Clinical Biomechanics 30 (2015) 558–564

Contents lists available at ScienceDirect

Clinical Biomechanics

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

Assessing the clinical utility of combined movement examination in symptomatic degenerative lumbar spondylosis

A.P. Monie [a,*], R.I. Price [a,b], C.R.P. Lind [a,c], K.P. Singer [a]

[a] Centre for Musculoskeletal Studies, School of Surgery, The University of Western Australia, Perth, Western Australia 6009, Australia
[b] Department of Medical Technology and Physics, Sir Charles Gairdner Hospital, Perth, Western Australia 6000, Australia
[c] Department of Neurosurgery, Sir Charles Gairdner Hospital, Perth, Western Australia 6000, Australia

ARTICLE INFO

Article history:
Received 13 August 2014
Accepted 8 April 2015

Keywords:
Lumbar spine
Combined movement examination
Angular movement
Disc prolapse
Surgery

ABSTRACT

Objectives: The aim of this study is to report the development and validation of a low back computer-aided combined movement examination protocol in normal individuals and record treatment outcomes of cases with symptomatic degenerative lumbar spondylosis.
Design: Test–retest, following intervention.
Background: Self-report assessments and combined movement examination were used to record composite spinal motion, before and following neurosurgical and pain medicine interventions.
Methods: 151 normal individuals aged from 20 years to 69 years were assessed using combined movement examination between L1 and S1 spinal levels to establish a reference range. Cases with degenerative low back pain and sciatica were assessed before and after therapeutic interventions with combined movement examination and a battery of self-report pain and disability questionnaires. Change scores for combined movement examination and all outcome measures were derived.
Findings: Computer-aided combined movement examination validation and intraclass correlation coefficient with 95% confidence interval and least significant change scores indicated acceptable reliability of combined movement examination when recording lumbar movement in normal subjects. In both clinical cases lumbar spine movement restrictions corresponded with self-report scores for pain and disability. Post-intervention outcomes all showed significant improvement, particularly in the most restricted combined movement examination direction.
Interpretation: This study provides normative reference data for combined movement examination that may inform future clinical studies of the technique as a convenient objective surrogate for important clinical outcomes in lumbar degenerative spondylosis. It can be used with good reliability, may be well tolerated by individuals in pain and appears to change in concert with validated measures of lumbar spinal pain, functional limitation and quality of life.

1. Introduction

Pragmatic treatment of patients with low back pain (LBP) and associated movement dysfunction is based upon an appreciation of the history of the patient's complaint and interpretation of the examination findings (Maitland, 1997). Assessing lumbar spine movement in the clinical setting to investigate dysfunction and to monitor changes in spinal movement characteristics of individuals over time, is routine clinical practice (Ha et al., 2013; Laird et al., 2014; Lyle et al., 2005; Maitland, 1997). Single plane movements are often unrepresentative of the actual movements of the lumbar spine, so have limited value in assessing lumbar function (Pearcy and Hindle, 1989). However, one examination method, originally described by Edwards (1979), which assesses both planar and combined plane (physiological) positions, is the combined movement examination (CME). The CME sequentially examines the patient's ability to actively side-flex the lumbar spine while in a flexed, neutral and extended position (Fig. 1).

Edwards (1979) and Maitland (1997) suggested that CME may be more informative than the standard planar spinal assessment, which was confirmed by Barrett et al. (1999) who reported acceptable CME intra-examiner reliability, as well as preliminary evidence concerning the effectiveness of CME in identifying reduced lumbar mobility in low back pain (LBP) subjects. In their work Barrett et al. used 3-D tracking to map the characteristics of the lumbar CME. To our knowledge, no other study has reported the putative use of lumbar CME in clinical practice using a computer-aided methodology to quantify movement

* Corresponding author at: Centre for Musculoskeletal Studies, School of Surgery M424, The University of Western Australia, Crawley, WA 6009, Australia.
E-mail address: aubrey.monie@research.uwa.edu.au (A.P. Monie).

