64 channel semi-disposable 13 × 5 2D electrode grids with an 8 mm inter-electrode distance (two grids bilaterally; OT Bioelettronica, Turin, Italy). Within the grids, 3 mm monopolar electrodes were spaced evenly and a corner electrode was missing to provide a directional reference. Before adhering to the skin, the grids were prepared by affixing a double-sided adhesive foam and filling the cavities for each electrode with an electroconductive gel to facilitate good contact between the electrode and the underlying skin (SPES Medica, Genoa, Italy).

The electrode grids were placed bilaterally with the inferomedial border of the lower grids placed 2 cm lateral to the spinous process of the L5 vertebrae, in line with previous studies (Falla et al., 2014, Sanderson et al., 2019a). The upper grids were placed 5 mm cranial to the superior borders of the lower grids and remained 2 cm lateral to the spinous processes (Fig. 2). Prior to electrode application, the skin was shaved to remove any hair, then scrubbed using a micro-abrasive paste to remove dead and keratinised skin cells (SPES Medica, Genoa, Italy). The region was then rinsed with water and dried to remove debris before electrodes were affixed to the skin and secured in place with tape (BSN Medical, Hamburg, Germany). Reference electrodes were placed on similarly prepared skin overlying the S1 spinous process and the right medial malleolus.

2.4.2. *Motion analysis*

Motion data for the three-dimensional lifting task were recorded using an 8-camera stereo-photogrammetric array (Smart DX, BTS Bioengineering, Milan, Italy). Retroreflective stick markers were adhered to the skin overlying T12 and S1 and bilaterally 10 cm lateral to T6 and T12. The markers were placed in triangular patterns overlying

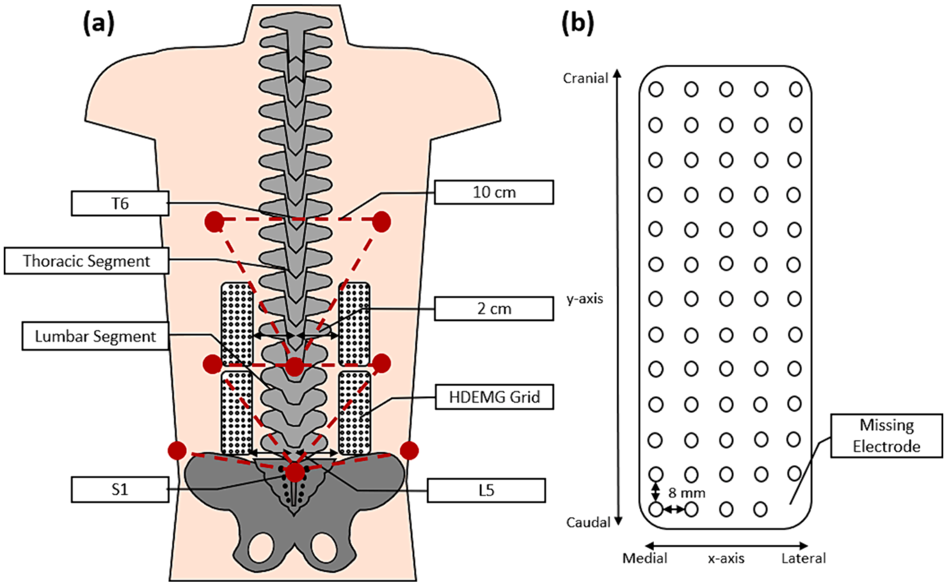

Fig. 2. Depicting (a) the approximate positioning of the HDEMG grids and reflective markers (marked in red) over the lumbar and thoracolumbar regions. The HDEMG grids were positioned 2 cm lateral to the spinous processes and spaced 5 mm between grids. The retroreflective markers were positioned over the spinous processes and 10 cm lateral, this arrangement allowed for the creation of two trunk segments, marked. (b) a schematic of the HDEMG electrode grid depicting the interelectrode distance, the positioning of the x- and y-axes and showing the location of the missing electrode. (Not to scale). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the spine and trunk, facilitating division of the region into functional areas, adapted from the technique described by Muller et al. (2016). The markers on S1 and 10 cm lateral to T12 marked the vertices of the Lumbar Segment (LS), and markers on T12 and 10 cm lateral to T6 marked the Thoracic Segment (TS) (Fig. 2). Retroreflective markers were also placed on the box, and the distal edge of each shelf (shelf 1-shelf 6).

Three-dimensional data were sampled continuously at 150 Hz throughout the task, and a synchronisation signal was recorded from the EMG amplifier alongside motion data. Data were saved for offline processing using the BTS SMART software suite (SMART Tracker, SMART Analyser; BTS Bioengineering, Milan, Italy).

2.5. *Data analysis*

Statistical analysis was completed using Statistica Version 13.3 (Tibco, USA), with an alpha level set at 0.05. The assumption of normality was checked using Q-Q plots and Kolmogorov-Smirnov tests as appropriate prior to additional analyses.

