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Abstract *(level 1 heading)*

Objective: The objective of this review is to identify and map current literature describing the center of rotation locations and migration paths during lumbar spine movements.

Introduction: The importance of lumbar spine kinematics has been described and altered kinematics has been associated with pain and injury. Intervertebral segments' center of rotations, the point around which spinal segments rotate, are important for determining the lumbar spine kinematics features and the potential for increased injury risk during movements. Although many studies have investigated the center of rotations of humans' lumbar spine, no review has summarized and organized the state of the science related to center of rotation locations and migration paths of the lumbar spine during lumbar spine movements.

Inclusion criteria: This review will consider studies that include human lumbar spines of any age and status condition (e.g. heathy, pathological) during lumbar spine movements. Quantitative study designs, including clinical, observational, laboratory biomechanical experimental studies, mathematical and computer modelling studies will be considered. Only studies published in English will be included, and there will be no limit on dates of publication.

Methods: PubMed, MEDLINE, Embase, the Cochrane Library Controlled Register of Trials, CINAHL, ACM Digital Library, Compendex, Inspec, Web of Science, Scopus, Google Scholar, and dissertation and theses repositories will be searched. After titles and abstracts screening of identified references, two independent reviewers will screen the full-text of identified studies and extract data. Data will be summarized and categorized, and a comprehensive narrative summary will be presented with the respective results.

Key words: Axis of rotation; center of rotation; lumbar spine; lumbar spine kinematics; lumbar spine movement

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Introduction *(level 1 heading)*

Low back pain (LBP) is a major healthcare challenge worldwide. The condition is incredibly common in all ages of the population, affecting 80% of people at some point in their life and approximately 7.3% of the population at any one time.[1-4] Even though the majority of LBP cases have no evidence of serious pathology, LBP is not a trivial situation for the patient or the global society. Low back pain is a highly burdensome condition and the leading cause of years lived with disability worldwide.[1] It is the most common reason for lost worked days in the United States,[5] has economic impact similar to cardiovascular diseases and cancer,[6] and has a substantial impact on the quality of life of individuals, especially in terms of financial wellbeing[7] and social identity.[8] Emerging research suggests that LBP is best viewed as a variable condition of a long duration, with the majority of cases resulting in either constant or fluctuating trajectories of symptoms.[9]

Despite LBP's high prevalence and impact on individuals and society, the etiology of LBP remains unclear. About 85% of LBP cases are still considered non-specific, as they are not resultant of any specific known pathology, such as vertebral fracture, spinal deformity or tumor.[10-12] Within the non-specific LBP cases, some studies have suggested that mechanical factors (such as prolonged sitting[13,14] and whole body vibration)[15,16] or genetic makeup[17] may affect the development or maintenance of LBP. On a more basic level, abnormal intersegmental movements of lumbar vertebra in terms of magnitude (e.g. abnormal increases or decreases in movement) and quality (e.g. abnormal coupling patterns) during lumbar movements (e.g. lumbar flexion and extension) have been suggested to increase the risk of injury or pain.[18-21] Theoretically, repeated abnormal segmental movements may damage spinal stabilizing structures by exceeding tissues' mechanical thresholds, which may impose abnormal demands on secondary restraints, creating spinal instability, injury and pain.[22] Since the stability of the spine is affected by the relative stability of three subsystems: active (i.e. muscles), passive (i.e. ligaments, vertebrae, and intervertebral discs), and neural (i.e. neuromuscular control), it has been hypothesized that the dysfunctions in any of these subsystems will lead to abnormal intervertebral movements.[23,24]

