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REVIEW

Three-dimensional kinematics of the lumbar spine during gait using marker-based systems: a systematic review

Robert Needham[a], Julie Stebbins[b] and Nachiappan Chockalingam[a]

[a]CSHER, Faculty of Health Sciences, Staffordshire University, Stoke on Trent, ST4 2DF, UK; [b]Nuffield Orthopaedic Centre, Oxford University Hospitals NHS Trust, Windmill Rd, Headington, Oxford, OX3 7HE, UK

ABSTRACT
To review the current scientific literature on the assessment of three-dimensional movement of the lumbar spine with a focus on the utilisation of a 3D cluster. Electronic databases PubMed, OVID, CINAHL, The Cochrance Library, ScienceDirect, ProQuest and Web of Knowledge were searched between 1966 and March 2015. The reference lists of the articles that met the inclusion criteria were also searched. From the 1530 articles identified through an initial search, 16 articles met the inclusion criteria. All information relating to methodology and kinematic modelling of the lumbar segment along with the outcome measures were extracted from the studies identified for synthesis. Guidelines detailing 3D cluster construction were limited in the identified articles and the lack of information presented makes it difficult to assess the external validity of this technique. Scarce information was presented detailing time-series angle data of the lumbar spine during gait. Further developments of the 3D cluster technique are required and it is essential that the authors provide clear instruction, definitions and standards in their manuscript to improve clarity and reproducibility.

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Lumbar kinematics; gait; three-dimensional; cluster; spine model

1. Introduction

There are many clinical scenarios where knowledge of lumbar spine motion during gait would be advantageous. One obvious application is the investigation of low back pain (LBP). It is generally believed that LBP is at least partially attributable to biomechanical influences, including the co-ordinated movement between the lumbar spine and pelvis.[1,2] Furthermore, individuals with a gait abnormality such as leg length discrepancy display asymmetrical patterns of movement in the lumbar region,[3] a compensatory movement that has been attributed to the development of LBP.[4] However, the lack of research into the co-ordination between the lumbar spine and lower limbs during gait has restricted our understanding of the effects of leg length discrepancy on the spine and to the potential link with LBP.[5]

The ability to reliably measure lumber spine motion could provide an understanding of the underlying mechanism behind a clinical condition such as LBP.[6] The structure and function of the lumbar spine is complex and, therefore, requires a measurement technique that can record three-dimensional movements. Radiological imaging is considered to be accurate and a technique that can measure inter-segmental movement of spinal vertebrae, yet this invasive method could be harmful to a patient. While electromagnetic tracking systems are a cheaper alternative and would be a suitable technique for assessing gait in a clinical setting,[7] the quantitative analysis of gait using marker based systems is well established and has been used in clinical contexts for several decades, in order to help diagnose, plan treatment and assess treatment outcomes.[8,9]

Using a marker based system, MacWilliams et al.[10] recently investigated three-dimensional motion of the lower back during gait by inserting wires into the spinous process of each vertebra of the lumbar spine. Although this technique of analysis can be applied in a dynamic situation and provides a "gold standard" measurement of bone movement, this invasive approach is inappropriate for routine clinical assessment. Nevertheless, the use of bone pins suggests non-negligible motion occurs at the lumbar spine during walking, which warrants the inclusion of a lumbar segment in kinematic models designed for clinical gait analysis.[10,11] Whilst the potential influence of soft tissue artefact is acknowledged when utilising marker based systems[12] the placement of markers on the

CONTACT Nachiappan Chockalingam n.chockalingam@staffs.ac.uk CSHER, Faculty of Health Sciences, Staffordshire University, Stoke on Trent ST4 2DF, UK

skin overlying the spinous processes of the vertebrae provides a non-invasive approach to assess dynamic movement of the lumbar spine. However, the difficulty in locating relevant anatomical landmarks to effectively define axial rotation in the transverse plane, limits the analysis of lumbar motion to the sagittal and frontal planes using this approach[13] Disregarding transverse plane movement of the lumbar spine could have clinical implications. For example, the compensatory movements created as a consequence of a leg length discrepancy have been shown to induce both a lateral flexion and axial rotation of the lumbar spine.[14,15] Moreover, such coupled motion in the frontal and transverse plane is a functional characteristic of the human spine,[16,17] which can be altered in the presence of LBP.[18]

An alternative method is to use a 3D cluster. This technique involves at least three markers positioned in a non-linear rigid configuration, attached to a rigid base which is placed onto the surface of the back. While limitations of this technique have been identified[19] the 3D cluster is able to measure transverse plane movement. The 3D cluster is often positioned at the distal end of the lumbar spine (T12/L1). Tracking movement in the distal region of the lumbar spine is assumed to represent movement across all vertebral joints, thus classifying the lumbar spine as a single rigid segment. Numerous 3D clusters have been proposed; however, a reproducible 3D cluster to assess lumbar segmental movement has yet to be rigorously defined and tested within the scientific literature.

Whilst there are several non-invasive approaches reported within the literature and the review of all these technologies are beyond the scope of this manuscript, marker-based systems are generally accepted to be the "gold standard" for gait and movement analysis. Therefore, the aim of this systematic review is to critically evaluate published literature on methods to assess three-dimensional movement of the lumbar spine during gait using marker-based systems, with a focus on providing a quality assessment of the research that employed the 3D cluster technique.

2. Methodology

2.1. Scope and boundaries

This review intends to examine the methodological considerations for three-dimensional analysis of lumbar movement using a 3D cluster. Areas for review include: participant characteristics, 3D cluster design and placement, kinematic model description, data collection procedures, data analysis techniques and outcome measures (i.e. range of motion, time-series kinematic waveform information). This review does not intend to critically analyse the mathematical procedures and algorithms used for maker detection or the technologies used for data capture.

2.2. Search strategy and review process

A search of relevant literature was performed using electronic publication databases including PubMed, OVID, CINAHL, The Cochrance Library, ScienceDirect, ProQuest and Web of Knowledge (between 1966 and March 2015). Keywords were selected from MeSH terminology and consisted of the words "lumb* (ar-o)" AND "gait" OR "walking" AND "three-dimensional" and were searched in the title, abstract and keywords fields of each database. For each database, additional filters were selected (human, academic/journal article, English, full text). Reference lists of the papers identified from the electronic search were screened for additional articles that were not found by the database search. The title and abstract of articles identified in the search strategy were evaluated for inclusion by one reviewer (RN). If insufficient information was provided in the title and abstract of an article, a full text evaluation was undertaken.

2.3. Inclusion/exclusion criteria

Studies were included if they met the following criteria: (1) gait was assessed using a marker-based system; no limitations were set on methodology procedures (i.e. walking speed and mode and surface gradient); (2) a 3D cluster was employed to assess movement of the lumbar region; (3) presented three-dimensional movement data (numerical and/or kinematic waveforms); and (4) studies were published in English as full papers.