2.5.1. *Participant characteristics*

Questionnaires were evaluated according to their respective guidelines (Breivik et al., 2008, Fairbank and Pynsent, 2000, Lovibond and Lovibond, 1995, Miller et al., 1991, Osman et al., 1997, Waddell et al., 1993). Student t-tests were then used to identify and test the significance of any differences between groups for questionnaire responses or demographic and anthropomorphic features at baseline. Mann-Whitney U tests were used to assess the changes in reported pain levels across the task duration.

2.5.2. *HDEMG data processing*

Signals collected from a total of 256 monopolar electrodes, equating to 128 monopolar signals for each side, were sampled at 2048 Hz and amplified by a factor of 150 (400 channel EMG Amplifier Quattrocento, OT Bioelettronica; −3dB, bandwidth 10–500 Hz). These signals were then converted using a 16-bit analogue to digital converter and saved on a computer hard drive and processed offline using custom MATLAB code (The Mathworks Inc., MA., USA) (Murillo et al., 2019, Sanderson et al., 2019a). Recorded signals were processed by first filtering using a 2nd order bandpass 20–350 Hz Butterworth filter. Then, the monopolar signals from the upper and lower grids for each side were combined to create large right and left grids.

Kinematic data were used to identify all movements to and from each shelf and the signals were divided accordingly. EMG data for any movements where the participants made a mistake in the movement pattern were discarded *in situ* and analysis recommenced at the next correct movement. As each movement was timed by a metronome for 2 s, within each shelf movement, the signals were divided into two epochs of 1 s each termed epoch 1 and epoch 2. For each signal and epoch, the root mean square (RMS) was calculated and plotted on a topographical map, representing the spatial distribution of activity within the investigated region. As in previous studies, the location of the centre of muscle activity (centroid) in both the x- and y-axes was calculated from these maps (Falla et al., 2014, Tucker et al., 2009). The entropy of the signals was also calculated for each epoch, this measure assesses signal complexity and is a measure of the spatial homogeneity of signals. Specifically, herein the measure evaluated the heterogeneity in the each of the recorded signals from the individual electrodes across the combined grid, therefore high entropy would represent similar homogenous signals across the grid, and low entropy would represent heterogeneous signals Martinez-Valdes et al., 2019. The entropy was averaged across each large grid to calculate one mean value for each side.

To comprehensively test hypotheses, the data epochs were split in different ways. In some analyses, data have been assessed in terms of their linear order in time, where epoch one is the first half of a movement. However, temporal epochs might not reflect the demands of the peripheral shelves as all movements either originated or terminated on shelf one. For example, epoch one of shelf one to four would be close to shelf one, and epoch two of the movement from shelf four to one would also be close to shelf one. Therefore, it was necessary to also consider how the task demands change at points in the movement vector closer to the peripheral shelves. Thus, in some analyses, data have instead been assessed by the spatial phase of the movement, in relation to the distance from central shelf one. In these analyses ‘proximal’ epochs would be the half of the movement immediately before or after the box is on shelf one, and ‘distal’ epochs would be the half of the movement immediately before or after the box is on the peripheral shelf (the points distal to the starting position on shelf one). As such, epochs have been identified according to temporal order (epoch 1 and epoch 2) and their spatial order (proximal epoch, distal epoch).

2.5.3. *HDEMG data analysis*

Analyses were conducted using data from both right and left sides independently and combined. Where no differences, or no consistent differences, were identified across cycles, the cycles have been averaged to create a mean value representing activity in the muscle for that shelf movement.

In order to test the hypothesis relating to the distribution of muscle activity during the task, statistical tests on the centroid data assessed the absolute location of the centroid throughout the task; the absolute shift in location of the centroid from epoch one of the first movement for each side; and the difference in the absolute location of the centroid between sides. Further, as this task was 3D in nature, for tasks which involved lateral movements, it was important to assess the difference in centroid location between the left and right sides. To do so, the absolute location of the centroid in the left grid was subtracted from that of the right for each axis. Thus, in this analysis, if both centroid locations were equal to zero then this would indicate that the right and left centroid location were at the same position in their respective axes. Statistical tests on these data considered the magnitude of the differences between sides in each axis during the varied movements. In order to evaluate hypotheses around how pain influences muscle activity, Pearson correlations were used to identify any relationships between movement of the centroid and reported pain level based on the NRS score. Movements of the centroid of the EMG amplitude map were correlated against the reported pain at the start of the task, maximum throughout the task, and the change in pain level throughout the task.

Factorial ANOVAs were used to examine the changes in muscle activity across the multiplanar task over the 10 cycles between the LBP and control group. Due to differences in biomechanical stresses in moving towards or away from each shelf, for a majority of analyses the dataset was split by movement vector ($n = 10$; shelf 1–2 – shelf 6–1). Each movement was further divided into epochs, these epochs reflected either the temporal ($n = 2$; Epoch 1/Epoch 2) or spatial ($n = 2$, proximal to shelf 1/distal to shelf 1) order of the task as described above. In order to maintain the stability of the analysis, not all factors were used simultaneously, and analyses were split by factors such as movement and epoch distance and assessed individually. For example, to examine the hypothesis of the effect of pain on the absolute distribution of muscle activity across the task, the centroid y-axis location dataset was split by movement vector, and a factorial ANOVA considered factors of cycle, pain status and side. Alternatively, to consider the left–right differences in the distribution of activity, the difference in y-axis centroid data between the left and right sides was split by spatial epoch and was considered using factors of movement vector, pain status and cycle.