Altered lumbar segmental motions in patients with LBP compared to asymptomatic subjects have been previously reported in the literature.[25-27] However, the specific patterns of altered lumbar segmental kinematics that relate to LBP remain unclear. Specifically, while some studies have observed that LBP patients display reduced lumbar range of motion and angular velocity,[25,28,29] others have reported increased range of motion in the upper lumbar region as well as increased lumbar segmental mobility in people with LBP compared to asymptomatic controls.[26,30] These discrepancies can be partly attributed to the lack of a standardized and systematic approach in conducting lumbar spine kinematics investigations and the use of varied instruments and equipment. For example, electromagnetic tracking, inertial sensing-based system, dynamic imaging, static radiographs and three-dimentional motion capture systems have all been used in previous studies investigating lumbar spine kinematics.[26,28,31-33] Although objective measures are needed to determine abnormal lumbar intersegmental movements during physiological and dynamic movements, there is still measurement variance between instruments tracking the actual lumbar vertebral motions and those attached to the skin overlying the lumbar vertebrae.[34] These methodological differences could influence measurement accuracy, producing conflicting results and precluding the establishment of lumbar kinematics alterations inherent in patients with LBP.

Center of rotation (COR) is defined as the point around which motion segments of the spine appear to move. It is therefore intrinsically linked to the two primary measures of joint kinematics: rotation and translation. Moreover, it has been long understood that the center of reaction force can be extrapolated from the COR, allowing the estimation of inter-joint shear and compression forces.[35] The ability of the COR to be resolvable into these parameters can be used to characterize/quantify the kinematic features of the lumbar spine and specific motion segments.[36,37] The use of COR location and migration paths therefore lends itself to a greater utility than its constituent parameters when evaluating lumbar spine and motion segment kinematics, as well as intersegmental conditions. Many studies have investigated the CORs of the human lumbar spine under various conditions (e.g. dynamic movements, post-surgical, structural failure, low back pain etc.)[38-41] and it is commonly noted that the locations of the CORs change during physiological movements, creating migration paths.[35,37,42,43] Additionally, not only is there variation of CORs position during a forward bend but, while the average COR is usually located between the posterior, upper quarter of the lower vertebra and lower quarter of the intervertebral disc, there is a large variance of CORs between studies.[44] Given that different COR locations have been described to impact the lumbar kinetics, kinematics and trunk muscle activation, it is important to outline all evidence and understand the results currently available. To date, no review has been conducted to summarize and organize the state of the evidence related to COR locations and migration paths of the lumbar spine during lumbar spine physiological movements of any status (i.e. healthy, pathological, post-surgical etc.).

This work is of great importance as it aims to inform clinicians and researchers so they may have a better understanding of the current evidence related to lumbar intersegmental movement and how it may relate to LBP and other lumbar spine conditions, and be able to provide recommendations on standardized approaches for future investigations. Specifically, the recommendations expected at the end of this review will constitute strong foundations for the design of research protocols evaluating lumbar kinetics, kinematics, muscle activity and biomechanical experiments through COR measurement. From a clinical perspective, this review may benefit the development of new standardized measurement tools that could be integrated in clinical practice to evaluate and manage patients with lumbar spine conditions.

Therefore, the objective of the current scoping review is to map the scientific literature describing COR locations and migration paths during lumbar spine physiological movements of lumbar spines of any status. A preliminary search for existing reviews on COR locations and migration during lumbar spine movements was conducted on 22 February 2019 for the following databases: *JBI Database of Systematic Reviews and Implementation Reports*, PROSPERO, Cochrane Library, PubMed, EBSCO and CINAHL. No similar reviews to the current proposed scoping review were found.

Review questions *(level 1 heading)*

Specifically, the two research questions addressed in this scoping review are:

i. What are the COR locations during physiological movements of the human lumbar spine in any condition?
ii. What are the migration paths of the COR in the human lumbar spine in any condition throughout physiological movements?

Inclusion criteria *(level 1 heading)*

Participants (level 2 heading)

This review will examine studies that include humans of any age (i.e. pediatric, youth, adult and older adults) in any condition (i.e. healthy, athlete, injured, pathological, post-surgery/instrumented, cadaveric) performing basic physiological movements of the lumbar spine (i.e. flexion, extension, lateral bending, axial rotation, or a combination of movements with and without axial loading).