2.4. Data extraction and methodological quality appraisal

Data extraction from the identified articles was based on questions from the quality assessment (Table 1) and was performed by one reviewer (RN). A second reviewer (NC) checked and verified the extracted data. The quality assessment criteria included 13 appraisal questions and were specifically designed to assess methodological procedures relating to kinematic modelling and the reproducibility of a marker set configuration.[20,21] Questions 4, 5, 6 and 8 were modified to assess the quality of the information relating to (1) the lumbar segment, (2) the structural dimensions and

Table 1. Assessment of research quality.

1. Are the research objectives or aims clearly stated?
2. Is the study clearly described?
3. Are appropriate subject information and anthropometric details provided?
4. Are the marker locations and structural dimensions of the rig/plate accurately described?
5. Is the lumbar segment clearly stated?
6. Is the reference position or rig/plate used to define anatomical/cluster frames reported?
7. Is the motion analysis equipment and set-up clearly described?
8. Is the segment/cluster co-ordinate system clearly defined?
9. Are the model properties clearly defined for all joints?
10. Are the methods used to describe the axes and order of rotations clearly described or referenced appropriately?
11. Are appropriate validation and reliability procedures documented and reported?
12. Are appropriate statistical methods used to describe the variability/reliability/repeatability of the model proposed?
13. Are numerical and waveform data representing global and relative information presented?
14. Are the main outcomes of the study stated?
15. Are the limitations of the study clearly described?

Questions were scored as follows: 2 = yes; 1 = limited detail; 0 = no.
Adapted from Bishop et al. [21].

materials used to construct the 3D cluster and (3) the reference frame of the co-ordinate system. Two additional questions were included in the quality appraisal; one to assess validation and reliability procedures (question 11) and the second to assess the reporting of lumbar movement in the form of numerical and kinematic waveform data (question 13). Each question was scored as follows: 2 = yes; 1 = limited detail; 0 = no. An article was deemed high quality if the total score was $\geq$ 24/30 (80%).[20,21]

3. Results

3.1. Search

The systematic search strategy utilised in this review is summarised in Figure 1. A total of 1530 published articles were identified in the electronic search of the selected databases. Following a review of the title and abstract of each article, 21 articles were deemed eligible for inclusion and full text examination was performed. A systematic hand search of the reference lists in these 21 studies further identified two articles that were not found in the initial electronic search. Subsequent assessment of the full text revealed seven articles that did not meet the inclusion criteria. In the two studies by Crosbie et al.[22,23] additional markers were applied on the surface of the back laterally to those attached to the spinous process. Although this method can define the transverse plane in a co-ordinate system, the independent movement between markers may influence segment angle calculations. The 3D cluster technique eliminates relative movement between the markers, thus the reason for the exclusion of the studies by Crosbie et al.[22,23] Morgenroth et al.[24] compared three-dimensional motion of the lumbar spine during gait in transfemoral amputees to a healthy control group; however, the semi-rigid plate was applied over the spinous process at the level of T8/T10. Due to the high contribution of the lower thoracic region to overall spinal movement, a decision was made by both reviewers (RN/NC) to exclude this study. In the two studies by Zhao et al.[25,26] the authors did not report numerical data or kinematic waveform data in the sagittal plane. Two articles did not use a marker based system.[27,28] A total of 16 articles were included for the final review.

3.2. Quality assessment

A summary of the quality assessment of the reviewed articles can be found in Figure 2(A). Using an approach proposed by Bishop et al.,[21] information required to sufficiently answer questions 4, 6, 8, 10–13 were not consistently provided in the articles included for review and this was represented by a median score of < 2 (Figure 2(B)). From the 16 articles reviewed, two articles were deemed to be high quality.[29,30]

3.3. Participant characteristics

Table 2 provides a summary of the total number of participants recruited, along with their health status, gender and age. Each study included participants who were considered otherwise healthy, with the exception of some studies including participants with back conditions such as acute[31,32] and chronic low back pain.[30,33] The effect of hip osteoarthritis on lumbar spine movement has also been examined[34] Three studies did not provide information on gender,[31,32,35] while five studies examined only male participants.[36–40] The remaining studies either assessed gender separately[33] or pooled lumbar angle data between genders.[29,30,41–44]

3.4. Methodology considerations and outcome measures

A variety of 3D clusters have been developed in an attempt to assess three-dimensional movement of the