http://dx.doi.org/10.1016/j.clinbiomech.2015.04.004
0268-0033/

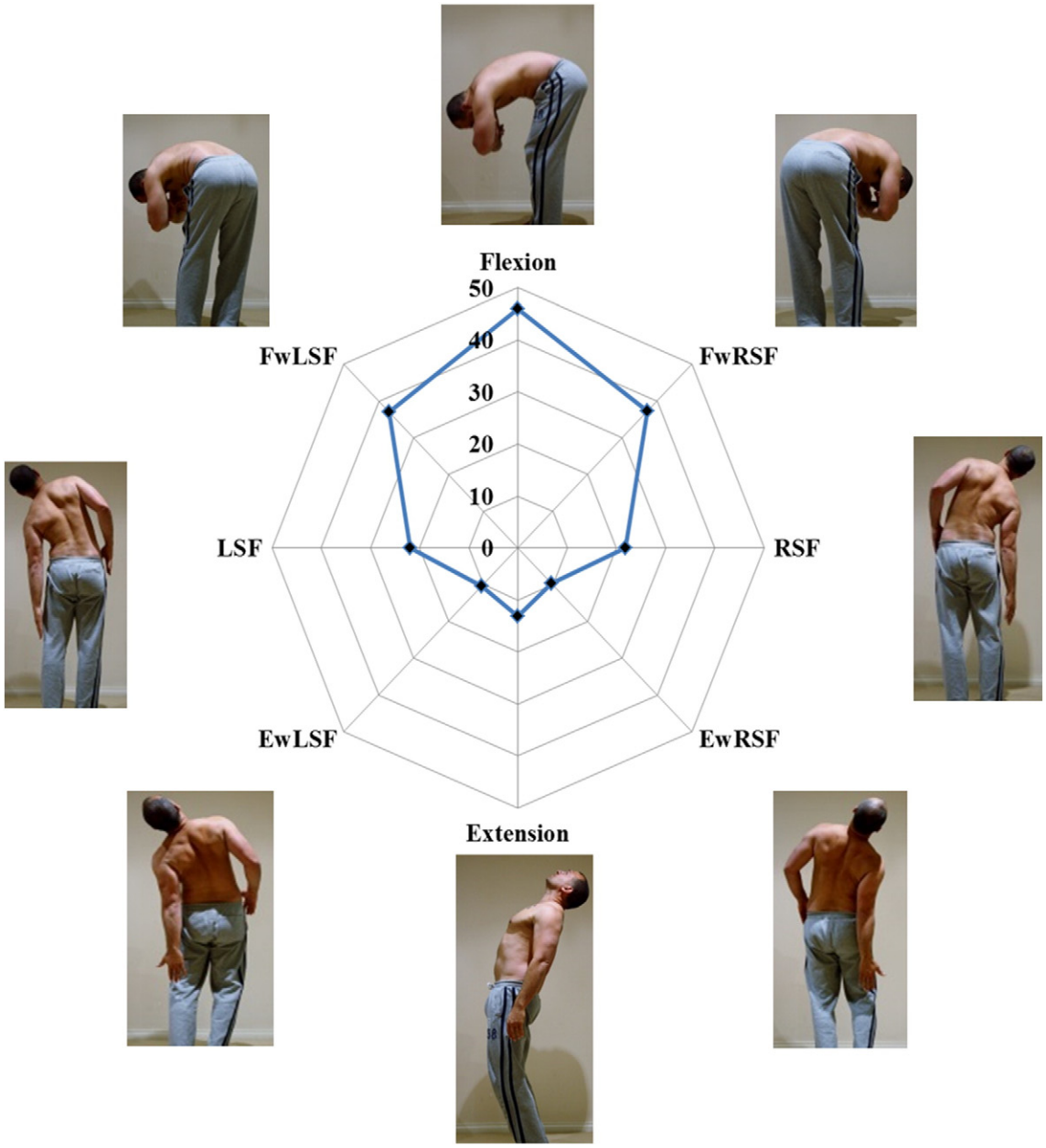

Fig. 1. Example of a healthy volunteer's Combined Movement Examination (CME) radial plot (in degrees of angular movement). Photographs in this figure illustrate the movement directions and end-points. Flexion with Left Side-Flexion (FwLSF), Flexion with Right Side-Flexion (FwRSF), Left Side-Flexion (LSF), Right Side-Flexion (RSF), Extension with Left Side-Flexion (EwLSF) and Extension with Right Side-Flexion (EwRSF).

patterns. Fig. 1 illustrates the eight low back positions of a lumbar CME and an example radial plot of a healthy volunteer, showing the symmetrical end-points (maximal angular movement) achieved.

The purpose of this paper is to report the intra- and inter-session reliability of lumbar CME using a validated MotionStar™ 3-D motion tracking system (Ascension Technology, VT, USA) (Fig. 2A) using custom software (LabVIEW V5.0, National Instruments, Austin USA). Secondly, to describe the development of a normal reference range (NRR) and subsequently to report proof of concept of CME as a tool to assess specific spinal pathology and monitor changes post-intervention. A CME NRR was developed to identify abnormal patterns, observe normalisation of CME post-intervention and compare the age and gender matched functional outcomes of two cases with different lumbar spine pathologies. It is not the intention of this paper to report clinical studies which did not use an objective quantification of lumbar spine movement.

2. Methods

2.1 . Validation of a non-invasive 3-D motion tracking system

A MotionStar™ 3-D motion tracking system was tested in our laboratory against a custom made triaxial goniometer to test consistency over time (Fig. 2A). Angular displacement of the sensors was calculated by the system, using Euler's method. Results demonstrated that the MotionStar™ is capable of reliably measuring angular movement with an intrinsic precision of 0.6°.

2.2 . CME data collection

After obtaining written consent and familiarisation of equipment and testing sequence, two skin mounted MotionStar™ sensors were placed over the volunteer's S1 and L1 spinous process, respectively.