Concept (level 2 heading)

The concepts addressed in this scoping review are the locations and migration paths of CORs during lumbar spine movements measured by, but not limited to: static and dynamic imaging, motion capture, sensor tracking, and mathematical models.

Context (level 2 heading)

The proposed scoping review will consider studies investigating the COR locations and migration paths during movements of the human lumbar spine conducted in any environment including, but not limited to: clinical or laboratory setting, and computer modelling from any geographical region.

Types of studies (level 2 heading)

This review will consider all types of quantitative study designs, including clinical and laboratory biomechanical experimental studies and observational designs (cohort studies, case-control studies, cross-sectional studies, case studies and descriptive studies). Additionally, mathematical and computer modelling studies will also be considered for inclusion. Studies published in English from database inception up to the date in which the search is conducted will be considered for inclusion.
Studies will be excluded if they: i) involve animal models, ii) investigate spine regions other than the lumbar region (e.g. thoracic, thoracolumbar, lumbosacral), or iii) explore other outcomes as a function of the center of rotation location (e.g. facet joint forces, intradiscal pressure, muscle activity, range of motion, kinematics with different COR locations).

Methods *(level 1 heading)*

This protocol has been registered with the Open Science Framework on 12 December 2018 (https://osf.io/znbca/).

The protocol has been developed based on the methodological framework for scoping reviews proposed by Arksey and O'Malley[45] and further refined based on the JBI methodology for scoping reviews.[46] The Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR)[47] was also followed.

Search strategy (level 2 heading)

It is anticipated that relevant studies will be found in health sciences as well as engineering databases. To ensure that all studies are identified, comprehensive search strategies will be developed by two librarians with experience in developing systematic search strategies: one specializing in health sciences and the other in engineering. They will work together to develop a basic multiple structured search strategy, and then refine the strategy individually to tailor the search strategy to their respective area of expertise.

The search strategies will be based on the framework recommended by JBI methodology for scoping reviews[46]: population, concept and context (PCC). This framework was adapted from the PICO strategy (population, intervention, comparison, outcome), which is commonly used to provide readers with specific information on the focus and applicability of clinical investigations and systematic reviews. Search strategies developed by both librarians (health sciences and engineering) will be peer-reviewed by other librarians from the same institution using the Peer Review of Electronic Search Strategies (PRESS) checklist.

The following descriptors, indexed terms, keywords and their combinations will be used to construct the strategies: lumbar vertebra*, lumbar spine*, lumbar segment*, lower spine*, center* of rotation, centre* of rotation, centrode, axis of rotation, axes of rotation and helical axis. The search strategy developed for MEDLINE is detailed in Appendix I. The reference lists of relevant articles will also be screened to locate potential additional relevant articles.

Information sources (level 3 heading)

The identification of studies relevant to this review will be achieved by searching published literature on health sciences and engineering electronic databases as well as gray literature including: PubMed, MEDLINE, Embase, the Cochrane Library Controlled Register of Trials, CINAHL, ACM Digital Library, Compendex, Inspec, Web of Science, Scopus, Google Scholar web search, and dissertation and theses repositories. Despite the potential overlap between PubMed and MEDLINE databases, preliminary searches resulted in unique references from both databases. Therefore, the developed search strategy will be conducted on both databases with specific efforts to remove duplicate publications.