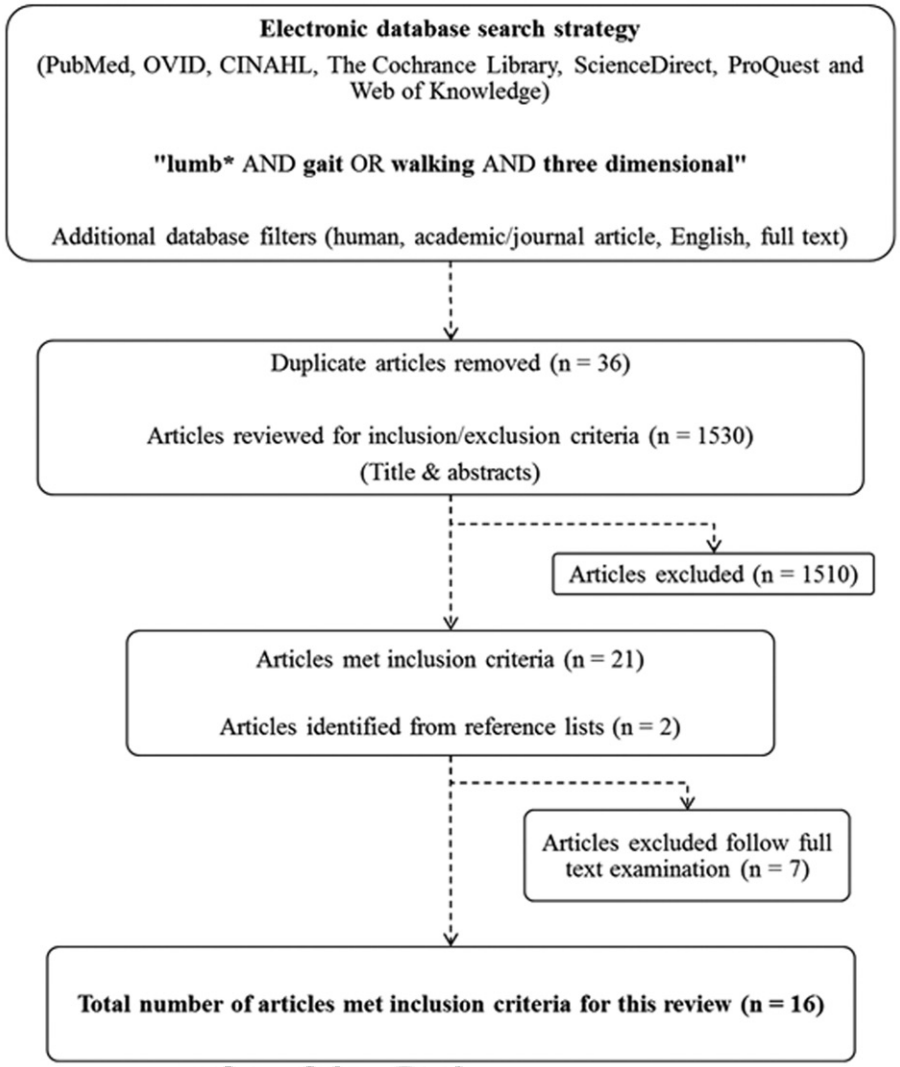

Figure 1. A flowchart to describe the systematic approach used to identify the literature included in the review.

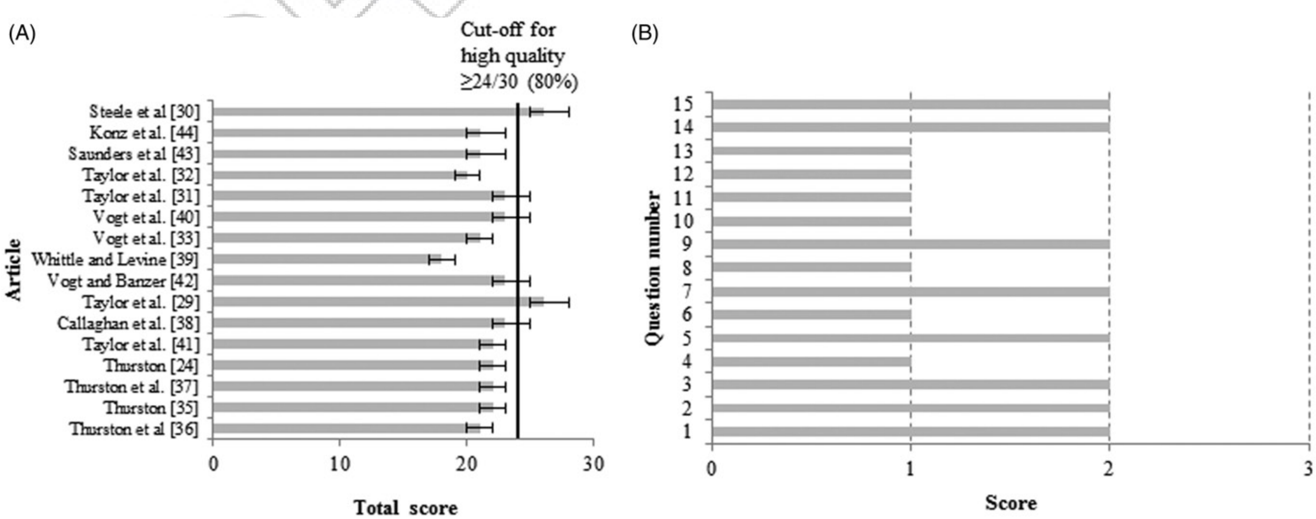

Figure 2. Quality assessment results (A); median score for each question (B).

Table 2. Participant characteristics.

Article	Health status	n	Gender	Age (years)
Thurston et al.[36]	Healthy	22	Male	NR
Thurston[35]	Healthy	2	NR	NR
Thurston et al. [37]	Healthy	48[a]	Male	Mean 32.3, range 16–74, (75% younger than 35)
Thurston[34]	Healthy	10	Male	Mean 63.4 ± SD 8.04 (Healthy)
	Patient (unilateral hip osteoarthrosis)	19		Mean 65.1 ± SD 7.77 (Patient)
Taylor et al.[41]	Healthy	16	Male/Female	5 Females/3 Males; mean 19.75 (PWS group) 5 Females/3 Males; mean 20.74 (SWS group)
Callaghan et al.[38]	Healthy	5	Male	Mean 25 ± SD 2.8
Taylor et al.[29]	Healthy	27	Male/Female	9 Females/5 Males; mean 20.6 ± SD 2.8 (PWS group) 7 Females/6 Males; mean 23.5 ± SD 5.1 (SWS group)
Vogt and Banzer[42]	Healthy	22	Male/Female	4 Females, range 27–32/18 Males, range 25–35
Whittle and Levine[39]	Healthy	20	Males	NR
Vogt et al.[33]	Healthy Patient (Chronic LBP)	56	Male/Female	6 Females, mean 29.5 ± SD 1.3/16 Males, mean 34.8 ± SD 5.2 (Healthy) 13 Females, mean 32.1 ± SD 3.4/21 Males, mean 36.3 ± SD 1.87 (Patient)
Vogt et al.[40]	Healthy 9	9	Male	Mean 28.7 ± SD 4.4
Taylor et al.[31]	Healthy 16 Patient (Acute LBP)	16	N/R	8 healthy participants, mean 33.3 ± SD 8.4 8 patients, mean 33.5 ± SD 8.8 *(Matched—age, gender, height)*
Taylor et al.[32]	Healthy 23 Patient (Acute LBP)	23	N/R	11 healthy participants, mean 39.0 ± SD 12.5 12 patients, mean 38.6 ± SD 11.9 *(Matched—age, gender, height)*
Saunders et al.[43]	Healthy 7	7	6 Males/1 Female	NR
Konz et al.[44]	Healthy 11 Patient (Kyphoscoliosis)	11	Male/Female NR	5 Female/5 Male, mean 27 ± SD 4 (Healthy) 1 Patient
Steele et al.[30]	Patient (Chronic LBP)	24	13 Males/11 Females	Training group (*n* = 17), mean 47 ± SD 13/Control group (*n* = 7), mean 42 ± SD 15

[a]of which, nineparticipants reported occasional LBP and 17 had a LLD greater than 1 cm.
NR, not reported; LLD, leg length discrepancy; PWS, preferred walking speed; SWS, slow walking speed; SD, standard deviation; LBP, low back pain.

