Change in Low Back Movement Patterns After Neurosurgical Intervention for Lumbar Spondylosis

Aubrey P. Monie, PhD, MMT,[a] Roger I. Price, PhD,[b] Christopher R.P. Lind, MBChB,[c] and Kevin P. Singer, PhD[a]

Abstract

Objectives: The purpose of this study was to assess the use of computer-aided combined movement examination (CME) to measure change in low back movement after neurosurgical intervention for lumbar spondylosis and to use a CME normal reference range (NRR) to compare and contrast movement patterns identified from lumbar disk disease, disk protrusion, and nerve root compression cases.

Methods: A test-retest, cohort observational study was conducted. Computer-aided CME was used to record lumbar range of motion in 18 patients, along with pain, stiffness, disability, and health self-report questionnaires. A minimal clinically important difference of 30% was used to interpret meaningful change in self-reports. z Scores were used to compare CME. Post hoc observation included subgrouping cases into 3 discrete pathologic conditions—disk disease, disk protrusion, and nerve root compression—to report intergroup differences in CME.

Results: Self-report data indicated that 11, 7, and 10 patients improved by ≥30% in pain, stiffness, and function, respectively. Three patients experienced clinically significant improvement in health survey. A CME pattern reduced in all directions suggested disk disease. Unilaterally restricted movement in side-flexed or extended directions suggested posterolateral disk protrusion with or without ipsilateral nerve root compression. Bilateral restrictions in extension suggested posterior disk protrusion with or without nerve root compression. In 11 of the 18 cases, CME converged toward the NRR after surgery.

Conclusion: We described the use of CME to identify atypical lumbar movement relative to an NRR. Data from this short-term postoperative study provide preliminary evidence for CME movement patterns suggestive of disk disease, disk protrusion, and nerve root compression. (J Manipulative Physiol Ther 2018;41:111-122)

Key Indexing Terms: *Range of Motion, Articular; Spine; Intervertebral Disk; Nerve Compression Syndromes; Neurosurgery*

Introduction

Low back pain (LBP) is a major public health problem. The lifetime prevalence is as high as 85% and the reported annual incidence in adults is 22% to 65%,[1] with 40% to 70% of those experiencing LBP seeking health care.[2] Despite increased efforts to understand LBP, knowledge of the underlying pathology and insights into optimizing clinical outcomes have advanced little in the last 2 decades.[3]

It is assumed that a large portion of LBP is caused or influenced by biomechanical factors.[4,5] Because all spinal structures are potentially a source of LBP,[6,7] an accurate diagnosis is often difficult to make.[8] Authors of a retrospective study of 170 patients undergoing diagnostic procedures for LBP suggested the intervertebral disk (IVD) and facet joints are the 2 most likely sources of pain, with prevalence of 42% and 31%, respectively.[9] Improved diagnostic accuracy would confer obvious cost advantages to the health system for enabling treatment to focus on particular sources of pain and would enable pathology-specific interventions to be grouped for clinical research.

A key component of clinical examination includes assessing the range of motion (ROM),[10] indicating spinal function, painful movement directions, response to intervention, or even permanent impairment. The literature reports various movement assessments including functional

[a] The Centre for Musculoskeletal Studies, School of Surgery, The University of Western Australia, Perth, Western Australia, Australia.
[b] Department of Medical Technology and Physics, Sir Charles Gairdner Hospital, Perth, Western Australia, Australia.
[c] Department of Neurosurgery, Sir Charles Gairdner Hospital, Perth, Western Australia, Australia.
Corresponding author: Aubrey P. Monie, PhD, MMT, The Centre for Musculoskeletal Studies, School of Surgery M424, The University of Western Australia, Perth, Crawley, Western Australia 6009, Australia. Tel.: +61 421717932.
(e-mail: aubrey.monie@research.uwa.edu.au).
Paper submitted July 10, 2017; in revised form August 20, 2017; accepted August 23, 2017.
0161-4754

https://doi.org/10.1016/j.jmpt.2017.08.008

activities of daily living,[11] planar movements,[12-14] and combined movement examinations (CMEs).[15-17] A lumbar CME is considered more informative than a planar movement examination[15,18] because this approach matches functional movements to the patient's presenting complaint and may reproduce symptoms that could in future help with diagnosis.[19]

The purpose of the present study was to use a CME testing procedure[20] to determine if specific movement patterns exist in cases of chronic lumbar spine dysfunction. To examine this, CME and self-report data in 18 patients who underwent neurosurgical intervention for confirmed lumbar spondylosis were compared with a CME normal reference range (NRR). Normalizing of postintervention CME was attributed to the structure treated and provided insight into structure-specific CME movement patterns. For example, if a patient had reduced left-side flexion (LSF) because of LBP and treating a left L4-5 disk protrusion normalized LSF, we attributed the reduced LSF CME pattern to the left L4-5 disk protrusion.

The purpose of this study was to assess the use of computer-aided CME to measure change in low back movement after neurosurgical intervention for lumbar spondylosis and to use a CME NRR to compare and contrast movement patterns identified from lumbar disk disease, disk protrusion, and nerve root compression cases.

Methods

This observational study was approved by the human research ethics committees at the University of Western Australia and Sir Charles Gairdner hospital (Perth, Western Australia, Australia). Patient information was provided, and consent was obtained in all cases.

A 3-D motion tracking system (MotionStar; Ascension Technology, Shelburne, Vermont)[20] with custom software (LabVIEW V5.0, National Instruments, Austin, Texas) was used to measure a standardized 8-direction CME (Fig 1). Proof of concept for the use of computer-aided CME and acceptable intrasession and intersession reliability have been reported elsewhere.[20]

Recruitment and CME Data Collection

Thirty-nine patients with LBP and/or leg pain diagnosed by neurosurgeons as originating from low back structures were recruited and attended a preintervention CME trial. Of these, 18 individuals received neurosurgical intervention and completed postintervention examination (Fig 2). Patients were recruited from a private physiotherapy practice (n = 2) and a neurosurgery department in a tertiary hospital (n = 16); the sample comprised 6 men (aged 49 ± 14 years) and 12 women (aged 50 ± 11 years).

After familiarization with test protocol, 2 skin-mounted MotionStar sensors (Ascension Technology) were placed over the volunteer's S1 and L1 spinous process. Data acquisition and postprocessing are described in detail elsewhere.[20] Patients were asked to remember their most painful and most stiff CME movement direction, followed by instruction and guidance into each of the 8 CME movement directions (Fig 1). Maximal data values for ROM were recorded according to a predefined sequence: flexion (Flex), flexion with added left-side flexion (FwLSF), flexion with added right-side flexion (FwRSF), LSF, right-side flexion (RSF), extension, extension with added left-side flexion (EwLSF), and extension with added right-side flexion (EwRSF).

