

Movement, posture and low back pain. How do they relate? A replicated single-case design in 12 people with persistent, disabling low back pain

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Abstract

Background: Movement and posture are commonly believed to relate to non-specific low back pain (NSLBP). While people with NSLBP appear to move and posture themselves differently from those without NSLBP, changes in movement and posture infrequently relate to improvements in NSLBP when analysed at a group-level. Additionally, little is known about how movement or posture change when clinical outcome improves.

Methods: Within-person relationships were investigated using a replicated, repeated measures, single-case design in 12 people with persistent, disabling NSLBP. Individually relevant movement and posture were captured using wearable sensors on up to 20 occasions over a 22-week period (5-week baseline, 12-week physiotherapy-led intervention, 5-week follow-up), while pain and activity limitation were collected concomitantly. A series of cross-correlation analyses estimated the presence, strength, and direction of relationships.

Results: Many participants ($n = 10/12$) had strong (e.g. $r = 0.91$, $p = <0.001$) relationships between changes in movement or posture and changes in pain and activity limitation, while some showed no strong association. Where relationships were observed, clinical improvement predominantly (93% or 57/61 relationships) related to increased spinal movement range and velocity during forward bending and lifting, reduced lumbar muscle EMG activity at maximum voluntary flexion, and increased posterior-pelvic-tilt during sitting and standing.

Conclusion: Within-person changes to individually relevant movement and posture appear to often relate to clinical outcome, but not always. When changes were related, movement and posture appear to return towards being 'less protective', however causal directions remain unknown. Important activities, movements, and postural parameters varied across the participants, highlighting the potential importance of individualized management.

Significance: Changes to individually relevant movement and posture appear to often relate to clinical outcome, but not always. Patient-specific activities, and movement or postural parameters that related to improved pain and activity limitation, varied across the 12 participants, highlighting the potential importance of individualised

management. Where clinical improvements were related to changes in movement or posture, participants consistently returned towards being 'less protective' (increased range and speed of movement, increased posterior-pelvic-tilt during sitting and standing). Mechanisms and generalizability remain unclear.

1 | INTRODUCTION

Low back pain (LBP) is common and costly (Deloitte, 2019; Hoy et al., 2014; Institute of Medicine, 2011). Approximately 90% of individuals with LBP are classified as having non-specific LBP because no specific patho-anatomical cause can be identified (Koes et al., 2010; Maher, Underwood, & Buchbinder, 2017). There is evidence that numerous, biopsychosocial factors contribute to NSLBP (Hartvigsen et al., 2018). Movement and posture are commonly believed by patients, clinicians and researchers to relate to NSLBP (Lin et al., 2013; Marras et al., 1995; Mottram & Blandford, 2019; O'Sullivan, 2005). A strong emphasis is placed on the assessment of movement and posture in people with NSLBP (Been & Kalichman, 2014; van Dijk et al., 2020) and interventions often aim to change movement or posture with the belief that this will improve pain or activity limitation (Karayannis, Jull, & Hodges, 2016).

Cross-sectional data demonstrates that, on average, people with back pain move their back slower, with less range of motion (ROM), and increased activity of their lumbar extensor muscles at maximum voluntary flexion (absence of the flexion-relaxation phenomenon; Watson, Booker, Main, & Chen, 1997) compared to people without back pain (Geisser et al., 2005; Gizzi, Röhrle, Petzke, & Falla, 2019; Laird, Gilbert, Kent, & Keating, 2014; Nolan, O'Sullivan, Newton, Singh, & Smith Benjamin, 2019). For posture, however, there does not appear to be a clear difference in standing lumbar lordosis angle or pelvic tilt angle between people with and without LBP (Laird et al., 2014) and differences in lumbar sitting posture or muscle activity were only found between people with and without LBP when types of LBP were subgrouped (Astfalck et al., 2010; Dankaerts, O'Sullivan, Burnett, & Straker, 2006). This may indicate that different movement and postural parameters are significant for different people, highlighting the potential importance of analysing individually relevant factors.

Despite some evidence that people with LBP move and may posture themselves differently, three systematic reviews reported that changes in these kinematic and muscle activity parameters infrequently accompany changes in pain or activity limitation (Laird, Kent, & Keating, 2012; Steiger, Wirth, de Bruin, & Mannion, 2012; Wernli et al., 2020). This may be because improvements in LBP are less related to changes in movement or posture than currently believed, or it may

represent limitations in the data and analyses used in the included studies of those reviews.

The first limitation is that analysing the relationship between change in two variables (such as movement and pain) only at a group level is imprecise because different people may have improved in different variables (for example, the people whose movement improved may not be the same people whose pain improved; Wernli et al., 2020). This highlights the need to analyse within-person relationships.

The second limitation is that investigating the same movement parameter across the whole group may dilute the strength of any relationship if different people have different pain-provoking movements and postures. It could be that the strength of those relationships may only be identified when *individually relevant* movements and postures are measured and analysed (Lillie et al., 2011; Tate, Perdices, Rosenkoetter, Shadish, et al., 2016; Wernli et al., 2020). Repeating measures over time also provides greater insight into how two variables relate (Tate, Perdices, Rosenkoetter, Shadish, et al., 2016). To date there is a paucity of literature investigating this phenomenon. This may be due to the historically complex and costly methods available to measure movements and postures (e.g. motion analysis laboratory). However, advances in wearable sensor accuracy to repeatedly measure individually relevant movements and postures in efficient and ecologically valid ways facilitate the investigation of this relationship (Artus, van der Windt, Jordan, & Hay, 2010; Dobkin, 2013; Mjosund et al., 2017).

Therefore, our aim was to investigate, in a replicated single-case study of 12 people with persistent disabling NSLBP, the within-person relationships between:

1. change in movement or posture, and change in pain
2. change in movement or posture, and change in activity limitation

2 | MATERIALS AND METHODS

2.1 | Design

An A-B-A', replicated single-case study of 12 individuals with persistent, disabling NSLBP. Movement or posture, pain, and activity limitation were measured on up to 20 occasions over 22 weeks.

Phase A consisted of weekly measures across a 5-week baseline phase during which participants received no intervention. The baseline phase was designed to act as a comparator to determine change within each person (Tate et al., 2013). *Phase B* was a 12-week intervention phase where participants received up to 10 sessions of a physiotherapist-led, individualized, behavioural intervention called Cognitive Functional Therapy (CFT) (O'Sullivan et al., 2018) and had the same measures as during *Phase A* collected on up to 10 occasions. Intervention onset was determined a priori to occur after the 5-week baseline phase. As the effect of behavioural interventions are expected to carry over after the intervention has ceased (a nonwithdrawable intervention), the subsequent *Phase A'* was used as a follow-up monitoring period during which participants received no intervention. This phase consisted of the same weekly measures over 5 weeks. As this study focussed on the relationship between two variables (*not* on optimizing internal validity to observe a treatment effect), no randomization was utilized (such as randomization of treatment commencement).