lumbar segment (Table 3). Four studies which employed a 3D cluster with a larger base required the use of a belt to ensure the cluster did not detach from the back surface.[34–37,43] Two studies did not report on the method used to attach the 3D cluster to the participants.[38,39] In a number of studies undertaken by Taylor et al.,[29,31,32,41] including the study by Konz et al.,[44] the authors utilised a smaller 3D cluster that could be applied to the back surface of the participants using double-sided adhesive tape. The remaining studies,[33,40,42] although citing the work of Thurston et al.[37] did not provide information about the structure and construction of the 3D cluster. While Konz et al.[44] attached a rubber base plate over L3, 15 studies applied the 3D cluster over the spinous process at the level of T12/L1. The number of markers that formed the cluster varied between three[30,33,38,40,42,44] and four.[29,34–37] Although some of the studies included in the review were follow-up investigations, only one study provided sufficient information that detailed the structural design of the 3D cluster.[29] Saunders et al.[43] employed a previously developed technique[45,46] and was referenced appropriately in the article (Table 3). Steele et al.[30] also implemented a 3D cluster design similar to that by Schache et al.,[45] but chose to use a flexible based wand marker instead of a rigid structure. Two additional markers were securely fixed to either side of the flexible base aligned with the spinous process at a level of T12. Seven studies used a treadmill,[29,31–33,41–43] while seven studies chose over-ground as the mode of walking.[30,34–39,44] One study compared differences in lumbar spine movement between over-ground and treadmill walking and found a significant difference in frontal plane movement.[40] Participants in all studies were asked to walk at a preferred speed, yet Taylor et al.[29,31,41] and Saunders et al.[43] are the only studies that have examined walking speed. A single study by Vogt et al.[42] noted the influence of walking on a sloped incline on lumbar spine kinematics (Table 4).

The calibration process and information about the gait laboratory set-up was provided in the majority of studies.[29,30,32–37,40–42] In addition, two studies validated the kinematic output from the proposed model by using a movement simulator[35] and a replica mechanical model of the spine.[44] Reliability analyses were performed and intra-class correlation or coefficients of variation were examined in three studies.[30,33,41,42] In all studies, mean and standard deviation were absolute values used to analyse the average performance between individuals and

Table 3. Hardware, software and custom made rig details.

Article	Motion analysis system (MAS)	Measurement frequency	Analysis software	Processing	3D cluster—location, number of markers	Rig/plate dimensions and materials	Attachment of rig/plate	Additional marker locations
Thurston et al.[36]	3 camera system	NR	NR	NR	1× T12, 4 markers 1× sacrum, 3 markers	NR	Belt, DSAT Belt, DSAT	N/A
Thurston[35]	Cited Thurston et al.[36]	NR	NR	NR	1× T12, 4 markers 1× sacrum, 3 markers	Perspex cones (9 mm diameter, 5 mm high)—schematic provided	Belt, DSAT Belt, DSAT	N/A
Thurston et al.[37]	Cited Thurston and Whittle	NR	NR	NR	1× T12, 4 markers 1× sacrum, 3 markers	NR	Belt, DSAT Belt, DSAT	N/A
Thurston[34]	Cited Thurston and Whittle	NR	NR	NR	1× T12, 4 markers 1× sacrum, 3 markers	NR	Belt, DSAT Belt, DSAT	N/A
Taylor et al.[41]	2 camera PEAK 3D	50 frames/s	NR	4th-order Butterworth low frequency 5 Hz	1× sacrum, 3 markers	Small rectangle orthogonal rig thermoplastic (8 cm × 5 cm) with 6 cm orthogonal pylon	Belt, DSAT	N/A
Callaghan et al.[38]	6 camera OPTOTRAK	60 Hz	NR	4th-order Butterworth low pass filter 6 Hz	1× T12-L1, 3 markers	NR	NR	N/A
Taylor et al.[29]	2 camera PEAK 3D	50 frames/s	NR	4th-order Butterworth low frequency 5 Hz	1× L1, 4 markers 1× sacrum, 2 markers	Thermoplastic plate (7 cm × 4 cm) with 6.5 cm orthogonal pylon/picture of rig provided	DSAT	2 markers PSIS
Vogt and Banzer[42]	ZEBRIS CMS 50	25 Hz	NR	2nd-order low pass filter cut-off frequency 8 Hz	1× T12, 3 markers	Triplet positions based on Thurston et al. (1983)	DSAT	N/A
Whittle and Levine[39]	VICON	NR	VICON Clinical Manager	NR	1× S1, 3 markers 1× T12/L1, 3 markers 1× sacrum, 2 markers	NR/figure provided, no dimensions	DSAT	N/A
Vogt et al.[33]	ZEBRIS CMS 70	30 Hz	NR	2nd-order low pass filter cut-off frequency 8 Hz	1× T12, 3 markers 1× S1, 3 markers	Triplet positions based on Thurston et al. (1983)	DSAT Belt, DSAT	N/A
Vogt et al.[40]	ZEBRIS CMS 70	N/R	NR	2nd-order low pass filter cut-off frequency 6 Hz	1× T12, 3 markers 1× S1, 3 markers	NR	NR	N/A
Taylor et al.[31]	2 camera PEAK 3D	50 frames/s	NR	4th-order Butterworth low frequency 5 Hz	1× L1, N/R 1× sacrum, N/R	NR	DSAT	NR
Taylor et al.[32]	2 camera PEAK 3D	50 frames/s	N/R	4th-order Butterworth filter, low frequency cut-off 5 Hz	1× L1, N/R 1× sacrum, N/R	Thermoplastic rig (7 cm × 4 cm) with 6.5 cm orthogonal pylon	DSAT	NR
Saunders et al.[43]	6 camera VICON 370	200 Hz	VICON	NR	1× T12, replica 3D cluster used by Schache et al.	Cited Schache et al.[42]	Belt, DSAT	2 ASIS/1 mid-PSIS
Konz et al.[44]	8 camera EAGLE DIGITAL	NR	KinTrak (Motion Analysis Corp.)	NR	1× L3, 3 markers, additional 3D clusters at C5 and T7	Limited/figure provided, no dimensions	DSAT	2 markers—L1/S1, 2 ASIS
Steele et al.[30]	10 camera VICON MX/T20	500 Hz	VICON Nexus/ Bodybuilder code (Schache et al. 2001)	4th-order Butterworth low frequency—cut-off frequency determined for each participant	1× T12 (adapted from Schache et al. (2001)	Cited Schache et al. (2001)	DSAT	2 ASIS/1 mid-PSIS

NR, not reported; DSAT, double-sided adhesive tape; N/A, not applicable.

Table 4. Kinematic model details and methodological procedures.