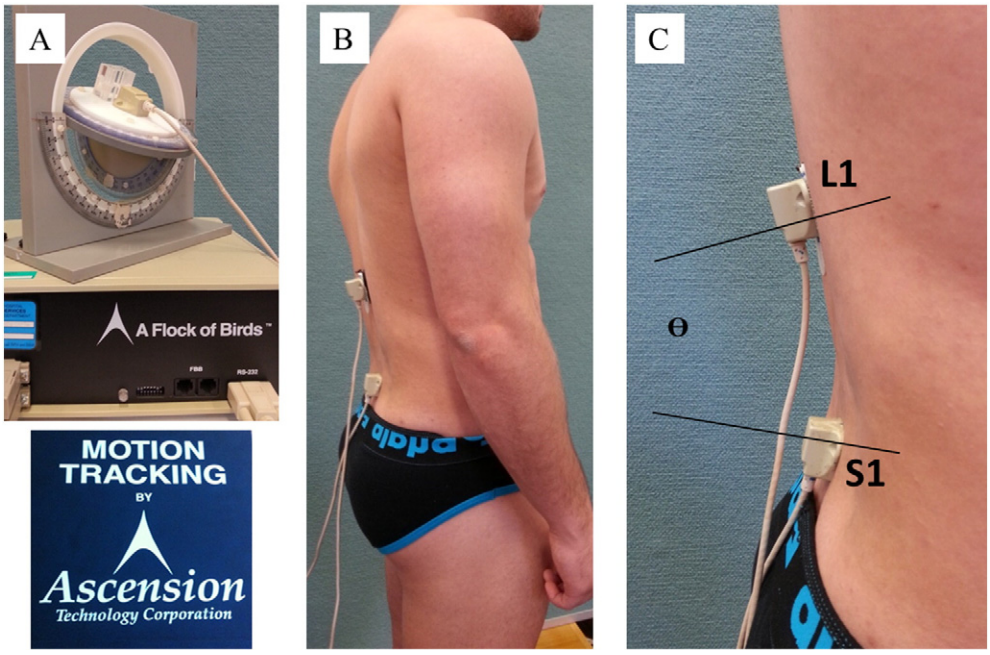

Fig. 2. The MotionStar™ system, with a motion tracking sensor mounted on tri-planar goniometer (A), example of sensor placement over L1 and S1 levels (B), and illustration to show how lordosis and angle of movement are calculated (C).

Skin marking and sensor mounting over the L1 landmark were performed while the patient maintained a partially flexed lumbar spine position in standing, with their hands on their knees. This made palpation of the L1 level easier and pre-stretched the skin under the sensor's double-sided tape, improving adhesion. In a relaxed standing position, all volunteers had their lumbar lordosis (angle between L1 and S1) recorded (Fig. 2B). This became their 'zeroed' starting position (centre of radial plot) (Fig. 1). The patient was then instructed to move within their comfortable limits during the CME while the MotionStar™ system acquired data and stored to disc at a rate of 50 Hz. Trial data were batch processed using a Butterworth 4th order, low pass (cf 4 Hz) filter, to remove high frequency (non-biological) noise. Maximum data values for each of the eight CME movement directions were recorded according to a pre-defined sequence: Flexion (Flex), Flexion with Left Side-Flexion (FwLSF), Flexion with Right Side-Flexion (FwRSF), Left Side-Flexion (LSF), Right Side-Flexion (RSF), Extension (Ext), Extension with Left Side-Flexion (EwLSF) and Extension with Right Side-Flexion (EwRSF).

A pilot study, comparing various CME sequences was trialled, with the current format producing the most consistent data with the least discomfort. Intra-session reliability studies involving ten normal volunteers indicated that there was no warm-up or fatigue effect over 5 repeated trials. For this reason, after a familiarisation trial, a single data collection was used on each subsequent test session.

2.3 . Reliability of computer-aided combined movement examination

Combined movement examination reliability data were assessed with intraclass correlation coefficients (ICC) and 95% confidence intervals for the five intra-session ($n = 10$) and five inter-session ($n = 10$) trials. In addition, the least significant change (LSC) method (Bonnick and Lewis, 2013) was used to represent variance of the CME outcomes. Data confirmed acceptable reliability for all eight CME movement directions (Table 1).

2.4 . Development of a normal reference range

MotionStar™ derived CME data was captured to develop a NRR ($n \geq 7$ for each decade of life and gender) for which a convenience sample of 151 asymptomatic participants was used. Volunteers were included in this study if they were aged between 20 and 69 years, had no previous spinal intervention, had no significant episode of low back pain requiring treatment in the previous 6 months, were able to follow verbal instructions and had a BMI ≤ 30. The NRR is displayed in Table 2.

2.5 . Examination of two cases of low back pain

Case A was a 53 year old male who presented with an antalgic gait, mild LBP and severe, acute anterolateral hip pain (VAS 9.7/10). Magnetic resonance (MR) imaging demonstrated a large left disc extrusion at the L2–3 level, with inferior sequestration of disc material resulting in impingement on the left L3 nerve (Fig. 3A, B). A discectomy was performed and post-operative assessments (self-reports and CME) recorded.

Case B was a 62 year old female who presented with chronic, intermittent medial shin pain aggravated by lumbar extension. Computerised tomography (CT) identified a hypertrophic L4–5 facet joint impinging on the L4 nerve root with associated L4 exit foramen stenosis (Fig. 4A, B).

Table 1
Intraclass correlation coefficient (ICC) and 95% confidence interval ICC and least significant change (LSC) values for each movement direction of lumbar spine combined movement examination (CME), examined using 10 cases with 5 trials performed for both intra-session and inter-session cohorts.