2.5.4. *Motion data processing*

Raw 3D data were tracked and labelled, any tracking errors were corrected or the errant portion was removed from the tracked and labelled file. A custom analysis protocol was created, first 3D tracks were interpolated and filtered using a 5 Hz low-pass Butterworth low-pass filter, then each track was cut at the synchronisation point (SMART

Analyser; BTS Bioengineering, Milan, Italy).

For the segmental analysis of the spine, the vertices identified earlier were used to create reference axes for each segment (lumbar segment, thoracic segment; LS, TS). Virtual points in the centre of each segment were created, and the reference axes were applied to these points. The Euler angle between these axes was calculated to investigate how these segments move in relation to each other. Using the varying distance between the markers on the box and on each shelf, movements to and from each shelf were reconstructed. The 3D tracks were cut between each shelf movement and time was normalised for each movement to the same shelf.

Motion data was normalised into 101 epochs for each cycle of each movement, representing a starting point and 100 % of the movement from the origin shelf to the target shelf. Where participants had made an error in the movement task, or the 3D data was lost, the analysis software discarded data for that cycle of the specific movement and replaced it with data from the subsequent cycle. As most participants had made an error in the first or last cycle, often only 9 cycles of movement data were available, so in order to assess gross changes in movement data was averaged into 3 sets of 3 completed cycles. The first set of cycles represented the first three correctly completed repetitions (Cycle 1–3), subsequent cycles were split into Cycle 4–6 and Cycle 7–9.

2.5.5. Motion data analysis

To test the hypothesis on the range of motion during the lifting task, motion data were considered for both the absolute motion pattern across cycles, and in terms of the shift from the first epoch within each group of cycles. To investigate the shift, the value of the first epoch was subtracted from each subsequent epoch to understand how the position had changed throughout the task. To assess differences between groups, repeated measures ANOVAs were used for each movement with factors of group (n = 2; LBP/CON), cycle (n = 3; Cycle 1–3, Cycle 4–6, Cycle 7–9) and time (N = 100, 1–100 %).

3. Results

3.1. Participant demographics

Fifteen Control (CON) and fourteen LBP participants (LBP) were recruited and completed the data collection process with complete datasets. Participant characteristics were similar between groups with no differences between groups for anthropomorphic features such as height, weight or BMI or for participant sex or age (Table 1). No differences were recorded between groups for the level of physical activity or measures of mental health (IPAQ, DASS-21; P > 0.05). However, as expected, the LBP group showed greater, yet minimal disability of 15.36 ± 6.95, compared to the CON value of 0.27 ± 1.0 (ODI; P < 0.0001). LBP participants also demonstrated greater fear avoidance (FABQ; LBP – 29.21 ± 13.51, CON – 3.13 ± 6.14) and pain catastrophising behaviours (PCS; LBP – 17.5 ± 9.37, CON – 6.27 ± 7.27) (P < 0.001 for all). Finally, differences were identified in the physical component of the SF-36 (LBP – 48.63 ± 4.76, CON – 57.94 ± 3.83; P < 0.0001), but not in the mental component (P > 0.05). Within the LBP group, participants recorded mild average pain on the day of testing of 2.68/10 ± 2.03, and retrospectively reported a moderate average pain over the previous month of 5.93/10 ± 1.69.

LBP participants found completing the task to be more exerting, as measured by the Borg scale, with an average reported exertion at the end of the task of 12.86 ± 1.7. CON participants reported a mean exertion of 10.87 ± 2.17, a difference of 1.99 between groups (P = 0.01). On average, LBP participants also reported greater maximum pain during the task of 4.89 ± 2.00 compared to the CON participants 0.8 ± 2.11 (P = 0.0003). As a result, the LBP group also displayed a greater mean change in reported pain levels across the task (2.21 increase ± 2.35) compared to the CON participants (0.8 increase ± 2.11).

Table 1
A summary of the characteristics of the sample, unless otherwise stated all values are listed as mean ± standard deviation. Results for the IPAQ reflect the proportion of participants who were identified as having high levels of activity. Where significant differences occurred between groups, the outcome is marked with an asterisk and a p-value is stated.