Article	Global co-ordinate frame	Lumbar segment co-ordinate frame	Joint/segment movement	Order of rotations/ Joint convention	Walking mode (Gradient)	Walking speed	Control of walking speed	Number of trials
Thurston et al.[36]	NR	NR	Lumbar relative to pelvis Pelvis relative to laboratory	NR	Overground (Level)	PWS	NR	5
Thurston[35]	NR	NR	Lumbar relative to pelvis Pelvis relative to laboratory	NR	Overground (Level)	PWS	Metronome	10
Thurston et al.[37]	NR	NR	Lumbar relative to pelvis Pelvis relative to laboratory	NR	Overground (Level)	PWS	NR	5
Thurston[34]	NR	NR	Lumbar relative to pelvis Pelvis relative to laboratory	NR	Overground (Level)	PWS	NR	5
Taylor et al.[41]	NR	NR	Lumbar relative to pelvis Pelvis relative to laboratory	Projected angles	Treadmill (Level)	PWS SWS—60% of PWS	Constant speed set by treadmill	6×8 s
Callaghan et al.[38]	NR	NR	Lumbar relative to pelvis	Euler XYZ	Overground Level)	PWS	Metronome	5
Taylor et al.[29]	A	A	Lumbar relative to laboratory Lumbar relative to pelvis Pelvis relative to laboratory	Frontal, Transverse, Sagittal (projection angles)	Treadmill (Level)	PWS SWS—60% of PWS	Constant speed set by treadmill	6×8 s
Vogt and Banzer[42]	NR	NR	Lumbar relative to pelvis Pelvis relative to laboratory	NR	Treadmill (Level/10% incline)	1.25 m/s	Constant speed set by treadmill	2 x 30s
Whittle and Levine[39]	NR	NR	Lumbar relative to pelvis Pelvis relative to laboratory	NR	Overground (Level)	PWS	NR	4
Vogt et al.[33]	NR	NR	Lumbar relative to pelvis Pelvis relative to laboratory	NR	Treadmill (Level)	1.25 m s^{-1}	Constant speed set by treadmill	1×30 s
Vogt et al.[40]	NR	N/R	Lumbar relative to pelvis Pelvis relative to laboratory	NR	TM/OG (Level)	1.25 m s^{-1}	Constant speed set by treadmill	1×30 s
Taylor et al.[31]	Cited Taylor et al.[32]	Cited Taylor et al[32]	Lumbar relative to laboratory Lumbar relative to pelvis Pelvis relative to laboratory	Cited Taylor et al.[32]	Treadmill (Level)	PWS FWS (+40% of PWS)	Constant speed set by treadmill	6
Taylor et al.[32]	Cited Taylor et al.[32]	Cited Taylor et al[32]	Lumbar relative to laboratory Lumbar relative to pelvis Pelvis relative to laboratory	Cited Taylor et al.[32]	Treadmill (Level)	PWS—1.36 m s^{-1}	Constant speed set by treadmill	6
Saunders et al.[43]	Cited Schache et al[41,42]	Cited Schache et al[41,42]	Lumbar relative to pelvis Pelvis relative to laboratory	Cited Grood & Suntay (1983)	Treadmill (Level)	1 and 2 m s^{-1}	Constant speed set by treadmill	10 s
Konz et al.[44]	A	A	Lumbar relative to pelvis Pelvis relative to laboratory	Transverse, Frontal, Sagittal	Overground (Level)	PWS—1.35 m s^{-1}	NR	NR
Steele et al.[30]	Cited Schache et al.[41,42]	Cited Schache et al.[41,42]	Lumbar relative to pelvis	Sagittal, Frontal, Tansverse	Overground (Level)			5

NR, not reported; PWS, preferred walking speed; SWS, slow walking speed; FWS, fast walking speed; A, acceptable; TM, treadmill; OG, overground.

variation in the data, respectively. While relative ROM values reporting movement between the lumbar spine and pelvis are provided in all studies, only a few studies present lumbar spine ROM values relative to a laboratory location (global).[29,31,32] Relative kinematic waveform data for all participants is reported in only six studies,[30,33–35,37,39,42] global kinematic waveform information is not documented in any of the studies under review (Table 5).

4. Discussion

This systematic review evaluated the relevant literature where a 3D cluster was employed to assess three-dimensional movement of the lumbar segment during gait, with a focus on participant characteristics and data collection conditions, methodological rigour and the quality of the outcome measures.

4.1. Participant characteristics and data collection conditions

Although matching experimental groups for age, gender and height[31,32] can potentially offset the variation between individuals, allowing for a comparison between data, five studies chose to pool lumbar angle data in regards to gender and age.[29,30,41–44] Vogt et al.[33] found no difference in pelvis and spine motion during gait between males and females, a finding supported by Crosbie et al..[23] However, with conflicting findings in the literature,[47,48] future studies need to account for potential gender differences and present this data accordingly. A consideration for age is also required. Whilst variability in spine ROM exists between individuals of a similar age, differences in spine motion between younger and older individuals is evident.[49,50]

Based on the papers included within this review, the application of the 3D cluster has primarily focused on the assessment of lumbar motion in healthy individuals or in those with acute or chronic LBP while walking at various speeds. However, during activities of daily living an individual is normally required to walk up and down stairs or on slopes at varying gradients, therefore altering ROM and the co-ordination pattern between the pelvis and lumbar segment. Using a treadmill, Vogt and Banzer[42] reported an increase in axial rotation of the lumbar segment of 3° while walking at an incline of 10% compared to level walking. This is the only study to date that has documented lumbar and pelvis ROM values for males during incline walking. It has been reported that gait kinematics differ between over-ground and treadmill walking;[40,51] however, the kinematic response of the lumbar spine to over-ground sloped walking is not known. Furthermore, knowledge of lumbar spine motion by means of a 3D cluster while decline walking is limited to the sagittal plane.[52] Gallagher et al.[53] recently investigated the possible mechanisms of LBP by asking participants to perform prolonged standing on a sloped surface. The authors found that altered kinematics when using a sloped platform reduced the perception of LBP. Thus, an understanding of the changes in lumbar spinal posture and movement patterns while walking on an incline/decline in healthy and pathological populations may assist in the design of rehabilitation strategies for patients with LBP.

4.2. Methodological considerations—3D cluster

This systematic review identified 16 articles that assessed three-dimensional movement of the lumbar segment during gait using a 3D cluster. However, the quality assessment revealed that only one study under review provided details regarding structural dimensions and about the materials used to construct the 3D cluster.[29] Whilst Saunders et al.[43] had access to a previously developed technique[45,46] and was referenced appropriately within the text, the remaining 14 articles offered limited information about materials and how the 3D cluster was assembled, therefore making it difficult to implement external validation research. This is an important aspect of the research process before the newly-constructed replica 3D cluster is used for experimental research. Also, authors cite earlier research but did not provide a schematic or figure of the replica 3D cluster built to show a comparison to the original design (Table 4).