All 18 patients were tested before intervention and retested at approximately 14 weeks after intervention.

Outcome Measures

A battery of self-report outcome measures were used to assess patients at each examination visit[21]: visual analog scale for pain (VASp) and low back stiffness (denoted as VASs), Roland-Morris Low Back Pain and Disability Questionnaire (RMDQ) and a Short Form health survey (SF-12). A VASs was included because clinical measures often do not seek information regarding the effect of lumbar stiffness on function.[22,23] A minimal clinically important difference (MCID) of 30% was used for all self-report data.[24] Combined movement examination data were also collected and expressed using z scores (standard scores for normally distributed data). In this study, z scores expressed each individual's ROM relative to their age and sex-matched NRR, indicating the magnitude of each movement direction, in standard deviations (+ or –) from the NRR mean.[25] For the 8 CME directions the maximum values were displayed in a radial plot and z scores calculated for each direction and trial.

Each patient's CME was evaluated alongside the neurosurgeon's diagnosis, treatment response, lumbar computed tomography or magnetic resonance imaging and matched NRR, in an effort to compare CME with identified pathologic conditions. A normal NRR (n = 159) was used to aid in comparing and contrasting each case's movement patterns.[20]

Statistical Analysis

A sample of convenience was derived from a tertiary hospital and private practice setting. z Scores were used to assess the clinical CME. This representation facilitates comparison with an NRR in each of the 8 CME movement directions, with reference to age and sex of each case.

Results

Change scores (%) were derived for: VASp and VASs in relation to their low back condition, SF-12 physical

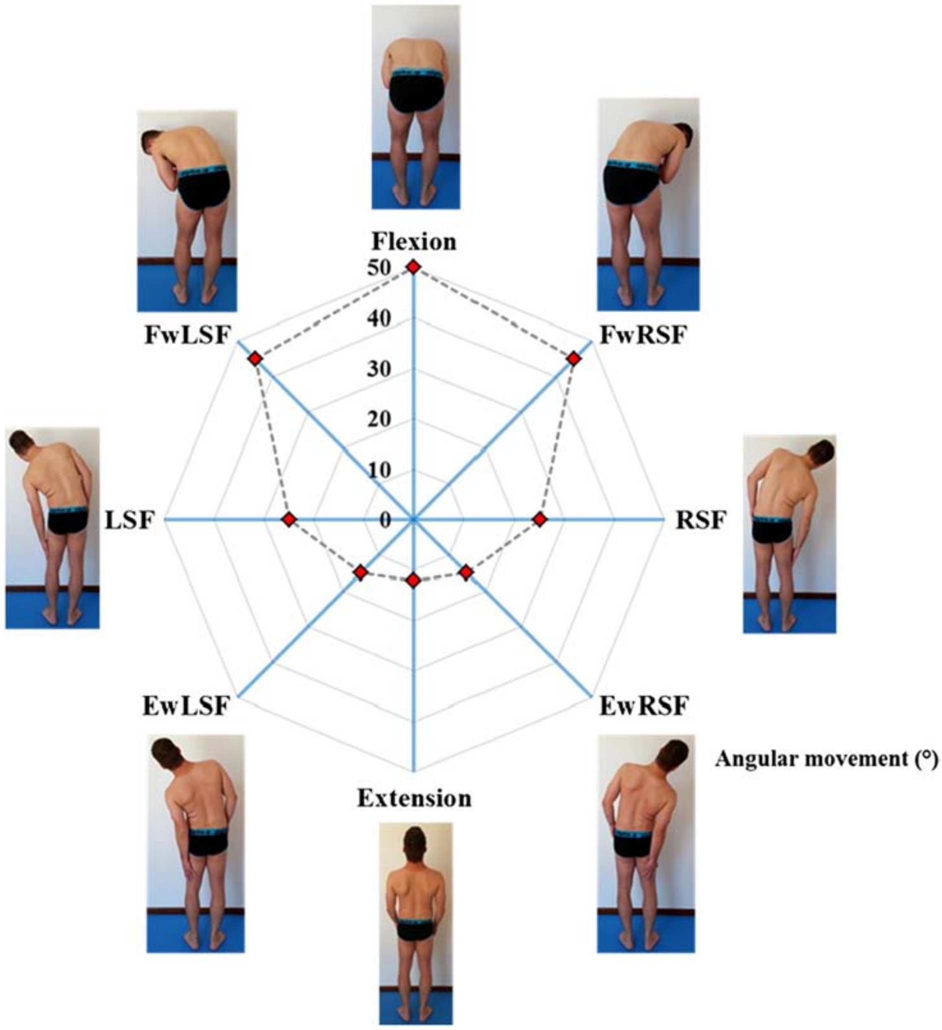

Fig 1. *Example of an asymptomatic combined movement examination radial plot in degree of angular movement. Photographs illustrate the movement directions and end-points, namely: flexion, flexion with left-side flexion (FwLSF), flexion with right-side flexion (FwRSF), left-side flexion (LSF), right-side flexion (RSF), extension, extension with left-side flexion (EwLSF), and extension with right-side flexion (EwRSF).*