Characteristic		CON	LBP	P-Value
Sex		6 Male, 9 Female	7 Male, 7 Female	–
Mean Age		26.87 ± 11.13	32.14 ± 14.64	–
Height (m)		1.73 ± 0.10	1.71 ± 0.07	–
BMI		23.12 ± 4.16	25.39 ± 3.56	–
ODI *		0.27 ± 1.03	15.36 ± 6.95	P < 0.0001
PCS *		6.27 ± 7.27	17.5 ± 9.37	P = 0.001
IPAQ		73.33 % High	85.71 % High	–
DASS-21		10.53 ± 10.51	18.29 ± 26.91	–
FABQ *		3.13 ± 6.14	29.21 ± 13.51	P < 0.0001
SF-36	**SF-PCS** *	57.94 ± 3.83	48.63 ± 4.76	P < 0.0001
	SF-MCS	52.13 ± 4.48	47.51 ± 14.07	–
PNRS	**Current Pain**	–	2.68 ± 2.03	–
	Average Pain	–	5.93 ± 1.69	–

Body Mass Index (BMI), Oswestry Disability Index (ODI), Pain Catastrophising Scale (PCS), International Physical Activity Questionnaire (IPAQ), Disability, Anxiety and Stress Scale (DASS), Fear Avoidance Beliefs Questionnaire (FABQ), Short Form Health Survey (SF-36), SF-36 Physical Component Summary (SF-PCS), SF-36 Mental Component Summary (SF-MCS), Pain Numerical Rating Scale (PNRS).

3.2. Muscle activity

The weighted centre of muscle activity can be quantified as the centroid of activity, the location of the this can inform on the where the muscle activity is focussed, and how this can change throughout the task. Bilaterally, across all cycles, for all movements and epochs, the LBP group had a significant and systematically more cranial position of the y-axis of the centroid of the EMG amplitude map (P < 0.05 for all comparisons, main effect, Fig. 3). On average, the centroid location along the y-axis was 3.94 mm more cranial for the LBP group than the CON group.

There were no significant differences between groups in the absolute variability in the position of the centroid along the y-axis for any movement or side across the task (P > 0.05, main effect). However, when assessing the differences in the location of the centroid along the y-axis between the left and right side, the CON group showed more variability in the craniocaudal position along the y-axis between the right and left sides across all movements compared to the LBP group (P <

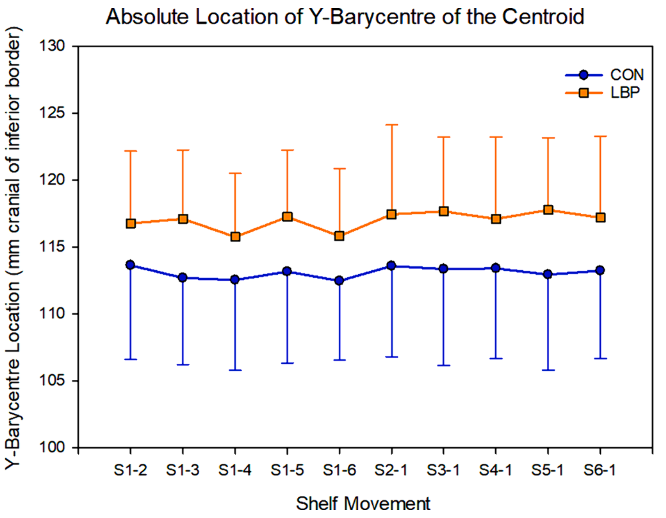

Fig. 3. Demonstrating the absolute location of the of the centroid along the Y-axis (craniocaudal) axis for all movements across the duration of the task. The data here is arranged first for movements away from shelf 1 and then for movements returning to shelf 1.

0.05, main effect). A significant interaction was identified in both lifting and lowering epochs, confirming that a different strategy was used by each group to complete each movement ($P = 0.02$ for Epoch 1 and $P = 0.0004$ for Epoch 2). When the epochs were considered for their proximity or distality to shelf 1, this interaction changed. In this analysis, there was no significant difference between groups in the right-left variability in movements proximal to shelf 1 ($P > 0.05$; Fig. 4**a**). However, in the distal portions of movements, the CON group demonstrated much greater variation in the centroid location between sides ($P < 0.0001$, Fig. 4**b**). The Pearson correlations revealed no relationships between the movement of the centroid; the movement of the centroid at distal points in the movement; or the difference between sides in centroid location, and the reported pain level ($P > 0.05$ for all correlations).

The absolute position of the centroid along the x-axis was somewhat less consistent, with significant systematic differences between groups in the absolute location of the centroid found in 13 out of 20 assessed conditions ($P < 0.05$, main effect; 10 movements, 2 sides). When investigating the absolute shift of the centroid, these results were clearer, with a greater displacement for those with LBP in the centroid identified in movements to and from shelf 2 only ($P = 0.028$ shelf 1–2; $P = 0.046$ shelf 2–1; $P > 0.05$ for all other shelf movements, main effect). When assessing variation between the right and left position of the centroid along the x-axis, similar results were identified to those of the y-axis. In the phases of movements proximal to shelf 1, while significant systematic differences were apparent between groups ($P = 0.012$), there was no difference for how each group completed each individual shelf movement ($P = 0.35$). However, in the phase of movement distal to shelf 1, there were both significant systematic differences between groups ($P = 0.0033$) and in how groups completed each movement, with the CON group showing greater variation ($P = 0.0012$). Fig. 5 illustrates the compiled mean locations of the centroid location on the right and left sides for all movements.