Different 3D clusters may possess different inertial properties. Although made from lightweight materials, the 3D cluster could experience perturbations from impact forces created during foot contact that may displace the structure away from the midline of the back. The 3D cluster could experience wobble' due to abrupt changes in momentum of the lumbar segment. Whilst the magnitude of inertial perturbations could be potentially influenced by individual participant characteristics such as skin elasticity and body composition, a belt is often attached to larger 3D clusters which in turn is wrapped around the lower thorax in an attempt to counteract this independent movement.[46] Validity and reliability procedures for this approach have been documented.[34–37,43,45] However, the interaction between the belt, rib cage and the 3D cluster could influence angle calculations, particularly for axial rotation in the transverse plane, which has been

Table 5. Outcome measures.

Article	Lumbar global ROM (°)	Lumbar Relative ROM (°)	Kinematic waveform data	Pelvis data	Temporal/distance information
Thurston et al.[36]	NR	S – 5.1, 0.62 (SEM)/Fr – 9.3, 1.08/T – 8.3, 1.0	Relative, one participant, S/Fr/T	ROM, global waveforms	Cadence—107 steps min^{-1} (mean)
Thurston[35]	NR	S – 7.1 ± 0.75/Fr – 8.7 ± 0.42/T – 6.0 ± 0.84 *(mean data collected over 3 days)*	Relative, all participants, S, Fr, T *(mean data over 3 days)*	ROM, global waveforms *(mean data over 3 days)*	NR
Thurston et al. [37]	NR	S – 5.2 ± 1.2/Fr – 8.5 ± 2.1/T – 8.3 ± 2.00	Relative, all participants, S, Fr, T	ROM, global waveforms	Cadence—108.7 steps min^{-1} (mean)
Thurston[34]	NR	Healthy, S – 5.2 ± 1.07/Fr – 6.8 ± 1.81/T – 8.8 ± 2.49 Patient, S – 5.2 ± 2.25/Fr – 7.2 ± 3.76/T – 7.7 ± 2.31	Relative, all participants, S, Fr, T	ROM, global waveforms	NR
Taylor et al.[41]	NR	S – 3.24 ± 0.95/Fr – 12.84 ± 3.0/T – 6.44 ± 1.47	NR	ROM	NR
Callaghan et al.[38]	NR	S – 6.46/Fr – 8.01/T – 8.76	Relative, one participant, S/Fr/T	NR	Cadence—103.2 steps min^{-1} (mean)
Taylor et al.[29]	S - 3.21 ± 0.68/Fr - 3.46 ± 1.32/T - 8.96 ± 2.98	S – 3.83 ± 1.56/Fr – 11.98 ± 1.86/T – 6.39 ± 1.86	NR	ROM	PWS—1.33 m s^{-1} (0.27 ± SD)
Vogt and Banzer[42]	NR	S – 2.4/Fr – 2.8/T – 6.8	Relative, all participants, S, Fr, T	ROM, global waveforms	1.25 m/s^{-1}
Whittle and Levine[39]	NR	S – 3.98 ± 1.21/Fr – 7.55 ± 1.65/T – 8.34 ± 2.19	Relative, all participants, S, Fr, T	ROM, global waveforms	NR
Vogt et al.[33]	NR	Healthy, *F* S – 2.36 ± 0.84/Fr – 2.86 ± 1.18/T – 6.88 ± 2.35 Healthy, *M* S – 2.45 ± 0.95/Fr – 2.82 ± 1.26/T – 6.73 ± 2.96 Patient, *F* S – 2.58 ± 0.65/Fr – 3.17 ± 1.26/T – 7.24 ± 2.75 Patient, *M* S – 2.47 ± 0.77/Fr – 3.11 ± 2.15/T – 8.64 ± 1.73	Relative, all participants, S, Fr, T	ROM, global waveforms	1.25 m s^{-1}
Vogt et al.[40]	NR	Over-ground (PWS) S – 4.4/Fr – 3.9/T – 8.2 Treadmill (PWS), S – 4.1/Fr – 2.8/T – 8.6 Treadmill (1.25 m s^{-1}) S – 3.3/Fr – 3.6/T – 7.8	NR	ROM	PWS OG 1.09 m s^{-1} PWS TM 0.86 m s^{-1}
Taylor et al.[31]	Healthy, S – 2.90 ± 0.60/Fr – 3.10 ± 1.40/T – 10.2 ± 3.90 Patient, S – 3.50 ± 1.3/Fr – 3.30 ± 1.40/T – 8.80 ± 2.40	Healthy, S – 3.40 ± 1.60/Fr – 10.20 ± 3.10/T – 6.20 ± 1.80 Patient, S – 3.10 ± 1.60/Fr – 8.40 ± 3.60/T – 5.70 ± 1.10	NR	ROM	Cadence—111.8 steps min^{-1} (mean)
Taylor et al.[32]	Healthy, S – 2.80 ± 0.90/Fr – 3.0 ± 1.30/T –9.0 ± 3.50 Patient, S – 3.30 ± 1.10/Fr – 3.10 ± 1.20/T – 9.70 ± 2.50	Healthy, S – 3.0 ± 1.30/Fr – 9.20 ± 2.70/T – 6.20 ± 2.0 Patient, S – 4.30 ± 3.10/Fr – 9.80 ± 3.90/T – 6.40 ± 1.40	NR	ROM	PWS—1.36 m s^{-1}
Saunders et al.[43]	NR	NR	Relative, one participant, S/Fr/T	NR	1 and 2 m s^{-1}
Konz et al.[44]	NR	Healthy, S – 4.10 ± 0.90/Fr – 5.70 ± 3.20/T – 9.80 ± 2.90 Patient, S – 4.60 ± 0.30/Fr – 2.4 ± 0.20/T – 5.2 ± 0.70	NR	ROM	1.35 m s^{-1}
Steele et al.[30]	NR	Patient (Training group), S – 10.61 ± 3.74/Fr – 3.92 ± 1.20/T – 8.85 ± 2.72	NR	ROM	PWS - NR

NR, not reported; S, sagittal; Fr, frontal; T, transverse; ROM, range of motion; SD, standard deviation; M, Male; F, female.