2.2 | Participants

Participants were recruited through word of mouth, social media, community advertising, and referrals from primary care practitioners. *Inclusion criteria were:* adults aged 18 years or older with a primary complaint of nonspecific LBP (between T12 and the gluteal folds) that was persistent (>12-weeks duration), disabling (≥ 5 points on the 23-item Roland Morris Disability Questionnaire [RMDQ]; Patrick et al., 1995), and nontrivial (a mean of $\geq 3/10$ across three 11-point Numeric Rating Scales identifying current, average, and worst pain over the last week; Manniche et al., 1994). Participants also had to report that their pain was provoked by movements or postures. *Exclusion criteria were:* dominant leg pain, a diagnosis of LBP related to specific pathologies (infection, cancer, inflammatory disorders, fracture, radicular pain with neurological deficit), pregnancy, an inability to adequately speak or understand English, a Body Mass Index $> 30 \text{ kg/m}^2$ (to limit validity concerns about body surface-based movement and postural measures in overweight or obese individuals), nondisabling LBP (mean baseline Patient Specific Functional Scale score $< 3/10$ for two consecutive weeks), and a planned leave of absence greater than two consecutive weeks throughout the 22-week study period (due to the intensive and frequent measurements required for analysis).

2.3 | Context

The study was conducted within a primary care musculoskeletal physiotherapy practice in Perth, Western Australia.

On occasion, measurements of movements and postures occurred at the participants home. Data were collected in two waves of six people between January and December 2018.

Each participant provided written informed consent prior to the start of the study. The study was approved by the Human Research Ethics Committee at Curtin University – approval number HRE2017-0706.

2.4 | Measures and equipment

2.4.1 | Repeated measures of pain intensity

Current pain, average pain, and worst pain over the last week were rated on an 11-point numerical rating scale collected via electronic questionnaire up to 20 times. The mean of these three pain ratings was used as a composite estimate of pain intensity (Manniche et al., 1994).

2.4.2 | Repeated measures of activity limitation

The Patient Specific Functional Scale (PSFS) (Westaway, Stratford, & Binkley, 1998) was collected via electronic questionnaire up to 20 times. Participants nominated three activities when asked to identify the *three most important activities of daily life that you are unable/find difficult to do over the last week as a result of your back problem*. They rated how well they were able to perform the activity compared to before their injury or problem on an 11-point numerical rating scale anchored by '0 = able' and '10 = unable'. The three PSFS activities were corroborated with the researcher collecting the movement and postural data during the first baseline session and if any further activities not listed were identified, they were subsequently also collected. The PSFS score reflecting the most disabling movement and (if applicable) posture was used for analysis.

A 23-item RMDQ (Patrick et al., 1995) was also collected at baseline.

2.4.3 | Repeated measures of movement and posture

The heterogeneity of LBP means that participants may have varying key activity limitations, and different movement, postural, and other biopsychosocial factors that contribute to their pain (Hartvigsen et al., 2018; Maher et al., 2017). Therefore, the specific movements and postures nominated by the participant in the PSFS were measured up to 20 times, with the most disabling (identified by the highest mean PSFS score across the baseline phase) movement and

(if applicable) posture used for analysis. For the movement and postural tasks, the environment was kept consistent (including surface, object lifted, seat height and the absence of a back support during sitting) and instructions were given to perform the task in a natural, self-selected way (including self-selected speed).

Sagittal plane kinematics were collected using two wireless wearable movement sensors (inertial measurement units or IMUs) sampling at 20 Hz and lumbar muscle activity was collected using two wearable surface electromyographic (EMG) sensors sampling at 300 Hz (v5 ViMove hardware and software, DorsaVi, Melbourne, Australia) (Figure 1). The clinical sensor system facilitated the frequent field-based measures required in this design and has demonstrated clinically acceptable agreement compared with the Vicon motion capture system, the industry reference standard (Mjosund et al., 2017). Using a standardised procedure, the IMUs were placed over T12 and S2, and the EMG sensors were applied two centimetres either side of L3 following light abrasion and cleaning of the skin. The IMUs were calibrated to vertical and the EMG was normalized to the mean of three sub-maximal isometric contractions performed at the start of each data collection session. The normalization task involved lying prone, bending the knees to 90°, then lifting the knees approximately five centimetres high for five seconds



FIGURE 1 The ViMove v5 wireless wearable sensor system to collect kinematics and muscle activity

(Dankaerts, O'Sullivan, Burnett, Straker, & Danneels, 2004). Further information about the sensor specifications and processing is detailed in Methods S1.

The most representative biomechanical parameters for each movement and posture were determined a priori (detailed in Methods S1). For bending, T12 peak ROM and mean flexion velocity (VEL), as well as the normalized EMG activity during the middle two seconds of a 5-s hold at peak voluntary flexion during forward bending (representing the flexion relaxation phenomenon; Watson et al., 1997) were output. If a participant had a normal flexion relaxation phenomenon (EMG silence at full flexion), they were still included in the analysis. The mean of three trials was analysed unless trials were excluded due to sensor error.

For lifting, the T12 angle at the start of the lifting phase and the mean lifting velocity were output, with the mean of three trials analysed. The parameters for the movements are presented visually in Figure 2.

For postures, the mean S2 angle over 15 s of self-selected unsupported sitting and standing, and the mean T12 angle over 15 s of sustained extension were output and analysed.

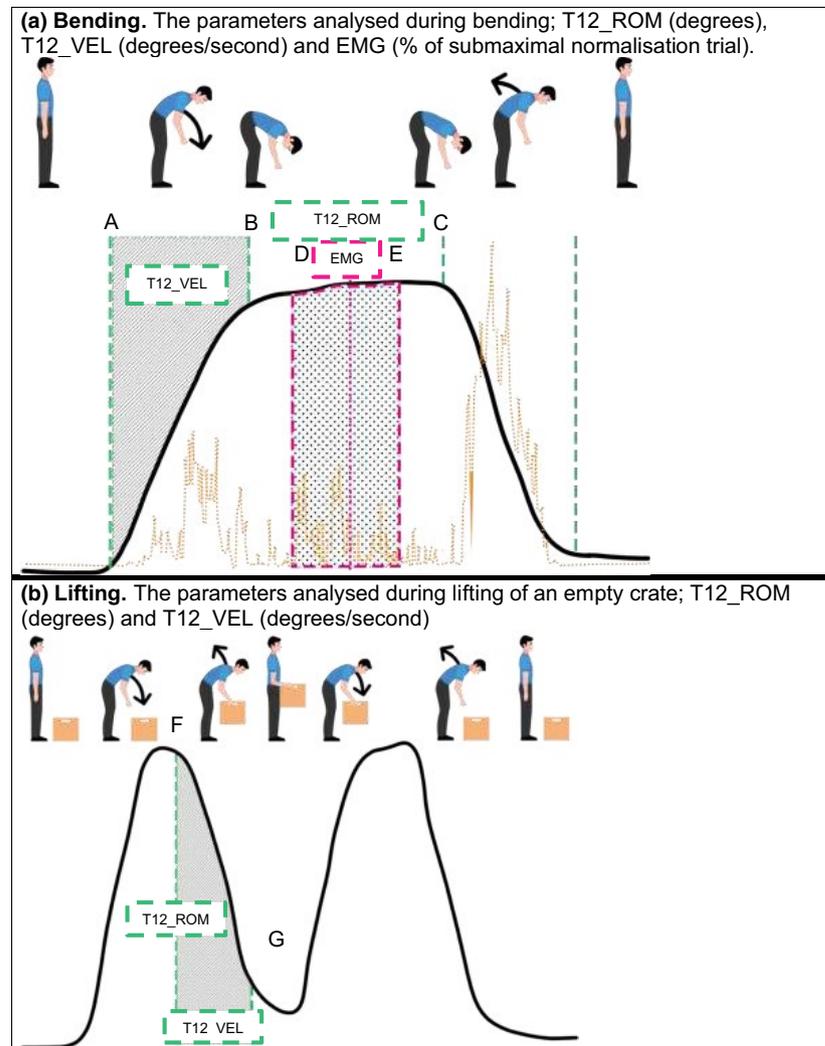
2.4.4 | Procedural fidelity and blinding

To ensure procedural fidelity, the researcher collecting the movement and postural data was not involved in the delivery of the intervention and participants were blind to the wearable sensor data. Data collection procedures were kept consistent within individuals and collected by the same person using the same procedures. The researcher assessing movement and postures was blind to all measures of pain and activity limitation, except during the last baseline session where the researcher conducted a qualitative interview unrelated to this manuscript investigating the participants perception of change (so 95% of measurement sessions were blinded).