Position	Intra-session			Inter-session		
	$ICC_{3,1}$	95% CI	LSC	$ICC_{3,1}$	95% CI	LSC
Flexion	0.92	(0.85–0.98)	5.2	0.92	(0.83–0.98)	6.4
FwRSF	0.93	(0.85–0.98)	6.6	0.86	(0.70–0.95)	7.4
RSF	0.94	(0.86–0.98)	6.9	0.90	(0.78–0.97)	8.0
EwRSF	0.95	(0.88–0.98)	5.0	0.71	(0.47–0.90)	9.0
Extension	0.95	(0.88–0.98)	4.5	0.78	(0.57–0.93)	6.7
EwLSF	0.95	(0.89–0.99)	5.0	0.74	(0.51–0.91)	7.4
LSF	0.92	(0.83–0.98)	5.3	0.82	(0.63–0.94)	9.1
FwLSF	0.94	(0.86–0.98)	7.0	0.93	(0.85–0.98)	7.0

Least significant change (LSC) in degrees calculated at $p < 0.05$ and 1 measurement per inter-session visit.

Table 2
Combined movement examination normal reference range for males and females aged 20 to 69 years of age. The mean, standard deviation and range for standing lordosis, BMI and each movement direction for males and females.

Gender	Age	n=	Statistic	BMI	Lordosis	Flexion	FwRSF	RSF	EwRSF	Extension	EwLSF	LSF	FwLSF
Male	20–29	17	Mean (SD)	24.3 (2.3)	26.4 (8.1)	48.7 (5.9)	41.6 (8.2)	29.0 (8.9)	15.7 (7.6)	19.0 (7.1)	16.3 (7.6)	25.6 (8.2)	40.5 (7.3)
			Range	7.2	28.4	21.4	33.8	33.8	21.7	25.3	28.9	27.3	26.7
	30–39	15	Mean (SD)	25.7 (2.9)	26.9 (7.9)	46.4 (5.5)	39.5 (8.9)	27.3 (11.0)	12.7 (6.2)	15.6 (5.5)	12.3 (5.4)	22.4 (7.8)	38.8 (8.1)
			Range	9.4	23.3	15.9	28.7	36.7	23.3	19.8	21.8	26.6	24.0
	40–49	7	Mean (SD)	26.9 (2.5)	33.1 (9.8)	45.4 (7.3)	37.2 (9.7)	24.4 (7.1)	8.1 (5.3)	12.2 (6.0)	8.8 (4.8)	23.3 (7.9)	36.8 (8.6)
			Range	7.6	31.9	19.5	25.0	21.5	13.4	18.0	11.0	23.7	28.4
	50–59	7	Mean (SD)	25.5 (3.4)	32.8 (5.6)	43.0 (7.0)	39.1 (7.4)	17.5 (7.8)	11.6 (8.0)	13.3 (5.0)	10.7 (5.8)	13.7 (6.5)	37.9 (8.9)
			Range	9.6	16.5	19.5	21.4	25.2	20.5	12.9	16.7	17.8	23.7
	60–69	12	Mean (SD)	25.6 (2.4)	31.4 (8.1)	41.1 (9.1)	34.9 (11.6)	18.6 (6.8)	10.2 (3.3)	12.9 (4.7)	11.6 (4.8)	15.5 (5.8)	33.5 (10.5)
			Range	7.0	22.0	25.9	34.2	21.8	10.5	15.3	16.8	19.7	32.2
Female	20–29	26	Mean (SD)	21.6 (2.5)	34.0 (5.9)	51.3 (9.5)	39.1 (9.6)	27.5 (10.0)	15.0 (5.5)	18.4 (5.6)	14.7 (4.5)	24.4 (8.5)	37.0 (11.1)
			Range	11.3	22.1	41.8	46.0	37.1	21.9	26.5	18.3	36.0	51.2
	30–39	23	Mean (SD)	22.5 (2.9)	32.2 (7.3)	49.3 (5.4)	38.2 (7.8)	24.6 (9.9)	13.4 (4.9)	16.3 (5.1)	13.9 (4.7)	22.6 (9.2)	40.5 (7.3)
			Range	11.7	26.0	21.7	26.7	37.8	17.8	16.2	17.9	38.8	28.7
	40–49	13	Mean (SD)	23.0 (2.9)	36.3 (9.3)	46.5 (6.5)	37.2 (7.4)	17.2 (8.7)	13.0 (7.3)	15.7 (6.2)	13.6 (5.7)	19.3 (6.1)	37.1 (6.9)
			Range	11.1	25.3	19.9	29.8	30.4	23.6	21.0	17.6	19.1	19.2
	50–59	19	Mean (SD)	22.8 (2.0)	33.6 (8.5)	40.0 (10.5)	31.5 (10.8)	19.9 (9.7)	11.8 (5.0)	14.5 (4.3)	12.0 (4.8)	15.6 (6.2)	30.7 (11.0)
			Range	12.2	45.2	38.3	36.5	34.4	25.1	23.5	21.7	31.7	38.2
	60–69	12	Mean (SD)	23.5 (1.1)	34.5 (8.2)	39.3 (11.3)	32.7 (9.2)	18.9 (8.3)	14 (6.7)	14.6 (6.4)	11.1 (4.7)	21.1 (4.6)	31 (7.9)
			Range	11.1	24.3	32.9	29.6	22.9	20.7	22.7	16.4	17.0	19.0

Lumbar lordosis and angular movement values are in degrees [°]. For explanation of acronyms, refer to Fig. 1.