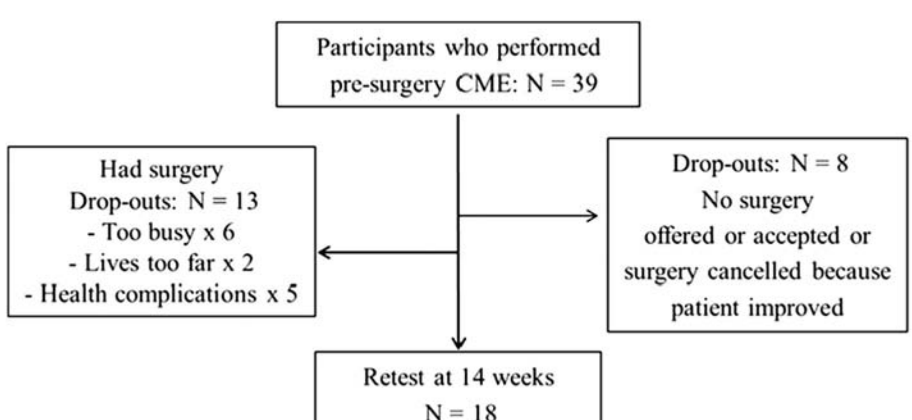

Fig 2. *Flow chart of participation.* CME*, combined movement examination.*

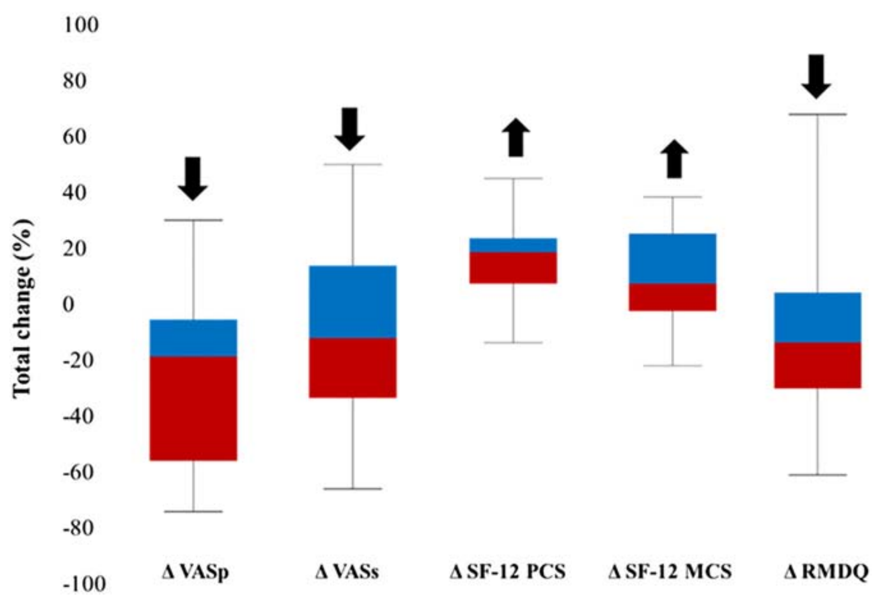

Fig 3. *Total change scores (%). Boxplot illustrating total change scores (Δ) for all patient's self-report questionnaires, with minimum, median, 25th and 75th percentiles, and maximum values. In each series, postintervention score minus preintervention score was used as the total change, expressed as a percentage. Arrows indicate the direction of improvement from baseline (0%). A minimal clinically important difference of 30% was used in this study.* MCS, *mental component score;* PCS, *physical component score;* RMDQ, *Roland-Morris Low Back Pain and Disability Questionnaire;* SF-12, *Short Form health survey;* VASp, *visual analog scale for pain;* VASs, *visual analog scale for stiffness.*

component scores (PCS) and mental component scores, and RMDQ. Of the 18 patients, 10 were most symptomatic in a combined lumbar position (FwRSF, FwLSF, EwRSF, or EwLSF), and VASs scores were higher than VASp scores in 11 of the 18 cases, indicating the value of assessing in combined movement positions and recording stiffness as an outcome measure. Total change scores for VASp, SF-12 PCS, and RMDQ were clinically significant in 61%, 16%, and 56% of all cases, respectively (where there was no floor or ceiling effect), at the retest. Total change scores (%) for self-reports and the direction of change in outcomes are depicted in Figure 3. A histogram plot (Fig 4) illustrates pre- and post-CME z scores for 3 representative case examples (A, H, and L), selected for their different single-structure diagnoses, in the 4 most informative CME movement directions (flexion, extension, EwLSF, and EwRSF).

Of the 18 patients, 17 had preintervention z scores of <-1.5 in at least 1 CME direction, indicating that movement was in the lower end of its range as defined by the equivalent NRR distribution, even with consideration of multiple comparisons of the CME variables. Summary data are reported in Table 1.

The clinical presentation and specific CME patterns of cases A, H, and L are discussed in detail because they comprised single-structure pathologic conditions, receiving single-structure intervention. Cases with multistructure and multilevel pathologic conditions, which received multilevel interventions, were more difficult to assess and changes were more difficult to attribute to single pathologic conditions and inform CME patterns suggestive of single structures.

Case A: Unilateral Discectomy for Posterolateral Disk Protrusion

A 56-year-old man presented with severe left-side anterolateral hip pain, mild LBP, antalgic gait with flexed low back and hips, and decreased skin sensation over the medial knee and medial calf muscle (Fig 5A). Magnetic resonance imaging indicated a large left-side posterolateral disk herniation with sequestration (Fig 5B and C).

Combined movement examination indicated a decreased ROM in extension, EwLSF, and LSF compared with the relevant NRR (Fig 5D). Postoperatively, the patient had experienced almost instant relief of pain in the hip and low back, and total change for VASp improved by 95%. Combined movement examination preoperative and postoperative ROM is illustrated in Figure 5D. z Scores at final retest indicate an increase in ROM in the affected CME directions, toward mean values of the relevant matched NRR. Figures 4B, C, and E illustrate the change in z score for extension, EwLSF, and LSF, respectively.

Case H: Bilateral Decompression for LBP and R > L Radiculopathy

A 42-year-old woman presented with a 24-month history of intermittent, severe LBP. This patient stood with a left-side lateral shift[26] and complained of intermittent lower limb pain (R > L) (Fig 6A). Conservative attempts to control pain and