Entropy is a measure of the heterogeneity in the signals across the recorded area, these data can indicate if there are differences in the uniformity of the activity. Significant differences were also identified in the entropy of the EMG amplitude map, across all cycles of all movements with sides assessed independently and combined ($P < 0.034$ for all). In all iterations of this analysis, the CON group showed higher levels of entropy, indicating more homogenous muscle activity, with differing levels of activity across the recorded area. Differences in topographical activity can be observed visually in representative EMG amplitude maps (Fig. 6), which indicate a more diffuse contraction for the CON group while the LBP group appeared to have less homogenous activity across the recorded region. However, these visual maps are only presented as a visual aid.

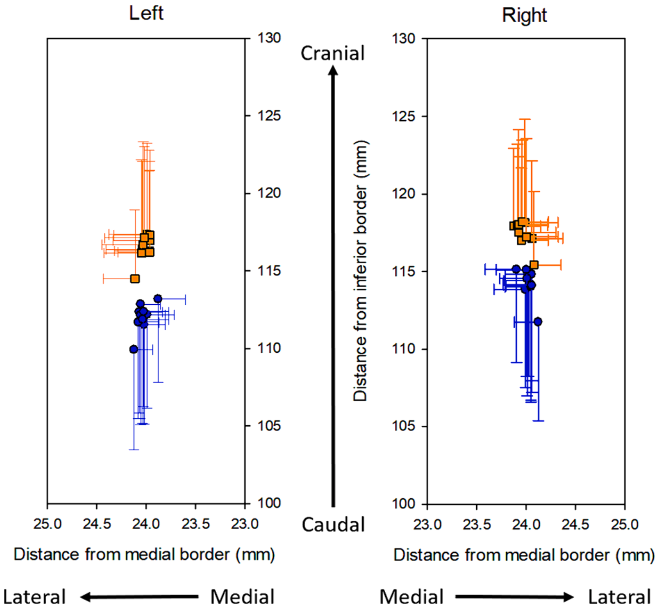

Fig. 5. This figure indicates the absolute location of the centroid in the x and y axes throughout the task. In this figure, each shelf movement is identified by a single point indicating the mean centroid location for the movement across all cycles and participants.

3.3. Kinematics results

The kinematics results relate to the 3D motion data and can inform on the movement performed to complete the task. Significant systematic differences were identified between groups in the absolute 3D movement patterns utilised to complete each movement ($P < 0.05$ for all). However, when the data were normalised for the starting position of each participant, and the angular deviation between the lumbar and thoracic segments from this point was considered, few consistent significant differences were identified between groups (Fig. 7 – representative movement).

Within the normalised angular deviation data, when considering

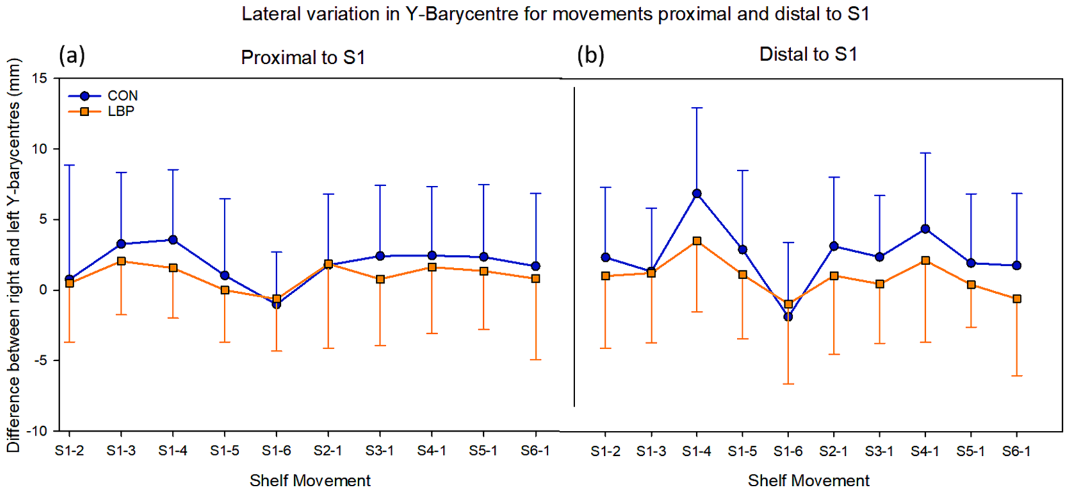

Fig. 4. Depicting the lateral variation between the right and left grids in the location of the centroid along the y-axis in movements (a) proximal to shelf 1 and (b) distal to shelf 1. In this graph, a more positive number indicates a more cranial centroid on the right grid, a more negative number indicates a more cranial centroid on the left grid. The data is arranged first for movements away from shelf 1 and then for movements returning to shelf 1.