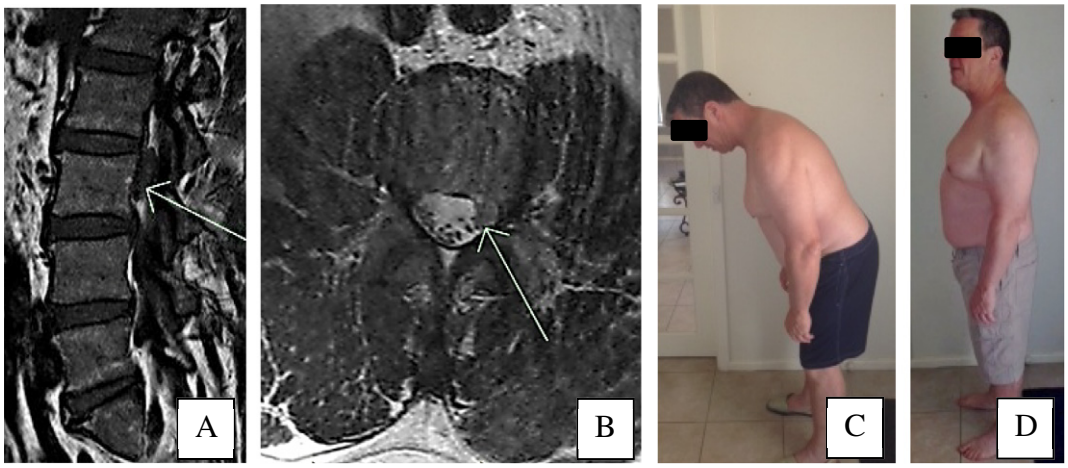

Fig. 3. T1 sagittal MR image of a 22 mm sequestration of L2–3 disc material (A). T2 axial MR image of the posterolateral position of the extruded disc material (B). Patient's standing position 16 days pre-operatively (C) compared with 24 weeks post-operatively (D).

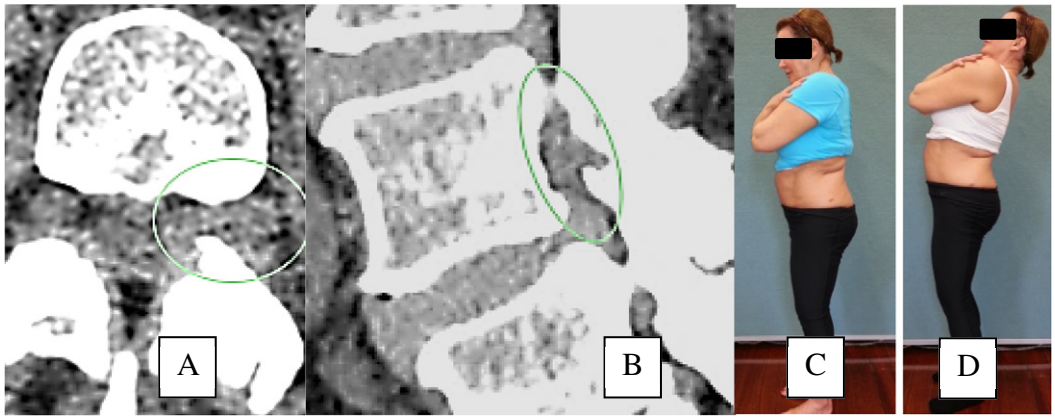

Fig. 4. Transverse CT image of the left L4 nerve root (A). Sagittal CT image of the stenotic L4 exit foramen (B). Patient's active extension 1 week prior to L4–5 epidural injection (C) and 12 weeks post injection (D).

2.6 . Outcome measures

The core battery of outcome measures were used to assess the patients pre-intervention and at three intervals, post-intervention (Deyo et al, 1998): Visual Analogue Scale (VAS), Roland Morris Low Back Pain and Disability Questionnaire (RMDQ) and a Short Form health survey (SF-12). The two cases participated in a CME trial on each of four assessment days with their CME values compared to our age and gender matched NRR. A change of ≥ 30% in all measures was considered clinically significant (Ostelo et al., 2008).

For the eight CME directions (Fig. 1) the maximum values were displayed in a radial plot and change scores calculated between trials.

3. Results

The maximum values for each of the patient's CME movements were plotted to observe changes over time. Fig. 5A illustrates the pre- and final post-operative trials for Case A, plus a comparison age (50–59) and gender matched normal plot. Fig. 5B illustrates the initial and final test values (total change) collected from CME of Case B. The age (60–69) and gender matched NRR data is plotted for comparison.

The natural standing lumbar lordosis and data values for each of the CME directions (Table 3) were compared with the matched CME NRR. Total change scores (%) in angular movement for each CME direction, between pre-intervention (trial 1) and post-intervention (trial 4) assessments are reported in Table 3.