2.5 | Analysis

A series of cross-correlation analyses were performed using Simulation Modelling Analysis (SMA Version 8.3.3, <http://clinicalresearcher.org>; Borckardt, 2008) to statistically estimate the significance, strength, and direction of relationships between each movement or postural parameter, and pain and activity limitation. A cross-correlation analyses (using SMA) correlates two streams of time-series data within the same person. SMA is a bootstrapping method effective at handling short time series data-streams (<30 measures), whilst both adjusting for autocorrelation and reducing the risk of Type I and II errors (Borckardt, 2008). SMA is a nonparametric approach, where the empirical *p*-value was equal to the proportion of times two data streams of the same size and

FIGURE 2 The outputs analysed during the (a) bending and (b) lifting movements^a. Solid black line (—): T12_ROM; Orange line (.....): EMG; A: flexion start; B: flexion end; C: re-extension start; D: EMG start; E: EMG end; F: lifting start; G: lifting end; T12_ROM: T12 range of motion (degrees); T12_VEL: T12 angular velocity (degrees per second); EMG: normalized lumbar muscle electromyography. ^aAngular velocity exceeding ± 7 degrees/second identified movement commencement, while angular velocity under ± 7 degrees/second identified movement cessation (Laird, Keating, Ussing, Li, & Kent, 2019)



autocorrelation are associated in 1,000 bootstrap samples at the observed value of r or greater. The strength of the correlation coefficients was assessed as nonsignificant, small ($r = 0.10$ to <0.30), medium ($r = 0.30$ to <0.50) and large ($r = \geq 0.50$) (Cohen, 1988). As per previous research utilizing cross-correlation analysis to examine temporal associations between variables in people with persistent, disabling LBP undergoing CFT intervention (Caneiro, Smith, Linton, Moseley, & O'Sullivan, 2019) correlations between movement or posture, and pain and activity limitation were estimated over a series of five time-lags from -2 to $+2$ weeks. This allowed consideration of the potential for change in movement or posture to either precede (positive lag), follow (negative lag), or occur concurrently (zero lag) with changes in pain or activity limitation over a 4-week period. The strongest correlation of the five lag estimates was reported, with all correlations presented in Table S2. As the constructs of interest had the potential to change during the baseline and follow-up phase, the analysis used all available data points during the 22-week study period.

In addition, a test for change in pain and activity limitation from the baseline to intervention was performed using a

series of simulation models (5,000 simulations) of the correlation between the phase vector (baseline phase compared to combined intervention and follow-up phase) and outcome (repeated measures of pain or activity limitation), that also provided its p -value. Although not directly related to the study aims, this test was performed to enable a summary of whether or not pain and activity limitation improved for each participant. A threshold of significance of $p = <.1$ was used for this analysis due to the exploratory nature of classifying whether or not a change had occurred.

Results were reported in varying levels of granularity, from individual participants and individual movements at various lags, right up to a single descriptive summary measure where all of the analysed relationships about changes to movement or posture were combined.

2.6 | Intervention

The physiotherapists utilized Cognitive Functional Therapy (CFT), an individualized, behavioural approach for the management of LBP, after serious and specific pathology has been

excluded (O'Sullivan et al., 2018). CFT is aligned to contemporary guidelines, providing individualized self-management that targets both psychological and physical barriers for recovery of people with disabling NSLBP (Maher et al., 2017). CFT targets both individually relevant movements and postures identified as painful and disabling for the person, as well as the cognitive and emotional factors that underpin them (O'Sullivan et al., 2018). It has shown promising results in the reduction of pain and activity limitation (Caneiro et al., 2019; O'Keeffe, O'Sullivan, Purtill, Bargary, & O'Sullivan, 2019; O'Sullivan, Dankaerts, O'Sullivan, & O'Sullivan, 2015; Vibe Fersum, O'Sullivan, Skouen, Smith, & Kvåle, 2013; Vibe Fersum, Smith, Kvåle, Skouen, & O'Sullivan, 2019), and therefore provided an opportunity to create change, facilitating the investigation of relationships between movement, posture, pain, and activity limitation.

Up to 10 sessions of CFT were provided over the 12-week intervention phase depending on the clinical course. The initial session was 60 min, while subsequent sessions were 30–45 min. Four specially trained physiotherapists who had undergone competency assessment by the developer of CFT (POS) provided the treatment. POS was present for the initial intervention session and monitored subsequent sessions through regular contact with the treating physiotherapists to ensure treatment fidelity.

2.7 | Registration

The study was registered with the Australian and New Zealand Clinical Trials Registry – ANZCTR study registration number: ACTRN12619001133123. There were no deviations from the protocol but updates to the selection criteria (excluding those with nondisabling LBP (two consecutive weeks with a mean PSFS < 3/10) and excluding those with a planned leave of absence greater than two consecutive weeks) were made. This occurred during the recruitment and baseline phase of the first six participants and was detailed in the trial registration.

The reporting of this study complies with the Single-Case Reporting guideline In Behavioural interventions (SCRIBE) 2016 (Tate, Perdices, Rosenkoetter, Shadish, et al., 2016).

2.8 | Procedural changes

A major benefit of replicated single-case designs are their flexibility (Tate, Perdices, Rosenkoetter, McDonald, et al., 2016) and, as this was a pragmatic study involving significant participant burden, a degree of flexibility was allowed to minimise this burden for individuals. If a participant was unwell, away or unable to make a data collection session, every attempt was made to collect the measures at another time or in their home. Only movement and postural measures with concomitant questionnaire measures were analysed. Movement and

postural measures for P01, P02, P04 and P05 were initially captured with novel, research grade IMUs and surface EMG wearable sensors. These were substituted for a more reliable version because fidelity checking of the data led to the detection of a hardware error after the second or third baseline measure (depending on the stage of the participant). This resulted in a shorter baseline period for those participants but did not affect the statistical analysis (Borckardt, 2008).

2.9 | Dissemination materials

The study was summarized into an infographic (Figure 3) and a video abstract was produced to facilitate dissemination and knowledge translation.

3 | RESULTS

3.1 | Participant characteristics

Twelve (six male and six female) individuals participated, aged from 22 to 76 years old - see Table 1 for the brief demographic characteristics of each participant. More detailed demographic characteristics and clinical features for each participant can be found in Table S1.

Duration of LBP ranged from 11 months to 17 years with many having had to take time off work due to their back pain. Participants had typically received many previous types of treatments and utilised multiple healthcare services without substantial benefit. Nine (75%) had other health co-morbidities and nine (75%) had family members with low back pain. The most commonly nominated PSFS movements and postures were forward bending, followed by sitting, walking, lifting and standing.