highlighted as a potential limitation of this technique.[19] To negate these potential pitfalls, the use of a smaller structure, fixing the 3D cluster to the back surface using only double-sided adhesive tape is an alternative approach; yet in these studies[29,32,33,39,41,42] the efficacy of this approach is questioned due to a lack of validation of the methods or/and limited evidence of reliability analysis (Table 6). In addition, the rigid base of the 3D cluster may not conform to the contours of the participant's back. For this reason, moulding the 3D cluster to the specific lumbar/trunk morphology of an individual may be a suitable option, particularly for those with a larger base of support.[19] Furthermore, Portus et al.[54] noted that, compared to a rigid base, a semi-rigid structure was less susceptible to excessive perturbation during a high impact task. Recently, Steele et al.[30] modified the 3D cluster designed by Schache et al.[45] and incorporated a semi-rigid base. Whilst a rationale for this approach was not provided by the authors, this smaller structure can be attached to the back surface using only double-sided adhesive tape. However, the two additional markers placed on the semi-rigid base can move independently, which does not offer a standardised approach to calculate segment angles due to the differences in lumbar/trunk morphology between individuals. Morgenroth et al.[24] examined the relationship between kinematics of the lumbar spine during gait and LBP in transfemoral amputees. In this study a semi-rigid base was also incorporated into the 3D cluster design, but instead of using a wand,[30] three individual markers were placed on a soft rubber plate. Similar to Steele et al.[30] the displacement of the individual markers on the semi-rigid base were not analysed. To remove the potential confounding influence of individual differences in lumbar/trunk morphology, Konz et al.[44] fabricated a rubber base plate with three reflective markers affixed that could be attached directly over the spinous process of L3 using double-sided adhesive tape. Although the 3D cluster devised by Konz et al.[44] conforms to the spinous process in a similar way to a single marker and that relative movement between the three markers would remain in a fixed position during dynamic movement, the authors did not examine the reliability of this method.

Non-invasive approaches, using the techniques outlined in this review, often define the lumbar spine as a rigid segment, positioning the 3D cluster at a level of T12/L1.[30–43] Markers on the 3D cluster provide the technical frame on which the co-ordinate system for the lumbar segment is created. Yet, the lumbar segment co-ordination systems are not reported in 11 studies[33–40,42] and eight failed to document the order of rotations.[33–37,39,40,42] The markers on the 3D cluster are also involved in tracking movement. Consequently, this technique assesses movement around this region of the spine relative to the pelvis. However, the 3D cluster disregards motion in other regions of the lumbar spine.[44] Using indwelling bone pins to assess three-dimensional motion of the lumbar vertebrae, MacWilliams et al.[10] revealed greater intersegmental vertebral movement in the frontal plane between L3–L4 than between other vertebrae. To date, Konz et al.[44] is the only study to have investigated movement at the level of L3 using a 3D cluster. Interestingly, this study reported similar ROM values when compared to studies that placed the 3D cluster over T12/L1, yet the authors did not provide kinematic waveform information. Thus, additional investigations similar to Konz et al.[44] are warranted, not only to document three-dimensional movement patterns around L3 during gait, but to provide information in a region of the spine that is susceptible to LBP or has to compensate for a gait abnormality such as LLD.

Table 6. Validity and reliability analysis.

Article	MBS calibration	Kinematic model validation	Type of reliability
Thurston et al.[36]	R	NR	NR
Thurston[35]	R	Movement simulator	Standard deviation
Thurston et al. [37]	Cited 3 articles	NR	Standard deviation
Thurston[34]	Cited 3 articles	NR	Standard deviation
Taylor et al.[41]	R	R (projected angle, segment length)	Standard deviation/ICC
Callaghan et al.[38]	NR	NR	NR
Taylor et al.[29]	R	Cited Taylor et al.[32]	Standard deviation/Cited Taylor et al.[30]
Vogt and Banzer[42]	Cited 1 article	NR	Standard deviation/CV
Whittle and Levine[39]	NR	NR	NR
Vogt et al.[33]	Cited 2 articles	NR	Standard deviation/CV
Vogt et al.[40]	Cited 3 articles	NR	NR
Taylor et al.[31]	NR	Cited Taylor et al.[32]	Standard deviation/Cited Taylor et al.[32
Taylor et al.[32]	R	NR	Standard deviation/Cited Taylor et al.[32
Saunders et al.[43]	NR	Cited Schache et al.[32]	Cited Schache et al.[41,42]
Konz et al.[44]	NR	Static mechanical Model—replica of the spine	NR
Steele et al.[30]	NR	Cited Schache et al.[32]	Standard deviation/CV

R, reported; NR, not reported; MBS, marker-based system; ICC, intra-class correlation; CV, coefficient of variation.

Considerations must be given to the kinematic modelling of the pelvis segment. In this review, all reported studies measured lumbar motion relative to the pelvis. In 13 studies,[29,31–42] the movement of the pelvis was tracked using a 3D cluster attached to the posterior aspect of the sacrum, while in three studies[30,43,44] the pelvis was tracked by individual markers attached on anatomical landmarks (left and right anterior superior iliac spine/mid posterior superior iliac spines). These kinematic modelling approaches of the pelvis produce different kinematic waveforms while walking, which can subsequently influence the interpretation of lumbar movement when analysed relative to the pelvis segment. For example, in an attempt to further understanding of the different kinematic modelling methods to assess pelvis motion during gait, Vogt et al.[55] examined the validity of a 3D cluster compared to the traditional method of placing individual markers on anatomical landmarks. Although this study employed a non-traditional system using ultrasound as opposed to opto-electronic system, the concept for data collection and analysis is still based on traditional marker clusters, which warranted the inclusion of the studies completed by Vogt et al. within this review.

The results from Vogt et al.[55] found no significant differences for ROM between methods. However, further analysis of the reported kinematic waveforms revealed different movement patterns in the frontal and sagittal plane while walking on a treadmill across the entire gait cycle. Therefore, a comparison of different kinematic modelling techniques of the pelvis and the lumbar spine while walking over-ground is required in order to investigate the interpretation of relative movement between these segments.

4.3. Outcome measures

Figure 3 highlights the consistency of lumbar segment ROM values in three-dimensions that can be collected within the same laboratory using the 3D cluster technique (Laboratories 1, 2 and 3). From this, a distinction between ROM in healthy individuals and those with a clinical condition is possible (Table 5). There is, however, varied lumbar ROM values reported in the frontal plane (relative to the pelvis) across the studies conducted in Laboratory Two.[29,31,32,41] In the latter studies[31,32] the participants were 33 ± 8.4 and 39 ± 12.5 years of age, respectively, and in both instances these participants exhibited lower pelvis obliquity ROM during gait in comparison to a younger cohort recruited in an earlier study[29] (Table 2). This observed reduction in pelvis obliquity ROM explains this variance of 3° between the studies, since there was no difference in lumbar ROM (relative to the global co-ordinate system) (Table 5). Based on this interpretation, the analysis of global ROM or kinematic waveform data during gait would assist in the explanation of relative movement between two segments. However, only three studies documented global ROM values for the lumbar segment.[29,31,32] Moreover, it is also evident in Table 6 that none of the studies included in this review provided kinematic waveform profiles in relation to global movement of a segment.