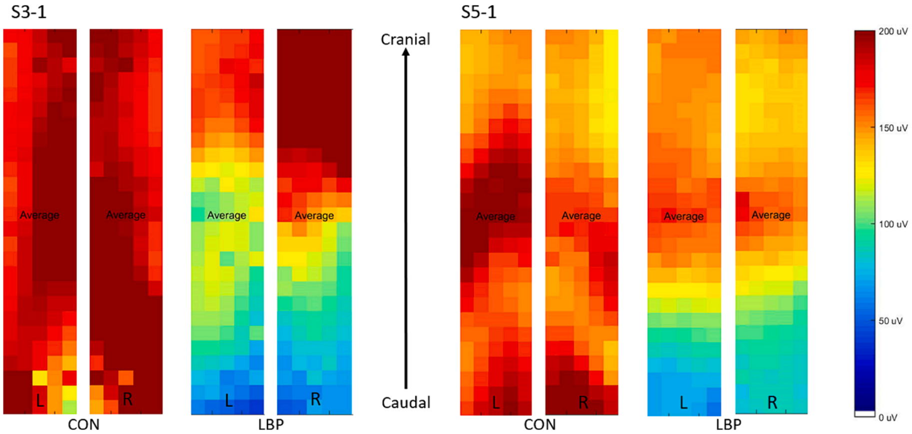

Fig. 6. Representative maps of muscle activity for the distal to shelf 1 aspect of the movement from shelf 3–1 and shelf 5–1. These maps indicate a more homogenous diffuse contraction in the CON group and a less diffuse and more cranially focussed contraction in the LBP group. They additionally show a differing distribution of the diffuse activity between movements for the CON participant.

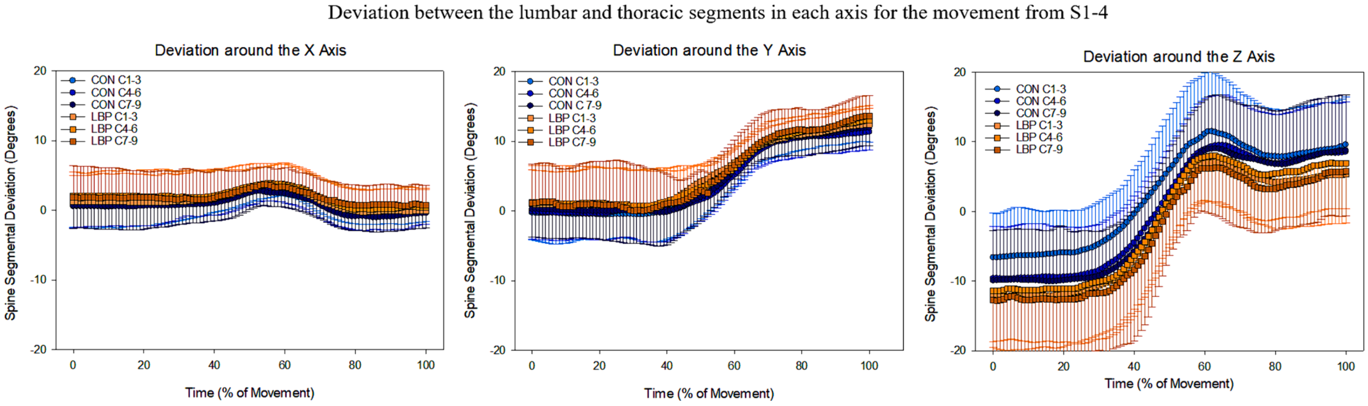

Fig. 7. Representative deviation between the LS and TS for the movement from shelf 1–4. Data are shown for each group of cycles in (a) X, (b) Y and (c) Z axes.

differences between groups for each movement ($n = 10$) and in each axis ($n = 3$), 20 main effect outcomes of factorial ANOVAs (e.g. LBP vs CON for S1-4, Y axis = one outcome) identified no systematic differences ($P > 0.05$), with the remaining 10 outcomes identifying systematic differences between groups ($P < 0.05$). Of these outcomes, seven identified differences were around the X-axis (frontal plane), one around the Y-axis (transverse plane) and two around the Z-axis (sagittal plane).

Around the X-axis, differences were identified within movements to shelf 3 and shelf 6, and in all movements returning to shelf 1 from peripheral shelves ($P < 0.05$ for all). The total range of deviation for both groups between the lumbar and thoracic segments for all movements in the X-axis was 4.9° (between 0.5° and 5.4°). For each movement where differences were identified, the LBP group showed on average 0.7° greater deviation than the CON group.

In all movements around the Y-axis for both groups, the total range of deviation between segments was 13.7° (0.9°-14.6°). No differences were identified for most movements, however around this axis the CON group showed on average 1.19° more deviation between segments for the movement shelf 6–1 ($P = 0.007$). For this movement, differences were also identified between groups across cycles, with the CON group showing greater variation in the movement pattern than the LBP group ($P = 0.022$). Differences in the movement pattern across cycles were also identified for the movement shelf 4–1 ($P = 0.019$). However, these were less consistent, with the LBP group showing greater deviation in initial cycles, and the CON group showing greater deviation in later cycles.

A total range of deviation of 13.3° (6.3°-19.6°) was identified around the Z-axis for both groups. Systematic differences in movement strategy were established around this axis for movements both to and from shelf 5 ($P = 0.024$, $P = 0.006$ respectively). In both cases, the LBP group demonstrated greater deviation with an increase of 0.39° for shelf 1–5 and an increase of 0.9° for shelf 5–1 when compared to the CON group movement strategy. Around this axis, significant differences were also identified between groups across cycles for movements from shelf 3–1 ($P < 0.0001$). In initial cycles, the CON group showed greater deviation for this movement, however in later cycles this was reversed and the LBP group showed greater deviation.