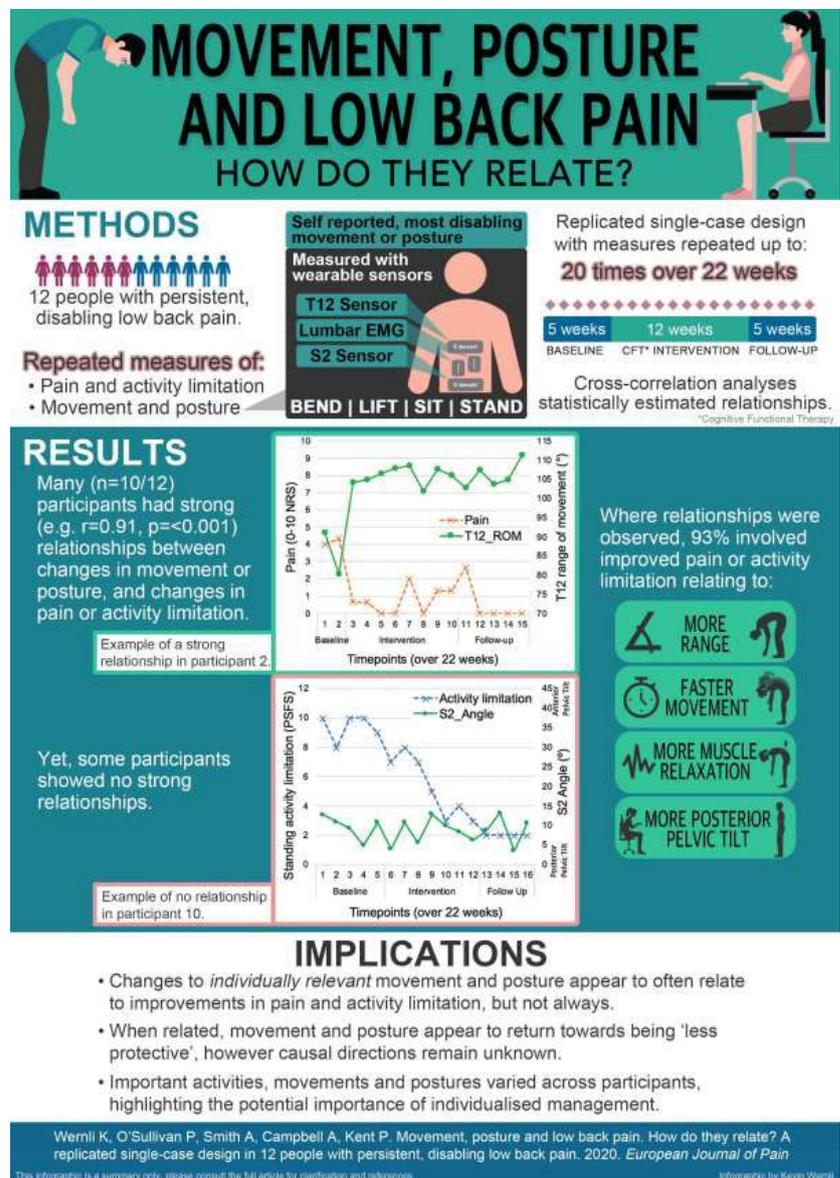
All participants completed all three phases of the study, including the 12-week intervention. The median number of intervention sessions was nine (range 6–10). There were no adverse events. Overall, 222 of the 240 of the scheduled measures (92.5%) were collected and no participant had a lapse in serial measures greater than 2 weeks. Twenty-two of the 816 (2.7%) movement and postural trials collected over the 22-week study period were excluded due to IMU error (e.g. sync error, sensor drift or clothing interference).

3.2 | Outcomes

3.2.1 | Change in pain and activity limitation

Nine of 12 (75%) participants (P02, P03, P06-P12) showed significant improvement in pain when comparing their baseline

FIGURE 3 An infographic summarizing the study



phase to their combined intervention and follow-up phases using simulation modelling analysis (Borckardt, 2008). Eleven of 12 (92%) participants (P02-P12) showed a significant improvement to their movement-based activity limitation (e.g. forward bending), while seven of eight (88%) participants (P4, P6-P11) showed a significant improvement to their posture-based activity limitation (e.g. sitting). The detailed results, as well as figures showing the plots of pain, movement-related activity limitation and posture-related activity limitation for each participant over the study period are presented in Results S1.

3.2.2 | Relationships

The strongest correlations between a lag of -2 and $+2$ weeks for each movement or postural parameter, and the proportion

of nonsignificant, small ($r = 0.10$ to <0.30), medium ($r = 0.30$ to <0.50), and large ($r = \geq 0.50$) correlation relationships (Cohen, 1988) are presented in Tables 2 and 3 with results for all time-lags displayed in Table S2. Ten of 12 (83%) participants (P02-P09, P11, P12) showed at least one large ($r = \geq 0.50$) and significant relationship between changes in a movement or posture and changes in pain or activity limitation, while P01 and P10 did not show any large ($r = \geq 0.50$) and significant relationships.

All 12 participants nominated movement-related activity limitations in their PSFS. Forward bending was the most disabling (highest mean baseline PSFS score) movement for 11 participants (P01-P05, P07-P012), while one participant's most disabling movement was lifting (P06). Changes in movement parameters were often strongly related to changes in pain and activity limitation (P02-P09, P11, P12), with many participants showing significant relationships with all

TABLE 1 Brief overview of participant baseline demographics, the most disabling patient specific functional activity (movement and if available, posture) and the number of assessment sessions available for analysis

Key baseline demographics						RMDQ (0–23)	Most disabling movement and (if applicable) posture nominated in PSFS	Number of assessment sessions available for analysis ^a
Participant	Age (years)	Gender	Duration of LBP					
P01	76	Female	Intermittent for ~15 years, intensified over last year		15	Forward bending ^b	15	
P02	38	Male	5 years and 3 months		17	Forward bending	15	
P03	40	Female	1 year 8 months		18	Forward bending	19 ^c	
P04	33	Male	9 years		16	Forward bending Sitting	18 (16 for postures)	
P05	68	Male	5–6 years		12	Forward bending Sitting	18	
P06	28	Female	11 months		19	Lifting Sitting	18 ^c	
P07	26	Female	7 years		22	Forward bending Sitting	20	
P08	50	Female	5 years		18	Forward bending Standing	19 (17 for postures)	
P09	43	Male	17 years		10	Forward bending Extension (sustained standing and looking up ladder)	20	
P10	22	Female	6 years		12	Forward bending Standing	20 (16 for postures)	
P11	26	Male	6 years		19	Forward bending ^d Standing	19 (18 for postures)	
P12	56	Male	3 years		18	Forward bending	18	

Abbreviations: LBP, Low back pain; PSFS, Patient Specific Functional Scale; RMDQ, 23-Item Roland Morris Disability Questionnaire.

^aMeasures that did not have corresponding movement and postural (due to device hardware failure), or pain and activity limitation measures (due to incomplete or delayed questionnaire responses) were excluded from the analysis.

^bNo normalised EMG data was available for P01 as she requested to be exempted from the normalisation procedure.

^cP03 and P06 had five measures captured over a three-week baseline phase because they were substitutes for two participants who were excluded because their PSFS score during the first two weeks did not reflect disabling LBP.