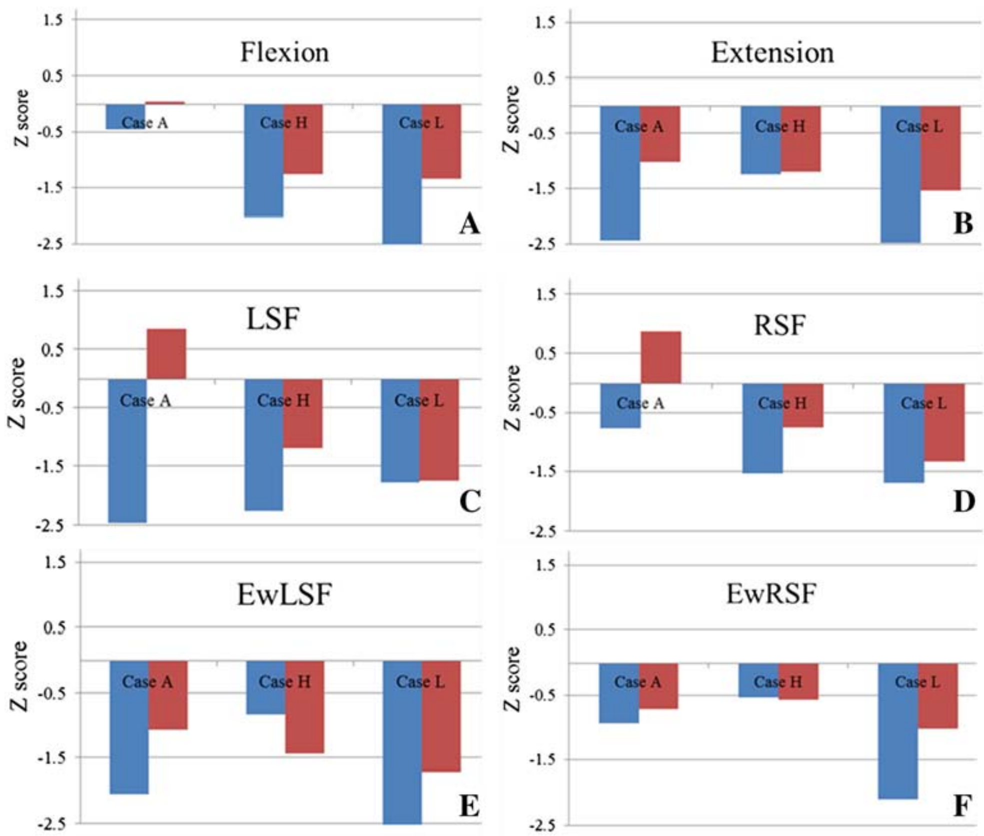

Fig 4. *Pre- and post-CME z scores for 3 different cases. Preintervention (blue) and postintervention (red) z scores for example cases: case A (left discectomy for low back pain and left hip pain), case H (bilateral discectomy for bilateral radiculopathy), and case L (fusion for degenerative disk disease), in the 6 most informative CME directions—flexion (A), extension (B), LSF (C), RSF (D), EwLSF (E), and EwRSF (F).* CME, *combined movement examination;* EwLSF, *extension with left-side flexion;* EwRSF, *extension with right-side flexion;* LSF, *left-side flexion;* RSF, *right-side flexion.*

improve function were refractory. Magnetic resonance imaging identified a marked right-sided disk protrusion at L4-5 (Fig 6B and C). Combined movement examination indicated the greatest movement restriction in the directions of left- and right-side flexion, with EwLSF, extension, and EwRSF also reduced (Fig 6D).

The patient underwent bilateral laminectomy and discectomy with good effect. At reassessment 12 weeks postoperative, lumbar spine movement had normalized to within 1 standard deviation (SD) of her age- and sex-matched NRR (Fig 6D) and standing lumbar lordosis increased by 8° toward the NRR mean. Total change scores for VASp, RMDQ, and SF-12 PCS were significantly improved (≥30%). z Scores for this case indicated improvements toward zero (0), with the largest changes occurring in the directions of FwLSF, LSF, and RSF. The most symptomatic movement directions, extension causing LBP and RSF causing right lower limb pain, were both asymptomatic at the 14-week postoperative retest.

Case L: Fusion for Degenerative Disk Disease Causing Chronic Severe LBP

A 44-year-old woman presented with chronic LBP and intermittent lower limb pain (L > R) (Fig 7A). Lumbar flexion reproduced her LBP (VASp 4.3) and extension was reported as being very stiff (VASs 9.3). Combined movement examination outcome measures indicated that movement in the flexed directions (FwLSF, flexion, and FwRSF) and extended directions (EwLSF, extension, and EwRSF) were all significantly reduced ($z \leq -2.0$) (Figs 4 and 7D).

Magnetic resonance imaging indicated bilateral L5-S1 pars defect, grade I (10 mm) spondylolisthesis, severe stenosis of the bilateral L5-S1 intervertebral foramen, and left L5 nerve root impingement (Fig 7B and C). The patient underwent L5-S1 posterior decompression, discectomy, and interbody fusion.

Reassessment at 13 weeks indicated improvements in all flexed and extended CME directions (Fig 7D). Total change data (%) for self-reports at 13 weeks confirmed clinically significant improvements (≥30%) in RMDQ. Pain score in flexion was significantly improved; however, pain was

Table 1. *Summary Table Reporting Each Patient's Age, Key Imaging Features, Diagnosis, Neurosurgical Intervention, and Total Change Scores for Self-Reports*

Case	Age	Imaging	Specialist Diagnosis	Intervention	Key Outcome Measures and CME Directions
A	56	L2-3 left posterolateral IVD protrusion	Radiculopathy	Left L2-3 discectomy	VASp 95%, RMDQ 80%, LSF, EwLSF, extension
B	61	L4-5 left IVD protrusion compressing the exiting L4 nerve	Radiculopathy	Far lateral left L4-5 microdiscectomy	VASp 41%, 10° increase to LL
C	28	L5-S1 left IVD protrusion	Radiculopathy	Left L5-S1 discectomy	VASp 100%, VASs 76%, flexion
D	44	L5-S1 bilateral facet and foraminal narrowing. Probable impingement	Radiculopathy	L1-2 laminectomy and discectomy	VASs 31%
E	57	L3-4 left IVD protrusion and right L4-5 IVD protrusion	Radiculopathy	Right L4-5 microdiscectomy	Extension and EwRSF, 28° increase to LL
F	58	L4-5 facets and left L5-S1 facet degeneration and L2-3 right IVD protrusion	Radiculopathy and canal stenosis	Left L4-5 laminectomy and facetectomy	VASp 83%, VASs 44%, RMDQ 75%, flexion, LSF, RSF
G	41	L5-S1 right posterolateral IVD prolapse	Radiculopathy	Right L5-S1 microdiscectomy	VASp 37%, VASs 44%, FwLSF
H	42	L4-5 IVD prolapse	Radiculopathy	L4-5 laminectomy and bilateral microdiscectomy	VASp 83%, VASs 44%, RMDQ 79%, RSF, LSF
I	58	L5-S1 spondylolisthesis and bilateral L5 nerve root compression	Radiculopathy	Bilateral L5-S1 lateral recess decompression	VASp 54%, LSF
J	67	L4-5 facet arthropathy, DDD, and lateral recess stenosis	Radiculopathy	Bilateral L4-5 hemilaminectomy	SF-12 MCS 30%, LL 42°, extension, EwLSF, FwLSF
K	31	L4-5 disk protrusion and bilateral neural compression	LBP and radiculopathy	L4-5 laminectomy and bilateral microdiscectomy	VASp 50%, SF-12 MCS 32%, LSF
L	49	L4-5 DDD	DDD	L4-5 fusion	VASp 78%, VASs 83%, RMDQ 33%, flexion, LSF, RSF
M	44	L5-S1 spondylolisthesis with left nerve compression	DDD and radiculopathy	L5-S1 decompression and fusion	RMDQ 46%, 8° decrease in LL, flexion, extension
N	45	L5-S1 DDD and right neural foramen stenosis	DDD and radiculopathy	L5-S1 fusion	Extension, EwRSF, LSF, RSF
O	70	L4-5 degenerative spinal stenosis	Radiculopathy	L4-5 fusion	RMDQ 40%, 12° decrease in LL, flexion
P	51	L4-5 spondylolisthesis and severe bilateral facet degeneration	LBP and radiculopathy	L4-5 fusion	VASp 41%, 12° increase in LL, extended directions
Q	40	L4-5 IVD prolapse	LBP and radiculopathy	L4-5 decompression and fusion	VASp 67%, VASs 68%, RMDQ 75%, 7° decrease in LL

Table 1. (*continued*)

Case	Age	Imaging	Specialist Diagnosis	Intervention	Key Outcome Measures and CME Directions
R	64	L3-4 R > L radiculopathy	Radiculopathy	L3-4 laminectomy	LSF, FwLSF, FwRSF, 20° increase in LL

CME, combined movement examination; *DDD,* degenerative disk disease; *EwLSF,* extension with added left-side flexion; *EwRSF,* extension with added right-side flexion; *FwLSF,* flexion with added left-side flexion; *FwRSF,* flexion with added right-side flexion; *IVD,* intervertebral disk; *LBP,* low back pain; *LL,* lumbar lordosis; *LSF,* left-side flexion; *MCS,* mental component score; *RMDQ,* Roland-Morris Low Back Pain and Disability Questionnaire; *RSF,* right-side flexion; *SF-12,* Short Form health survey; *VASp,* visual analog scale for pain; *VASs,* visual analog scale for low back stiffness.

reported in EwLSF, causing isolated left-side LBP. Left lower limb pain had improved by 70%.