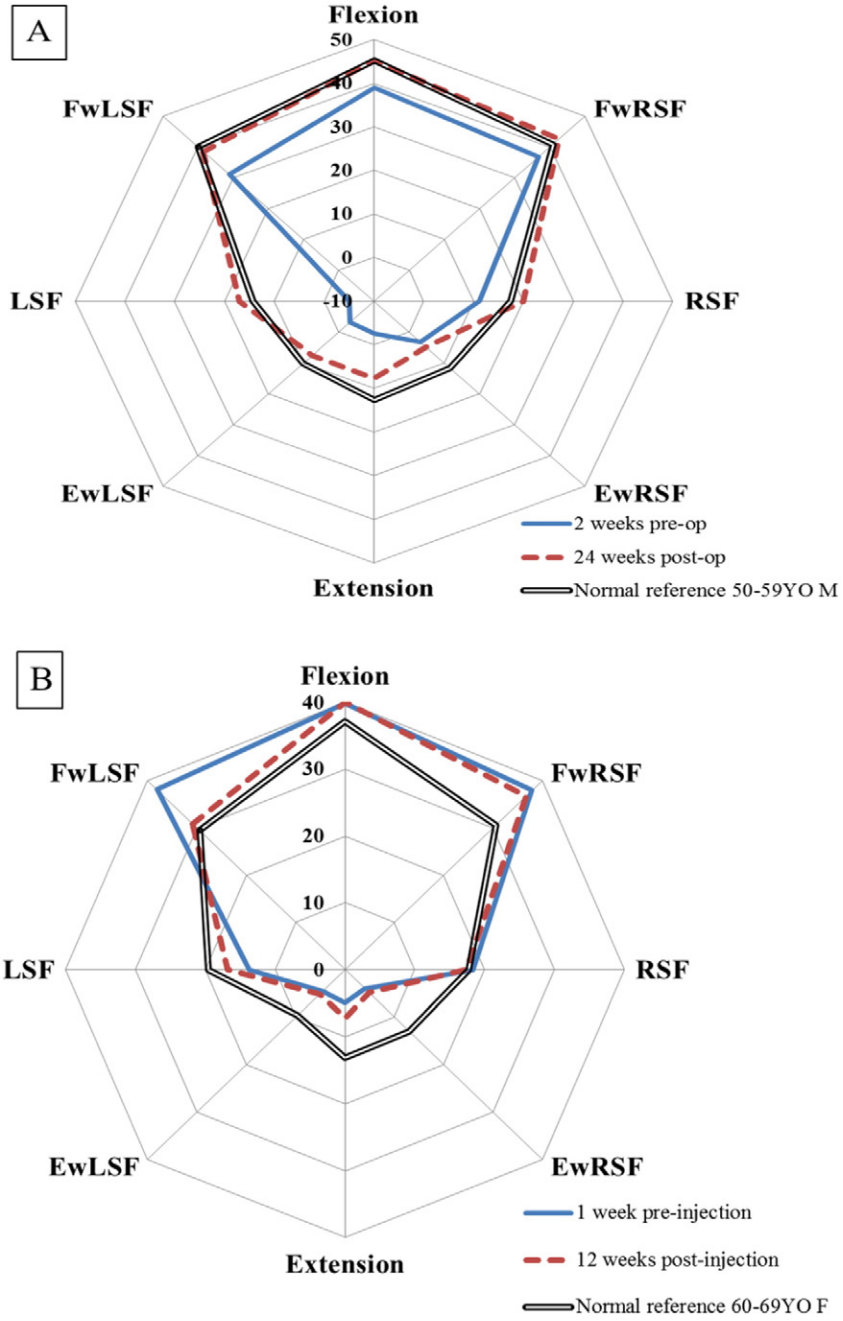

Fig. 5. The first and last trial for Case A and the average normal male CME data for 50–59 years of age (A). Case B shows pre-injection and final post-injection CME. The average normal female CME data for 60–69 years of age (B). Data are in degrees of angular movement.

Table 3
Maximum angular movement for each of the patient's CME movement directions, plus standing lordosis values at each trial with total change scores (%).

Case A CME Trials	Flexion	FwRSF	RSF	EwRSF	Extension	EwLSF	LSF	FwLSF	Lordosis
2 weeks pre-op	38.9	36.8	11.2	3.2	−2.5	−3.2	−5	31.1	23.1
24 weeks post-op	45.2	42.6	20	4.9	7.6	7.6	17.1	38.5	36.9
Total change (%)	16.2%	15.8%	78.6%	53.1%	404.0%	337.5%	442.0%	23.8%	59.7%
Case B CME Trials	Flexion	FwRSF	RSF	EwRSF	Extension	EwLSF	LSF	FwLSF	Lordosis
1 week pre-injection	39.8	37.9	18.3	3.9	4.9	4.6	13.6	38.1	34.7
12 weeks post-injection	40.0	36.7	17.4	4.9	7.1	5.1	16.8	30.8	34.1
Total change (%)	0.5%	−3.2%	−5.0%	23.4%	45.8%	11.6%	23.2%	−19.1%	−1.8%

All angular movement values are in degrees (°). For explanation of acronyms, please refer to Fig. 1.