^dThe EMG data for P11 was excluded due to validity concerns related to spinal fusion surgery causing scar tissue underlying the EMG sensors.

TABLE 2 The strongest cross-correlations^a between *movement*, pain and activity limitation for each participant between time-lag^b -2 and +2 weeks

Participant, PSFS activity and movement parameter	Strongest cross-correlation between time-lag -2 and +2 weeks		Proportion showing relationship			Total significant relationships
	Pain (Tri.I.NRS)	Activity limitation (PSFS)	NonSignificant	Small ($r = 0.10 - <0.30^*$)	Medium ($r = 0.30 - <0.50^*$)	
P01						
Forward bending ^c						
T12_ROM	$r = -0.48$ $p = .034^*$ (LAG:0)	$r = +0.22$ $p = .212$ (LAG:-2)	3	1		1/4 (25%)
T12_VEL	$r = -0.41$ $p = .054$ (LAG:+2)	$r = +0.33$ $p = .099$ (LAG:0)				
P02						
Forward bending						
T12_ROM	$r = -0.78$ $p = .001^*$ (LAG:0)	$r = -0.78$ $p = .000^*$ (LAG:0)			6	6/6 (100%)
T12_VEL	$r = -0.68$ $p = .005^*$ (LAG:0)	$r = -0.80$ $p = .000^*$ (LAG:0)				
EMG	$r = +0.77$ $p = .002^*$ (LAG:0)	$r = +0.68$ $p = .000^*$ (LAG:0)				
P03						
Forward bending						
T12_ROM	$r = -0.71$ $p = .004^*$ (LAG:0)	$r = -0.77$ $p = .002^*$ (LAG:0)	2		4	4/6 (67%)
T12_VEL	$r = -0.53$ $p = .017^*$ (LAG:0)	$r = -0.65$ $p = .003^*$ (LAG:0)				
EMG	$r = +0.34$ $p = .073$ (LAG:0)	$r = -0.27$ $p = .117$ (LAG:-2)				
P04						
Forward bending						
T12_ROM	$r = -0.59$ $p = .016^*$ (LAG:+1)	$r = -0.70$ $p = .003^*$ (LAG:+1)			6	6/6 (100%)
T12_VEL	$r = -0.58$ $p = .031^*$ (LAG:0)	$r = -0.81$ $p = .002^*$ (LAG:0)				
EMG	$r = +0.68$ $p = .004^*$ (LAG:+1)	$r = +0.88$ $p = .000^*$ (LAG:+1)				
P05						
Forward bending						
T12_ROM	$r = -0.76$ $p = .003^*$ (LAG:0)	$r = -0.67$ $p = .006^*$ (LAG:0)	1	3	2	5/6 (83%)
T12_VEL	$r = -0.39$ $p = .013^*$ (LAG:-2)	$r = -0.39$ $p = .022^*$ (LAG:-2)				
EMG	$r = +0.35$ $p = .041^*$ (LAG:+2)	$r = +0.33$ $p = .069$ (LAG:0)				
P06						
Lifting						

(Continues)

TABLE 2 (Continued)

Participant, PSFS activity and movement parameter	Strongest cross-correlation between time-lag -2 and +2 weeks		Proportion showing relationship				Total significant relationships
	Pain (Tri.NRS)	Activity limitation (PSFS)	NonSignificant	Small ($r = 0.10-0.30^*$)	Medium ($r = 0.30-0.50^*$)	Large ($r = \geq 0.50^*$)	
T12_ROM	$r = -0.69 p = .005^*$ (LAG:+2)	$r = -0.72 p = .005^*$ (LAG:+2)				4	4/4 (100%)
T12_VEL	$r = -0.72 p = .008^*$ (LAG:0)	$r = -0.79 p = .001^*$ (LAG:0)					
P07							
Forward bending							
T12_ROM	$r = +0.55 p = .004^*$ (LAG:0)	$r = +0.52 p = .012^*$ (LAG:0)	3	1	2		3/6 (50%)
T12_VEL	$r = -0.41 p = .036^*$ (LAG:-1)	$r = -0.44 p = .050$ (LAG:0)					
EMG	$r = -0.24 p = .120$ (LAG:0)	$r = -0.18 p = .179$ (LAG:0)					
P08							
Forward bending							
T12_ROM	$r = -0.69 p = .006^*$ (LAG:+2)	$r = -0.65 p = .015^*$ (LAG:+2)			6		6/6 (100%)
T12_VEL	$r = -0.86 p = .003^*$ (LAG:0)	$r = -0.81 p = .005^*$ (LAG:0)					
EMG	$r = +0.52 p = .015^*$ (LAG:+1)	$r = +0.53 p = .013^*$ (LAG:+1)					
P09							
Forward bending							
T12_ROM	$r = -0.64 p = .016^*$ (LAG:-2)	$r = -0.69 p = .006^*$ (LAG:-2)			6		6/6 (100%)
T12_VEL	$r = -0.81 p = .000^*$ (LAG:+1)	$r = -0.80 p = .000^*$ (LAG:+2)					
EMG	$r = +0.91 p = .000^*$ (LAG:0)	$r = +0.82 p = .000^*$ (LAG:-1)					
P10							
Forward bending							
T12_ROM	$r = +0.41 p = .060$ (LAG:0)	$r = +0.37 p = .069$ (LAG:0)	4	2			2/6 (33%)
T12_VEL	$r = -0.49 p = .015^*$ (LAG:+2)	$r = -0.44 p = .032^*$ (LAG:+2)					
EMG	$r = -0.32 p = .065$ (LAG:+2)	$r = -0.26 p = .131$ (LAG:-1)					
P11							
Forward bending ^c							
T12_ROM	$r = -0.86 p = .000^*$ (LAG:0)	$r = -0.91 p = .000^*$ (LAG:0)			4		4/4 (100%)
T12_VEL	$r = -0.88 p = .000^*$ (LAG:0)	$r = -0.87 p = .001^*$ (LAG:0)					
P12							
Forward bending							

(Continues)

TABLE 2 (Continued)

Participant, PSFS activity and movement parameter	Strongest cross-correlation between time-lag -2 and +2 weeks		Proportion showing relationship			Total significant relationships
	Pain (Tri.NRS)	Activity limitation (PSFS)	NonSignificant	Small ($r = 0.10$ – $<0.30^*$)	Medium ($r = 0.30$ – $<0.50^*$)	
T12_ROM	$r = -0.57$ $p = .011^*$ (LAG:+2)	$r = -0.55$ $p = .041^*$ (LAG:0)				6/6 (100%)
T12_VEL	$r = -0.62$ $p = .013^*$ (LAG:0)	$r = -0.65$ $p = .004^*$ (LAG:0)				
EMG	$r = +0.77$ $p = .000^*$ (LAG:0)	$r = +0.60$ $p = .002^*$ (LAG:+1)			6	

Abbreviations: EMG, Electromyographic activity of the lumbar muscles normalised to an isometric, sub-maximal contraction (%Submax); PSFS, Patient Specific Functional Scale (0–10 scale); S2_Angle, Mean angle of the upper sacrum (S2) sensor during static posture (degrees); T12_ROM, Peak range of movement of the thoracolumbar (T12) sensor (degrees); T12_VEL, Mean velocity of the thoracolumbar (T12) sensor (degrees/sec); Tri.NRS, Mean numerical rating of current pain, average and worst pain over last week (0–10 scale).