Discussion

In this preliminary study, we sought to investigate specific movement patterns for degenerative disk disease, disk protrusion, and nerve root compression using CME. Finally, we sought to determine if CME would converge toward the age- and sex-matched NRR after neurosurgical intervention for LBP.

Validated self-report questionnaires were used as additional outcome measures to identify change in pain, stiffness, health, and function. This also served as a measure of successful intervention, allowing improvements to be putatively attributed to specific structures, as well as consideration of CME patterns.

To investigate a hypothetical specific movement pattern, we attempted to control variables and focused on CME from those cases with imaging showing a single involved level and, where possible, single-structure changes. Six cases were selected for this purpose, including 2 unilateral discectomies (cases A, B), 2 bilateral discectomies (cases H, J), and 2 fusion cases (cases L, M). Discerning how single-structure pathologic conditions affect CME ROM may confer some insight into more complex multilevel and multistructure cases.

The 2 unilateral discectomy patients presented before surgery with lumbar lordoses of 16° and 29° less than their respective NRR means. This measure is not depicted in the CME radial plots and should be considered when interpreting ROM changes because the starting position will always present as the center of a radial plot [0,0] (Fig 1), despite differences in lumbar lordosis between patients and if lordosis changes as a result of surgical intervention. Before surgery, z scores for case A in extension, EwLSF, and LSF were all <–2.0. All other CME directions were within 1 SD of the NRR mean. At 14 weeks postoperatively, extension, EwLSF, and LSF ROM had increased and were 1 SD closer to the NRR mean. In case B, the CME radial plot appeared relatively normal in the extended directions compared with the NRR; however, before surgery the patient's lumbar lordosis was 3°, compared with the respective NRR mean of 32°. With an additional 10° recorded during CME extension, total lumbar extension before surgery was 13°. In this case, standing lumbar lordosis increased by 10° at the 14-week retest, with an additional 21° of active ROM extension, resulting in total lumbar extension of 31°.

In case A, the reduced ROM on the left side, illustrated in the CME plot (Fig 5D), was putatively attributed to left side L2-3 posterolateral disk protrusion. The majority of the patient's pain was in the region of the anterolateral hip. After surgery, the patient reported immediate relief of hip symptoms and the ability to stand straight. Preoperative vs postoperative CME indicated a 14° increase in standing lordosis, with a postoperative lordosis equal to the NRR mean lordosis value of 36°.

Further studies with larger numbers of surgical cases would be required to test for clinically meaningful changes in lordosis, for comparison with CME radial plots. Figure 8A illustrates a proposed CME pattern for painful posterolateral disk protrusion and/or radiculopathy, which may cause LBP and/or ipsilateral lower limb symptoms, respectively.

In the 2 bilateral posterior decompression patients (cases H and J), preoperative lordosis was less than one-third that of their NRR mean, with increases in lordosis of 8° and 30° at the 14-week retest, respectively. Once again, the CME plot did not indicate the effects of the lordosis change on ROM; however, when factoring in the increased lordosis between trials, the total amount of lumbar extension increased in both cases.

In case H, a large central posterior disk protrusion had resulted in mild LBP, severe lower limb pain, and decreased ROM in all extended CME movement directions, with pain relief in the flexed directions. Preoperative CME radial plot indicated large restrictions in side-flexed and extended CME directions, which were also the most symptomatic movement directions. Postoperatively, there was no lower limb pain, and LBP was low (VASp = 0.6) during CME.

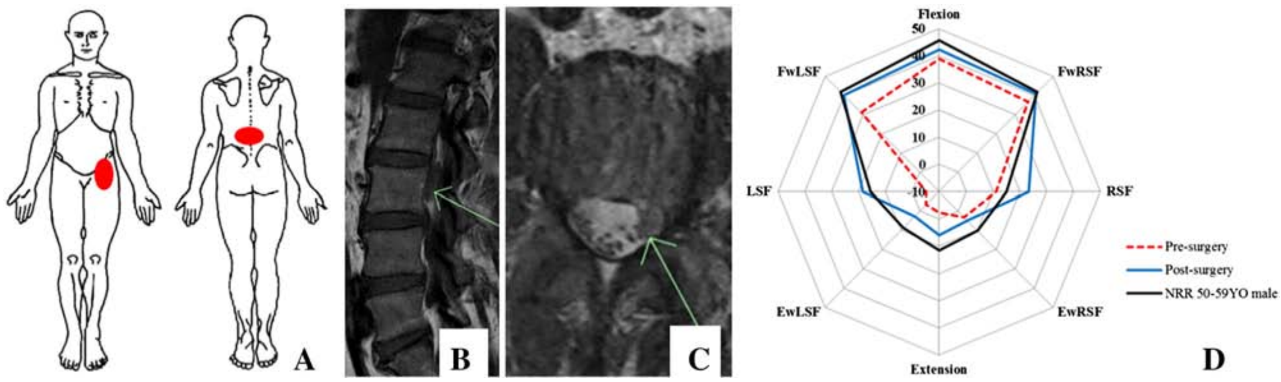

Fig 5. *Case A's pain diagram illustrating the area of hip and low back pain (red) (A). Magnetic resonance images showing sequestrated disk material (green arrow) (B) and left posterolateral disk protrusion (green arrow) (C). Combined movement examination radial plot illustrating decreased LSF, EwLSF, and extension preoperatively, with range of motion increases in LSF, EwLSF, and extension postoperatively (D).* CME, *combined movement examination;* EwLSF, *extension with left-side flexion;* EwRSF, *extension with right-side flexion;* FwLSF, *flexion with left-side flexion;* FwRSF, *flexion with right-side flexion;* LSF, *left-side flexion;* NRR, *normal reference range;* RSF, *right-side flexion.*

Figure 8B illustrates a proposed CME movement pattern for a painful central disk protrusion and/or bilateral nerve root compression causing LBP and/or bilateral lower limb symptoms, respectively.