Self-report outcome data for the two cases, for the index assessments are presented in Table 4. Clinically important improvements (≥30%) are evident in the VAS, RMDQ, and SF-12 domains.

4. Discussion

Outcome assessment for low back pain is complex and typically involves multiple dimensions. Self-report surveys and lumbar kinematics provide insight into the response of low back conditions to management (Deyo et al., 1998; Williams et al., 2013). Measures should be reliable, valid, practical, and for convenience, brief where possible. According to Deyo et al. (1998), assessments of severity and frequency of symptoms such as the RMDQ and SF-12 outcome measures for low back dysfunction are particularly useful for research purposes. However, outcome measures placing emphasis on pain, function and quality of life do not provide the clinician with feedback on the direction and magnitude of movement pattern disturbance (Lyle et al., 2005), the potential structure(s) at fault or departure from normal movement according to age and gender.

In this report we describe the development of a CME assessment model for the lumbar spine. Intra-session and inter-session trials showed CME to be very reliable for all movement directions. This is consistent with the study by Mieritz et al. (2012) reporting a systematic review on the reliability of 3-D measures of the lumbar spine. Further, we have established a preliminary NRR for lumbar CME with which to contrast cases of specific lumbar dysfunction.

To date, only Barrett et al. (1999) have reported preliminary evidence for use of the CME to identify reduced spinal mobility in LBP patients. They did not report normal reference values or test for directional movement restrictions and attribute these to specific diagnoses. The present report investigated the novel application of CME to assess change to both the magnitude and direction of dysfunction and consequently to demonstrate a tendency towards age and gender matched normalisation of low back movement after intervention. Spinal 3-D motion behaviour was described by Ha et al. (2013) as a useful assessment in monitoring changes in spinal movement in an individual over time. As spinal movement is not isolated to pure cardinal planes, 3-D information may confer greater insight into the clinical analysis of aberrant spinal mechanics.

The ability for CME to detect specific directions of restricted movement and to predict biomechanical causes has been hypothesised though not previously examined (Brown, 1988). In this investigation the CME had sufficient sensitivity to detect the greatest restriction and subsequent improvement, in the direction of the confirmed structural spinal abnormality and response to composite loading. Interestingly, passive spinal structures make up the majority of the common pathologies in the lumbar spine (Press, 2007). According to Cunningham et al. (2007) and Little et al. (2007) osseoligamentous tissues and the disc anulus are the primary contributors to spinal stiffness. This may direct a clinician to consider specific structures causing movement restrictions in specific CME directions. Pearcy and Hindle (1989) discuss the potential diagnostic value of 3-D lumbar movement assessment however no studies have substantiated this claim in pathoanatomical terms.

An age and gender matched CME NRR was used to guide provisional outcome goals. When observing Case A's final CME radial plot (Fig. 5A), it is clear that the original movement restriction was normalised, resulting in a symmetrical pattern, comparable to the age and gender matched CME plot. Fig. 5B highlights that the extension range of Case B, after 12 weeks, though no longer painful or causing reported disability, is still well below the age and gender matched average. Facet joint hypertrophy at the L4–5 level (Fig. 4A) would contribute to the patient's movement impairment. Patients, who demonstrate little change in their CME pattern, yet report marked clinical improvement in their pain and function—as in Case B, may reflect a sub-group with structural pathology for whom initial pain management is the appropriate intervention prior to a surgical opinion if symptoms persist. In both cases, the self-report results highlight clinically important improvements in pain, disability and health outcomes. In Case B, her pain score decreased by 23% (Table 4), to zero (VAS 0/10), at the twelve week final assessment.

Several previous studies have reported planar lumbar motion measures (Madson et al., 1999; Pearcy and Hindle, 1989; Troke et al., 2005), very few have described combined or coupled lumbar movement (Ha et al., 2013; Russell et al., 1993) and no report to our knowledge uses CME as an outcome measure when comparing symptomatic cases to an age and gender matched NRR. Furthermore, there seems to be a lack of normative data which can be used to inform outcomes from intervention to manage spinal pain. A systematic review and meta-analysis by Laird et al. (2014), comparing lumbar kinematics in people with and without LBP, concluded that their results do not improve the understanding of the relationship between movement and pain in individuals. They also noted the difficulty in attempting a meaningful interpretation of the data due to the varied methodologies, samples and symptoms reported by the different studies.

Future investigations: Further studies are currently underway with larger clinical cohorts of cases diagnosed with: lumbar stenosis; confirmed facet joint dysfunction or disc herniation. We will test the hypotheses that CME can assist in the provisional diagnostic sub-grouping of mechanical back pain syndromes and, with the use of a NRR, predict the extent, rate and pattern of recovery from specific neurosurgery or pain management interventions.

Table 4
Change in self-report instruments (pre- and post-intervention) for Visual Analogue Scale (VAS), Short Form Health Survey Physical Component Score (SF-12 PCS), Short Form Health Survey Mental Component Score (SF-12 MCS) and Roland Morris Low Back Pain Disability Questionnaire (RMDQ).