^aCross-correlation analyses performed using Simulation Modelling Analysis.

^bA lag of zero indicates the two variables likely occurred together, a positive lag indicates that a change in movement or posture likely preceded a change in pain or activity limitation, and a negative lag indicates that a change in movement or posture likely followed a change in pain or activity limitation.

^cNo normalised EMG data available for analysis. P01 requested to be exempt from the normalisation task and P11 had significant scar tissue underlying the sEMG sensors following lumbar fusion surgery resulting in validity concerns of the EMG data.

* $p < 0.05$.

parameters (ROM, speed and EMG activity). However, some participants only had significant relationships with select movement parameters or with just pain or activity limitation (e.g. P01 showed significant relationships with changes in range and pain, but not velocity and pain, while P10 showed significant relationships with changes in velocity but not range for both pain and activity limitation). Changes in lumbar EMG activity were also often but not always related to changes in pain or activity limitation among the participants, with relationships identified in six of nine participants (P02, P04, P05, P08, P09, and P11).

Of the eight participants that nominated a posture-related activity limitation in their PSFS (P04–P11), sitting was the most disabling in four (P04–P07), standing was the most disabling in three (P08, P10, P11), and sustained extension was the most disabling in one (P09). Similar to relationships for movements, relationships between changes in posture and changes in pain and activity limitation were found in some participants (P04, P06–P08 and P11), but not all.

Figure 4 displays raw data plots for exemplar cases that did and did not show relationships while a summary of the relationships, their direction and strength for each movement and posture is provided in Table 4.

3.2.3 | Summary of relationships and their directionality

Of the 82 investigations of association between changes in movement or posture, and changes in pain and activity limitation, a relationship was identified 61 (74%) times. Of these 61 relationships, increased ROM and velocity during bending and lifting, less muscle activity during end of range voluntary flexion, and increased posterior-pelvic-tilt during sitting and standing were related to improved pain and activity limitation 57 (93%) times.

Of the remaining 21 associations investigated where a relationship was not identified, 16 (20% of all associations investigated) involved improvements in pain or activity limitation in the absence of a relationship with movement or posture, and 5 (6%) involved no change to pain or activity limitation.

3.2.4 | Time-lag

Thirty-three of 61 (54%) of the strongest significant relationships occurred at a time-lag of zero, 19 of 61 (31%) at a positive time-lag, and 9 of 61 (15%) at a negative time-lag. This indicates that when analysed at a frequency of almost weekly, relationships between movements or postures, and pain and activity limitation were largest when analysed contemporaneously, suggesting that changes usually occurred together.

TABLE 3 The strongest cross-correlations^a between the most disabling *posture*, pain and activity limitation for each participant between time-lag^b -2 and +2 weeks

Participant, PSFS activity and postural parameter	Strongest cross-correlation between time-lag -2 and +2 weeks		Proportion showing relationship			Total significant relationships
	Pain (Tri.NRS)	Activity limitation (PSFS)	NonSignificant	Small ($r = 0.10$ — <0.30 [*])	Medium ($r = 0.30$ — <0.50 [*])	
P04						
Sitting ^c						
S2_Angle	$r = +0.37$ $p = .105$ (LAG:+1)	$r = +0.60$ $p = .016$ (LAG:0)	1		1	1/2 (50%)
P05						
Sitting						
S2_Angle	$r = +0.18$ $p = .198$ (LAG:-2)	$r = +0.26$ $p = .108$ (LAG:-2)	0			0/2 (0%)
P06						
Sitting						
S2_Angle	$r = +0.63$ $p = .003$ (LAG:+2)	$r = +0.58$ $p = .017$ (LAG:+2)			2	2/2 (100%)
P07						
Sitting						
S2_Angle	$r = -0.59$ $p = .004$ (LAG:-1)	$r = -0.64$ $p = .002$ (LAG:-2)			2	2/2 (100%)
P08						
Standing ^c						
S2_Angle	$r = +0.30$ $p = .056$ (LAG:0)	$r = +0.37$ $p = .035$ (LAG:0)	1		1	1/2 (50%)
P09						
Sustained extension						
T12_Angle	$r = -0.26$ $p = .102$ (LAG:-1)	$r = -0.34$ $p = .051$ (LAG:0)	2			0/2 (0%)
P10						
Standing ^c						
S2_Angle	$r = +0.11$ $p = .304$ (LAG:+2)	$r = +0.09$ $p = .324$ (LAG:+2)	2			0/2 (0%)
P11						
Standing ^c						
S2_Angle	$r = +0.79$ $p = .002$ (LAG:0)	$r = +0.79$ $p = <.001$ (LAG:-1)	0		2	2/2 (100%)

Abbreviations: PSFS, Patient Specific Functional Scale (0–10 scale); S2_Angle, Mean angle of the upper sacrum (S2) sensor during static posture (degrees), T12_Angle, Mean angle of thoracolumbar (T12) sensor during static posture; Tri.NRS, Mean numerical rating of current pain, average and worst pain over last week (0–10 scale).

^aCross-correlation analyses performed using Simulation Modelling Analysis.

^bA lag of zero indicates the two variables likely occurred together, a positive lag indicates that a change in movement or posture likely preceded a change in pain or activity limitation, and a negative lag indicates that a change in movement or posture likely followed a change in pain or activity limitation.

^cOutliers removed.

^{*} $p = <0.05$.