Study selection (level 2 heading)

After de-duplication of publications retrieved from searches in the abovementioned databases, two-level screening will be conducted to select relevant studies. The first level will include screening of titles and abstracts by two independent reviewers (MF and DDC) in order to identify publications that are eligible for full-text screening. The second level will involve the same two reviewers (MF and DDC) independently assessing the full-text articles' eligibility based on the inclusion/exclusion criteria. Any disagreements between reviewers regarding study eligibility will be resolved through discussion with a third reviewer (AB) until full consensus is achieved. Reasons for exclusion of full-text articles will also be recorded. Given that this is a scoping review, methodological quality assessment will not be conducted. Therefore, studies will not be excluded based on their methodological quality. A PRISMA-ScR flow diagram will be used to summarize the results of this search process.[48]

Data extraction (level 2 heading)

Data of included studies will be extracted by two independent reviewers (MF and AB). A data extraction form will be developed to extract study characteristics (authors, year of publication, country, and the study design) and detailed information regarding: i) sample or population (i.e. sample size, type of sample, sample status [e.g., healthy, injured, pathological, instrumented]); ii) COR measurement (i.e. COR measure/calculation method, COR location or migration path); and iii) lumbar spine (e.g. lumbar movement in which COR was measured, lumbar levels) of each included study in the scoping review. A provisional data extraction form is detailed in Appendix II. Information to be extracted from included studies may be refined and additional categories added during the data extraction process.

Data presentation (level 2 heading)

General and specific descriptions of the locations and migration paths of COR locations during lumbar spine movements will be combined and summarized, producing a list of locations and migration paths that have been reported in the literature. Firstly, a summary of the overall characteristics of each included study, such as population, study setting and method for measuring COR location will be presented. In order to present the data in a comprehensive and useful manner, data summaries will be divided and sub-divided into emerging categories. Some anticipated categories are: i) type of sample (e.g. human, modelling data); ii) status of the participants (e.g. healthy, post-surgical, or pathological); and iii) physiological movements investigated (e.g. COR during flexion, extension, lateral bending, and axial rotation). However, additional categories may emerge during the screening and data extraction stages. The categories to be used as primary, secondary or tertiary are planned to be as described above (i.e., the primary category being type of sample, secondary status of sample and tertiary the movement); however, categories may change based on the data extracted and on what the authors judge to be most comprehensive. Results of this study will be presented descriptively with the supplementation of tables, figures and graphs. To ensure adequate reporting quality, the PRISMA-ScR checklist will be used.[47]

References *(level 1 heading)*

1. Hoy D, Bain C, Williams G, March L, Brooks P, Blyth F, et al. A systematic review of the global prevalence of low back pain. Arthritis Rheum. 2012;64(6):2028–37.
2. Kamper SJ, Williams CM. Musculoskeletal Pain in Children and Adolescents: A Way Forward. J Orthop Sport Phys Ther. 2017;47(10):702-4.
3. Hartvigsen J, Christensen K, Frederiksen H. Back pain remains a common symptom in old age. A population-based study of 4486 Danish twins aged 70-102. Eur Spine J. 2003;12(5):528-34.
4. James SL, Abate D, Abate KH, Abay SM, Abbafati C, Abbasi N, et al. Global, regional, and national incidence, prevalence, and years lived with disability for 354 diseases and injuries for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet. 2018;392(10159):1789–858.
5. Bone and Joint Initiative USA. The Burden of Musculoskeletal Diseases in the United States. [Internet]. 3rd ed. 2015 [cited DATE]. Available from: http://www.boneandjointburden.org/docs/The Burden of Musculoskeletal Diseases in the United States %28BMUS%29 3rd Edition %28Dated 12.31.16%29.pdf
6. Maniadakis N, Gray A. The economic burden of back pain in the UK. Pain. 2000;84(1):95-103.
7. Schofield D, Kelly S, Shrestha R, Callander E, Passey M, Percival R. The impact of back problems on retirement wealth. Pain. 2012;153(1):203-10.
8. Hondras M, Hartvigsen J, Myburgh C, Johannessen H. Everyday burden of musculoskeletal conditions among villagers in rural Botswana: A focused ethnography. J Rehabil Med. 2016;48(5):449–55.
9. Dunn KM, Hestbaek L, Cassidy JD. Low back pain across the life course. Best Pract Res Clin Rheumatol. 2013;27(5):591–600.
10. Balagué F, Mannion AF, Pellisé F, Cedraschi C. Non-specific low back pain. Lancet [Internet]. 2012 Feb 4 [cited 2012 Jul 18];379(9814):482–91. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21982256
11. Deyo RA, Weinstein JN. Low Back Pain. N Engl J Med. 2001;344(5):363–70.
12. Cuesta-Vargas A, Farasyn A, Gabel CP, Luciano JV. The mechanical and inflammatory low back pain (MIL) index: development and validation. BMC Musculoskelet Disord. 2014;15(1):12.
13. Pengel LH, Herbert RD, Maher CG, Refshauge KM. Acute Low Back Pain: systematic review of its prognosis. 2003;327(7410):323.
14. Dunk NM, Callaghan JP. Lumbar spine movement patterns during prolonged sitting differentiate low back pain developers from matched asymptomatic controls. Work. 2010;35(1):3–14.
15. Okunribido OO, Shimbles SJ, Magnusson M, Pope M. City bus driving and low back pain: A study of the exposures to posture demands, manual materials handling and whole-body vibration. Appl Ergon. 2007;38(1):29–38.
16. Burström L, Nilsson T, Wahlström J. Whole-body vibration and the risk of low back pain and