Modest improvements were observed in the 2 fusion cases (L and M) and 2 factors are likely to contribute to this observation. Segmental fusion results in a global reduction in available range. Second, pain was decreased, therefore allowing the patient to move easier in all directions, resulting in a more symmetrical CME radial plot postoperatively (Fig 7D). In case M, the post-surgery trial indicated a 5° increase in lordosis and increased ROM by greater than 1 SD of the NRR mean in EwLSF and EwRSF. Postoperative CME for case L indicated larger increases in ROM, with an average z score increase, toward their respective NRR mean of 1.1 in the flexed and extended directions.

In case L, the L5-S1 IVD is loaded and deformed in multiple movement directions.[27] During active movement, loading in the 8 cardinal directions of CME, this may trigger mechanical nociceptors within a sensitized annulus fibrosus.[28,29] This global reduction in CME, with z scores ≤–2.5 in flexion and extension, has been identified as a common presentation during our treatment of patients receiving pain specialist epidural injection or fusion surgery for related IVD pathologic conditions.[30]

In the majority of the fusion cases, it was noted that CME had globally reduced ROM. Figure 8C illustrates a proposed CME pattern for a painful degenerative disk that indicates a post-procedure global reduction of movement in all CME directions.

Although preliminary evidence for CME pain patterns is presented, additional surgical cases are required to verify these initial trends that reflect the subgrouping described. The inclusion criteria for this descriptive study did not specify single-level, single-structure patients. As a preliminary investigation of lumbar CME in cases with mechanical LBP, all presentations satisfying our limited inclusion criteria were investigated for the purpose of informing future hypotheses and lumbar CME research.

The secondary aim, to identify if all patients' CME would converge toward their respective NRR values was not confirmed in 7 of the 18 cases. A clinically significant change in ROM (>30%) was not evident in 5 cases of discectomy and 2 cases of fusion. Reasons for this include the regression of the patient's condition; postoperative complications; large changes in lordosis between trials; multiple segment pathologic conditions and/or untreated structures at the level of discectomy, such as degenerative facet joints; and decreased ROM as a result of fusion surgery, fear avoidance, and hypervigilance. However, it should be noted that almost two-thirds of patients improved toward their respective NRR values for CME. A longer-term follow-up would assist in testing whether CME patterns improve further, apart from fusion cases.

Spinopelvic alignment, including lumbar lordosis and pelvic incidence, is an important factor to consider when attempting achieving sagittal balance and should be considered when comparing preoperative and postoperative CME radial plots. Small changes in alignment have been reported to result in large increases in facet compressive loads and large stress peaks in the posterior annulus of the IVD.[31] Mehta et al[32] reported that reduced lumbar lordosis is associated with pain, sagittal imbalance, and poor surgery outcomes, whereas Sorensen et al[33] reported lumbar lordosis was greater in patients with LBP, compared with asymptomatic patients, further confirmation that spinopelvic alignment is a balancing act. Changes in lumbar lordosis are a recognized, important factor to consider when measuring lumbar CME given the influence of lordosis on sagittal balance, spinal kinematics, and lumbar spine pathologic conditions.

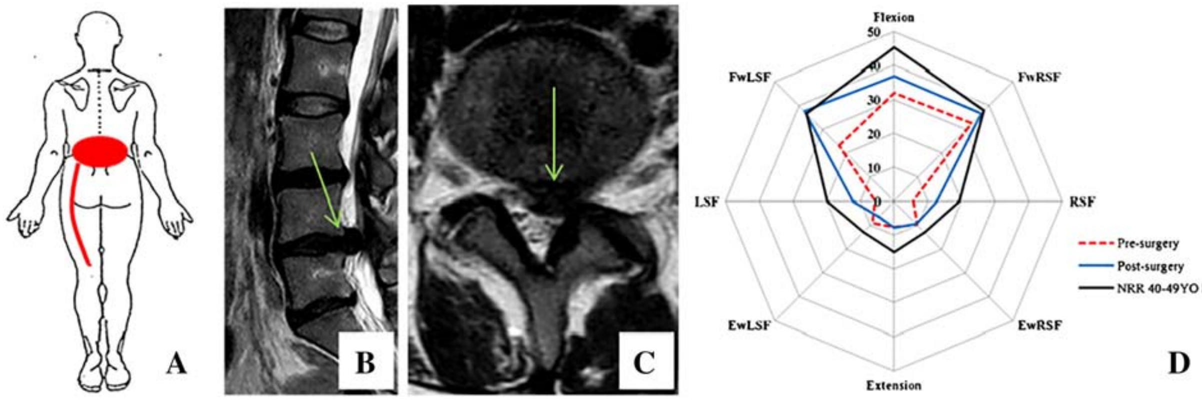

Fig 6. *Case H's pain diagram illustrating the area of low back pain, intermittent left lower limb pain (red) (A). Sagittal section magnetic resonance imaging showing posterior disk protrusion (green arrow) (B) and axial L4-5, left paracentral disk protrusion (green arrow) (C). Computer-aided CME radial plot illustrating most restricted movement preoperatively in the direction of RSF, EwRSF, extension, EwLSF, LSF, and FwLSF; marked change in FwLSF, LSF, and RSF at final retest; and an age- (40-49) and sex-matched NRR (D).* CME, *combined movement examination;* EwLSF, *extension with left-side flexion;* EwRSF, *extension with right-side flexion;* FwLSF, *flexion with left-side flexion;* FwRSF, *flexion with right-side flexion;* LSF, *left-side flexion;* NRR, *normal reference range;* RSF, *right-side flexion.*

Future research, with larger numbers of cases per pathoanatomic diagnosis—namely, IVD disease, disk protrusion, and nerve root compression—would be required to test the preliminary evidence reported in this study.

Limitations and Future Studies

These preliminary results must be reviewed within the limitations of the study. The first limitation is that CME is not a level-specific movement analysis. Combined movement examination is a global indication of L1 to S1 movement. Additional sensors would be required to measure intersegmental movement.[34] The second is the sample size. This cohort investigation was designed to generate hypotheses based on the possibility of movement signatures related to specific pathologic conditions, and as such, no formal power calculations were performed. Third, this was an observational study that examined routine neurosurgical intervention and therefore was not designed to assess the efficacy of the surgical interventions planned for each case.