Case A	VAS LBP	VAS Hip	SF-12 PCS*	SF-12 MCS*	RMDQ
2 weeks pre-op	0.8	9.7	26.8	32.9	20
24 weeks post-op	0.2	0.2	55.5	57.8	1
Improvement (%)	75.0%	97.9%	50.7%	41.0%	79.2%
Case B	VAS Shin		SF-12 PCS*	SF-12 MCS*	RMDQ
1 week pre-epidural	2.3		39.9	47.0	10
12 weeks post-epidural	0.0		59.9	43.6	0
Improvement (%)	100.0%		35.3%	−5.6%	41.7%

* Normal SF-12 health survey: mean = 50, SD = 10.

The present study provides normative data for CME that may inform future clinical studies of this technique as a convenient objective surrogate for important clinical outcomes in lumbar degenerative spondylosis. It can be used with good reliability, may be well tolerated by individuals in pain and appears to change in concert with validated measures of lumbar spinal pain, functional limitation and quality of life.

5. Conclusion

The CME is a reliable movement examination and may be a useful outcome measure for individuals with low back movement dysfunction. A normal CME reference range provides an expected movement outcome matched to age and gender, although care must be taken to consider individual anatomical variations and clinical presentations. These case-studies provide initial evidence that CME may possess sufficient sensitivity to detect the nature of spinal dysfunction and the natural history following intervention.

Conflict of interest statement

No authors have benefitted financially as a direct consequence of this study or publication.

References

Barrett, C.J., Singer, K.P., Day, R., 1999. Assessment of combined movements of the lumbar spine in asymptomatic and low back pain subjects using a three-dimensional electromagnetic tracking system. Man. Ther. 4, 94–99.
Bonnick, S.L., Lewis, L.A., 2013. Bone Densitometry for Technologists. 3rd ed. Springer, New York, p. 172.
Brown, L., 1988. An introduction to the treatment and examination of the spine by combined movements. Physiotherapy 74, 347–353.
Cunningham, H., Little, J.P., Pearcy, M.J., Adam, C.J., 2007. The effect of soft tissue properties on overall biomechanical response of a human lumbar motion segment: a preliminary finite element study. In: Brebbia, C.A. (Ed.), Modelling in Medicine and Biology VII, pp. 93–102.
Deyo, R.A., Battie, M., Beurskens, A.J., Bombardier, C., Croft, P., Koes, B., Malmivaara, A., Roland, M., Von Korff, M., Waddell, G., 1998. Outcome measures for low back pain research. A proposal for standardized use. Spine 23, 2003–2013.
Edwards, B., 1979. Combined movements of the lumbar spine: examination and clinical significance. Aust. J. Physiother. 25, 147–152.
Ha, T.-H., Saber-Sheikh, K., Moore, A.P., Jones, M.P., 2013. Measurement of lumbar spine range of movement and coupled motion using inertial sensors—a protocol validity study. Man. Ther. 18, 87–91.
Laird, R., Gilbert, J., Kent, P., Keating, J., 2014. Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. BMC Musculoskelet. Disord. 15, 229.
Little, J.P., Pearcy, M.J., Adam, C.J., 2007. Coupled rotations in the lumbar spine—are these a consequence of passive spinal anatomy? In: Brebbia, C.A. (Ed.), Modelling in Medicine and Biology VII, pp. 83–92
Lyle, M.A., Manes, S., McGuinness, M., Ziaei, S., Iversen, M.D., 2005. Relationship of physical examination findings and self-reported symptom severity and physical function in patients with degenerative lumbar conditions. Phys. Ther. 85, 120–133.
Madson, T.J., Youdas, J.W., Suman, V.J., 1999. Reproducibility of lumbar spine range of motion measurements using the back range of motion device. J. Orthop. Sports Phys. Ther. 29, 470–477.
Maitland, G.D., 1997. Vertebral Manipulation. Fifth ed. Butterworth Heinemann, Oxford, p. 269.
Mieritz, R.M., Bronfort, G., Kawchuk, G., Breen, A., Hartvigsen, J., 2012. Reliability and measurement error of 3-dimensional regional lumbar motion measures: a systematic review. J. Manip. Physiol. Ther. 35, 645–656.
Ostelo, R.W.J.G., Deyo, R.A., Stratford, P., Waddell, G., Croft, P., Von Korff, M., Bouter, L.M., de Vet, H.C., 2008. Interpreting change scores for pain and functional status in low back pain—towards international consensus regarding minimal important change. Spine 33, 90–94.
Pearcy, M.J., Hindle, R.J., 1989. New method for the non-invasive 3-dimensional measurement of human back movement. Clin. Biomech. 4, 73–79.
Press, J., 2007. Low back pain. In: Brukner, p, khan, k (Eds.), Clinical Sports Medicine, 3rd ed. McGraw Hill, NSW, pp. 354–356.
Russell, P., Pearcy, M.J., Unsworth, A., 1993. Measurement of the range and coupled movements observed in the lumbar spine. Br. J. Rheumatol. 32, 490–497.
Troke, M., Moore, A.P., Maillardet, F.J., Cheek, E., 2005. A normative database of lumbar spine ranges of motion. Man. Ther. 10, 198–206.
Williams, J.M., Haq, I., Lee, R.Y., 2013. A novel approach to the clinical evaluation of differential kinematics of the lumbar spine. Man. Ther. 18, 130–135.