4. Discussion

This study aimed to use HDEMG and 3D motion analysis to investigate the influence of the presence of LBP on the distribution of muscle activity across the lumbar and thoracolumbar regions during a multiplanar lifting task. This study found that, regardless of the direction of movement during the phases of the multiplanar task, LBP participants appeared to use a consistent motor control strategy to complete all movements. This strategy was characterised by muscle activity in the ES which was less heterogeneous and had a distribution which was focussed more cranially; further the distribution of activity demonstrated less variation between sides across movements. In essence, this activation pattern could be characterised as less diffuse, and more cranially focused in people with LBP, than CON participants. Despite these differences in muscle activity, there were few consistent differences in the 3D movement strategy, indicating that the task was completed in a similar manner, yet activating the ES differently.

4.1. Muscle activity

The results of this study suggest that there are differences in the muscle activation pattern used by individuals with LBP and those without pain to complete a three-dimensional task. As the task herein was multiplanar by design, variability in the location of the centroid was considered between the left and right sides to better understand how participants completed the complex turning movements. EMG is primarily employed to assess the muscular activity created to produce movement (Merletti and Parker, 2004), and in this task a variety of different movements were required. Muscular coordination between sides is essential to produce varied 3D movements and has been studied extensively using bipolar EMG (MacDonald et al., 2010, Williams et al., 2013, Willigenburg et al., 2013). While the neural drive to synergistic muscles cannot be implied from EMG amplitude alone (Martinez-Valdes et al., 2018), assessing relative characteristics of the left and right ES via the centroid location is a potential vector to understand the motor strategy employed in response to these varied task demands.

At the points in the task proximal to shelf 1, participants in both groups showed similar motor strategies between sides, as could be expected for a sagittal monoplanar movement. However, at points in the task which were spatial distal to shelf 1 (closer to the peripheral shelves), the LBP group continued to show similar activity between sides whereas the CON group demonstrated differential activity of the ES in response to directional task demands. As there were no differences in the variation in the centroid location in LBP participants for most movements these results indicate that LBP participants activated the same muscle regions for all movements, despite varying demands. Similar continual activity patterns in specific regions have been identified previously in studies investigating the influence of pain on muscle activity and have been linked to increased localised fatigue and ischemia (Abboud et al., 2014, Barbero et al., 2016, Falla et al., 2014, Madeleine et al., 2006). However, as the CON participants also did not show systematic variability in the centroid location as was shown in these previous studies, it is speculated that the temporary differences in muscle activity between sides in the CON group might provide relief of these symptoms.

Across the whole task, the location of the centroid of the EMG amplitude map in the LBP group appeared to be less varied and more cranially focussed. Previously, differences have been reported between groups in the overall variability in centroid location throughout a task (Abboud et al., 2014, Falla et al., 2014, Martinez-Valdes et al., 2019). However, no such variability was identified here, with the only differences occurring in the position of the centroid along the x-axis for sagittal plane movements to and from shelf 2. However, this divergence from the literature base could be expected, as these previous tasks were either monoplanar or static. Martinez-Valdes et al (2019) reported a caudal shift of the centroid along the y-axis in a group of elite rowers with LBP and a cranial shift in a CON group, however the task was a repetitive rowing task presenting different biomechanical challenges to lifting. Falla et al (2014) reported a reduced variability in the y-axis coordinate of the centroid for a group of people with LBP during a lifting task. However, in this instance, the task was a repeated movement between anterior shelves. Thus, differences between groups might have developed due to a shift of activity away from more localised fatigue due to the repeated task, rather than the cyclical task presented here. Where more complex, yet still primarily monoplanar, tasks have been considered over a similar muscle region, the size and location of activity extracted from HDEMG was found to be the same between individuals with and without LBP (Serafino et al., 2021).

Across the task, the LBP group employed a pattern of activation which appeared to be consistently less diffuse and more cranially focussed. This pattern of activity was identified via the systematically more cranial centroid location and lower entropy of the EMG amplitude map, indicating a less homogenous contraction, which was also qualitatively identified in topographical maps of muscle activity. Similar findings were reported previously in LBP populations during static and monoplanar tasks, and the biomechanical implications were discussed (Arvanitidis et al., 2022, Lariviere et al., 2002, Sanderson et al., 2019a, Sanderson et al., 2019b). Briefly, different regions of the ES work collectively to produce movement (Bogduk, 2005, Macintosh and Bogduk, 1991), however this regional synergy appears to be diminished in LBP participants with reduced activity of the caudal ES. As movements in this task required lumbar ES contractions, it is thought that greater caudal ES activity might be more biomechanically favourable given the increased shear forces on the lower lumbar vertebrae (Bogduk, 2005, Christophy et al., 2012). However, the cranial activity identified indicated a deselection of this region in favour of the more cranial regions. It is difficult to discern the impact of this activity pattern, as debate surrounds the concept of an ‘optimum’ lifting strategy (Nolan et al., 2018); however the higher exertion indicated by Borg RPE and pain levels by PNRS following the task allows speculation that the LBP strategy might require more effort and so be less favourable.