sciatica: a systematic review and meta-analysis. Int Arch Occup Environ Health. 2015;88(4):403–18.

17. Livshits G, Popham M, Malkin I, Sambrook PN, MacGregor AJ, Spector T, et al. Lumbar disc degeneration and genetic factors are the main risk factors for low back pain in women: The UK Twin Spine Study. Ann Rheum Dis. 2011;70(10):1740–5.
18. Kaigle A, Ekström L, Holm S, Rostedt M, Hansson T. In vivo dynamic stiffness of the porcine lumbar spine exposed to cyclid loading. J Spinal Disord. 1998;11(1):65–70.
19. Iguchi T, Kanemura A, Kasahara K, Sato K, Kurihara A, Yoshiya S, et al. Lumbar instability and clinical symptoms: Which is the more critical factor for symptoms: Sagittal translation or segment angulation? J Spinal Disord Tech. 2004;17(4):284–90.
20. Kanemura A, Doita M, Kasahara K, Sumi M, Kurosaka M, Iguchi T. The Influence of Sagittal Instability Factors on clinical lumbar spinal symptoms. 2009;22(7):479–85.
21. Ahmadi A, Maroufi N, Behtash H, Zekavat H, Parnianpour M. Kinematic analysis of dynamic lumbar motion in patients with lumbar segmental instability using digital videofluoroscopy. Eur Spine J. 2009;18(11):1677–85.
22. Mulholland RC. The myth of lumbar instability: The importance of abnormal loading as a cause of low back pain. Eur Spine J. 2008;17(5):619–25.
23. Panjabi MM. The stabilizing system of the spine. Part II. Neutral zone and instability hypothesis. J Spinal Disord. 1992;5(4):390-6.
24. Panjabi MM. A hypothesis of chronic back pain: Ligament subfailure injuries lead to muscle control dysfunction. Eur Spine J. 2006;15(5):668–76.
25. Vaisy M, Gizzi L, Petzke F, Consmüller T, Pfingsten M, Falla D. Measurement of Lumbar Spine Functional Movement in Low Back Pain. Clin J Pain. 2015;31(10):876–85.
26. Kulig K, Powers CM, Landel RF, Chen H, Fredericson M, Guillet M, et al. Segmental lumbar mobility in individuals with low back pain: in vivo assessment during manual and self-imposed motion using dynamic MRI. BMC Musculoskelet Disord. 2007;8(1):1–10.
27. Ochia RS, Inoue N, Takatori R, Andersson GBJ, An HS. In Vivo Measurements of Lumbar Segmental Motion During Axial Rotation in Asymptomatic and Chronic Low Back Pain Male Subjects. Spine. 2007;32(13):1394–9.
28. Shum GLK, Crosbie J, Lee RYW. Effect of low back pain on the kinematics and joint coordination of the lumbar spine and hip during sit-to-stand and stand-to-sit. Spine. 2005;30(17):1998–2004.
29. Lee JK, Desmoulin GT, Khan AH, Park EJ. Comparison of 3D spinal motions during stair-climbing between individuals with and without low back pain. Gait Posture. 2011;34(2):222–6.
30. Gombatto SP, D'Arpa N, Landerholm S, Mateo C, O'Connor R, Tokunaga J, et al. Differences in kinematics of the lumbar spine and lower extremities between people with and without low back pain during the down phase of a pick up task, an observational study. Musculoskelet Sci Pract. 2017;28:25–31.