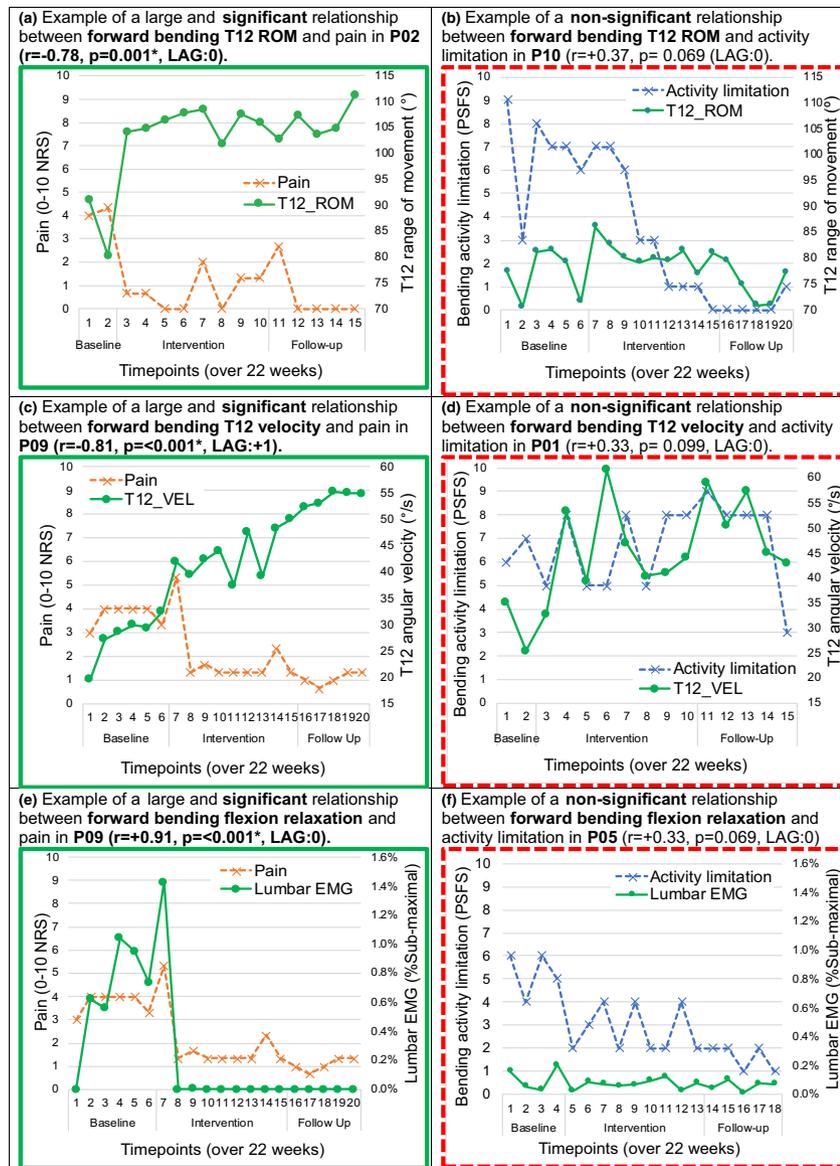


FIGURE 4 Raw data plots exemplifying significant and nonsignificant ($p \leq .05$) relationships between changes in movement or posture, and changes in pain or activity limitation using cross-correlation^a analysis (between time-lag^b -2 to $+2$ weeks).

^aCross-correlation analyses performed using Simulation Modelling Analysis.

^bA lag of zero indicates the two variables likely occurred together, a positive lag indicates that a change in movement or posture likely *preceded* a change in pain or activity limitation, and a negative lag indicates that a change in movement or posture likely *followed* a change in pain or activity limitation.

Solid green border (—): significant relationship; Dashed red border (- - -): nonsignificant relationship; TriNRS: Mean numerical rating of current pain, average and worst pain over last week (0–10 scale); PSFS: Patient Specific Functional Scale (0–10 scale); ROM: Range of movement; VEL: T12 angular velocity (degrees per second). * $p < .05$

4 | DISCUSSION

This study investigated the relationship between (a) within-person changes in objectively measured, individually relevant movement or postural parameters, and (b) within-person changes in self-reported pain and activity limitation, in people with persistent, disabling non-specific LBP. Measures were repeated up to 20 times over a 22-week period in each ($n = 12$) participant to allow the presence and strength of

relationships to be statistically estimated over a clinically relevant period. The majority of participants experienced improvements in pain and activity limitation following the onset of the intervention. Most of the time, this improvement was strongly related to changes in movement or posture, but improvements in pain and activity limitation were sometimes unrelated to changes in movement or posture.

That relationships between repeated measures of movement or posture, and pain and activity limitation occurred

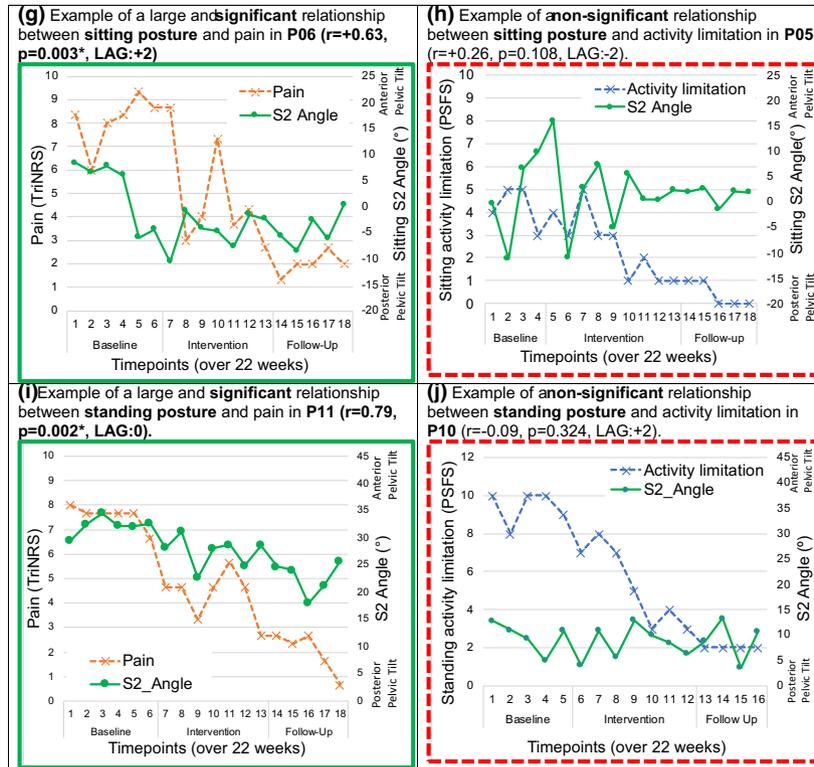


FIGURE 4 Continued

in 74% (61 of 82) of the relationships analysed shows that frequently, changes in movement or posture are related to improved pain and activity limitation when parameters during individually relevant activities are analysed at a within-person level. The frequent identification of a relationship in the current study is in contrast with previous systematic reviews where relationships between changes in movement were infrequently identified (29%, 31% and 'infrequently' among the Steiger et al. (2012), Wernli et al. (2020), and Laird et al. (2012) reviews, respectively. This difference may be due to the ability of the current study to: accommodate individually relevant movements and postures, analyse at a within-person level and the individualized nature of the intervention (O'Sullivan et al., 2018; Wernli et al., 2020).

The within-person design of the current study aligns with contemporary calls for individualized approaches to healthcare (Lillie et al., 2011; O'Brien et al., 2010) and allowed novel insights into relationship frequency, strength and direction. With 10 demonstrations of inter-subject replication of a strong relationship, the current study exceeds the minimum of three replications threshold recommended for the purpose of generality for single-case intervention research (Tate et al., 2013). Although relationships were frequently found, 20% of the time (16 of 82 associations investigated), pain and activity limitation improved despite not being related to changes in movement and posture. It may be that: (a) these particular movement and postural

parameters were simply unrelated to that participants presentation, (b) that other, unmeasured factors may have been more related to their improvement, and/or (c) that the participant did not have a movement or postural 'impairment' amenable to change in the first place. A recent cohort study of 266 people (Laird, Keating, & Kent, 2018) that found a sub-group (25%) of people with LBP move 'like people without LBP' is some support for that notion and suggests that the importance of movement and posture is variable amongst people with NSLBP.