4.2. Movement strategy

While clear differences in the muscle activity strategy were identified, there were few consistent differences between groups in the movement strategy. The task was chosen to reflect functional lifting; however, it is thought that the use of the metronome and advice to limit lower limb movement prohibited much variation in the movement strategy. As noted in the methodology, participants were asked to lift naturally without excessive lower limb movement to ensure the task reflected normal lifting and to focus the task on the lumbar region of interest but this instruction might have constrained the lifting pattern used. Where small differences were identified between the lumbar and thoracic segments, generally the LBP group demonstrated slightly greater deviation at stages in the movement cycle distal to shelf 1. It is therefore possible that while the general strategy employed by the LBP group was similar to the CON group, reduced precision in 3D movements as reported previously may increase spinal deviation (Willigenburg et al., 2013). This is especially highlighted by the minor differences in the coronal plane, with increased LBP deviation of less than 1° which could be attributed to minor imprecisions.

Previous investigations have identified differences between groups in spinal range of motion during lifting tasks (Falla et al., 2014, Shojaei et al., 2017). However, the task used here was multiplanar and more complex. Participants were allowed a practice cycle, however the overall movement strategy consistency might be due in part to the concentration required to maintain the pattern. Similar studies reported reduced variability of spinal movements in LBP participants when completing cognitive duel tasks (Van Daele et al., 2010).

4.3. Study participants

The sample was broadly reflective of the combined characteristics of individuals experiencing mild to moderate chronic, non-specific LBP who are still able to complete tasks of daily life (Carlesso et al., 2018). The participants were not under active management for LBP at the time of testing and so experienced lower levels of pain; on the day of testing the average level of LBP within the group was 2.86/10, classified as mild. However the group reported an average pain over the previous month of 5.93/10, at the higher end of the moderate pain classification (Breivik et al., 2008). Therefore, the motor control pattern identified here might not be generalisable to populations experiencing greater levels of pain, however, it is speculated that with greater pain the patterns identified here might be magnified (Arendt-Nielsen and Graven-Nielsen, 2008).

4.4. Strengths and Limitations

This study used HDEMG bilaterally across the lumbar and thoracolumbar regions to allow characterisation of muscle activity across the lower back. HDEMG has recently been shown to be reliable for use in measing muscle activity from the erector spinae muscle (van Helden et al., 2022). The multiplanar task employed was reflective of occupational lifting tasks and may allow insights into the provocation of pain and development of fatigue with lifting.

It is relevant to consider how the anthropomorphic and anatomical differences in the sample might influence the results. It is well established that EMG data can be affected by a myriad of factors, including the muscle fibre direction relative to the electrodes, distribution of subcutaneous fat, and location of the innervation zone which are all individual to the participant (Afsharipour et al., 2019). As ultrasound was not used, and the limb length and trunk length were not measured, and it is difficult to estimate how this would impact the results presented herein. While steps were taken to mitigate the effect of anthropometry on task performance (e.g. shelf distance and height were based on anthropomorphic factors rather than a set distance) it is nonetheless possible that there is an impact on the task performance. Further, there was no assessment of subcutaneous fat distribution, a factor which can influence the presentation of muscle activity (Farina et al., 2002). While it is not possible to completely control for these factors, it is suggested that further studies in this field ensure that the influence of anthropology is factored into the experimental design.

The motion analysis software automatically replaced deleted cycles with data from subsequent repetitions, so the decision to average across cycles was made in order to draw comparisons. However, this averaging prohibited comparisons which might elucidated the differences in movement strategy identified to some shelves.

Due to the complex nature of the task, it was not possible to complete analysis which would allow direct comparison to monoplane tasks. For example it was not possible to complete a representative maximal or submaximal contraction due to directional changes and individual variation in movement, and so between group comparisons of amplitude were not appropriate to report, in line with the recent CEDE consensus statement on amplitude normalisation (Besomi et al., 2020). Similarly, previous work has shown that subgroups of people with LBP display differences in trunk muscle activity related to the direction of movement (Hemming et al., 2019). Due to the multiplanar nature of task, these subgroups were not explored but could have influenced the movement strategy. Further research might focus instead on specific oblique movements to investigate these phenomena in more detail, in a way that a maximal contraction would be possible for normalisation purposes and subgroup differences could be explored.

5. Conclusions

This study showed that participants with LBP appeared to use a motor control strategy which had consistently less diffuse and more cranially focussed activity of their ES. This strategy appeared to produce few differences in the movement strategy, however was present simultaneously with increased exertion across the task.

CRediT authorship contribution statement

A. Sanderson: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C. Cescon:** Writing – review & editing, Methodology, Investigation, Formal analysis. **E. Martinez-Valdes:** Writing – review & editing, Methodology, Investigation. **A. Rushton:** Writing – review & editing, Supervision, Methodology, Investigation. **N.R. Heneghan:** Writing – review & editing, Supervision, Methodology, Investigation. **P. Kuithan:** Writing – review & editing, Data curation. **M. Barbero:** Writing – review & editing, Methodology, Investigation. **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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