Further studies with larger sample sizes of single-level, single-structure cases are required to investigate

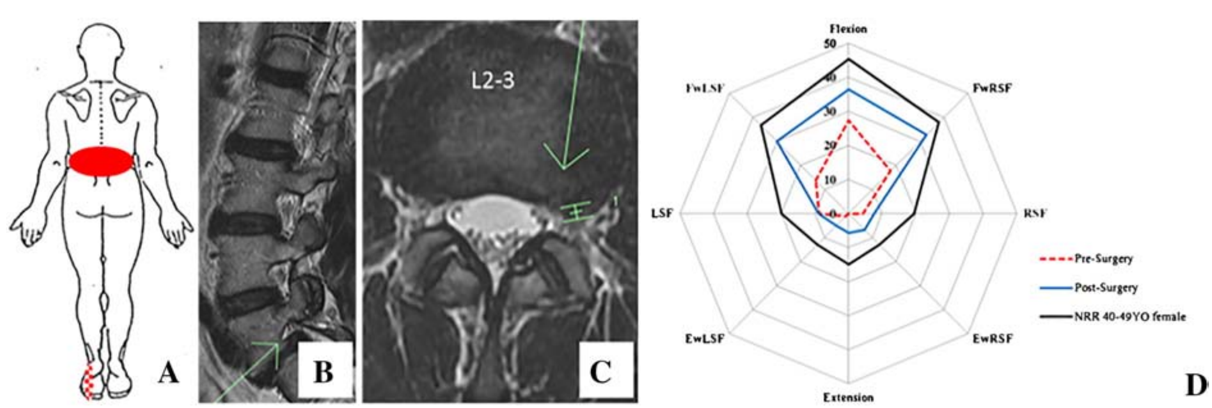

Fig 7. *Case L's pain diagram illustrating the area of low back pain (red) (A). Sagittal magnetic resonance images showing L5-S1 spondylolisthesis (B) narrowing at the left L2-3 intervertebral foramen (C). Combined movement examination radial plot with global increased movement after L5-S1 fusion surgery (D). Note that there is no change to LSF postoperatively. This is attributed to the unchanged L2-3 pathologic condition.* CME, *combined movement examination;* EwLSF, *extension with left-side flexion;* EwRSF, *extension with right-side flexion;* FwLSF, *flexion with left-side flexion;* FwRSF, *flexion with right-side flexion;* LSF, *left-side flexion;* NRR, *normal reference range;* RSF, *right-side flexion.*

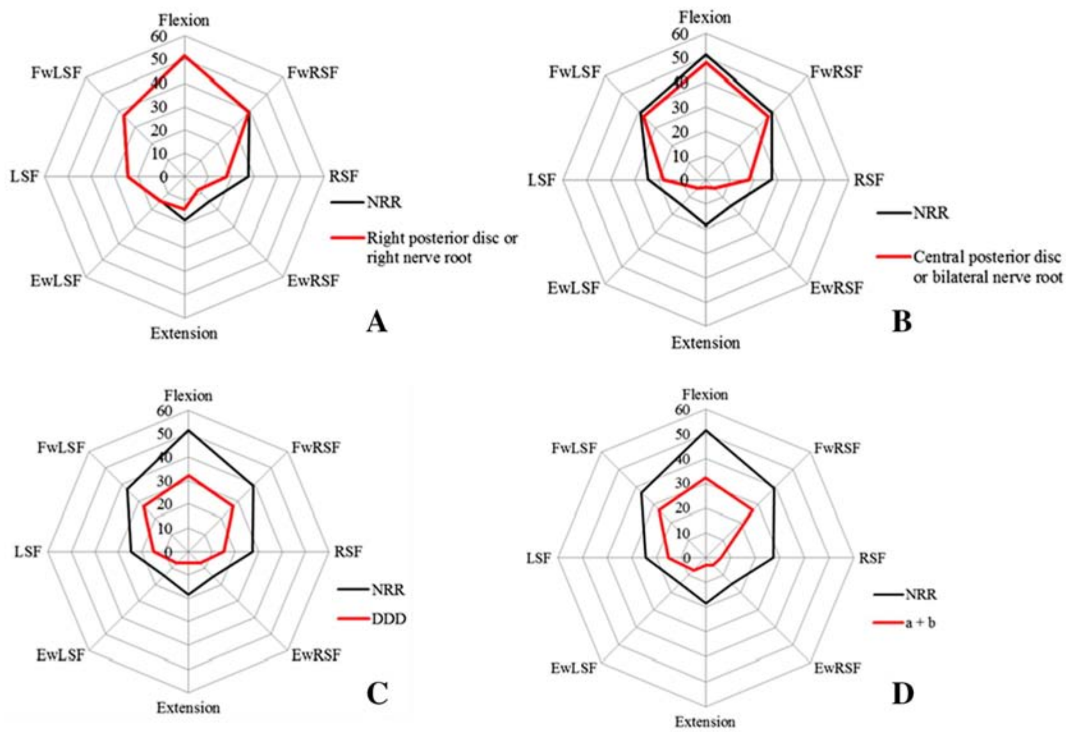

Fig 8. *Example radial plots of 4 common CME presentations identified in this study. Right-side posterolateral disk or nerve root disease causing right-side low back pain or right-side radiculopathy as a result of IVF stenosis (A), central posterior disk protrusion and/or central canal or bilateral IVF stenosis, causing low back pain and/or bilateral lower limb symptoms, respectively (B), symptomatic degenerative disk disease, without protrusion (C), and multistructure pathologic conditions such as degenerative disk disease and right side posterolateral disk protrusion (D).* CME, *combined movement examination;* EwLSF, *extension with left-side flexion;* EwRSF, *extension with right-side flexion;* FwLSF, *flexion with left-side flexion;* FwRSF, *flexion with right-side flexion;* IVF, *intervertebral foramen;* LSF, *left-side flexion;* NRR, *normal reference range;* RSF, *right-side flexion.*

CME-specific movement signatures and MCID outcome parameters. Further investigation is also warranted in patients who have no change with CME after intervention. Reasons for no immediate or short-term change may include multilevel pathologic condition, movement adaptations, and pain being confounded by dominant psychosocial issues[35] or comorbidities.

Conclusion

This preliminary study reports the novel utility in using CME and self-report data compared with an age- and sex-matched NRR to investigate mechanical LBP. Specific CME movement signatures for IVD pain, unilateral posterolateral disk protrusion and/or unilateral nerve root compression, and central disk protrusion and/or bilateral nerve root compression are proposed. In almost two-thirds of cases, postoperative CME was reported to converge toward the NRR. The remaining patients all had complications that may have mitigated this outcome.

Funding Sources and Potential Conflicts of Interest

There were no sources of funding or conflicts of interest associated with this research.

Contributorship Information

Concept development (provided idea for the research): C.R.P.L, K.P.S.

Design (planned the methods to generate the results): A.P.M., R.I.P., C.R.P.L., K.P.S.

Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): A.P.M., R.I.P., C.R.P.L., K.P.S.

Data collection/processing (responsible for experiments, patient management, organization, or reporting data): A.P.M.

Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): A.P.M., R.I.P., K.P.S.

Literature search (performed the literature search): A.P.M.

Writing (responsible for writing a substantive part of the manuscript): A.P.M.

Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): A.P.M., C.R.P.L, K.P.S.