The nomination of different PSFS activities and the diverse presence and strength of relationships (both within-person and between people) highlights that different activities, and movement and postural parameters are likely to be important for different people. For example, forward bending was the most disabling pain-provoking task for both P12 and P07, yet P12 showed a significant and strong relationship with EMG, while P07 showed no strong relationship with EMG. This heterogeneity is supported by previous research utilizing a similar design that identified unique patterns of change and variable relationships between proposed mediators and disability across four participants with persistent, disabling NSLBP and high pain-related fear (Caneiro et al., 2019). Notably, Caneiro et al. (2019) related two self-report variables, while the current study related an objectively measured and a self-report variable, reducing the potential bias present when correlating two self-report variables. It appears that people with NSLBP likely have unique

TABLE 4 A summary of the number, direction and strength of cross-correlation^a relationships observed for each movement and posture

Activity	Parameter	% observed relationship with pain	% observed relationship with activity limitation	% and direction of movement related to improved pain or activity limitation	Range of significant cross-correlation values
Forward bending (most disabling movement in 11 participants - P01-P05, P07-P12)	ROM (peak T12 angle)	91% (10 out of 11 participants)	82% (9 out of 11 participants)	89% increased ROM (17 out of 19 relationships)	$r = -0.48$ to -0.91
	Speed (T12 angular velocity)	91% (10 out of 11 participants)	82% (9 out of 11 participants)	100% increased speed (19 out of 19 relationships)	$r = -0.39$ to -0.87
	Lumbar muscle activity (EMG)	67% (6 out of 9 participants)	56% (5 out of 9 participants)	100% less muscle activity (11 out of 11 relationships)	$r = +0.35$ to $+0.91$
Lifting (most disabling movement in 1 participant - P06)	ROM ^b (T12 Angle)	100% (1 out of 1 participant)	100% (1 out of 1 participant)	100% increased ROM (2 out of 2 relationships)	$r = -0.69$ and -0.72
	Speed (T12 angular velocity)	100% (1 out of 1 participant)	100% (1 out of 1 participant)	100% increased ROM (2 out of 2 relationships)	$r = -0.72$ and -0.79
Sitting (most disabling posture in 4 participants - P04-P07)	S2 Angle	50% (2 out of 4 participants)	75% (3 out of 4 participants)	60% increased posterior-pelvic-tilt (3 out of 5 relationships)	$r = +0.58$ to $+0.64$
	S2 Angle	33% (1 out of 3 participants)	66% (2 out of 3 participants)	100% increased posterior-pelvic-tilt (3 out of 3 relationships)	$r = +0.37$ and $+0.79$
Sustained extension (most disabling posture in 1 participant - P09)	T12 Angle	0% (0 out of 1 participant)	0% (0 out of 1 participant)	No relationship identified	No relationship identified

^aCross-correlation analyses performed using Simulation Modelling Analysis.

^bT12 angle at commencement of lifting.

and individually relevant relationships between numerous biopsychosocial factors that influence their presentation and clinical outcome. In heterogenous and complex conditions, rigorous single-case designs with repeated measures provide an opportunity to gather insight into the complex interplay between multiple factors of interest from a within-person, individualized perspective (Caneiro et al., 2019; Kratochwill et al., 2012).

To our knowledge, no other studies have statistically estimated relationships between repeated measures of movement, posture, pain and activity limitation, limiting our ability to make comparisons with other literature. However, a small number of case-reports ($n = 1$) utilizing repeated measures found mixed results when visually estimating an association. Some reported changes to movement that *were* associated with improvements in pain and activity limitation (Jones & Wolf, 1980; Ohtsuki, 2014; Robinson, 2016; Wolf, Nacht, & Kelly, 1982), while some did not (Johansson & Lindberg, 1995; Takasaki & May, 2018). Limitations such as the investigation of only a single participant, no statistical analysis, no assessor blinding, a lack of valid and reliable measurement equipment, selection bias, and selective reporting (due to a lack of registered protocols) may have influenced the findings of those studies. However, when relationships were observed in the those studies, the direction of the movement changes (namely increased spinal ROM and reduced lumbar EMG activity; Jones & Wolf, 1980; Ohtsuki, 2014; Robinson, 2016; Wolf et al., 1982) related to improved pain and activity limitation were concordant with the current findings.

The direction of change in movement and posture in the presence of a relationship was very consistent in this study. That 93% of the time (57 out of 61 associations investigated), increased movement ROM or speed, reductions in lumbar muscle activity at maximum voluntary flexion, or increased posterior-pelvic-tilt during sitting and standing postures were related to improved pain and activity limitation could be interpreted as a potential reduction in 'protective' movement and postural behaviours (O'Sullivan et al., 2018). This finding aligns with a recent systematic review of cohort studies that found increased movement ROM, velocity and flexion-relaxation related to improved pain and activity limitation 93% of the time when relationships between within-person changes in movement and pain or activity limitation were identified in 2,739 people from 27 cohort studies (Wernli et al., 2020). The replication in the current study of those cohort study findings, further support the generality of the findings (Tate et al., 2013). Causal directions, however, (e.g. whether less protective movement and postural patterns resulted in changes to pain or activity limitation, vice versa, or whether changes in both had a separate common cause) remain unknown. Carefully designed experimental and mediational studies, that include psychological factors known to be important for

people with disabling NSLBP, such as pain catastrophising, fear and pain self-efficacy, would be required to make causal inferences (Lee et al., 2017; Matheve, De Baets, Bogaerts, & Timmermans, 2019).

Psychological factors (such as pain catastrophising, fear and pain self-efficacy) have been shown to relate more to improved pain or activity limitation than physical parameters such as movement or abdominal muscle function (Mannion, Caporaso, Pulkovski, & Spratt, 2012; Mannion et al., 2001; Nordstoga, Meisingset, Vasseljen, Nilsen, & Unsgaard-Tondel, 2019). Psychological factors have also been shown to influence the embodiment of cautious and protective movement behaviours (Matheve et al., 2019; Olugbade, Bianchi-Berthouze, & Williams, 2019; Osumi et al., 2019) and mediate improvement (Lee et al., 2017; Liew et al., 2020; Mansell, Kamper, & Kent, 2013; Smeets, Vlaeyen, Kester, & Knottnerus, 2006). It may be that threat reduction, following the safe completion of previously painful, feared, or avoided activities perceived as dangerous or damaging, led to clinical improvement, irrespective of whether this was related to changes in movement or posture (Mannion et al., 2012; Steiger et al., 2012). The influence of other unmeasured biopsychosocial and contextual factors on the findings of this study remain unknown.

5 | LIMITATIONS

The study design facilitated the within-person investigation of the relationship between changes in individually relevant movements or postures, and changes in pain and activity limitation. The generality of the study is supported by replication of the findings across participants and alignment of the findings with a recent systematic review of cohort studies (Wernli et al., 2020). Additionally, the demographics of the participants represent the heterogenous populations that clinicians likely encounter. However, only participants reporting pain specifically provoked by movements or postures were included, so it is unknown how broadly the findings relate to all people with low back pain. Furthermore, we only analysed T12 kinematics and lumbar muscle activity for movements and S2 or T12 kinematics for postures to minimize complexity and the number of analyses. Also, the sensors may not provide adequate accuracy to measure small and subtle changes, or lumbar inter-segmental changes which would have required laboratory-based measurements that were not feasible with the current study's field-based design. It is also unknown whether task familiarity or 'the observer effect' influenced our findings. A component of the individualized and integrated biopsychosocial intervention involves the assessment and (if applicable) targeting of meaningful movement and posture, which may mean a relationship was identified more often than it would be using other interventions.

6 | CONCLUSIONS

Changes to individually relevant movement and posture appear to often relate to clinical outcome, but not always. The heterogeneity of the relationships highlights the importance of identifying individually relevant activities (e.g. by using the PSFS) as well as considering diverse movement and postural parameters in people with NSLBP. When relationships were identified, and pain or activity limitation improved, movement and posture appeared to return towards being 'less protective', however, the influence of other biopsychosocial factors on this change remains unclear.

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CONFLICTS OF INTEREST

The authors certify that they have no affiliations with, financial involvement or conflicts of interest in any organisation or entity with a direct financial interest in the subject matter or materials discussed in the article.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and design of the study. KW performed data collection and analysis with input from PK, AC, PO and AS. KW prepared the draft of the manuscript. All authors discussed the results and commented on the manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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