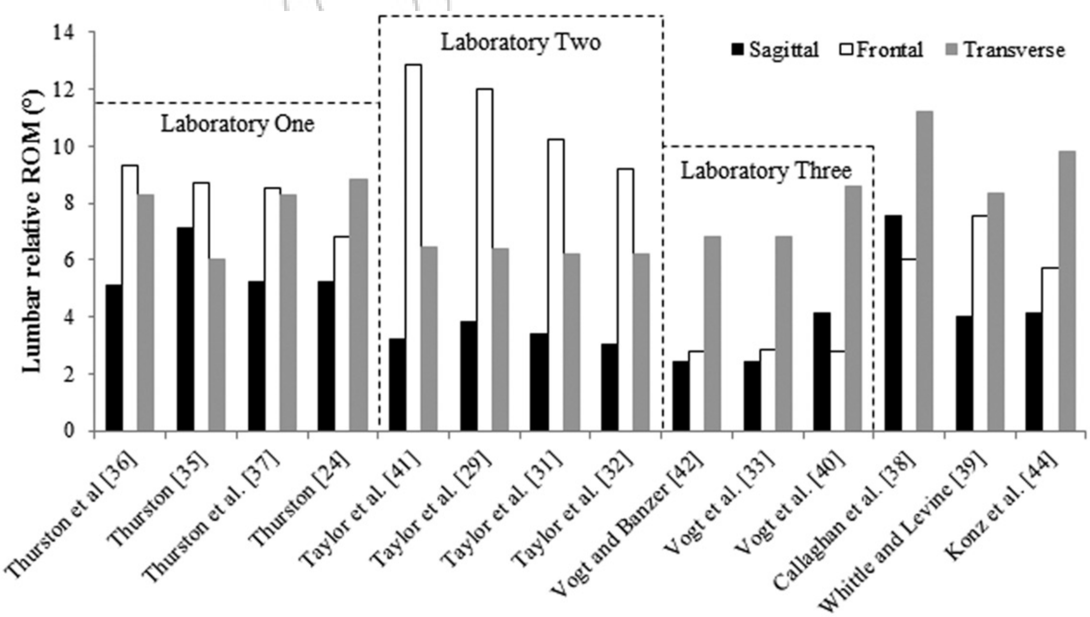

Figure 3. A bar chart to show mean relative range of motion for the sagittal, frontal and transverse plane while walking at a preferred speed.

It is also important to highlight that only six studies provided relative kinematic waveform profiles across all participants in three planes of movement.[33–35,37,39,42] Merely reporting ROM values[29–32,40,41,44] limits our understanding of movement strategies over time that kinematic waveform analysis is able to attain.[56,57] Furthermore, Vogt et al.[33] reported no differences in lumbar ROM between individuals with and without chronic LBP, although dissimilar compensatory movements and lumbar motion asymmetry can still be present.[18] In this review, Thurston[34] noted a difference of 0.3° in frontal plane lumbar ROM between patients with hip arthrosis and healthy controls. However, the kinematic waveform for lateral flexion of the lumbar spine differed between the two groups over the entire gait cycle. Thurston[34] also reported waveform data for the pelvis segment and, similar to the lumbar segment, hip arthrosis altered the kinematic profiles in all three planes of movement. These findings from Thurston,[34] along with other investigations,[22,57,58] highlights the dynamic interaction that exists between the lower limbs, pelvis and spine. The inclusion of an examination of hip–pelvis–lumbar co-ordination in a clinical setting could provide an objective assessment of spinal dysfunction.[1,2,56,58,59]

Intra- and inter-variability is inherent in all biological systems[60] and is, therefore, an important parameter to measure. The majority of studies included for review decided to record between 4–6 trials (Table 4) and linear statistical methods such as standard deviation, intraclass correlations and coefficients of variation were used to analyse the variance of ROM values between trials and individuals (Table 6). However, these discrete measures do not indicate where the variance is within time-series data. The standard deviation band that accompanies a kinematic waveform provides information about variance during movement, yet only three studies in this review reported such findings.[33,39,42] In six studies that provide time-series angle data in three-dimensions[33–35,37,39,42] all kinematic waveforms represented the mean performance of the group. Analysing the average performance between individuals disregards the movement pattern strategy of how any given individual has performed and potentially ignores key information about the performance of a task.[61,62] Vogt et al.[33] highlights the advantage of single-subject analysis to assist in the interpretation of kinematic waveforms that is not possible from linear averaging statistics. In this study, the authors demonstrate that, while ROM and standard deviation values do not differ between healthy individuals and those with chronic LBP, analysis of kinematic waveforms for one patient revealed greater variability in lumbar movement throughout the gait cycle compared to a healthy participant. The differences in the kinematic waveforms were due to the variability in the stride-to-stride movement, which is a finding supported recently by Steele et al.[30] Steele et al.[30] examined lumbar kinematic variability during gait in participants with chronic LBP before and after a 12-week isolated lumbar extension exercise intervention. The authors reported no significant differences in ROM for the intervention group. However, an assessment of the sagittal plane kinematic waveform from one participant from the training group revealed less variability between individual trials. Therefore, it seems that presenting individual trials of time-series angle and variability data will allow the clinician to analyse the individual response to an intervention programme. Further evidence to support the use of single subject analysis has been documented.[63,64]

4.4. Recommendations

Based on the systematic appraisal of the current literature, any future research studies should use an appropriate marker cluster and should report the following information: (1) for replicating the study, (2) for accurate understanding of the results and (3) to improve the external validity.

- Details on the structural dimensions and materials used to construct the 3D must be clearly defined. A schematic of the 3D cluster must be reported. If previous recommendations are cited in the methodology, the authors must provide details and a schematic of the replica 3D cluster for comparative purposes and to support data interpretation.
- Details of the inertial properties of the 3D cluster should be provided. The 3D cluster should be of appropriate size and shape and the design should allow for it to be attached to the back surface using only double-sided adhesive tape. This will avoid the limitations from other structures which are used to secure the marker clusters.
- The relative distance between markers affixed to the semi-rigid structure must remain constant and should be reported. The use of a semi-rigid structure will allow for specific lumbar/trunk morphology considerations and would be less susceptible to excessive perturbation during a high impact task.
- Kinematic waveforms must be reported for both global and relative movements in addition to discrete measurements such as the RoM. This will provide a greater understanding of the actual movement recorded using the 3D cluster along

with the underlying movement data for effective clinical management.

5. Conclusion

The scarcity of details in published studies regarding the materials and construction of the 3D cluster limits the opportunity to investigate the external validity of this approach. In addition, the lack of validation and reliability analysis has restricted the application of such techniques in clinical settings. Furthermore, scarce information about functional movement using kinematic waveform information restricts the practical use of the data available to support clinical intervention programmes. Therefore, if this technique is to provide a reliable understanding of lumbar movement, it is recommended that future studies that employ a 3D cluster follow the recommendations outlined in this systematic review.

Disclosure statement

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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