Practical Applications

- Combined movement examination may be used as an objective outcome measure for patients with LBP.
- Combined movement examination patterns may exist for lumbar disk disease, disk protrusion, and nerve root compression.
- Specific CME patterns may assist with diagnosis and treatment of patients with LBP.

References

1. Hoy D, Bain C, Williams G, et al. A systematic review of the global prevalence of low back pain. *Arthritis Rheum.* 2012; 64(6):2028-2037.
2. Joud A, Petersson IF, Englund M. Low back pain: epidemiology of consultations. *Arthritis Care Res.* 2012; 64(7):1084-1088.
3. Hancock M, Maher C, Laslett M, Hay E, Koes B. Discussion paper: what happened to the 'bio' in the bio-psycho-social model of low back pain? *Eur Spine J.* 2011;20(12): 2105-2110.
4. Mieritz RM, Bronfort G, Kawchuk G, Breen A, Hartvigsen J. Reliability and measurement error of 3-dimensional regional lumbar motion measures: a systematic review. *J Manipulative Physiol Ther.* 2012;35(8):645-656.
5. Bogduk N, Aprill C, Derby R. Lumbar discogenic pain: state-of-the-art review. *Pain Med.* 2013;14(6):813-836.
6. Biyani A, Andersson GBJ. Low back pain: pathophysiology and management. *J Am Acad Orthop Surg.* 2004;12(2): 106-115.
7. Laplante BL, Ketchum JM, Saullo TR, DePalma MJ. Multivariable analysis of the relationship between pain referral patterns and the source of chronic low back pain. *Pain Physician.* 2012;15(2):171-178.
8. Germon TJ, Hobart JC. Definitions, diagnosis, and decompression in spinal surgery: problems and solution. *Spine J.* 2015;15(3 Suppl):S5-S8.
9. DePalma MJ, Ketchum JM, Saullo T. What is the source of chronic low back pain and does age play a role? *Pain Med.* 2011;12(2):224-233.
10. Littlewood C, May S. Measurement of range of movement in the lumbar spine—what methods are valid? A systematic review. *Physiotherapy.* 2007;93(3):201-211.
11. Bible JE, Biswas D, Miller CP, Whang PG, Grauer JN. Normal functional range of motion of the lumbar spine during 15 activities of daily living. *J Spinal Disord Tech.* 2010;23(2):106-112.
12. Burton AK. Regional lumbar sagittal mobility—measurement by flexicurves. *Clin Biomechanics.* 1986;1(1):20-26.
13. Lee BW, Lee JE, Lee SH, Kwon HK. Kinematic analysis of the lumbar spine by digital videofluoroscopy in 18 asymptomatic subjects and 9 patients with herniated nucleus pulposus. *J Manipulative Physiol Ther.* 2011;34(4):221-230.
14. Ha T-H, Saber-Sheikh K, Moore AP, Jones MP. Measurement of lumbar spine range of movement and coupled motion using inertial sensors—a protocol validity study. *Man Ther.* 2013;18(1):87-91.
15. Edwards B. Combined movements of the lumbar spine: examination and clinical significance. *Aust J Physiother.* 1979;25(4):147-152.
16. Monie AP, Barrett CJ, Price RI, Lind CRP, Singer KP. Computer-aided combined movement examination of the lumbar spine and manual therapy implications: case report. *Man Ther.* 2016;21:297-302.
17. Barrett CJ, Singer KP, Day R. Assessment of combined movements of the lumbar spine in asymptomatic and low back pain subjects using a three-dimensional electromagnetic tracking system. *Man Ther.* 1999;4(2):94-99.
18. Maitland GD. *Vertebral Manipulation*. 5th ed. Oxford, UK: Butterworth Heinemann; 1997.
19. Haswell K, Williams M, Hing W. Interexaminer reliability of symptom-provoking active sidebend, rotation and combined movement assessments of patients with low back pain. *J Man Manipulative Ther.* 2004;12(1):11-20.
20. Monie AP, Price RI, Lind CRP, Singer KP. Assessing the clinical utility of combined movement examination in symptomatic degenerative lumbar spondylosis. *Clin Biomechanics.* 2015;30(6):558-564.
21. Chiarotto A, Deyo RA, Terwee CB, et al. Core outcome domains for clinical trials in non-specific low back pain. *Eur Spine J.* 2015;24(6):1127-1142.
22. Johnson C. Measuring pain. Visual analog scale versus numeric pain scale: what is the difference? *J Chiropr Med.* 2005;4(1):43-44.
23. Hart RA, Gundle KR, Pro SL, Marshall LM. Lumbar Stiffness Disability Index: pilot testing of consistency, reliability, and validity. *Spine J.* 2013;13(2):157-161.
24. Ostelo RWJG, Deyo RA, Stratford P, et al. Interpreting change scores for pain and functional status in low back pain—towards international consensus regarding minimal important change. *Spine.* 2008;33(1):90-94.
25. Bonnick SL, Lewis LA. *Bone Densitometry for Technologists*. 3rd ed. New York, NY: Springer; 2013.
26. Laslett M. Manual correction of an acute lumbar lateral shift: maintenance of correction and rehabilitation: a case report with video. *J Man Manip Ther.* 2009;17(2):78-85.
27. Zou J, Yang HL, Miyazaki M, et al. Dynamic bulging of intervertebral discs in the degenerative lumbar spine. *Spine.* 2009;34(23):2545-2550.
28. Coppes MH, Marani E, Thomeer RTWM, Groen GJ. Innervation of "painful" lumbar discs. *Spine.* 1997;22(20):2342-2349.
29. Brisby H. Pathology and possible mechanisms of nervous system response to disc degeneration. *J Bone Joint Surg Am.* 2006;88(suppl 2):68-71.
30. Monie AP, Price RI, Lind CRP, Singer KP. Structure specific movement patterns in patients with chronic low back dysfunction using lumbar combined movement examination. *J Man Physiol Therapeutics.* 2017;40(5):340-349.
31. Adams MA, Hutton WC. The effect of posture on the role of the apophysial joints in resisting intervertebral compressive forces. *J Bone Joint Surg Br.* 1980;62(3):358-362.

32. Mehta VA, Amin A, Omeis I, Gokaslan ZL, Gottfried ON. Implications of spinopelvic alignment for the spine surgeon. *Neurosurgery.* 2015;76(suppl 1):S42-S56.
33. Sorensen CJ, Norton BJ, Callaghan JP, Hwang C-T, Van Dillen LR. Is lumbar lordosis related to low back pain development during prolonged standing? *Man Ther.* 2015;20:553-557.
34. Alqhtani RS, Jones MD, Theobald PS, Williams JM. Reliability of an accelerometer-based system for quantifying multiregional spinal range of motion. *J Manipulative Physiol Ther.* 2015;38(4):275-281.
35. Deyo RA. Biopsychosocial care for chronic back pain. *BMJ.* 2015;350:h538.