31. Abbott JH, Fritz JM, McCane B, Shultz B, Herbison P, Lyons B, et al. Lumbar segmental mobility disorders: comparison of two methods of defining abnormal displacement kinematics in a cohort of patients with non-specific mechanical low back pain. BMC Musculoskelet Disord. 2006;7(1):1–11.
32. Gombatto SP, D'Arpa N, Landerholm S, Mateo C, O'Connor R, Tokunaga J, et al. Differences in kinematics of the lumbar spine and lower extremities between people with and without low back pain during the down phase of a pick up task, an observational study. Musculoskelet Sci Pract. 2017;28:25–31.
33. Lee JK, Desmoulin GT, Khan AH, Park EJ. Comparison of 3D spinal motions during stair-climbing between individuals with and without low back pain. Gait Posture. 2011;34(2):222–6.
34. Zhengyi Yang, Heather Ting Ma, Deming Wang, Lee R. Error analysis on spinal motion measurement using skin mounted sensors. 2009;4740–3.
35. Bogduk N, Amevo B, Pearcy M. A biological basis for instantaneous centres of rotation of the vertebral column. Proc Inst Mech Eng Part H J Eng Med. 1995;209(3):177–83.
36. Senteler M, Aiyangar A, Weisse B, Farshad M, Snedeker JG. Sensitivity of intervertebral joint forces to center of rotation location and trends along its migration path. J Biomech. 2018;70:140–8.
37. Aiyangar A, Zheng L, Anderst W, Zhang X. Instantaneous centers of rotation for lumbar segmental extension in vivo. J Biomech. 2017;52:113–21.
38. Alapan Y, Demir C, Kaner T, Guclu R, Inceoğlu S. Instantaneous center of rotation behavior of the lumbar spine with ligament failure. J Neurosurg Spine. 2013;18(6):617–26.
39. Wattananon P, Intawachirarat N, Cannella M, Sung W, Silfies SP. Reduced instantaneous center of rotation movement in patients with low back pain. Eur Spine J. 2017;27(1):154–62.
40. Inoue M, Mizuno T, Sakakibara T, Kato T, Yoshikawa T, Inaba T, et al. Trajectory of instantaneous axis of rotation in fixed lumbar spine with instrumentation. J Orthop Surg Res. 2017;12(1):1–8.
41. Liu Z, Tsai T, Wang S, Wu M, Zhong W, Li J, et al. Sagittal plane rotation center of lower lumbar spine during a dynamic weight-lifting activity. J Biomech. 2016;49(3):371–5.
42. Ogston N, Gertzbein SD, Tile M, Kapasouri A, Rubenstein J. Centrode patterns in the lumbar spine . Baseline studies in normal subjects. Clin Biomech. 1987;2(2):108.
43. Yoshioka T, Tsuji H, Hirano N, Sainoh S. Motion Characteristic of the normal lumbar in young adults: instantaneous axis of rotation and vertebral center motion analyses. J Spinal Disord. 1990;3(2):103–13.
44. Widmer J, Fornaciari P, Senteler M, Roth T, Snedeker JG, Farshad M. Kinematics of the Spine Under Healthy and Degenerative Conditions: A Systematic Review. Ann Biomed Eng. 2019;47(7):1491–522.
45. Arksey H, O'Malley L. Scoping studies: Towards a methodological framework. Int J Soc Res Methodol Theory Pract. 2005;8(1):19–32.
46. Peters MDJ, Godfrey CM, Khalil H, McInerney P, Parker D, Soares CB. Guidance for conducting

systematic scoping reviews. Int J Evid Based Healthc. 2015;13(3):141–6.

47. Aromataris E, Munn Z (Editors). Joanna Briggs Institute Reviewer's Manual [Internet]. Adelaide: Joanna Briggs Institute; 2017 [cited DATE]. Available from: https://reviewersmanual.joannabriggs.org/.

48. Tricco AC, Lillie E, Zarin W, O'Brien K, Colquhoun H, Kastner M, et al. A scoping review on the conduct and reporting of scoping reviews. BMC Med Res Methodol. 2016;16(1):1–10.

49. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. Ann Intern Med. 2018;169(7):467–73.

Appendix I: Search strategy for MEDLINE *(level 1 heading)*

Search conducted February 2019, retrieving 1134 references.

1. MH Lumbar Vertebrae
2. TI lumbar* or AB lumbar*
3. TI lower n2 spinal* or AB lower n2 spinal*
4. TI lower n2 spine* or AB lower n2 spine*
5. TI (L1 or L2 or L3 or L4 or L5) or AB (L1 or L2 or L3 or L4 or L5)
6. TI (L-1 or L-2 or L-3 or L-4 or L-5) or AB (L-1 or L-2 or L-3 or L-4 or L-5)
7. TI body n2 joint or AB body n2 joint*
8. TI human n2 joint* or AB human n2 joint*
9. **1-8/OR [**lumbar spine]**

10. MH Rotation
11. TI (axes* AND rotation*) or AB (axes* AND rotation*)
12. TI (axis* AND rotation*) or AB (axis* AND rotation*)
13. TI (axis* AND helical*) or AB (axis* AND helical*)
14. TI (axes* AND helical*) or AB (axes* AND helical*)
15. TI (center* AND rotation*) or AB (center* AND rotation*)
16. TI (centre* AND rotation*) or AB (centre* AND rotation*)
17. TI centrod* or AB centrod*
18. TI motion n2 characteristic* or motion n2 characteristic*
19. **10-18/OR [**center of rotation]**

20. 9 AND 19
21. LIMIT 20 English Language
22. LIMIT 21 NOT (animal* NOT human*)

Appendix II: Provisional data extraction form *(level 1 heading)*

Study characteristics:

- **Human studies:**
  - Author
  - Year of publication
  - Population characteristics
    - Living status (live vs. cadaveric)
    - Age
    - Sex
  - Sample size (n)
  - Sample status (i.e. healthy, injured, pathological, rehabilitated, instrumented)
  - Lumbar level
  - Motion characteristics (e.g. flexion, extension, lateral bending, axial rotation, combined movement)
  - Loading characteristics (e.g. axial loading, active/passive movement)
  - Method of center-of-rotation location measurement (e.g. imaging, motion capture, mathematical model estimation)
  - Center-of-rotation location/migration path

- **Modeling studies:**
  - Author
  - Year of publication
  - Model characteristics
    - Type of model
    - Source of data and characteristics (e.g. age, sex, condition: healthy, injured, pathological, instrumented, etc.)
    - Geometry (personalized/generic/idealized)
    - Material characteristics
  - Number of models and boundary conditions
  - Lumbar level
  - Motion characteristics (e.g. flexion, extension, lateral bending, axial rotation, combined movement)
  - Loading characteristics (e.g. axial loading, active/passive movement)
  - Method of center-of-rotation location measurement (e.g. imaging, motion capture, mathematical model estimation)
  - Center-of-rotation location/migration path